ECEN 667
Power System Stability

Lecture 19: Voltage Stability

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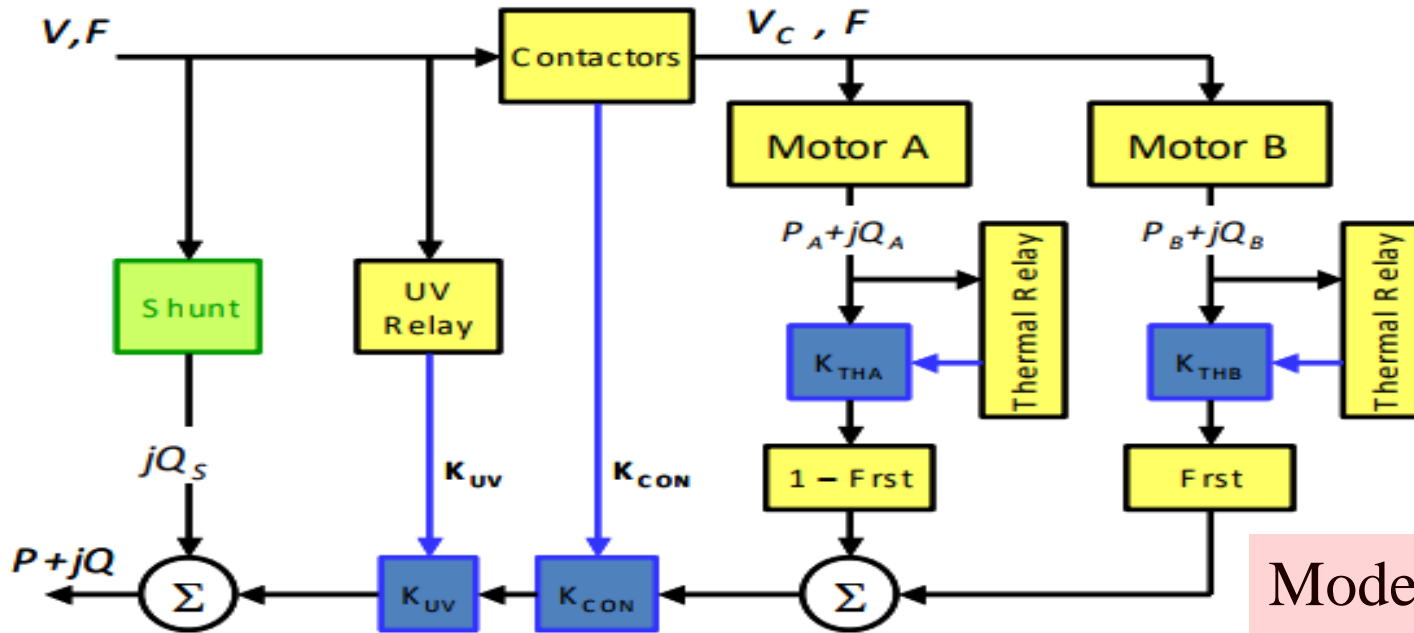
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Announcements

- Read Chapter 8

- Homework 5 is due on Tuesday Nov 12

Single Phase Induction Motor Loads

- A new load model is one that explicitly represents the behavior of single phase induction motors, which are quite small and stall very quickly

    - Single phase motors also start slower than an equivalent three phase machine

- New single phase induction motor model (LD1PAC) is a static model (with the assumption that the dynamics are fast), that algebraically transitions between running and stalled behavior based on the magnitude of the terminal voltage

Single Phase Induction Motor Loads

The compressor motor model is divided into two parts:
   Motor A – Those compressors that can't restart soon after stalling
   Motor B – Those compressors that can restart soon after stalling

If Mbase > 0 then this value of *MVAbase* is used and the *CompLF* = 1.0
If Mbase = 0 then *MVABase* = *Pinit* * *Pul* and *CompLF* = 1.0
If Mbase < 0 then *CompLF* = abs(*Mbase*) and *MVABase* = *Pinit**Pul/*CompLF*

The values of *Vstall* and *Vbrk* are adjusted according to the value of *LFAdj*.
   $Vstall = Vstall[1 + LFAdj(CompLF - 1)]$
   $Vbrk = Vbrk[1 + LFAdj(CompLF - 1)]$

Model is mostly algebraic, but with stalling behavior

Composite Load Models

- Many aggregate loads are best represented by a combination of different types of load
    - Known as composite load models
    - Important to keep in mind tbat the actual load is continually changing, so any aggregate load is at best an approximation
    - Hard to know load behavior to extreme disturbances without actually faulting the load
- Early models included a number of loads at the transmission level buses (with the step-down transformer), with later models including a simple distribution system model

CLOD Model

- The CLOD model represents the load as a combination of large induction motors, small induction motors, constant power, discharge lighting, and other


