

# ECEN 667

## Power System Stability

### Lecture 16: Load Modeling

---

Prof. Adam Birchfield

Dept. of Electrical and Computer Engineering

Texas A&M University

[abirchfield@tamu.edu](mailto:abirchfield@tamu.edu)



TEXAS A&M  
UNIVERSITY

# Announcements

---



- HW #4 is on the website, due Oct 30<sup>th</sup> at 8 AM.
- HW #5 is on the website, due Nov 20<sup>th</sup> at 8 AM.
- Review the slides and PowerWorld examples
- **Exam 2 will be Tuesday, Dec. 2<sup>nd</sup>, 2025**

# Load Modeling

---



- Load modeling is certainly challenging!
- For large system models an aggregate load can consist of many thousands of individual devices
- The load is constantly changing, with key diurnal and temperature variations
  - For example, a higher percentage of lighting load at night, more air conditioner load on hot days
- Load model behavior can be quite complex during the low voltages that may occur in transient stability
- Testing aggregate load models for extreme conditions is not feasible – we need to wait for disturbances!

# Load Modeling, cont.

---



- Traditionally load models have been divided into two groups
  - Static: load is a algebraic function of bus voltage and sometimes frequency
  - Dynamic: load is represented with a dynamic model, with induction motor models the most common
- The simplest load model is a static constant impedance
  - Has been widely used
  - Allowed the  $\mathbf{Y}_{bus}$  to be reduced, eliminating essentially all non-generator buses
  - Presents no issues as voltage falls to zero
  - No longer commonly used

# Load Modeling References

---



- Many papers and reports are available!
- A classic reference on load modeling is by the IEEE Task Force on Load Representation for Dynamic Performance, "Load Representation for Dynamic Performance Analysis," IEEE Trans. on Power Systems, May 1993, pp. 472-48
- NERC 2016, "Dynamic Load Modeling"; available at <https://www.nerc.com/comm/PC/LoadModelingTaskForceDL/Dynamic%20Load%20Modeling%20Tech%20Ref%202016-11-14%20-%20FINAL.PDF>
- NERC Reliability Guideline, "Developing Load Model Composition Data, 2017"
- EPRI Technical Guide to Composite Load Modeling, Sept. 2020
  - <https://www.epri.com/research/programs/027570/results/3002019209>

# ZIP Load Model (Covered Last Lecture)



- Another common static load model is the ZIP, in which the load is represented as

$$P_{Load,k} = P_{BaseLoad,k} (P_{z,k} |\bar{V}_k|^2 + P_{i,k} |\bar{V}_k| + P_{p,k})$$

$$Q_{Load,k} = Q_{BaseLoad,k} (Q_{z,k} |\bar{V}_k|^2 + Q_{i,k} |\bar{V}_k| + Q_{p,k})$$

- Some models allow more general voltage dependence

$$P_{Load,k} = P_{BaseLoad,k} (a_{1,k} |\bar{V}_k|^{n_1} + a_{2,k} |\bar{V}_k|^{n_2} + a_{3,k} |\bar{V}_k|^{n_3})$$

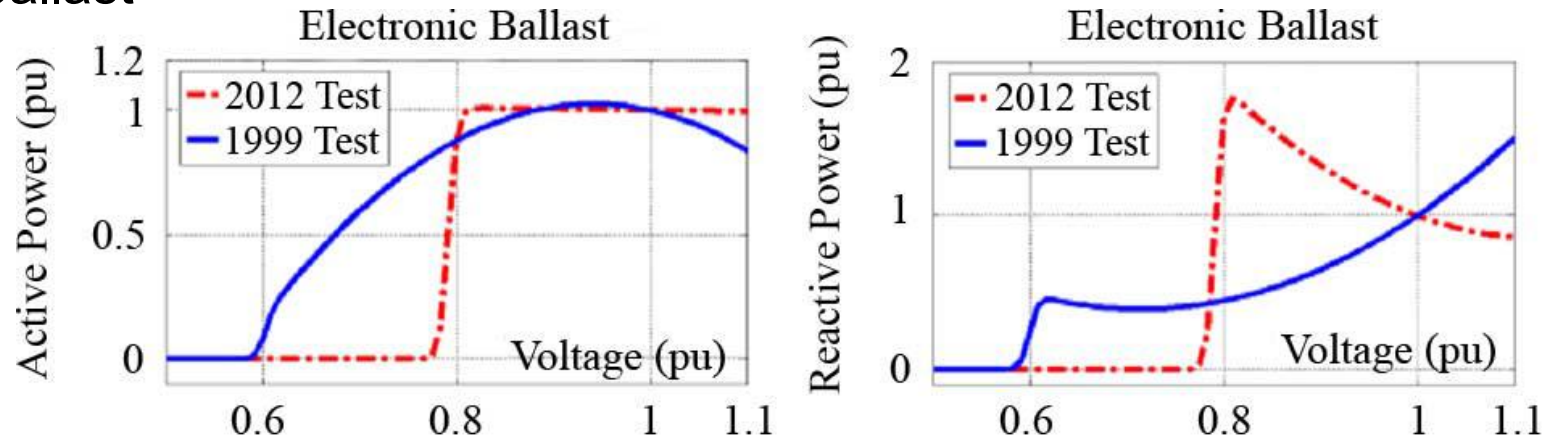
$$Q_{Load,k} = Q_{BaseLoad,k} (a_{4,k} |\bar{V}_k|^{n_4} + a_{5,k} |\bar{V}_k|^{n_5} + a_{6,k} |\bar{V}_k|^{n_6})$$

The voltage exponent for reactive power is often  $> 2$

# ZIP Model Coefficients



- An interesting paper on the experimental determination of the ZIP parameters is A. Bokhari, et. al., "Experimental Determination of the ZIP Coefficients for Modern Residential and Commercial Loads, and Industrial Loads," *IEEE Trans. Power Delivery*, 2014
  - Presents test results for loads as voltage is varied; also highlights that load behavior changes with newer technologies
    - Below figure (part of fig 4 of paper), compares real and reactive behavior of light ballast



# ZIP Model Coefficients, cont.



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
LCD Television	1	100	120	208.03	-20.58	0.11	-0.17	1.06	1.58	-1.72	1.14
LED light	1	100	120	3.38	5.85	0.58	1.13	-0.71	1.78	-0.8	0.02
Magnetic ballast	1	100	120	81.23	8.2	-1.58	3.79	-1.21	36.18	-67.78	32.6
Mercury vapor HID light	2	100	120	268.27	77.66	0.52	1.02	-0.54	-1.33	2.4	-0.07
Metal halide HID electronic ballast	2	100	120	113.7	26.37	1	-2.02	2.02	8.8	-18.64	10.84
Metal halide HID magnetic ballast	2	100	120	450	102.94	0.86	-0.66	0.8	32.54	-59.83	28.29
Microwave	2	100	120	1365.53	451.02	1.39	-1.96	1.57	50.07	-93.55	44.48
Minibar	1	100	120	90.65	126.94	2.5	-4.1	2.6	2.56	-2.76	1.2
PC (Monitor & CPU)	1	100	120	118.9	172.79	0.2	-0.3	1.1	0	0.6	0.4

The Z,I,P coefficients sum to zero; note that for some models the absolute values of the parameters are quite large, indicating a difficult fit

A portion of Table VII from the Bokhari 2014 paper

# Discharge Lighting Models



- Discharge lighting (such as fluorescent lamps) have been at major portion of the load (10-15%) though now it is getting increasingly replaced by LEDs
- Discharge lighting has been modeled for sufficiently high voltage with a real power as constant current and reactive power with a high voltage dependence
  - Linear reduction for voltage between 0.65 and 0.75 pu
  - Extinguished (i.e., no load) for voltages below

$$P_{DischargeLighting} = P_{Base}(|\bar{V}_k|)$$

$$Q_{DischargeLighting} = Q_{Base}(|\bar{V}_k|^{4.5})$$

May need to change with newer electronic ballasts – e.g., reactive power increasing as the voltage drops!

# Static Load Model Frequency Dependence



- Frequency dependence is sometimes included, to recognize that the load could change with the frequency

$$P_{Load,k} = P_{BaseLoad,k} (P_{z,k} |\bar{V}_k|^2 + P_{i,k} |\bar{V}_k| + P_{p,k}) (1 + P_{f,k} (f_k - 1))$$

$$Q_{Load,k} = Q_{BaseLoad,k} (Q_{z,k} |\bar{V}_k|^2 + Q_{i,k} |\bar{V}_k| + Q_{p,k}) (1 + Q_{f,k} (f_k - 1))$$

- Here  $f_k$  is the per unit bus frequency, which is calculated as

$$\theta_k \rightarrow \boxed{\frac{s}{1+sT}} \rightarrow f_k$$

- Typical values for  $P_f$  and  $Q_f$  are 1 and -1 respectively

A typical value for T is about 0.02 seconds. Some models just have frequency dependence on the constant power load

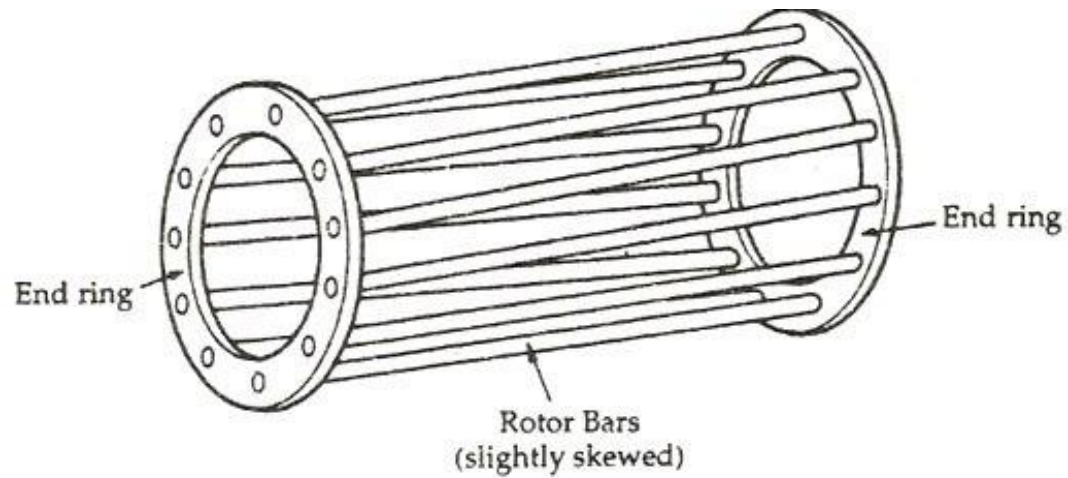
# Induction Machines

---

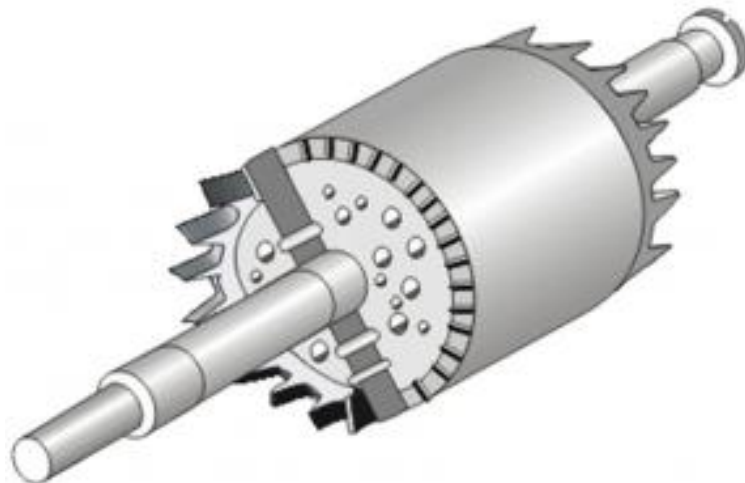


- Term induction machine is used to indicate either generator or motor; most uses are as motors
- Induction machines have two major components
  - A stationary stator, which is supplied with an ac voltage; windings in stator create a rotating magnetic field
  - A rotating rotor, in which an ac current is induced (hence the name)
- Two basic design types based on rotor design
  - Squirrel-cage: rotor consists of shorted conducting bars laid into magnetic material in a cage structure
  - Wound-rotor: rotor has windings similar to stator, with slip rings used to provide external access to the rotor windings

