ECEN 667
Power System Stability

Lecture 17: Load Modeling, Voltage Stability

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Announcements

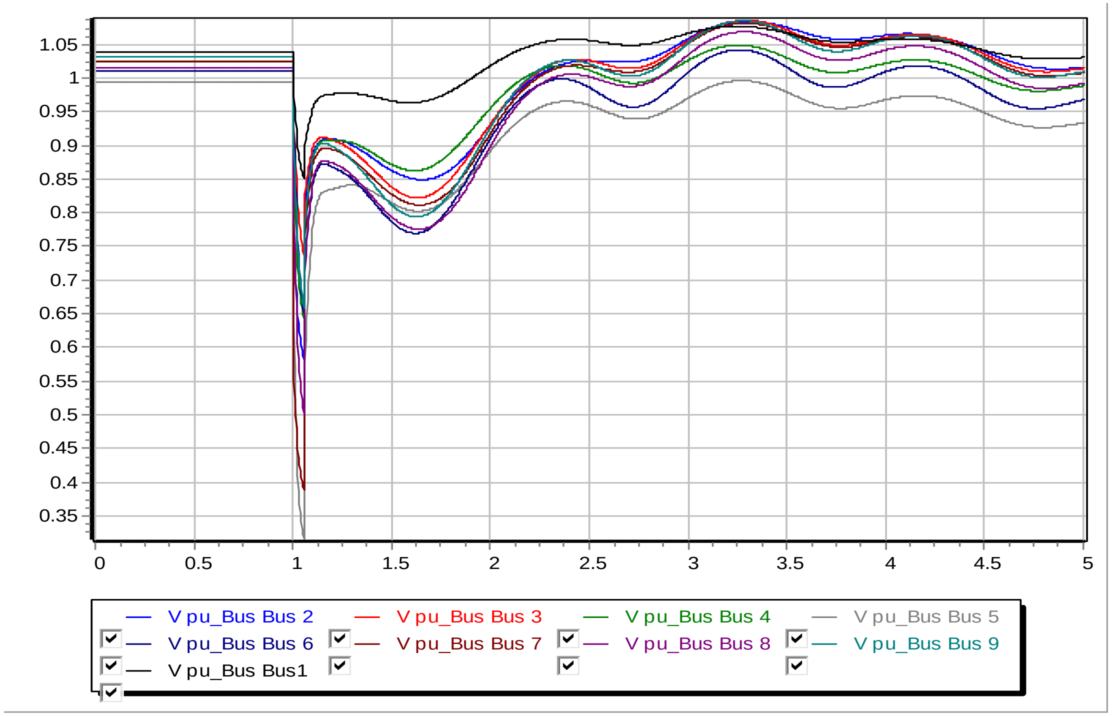
- Read Chapter 7
- Homework 5 is due today
- Homework 6 is due on November 11

Induction Motor Stalling

- Height of the torque-speed curve varies with the square of the terminal voltage
- When the terminal voltage decreases, such as during a fault, the mechanical torque can exceed the electrical torque
  - This causes the motor to decelerate, perhaps quite quickly, with the rate proportional to its inertia
  - This deceleration causing the slip to increase, perhaps causing the motor to stall with s=1, resulting in a high reactive current draw
  - Too many stalled motors can prevent the voltage from recovering

Motor Stalling Example

- Using case WSCC_CIM5, which models the WSCC 9 bus case with 100% induction motor load
- Change the fault scenario to say a fault midway between buses 5 and 7, cleared by opening the line

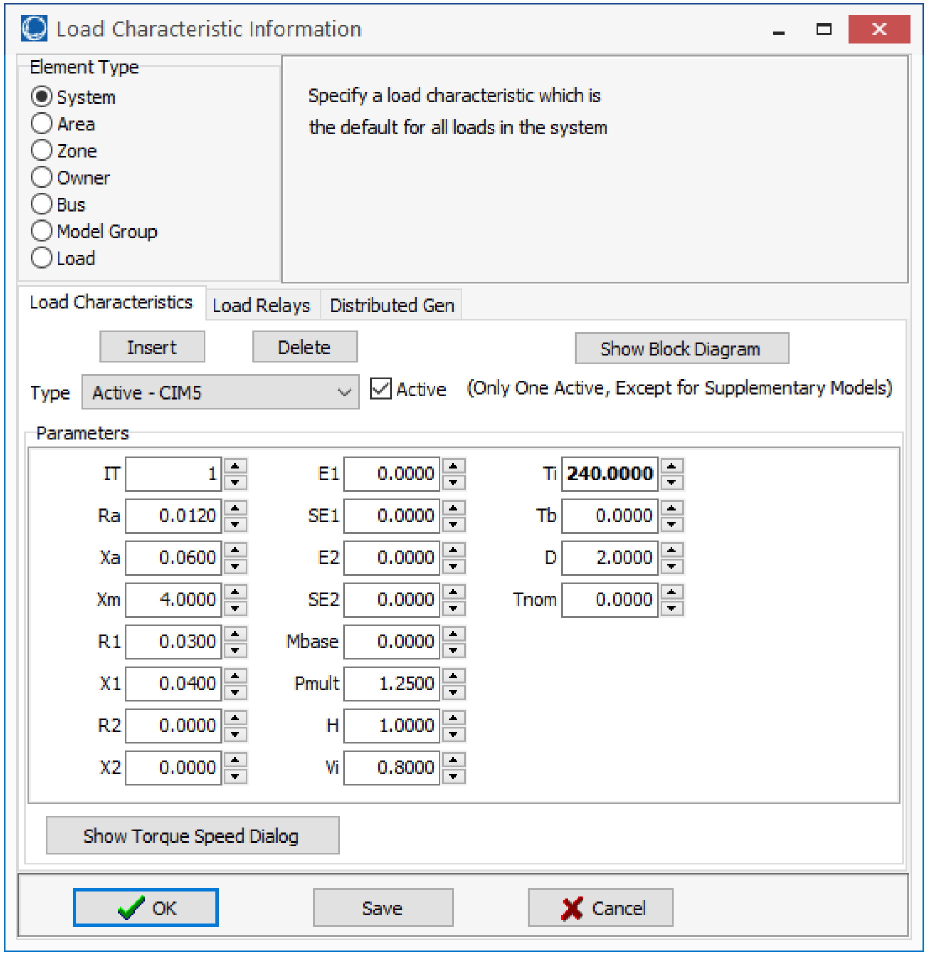


Results are for a 0.05 second fault

Usually motor load is much less than 100%

Impact of Model Protection Parameters

- Some load models, such as the CIM5, have built-in protection system models. For CIM5 the Vi and Ti fields are used to disconnect the load when its voltage is less than Vi for Ti cycles
  - When running simulations you need to check for such events