Transmission Bus

Distribution Bus

Distribution Capacitors

Large Motors Small Motors Constant Power Other Discharge Lighting

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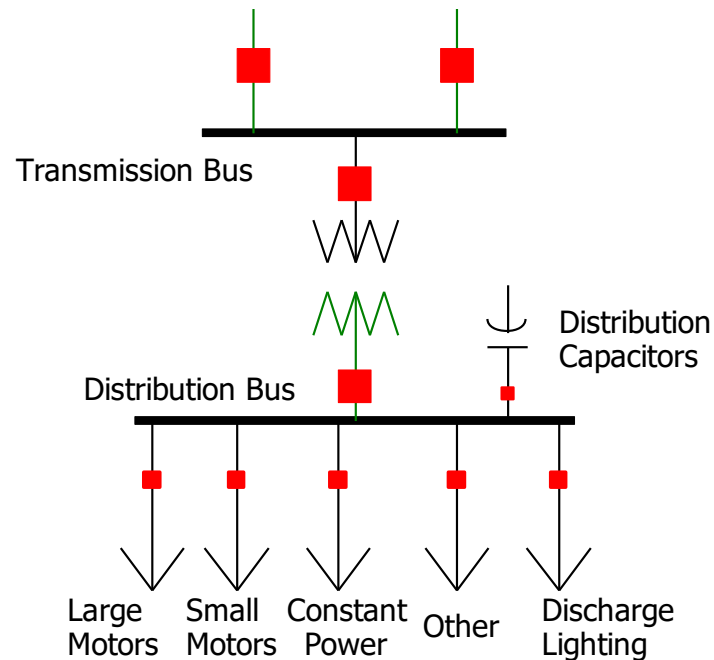
CLOD Model

- Different load classes can be defined

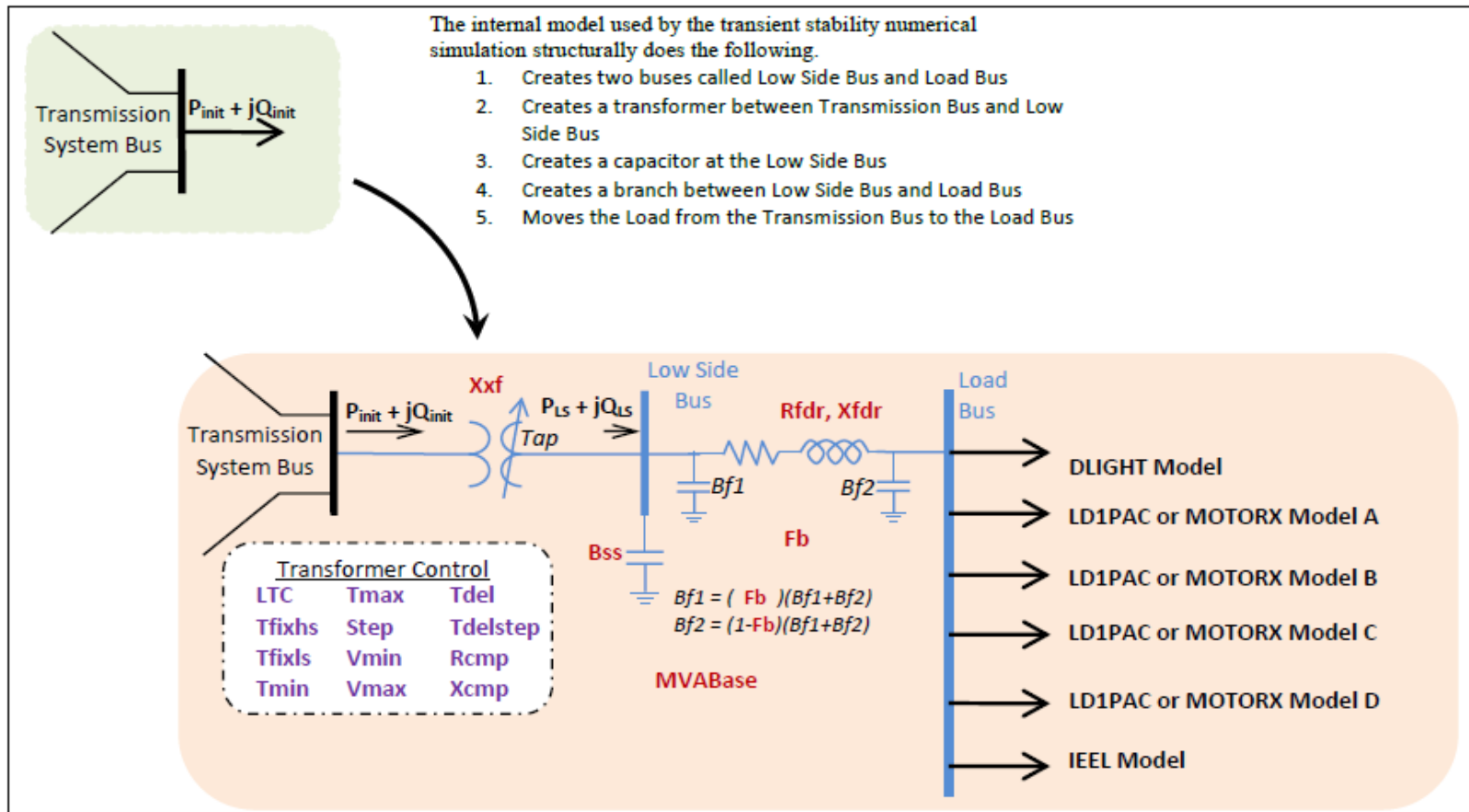| Customer Class	Large Motor	Small Motor	Discharge Lighting	Constant Power	Remaining (PI, QZ)
Residential	0.0	64.4	3.7	4.1	27.8
Agriculture	10.0	45	20	4.5	19.5
Commercial	0.0	46.7	41.5	4.5	7.3
Industrial	65.0	15.0	10.0	5.0	4.0
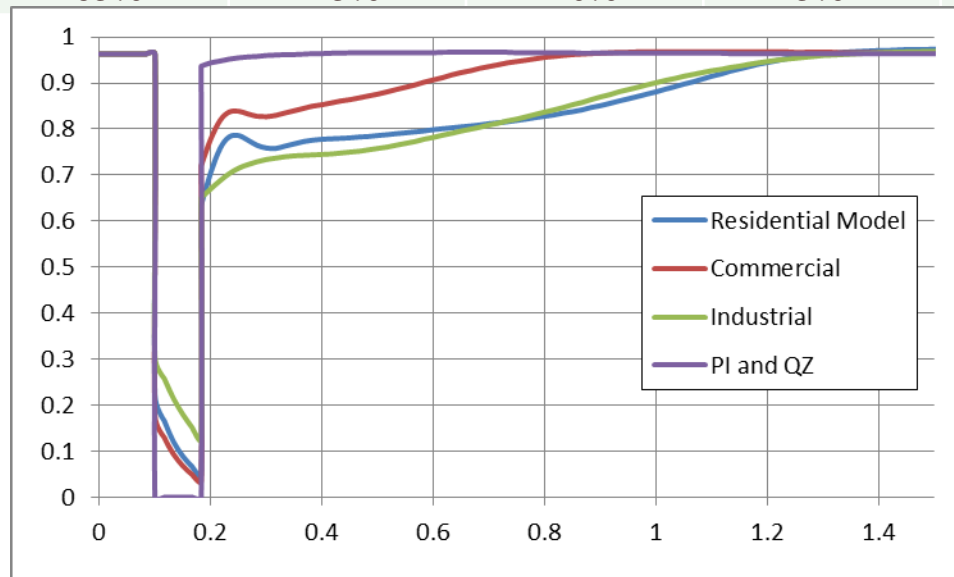
Comparison of voltage recovery for different model types

