ECEN 667
Power System Stability

Lecture 19: Load Modeling and Voltage Stability

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

Announcements

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

Motor Starting

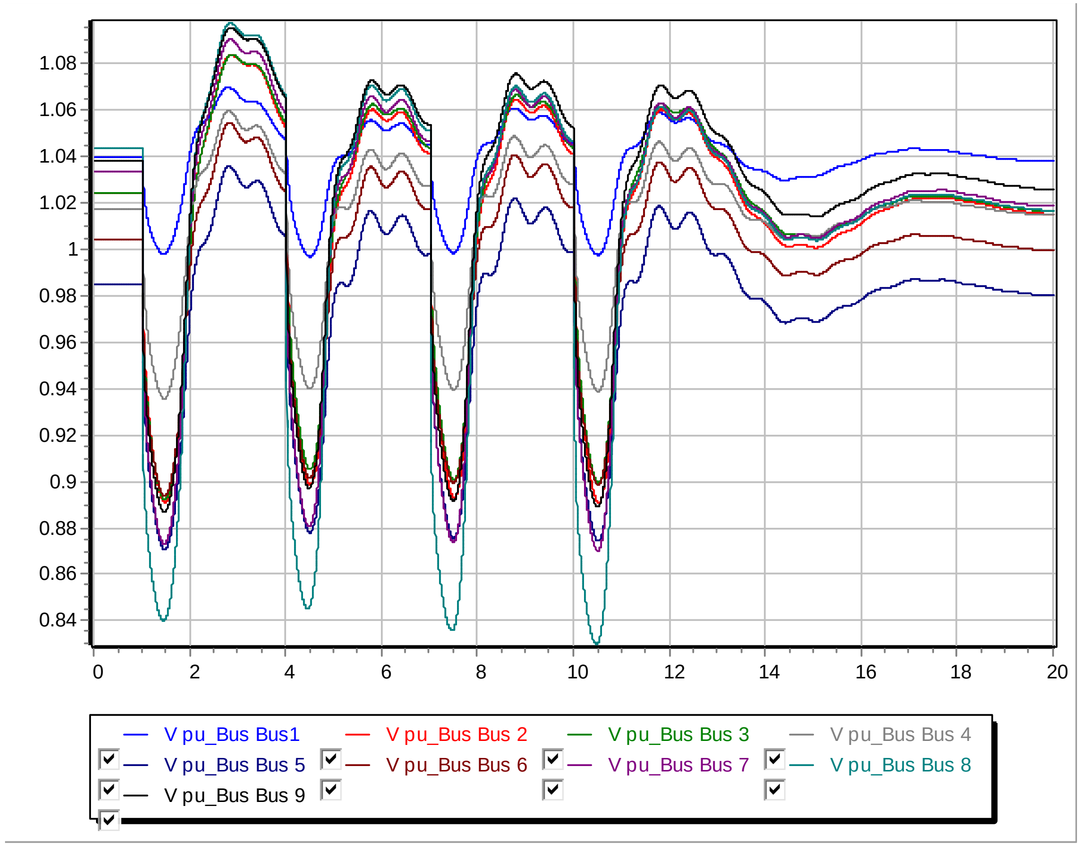
- Motor starting analysis looks at the impacts of starting a motor or a series of motors (usually quite large motors) on the power grid
  - Examples are new load or black start plans
- While not all transient stability motor load models allow the motor to start, some do
- When energized, the initial condition for the motor is slip of 1.0
- Motor starting can generate very small time constants

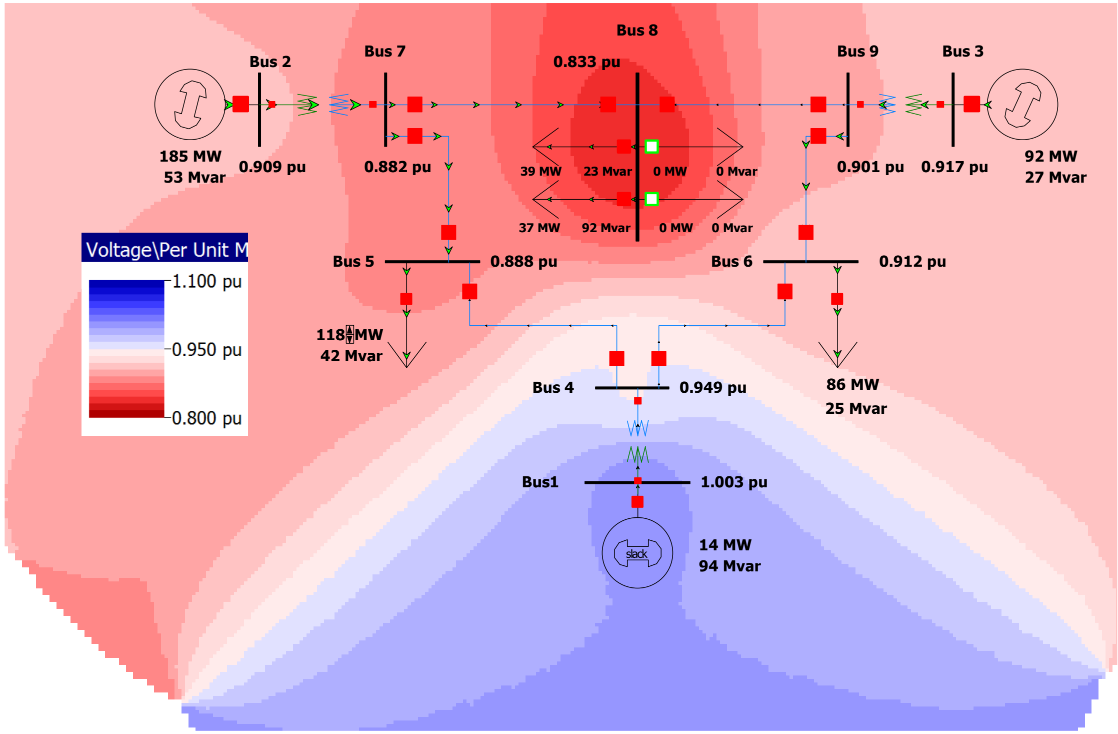
Motor Starting Example

- Case WSCC_MotorStarting takes the previous WSCC case with 100% motor load, and considers starting the motor at bus 8
- In the power flow the load at bus 8 is modeled as zero (open) with a CIM5
- The contingency is closing the load
  - Divided into four loads to stagger the start (we can't start it all at once)
- Since power flow load is zero, the CIM5 load must also specify the size of the motor
  - This is done in the Tnom field and by setting an MVA base value

Motor Starting Example

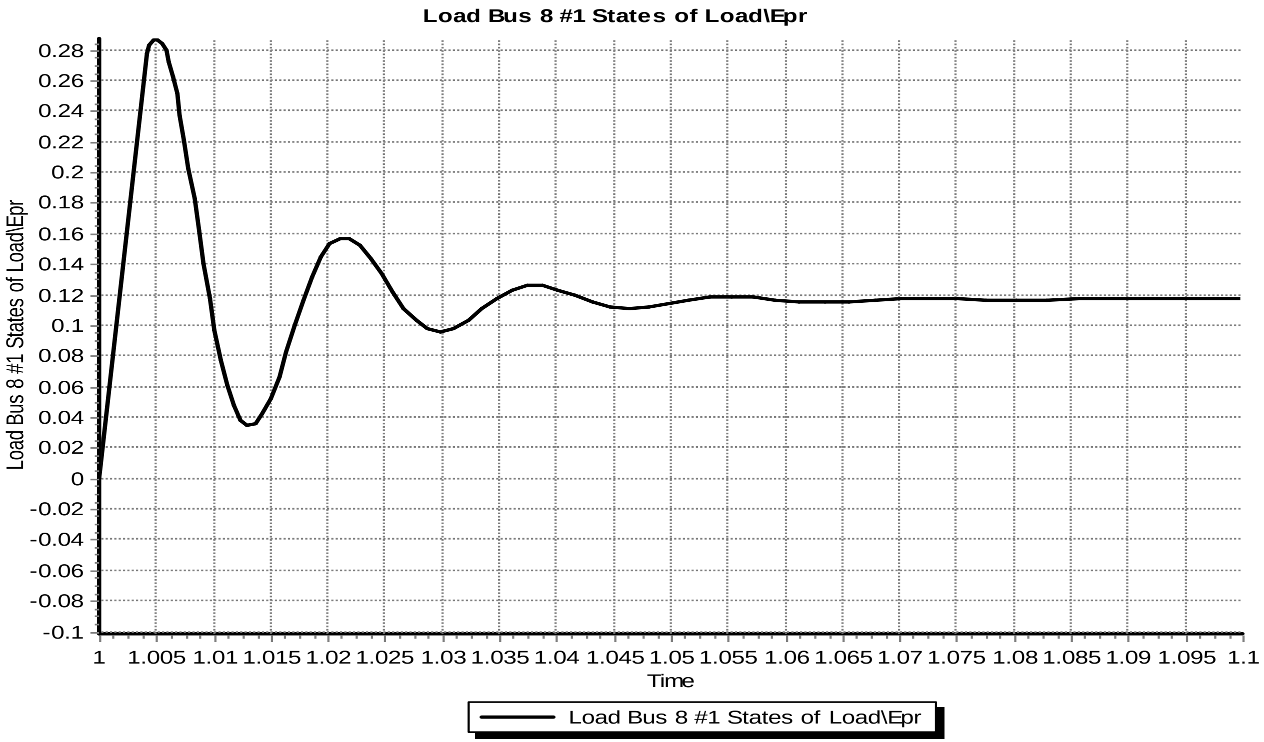
- Below graph shows the bus voltages for starting the four motors three seconds apart





Motor Starting: Fast Dynamics

- One issue with the starting of induction motors is the need to model relatively fast initial electrical dynamics
  - Below graph shows E'r for a motor at bus 8 as it is starting



Time scale is from 1.0 to 1.1 seconds

Motor Starting: Fast Dynamics

- These fast dynamics can be seen to vary with slip in the $\omega_s s$ term

$$V_D = E'_D + R_s I_D - X' I_Q$$

$$V_Q = E'_Q + R_s I_Q + X' I_D$$

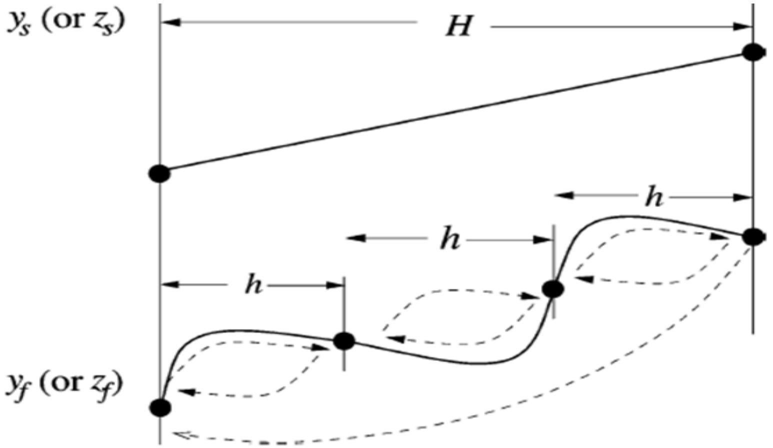
$$\frac{dE'_D}{dt} = \omega_s s E'_Q - \frac{1}{T'_o}\left(E'_D + \left(X - X'\right) I_Q\right)$$

$$\frac{dE'_Q}{dt} = -\omega_s s E'_D - \frac{1}{T'_o}\left(E'_Q - \left(X - X'\right) I_D\right)$$

- Simulating with the explicit method either requires a small overall Δt or the use of multi-rate methods

Multi-Rate Explicit Integration

- Key idea is to integrate some differential equations with a potentially much faster time step then others



- Faster variables are integrated with time step h, slower variable with time step H
  - Slower variables assumed fixed or interpolated during the faster time step integration

Figure from Jingjia Chen and M. L. Crow, "A Variable Partitioning Strategy for the Multirate Method in Power Systems," Power Systems, IEEE Transactions on, vol. 23, pp. 259-266, 2008.

Multi-Rate Explicit Integration

- First proposed by C. Gear in 1974
- Power systems use first presented by M Crow in 1994
- In power systems usually applied to some exciters, stabilizers, and to induction motors when their slip is high
- Subinterval length can be customized for each model based on its parameters (in range of 4 to 128 times the regular time step)
- Tradeoff in computation

C. Gear, Multirate Methods for Ordinary Differential Equations, Univ. Illinois at Urbana-Champaign, Tech. Rep., 1974.

M. Crow and J. G. Chen, “The multirate method for simulation of power system dynamics,” *IEEE Trans. Power Syst.*, vol. 9, no. 3, pp.1684–1690, Aug. 1994.

