Load Modeling

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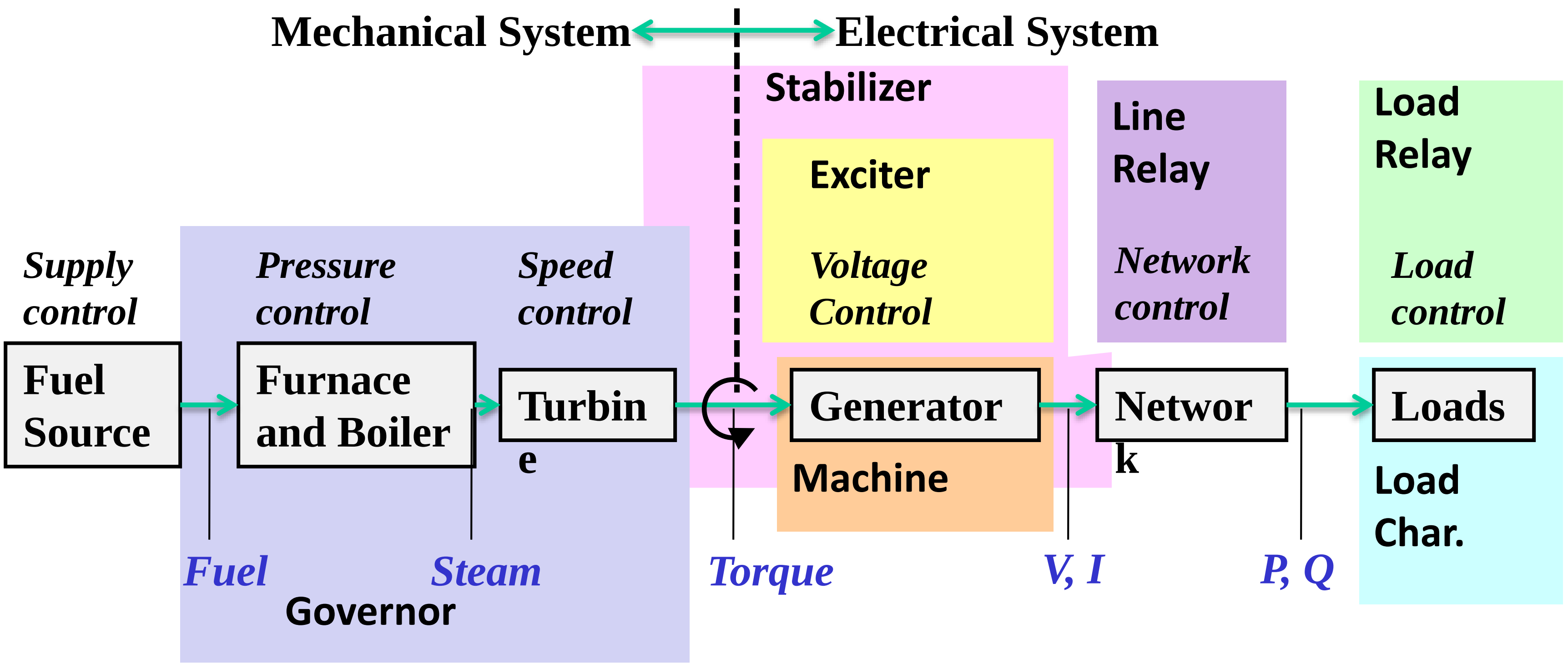
Dynamic Models in the Physical Structure



P. Sauer and M. Pai, *Power System Dynamics and Stability*, Stipes Publishing, 2006.

Load Modeling

- Traditionally load models have been divided into two groups
  - **Static/Algebraic**: 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 **Ybus** to be reduced, eliminating essentially all non-generator buses
  - Presents no issues as voltage falls to zero
  - Is rapidly falling out of favor because that's not how loads behave!

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. 472-482
- A more recent report that provides a good overview is "Final Project Report Loading Modeling Transmission Research" from Lawrence Berkeley National Lab, March 2010

ZIP Load Model

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

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

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

- Some models allow more general voltage dependence

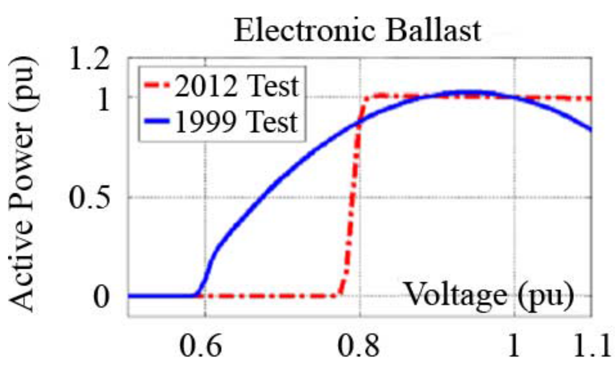
$$P_{Load,k} = P_{BaseLoad,k}\left(a_{1,k}\left|\bar{V}_k\right|^{n1} + a_{2,k}\left|\bar{V}_k\right|^{n2} + a_{3,k}\left|\bar{V}_k\right|^{n3}\right)$$