WECC Composite Load Model

- Contains up to four motors or single phase induction motor models; also includes potential for solar PV

The internal model used by the transient stability numerical simulation structurally does the following.

1. Creates two buses called Low Side Bus and Load Bus
2. Creates a transformer between Transmission Bus and Low Side Bus
3. Creates a capacitor at the Low Side Bus
4. Creates a branch between Low Side Bus and Load Bus
5. Moves the Load from the Transmission Bus to the Load Bus

Modeling Time Variation in Load

- Different time varying composite model parameters are now being used
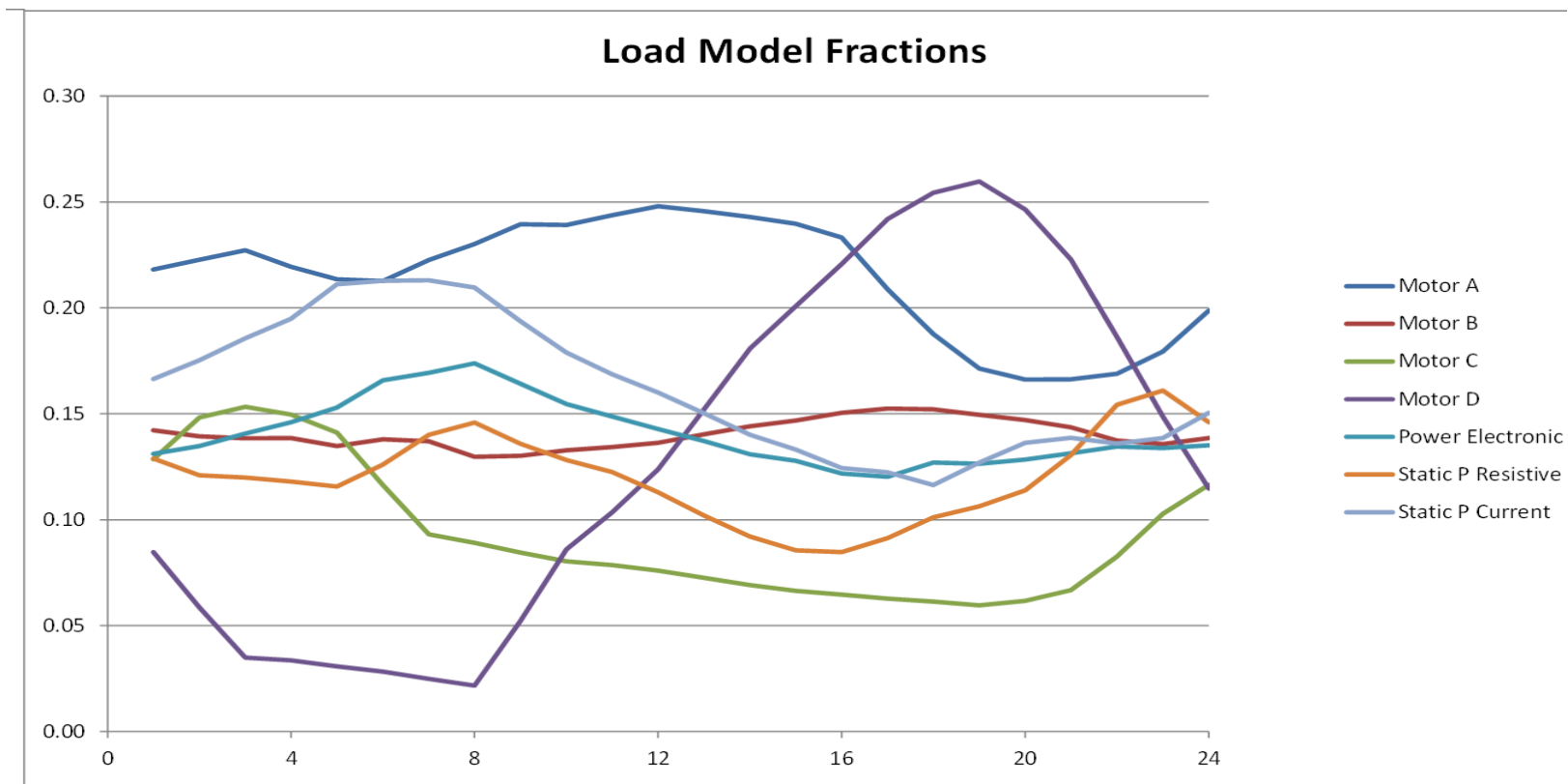
Example of varying composite load percentages over a day

Current Research

- Current topics for load modeling research include assessment of how much the load model maters

- Another issue is how to determine the load model parameters – which ones are observable under what conditions

  – For example, motor stalling can not be observed except during disturbances that actually cause the motors to stall

  – Not important to precisely determine parameters that ultimately do not have much influence on the final problem solution; of course these parameters would be hard to observe

- Correctly modeling embedded distribution level generation resources, such as PV, is important

Scientific Modeling Quotes

- "*All models are wrong but some are useful,*"
  - George Box, *Empirical Model-Building and Response Surfaces*, (1987, p. 424)
  - Box went on to say that the practical question is how wrong they have to be to not be useful

- "*Everything should be made as simple as possible, but not simpler.*"
  - Albert Einstein [maybe]

- "*With four parameters I can fit an elephant, and with five I can make him wiggle his trunk*".
  - John von Neumann
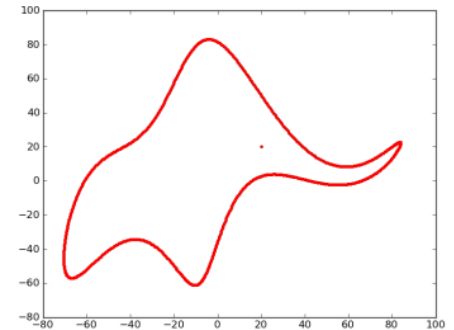
Power System Voltage Stability

- **Voltage Stability**: The ability to maintain system voltage so that both power and voltage are controllable. System voltage responds as expected (i.e., an increase in load causes proportional decrease in voltage).

- **Voltage Instability**: Inability to maintain system voltage. System voltage and/or power become uncontrollable. System voltage does not respond as expected.