Element Type
● System
○ Area
○ Zone
○ Owner
○ Bus
○ Model Group
○ Load

Specify a load characteristic which is the default for all loads in the system

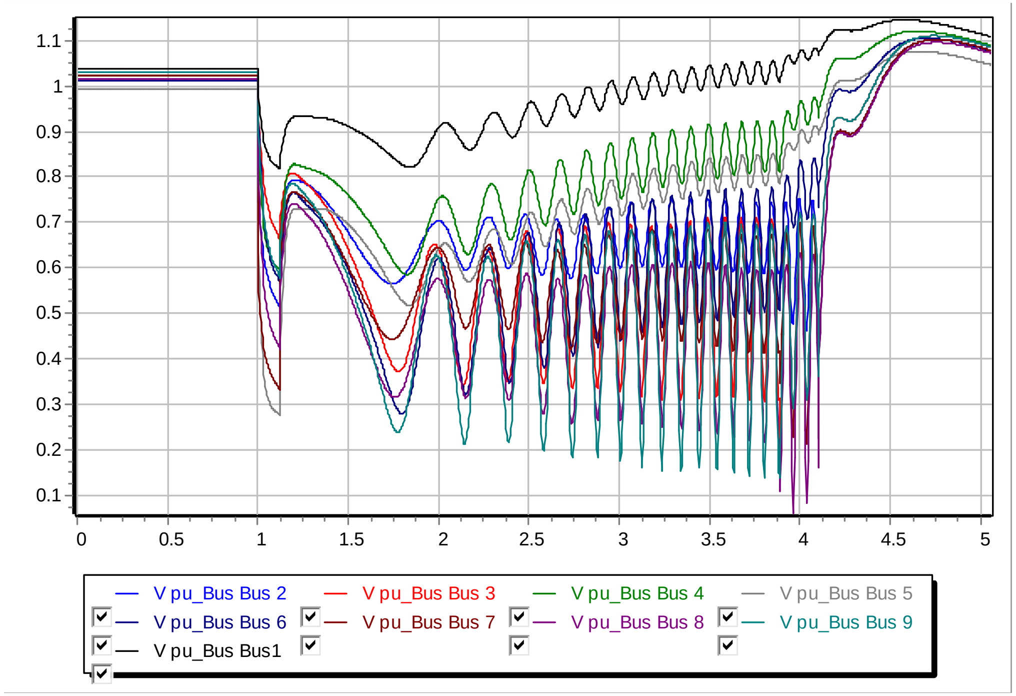
Type: Active - CIM5 ☑ Active (Only One Active, Except for Supplementary Models)

Parameters

IT	1	E1	0.0000	Ti	240.0000
Ra	0.0120	SE1	0.0000	Tb	0.0000
Xa	0.0600	E2	0.0000	D	2.0000
Xm	4.0000	SE2	0.0000	Tnom	0.0000
R1	0.0300	Mbase	0.0000		
X1	0.0400	Pmult	1.2500		
R2	0.0000	H	1.0000		
X2	0.0000	Vi	0.8000		

Motor Stalling With Longer Fault

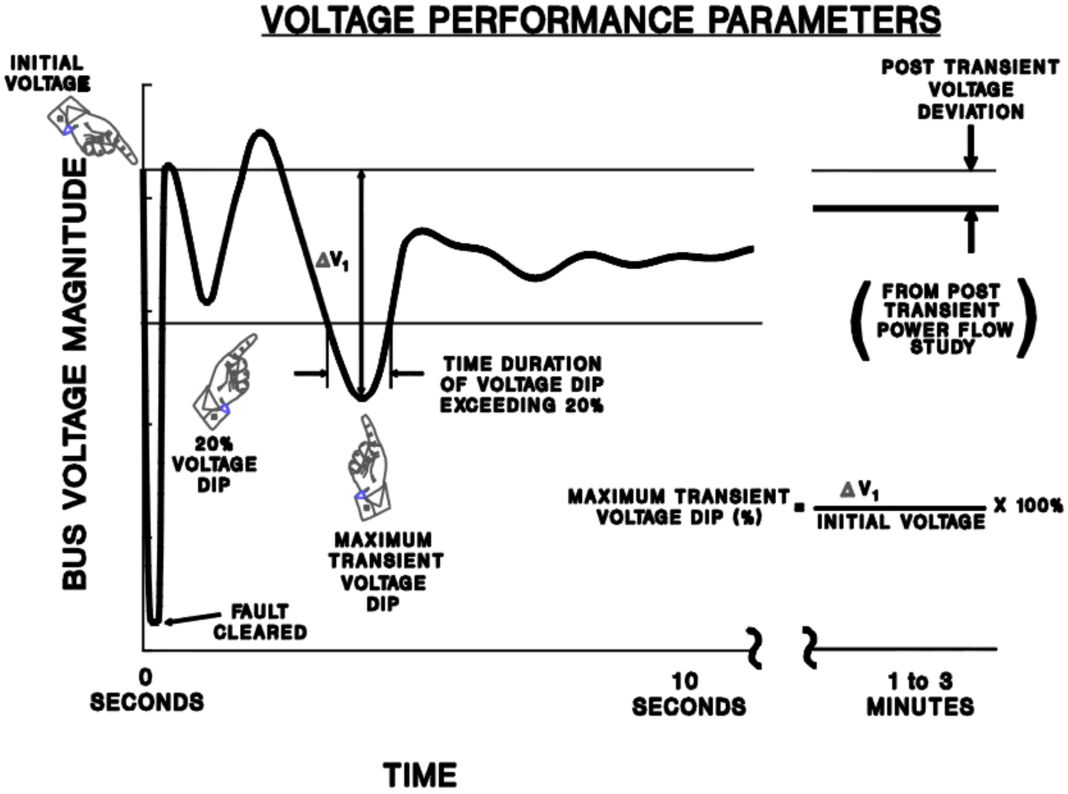
- The below image shows the WECC_CIM5 system with the fault clearing extended to 0.12 seconds



The models are no longer giving realistic results; two generators trip on over speed; then the load trips after 4 seconds.