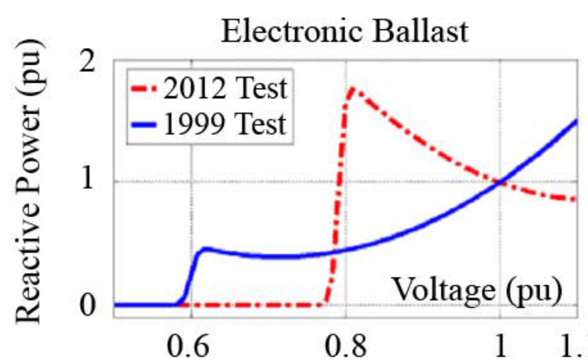
$$Q_{Load,k} = Q_{BaseLoad,k}\left(a_{4,k}\left|\bar{V}_k\right|^{n4} + a_{5,k}\left|\bar{V}_k\right|^{n5} + a_{6,k}\left|\bar{V}_k\right|^{n6}\right)$$

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

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

A portion of Table VII from Bokhari 2014 paper

The Z,I,P coefficients sum to 1.000; note that for some models the absolute values of the parameters are quite large, indicating a difficult fit

Discharge Lighting Models

- Discharge lighting (such as fluorescent lamps) is a major portion of the load (10-15%)
- 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

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

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

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

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

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

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

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

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

- Typical values for Pf and Qf are 1 and -1 respectively

Induction Motor Models

- Induction motors, both three phase and single phase, make up a very large percentage of the load
- Next several slides describe how induction motors are modeled in transient stability
  - This model would not apply to induction motors controlled by ac drives, since the converter in the drive will make the motor's behavior independent of the source voltage (up to a point); it will look more like a constant power load
- Originally invented independently by Galileo Ferraris (1885) and Nikola Tesla (1887)
  - Tesla received the US patent in 1888
  - Key to growth of ac, as opposed to dc, electric systems

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

Induction Machine Overview

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

$$N_s = f_s \frac{120}{p}$$ where N_s is the synchronous speed in RPM, f_s 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 ω_s is the stator electrical frequency, ω_m is mechanical speed, and ω_r is the rotor electrical frequency

Induction Machine Slip

- Key value is slip, s, defined as

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

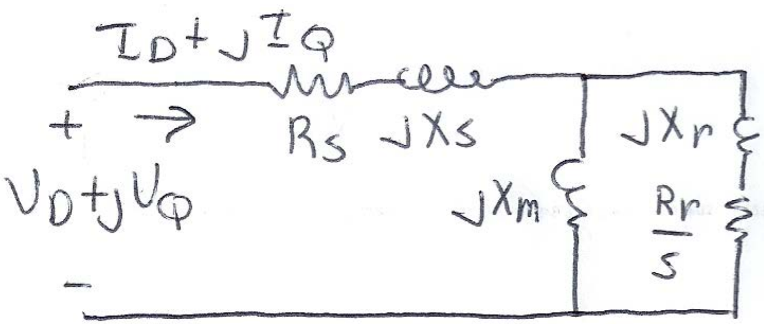
wherer N_s is the synchronous speed, and

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 (Rr/s) models the rotor electrical losses (Rr) and the mechanical power Rr(1-s)/s

Induction Machine Dynamics

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

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

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

- 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

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

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

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

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

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

All calculations are done on the network reference frame

Induction Machine Dynamics

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

$$T_E = \frac{\left(E'_D I_D + E'_Q I_Q\right)}{\omega_s}$$

$$P_E = V_D I_D + V_Q I_Q$$

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

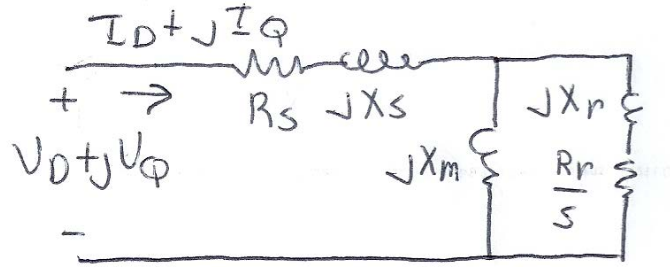
- Similar to a synchronous machine, once the initial values are determined the differential equations are fairly easy to simulate
  - Key initial value needed is the slip