- **Voltage Collapse**: Process by which voltage instability leads to unacceptably low voltages in a significant portion of the system. Typically results in loss of system load.
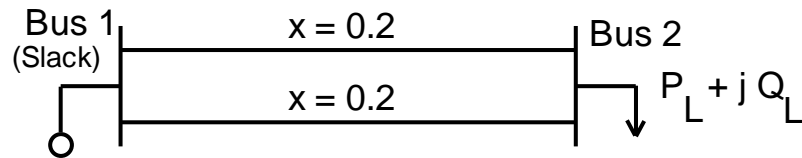
Voltage Stability

- Two good references are
  - P. Kundur, et. al., "Definitions and Classification of Power System Stability," *IEEE Trans. on Power Systems*, pp. 1387-1401, August 2004.
  - T. Van Cutsem, "Voltage Instability: Phenomena, Countermeasures, and Analysis Methods," *Proc. IEEE*, February 2000, pp. 208-227.
- Classified by either size of disturbance or duration
  - Small or large disturbance: small disturbance is just perturbations about an equilibrium point (power flow)
  - Short-term (several seconds) or long-term (many seconds to minutes)

Small Disturbance Voltage Stability

- Small disturbance voltage stability can be assessed using a power flow (maximum loadability)

- Depending on the assumed load model, the power flow can have multiple (or no solutions)

- PV curve is created by plotting power versus voltage

Bus 1 (Slack) — x = 0.2 — x = 0.2 — Bus 2, $P_L + j\,Q_L$

Assume $V_{slack}=1.0$

$$P_L - BV \sin \theta = 0$$

$$Q_L + BV \cos \theta - BV^2 = 0$$

Where B is the line susceptance =-10,
$V\angle\theta$ is the load voltage

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Small Disturbance Voltage Stability

- Question: how do the power flow solutions vary as the load is changed?

- A Solution: Calculate a series of power flow solutions for various load levels and see how they change

- Power flow Jacobian

$$\mathbf{J}(\theta,V) = \begin{bmatrix} -BV\cos\theta & -B\sin\theta \\ -BV\sin\theta & B\cos\theta - 2BV \end{bmatrix}$$

$$\det \mathbf{J}(\theta,V) = VB^2\left(2V\cos\theta - \cos^2\theta - \sin^2\theta\right)$$

Singular when $\left(2V\cos\theta - 1\right) = 0$

Maximum Loadability When Power Flow Jacobian is Singular

- An important paper considering this was by Sauer and Pai from IEEE Trans. Power Systems in Nov 1990, "Power system steady-state stability and the load-flow Jacobian"

- Other earlier papers were looking at the characteristics of multiple power flow solutions

- Work with the power flow optimal multiplier around the same time had shown that optimal multiplier goes to zero as the power flow Jacobian becomes singular

- The power flow Jacobian depends on the assumed load model (we'll see the impact in a few slides)

Relationship Between Stability and Power Flow Jacobian

- The Sauer/Pai paper related system stability to the power flow Jacobian by noting the system dynamics could be written as a set of differential algebraic equations

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

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

Linearing about an equilibrium gives

$$\begin{bmatrix} \Delta\dot{\mathbf{x}} \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial \mathbf{f}}{\partial \mathbf{x}} & \dfrac{\partial \mathbf{f}}{\partial \mathbf{y}} \\ \dfrac{\partial \mathbf{g}}{\partial \mathbf{x}} & \dfrac{\partial \mathbf{g}}{\partial \mathbf{y}} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{x} \\ \Delta\mathbf{y} \end{bmatrix}$$

Relationship Between Stability and Power Flow Jacobian

- Then

  Assuming $\dfrac{\partial \mathbf{g}}{\partial \mathbf{y}}$ is nonsingular then

  $$\Delta \dot{\mathbf{x}} = \left[\frac{\partial \mathbf{f}}{\partial \mathbf{x}} - \frac{\partial \mathbf{f}}{\partial \mathbf{y}} \left[\frac{\partial \mathbf{g}}{\partial \mathbf{y}} \right]^{-1} \frac{\partial \mathbf{g}}{\partial \mathbf{x}} \right] \Delta \mathbf{x}$$

- What Sauer and Pai show is if $\partial \mathbf{g}/\partial \mathbf{y}$ is singular then the system is unstable; if $\partial \mathbf{g}/\partial \mathbf{y}$ is nonsingular then the system may or may not be stable

- Hence it provides an upper bound on stability

Bifurcations

- In general, bifurcation is the division of something into two branches or parts

- For a dynamic system, a bifurcation occurs when small changes in a parameter cause a new quality of motion of the dynamic system

- Two types of bifurcation are considered for voltage stability

    - Saddle node bifurcation is the disappearance of an equilibrium point for parameter variation; for voltage stability it is two power flow solutions coalescing with parameter variation

    - Hopf bifurcation is cause by two eigenvalues crossing into the right-half plane