Transient Limit Monitors

- There are different performance criteria that need to be met for a scenario

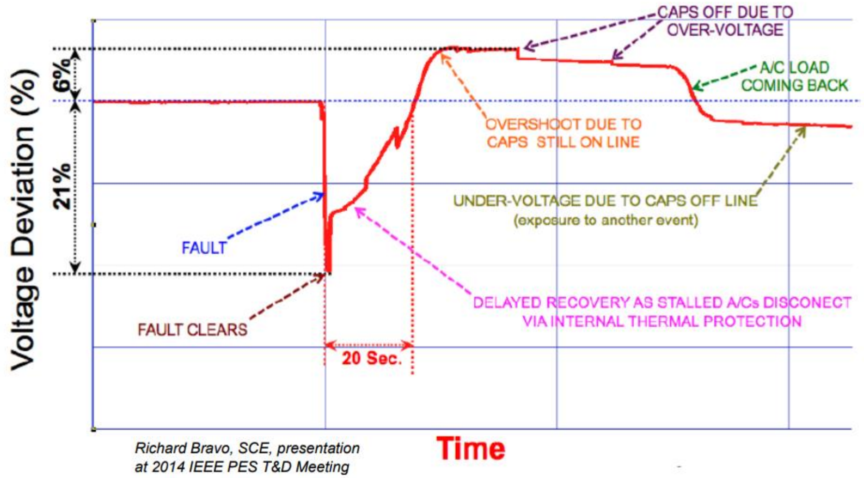


Similar performance criteria exist for frequency deviations

Image from WECC Planning and Operating Criteria

A Concern: Fault Induced Delayed Voltage Recovery (FIDVR)

- FIDVR is a situation in which the system voltage remains significantly reduced for at least several seconds following a fault (at either the transmission or distribution level)
  - It is most concerning in the high voltage grid, but found to be unexpectedly prevalent in the distribution system
- Stalled residential air conditioning units are a key cause of FIDVR – they can stall within the three cycles needed to clear a fault



Richard Bravo, SCE, presentation at 2014 IEEE PES T&D Meeting

Image Source: NERC, Fault Induced Delayed Voltage Recovery (FIDVR) Advisory, July 2015

Motor Starting

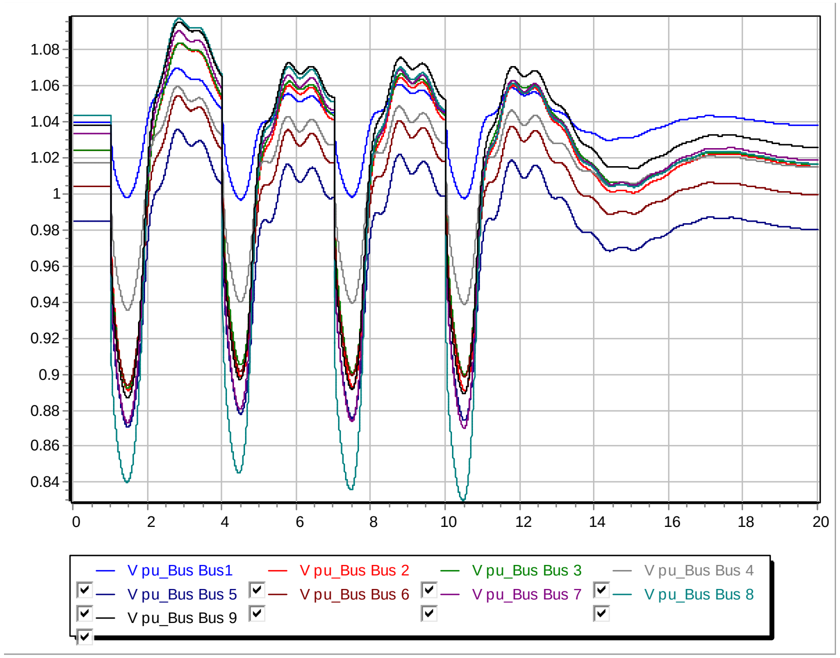
- Motor starting analysis looks at the impacts of starting a motor or a series of motors (usually quite large motors) on the power grid
  - Examples are new load or black start plans
- While not all transient stability motor load models allow the motor to start, some do
- When energized, the initial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

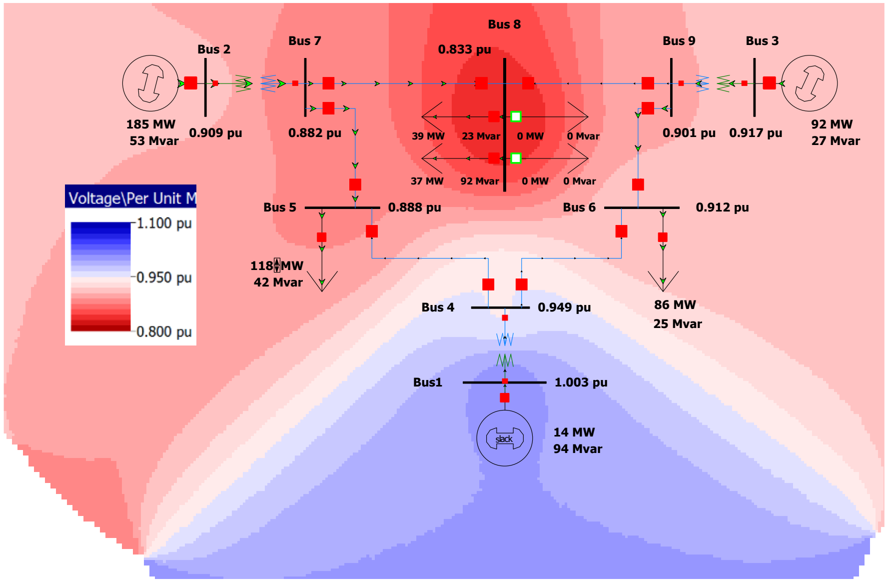
Motor Starting Example

- 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

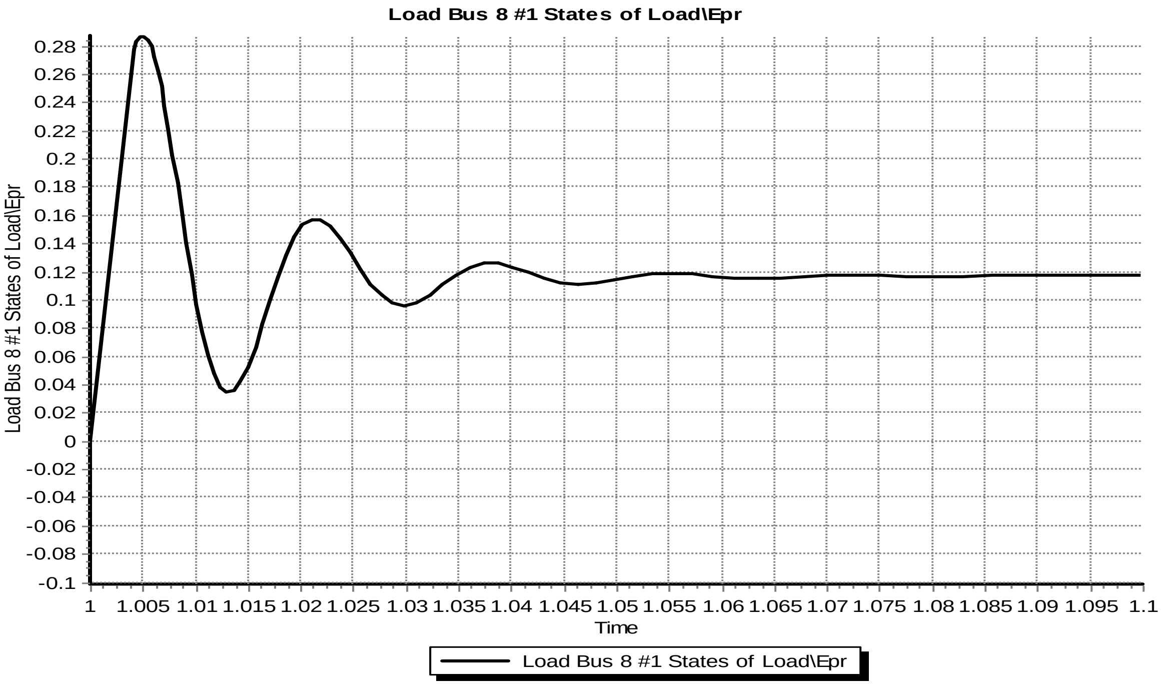
- Below graph shows the bus voltages for starting the four motors three seconds apart