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

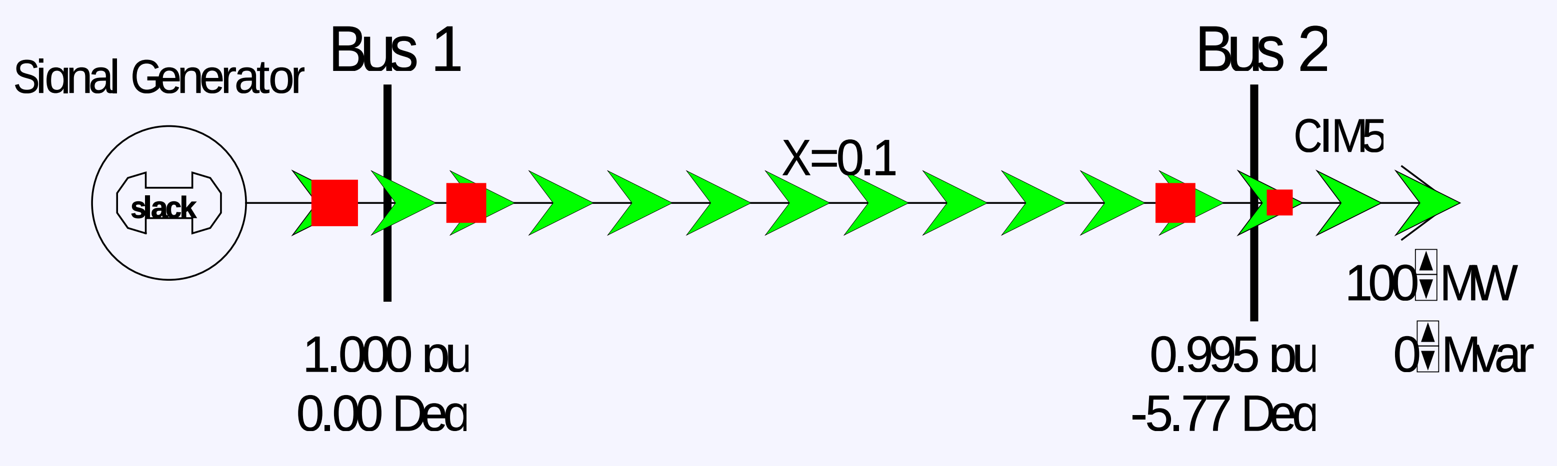
Torque-Speed Curves

- 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

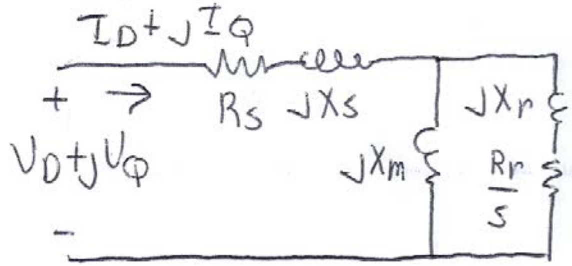
- Assume the below 60 Hz system, with the entire load modeled as a single cage induction motor with per unit values on a 125 MVA base of H=1.0, Rs=0.01, Xs=0.06,



PowerWorld case **B2_IndMotor**

Induction Motor Example

- 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



$$Z_{in} = (R_s + jX_s) + \frac{jX_m\left(\frac{R_r}{s} + jX_r\right)}{\frac{R_r}{s} + j\left(X_r + X_m\right)}, \qquad \bar{I} = \frac{\bar{V}}{Z_{in}} = \frac{0.995\angle 0^\circ}{Z_{in}}$$

- Then with s=1 we get

Note, values are per unit on a 125 MVA base

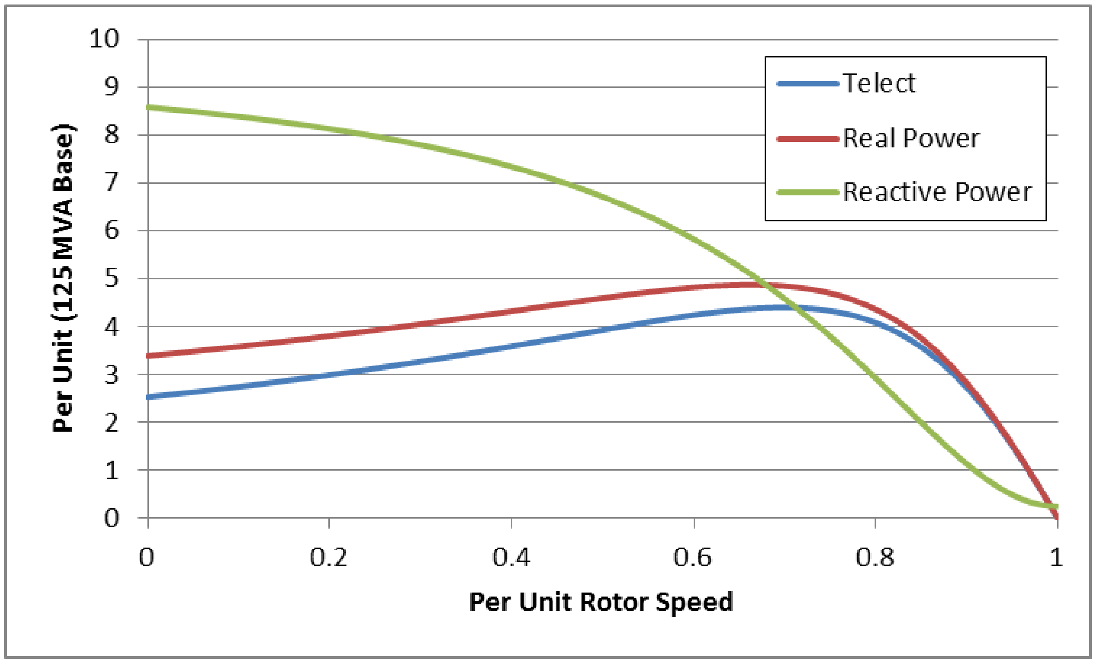
$$\bar{I} = \frac{0.995}{0.0394 + j0.0998} = 3.404 - j8.624 \rightarrow S = 3.387 + j8.581$$