PV and QV Curves

- PV curves can be traced by plotting the voltage as the real power is increased; QV curves as reactive power is increased
  - At least for the upper portion of the curve
- Two bus example PV and QV curves
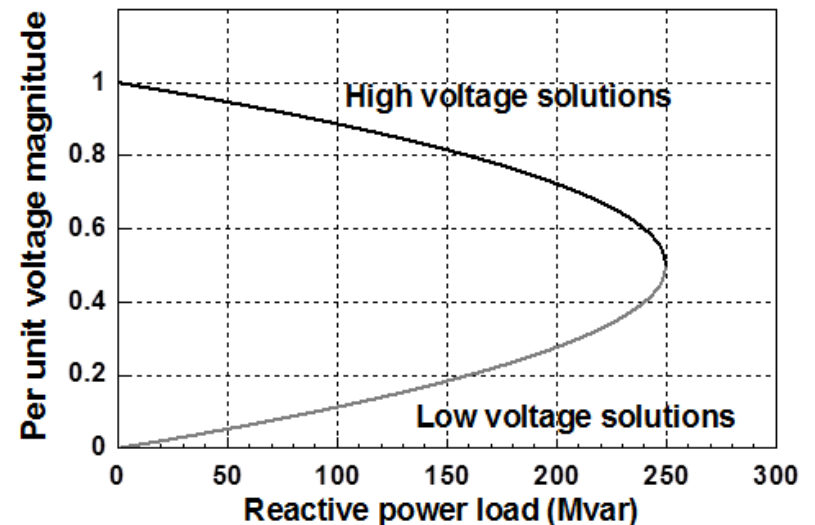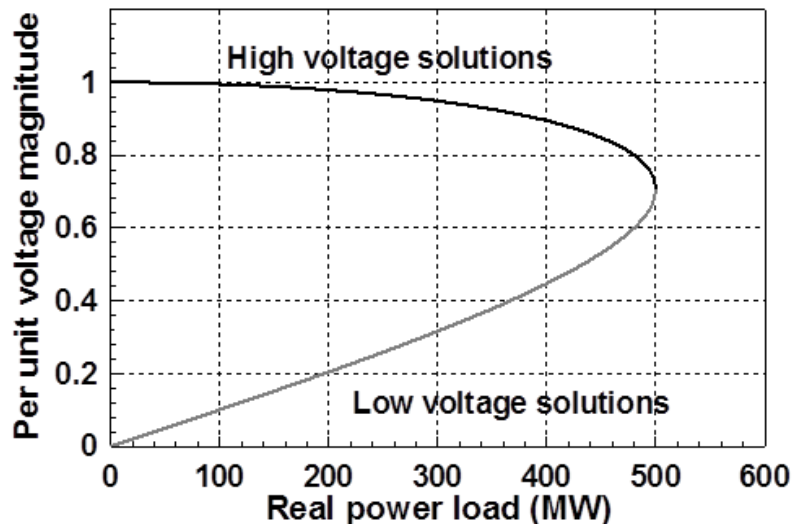
Small Disturbance Voltage Collapse

- At constant frequency (e.g., 60 Hz) the complex power transferred down a transmission line is $S=VI^*$
  - V is phasor voltage, I is phasor current
  - This is the reason for using a high voltage grid

- Line real power losses are given by RI^2 and reactive power losses by XI^2
  - R is the line's resistance, and X its reactance; for a high voltage line $X \gg R$