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

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

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

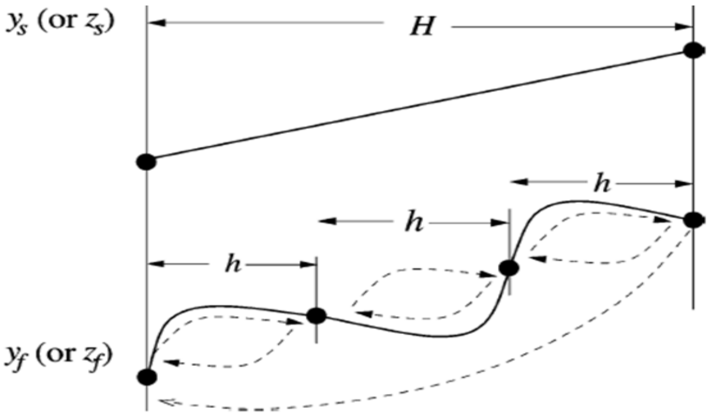
$$\frac{dE'_D}{dt} = \omega_s s E'_Q - \frac{1}{T'_o}\left(E'_D + \left(X - X'\right) I_Q\right)$$

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

- 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 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

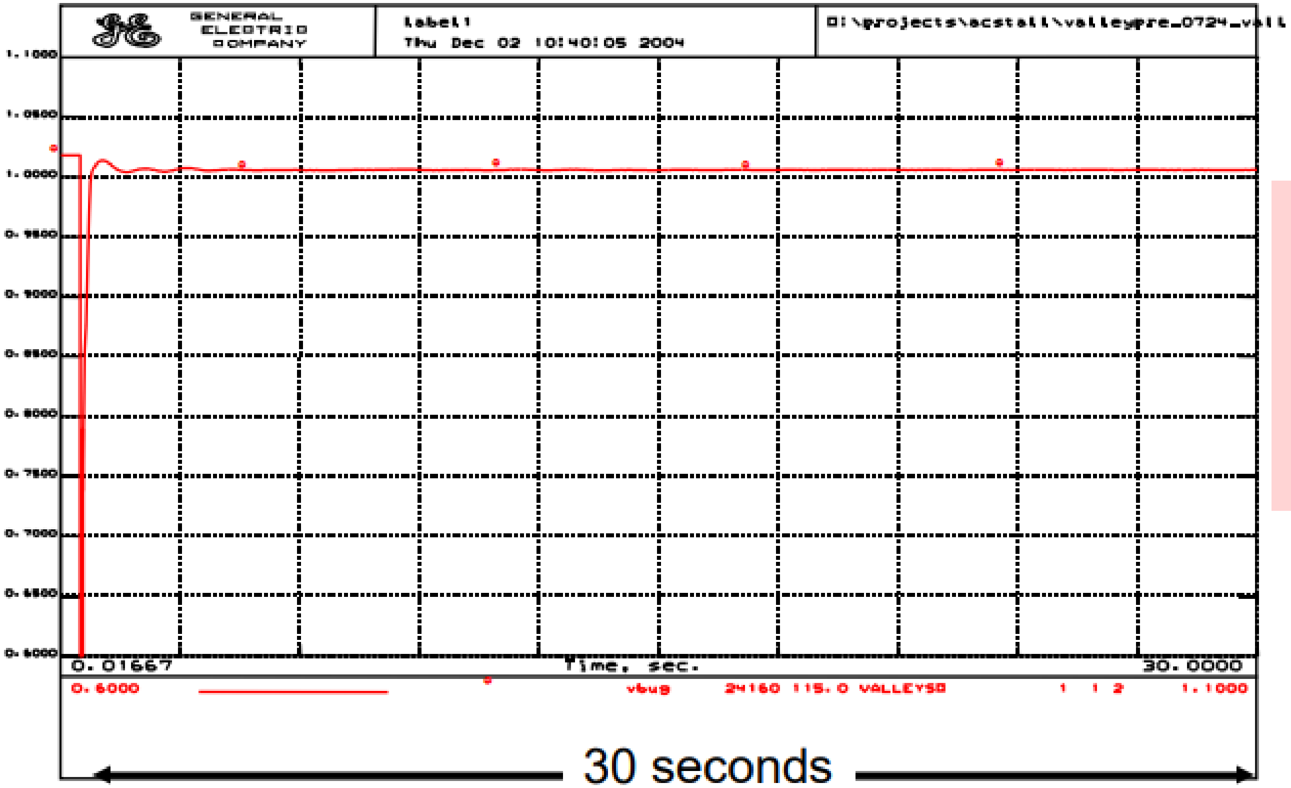
Need for Better Load Modeling: History of Load Modeling in WECC