Induction Motor Example

- 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 cloth 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

$$P_E = V_D I_D + V_Q I_Q$$

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

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

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

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

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

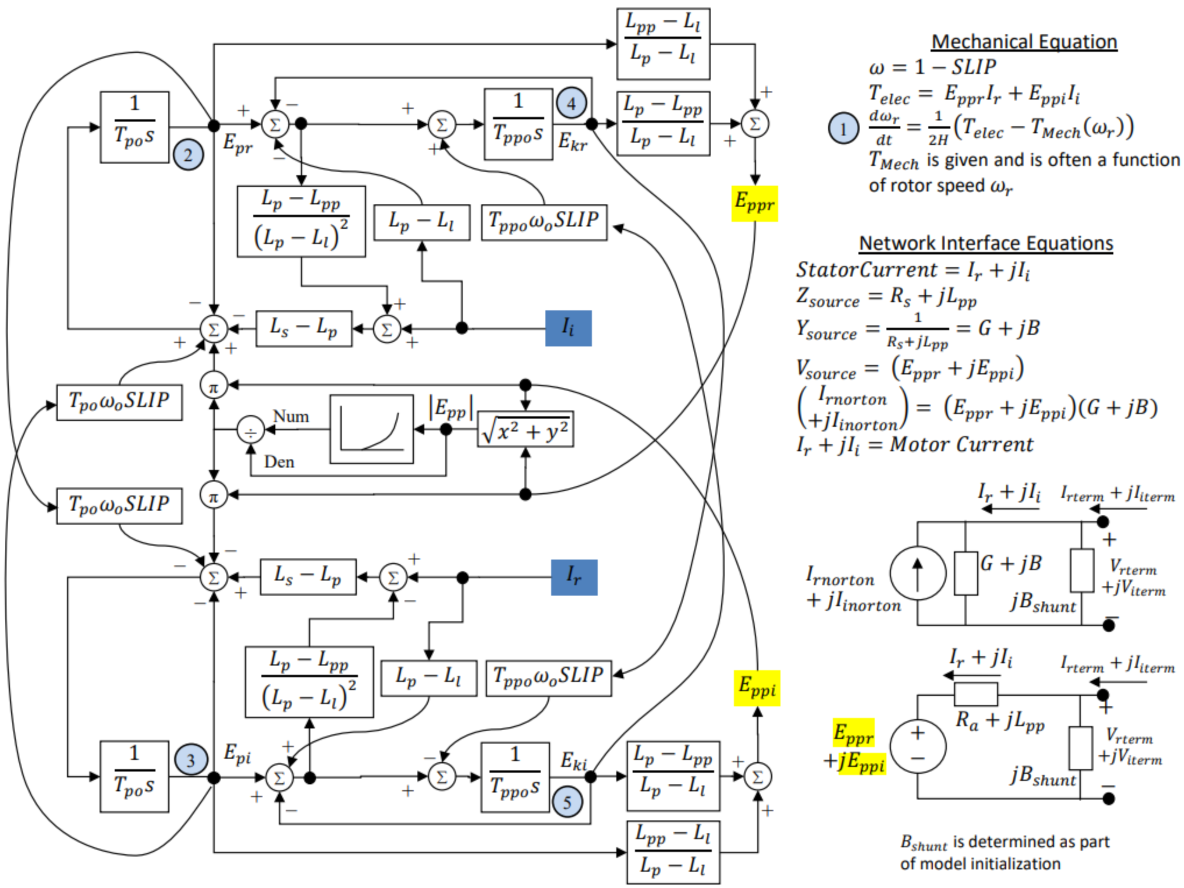
Initial slip in example is 0.0251

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

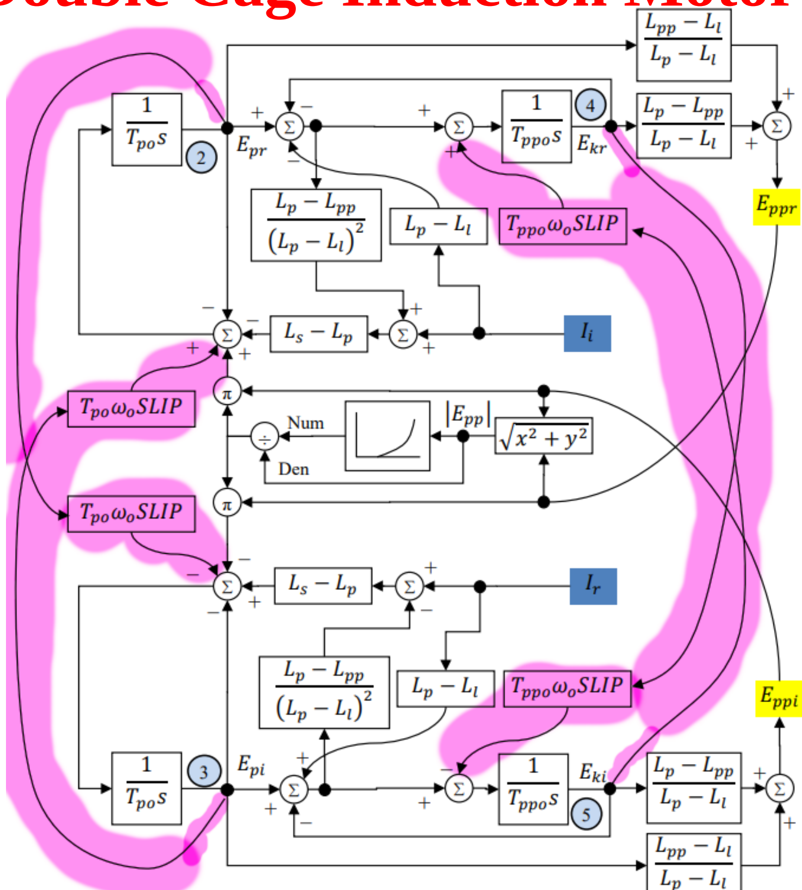
- Double cage rotors are modeled by adding two additional differential equations