- Increased reactive power tends to drive down the voltage, which increases the current, which further increases the reactive power losses
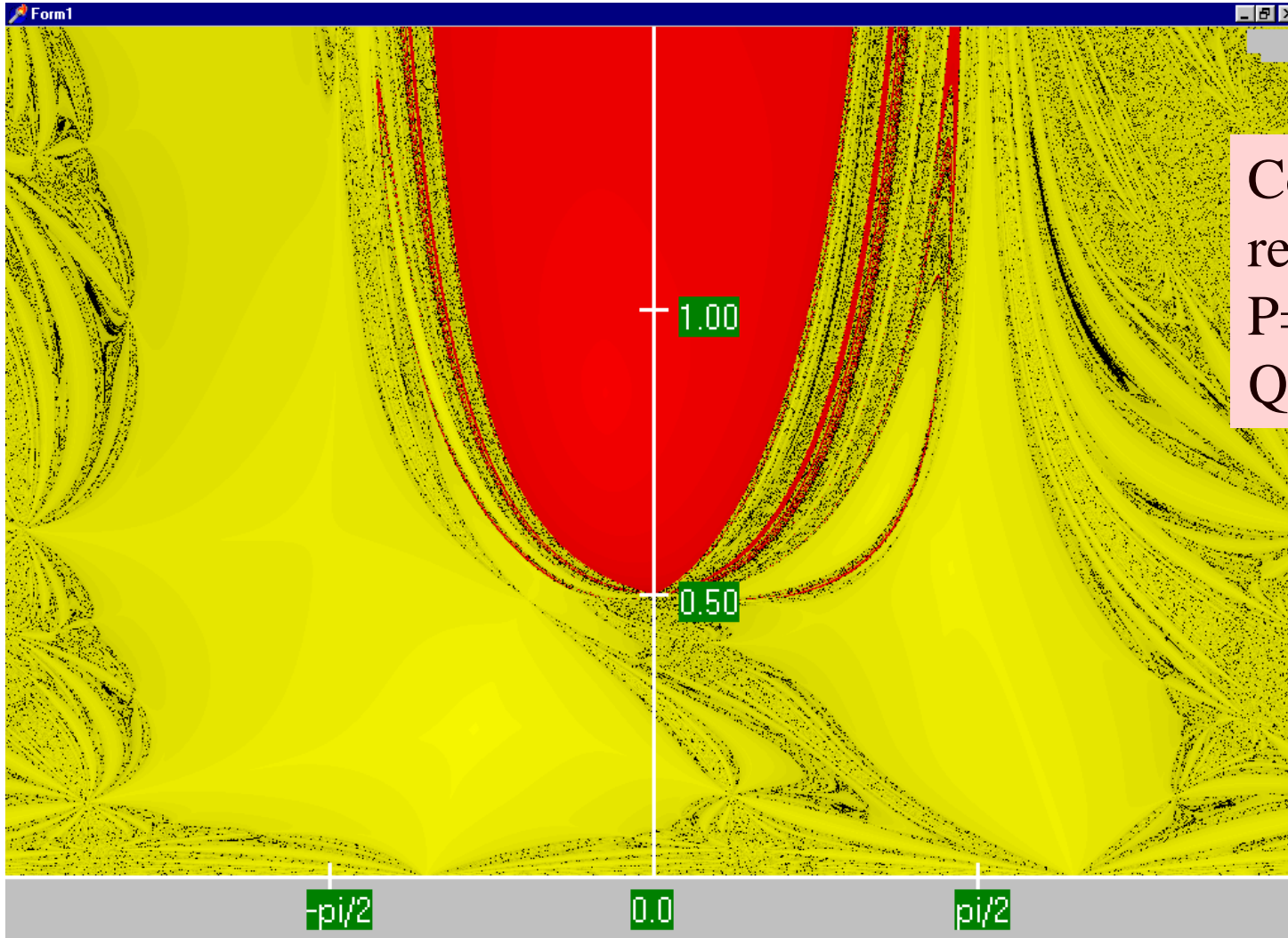
PowerWorld Two Bus Example