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

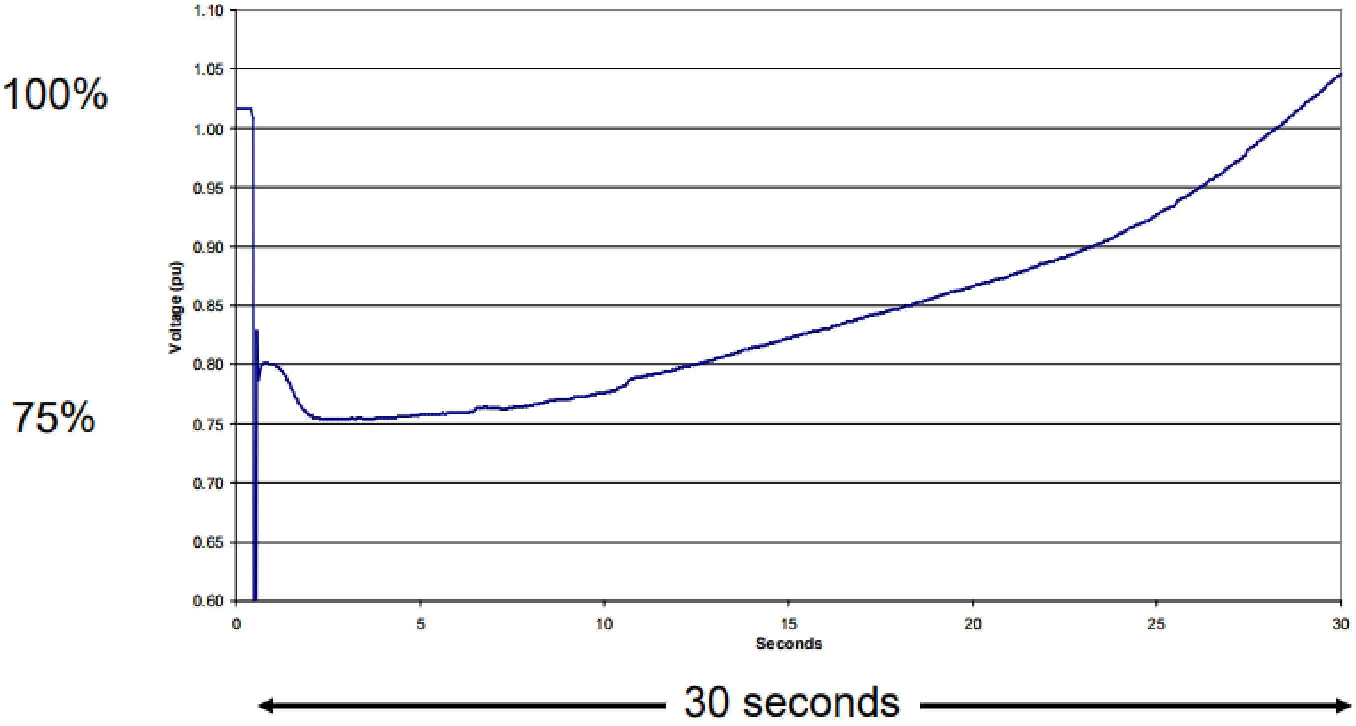


Vertical scale goes down to about 0.6 per unit

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

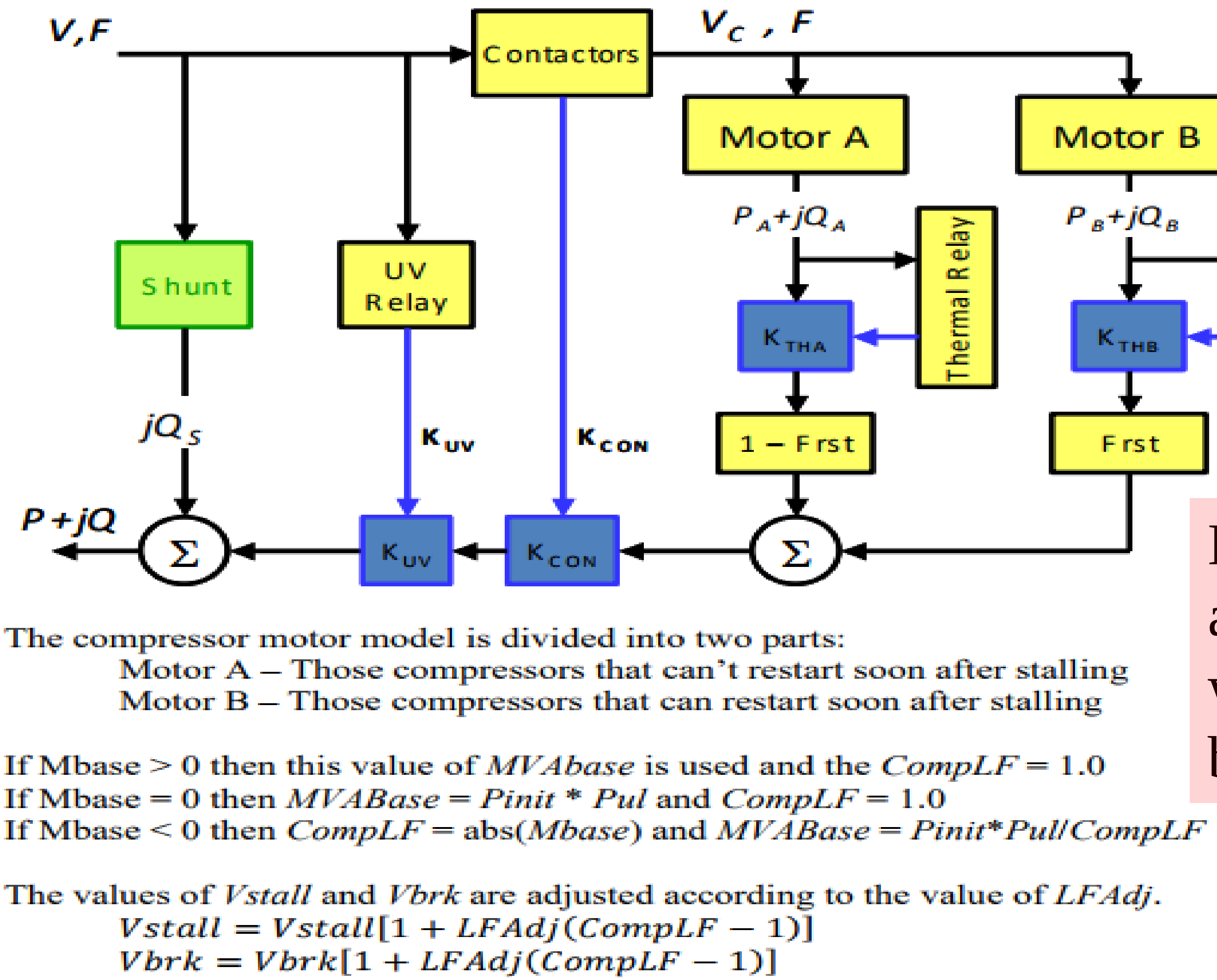
What is LD1PAC

- LD1PAC is the model that is embedded inside the "composite load model"
  - This is the CMPLDW or CMLD
- Purpose is NOT to model *one* air conditioner
- 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



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*.

