ECEN 667
Power System Stability

Lecture 20: Voltage Stability, Oscillations

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Announcements

- Read Chapter 8
- Homework 6 is due on Tuesday Nov 21

Power System Stability Terms

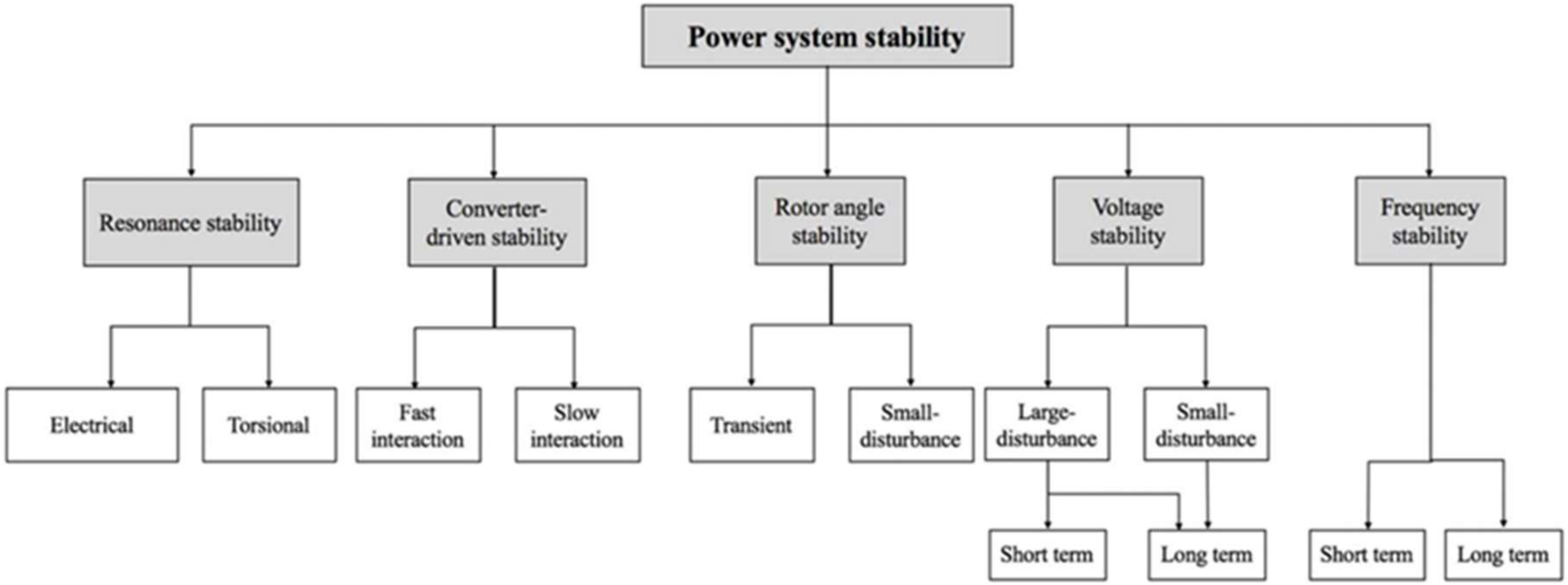
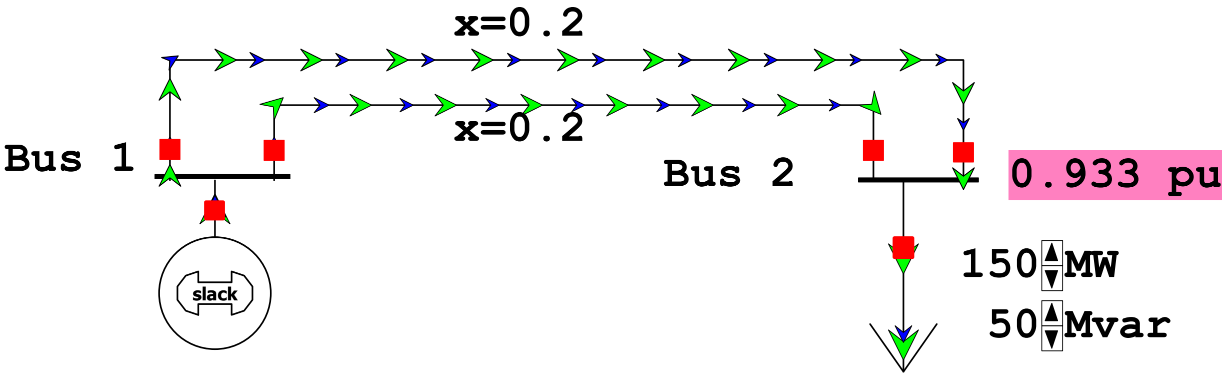
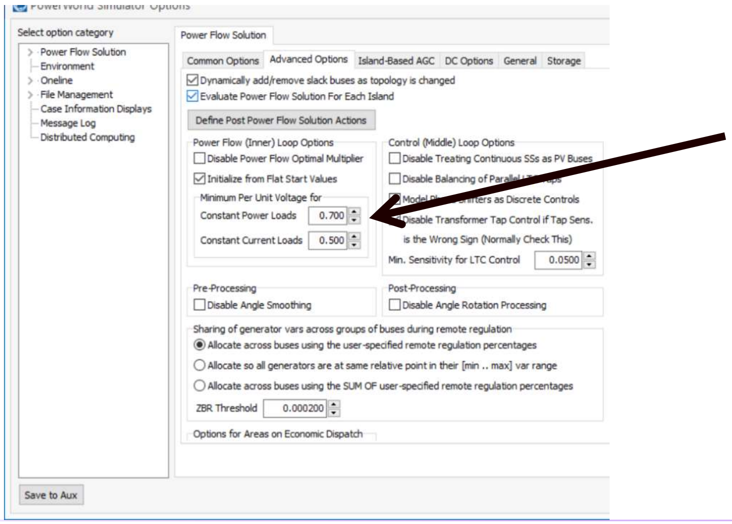


Fig. 4. Classification of power system stability

[a] IEEE/PES Power System Dynamic Performance Committee, "Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies", PES-TR77, April 2020

PowerWorld Two Bus Example





☑ Dynamically add/remove slack buses as topology is changed
☑ Evaluate Power Flow Solution For Each Island

Power Flow (Inner) Loop Options
☐ Disable Power Flow Optimal Multiplier
☑ Initialize from Flat Start Values
Minimum Per Unit Voltage for
Constant Power Loads 0.700
Constant Current Loads 0.500

Control (Middle) Loop Options
☐ Disable Treating Continuous SSs as PV Buses
☐ Disable Balancing of Parallel LTC Taps
☑ Model Phase Shifters as Discrete Controls
☑ Disable Transformer Tap Control if Tap Sens. is the Wrong Sign (Normally Check This)
Min. Sensitivity for LTC Control 0.0500