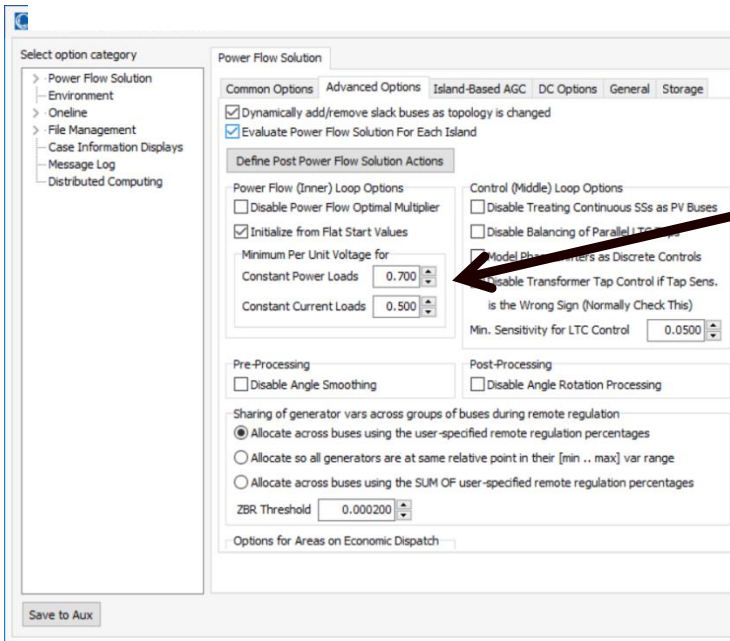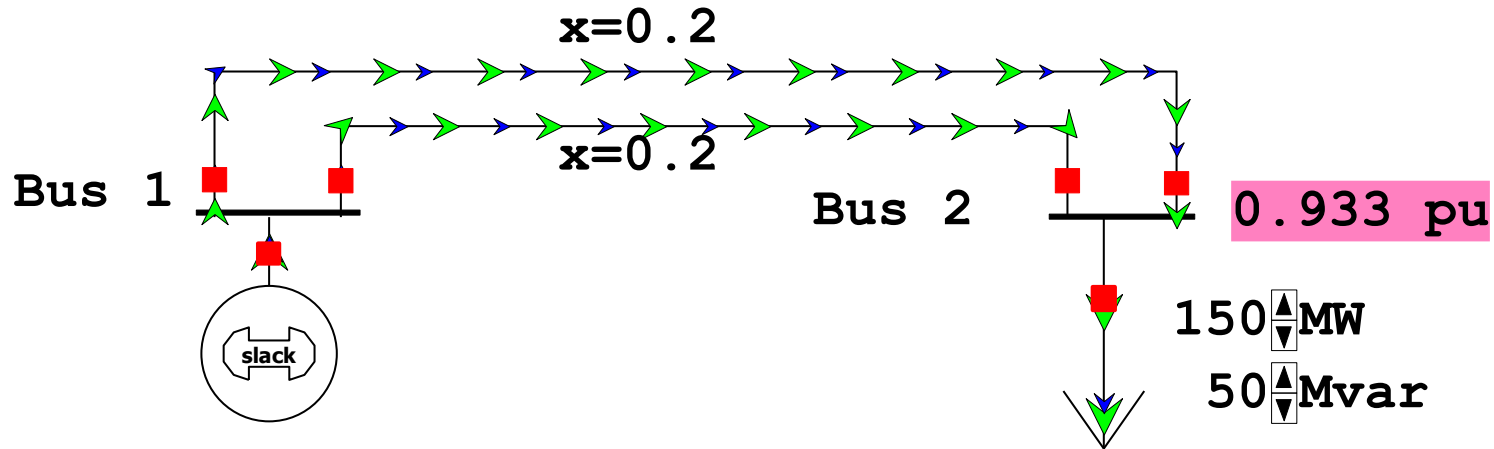
Commercial power flow software usually auto converts constant power loads at low voltages; set these fields to zero to disable this conversion