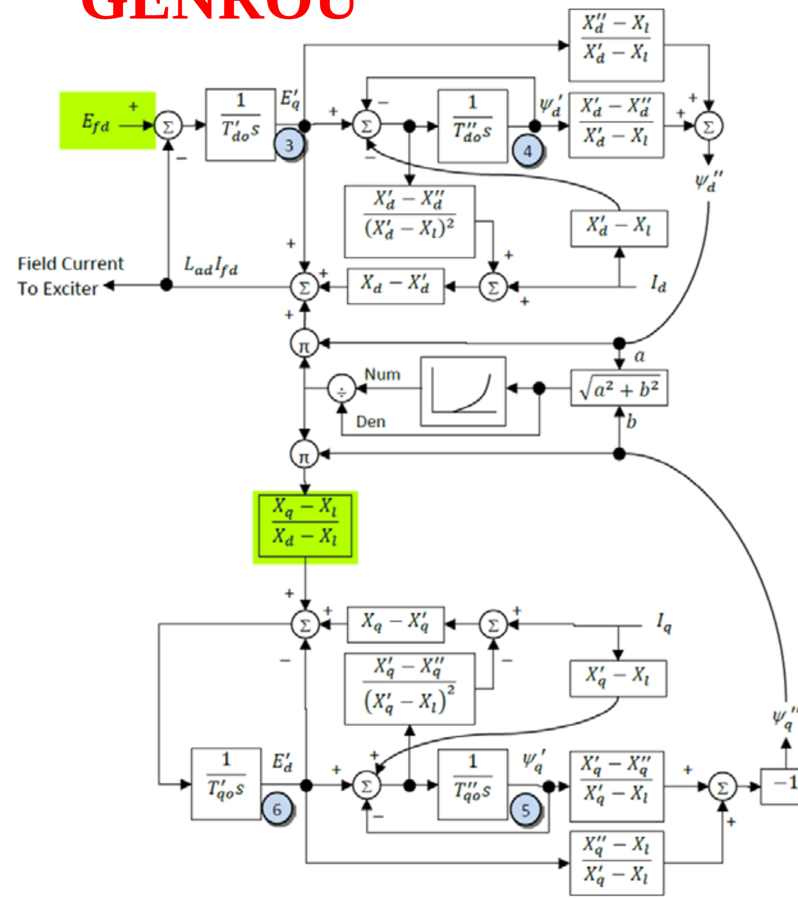
Notice saturation in the middle of this block diagram (we'll not discuss that again)

Induction Motor and Synchronous Machine are very similar!

Double Cage Induction Motor



GENROU

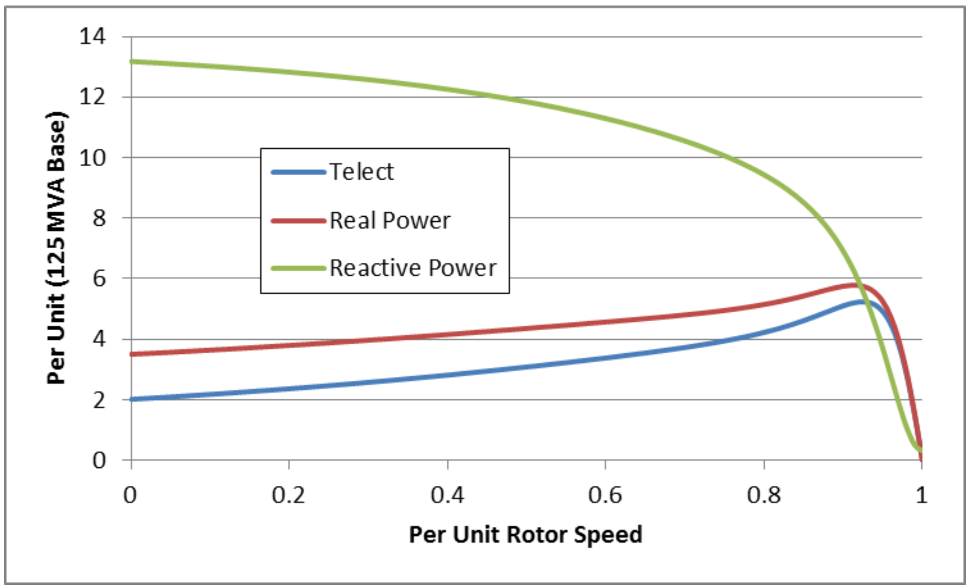


No Efd on Induction Motor

SLIP Terms do not exist for synchronous machine

Double Cage Induction Motor Model

- The previous example can be extended to model a double cage rotor by setting R2=0.01, X2=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