AC Motor Drives

- A historical shortcoming of ac motors was their lack of speed control when supplied by a fixed frequency ac
- With advances in power electronics it is now common to use an ac-ac converter to provide the machine with a varying and controllable ac frequency; this allows for variable speed operation
  - Known as a variable frequency drives (VFDs)
- Variable speed operation can result in significant energy savings – speed becomes on optimization parameter
- Commonly use V/Hz control to keep the flux constant

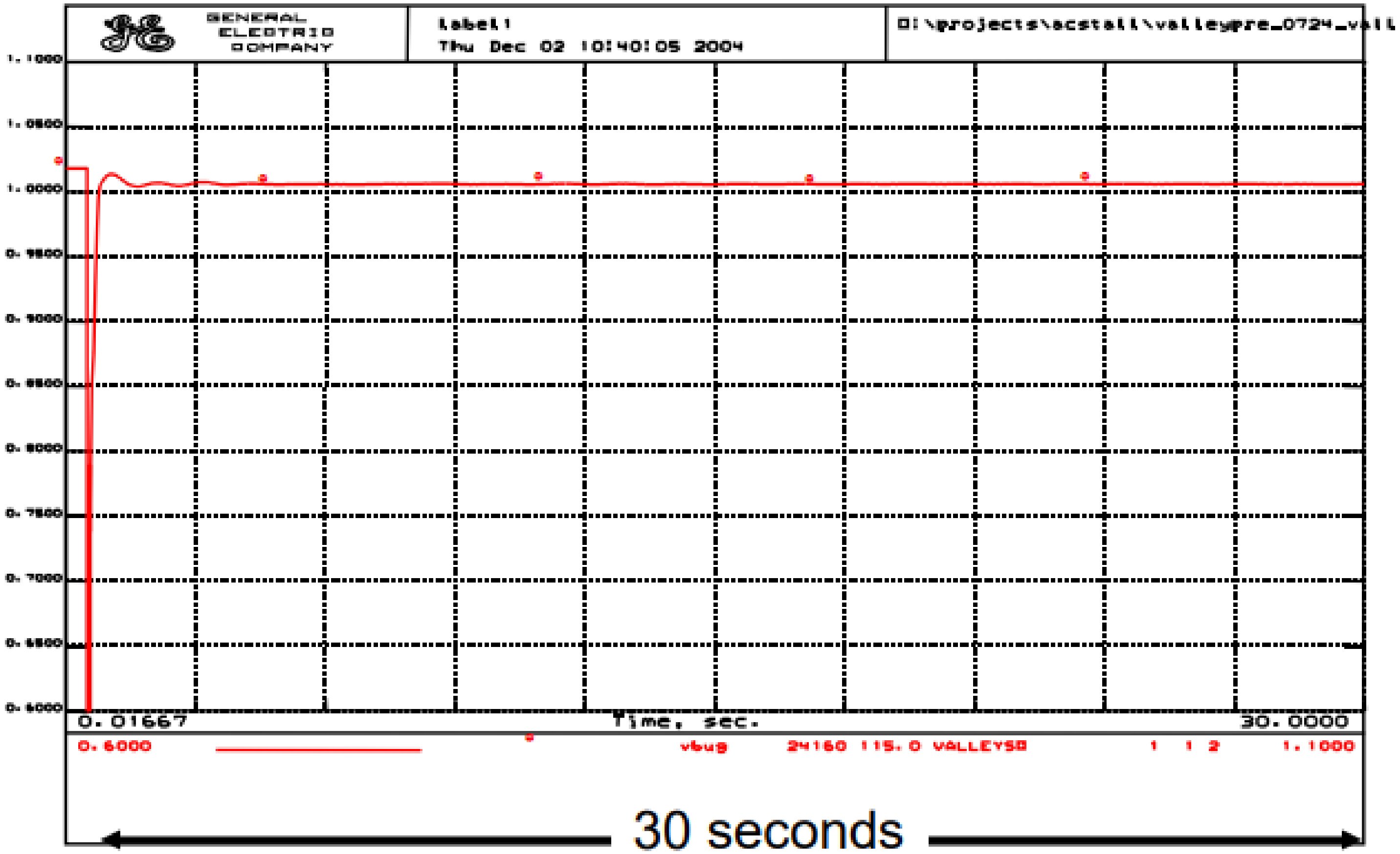
Need for Better Load Modeling: History of Load Modeling in WECC

- 1990's – Constant current real, constant impedance reactive models connected to a transmission bus
  - IEEE Task Force recommends dynamic load modeling, however it does not get traction in the industry
- 1996 – Model validation study for July 2 and August 10 system outages:
  - Need for motor load modeling to represent oscillations and voltage decline
- 2000's – WECC "Interim" Load Model: – 20% of load is represented with induction motors
  - Tuned to match inter-area oscillations for August 10 1996 and August 4, 2000 oscillation events …

Source: certs.lbl.gov/sites/all/files/5-6-kosterev-undrill-load-modeling-in-wecc.pdf

Need for Better Load Modeling: History of Load Modeling in WECC

- What simulations done using the interim load model indicated would occur



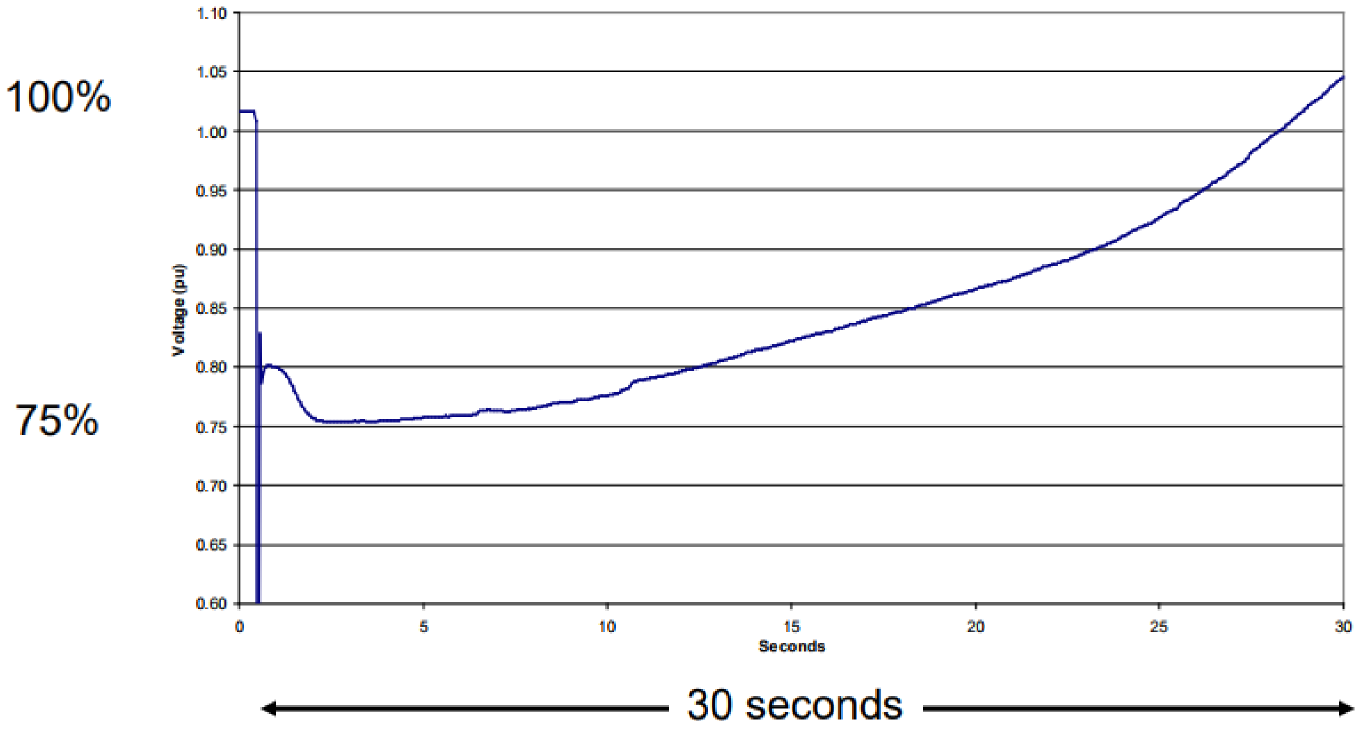
Vertical scale goes down to about 0.6 per unit

Hence the simulations indicated rapid voltage recovery following the fault

Source: certs.lbl.gov/sites/all/files/5-6-kosterev-undrill-load-modeling-in-wecc.pdf

Need for Better Load Modeling: History of Load Modeling in WECC

- What was actually sometimes occurring, known as fault induced delayed voltage recovery (FIDVR)
  - Seen in 1980’s; traced to stalling air-conditioning load



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

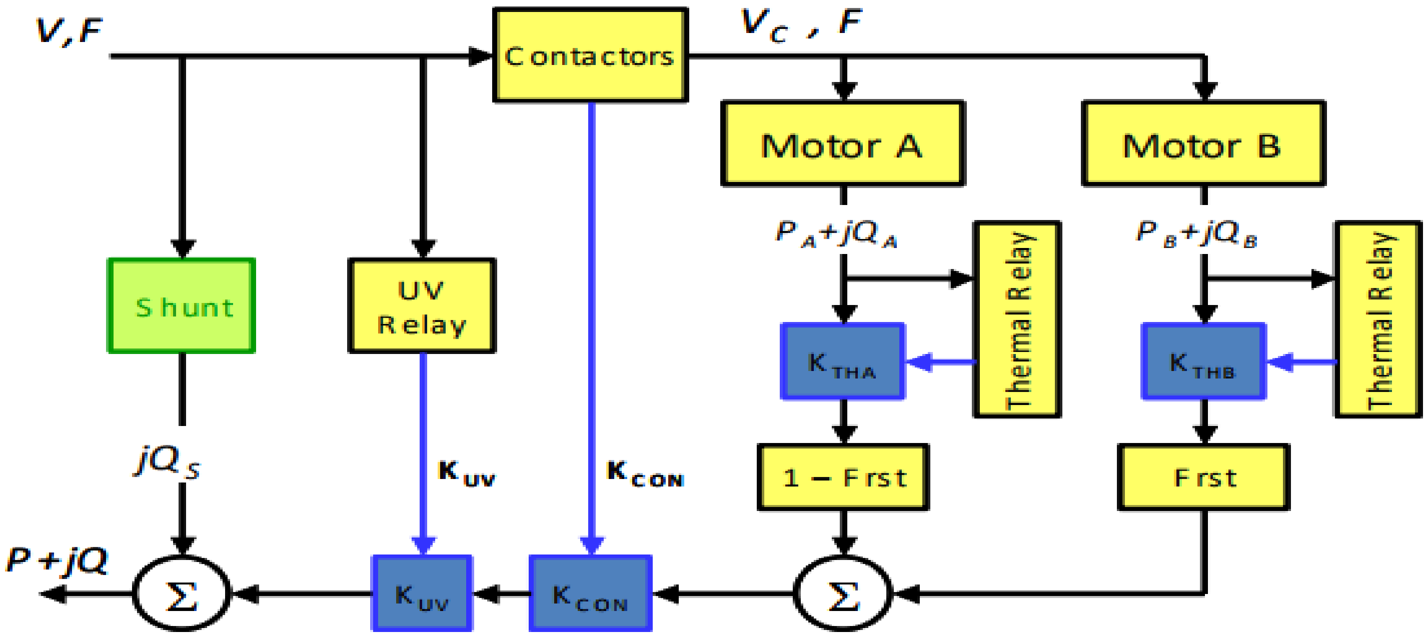
What is LD1PAC

- LD1PAC is the model that is often embedded inside a more complex load model
  - This more complex model is known as the Composite Load Model (CMPLDW or CMLD)
- Purpose is of the LD1PAC is not to model *one* air conditioner
- Rather, the purpose of this simulation model is to represents 1000s of air-conditioners in a single model
  - We are not modeling the dynamics of the compressor, induction motor, or anything specifically
  - We couldn’t get that input data for 1000s of devices anyway!