Pre-Processing
☐ Disable Angle Smoothing

Post-Processing
☐ Disable Angle Rotation Processing

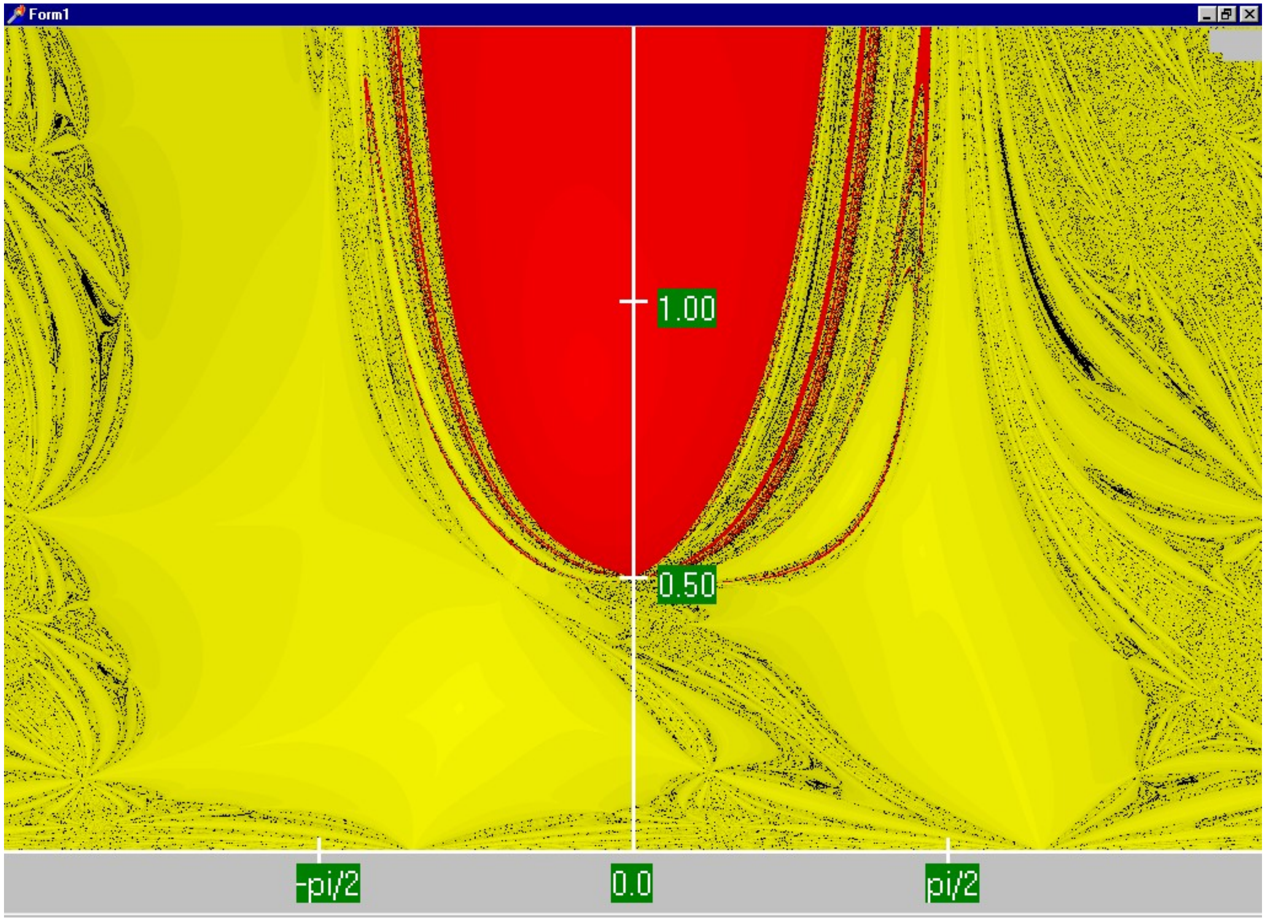
Sharing of generator vars across groups of buses during remote regulation
● Allocate across buses using the user-specified remote regulation percentages
○ Allocate so all generators are at same relative point in their [min .. max] var range
○ Allocate across buses using the SUM OF user-specified remote regulation percentages
ZBR Threshold 0.000200

Options for Areas on Economic Dispatch

Commercial power flow software usually auto converts constant power loads at low voltages; set these fields to zero to disable this conversion

Case is **Bus2_PV**

Power Flow Region of Convergence

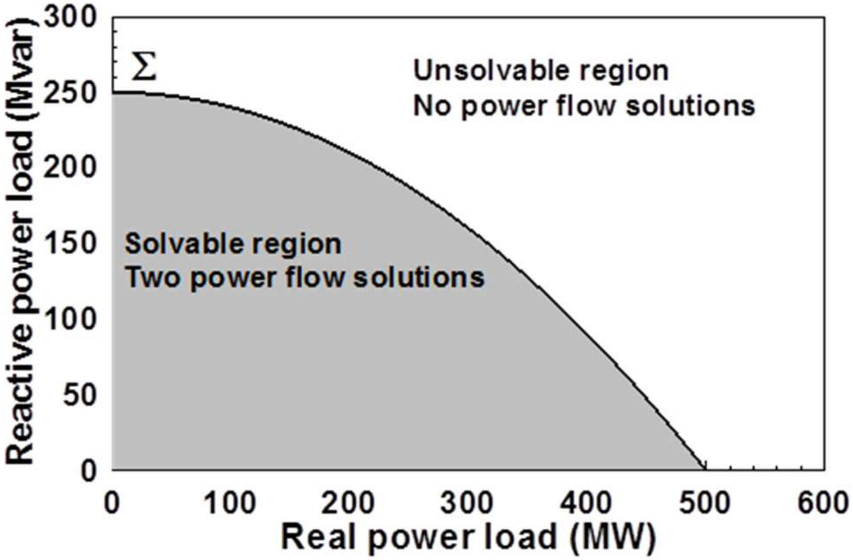


Convergence regions with P=100 MW, Q=0 Mvar

Load Parameter Space Representation

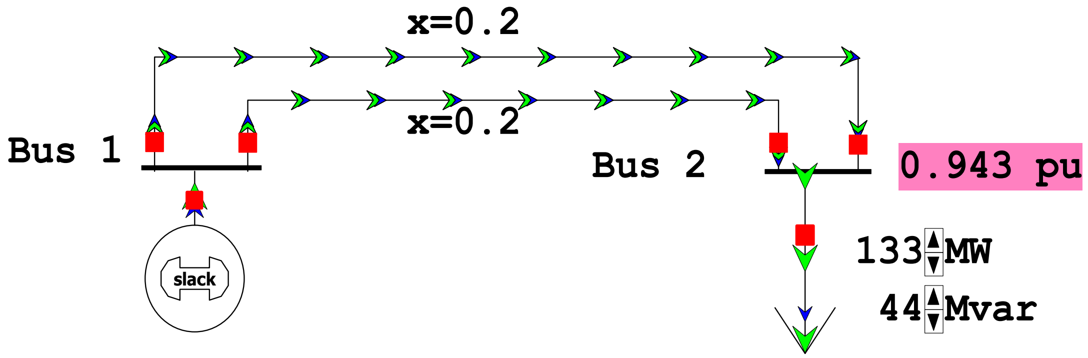
- With a constant power model there is a maximum loadability surface, Σ
  - Defined as point in which the power flow Jacobian is singular
  - For the lossless two bus system it can be determined as

$$-\frac{P_L^2}{B} + Q_L + \frac{1}{4}B = 0$$



Load Model Impact

- With a static load model regardless of the voltage dependency the same PV curve is traced
  - But whether a point of maximum loadability exists depends on the assumed load model
    - If voltage exponent is > 1 then multiple solutions do not exist (see B.C. Lesieutre, P.W. Sauer and M.A**.** Pai "Sufficient conditions on static load models for network solvability," NAPS 1992, pp. 262-271)