# Squirrel Cage Rotor Picture



[Image 1 Source: www.quora.com/What-will-happen-If-the-Squirrel-cage-motor-rotor-conductors-are-not-skewed](http://www.quora.com/What-will-happen-If-the-Squirrel-cage-motor-rotor-conductors-are-not-skewed)



Embedded in laminated magnetic material

[Image 2 Source: www.polytechnichub.com/squirrel-cage-rotor/](http://www.polytechnichub.com/squirrel-cage-rotor/)

# Induction Machine Overview

---



- Speed of rotating magnetic field (synchronous speed) depends on number of poles

$$N_s = f_s \frac{120}{p} \quad \text{where } N_s \text{ is the synchronous speed in RPM, } f_s \text{ is}$$

the stator electrical frequency (e.g., 60 or 50Hz) and  $p$  is the number of poles

- Frequency of induced currents in rotor depends on frequency difference between the rotating magnetic field and the rotor

$$\omega_r = \omega_s - \left(\frac{p}{2}\right) \omega_m$$

where  $\omega_s$  is the stator electrical frequency,  $\omega_m$  is mechanical speed, and  $\omega_r$  is the rotor electrical frequency

# Induction Machine Slip

---



- Key value is slip,  $s$ , defined as

$$s = \frac{N_s - N_{act}}{N_s}$$

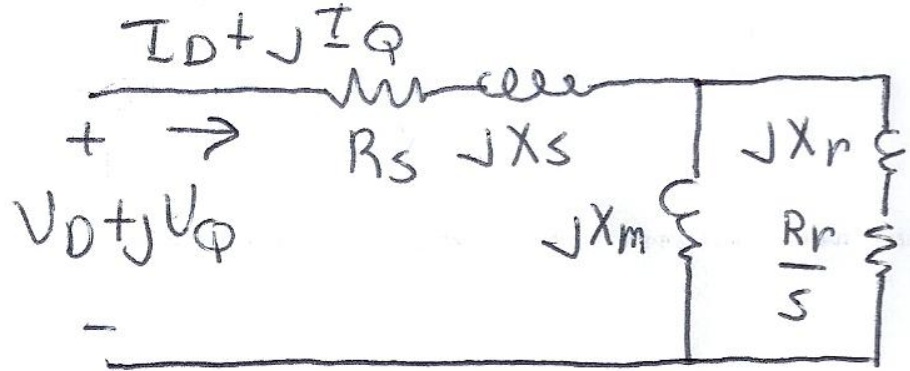
where  $N_s$  is the synchronous speed, and  
 $N_{act}$  is the actual speed (in RPM)

- As defined, when operating as a motor an induction machine will have a positive slip, slip is negative when operating as a generator
  - Slip is zero at synchronous speed, a speed at which no rotor current is induced;  $s=1$  at stand still

# Basic Induction Machine Model



- A basic (single cage) induction machine circuit model is given below
  - Model is derived in an undergraduate machines class



$$\frac{R_r}{s} = R_r + \frac{(1-s)}{s} R_r$$

- Circuit is useful for understanding the static behavior of the machine
- Effective rotor resistance ( $R_r/s$ ) models the rotor electrical losses ( $R_r$ ) and the mechanical power  $R_r(1-s)/s$

# Induction Machine Dynamics

---



- Expressing all values in per unit (with the base covered later), the mechanical equation for a machine is

$$\frac{ds}{dt} = \frac{1}{2H} (T_M - T_E)$$

where  $H$  is the inertia constant,  $T_M$  is the mechanical torque and  $T_E$  is the electrical torque (to be defined)

- Similar to what was done for a synchronous machine, the induction machine can be modeled as an equivalent voltage behind a stator resistance and transient reactance (later we'll introduce, but not derive, the subtransient model)

# Induction Machine Dynamics, cont.



- Define

$$X' = X_s + \frac{X_r X_m}{X_r + X_m}$$

$$X = X_s + X_m$$

where  $X'$  is the apparent reactance seen when the rotor is locked ( $s=1$ ) and  $X$  is the synchronous reactance

- Also define the open circuit time constant

$$T_o' = \frac{(X_r + X_m)}{\omega_s R_r}$$

# Induction Machine Dynamics, cont.



- Electrically the induction machine is modeled similar to the classical generator model, except here we use the "motor convention" in which  $I_D + jI_Q$  is assumed positive into the machine

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

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

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

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

All calculations are done on the network reference frame

# Induction Machine Dynamics, cont.



- The induction machine electrical torque,  $T_E$ , and terminal electrical load,  $P_E$ , are then

$$T_E = \frac{(E'_D I_D + E'_Q I_Q)}{\omega_s}$$
$$P_E = V_D I_D + V_Q I_Q$$

Recall we are using the motor convention so positive  $P_E$  represents load

- Similar to a synchronous machine, once the initial values are determined the differential equations are fairly easy to simulate
  - Key initial value needed is the slip

# Specifying Induction Machine Parameters

---

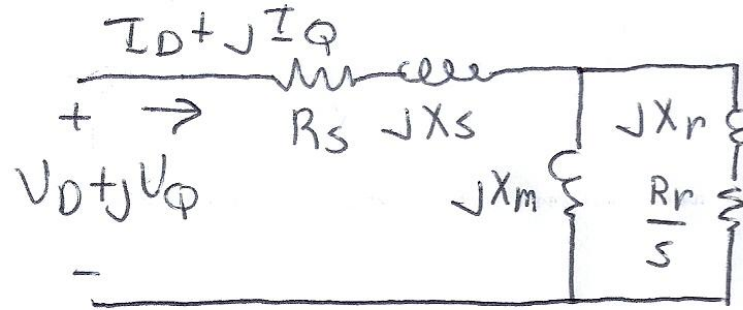


- In transient stability packages induction machine parameters are specified in per unit
  - If unit is modeled as a generator in the power flow (such as CIMTR1 or GENWRI) then use the generator's MVA base (as with synchronous machines)
  - With loads it is more complicated.
    - Sometimes an explicit MVA base is specified. If so, then use this value. But this can be cumbersome since often the same per unit machine values are used for many loads
    - The default is to use the MW value for the load, often scaled by a multiplier (say 1.25)

# Determining the Initial Values



- To determine the initial values, it is important to recognize that for a fixed terminal voltage there is only one independent value: the slip,  $s$ 
  - For a fixed slip, the model is just a simple circuit with resistances and reactances



- The initial slip is chosen to match the power flow real power value. Then to match the reactive power value (for either a load or a generator), the approach is to add a shunt capacitor in parallel with the induction machine
- We'll first consider torque-speed curves, then return to determining the initial slip

# Torque-Speed Curves

---



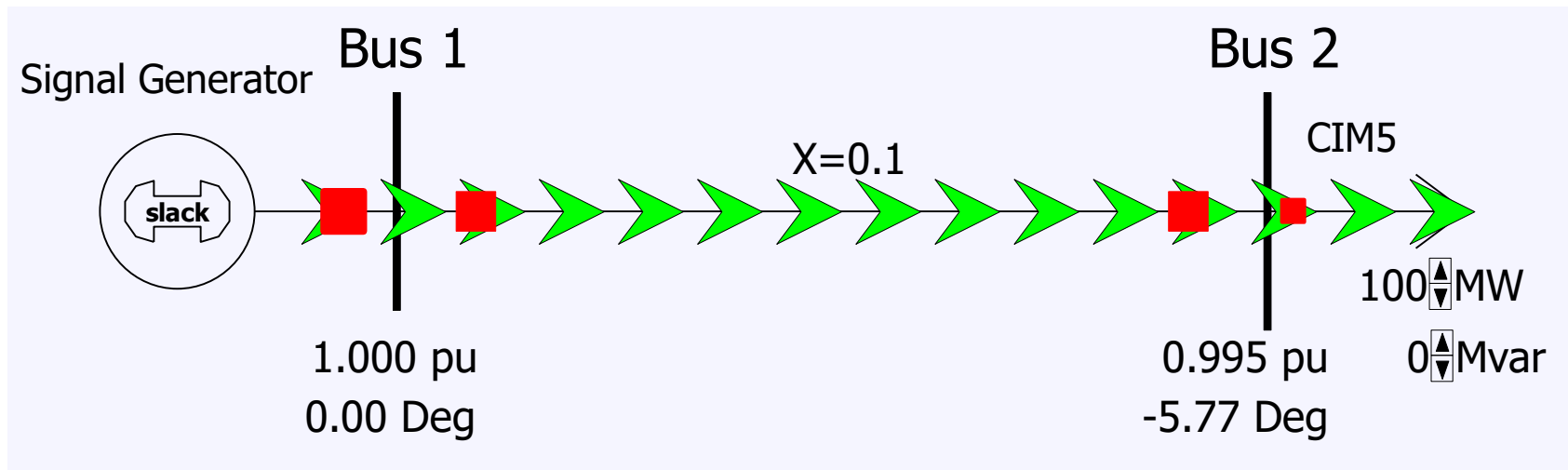
- To help understand the behavior of an induction machine it is useful to plot various values as a function of speed (or equivalently, slip)
  - Solve the equivalent circuit for a specified terminal voltage, and varying values of slip
  - Plot results
  - Recall torque times speed = power
    - Here speed is the rotor speed
  - When using per unit, the per unit speed is just  $1-s$

$$P_E = T_E(1 - s)$$

# Induction Motor Example



- Assume the below 60 Hz system, with the entire load modeled as a single cage induction motor with per unit values on a 125 MVA base of  $H=1.0$ ,  $R_s=0.01$ ,  $X_s=0.06$ ,  $X_m=4.0$ ,  $R_r=0.03$ ,  $X_r=0.04$ 
  - In the CIM5 model  $R_1=R_r$  and  $X_1=X_r$



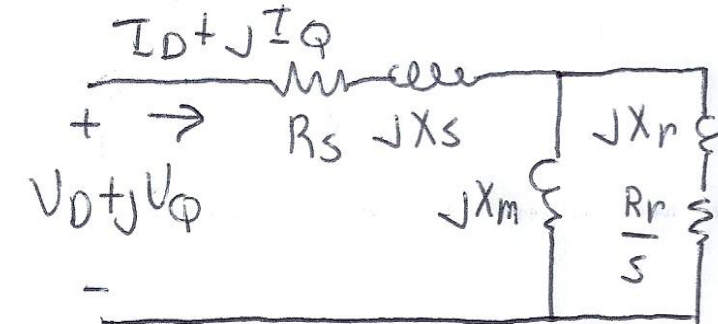
PowerWorld case **B2\_IndMotor**

# Induction Motor Example, cont.



- With a terminal voltage of  $0.995 \angle 0^\circ$  we can solve the circuit for specified values of  $s$
- The input impedance and current are

$$Z_{in} = (R_s + jX_s) + \frac{jX_m \left( \frac{R_r}{s} + jX_r \right)}{\frac{R_r}{s} + j(X_r + X_m)}$$



$$\bar{I} = \frac{V}{Z_{in}} = \frac{0.995 \angle 0^\circ}{Z_{in}}$$

- Then with  $s=1$  we get

$$\bar{I} = \frac{0.995}{0.0394 + j0.0998} = 3.404 - j8.624 \rightarrow S = 3.387 + j8.581$$