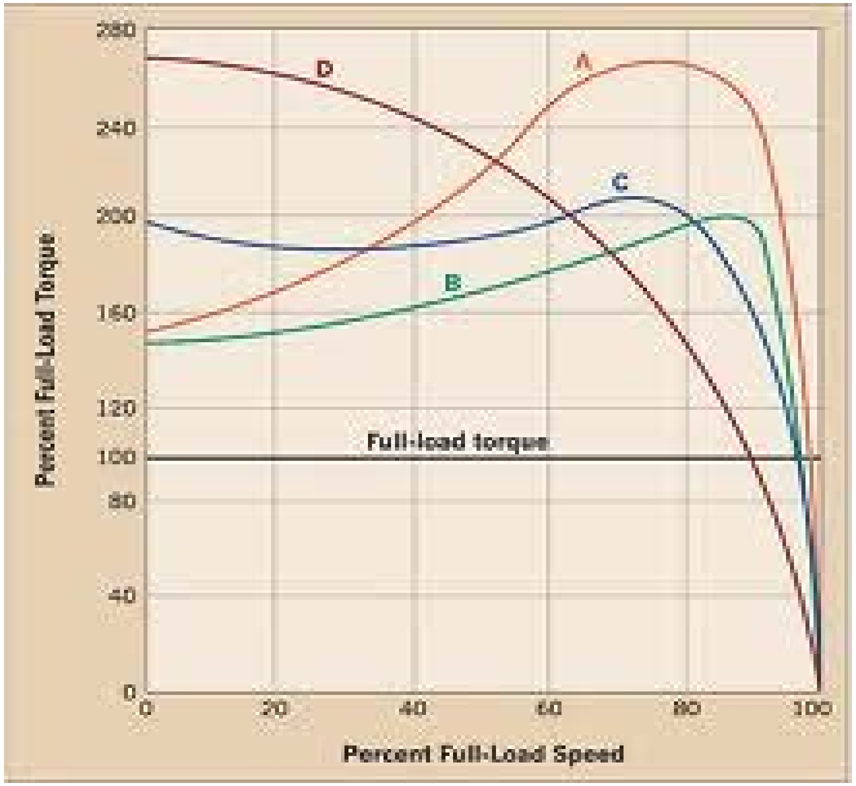
PowerWorld case B2_IndMotor_DoubleCage

Induction Motor Mechanical Load

- An induction motor is operating in steady-state when the electrical torque is equal to the mechanical torque
- Mechanical torque depends on the type of load
  - Usually specified as function of speed, $T_M=T_{base}(\omega_r)^m$
  - Torque of fans and pumps varies with the square of the speed, conveyors and hoists tend to have a constant torque
- Total power supplied to load is equal to torque times speed
  - Hence the exponent is m+1, with $P_M=P_{base}(\omega_r)^m$

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

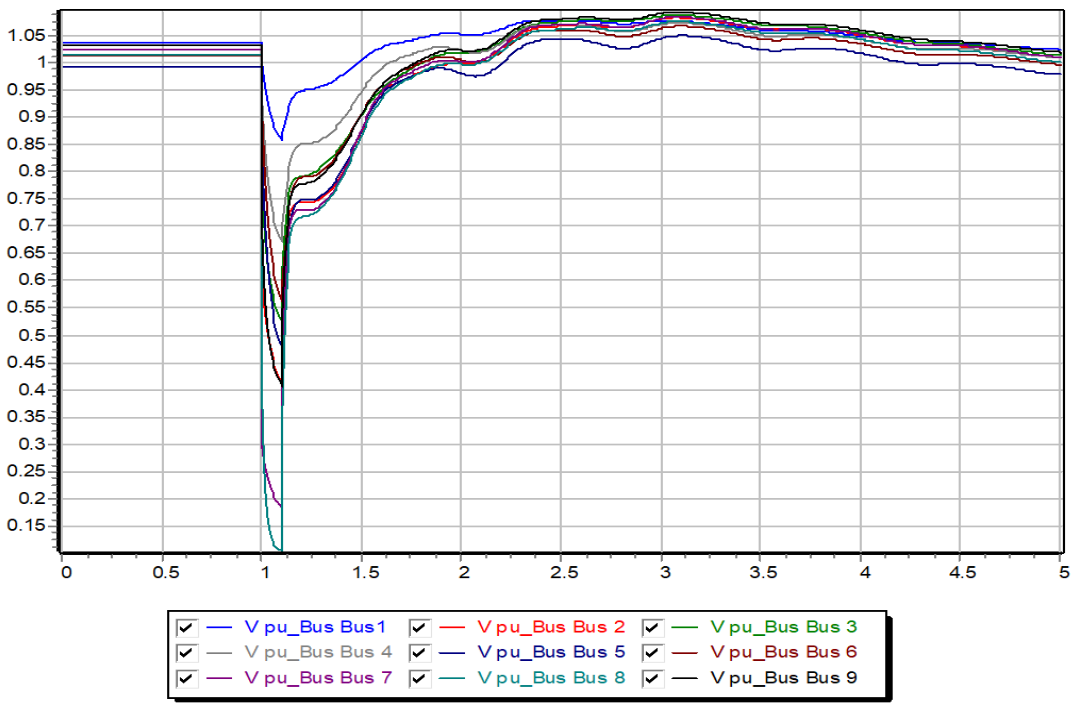
Image source: ecmweb.com/motors/understanding-induction-motor-nameplate-information

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 *maximum* 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 very 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