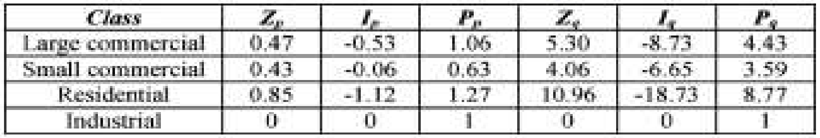


Change the load to constant impedance; hence it becomes a linear model

ZIP Model Coefficients

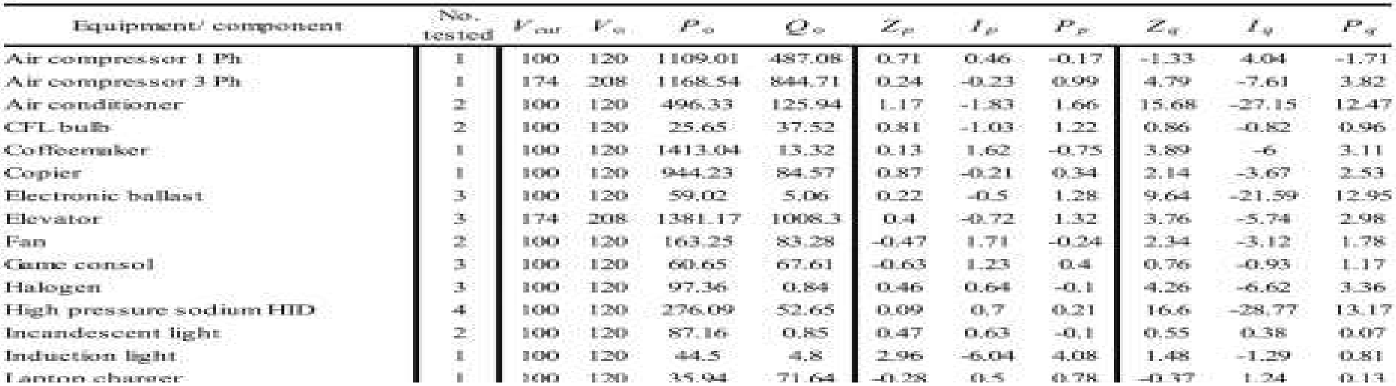
- One popular static load model is the ZIP; lots of papers on the “correct” amount of each type

TABLE I
ZIP COEFFICIENTS FOR EACH CUSTOMER CLASS



Class	Z_p	I_p	P_p	Z_q	I_q	P_q
Large commercial	0.47	-0.53	1.06	5.30	-8.73	4.43
Small commercial	0.43	-0.06	0.63	4.06	-6.65	3.59
Residential	0.85	-1.12	1.27	10.96	-18.73	8.77
Industrial	0	0	1	0	0	1

TABLE VII
ACTIVE AND REACTIVE ZIP MODEL. FIRST HALF OF THE ZIPS WITH 100-V CUTOFF VOLTAGE. SECOND HALF REPORTS THE ZIPS WITH ACTUAL CUTOFF VOLTAGE



Equipment/ component	No. tested	V_{cut}	V_o	P_o	Q_o	Z_p	I_p	P_p	Z_q	I_q	P_q
Air compressor 1 Ph	1	100	120	1109.01	487.08	0.71	0.46	-0.17	-1.33	4.04	-1.71
Air compressor 3 Ph	1	174	208	1168.54	844.71	0.24	-0.23	0.99	4.79	-7.61	3.82
Air conditioner	2	100	120	496.33	125.94	1.17	-1.83	1.66	15.68	-27.15	12.47
CFL bulb	2	100	120	25.65	37.52	0.81	-1.03	1.22	0.86	-0.82	0.96
Coffeemaker	1	100	120	1413.04	13.32	0.13	1.62	-0.75	3.89	-6	3.11
Copier	1	100	120	944.23	84.57	0.87	-0.21	0.34	2.14	-3.67	2.53
Electronic ballast	3	100	120	59.02	5.06	0.22	-0.5	1.28	9.64	-21.59	12.95
Elevator	3	174	208	1381.17	1008.3	0.4	-0.72	1.32	3.76	-5.74	2.98
Fan	2	100	120	163.25	83.28	-0.47	1.71	-0.24	2.34	-3.12	1.78
Game consol	3	100	120	60.65	67.61	-0.63	1.23	0.4	0.76	-0.93	1.17
Halogen	3	100	120	97.36	0.84	0.46	0.64	-0.1	4.26	-6.62	3.36
High pressure sodium HID	4	100	120	276.09	52.65	0.09	0.7	0.21	16.6	-28.77	13.17
Incandescent light	2	100	120	87.16	0.85	0.47	0.63	-0.1	0.55	0.38	0.07
Induction light	1	100	120	44.5	4.8	2.96	-6.04	4.08	1.48	-1.29	0.81
Laptop charger	1	100	120	35.94	71.64	-0.28	0.5	0.78	-0.37	1.24	0.13

Table 1 from M. Diaz-Aguilo, et. al., “Field-Validated Load Model for the Analysis of CVR in Distribution Secondary Networks: Energy Conservation,” *IEEE Trans. Power Delivery*, Oct. 2013

ZIP Model Coefficients

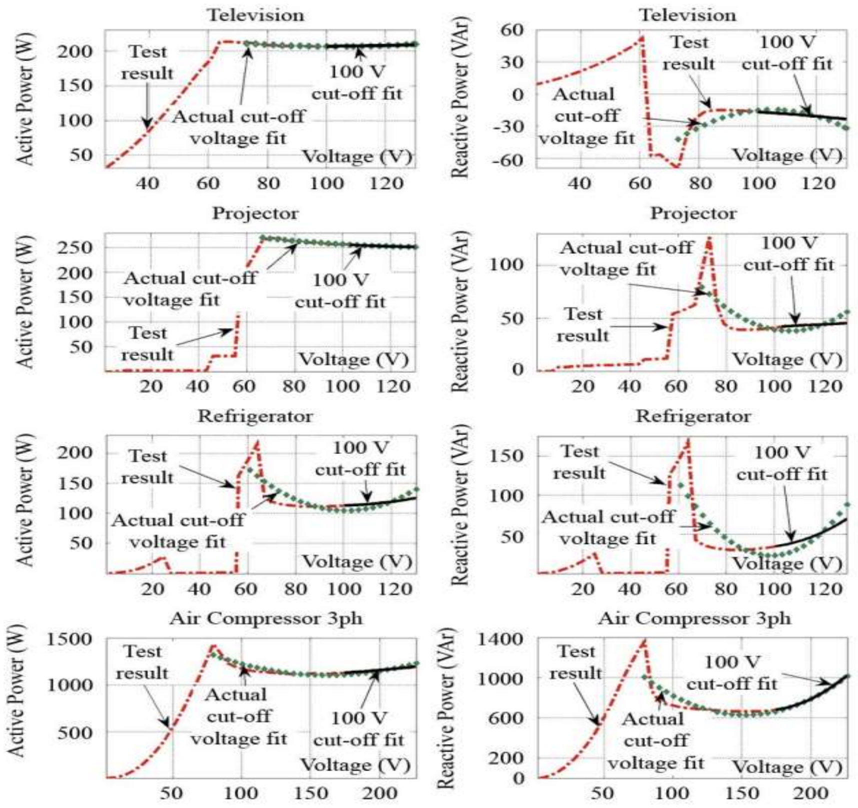


Fig. 3. Active and reactive test results with constrained curve fitting. The ZIP curve with the 100-V cutoff is shown in the solid line and ZIP with the actual cutoff voltage in the dashed line. The two sets of ZIPs are shown in Table VII.