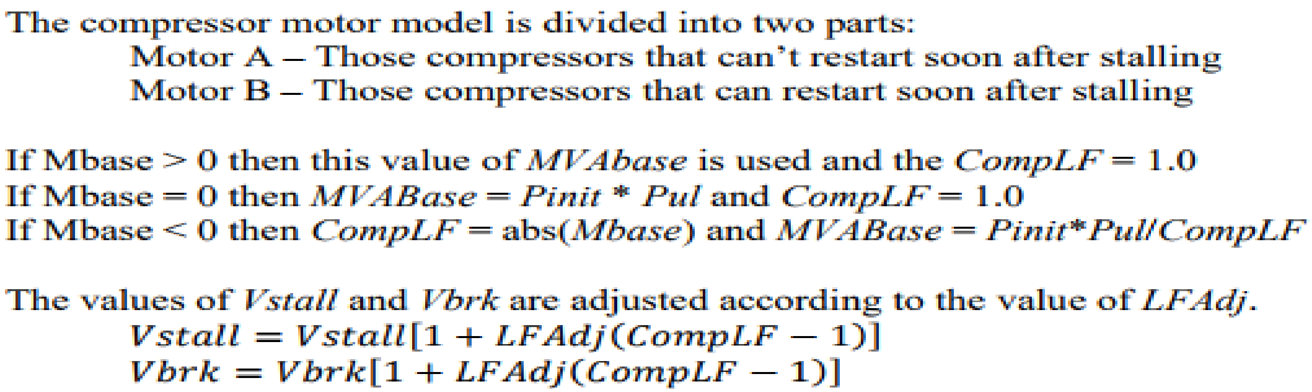
What does LD1PAC Model?

- LD1PAC is a performance model
- Laboratory tests give the *steady-state* P and Q as a function of terminal voltage
- Then build a bunch of various tripping logic around this
  - Under Voltage Relay
  - “Contactor” Tripping (voltage drops and some air conditioners trip, while others do not)
  - Thermal relays (over-heating relays)
- Also build a transition from a “Stall” and “Operating” mode
  - We are NOT modeling the motor dynamics explicitly

Single Phase Induction Motor Loads



Model is mostly algebraic, but with stalling behavior



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*.

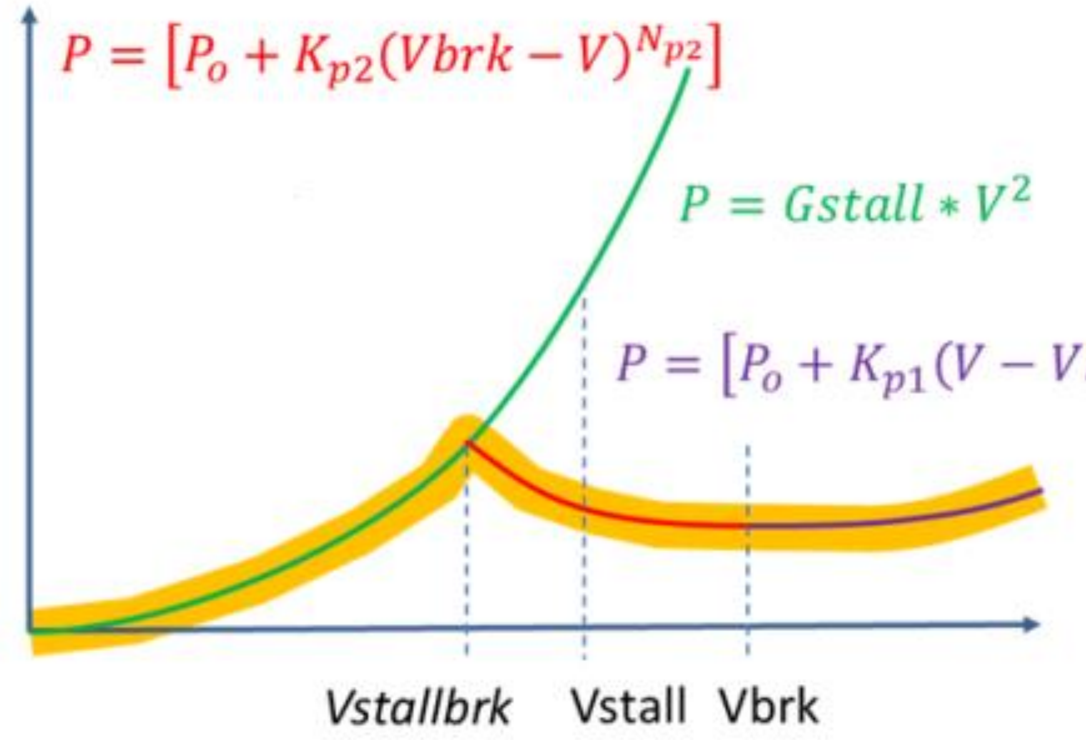
$$Vstall = Vstall[1 + LFAdj(CompLF - 1)]$$
$$Vbrk = Vbrk[1 + LFAdj(CompLF - 1)]$$

“MotorA” and “MotorB”

- Motor A and Motor B represent 2 types of motors
  - Motor A → for a certain fraction of motors, once they stall they will remain stalled forever
    - They can’t say that way forever obviously!
    - In the simulation they will sit there for several seconds consuming a huge amount of MW and Mvar
    - Eventually the thermal relays will trip them off-line
  - Motor B → Another fraction of motors will “restart” once the voltage goes above Vrst for Trst seconds
- We throw around terms like “stall” and “restart”
  - But, we are NOT simulating rotor speed so what does this even mean!
  - These are just transitions between modes of operation in the model

Performance Curves

- Yellow-highlighted curve represents the real power as a function of voltage when the motor is "operating"
- Green Line represents the real power when we are "Stalled" (it's a pure impedance then)

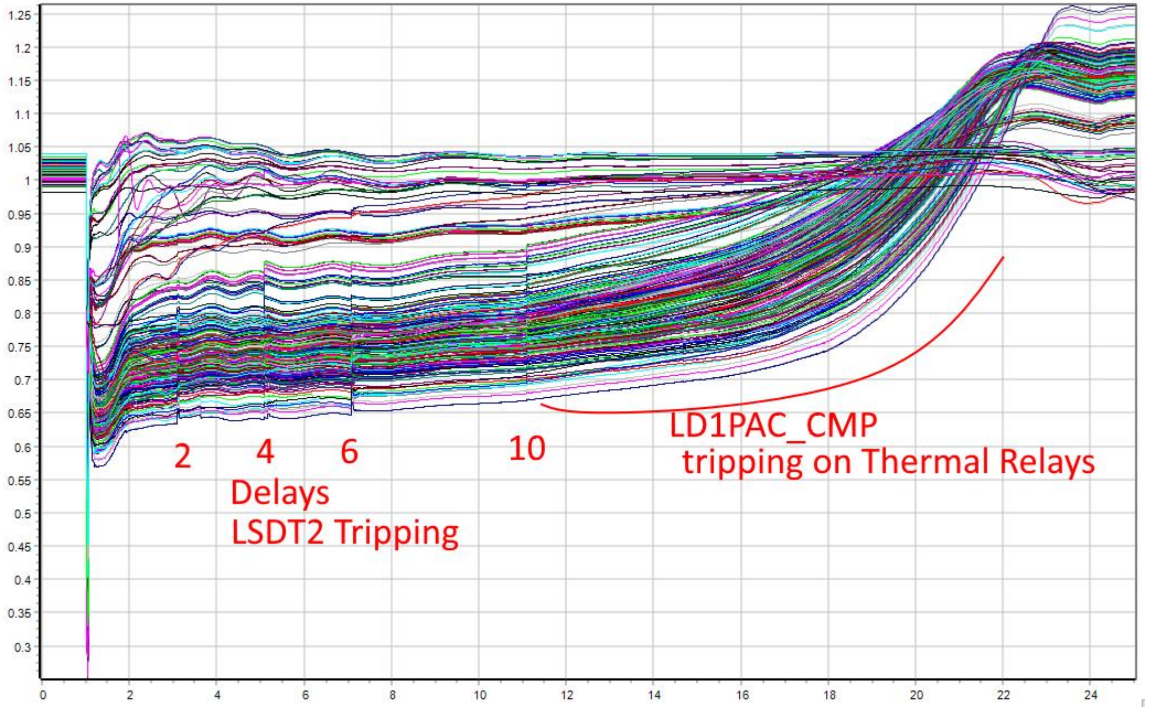


Transition between “Operating” and “Stall” Curves

- In existing LD1PAC and CMPLDW/CMLD models this transition is defined simply as
  - If Voltage < Vstall for more than Tstall seconds, then immediately flip to the green stall curve
  - The “Motor A” fraction of the model will remain there until the thermal relay trips it
  - The “Motor B” fraction of the model will monitor to see if Voltage > Vrst for more that Trst seconds, and then immediately flip back to the yellow operating curve.
- There has been much debate about how to set Vstall/Tstall
  - Initial values had Vstall too high and Tstall too short so that this happened too often

LD1PAC behavior

- Slow Voltage Recover caused by a bunch of air conditioner stalling
- Eventually they trip off-line due to thermal relays and voltage recovers



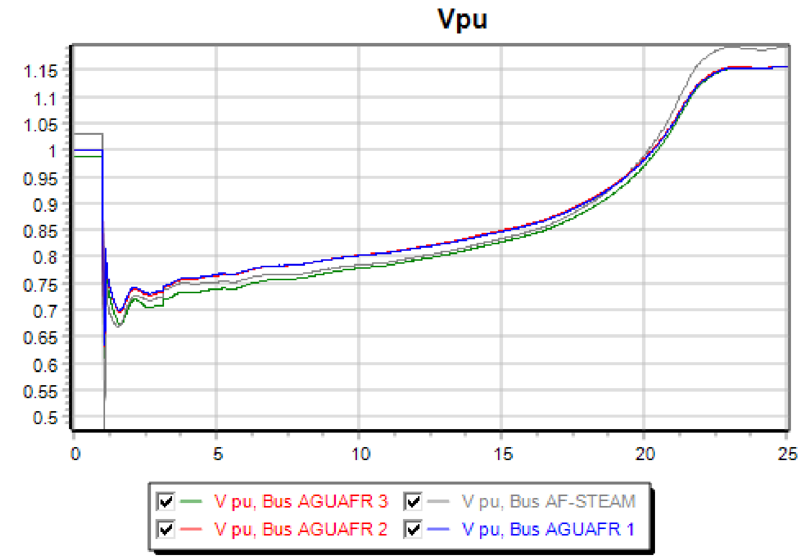
2 4 6 10

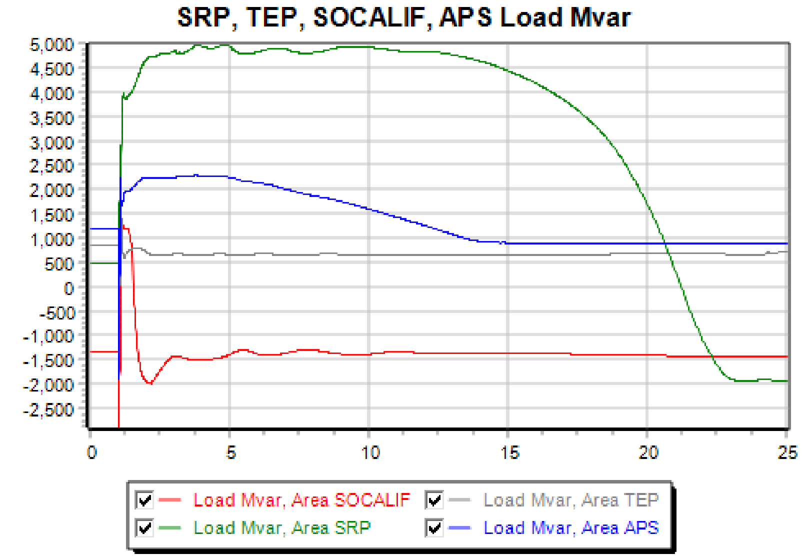
Delays

LSDT2 Tripping

LD1PAC_CMP

tripping on Thermal Relays





Air-Conditioner Stalling Testing

- Testing was done by
  - Bernard Lesieutre (Lawrence Berkeley National Lab and the University of Wisconsin-Madison)
  - Steve Yang and Dmitry Kosterev (Bonneville Power Administration)

https://www.osti.gov/servlets/purl/1183173

- They found that when stalling happened, it happened extremely quickly (the motors are very small and have very little inertia)