Note, values are per unit on a 125 MVA base

# Induction Motor Example, cont.

---

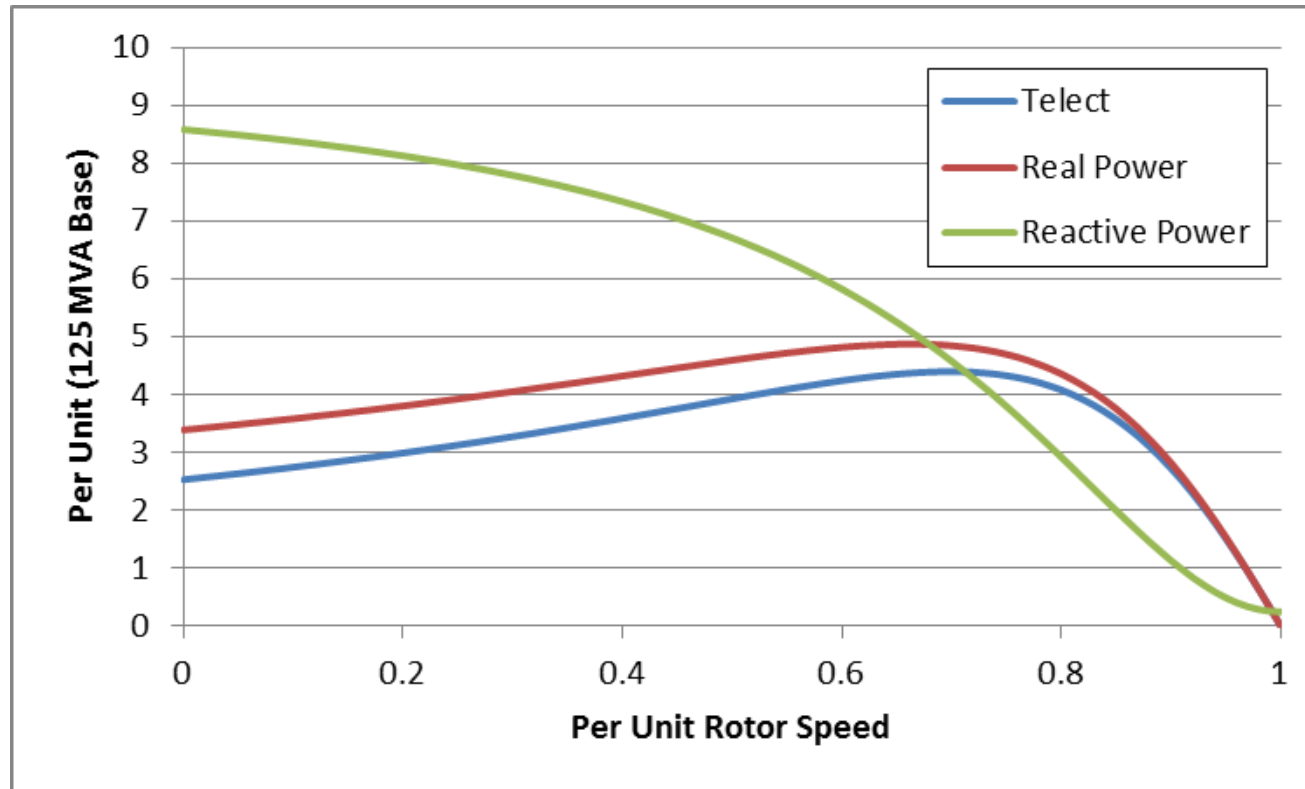


- PowerWorld allows for display of the variation in various induction machine values with respect to speed
  - Right click on load, select Load Information Dialog, Stability
  - On bottom of display click Show Torque Speed Dialog
  - Adjust the terminal voltage and pu scalar as desired; set  $v=0.995$  and the pu scalar to 1.0 to show values on the 125 MVA base used in the previous solution
  - Right click on column and select Set/Toggle/Columns, Plot Column to plot the column

# Induction Motor Example Torque-Speed Curves



- The below graph shows the torque-speed curve for this induction machine; note the high reactive power consumption on starting (which is why the lights may dim when starting a clothes dryer!)



From the graph you can see with a 100 MW load (0.8 pu on the 125 MW base), the slip is about 0.025

# Calculating the Initial Slip



- One way to calculate the initial slip is to just solve the below five equations for five unknowns ( $s$ ,  $I_D$ ,  $I_Q$ ,  $E'_D, E'_Q$ ) with  $P_E$ ,  $V_D$  and  $V_Q$  inputs

$$P_E = V_D I_D + V_Q I_Q$$

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

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

$$\frac{dE'_D}{dt} = 0 = \omega_s s E'_Q - \frac{1}{T'_o} (E'_D + (X - X') I_Q)$$

$$\frac{dE'_Q}{dt} = 0 = \omega_s s E'_D - \frac{1}{T'_o} (E'_Q - (X - X') I_D)$$

These are nonlinear equations that can have multiple solutions so use Newton's method, with an initial guess of  $s$  small (say 0.01)

Initial slip in example is 0.0251

# Double Cage Induction Machines

---

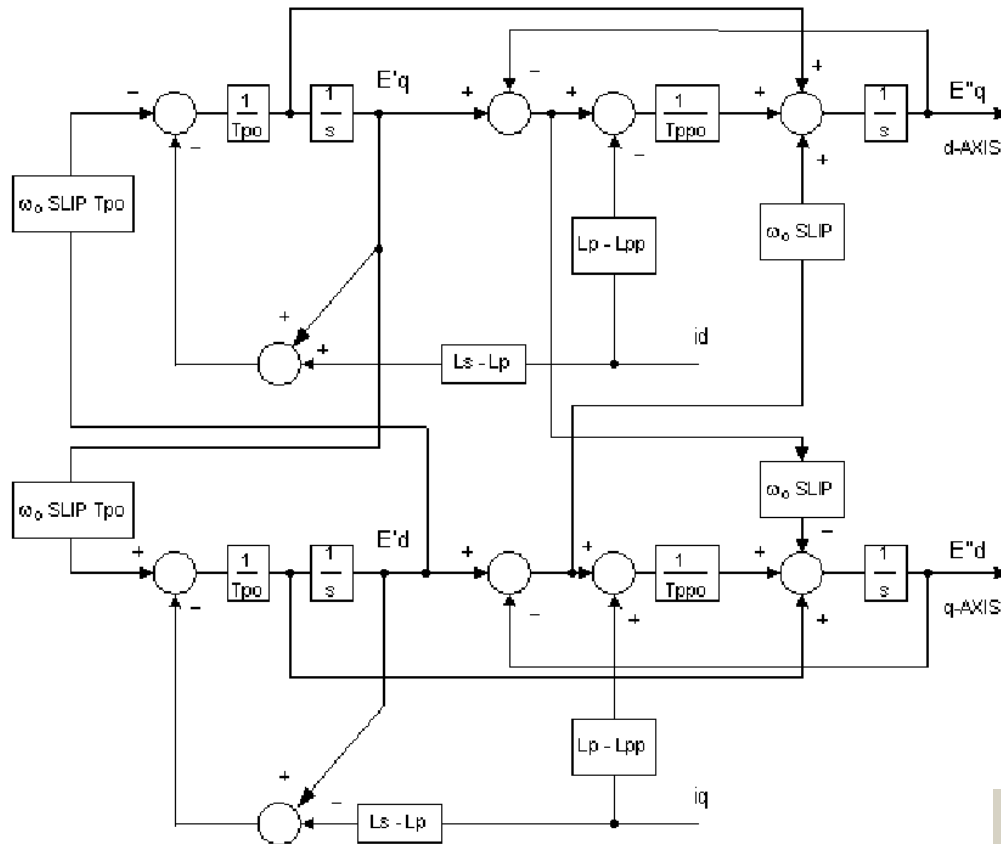


- In the design of induction machines, there are various tradeoffs, such as between starting torque (obviously one needs enough to start) and operating efficiency
  - The highest efficiency possible is 1-slip, so operating at low slip is desirable
- A common way to achieve high starting torque with good operating efficiency is to use a double cage design
  - E.g., the rotor has two embedded squirrel cages, one with a high  $R$  and lower  $X$  for starting, and one with lower  $R$  and higher  $X$  for running
  - Modeled by extending our model by having two rotor circuits in parallel; add subtransient values  $X''$  and  $T''_o$ .

# Example Double Cage Model



- Double cage rotors are modeled by adding two additional differential equations



Some models also include saturation, a topic that we will skip

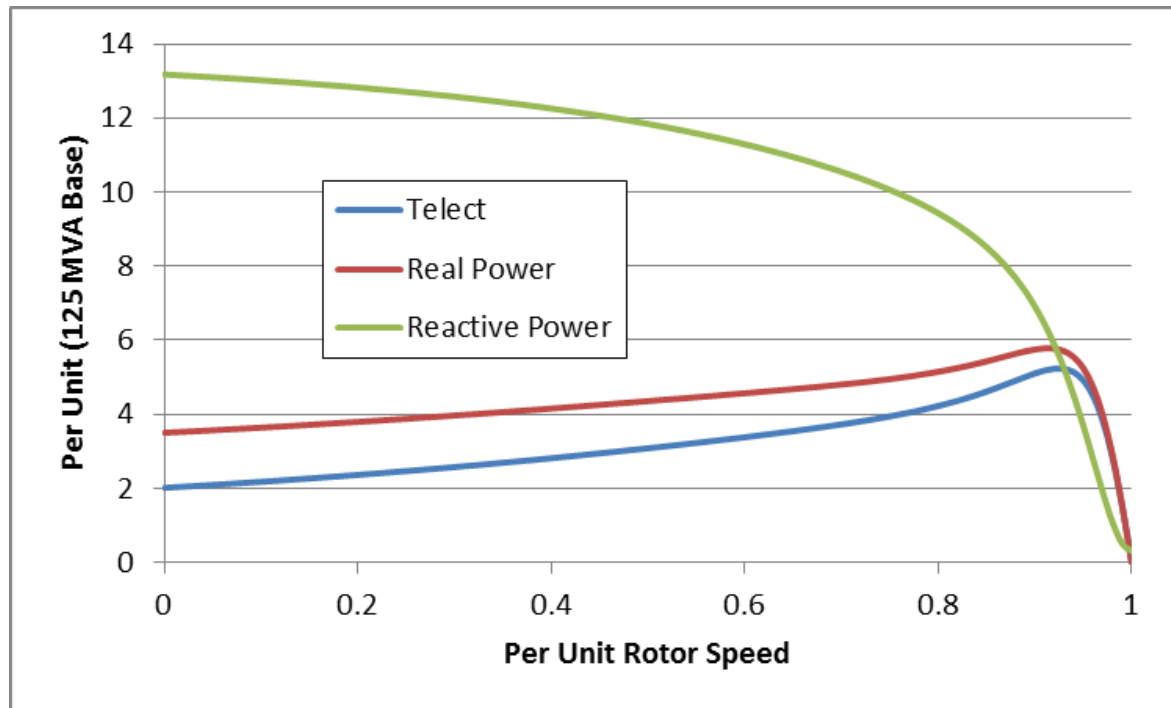
PowerWorld case  
**B2\_IndMotor\_DoubleCage**

Image source: PSLF Manual, version 18.1\_02; MotorW

# Double Cage Induction Motor Model



- The previous example can be extended to model a double cage rotor by setting  $R_2=0.01$ ,  $X_2=0.08$ 
  - The below graph shows the modified curves, notice the increase in the slope by  $s=0$ , meaning it is operating with higher efficiency ( $s=0.0063$  now!)