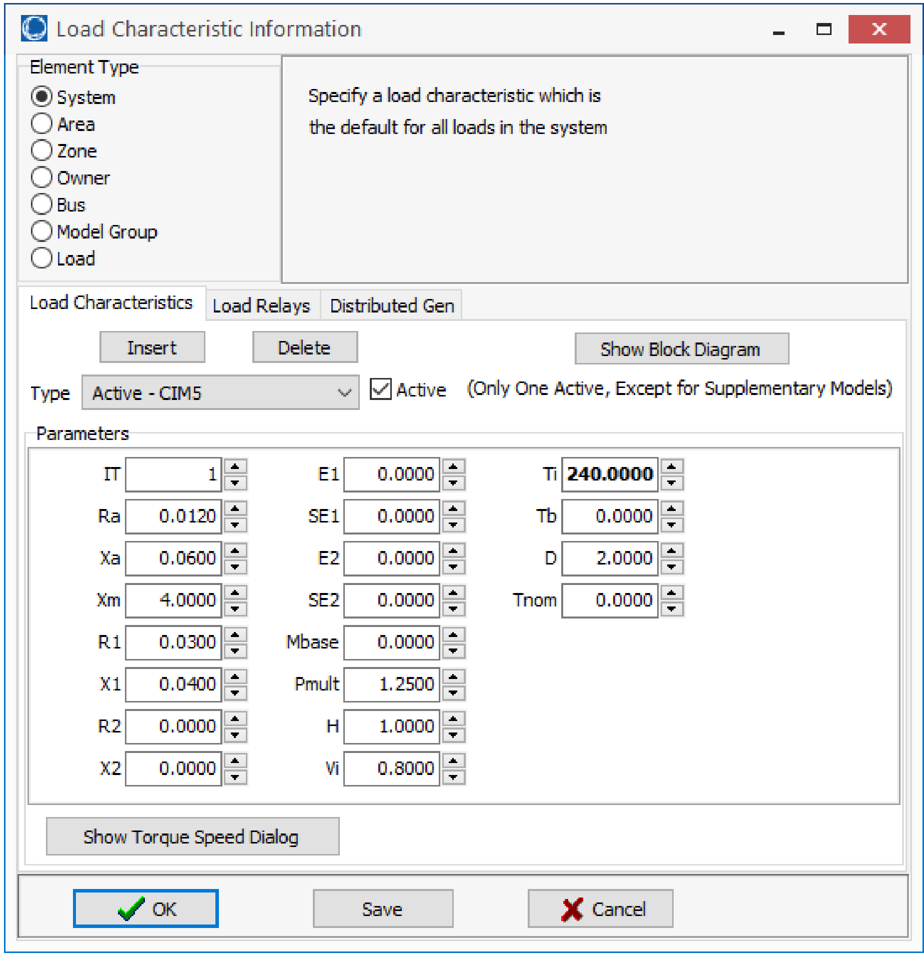


Results are for a 0.1 second fault

Usually motor load is much less than 100%

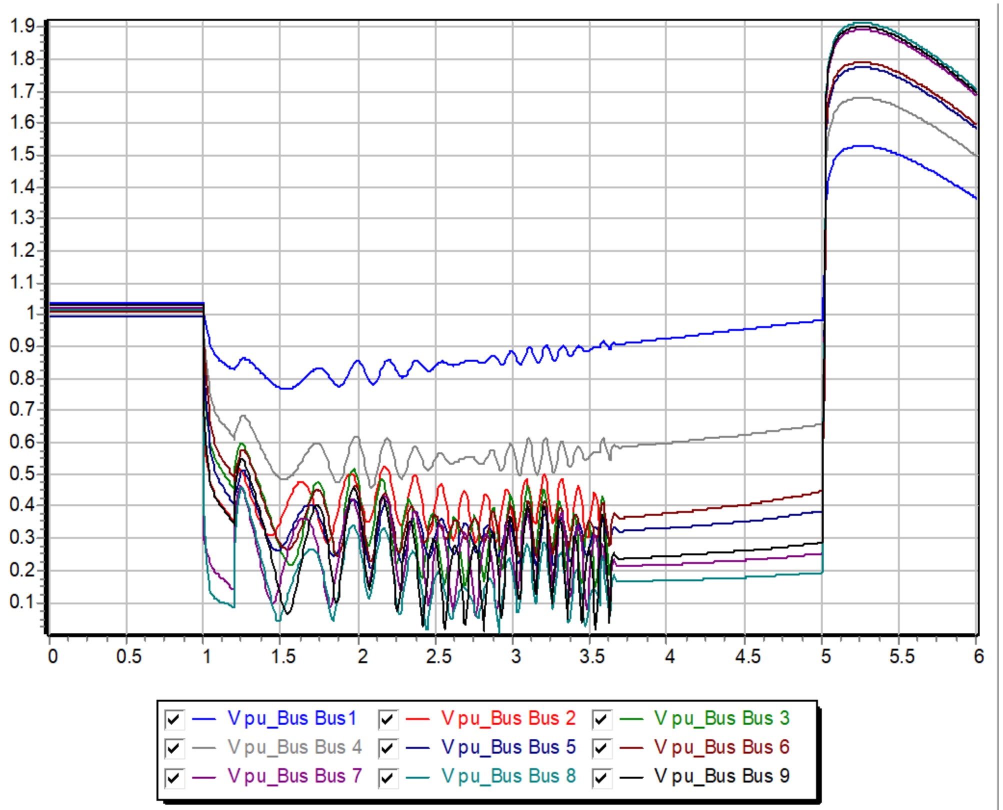
Impact of Model Protection Parameters

- 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



Motor Stalling With Longer Fault

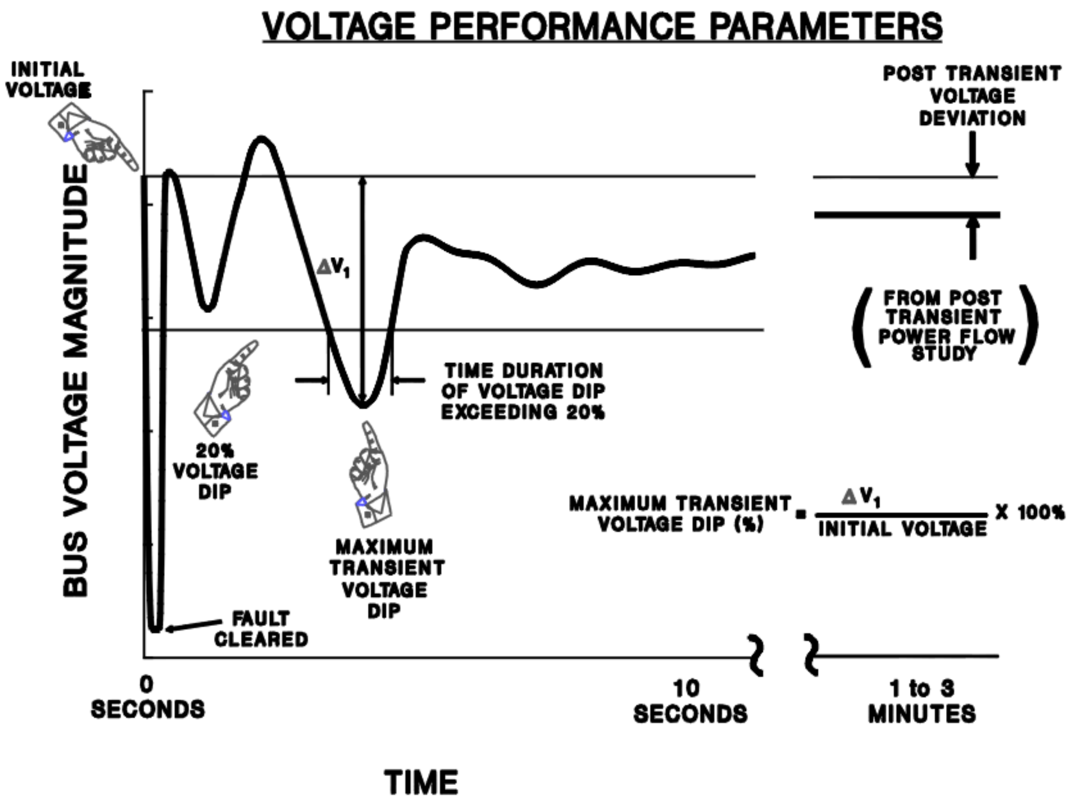
- The below image shows the WECC_CIM5 system with the fault clearing extended to 0.2 seconds