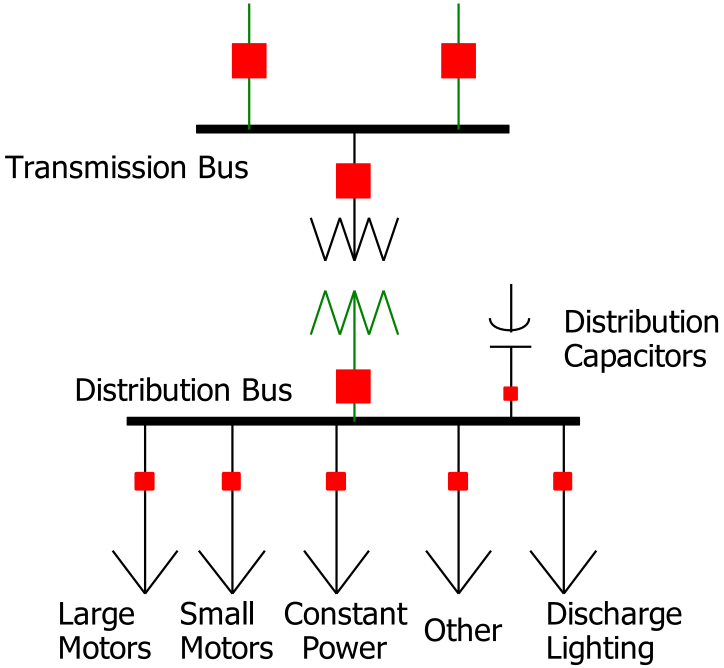
https://gig.lbl.gov/sites/all/files/6b-quint-composite-load-model-data.pdf

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 that 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

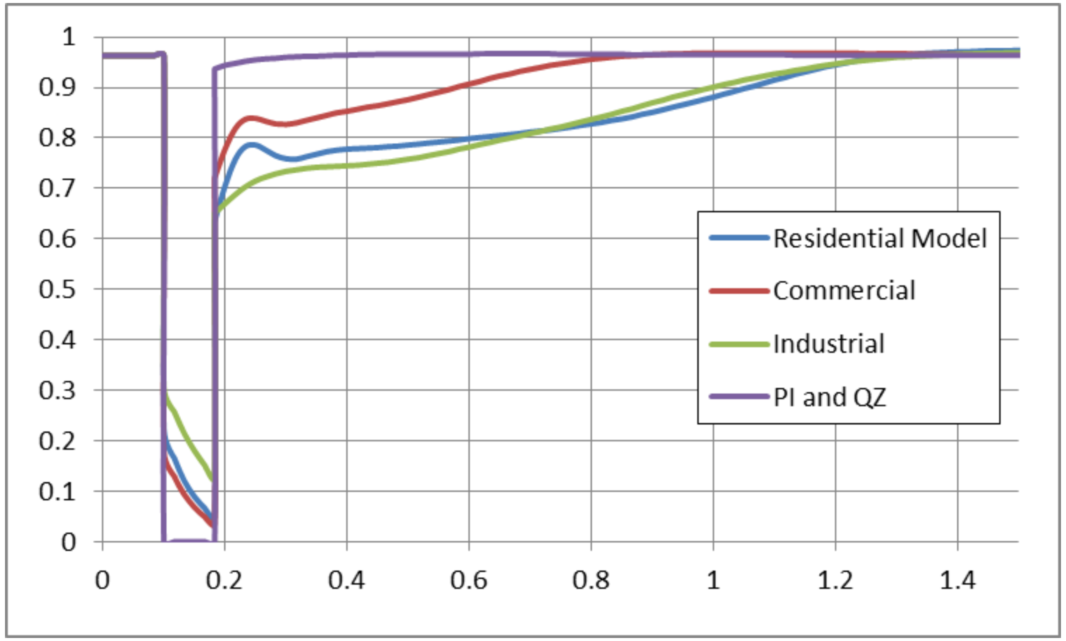
- The CLOD model represents the load as a combination of large induction motors, small induction motors, constant power, discharge lighting, and other



CLOD Model

- Different load classes can be defined

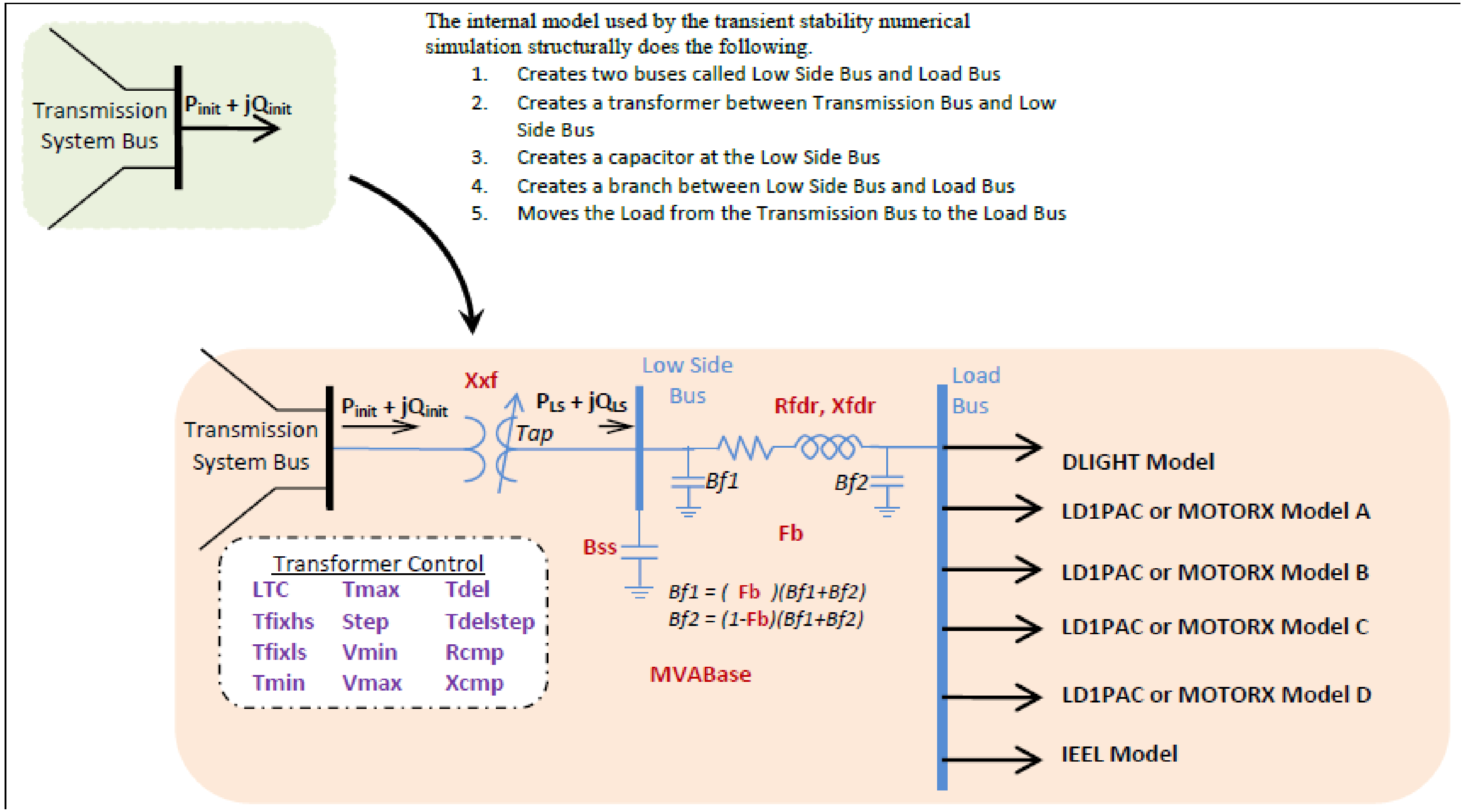
Customer Class	Large Motor	Small Motor	Discharge Lighting	Constant Power	Remaining (PI, QZ)
Residential	0.0	64.4	3.7	4.1	27.8
Agriculture	10.0	45	20	4.5	19.5
Commercial	0.0	46.7	41.5	4.5	7.3
Industrial	65.0	15.0	10.0	5.0	4.0



Comparison of voltage recovery for different model types

Composite Load Model

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

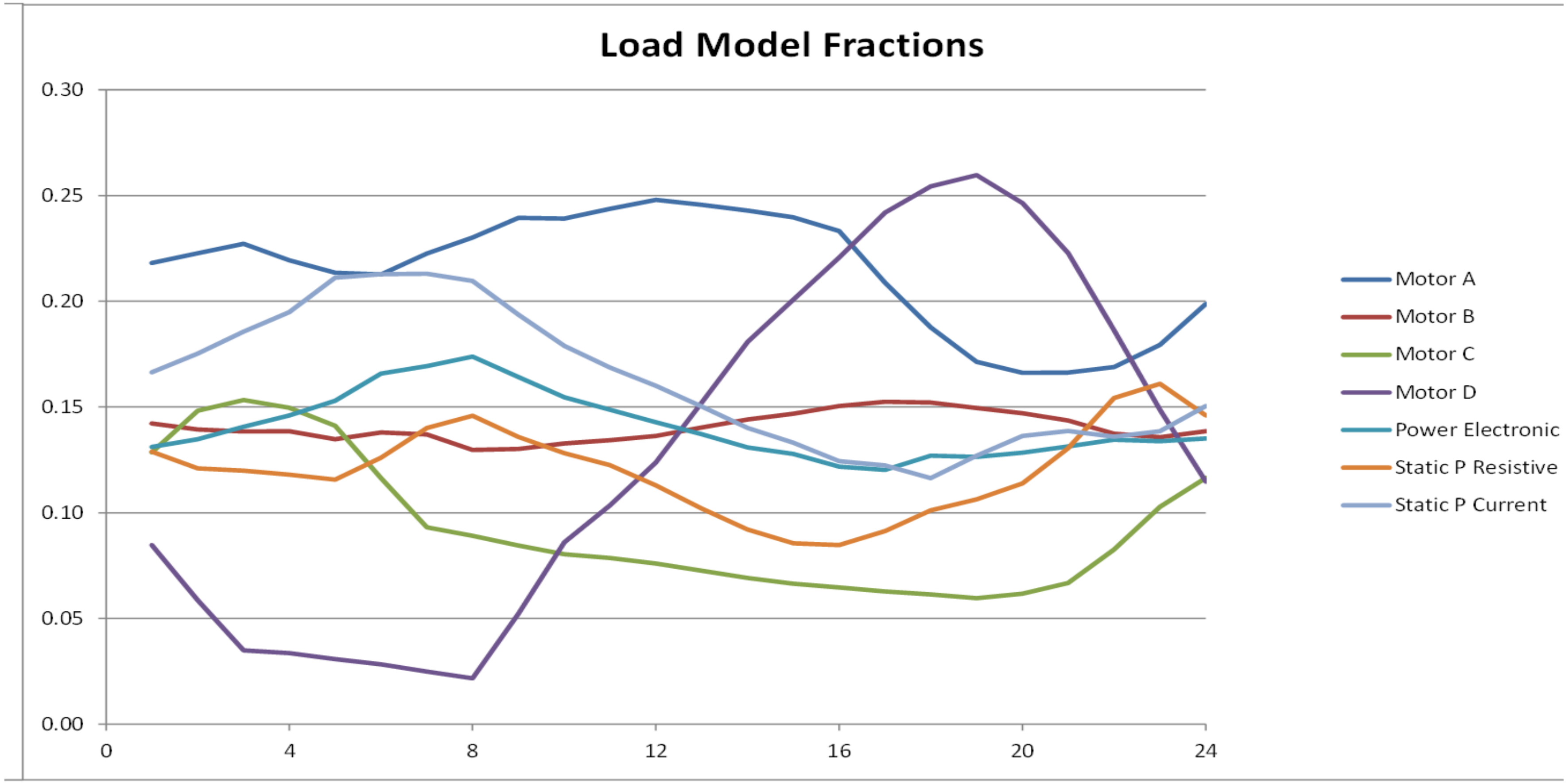


The internal model used by the transient stability numerical simulation structurally does the following.

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

Aggregate Motor Model with Tripping (part of CMPLDW)

- What does it mean when a motor model says “50% tripped”
  - Think of it as ONE set of equations representing set of identical motors.
  - When we say 50% tripped it just means that we now have 50% of the current injection as we did before (and double the Norton impedance)
  - It’s essentially a scalar multiplier on those things
- What does it mean when some of these induction motors “restart”
  - We are NOT modeling the motor starting from zero speed with the large current spikes that go with that
  - Basically we’re pretending that all the motors continued to spin and operate after they tripped, they just magically were no longer seen by the power system
  - When they “restart”, they magically return operating at full load and speed.

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
- Correctly modeling embedded distribution level generation resources, such as PV, is important
- See EPRI Technical Guide to Composite Load Modeling, September 2020
  - https://www.epri.com/research/programs/027570/results/3002019209

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.