Figure 3 from A, Bokhari, et. al., "Experimental Determination of the ZIP Coefficients for Modern Residential, Commercial, and Industrial Loads," *IEEE Trans. Power Delivery*, June. 2014

Application: Conservation Voltage Reduction (CVR)

- If the “steady-state” load has a true dependence on voltage, then a change (usually a reduction) in the voltage should result in a total decrease in energy consumption
- If an “optimal” voltage could be determined, then this could result in a net energy savings
- Some challenges are 1) the voltage profile across a feeder is not constant, 2) the load composition is constantly changing, 3) a decrease in power consumption might result in a decrease in useable output from the load, and 4) loads are dynamic and an initial decrease might be balanced by a later increase

CVR Issues

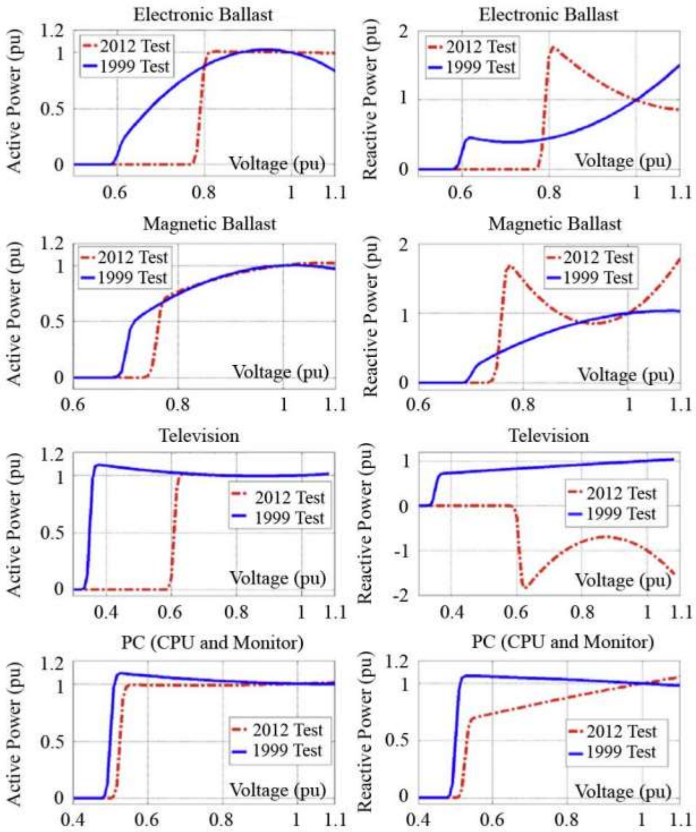
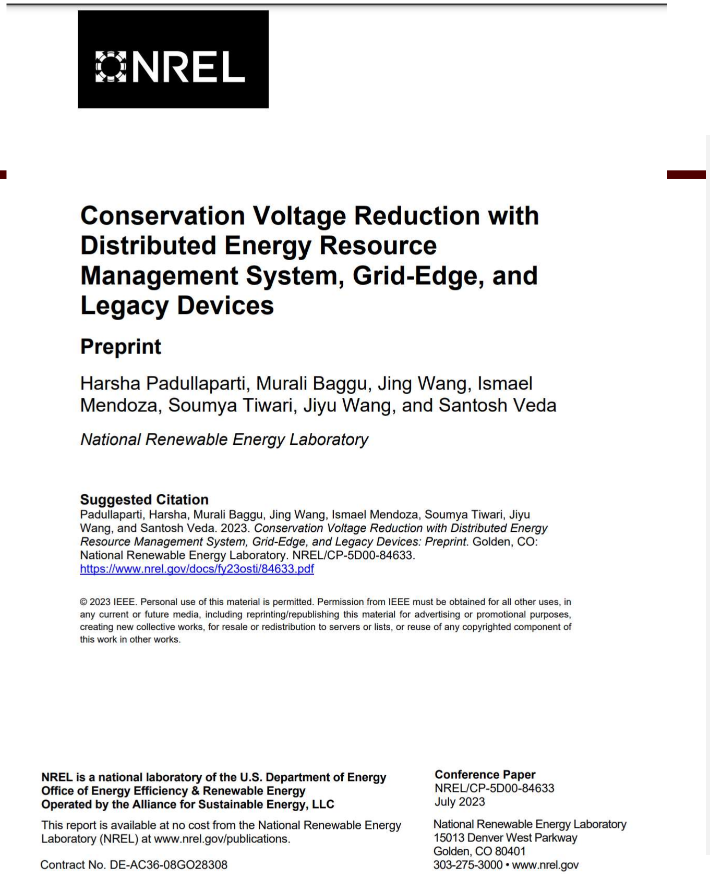


Fig. 4. Comparison of active and reactive powers between old and new appliances.



NREL

Conservation Voltage Reduction with Distributed Energy Resource Management System, Grid-Edge, and Legacy Devices

Preprint

Harsha Padullaparti, Murali Baggu, Jing Wang, Ismael Mendoza, Soumya Tiwari, Jiyu Wang, and Santosh Veda

National Renewable Energy Laboratory

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https://www.nrel.gov/docs/fy23osti/84633.pdf

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Figure 4 from A, Bokhari, et. al., “Experimental Determination of the ZIP Coefficients for Modern Residential, Commercial, and Industrial Loads,” *IEEE Trans. Power Delivery*, June. 2014

- The gist of the 2023 NREL paper is distributed generation (like PV) can help with CVR through better feeder voltage regulation

Dynamic Load Response

- As first reported in the below paper, following a change in voltage there will be a dynamic load response
  - Residential supply voltage should be between 114 and 126 V
- If there is a heating load the response might be on the order of ten minutes
- Longer term issues can also come into play

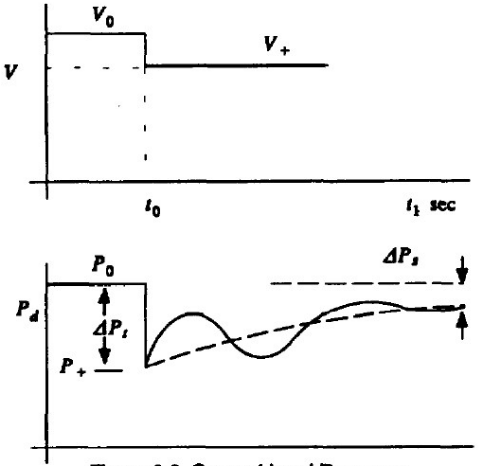


Figure 2.2 General Load Response

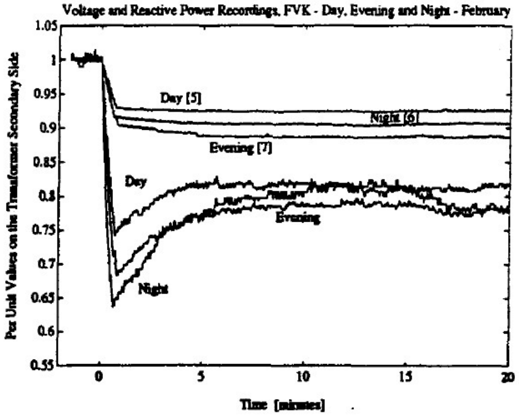
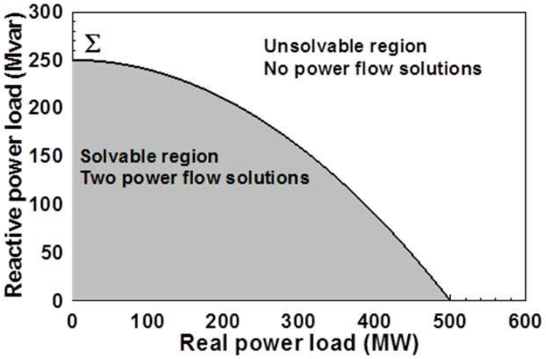


Figure 4.4b. Voltage and reactive power recordings after a voltage reduction in FVK: February: day, evening and night. The number of tap-changer steps used for the ramp is shown in brackets.