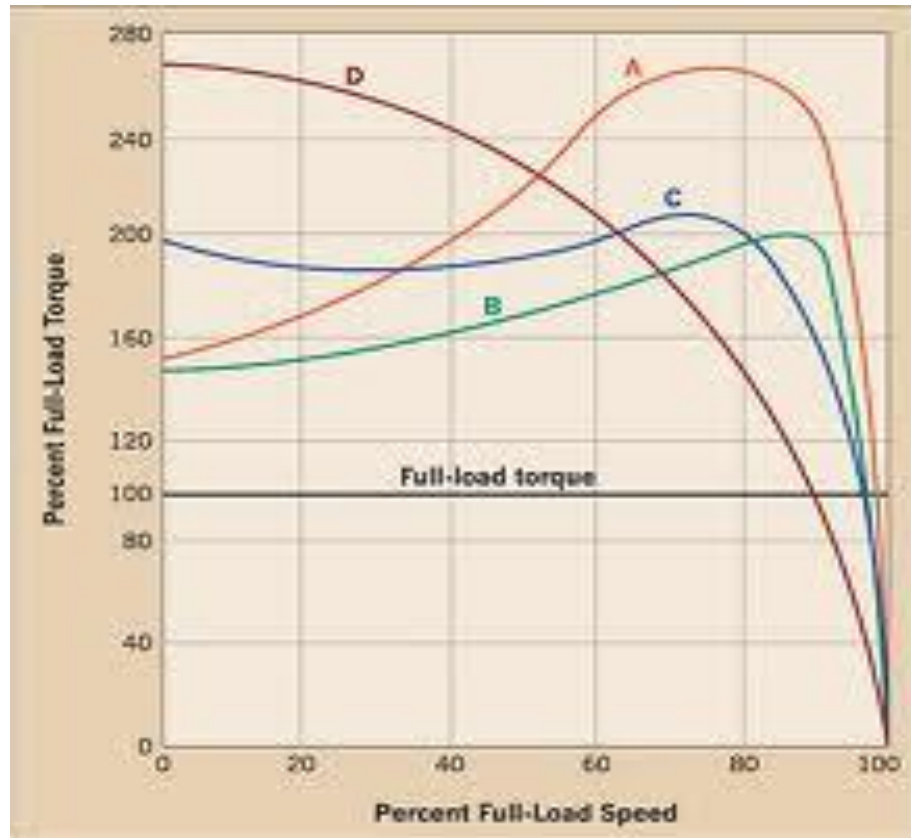


The additional winding does result in lower initial impedance and hence a higher starting reactive power

# Induction Motor Classes



- Four major classes of induction motors, based on application. Key values are starting torque, pull-out torque, full-load torque, and starting current



In steady-state the motor will operate on the right side of the curve at the point at which the electrical torque matches the mechanical torque

- A: Fans, pumps machine tools
- B: Similar to A
- C: Compressors, conveyors
- D: High inertia such as hoists

# Induction Motor Stalling

---

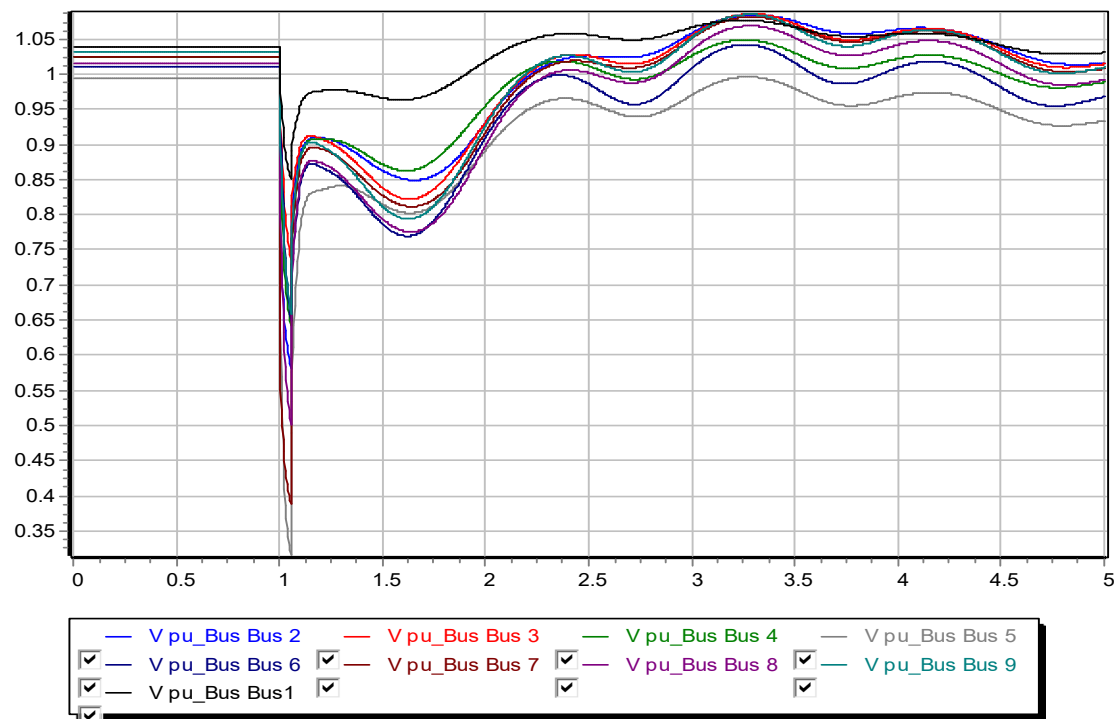


- Height of the torque-speed curve varies with the square of the terminal voltage
- When the terminal voltage decreases, such as during a fault, the mechanical torque can exceed the electrical torque
  - This causes the motor to decelerate, perhaps quite quickly, with the rate proportional to its inertia
  - 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  $V_i$  and  $T_i$  fields are used to disconnect the load when its voltage is less than  $V_i$  for  $T_i$  cycles
  - When running simulations you need to check for such events

Load Characteristic Information

Element Type

System  
 Area  
 Zone  
 Owner  
 Bus  
 Model Group  
 Load

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

Load Characteristics | Load Relays | Distributed Gen

Insert Delete Show Block Diagram

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		

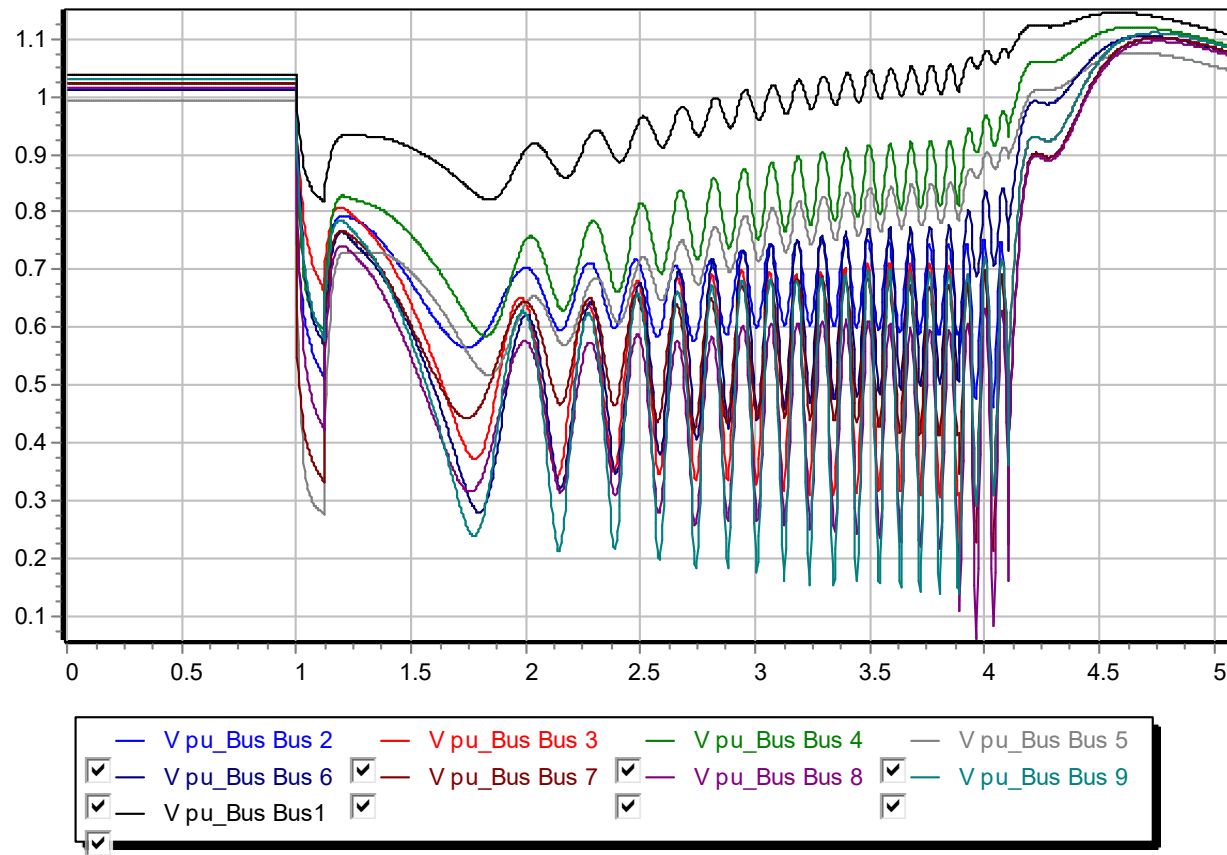
Show Torque Speed Dialog

OK Save Cancel

# Motor Stalling With Longer Fault



- The below image shows the WECC\_CIM5 system with the fault clearing extended to 0.12 seconds



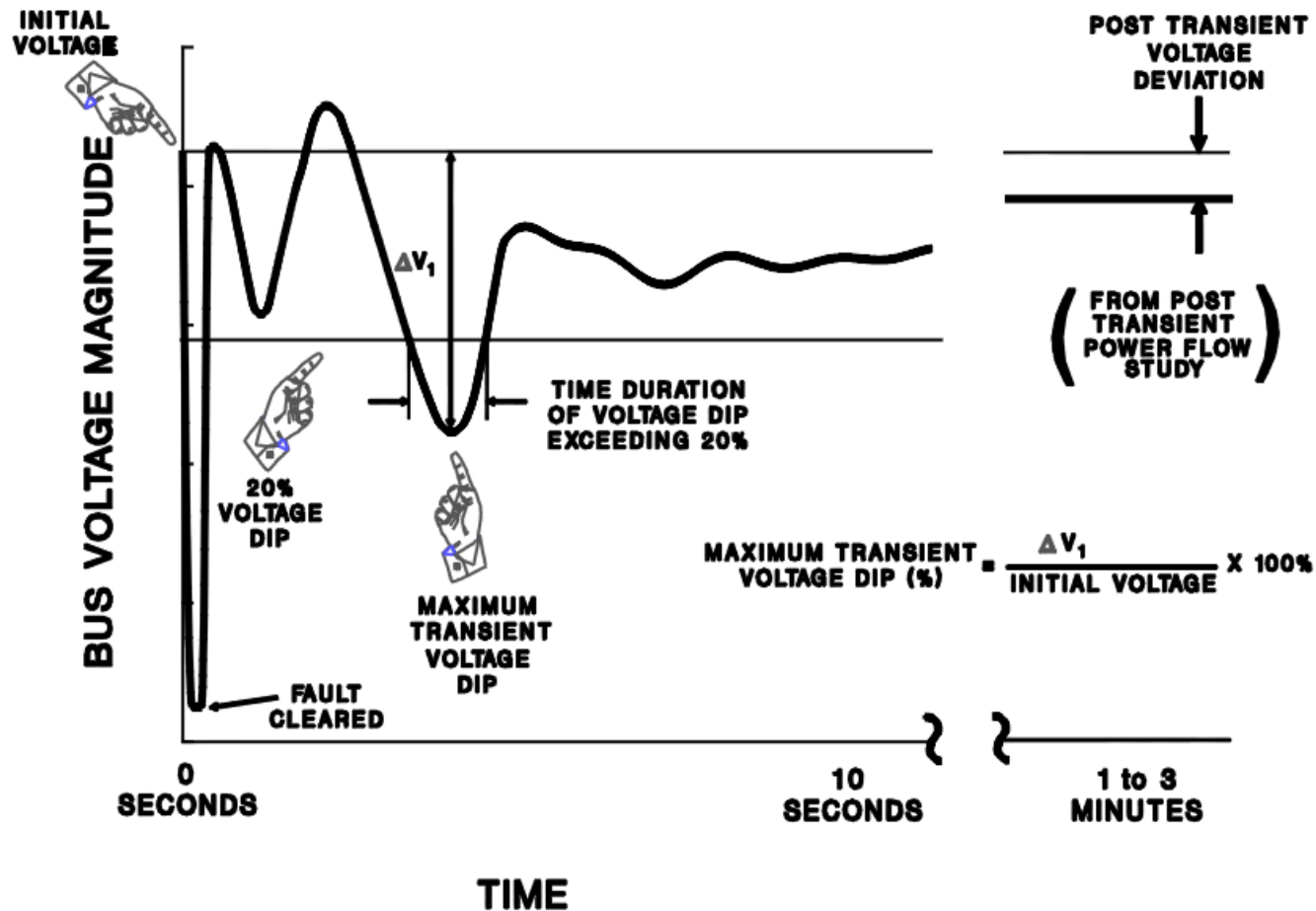
The models are no longer giving realistic results; two generators trip on over speed; then the load trips after 4 seconds.