Power System Stability Terms

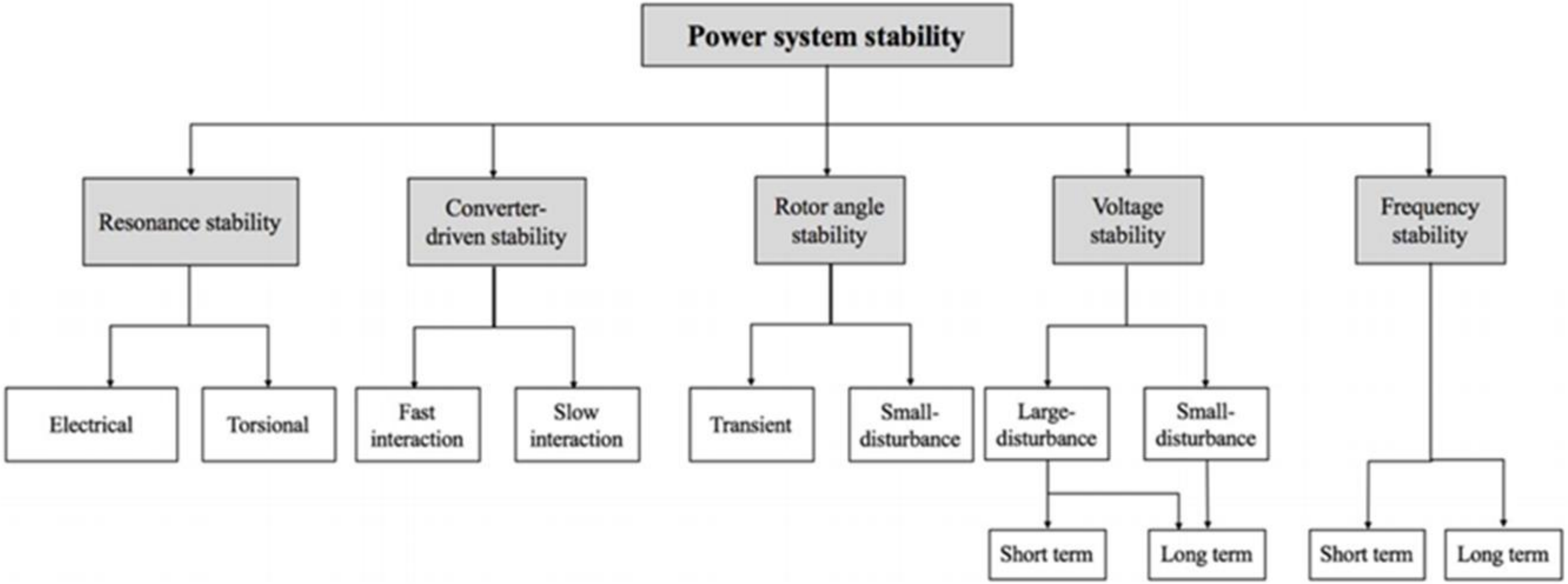


Fig. 4. Classification of power system stability

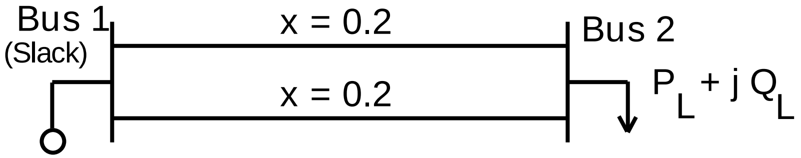
[a] IEEE/PES Power System Dynamic Performance Committee, "Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies", PES-TR77, April 2020

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



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

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: Singular Power Flow Jacobian

- 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)

Voltage Stability and the 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

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

Voltage Stability and the Power Flow Jacobian

- Then

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

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

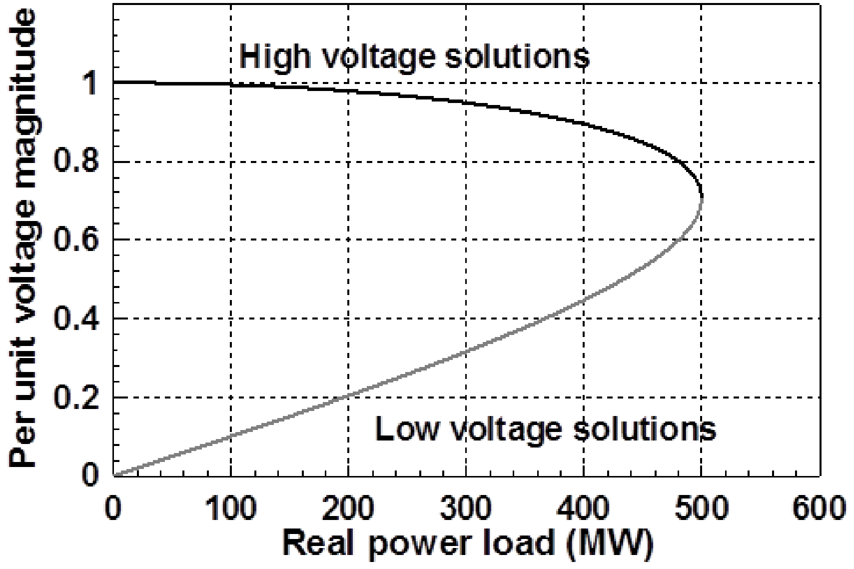
- What Sauer and Pai show is if $\partial \mathbf{g} / \partial \mathbf{y}$ is singular then the system is unstable; if $\partial \mathbf{g} / \partial \mathbf{y}$ is nonsingular then the system may or may not be stable
- Hence it provides an upper bound on stability

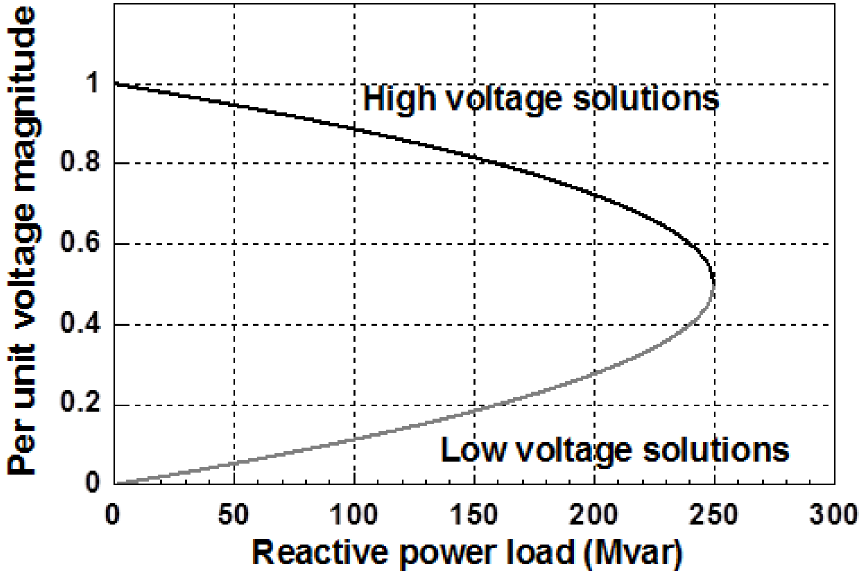
Bifurcations

- 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

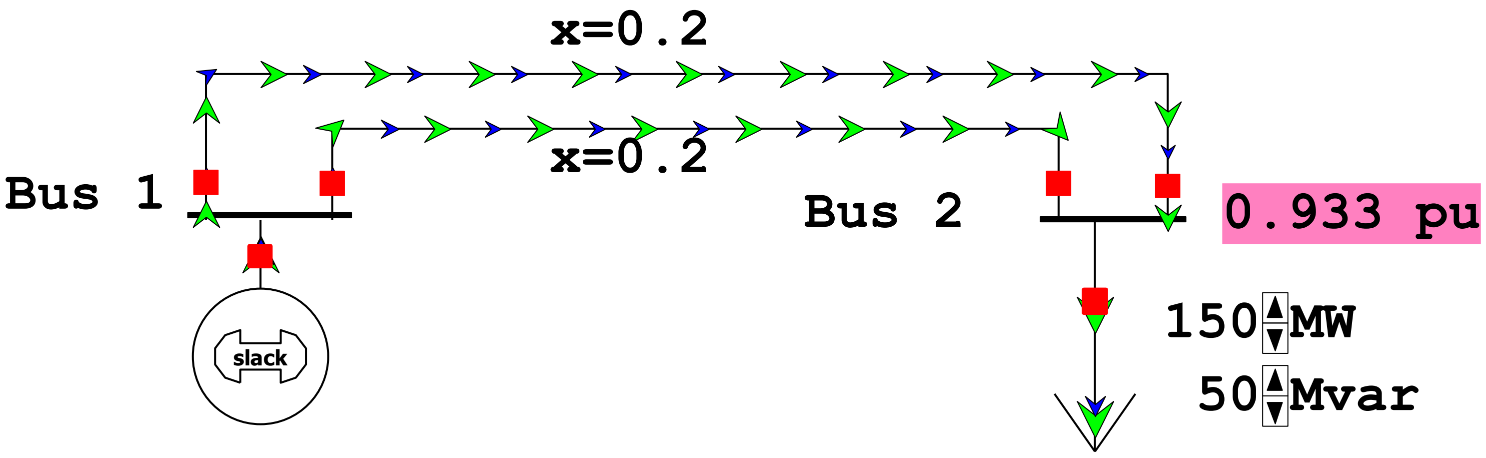


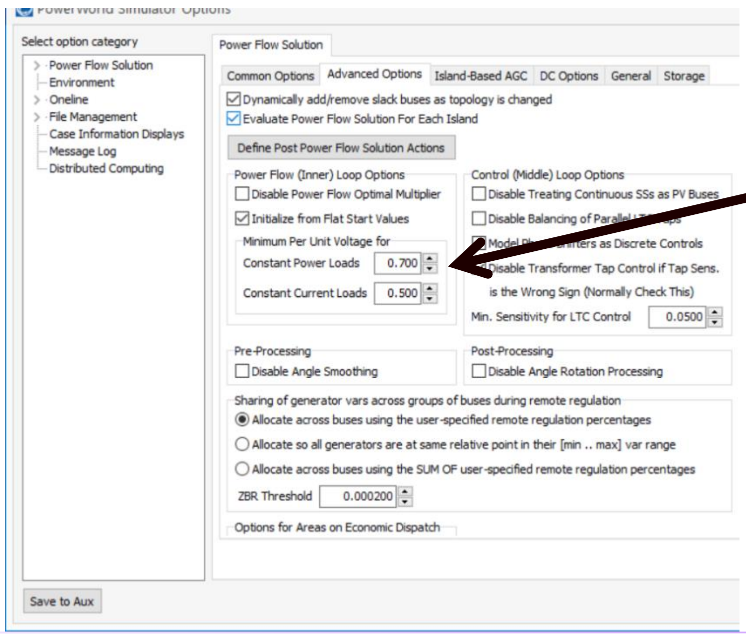


Small Disturbance Voltage Collapse

- 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 >> 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




PowerWorld Simulator Options

Select option category

- Power Flow Solution
- Environment
- Oneline
- File Management
- Case Information Displays
- Message Log
- Distributed Computing

Power Flow Solution

Common Options | Advanced Options | Island-Based AGC | DC Options | General | Storage

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

Define Post Power Flow Solution Actions

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 L[illegible]ps
☑ Model Ph[illegible]ters 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