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

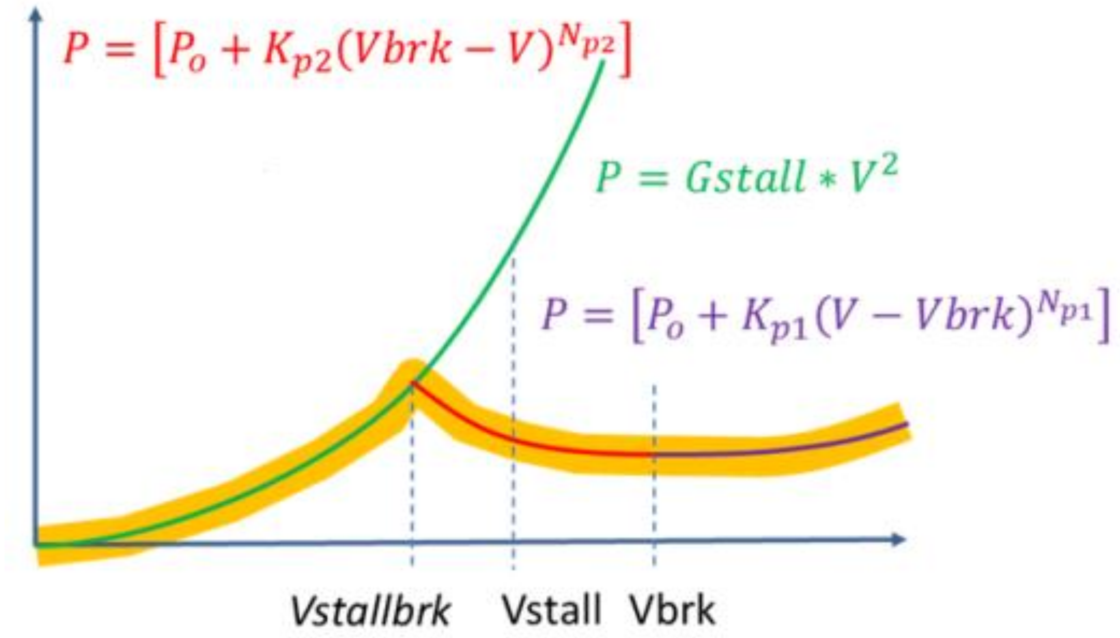
Model is mostly algebraic, but with stalling behavior

“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)

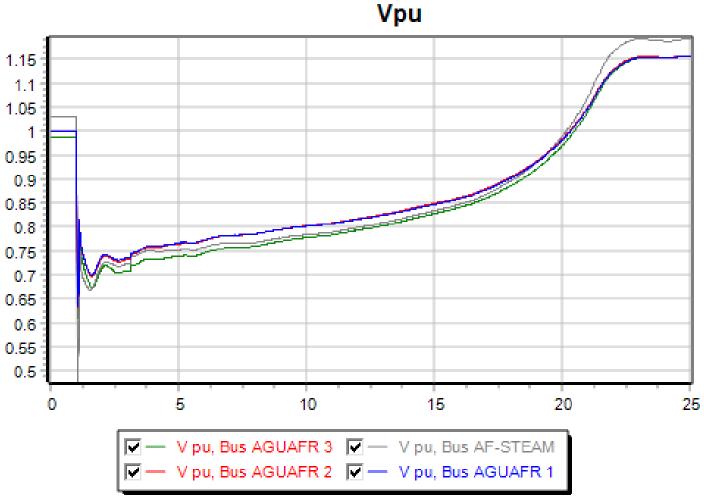


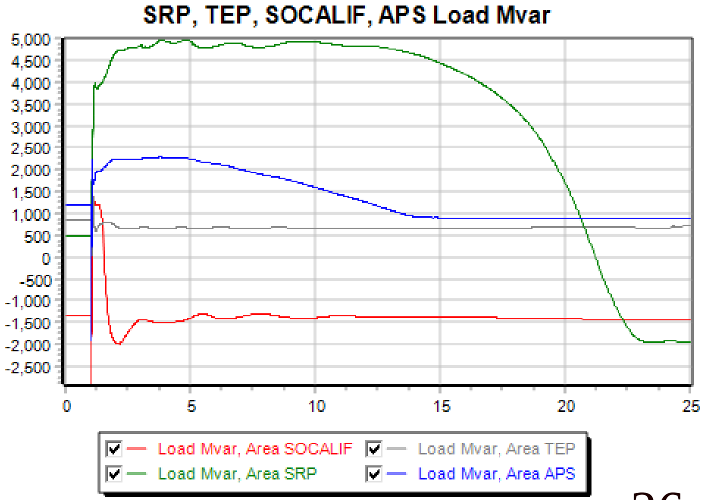
Transition between the "Operating" and "Stall" Curves

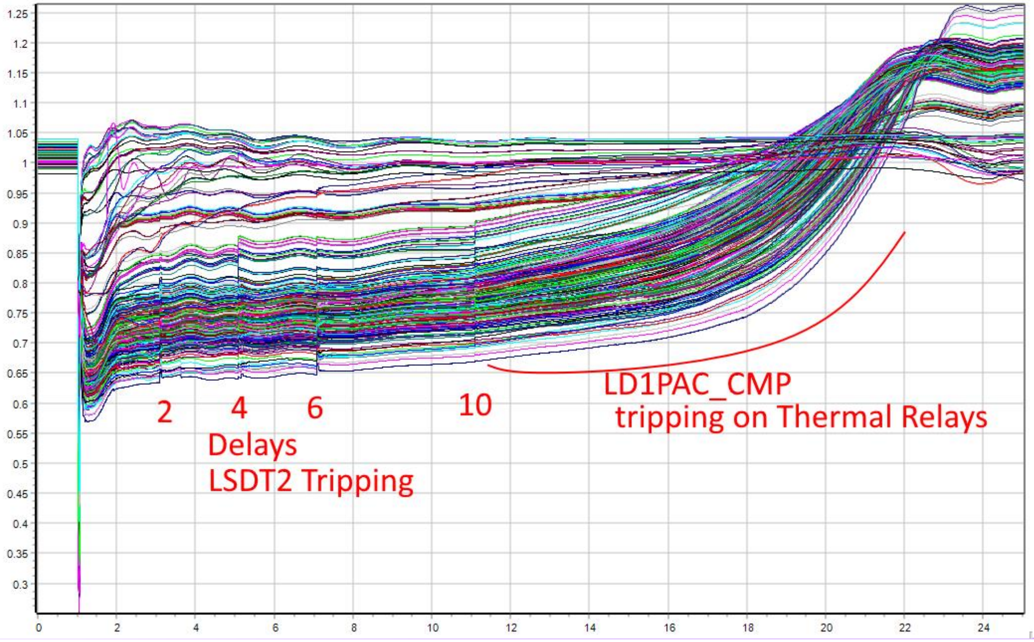
- In existing LD1PAC and CMPLDW/CMLD models this transition is defined simply as
  - If Voltage < Vstall for more than Tstall seconds, then immediately flip to the green stall curve
  - The "Motor A" fraction of the model will remain there until the thermal relay trips it
  - The "Motor B" fraction of 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


Vpu


SRP, TEP, SOCALIF, APS Load Mvar



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)

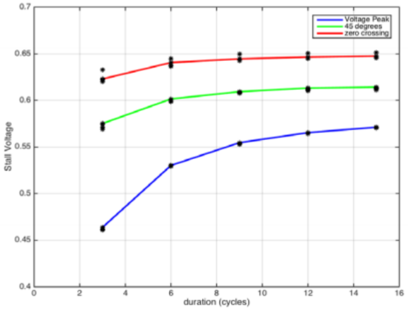
https://www.osti.gov/servlets/purl/1183173