# Transient Limit Monitors



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

## VOLTAGE PERFORMANCE PARAMETERS



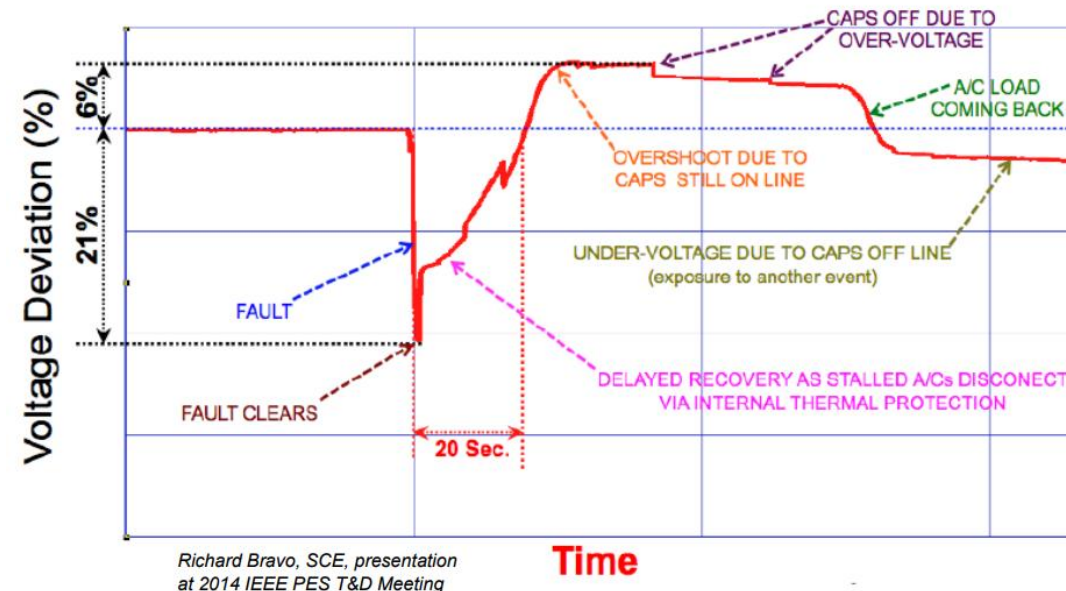
Similar performance criteria exist for frequency deviations

Image from WECC Planning and Operating Criteria

# 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



# 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

---

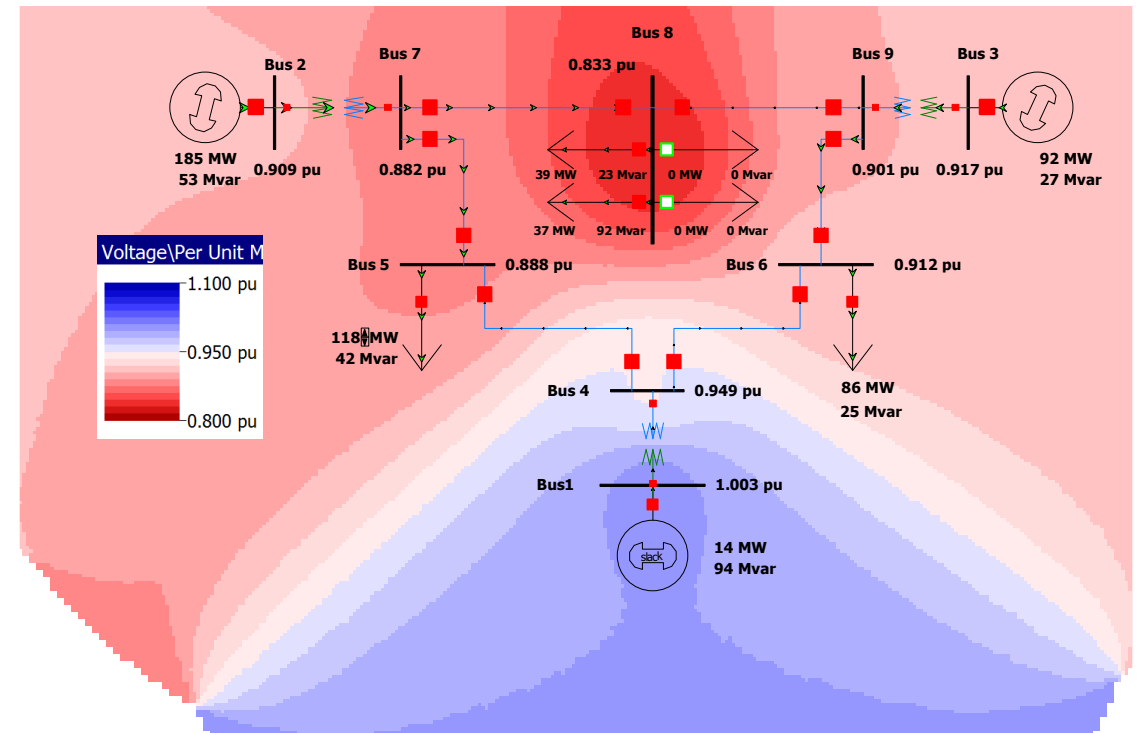
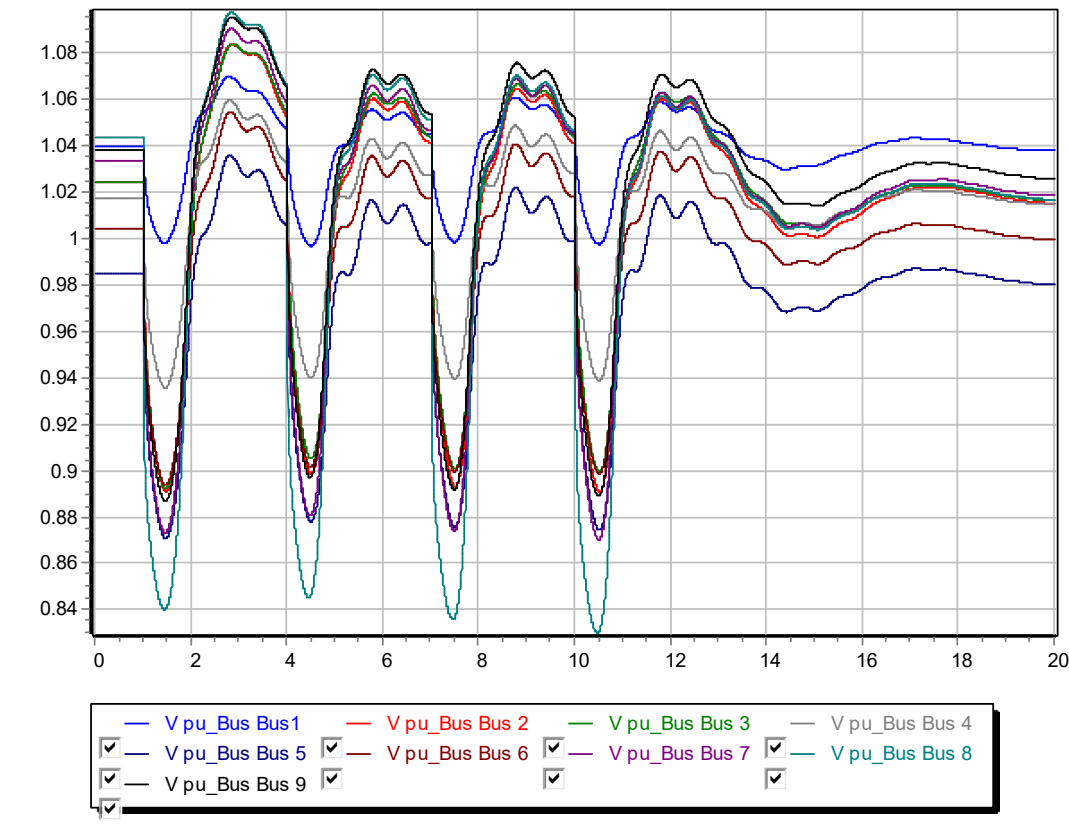


- Case WSCC\_MotorStarting takes the previous WSCC case with 100% motor load, and considers starting the motor at bus 8
- In the power flow the load at bus 8 is modeled as zero (open) with a CIM5
- The contingency is closing the load
  - Divided into four loads to stagger the start (we can't start it 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, cont.



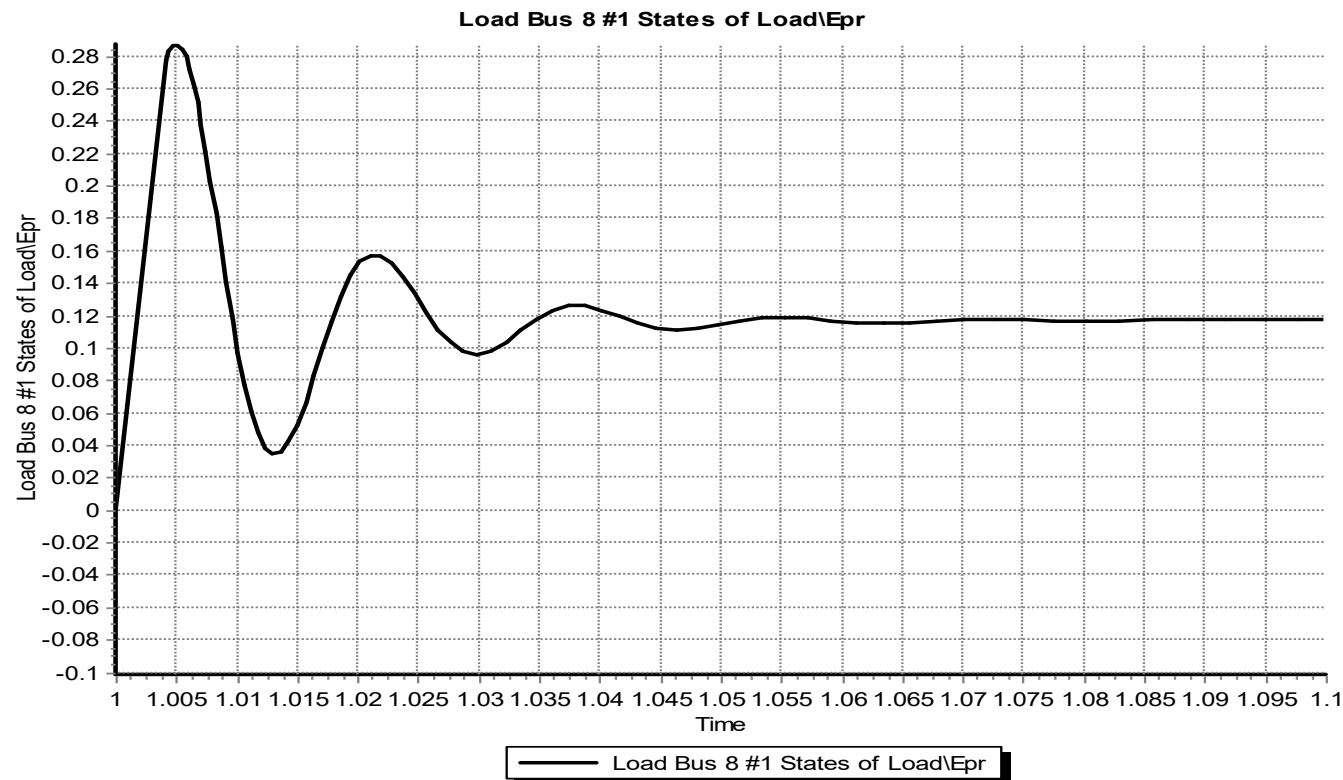
- Below graph shows the bus voltages for starting the four motors three seconds apart