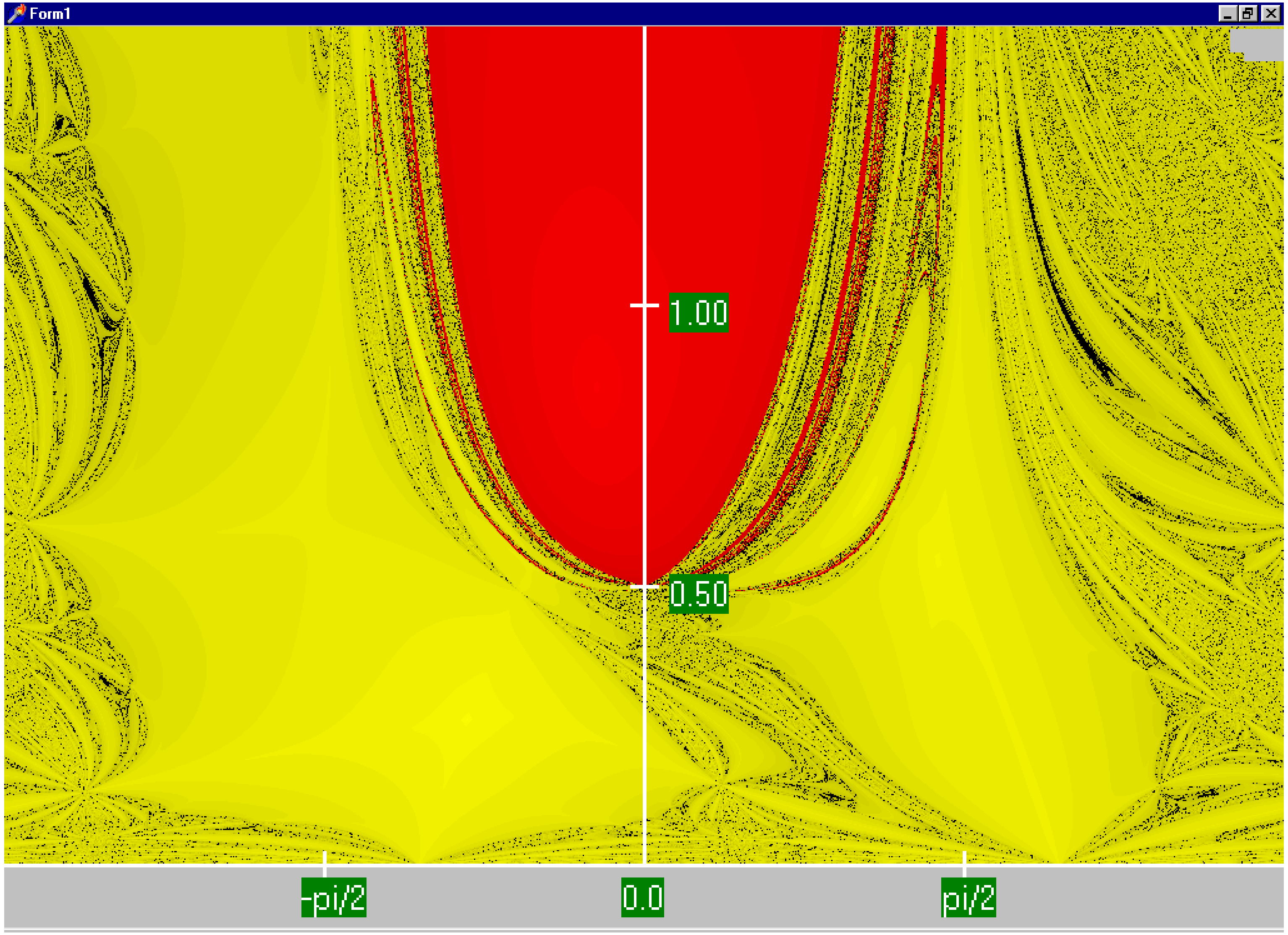
Options for Areas on Economic Dispatch

Save to Aux

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

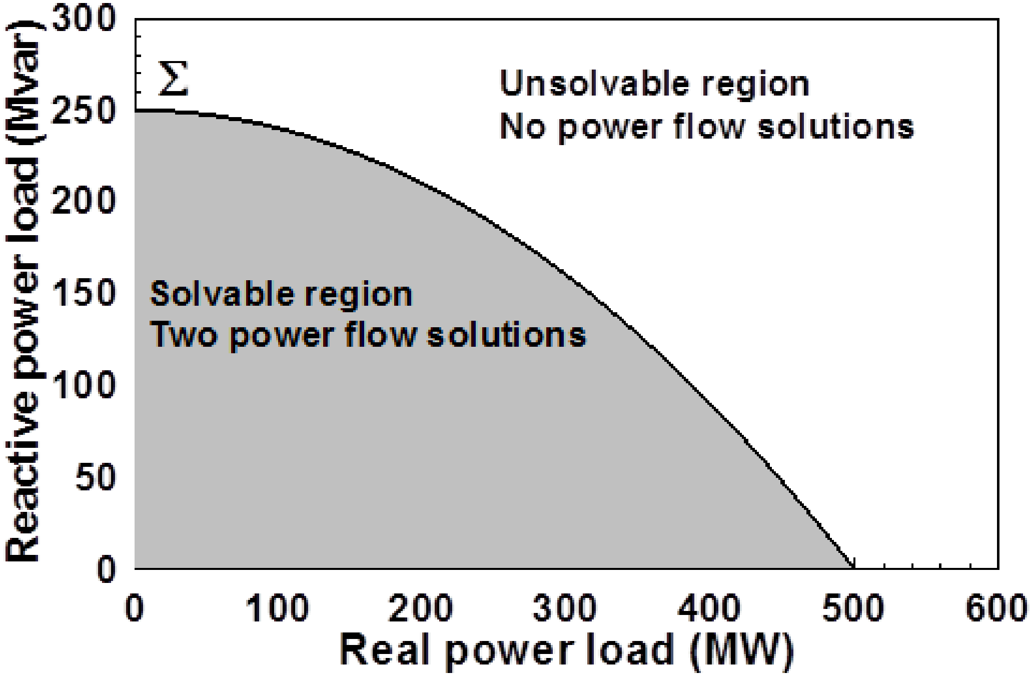


Convergence regions with P=100 MW, Q=0 Mvar

Load Parameter Space Representation

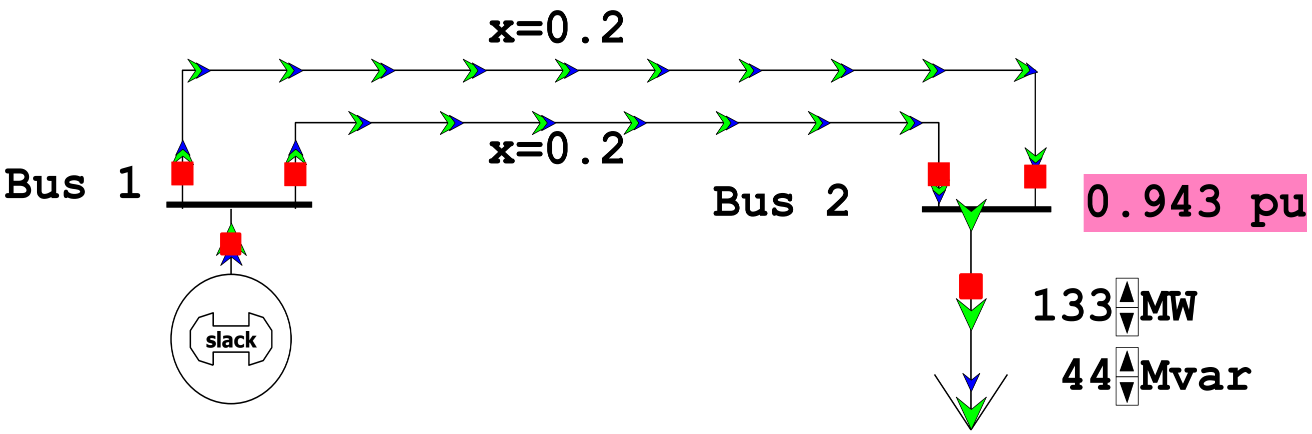
- With a constant power model there is a maximum loadability surface, Σ
  - Defined as point in which the power flow Jacobian is singular
  - For the lossless two bus system it can be determined as

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



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

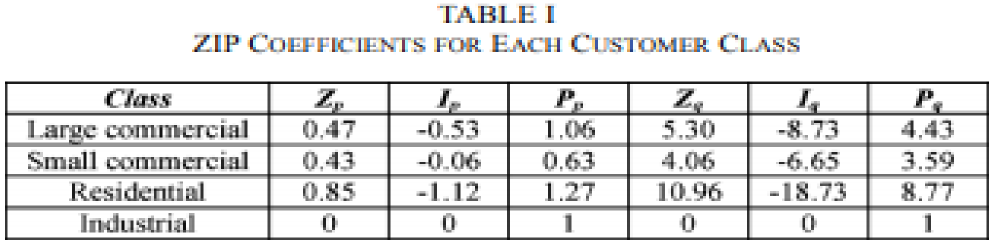


TABLE I
ZIP COEFFICIENTS FOR EACH CUSTOMER CLASS

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

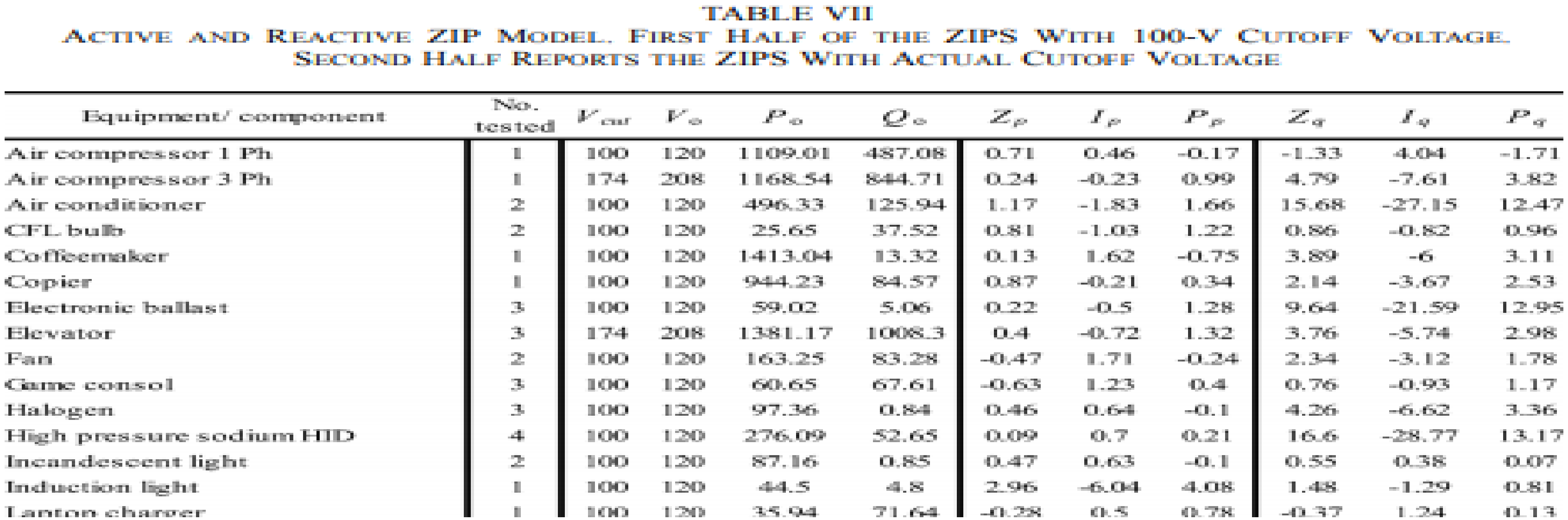


TABLE VII
ACTIVE AND REACTIVE ZIP MODEL. FIRST HALF OF THE ZIPS WITH 100-V CUTOFF VOLTAGE. SECOND HALF REPORTS THE ZIPS WITH ACTUAL CUTOFF VOLTAGE

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

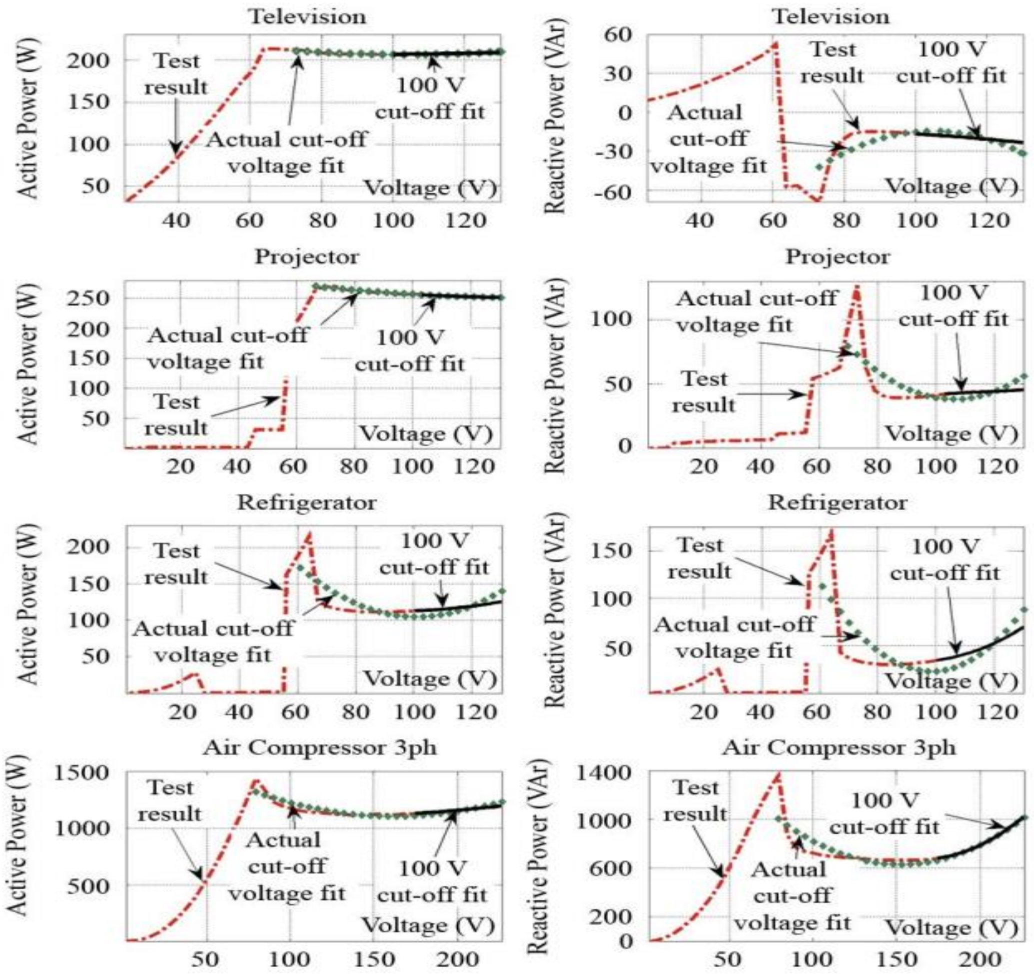


Fig. 3. Active and reactive test results with constrained curve fitting. The ZIP curve with the 100-V cutoff is shown in the solid line and ZIP with the actual cutoff voltage in the dashed line. The two sets of ZIPs are shown in Table VII.