Useful paper and figure reference: D. Karlsson, D.J. Hill, "Modeling and Identification of Nonlinear Dynamic Loads in Power Systems," IEEE. Trans. on Power Systems, Feb 1994, pp. 157-166

Determining a Metric to Voltage Collapse

- The goal of much of the voltage stability work was to determine an easy to calculate metric (or metrics) of the current operating point to voltage collapse
  - PV and QV curves (or some combination) can determine such a metric along a particular path
  - Goal was to have a path independent metric. The closest boundary point was considered, but this could be quite misleading if the system was not going to move in that direction
  - Any linearization about the current operating point (i.e., the Jacobian) does not consider important nonlinearities like generators hitting their reactive power limits



Assessing Voltage Margin Using PV and QV Curve Analysis

- A common method for assessing the distance in parameter space to voltage instability (or an undesirable voltage profile) is to trace how the voltage magnitudes vary as the system parameters (such as the loads) are changed in a specified direction
  - If the direction involves changing the real power (P) this is known as a PV curve; if the change is with the reactive power (Q) then this is a QV curve
- PV/QV curve analysis can be generalized to any parameter change, and can include the consideration of contingencies

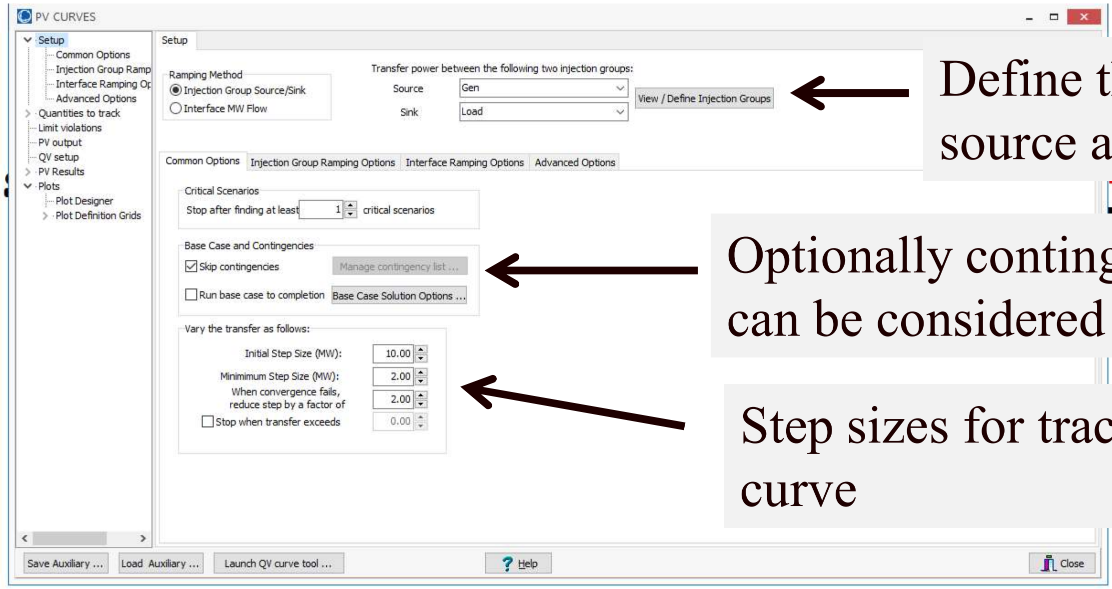
PV and QV Analysis in PowerWorld

- Requires setting up what is known in PowerWorld as an injection group
  - An injection group specifies a set of objects, such as generators and loads, that can inject or absorb power
  - Injection groups can be defined by selecting **Case Information, Aggregation, Injection Groups**
- The PV and/or QV analysis then varies the injections in the injection group, tracing out the PV curve
- This allows optional consideration of contingencies
- The PV tool can be displayed by selecting **Add-Ons, PV**

This has already been done in the **Bus2_PV** case

PV and QV Analysis in PowerWorld: Two Bus Example

- Setup page defines the source and sink and step size



Ramping Method
● Injection Group Source/Sink
○ Interface MW Flow

Transfer power between the following two injection groups:
Source: Gen
Sink: Load

Critical Scenarios
Stop after finding at least 1 critical scenarios

Base Case and Contingencies
☑ Skip contingencies
☐ Run base case to completion

Vary the transfer as follows:
Initial Step Size (MW): 10.00
Minimum Step Size (MW): 2.00
When convergence fails, reduce step by a factor of 2.00
☐ Stop when transfer exceeds 0.00

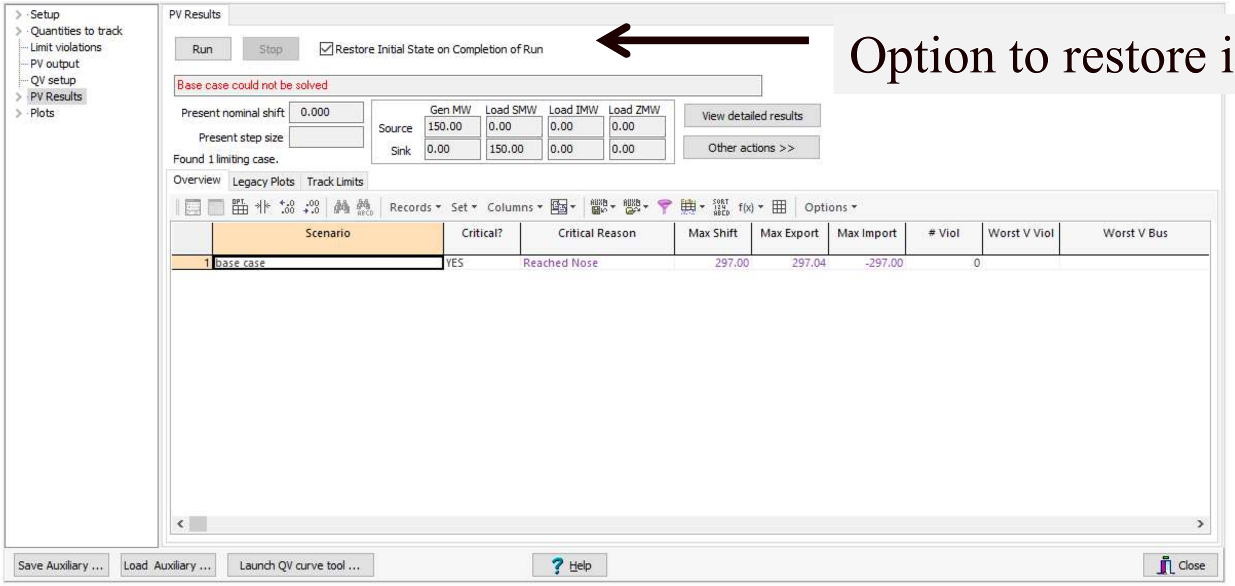
Define the source and sink

Optionally contingencies can be considered

Step sizes for tracing the curve

PV and QV Analysis in PowerWorld: Two Bus Example

- The PV Results Page does the actual solution
  - Plots can be defined to show the results
    - This should be done beforehand
  - **Other Actions**, **Restore initial state** restores the pre-study state



☑ Restore Initial State on Completion of Run

Base case could not be solved

Present nominal shift: 0.000

Present step size:

Found 1 limiting case.