# 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



# Motor Starting: Fast Dynamics, cont.



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

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

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

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

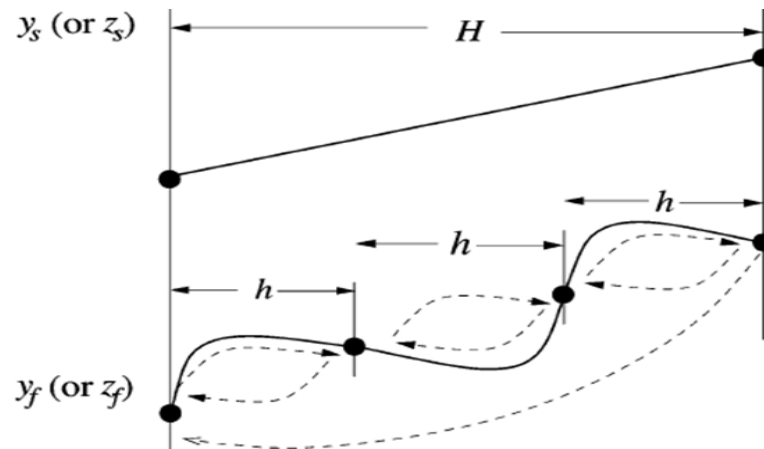
$$\frac{dE'_Q}{dt} = -\omega_s s E'_D - \frac{1}{T'_o} (E'_Q - (X - X') I_D)$$

- Simulating with the explicit method either requires a small overall  $\Delta t$  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 than 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, cont.

---



- 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.

# Load Modeling, cont.

---



- Traditionally load models have been divided into two groups
  - Static: load is a algebraic function of bus voltage and sometimes frequency
  - Dynamic: load is represented with a dynamic model, with induction motor models the most common
- The simplest load model is a static constant impedance
  - Has been widely used
  - Allowed the  $\mathbf{Y}_{bus}$  to be reduced, eliminating essentially all non-generator buses
  - Presents no issues as voltage falls to zero
  - No longer commonly used

# 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 an optimization parameter
- Commonly use V/Hz control to keep the flux constant

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

---

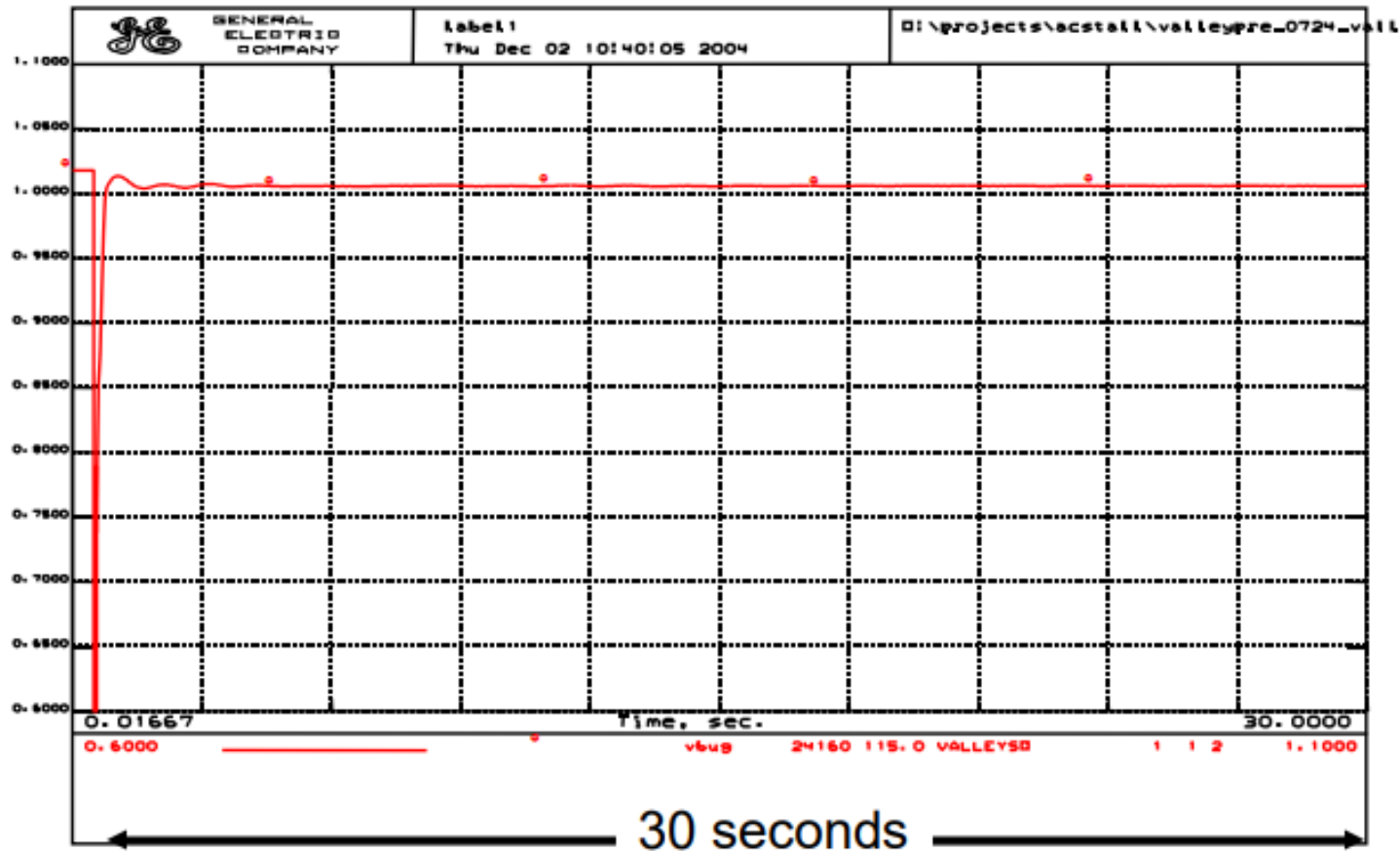


- 1990's – Constant current real, constant impedance reactive models connected to a transmission bus
  - IEEE Task Force recommends dynamic load modeling, however it does not get traction in the industry
- 1996 – Model validation study for July 2 and August 10 system outages:
  - Need for motor load 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

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



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



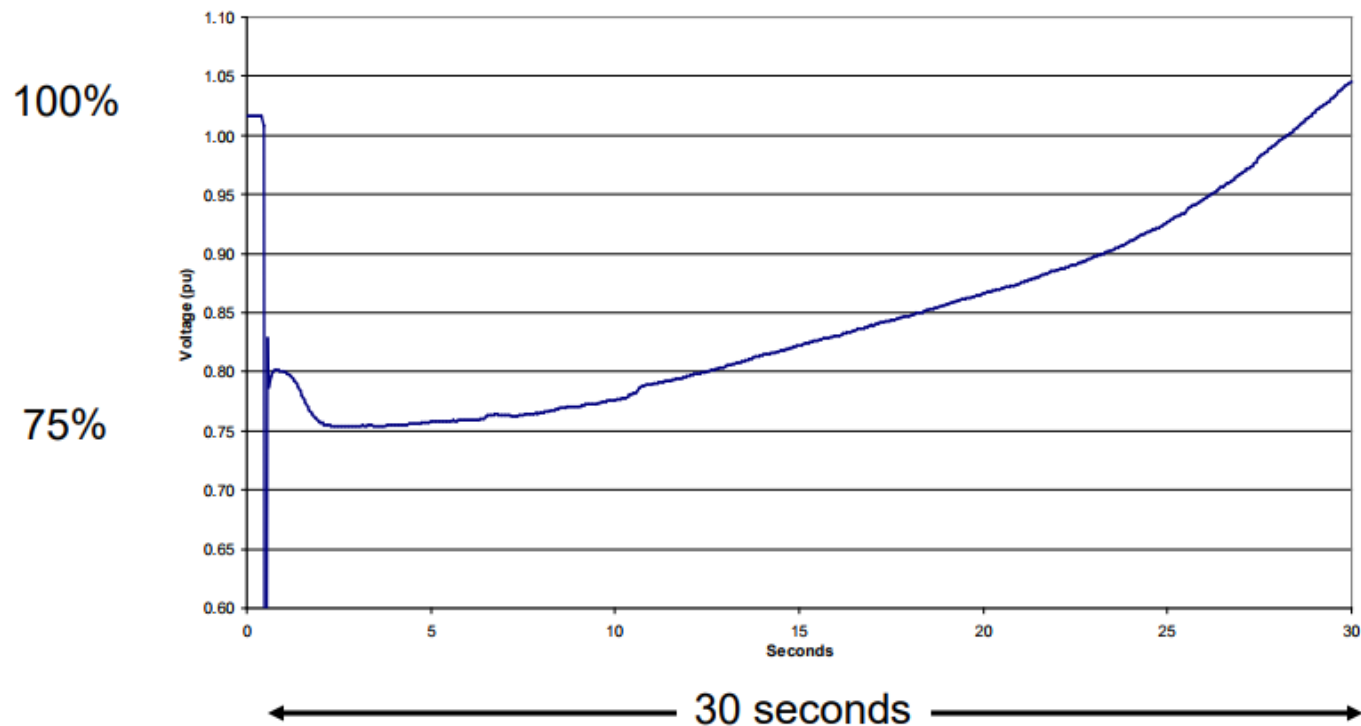
Vertical scale goes down to about 0.6 per unit

Hence the simulations indicated rapid voltage recovery following the fault

# Need for Better Load Modeling: History of Load Modeling in WECC, cont.



- What was actually sometimes occurring, 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 of the LD1PAC is not to model one air conditioner
- Rather, the purpose of this simulation model is to represent 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!