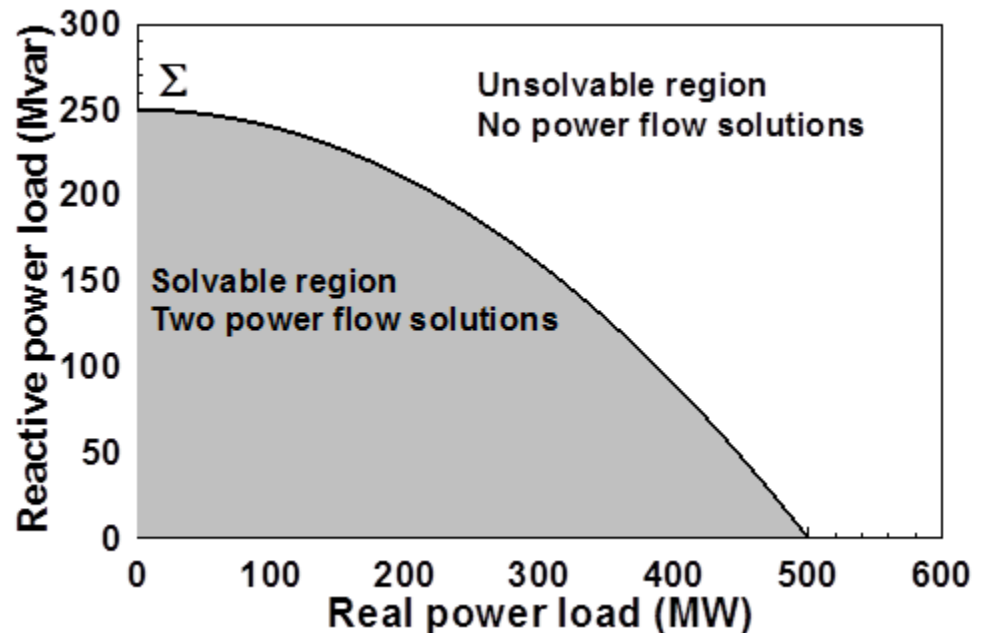Case is **Bus2_PV**

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

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

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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)

x=0.2

x=0.2

Bus 1

Bus 2

slack

0.943 pu

133 MW

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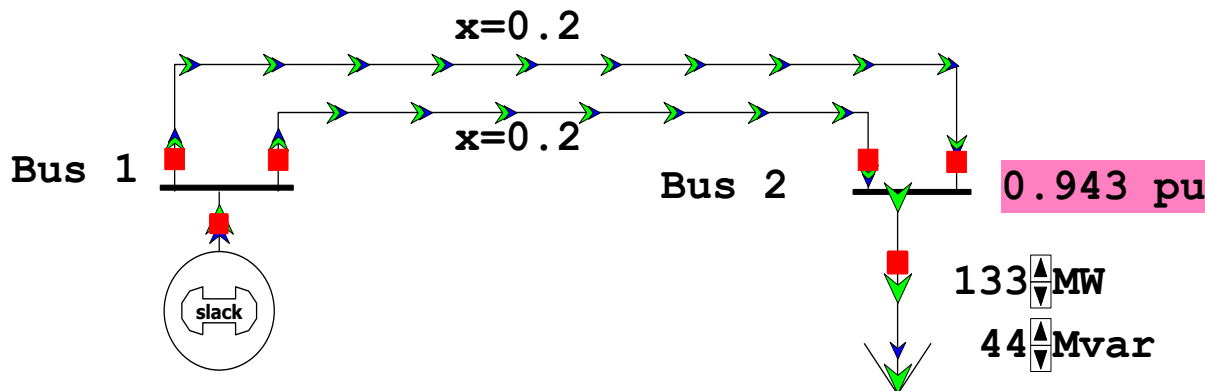
Change load to constant impedance; hence it becomes a linear model

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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

Table 7 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