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

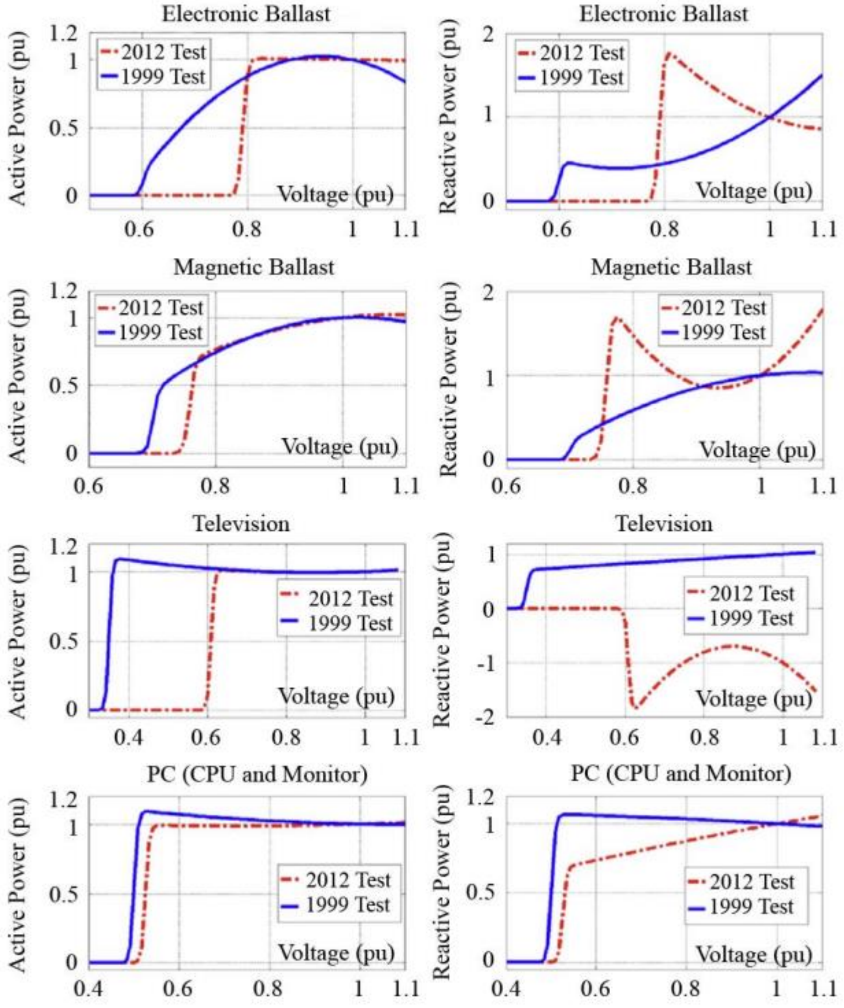
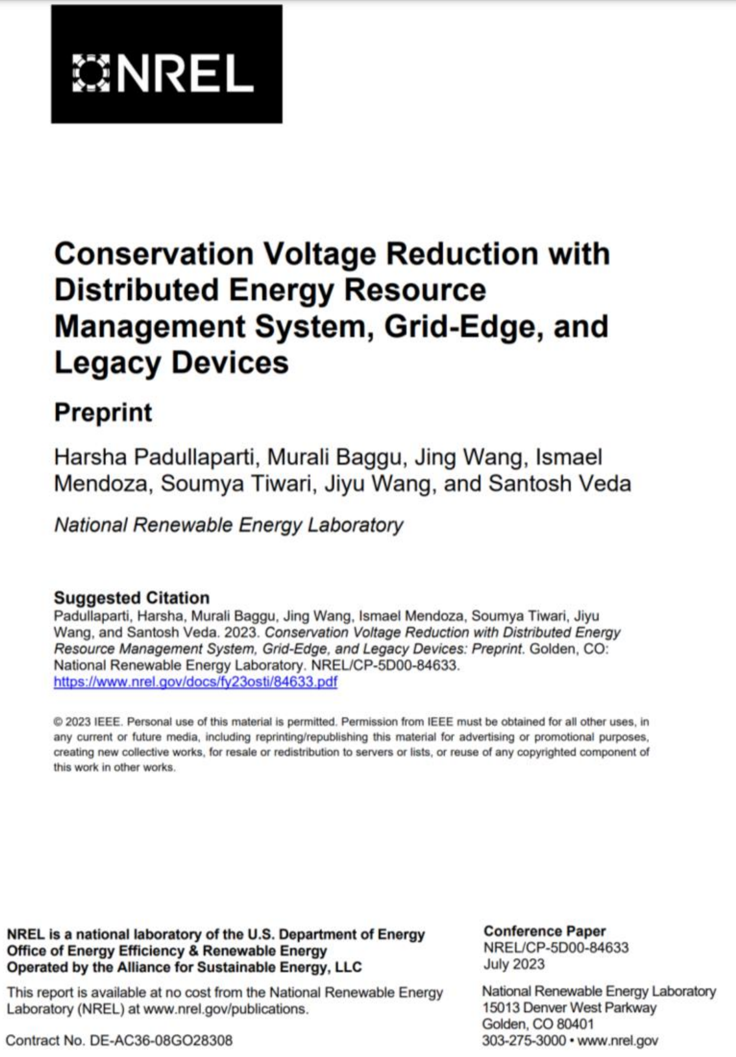


Fig. 4. Comparison of active and reactive powers between old and new appliances.



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

Suggested Citation
Padullaparti, Harsha, Murali Baggu, Jing Wang, Ismael Mendoza, Soumya Tiwari, Jiyu Wang, and Santosh Veda. 2023. *Conservation Voltage Reduction with Distributed Energy Resource Management System, Grid-Edge, and Legacy Devices: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5D00-84633.
https://www.nrel.gov/docs/fy23osti/84633.pdf

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5D00-84633
July 2023

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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

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

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

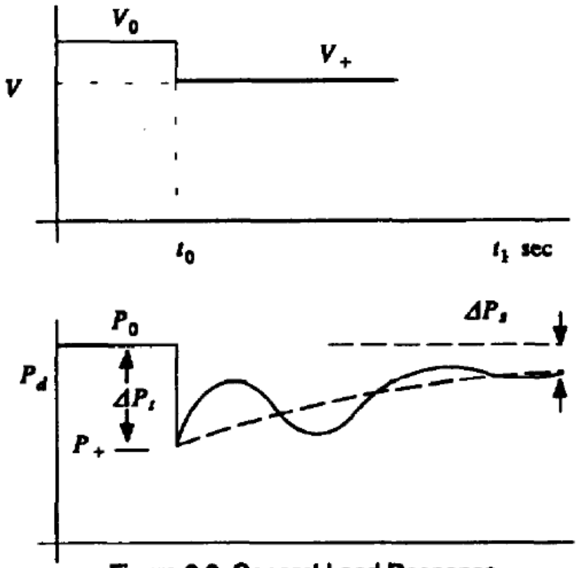


Figure 2.2 General Load Response

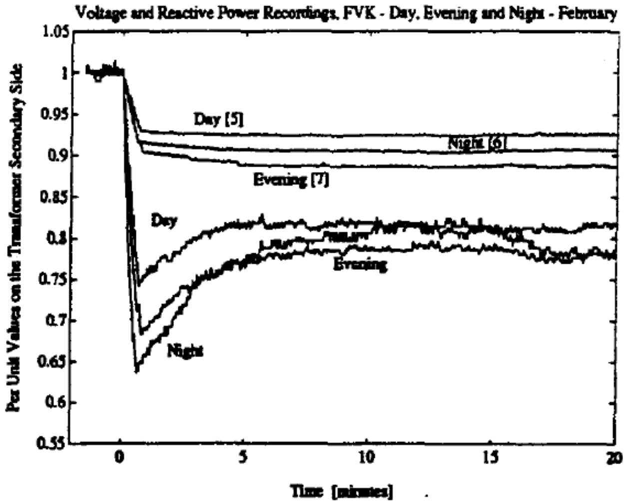
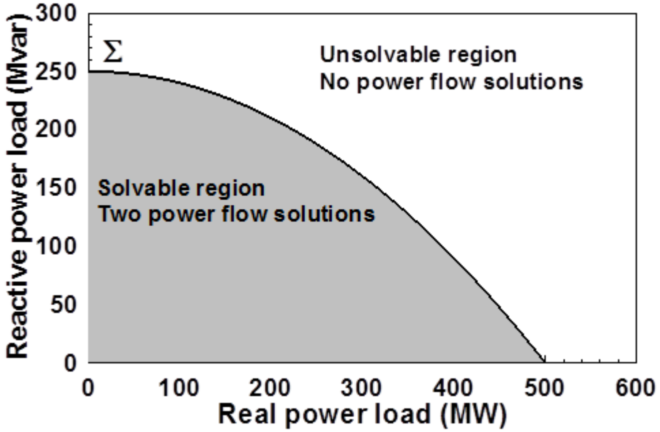


Figure 4.4b. Voltage and reactive power recordings after a voltage reduction in FVK: February; day, evening and night. The number of tap-changer steps used for the ramp is shown in brackets.