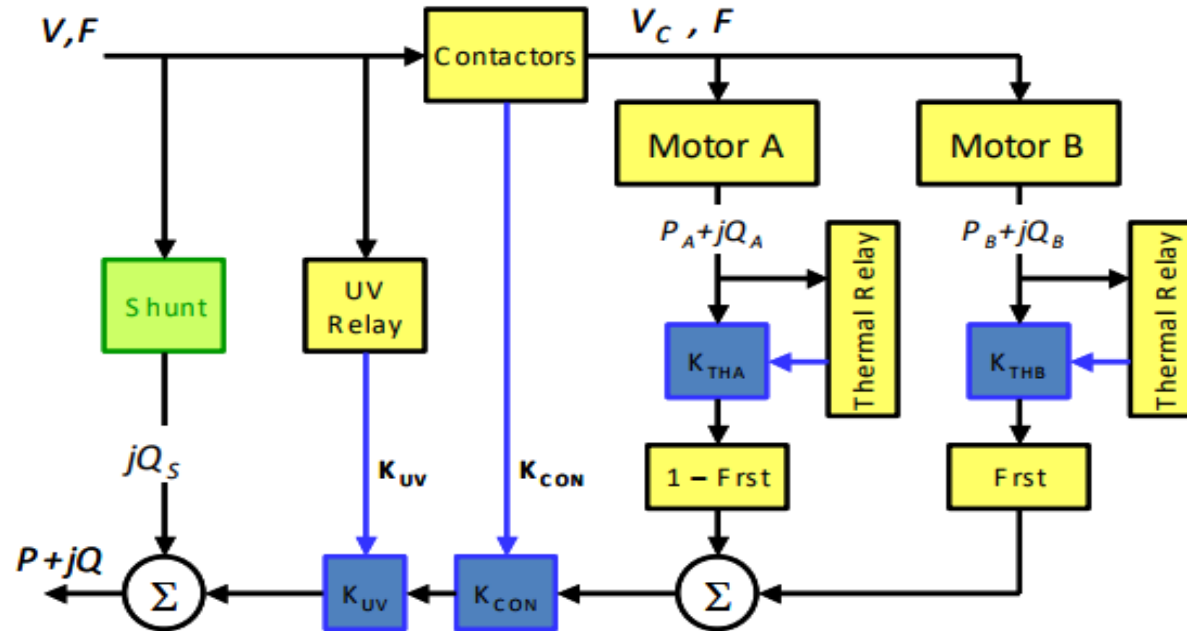
# What does LD1PAC Model?

---



- 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, cont.



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  $M_{base} > 0$  then this value of  $MV_{base}$  is used and the  $CompLF = 1.0$

If  $M_{base} = 0$  then  $MV_{base} = P_{init} * P_{ul}$  and  $CompLF = 1.0$

If  $M_{base} < 0$  then  $CompLF = \text{abs}(M_{base})$  and  $MV_{base} = P_{init} * P_{ul} / CompLF$

The values of  $V_{stall}$  and  $V_{brk}$  are adjusted according to the value of  $LFAdj$ .

$$V_{stall} = V_{stall}[1 + LFAdj(CompLF - 1)]$$

$$V_{brk} = V_{brk}[1 + LFAdj(CompLF - 1)]$$

# “MotorA” and “MotorB”

---

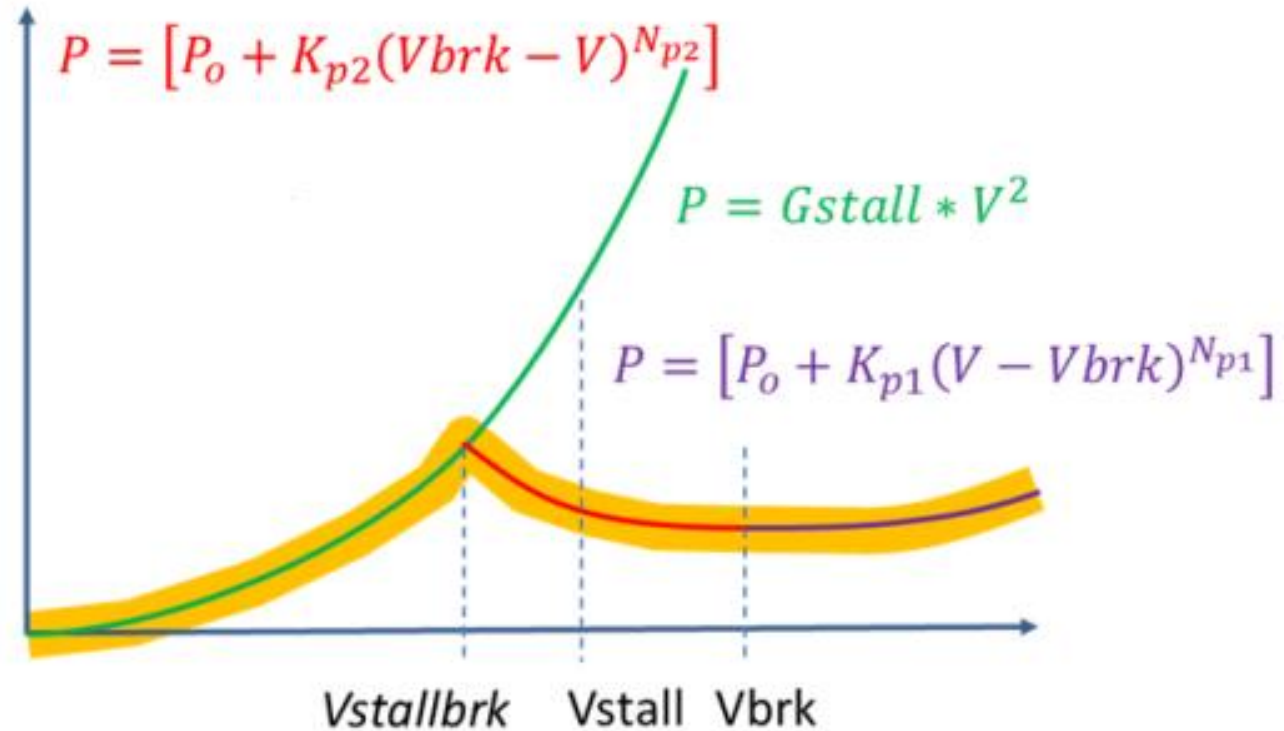


- Motor A and Motor B represent 2 types of motors
  - Motor A → for a certain fraction of motors, once they stall they will remain stalled forever
    - They can't stay that way forever obviously!
    - In the simulation they will sit there for several seconds consuming a huge amount of MW and Mvar
    - Eventually the thermal relays will trip them off-line
  - Motor B → Another fraction of motors will “restart” once the voltage goes above  $V_{rst}$  for  $T_{rst}$  seconds
- We throw around terms like “stall” and “restart”
  - But, we are not simulating rotor speed so what does this 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

---

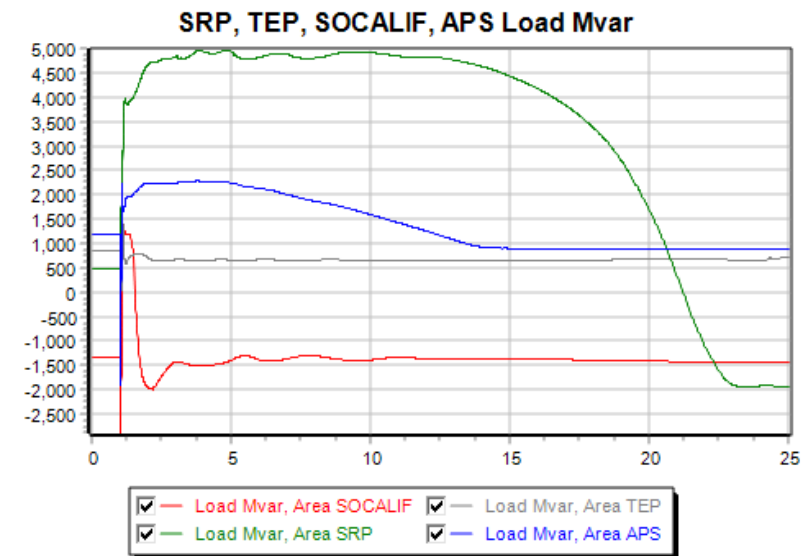
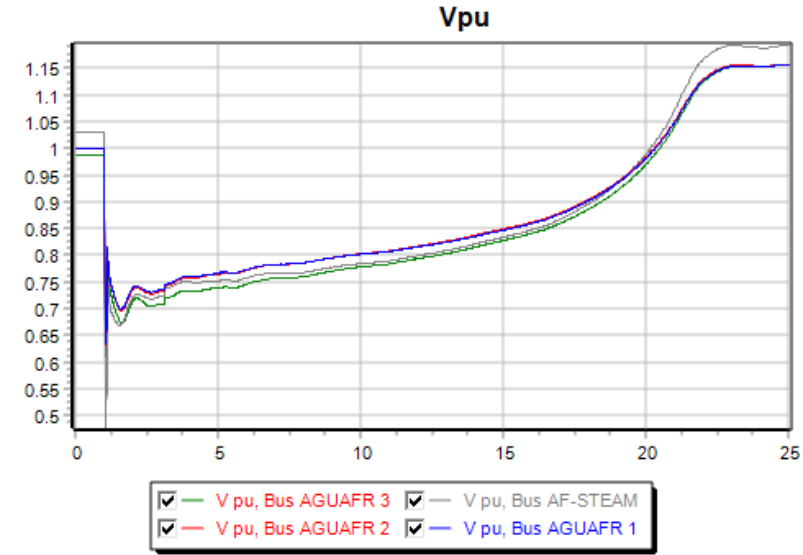
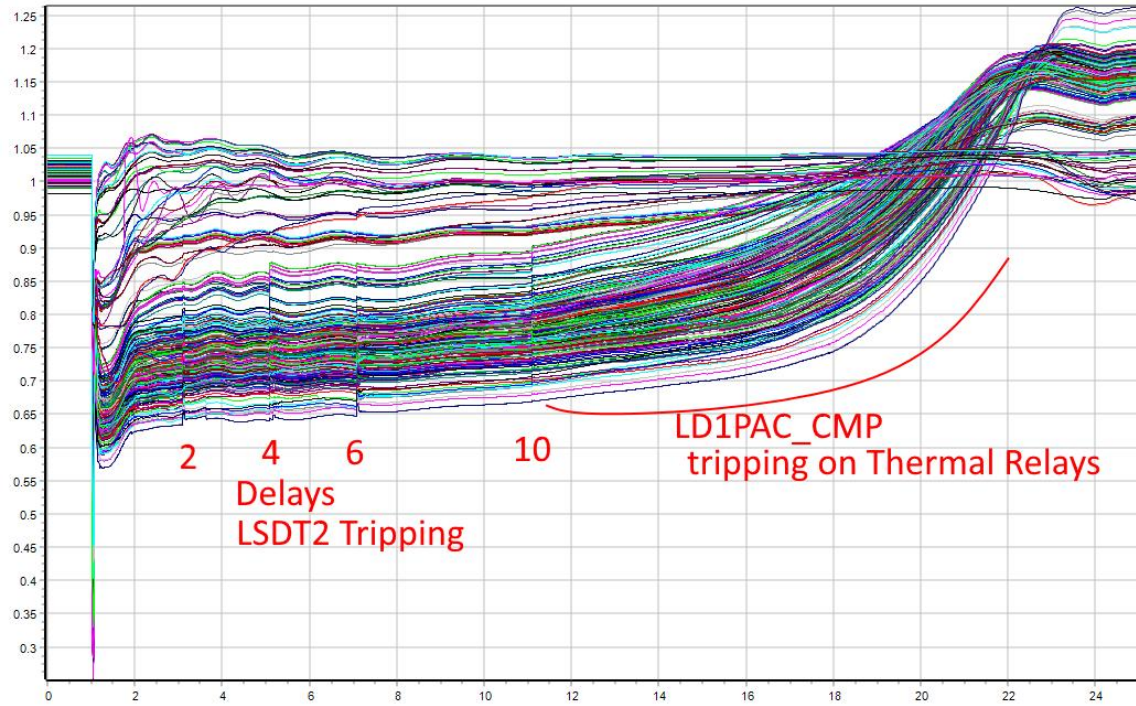


- In existing LD1PAC and CMPLDW/CMLD models this transition is defined simply as
  - If Voltage  $< V_{stall}$  for more than  $T_{stall}$  seconds, then immediately flip to the green stall curve
  - The “Motor A” fraction of the model will remain there until the thermal relay trips it
  - The “Motor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