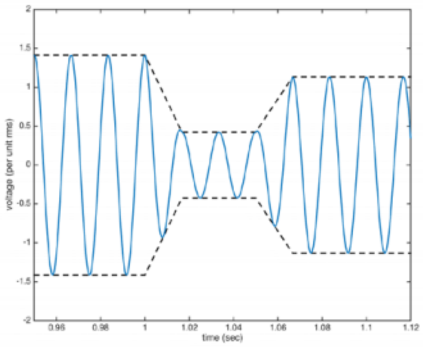
- They found that when stalling happened, it happened extremely quickly (the motors are very small and have very little inertia)

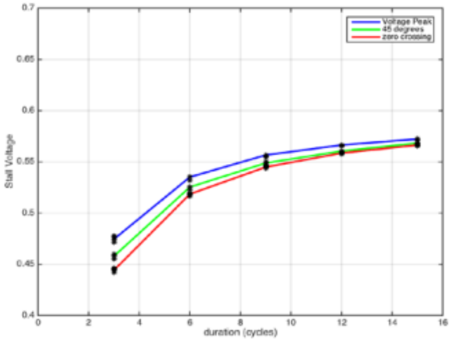
https://gig.lbl.gov/sites/all/files/6b-quint-composite-load-model-data.pdf

Air-Conditioner Stalling Testing

- Initial laboratory testing found that the “point-on-wave” (where in the sine wave) that fault was applied great impacted whether stalling occurred
  - This led to initial Vstall = 0.6 → resulted in a LOT of stalling simulations which did not match reality
- Follow-up laboratory testing modified the voltage magnitude (fault) applied over 1 cycle and results showed that the point-on-wave effect went away







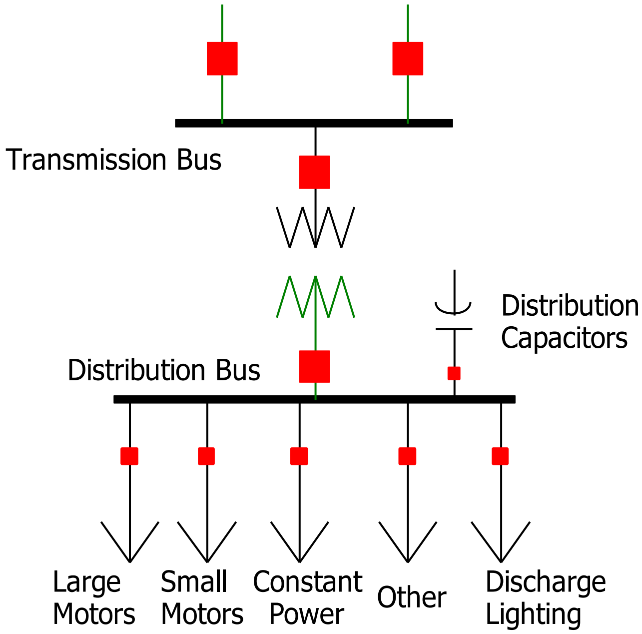
https://gig.lbl.gov/sites/all/files/6b-quint-composite-load-model-data.pdf

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

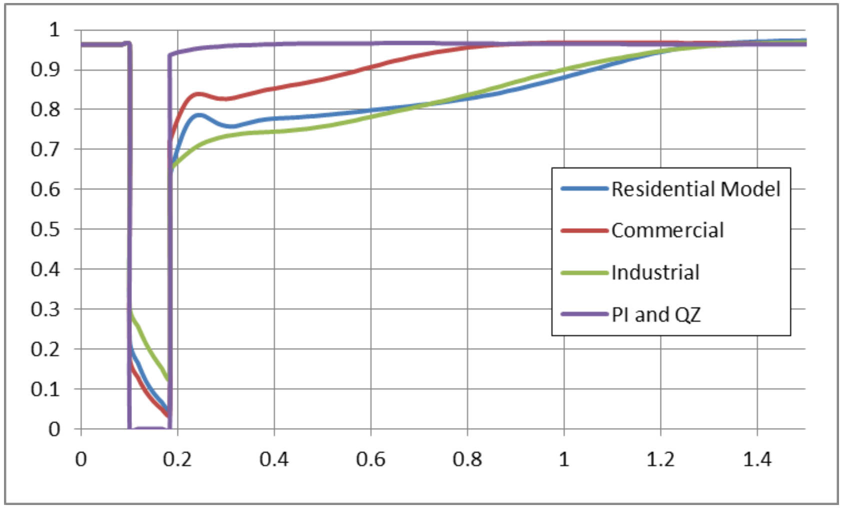
- The CLOD model represents the load as a combination of large induction motors, small induction motors, constant power, discharge lighting, and other



CLOD Model

- Different load classes can be defined

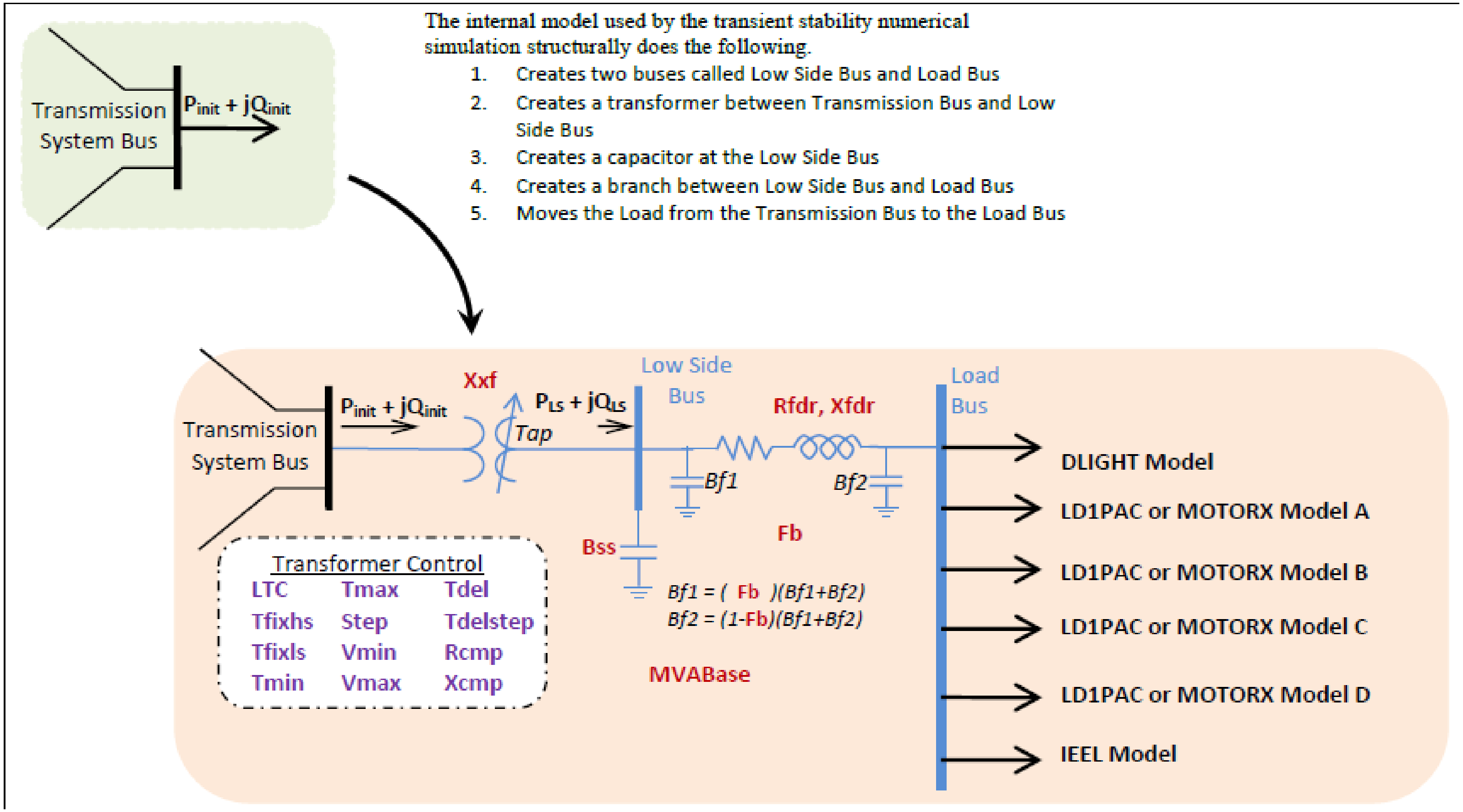
Customer Class	Large Motor	Small Motor	Discharge Lighting	Constant Power	Remaining (PI, QZ)
Residential	0.0	64.4	3.7	4.1	27.8
Agriculture	10.0	45	20	4.5	19.5
Commercial	0.0	46.7	41.5	4.5	7.3
Industrial	65.0	15.0	10.0	5.0	4.0