	Gen MW	Load SMW	Load IMW	Load ZMW
Source	150.00	0.00	0.00	0.00
Sink	0.00	150.00	0.00	0.00

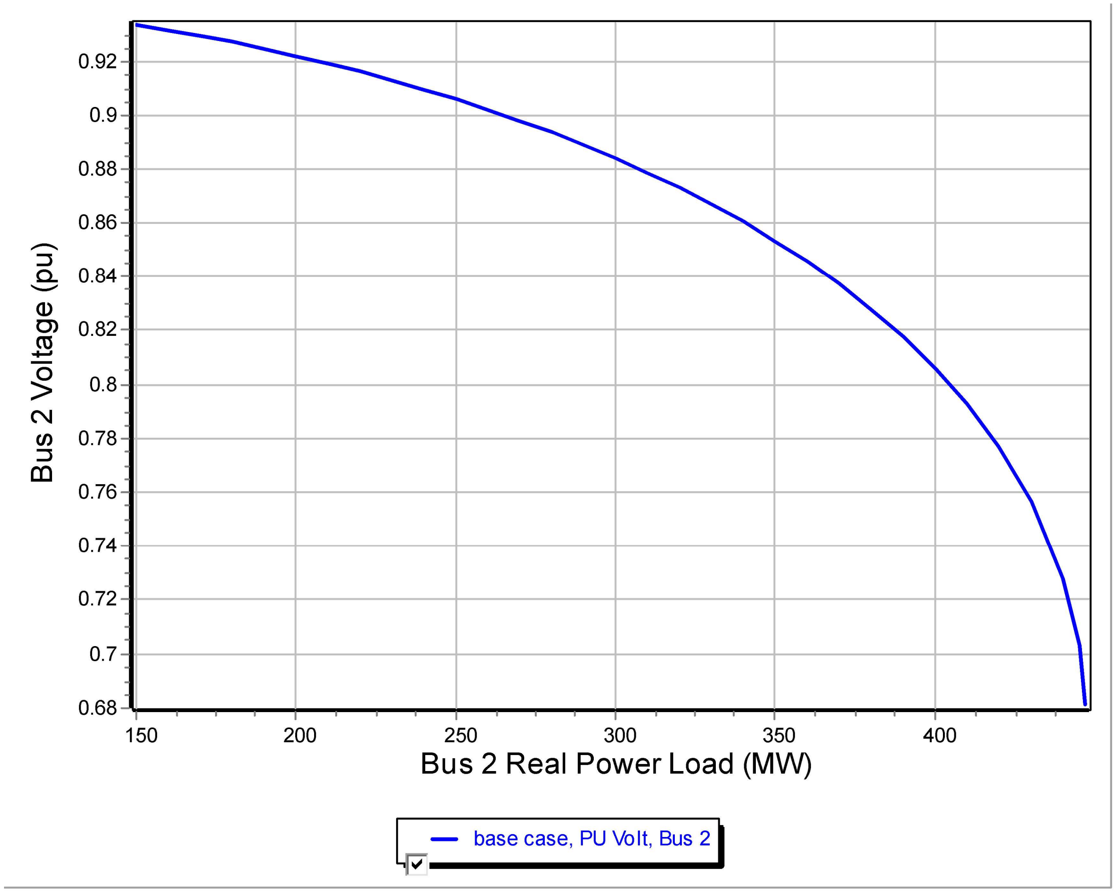
	Scenario	Critical?	Critical Reason	Max Shift	Max Export	Max Import	# Viol	Worst V Viol	Worst V Bus
1	base case	YES	Reached Nose	297.00	297.04	-297.00	0		

Option to restore initial state

Click the **Run** button to run the PV analysis;

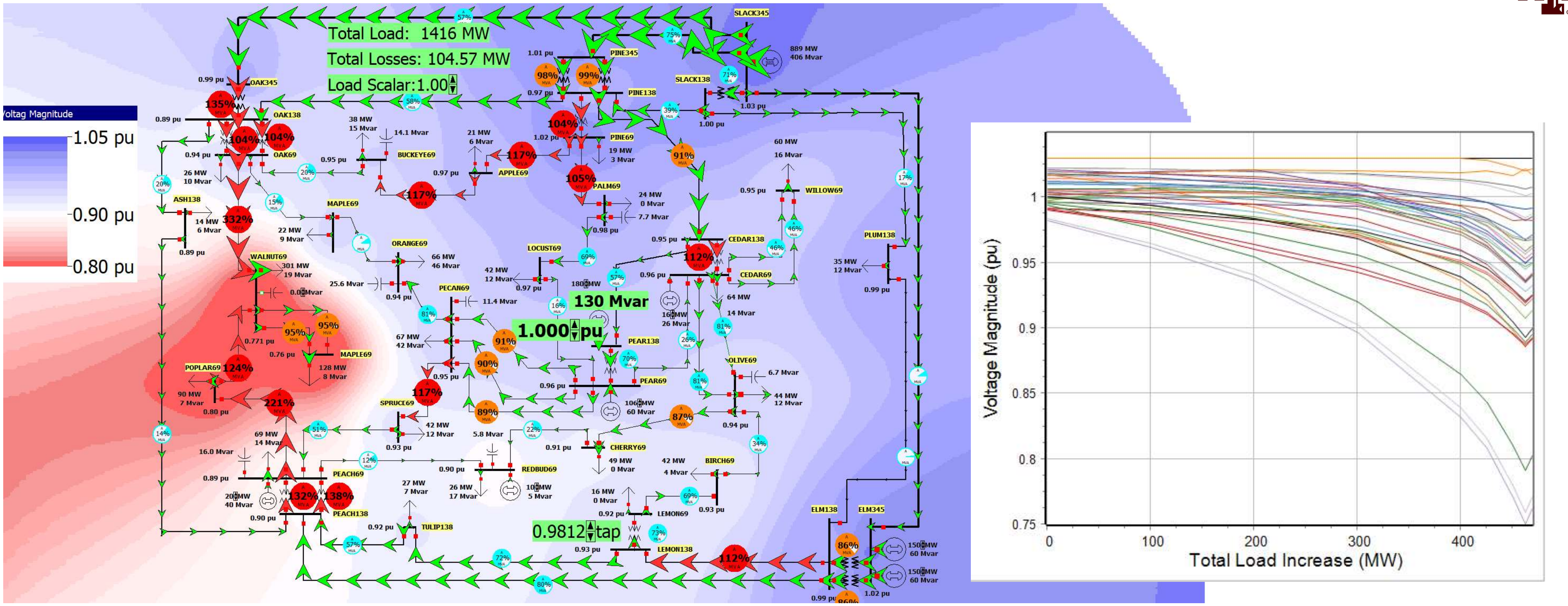
Check the **Restore Initial State on Completion of Run** to restore the pre-PV state (by default it is not restored)

PV and QV Analysis in PowerWorld: Two Bus Example



To restore the starting case, on the **PV Results** page select **Other Actions, Restore Initial State**

PV and QV Analysis in PowerWorld: 37 Bus Example



Usually other limits also need to be considered in doing a realistic PV analysis; example case is **Bus37_PV**

Oscillations

- An oscillation is just a repetitive motion that can be either undamped, positively damped (decaying with time) or negatively damped (growing with time)
- If the oscillation can be written as a sinusoid then

$$e^{\alpha t}\left(a\cos(\omega t)+b\sin(\omega t)\right)=e^{\alpha t}C\cos(\omega t+\theta)$$

$$\text{where } C=\sqrt{A^2+B^2} \text{ and } \theta=\tan\left(\frac{-b}{a}\right)$$