# 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)
- 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

---

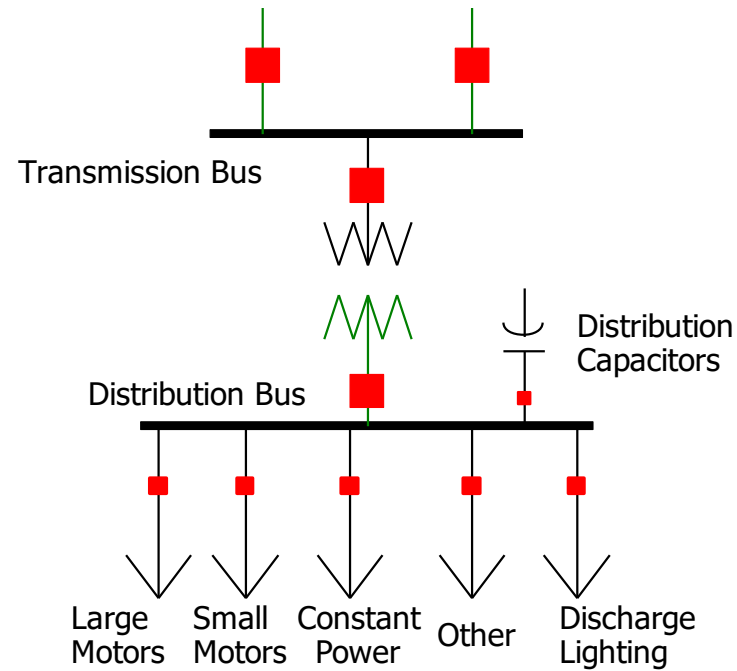


- Many aggregate loads are best represented by a combination of different types of load
  - Known as composite load models
  - Important to keep in mind that the actual load is continually changing, so any aggregate load is at best an approximation
  - Hard to know load behavior to extreme disturbances 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

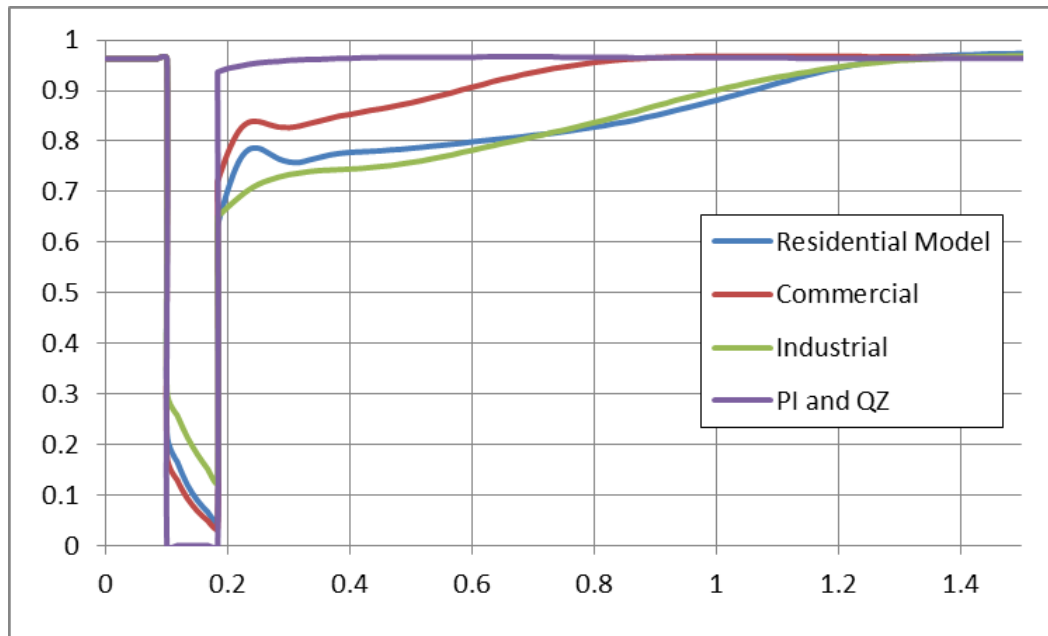


# CLOD Model, cont.



- 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

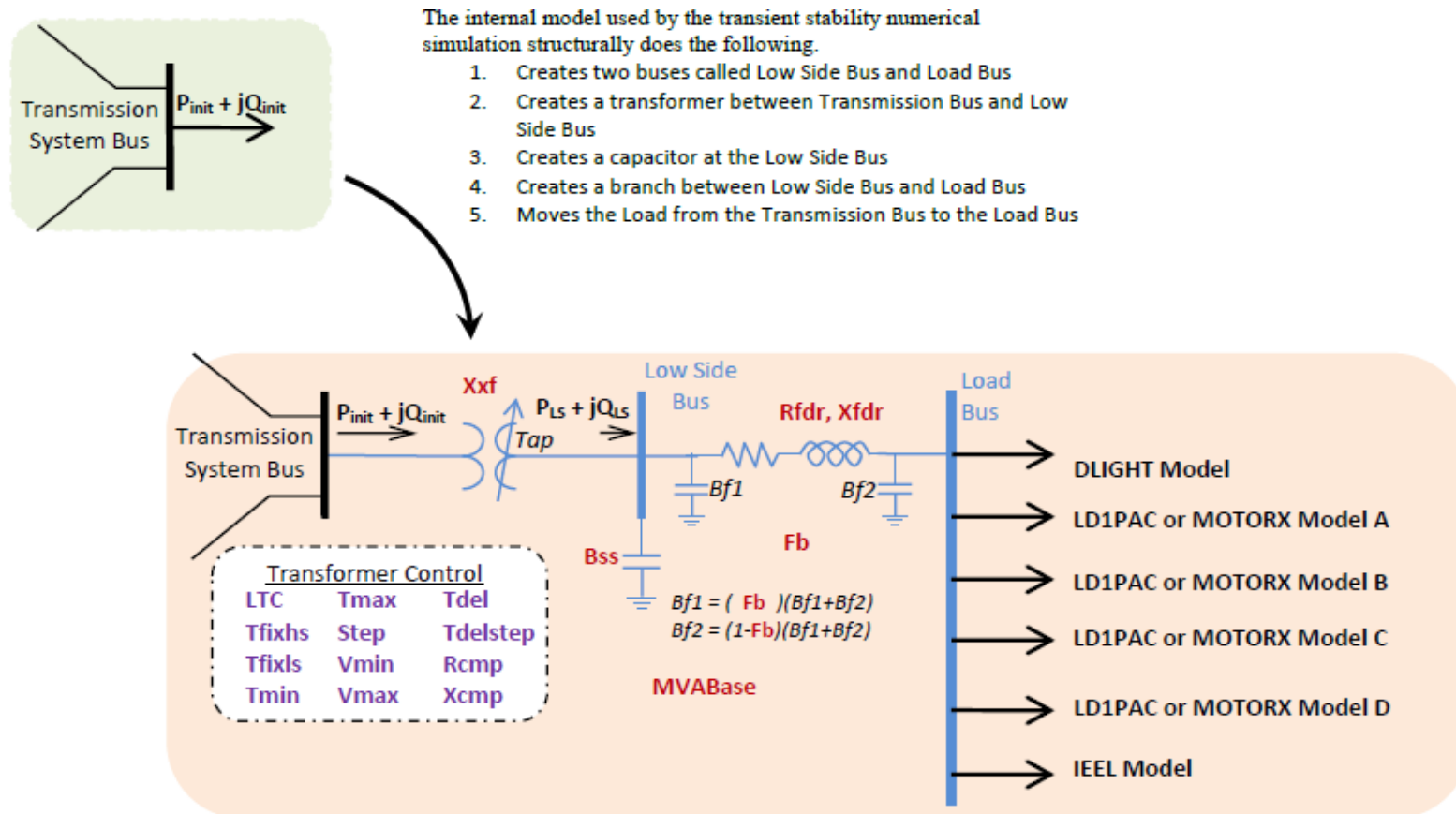


Comparison of voltage recovery for different model types

# Composite Load Model



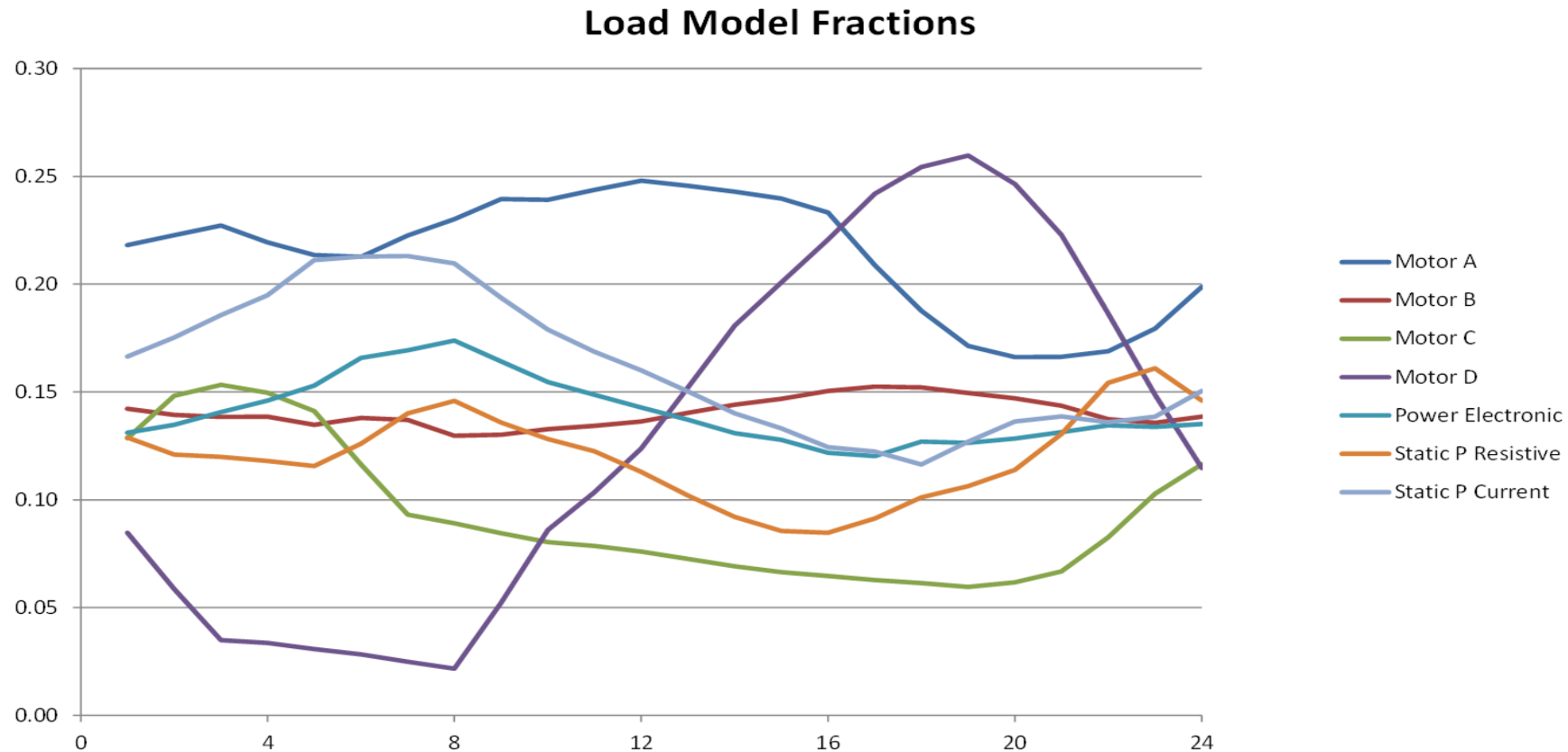
- Contains up to four motors or single phase induction motor models; also includes potential for solar PV



# 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 matters
- 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>