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

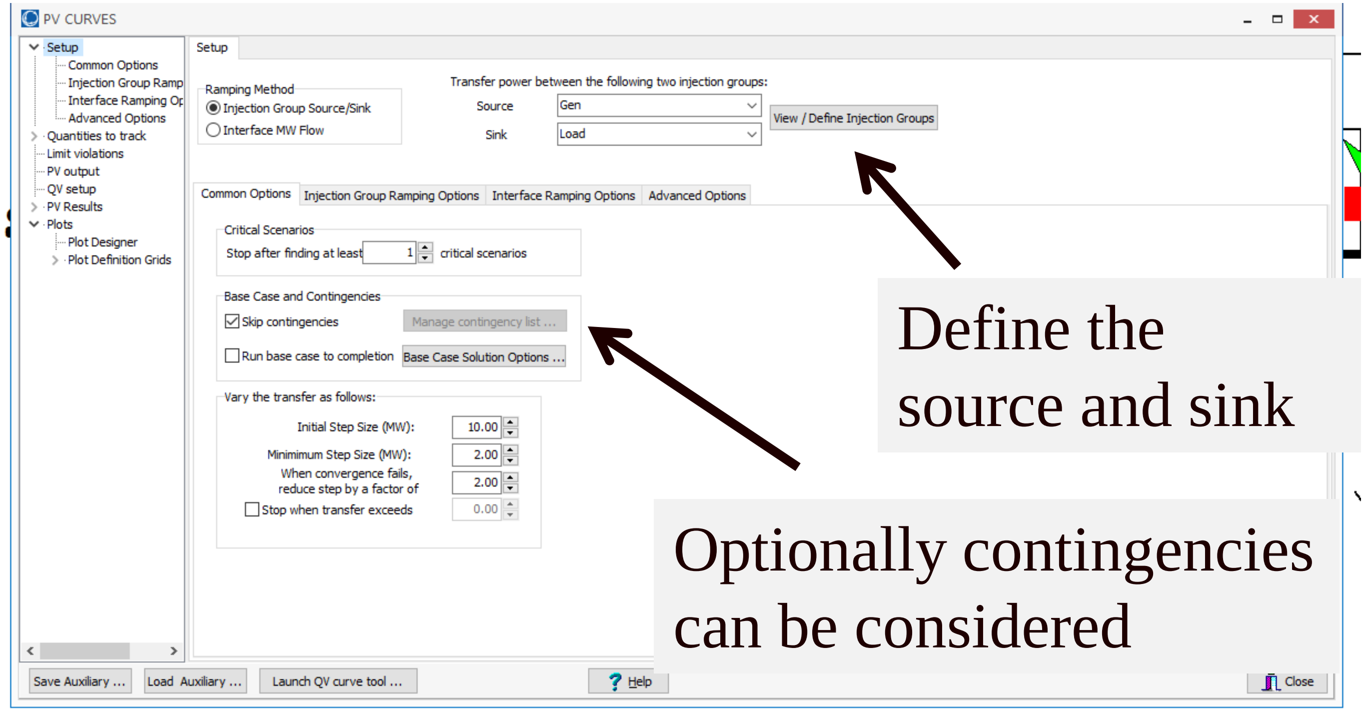
PV and QV Analysis in PowerWorld

- 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

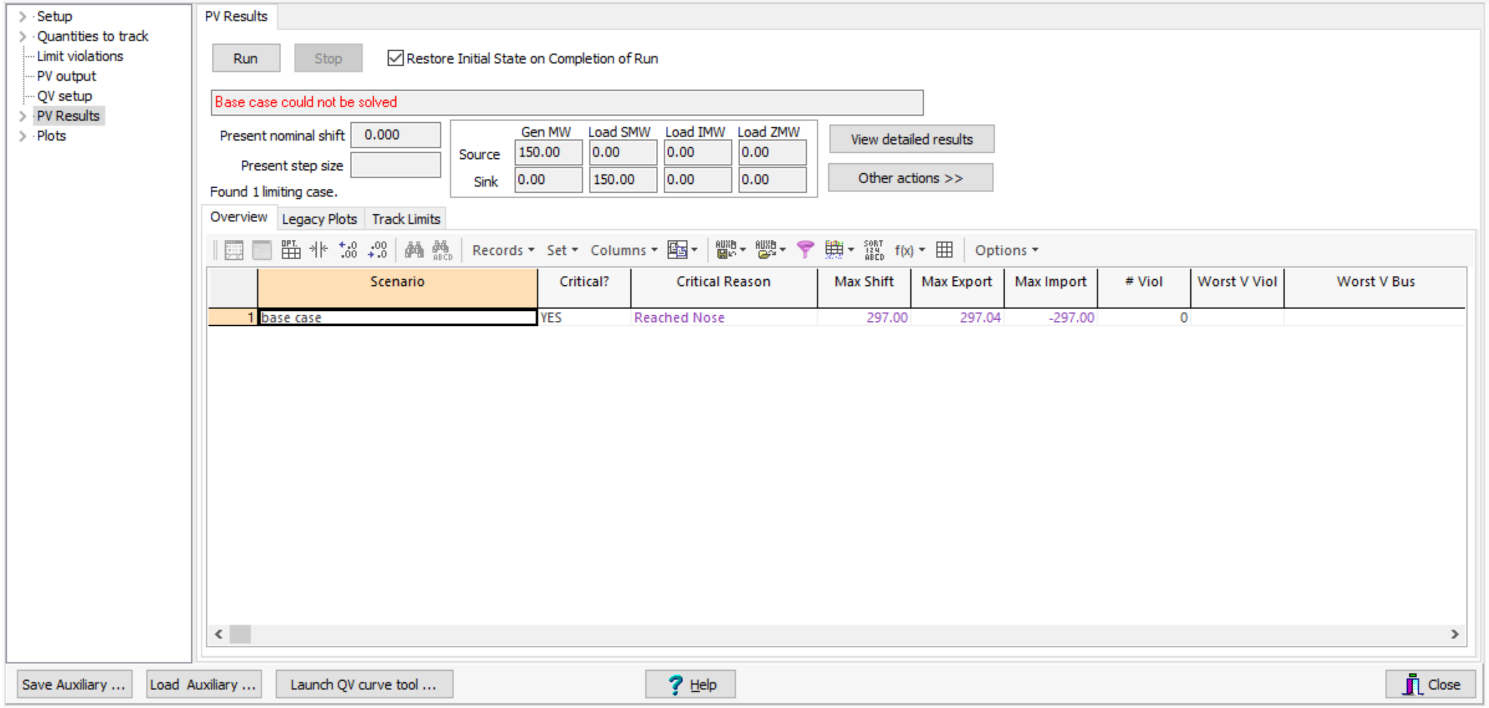
Vary the transfer as follows:
Initial Step Size (MW): 10.00
Minimimum Step Size (MW): 2.00
When convergence fails, reduce step by a factor of 2.00
☐ Stop when transfer exceeds 0.00

Define the source and sink

Optionally contingencies can be considered

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.

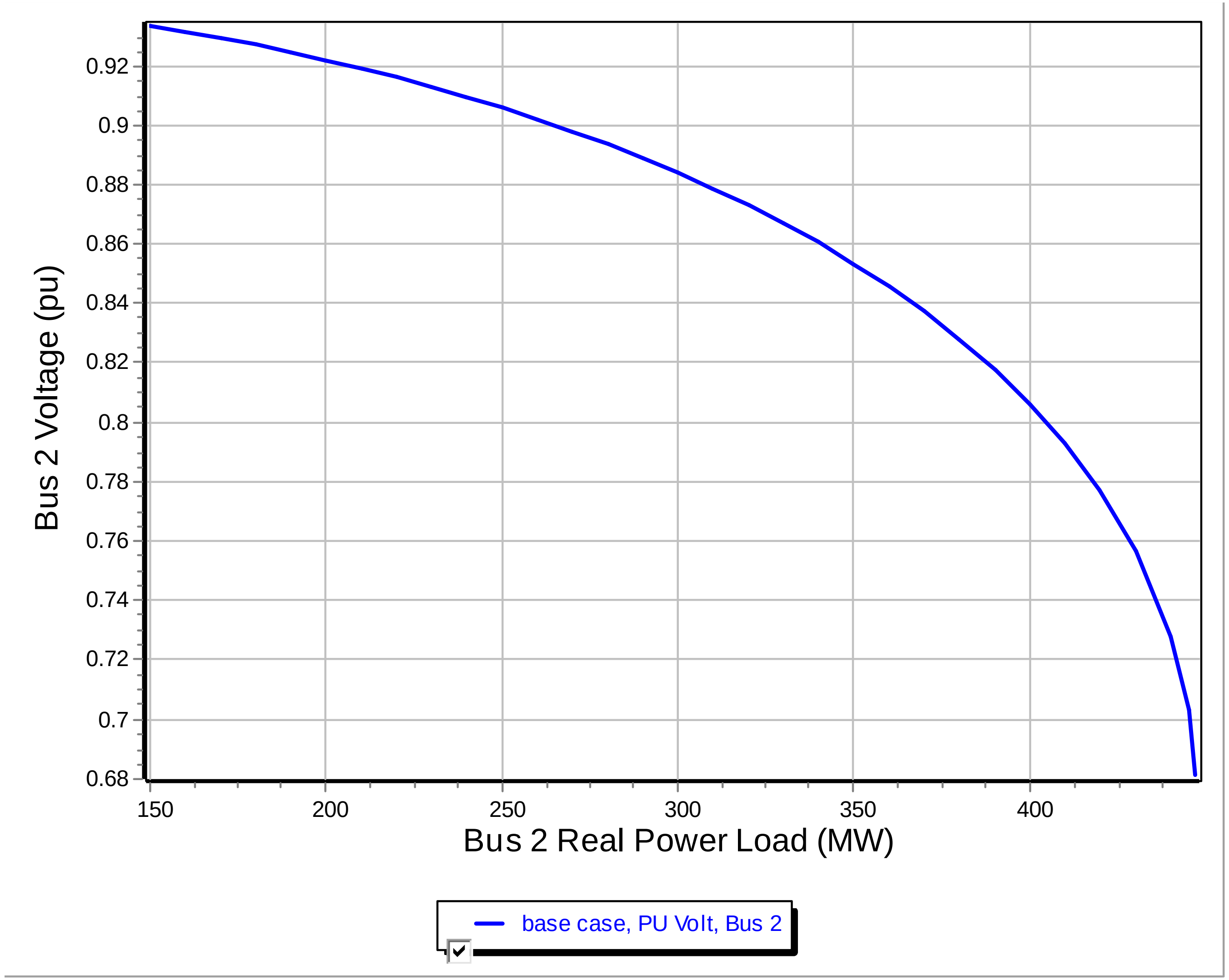
	Gen MW	Load SMW	Load IMW	Load ZMW
Source	150.00	0.00	0.00	0.00
Sink	0.00	150.00	0.00	0.00

	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		

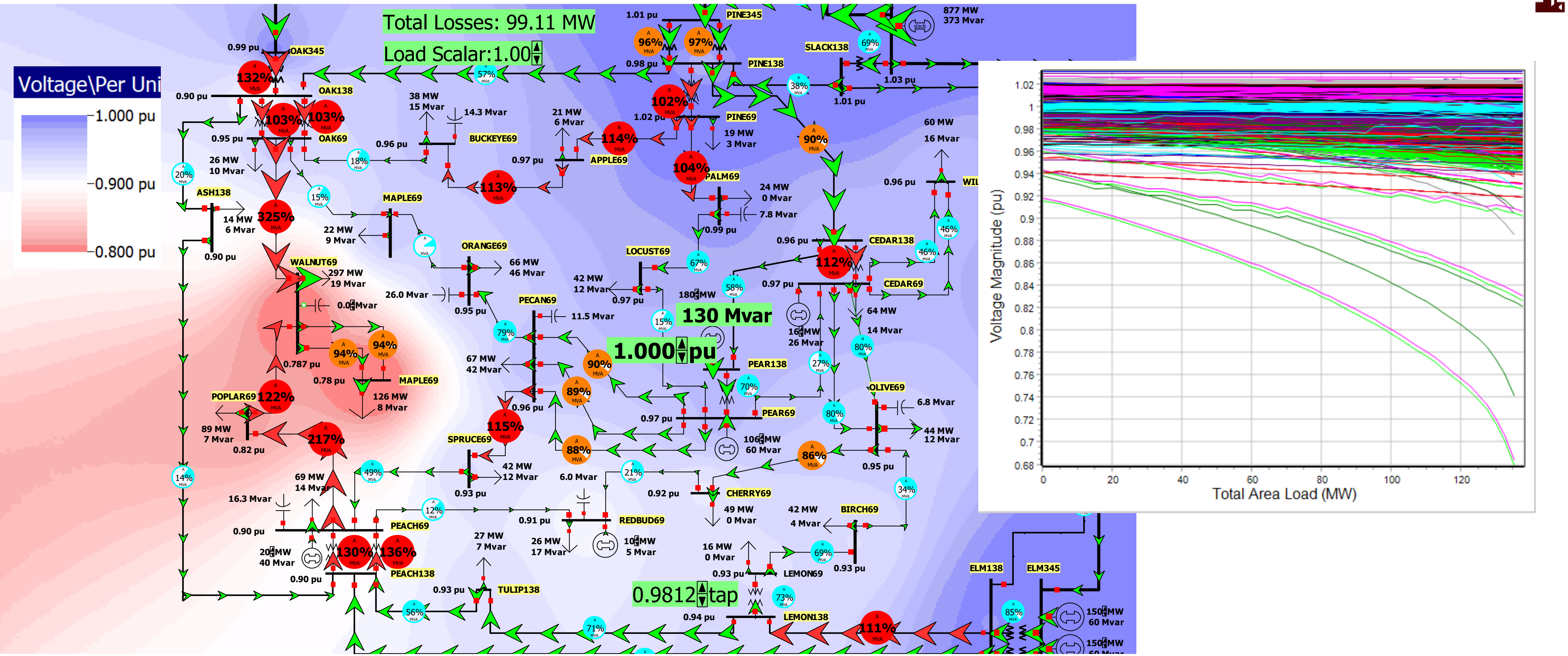
Click the Run button to run the PV analysis;

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



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**