- The damping ratio is

$$\xi=\frac{-\alpha}{\sqrt{\alpha^2+\omega^2}}$$

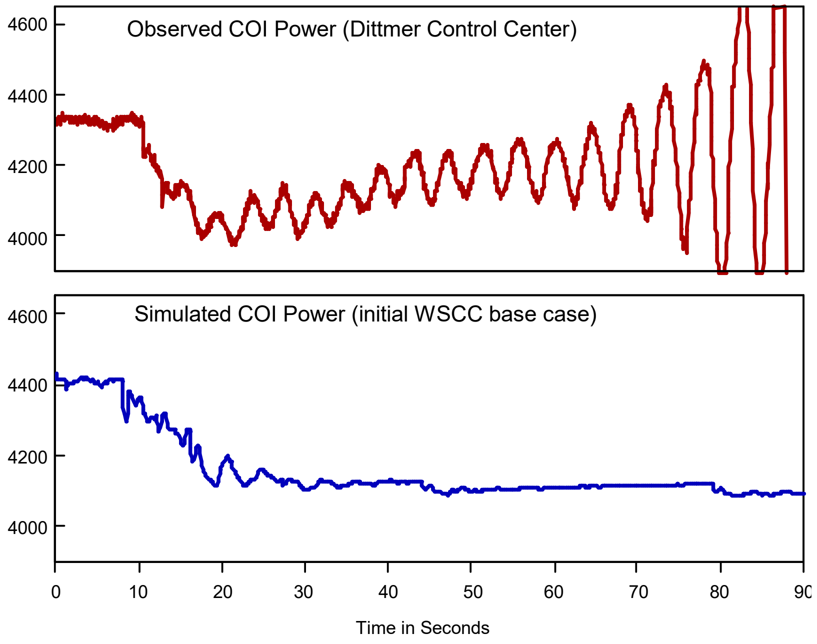
The percent damping is just the damping ratio multiplied by 100; goal is sufficiently positive damping

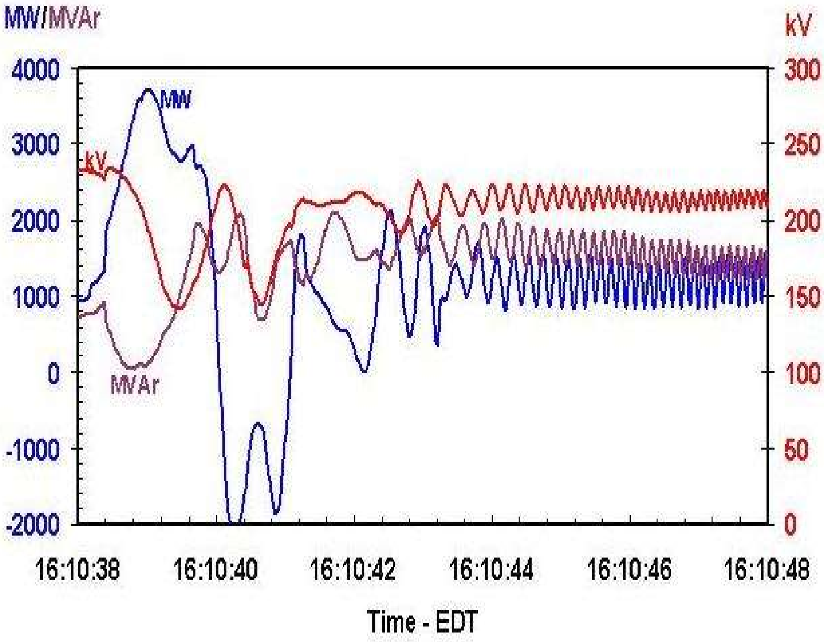
Power System Oscillations

- Power systems can experience a wide range of oscillations, ranging from highly damped and high frequency switching transients to sustained low frequency (< 2 Hz) inter-area oscillations affecting an entire interconnect
- Types of oscillations include
  - Transients: Usually high frequency and highly damped
  - Local plant: Usually from 1 to 5 Hz
  - Inter-area oscillations: From 0.15 to 1 Hz
  - Slower dynamics: Such as AGC, less than 0.15 Hz
  - Subsynchronous resonance: 10 to 50 Hz (less than synchronous)

Example Oscillations

- The left graph shows an oscillation that was observed during a 1996 WECC Blackout, the right from the 8/14/2003 blackout





References

- For the 1996 WECC blackout, more information is available at
  - www.nerc.com/pa/rrm/ea/System%20Disturbance%20Reports%20DL/1996System Disturbance.pdf; the July 2, 1996 event was caused by a tree contact
- Charlie Concordia wrote a paper on electric grid oscillations in 1938
  - C. Concordia, S. B. Crary, J.M. Lyons, Stability Characteristics of Turbine Generators, *AIEE Transactions*, vol. 57, pp. 732-744, 1938.
- There is a 2021 NERC document on oscillations at www.nerc.com/comm/PC/SMSResourcesDocuments/Interconnection_Oscillation_Analysis.pdf
  - Also see T.J. Overbye, S. Kunkolienkar, F. Safdarian, A. Birchfield, "On the Existence of Dominant Inter-Area Oscillation Modes in the North American Eastern Interconnect Stability Simulations", 57th Hawaii International Conference on System Sciences, Honolulu, HI, January 2024 (on Overbye.engr.tamu.edu)

Modes

- A mode is a concept from linear system analysis
  - Electric grids certainly are not linear, but usually their response to small disturbances is approximated as linear
- A mode corresponds to one of the eigenvalues of the response or, for oscillations, a complex pair of eigenvalues
- A mode has a frequency and damping; all parts of the system oscillate with this pattern
- The mode shape tells how parts of the system participate in the mode
- There can be multiple modes in a system; power systems can have many modes

Causes of Power System Oscillations

- The response of a simple system can be divided into its natural response versus its forced response
    - The natural response tells how the system will response to an initial disturbance without any additional (external) influences; this response shows the system's modes
    - A forced response is associated with an external disturbance; if the external disturbance is periodic then the system will oscillate at least partially at this frequency
    - Often forced oscillations are due to control failures
- Resonance occurs when a forced response is at a similar frequency to one of the system's modes
- An power system can experience both types of oscillations

Forced Oscillations in WECC (from [1])

- Summer 2013 24 hour data: 0.37 Hz oscillations observed for several hours. Confirmed to be forced oscillations at a hydro plant from vortex effect.
- 2014 data: Another 0.5 Hz oscillation also observed. Source points to hydro unit as well. And 0.7 Hz. And 1.12 Hz. And 2 Hz.
- Resonance possible when system modes are poorly damped and close to the forcing function. Resonance can be observed in model simulations.

1. M. Venkatasubramanian, "Oscillation Monitoring System", June 2015
http://www.energy.gov/sites/prod/files/2015/07/f24/3.%20Mani%20Oscillation%20Monitoring.pdf

Observing Modes and Damping

- With the advent of wide-scale PMU deployments, the modes and damping can be observed two ways
  - Event (ringdown) analysis – this requires an event
  - Ambient noise analysis – always available, but not as distinct