Comparison of voltage recovery for different model types

WECC Composite Load Model

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

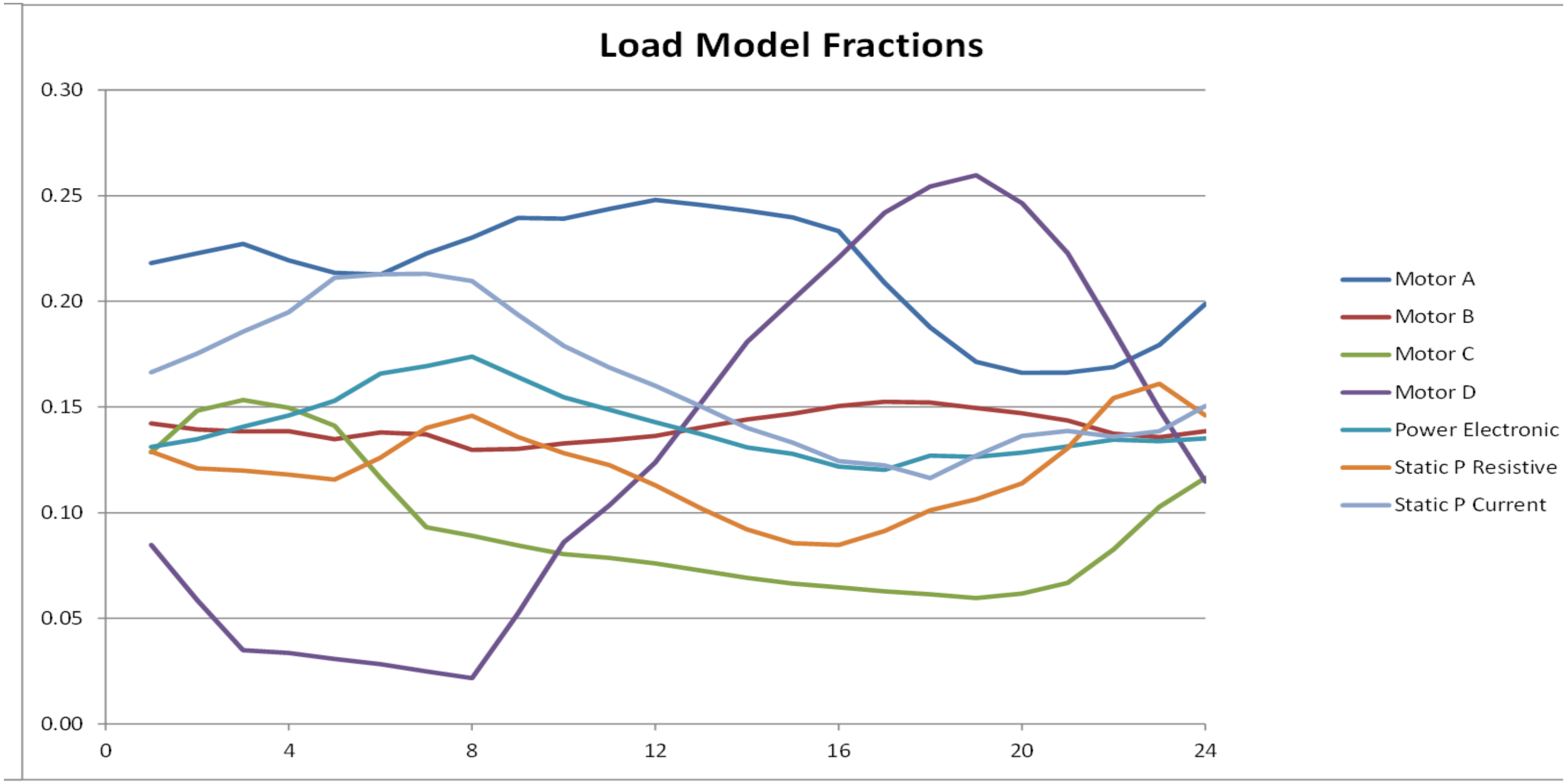


The internal model used by the transient stability numerical simulation structurally does the following.

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

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.

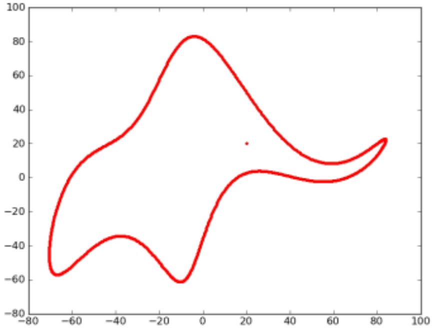
Current Research

- 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, August 2020 (with a draft at the below link)

https://www.wecc.org/Administrative/Mitra%20-%20Technical%20Guide%20on%20Composite%20Load%20Modeling.pdf

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

“Drawing an elephant with four complex parameters” by Jurgen Mayer, Khaled Khairy, and Jonathon Howard, Am. J. Phys. 78, 648 (2010), DOI:10.1119/1.3254017

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)