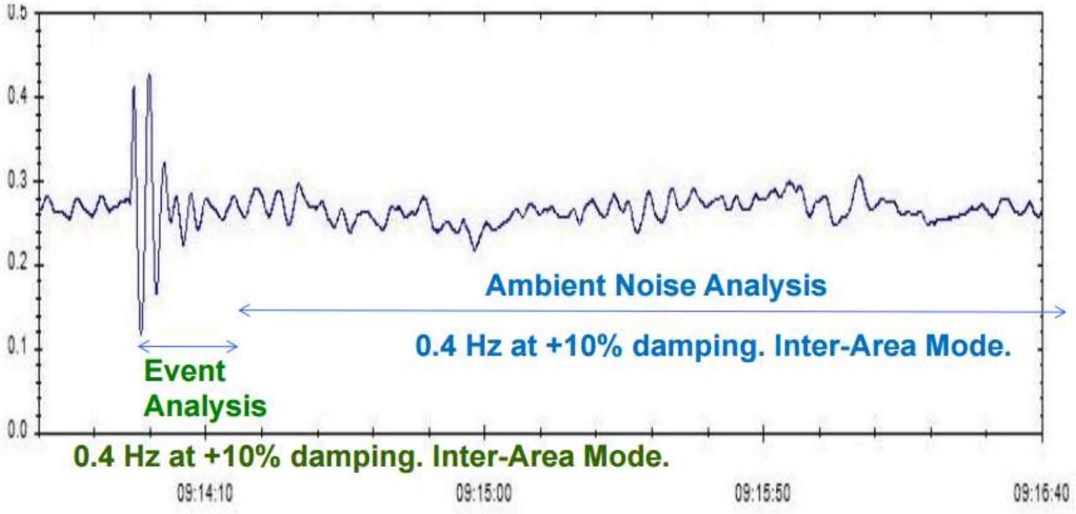


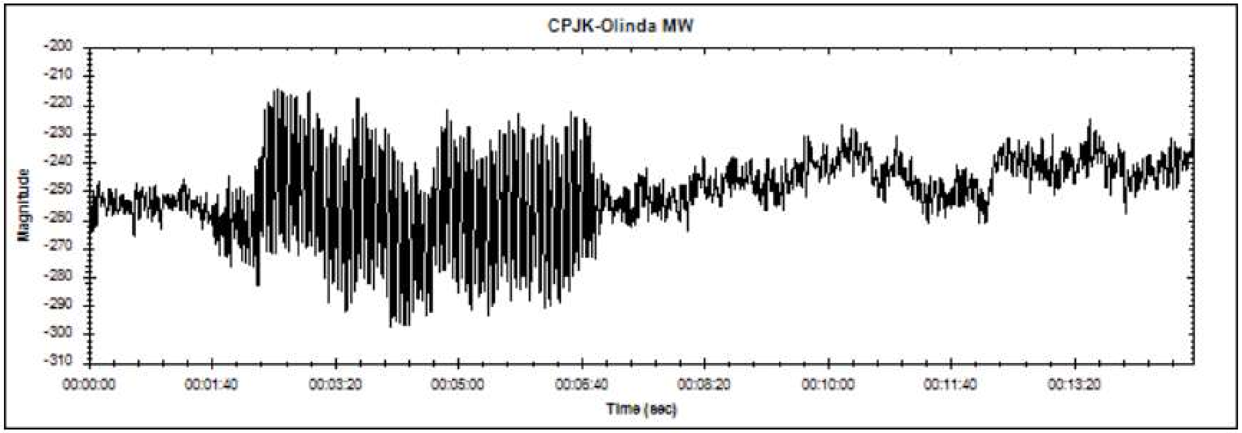
Image Source: M. Venkatasubramanian, “Oscillation Monitoring System”, June 2015
http://www.energy.gov/sites/prod/files/2015/07/f24/3.%20Mani%20Oscillation%20Monitoring.pdf

Resonance with Interarea Mode [1]

- Resonance effect high when:
  - Forced oscillation frequency near system mode frequency
  - System mode poorly damped
  - Forced oscillation location near the two distant ends of mode
- Resonance effect medium when
  - Some conditions hold
- Resonance effect small when
  - None of the conditions holds

1. M. Venkatasubramanian, "Oscillation Monitoring System", June 2015
http://www.energy.gov/sites/prod/files/2015/07/f24/3.%20Mani%20Oscillation%20Monitoring.pdf

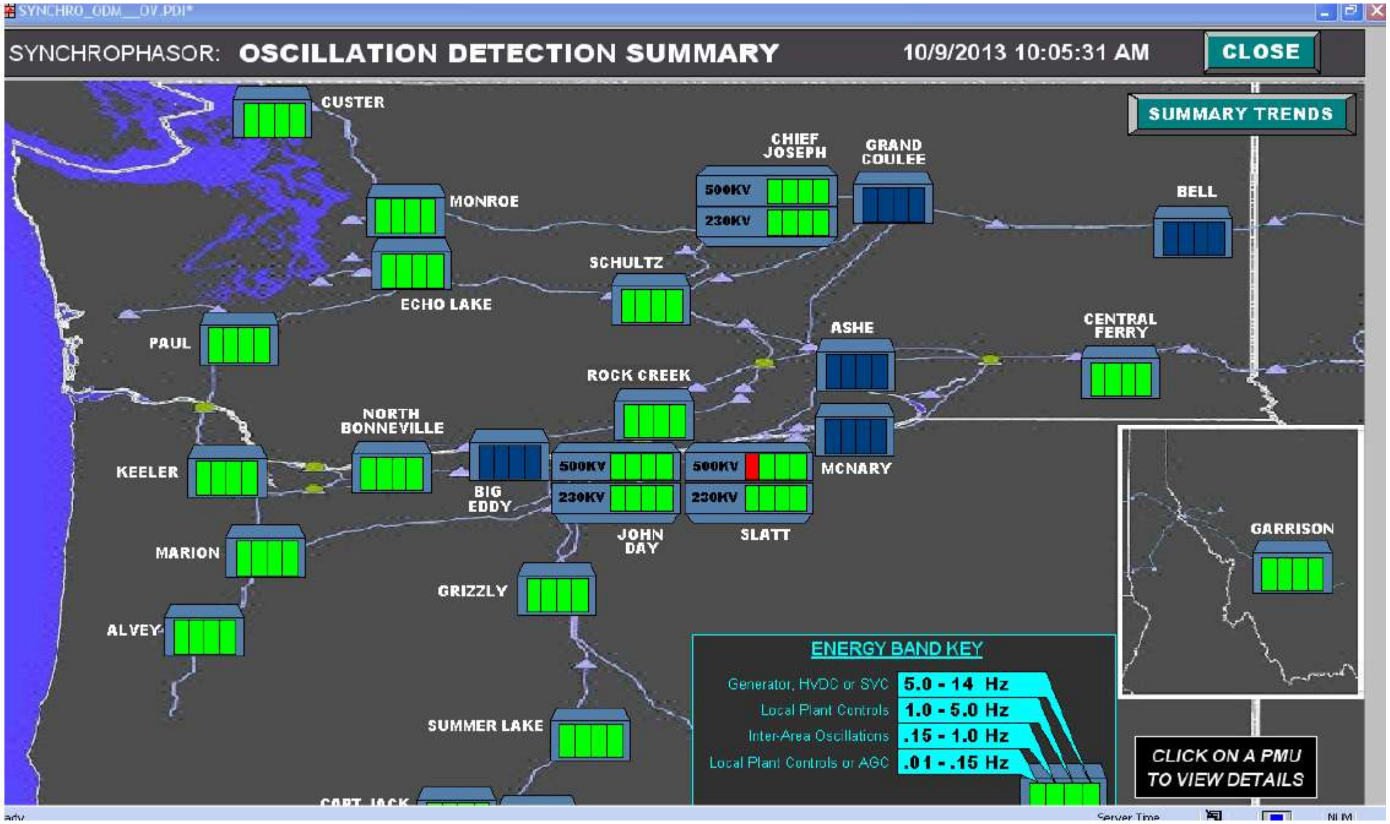
Medium Resonance on 11/29/2005



- 20 MW 0.26 Hz Forced Oscillation in Alberta Canada
- 200 MW Oscillations on California-Oregon Inter-tie
- System mode 0.27 Hz at 8% damping
- Two out of the three conditions were true.

1. M. Venkatasubramanian, "Oscillation Monitoring System", June 2015
http://www.energy.gov/sites/prod/files/2015/07/f24/3.%20Mani%20Oscillation%20Monitoring.pdf

An On-line Oscillation Detection Tool



ENERGY BAND KEY

Generator, HVDC or SVC	5.0 - 14 Hz
Local Plant Controls	1.0 - 5.0 Hz
Inter-Area Oscillations	.15 - 1.0 Hz
Local Plant Controls or AGC	.01 - .15 Hz

Image source: WECC Joint Synchronized Information Subcommittee Report, October 2013