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

Motor Starting

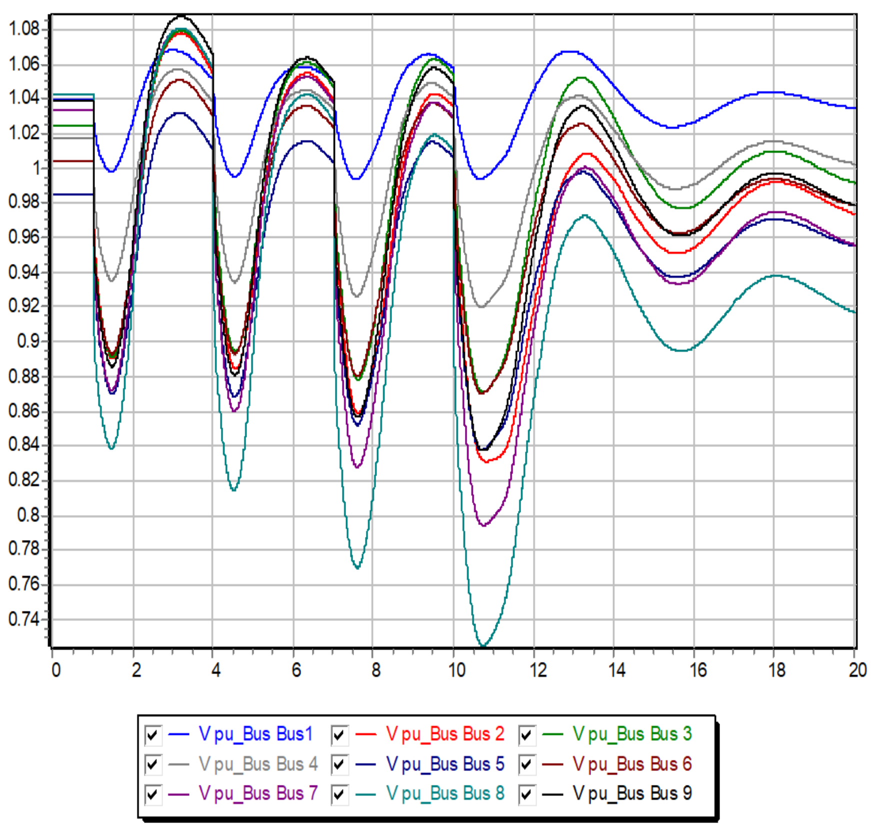
- Motor starting analysis looks at the impacts of starting a motor or a series of motors (usually quite large motors) on the power grid
  - Examples are new load or black start plans
- While not all transient stability motor load models allow the motor to start, some do
- When energized, the initial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

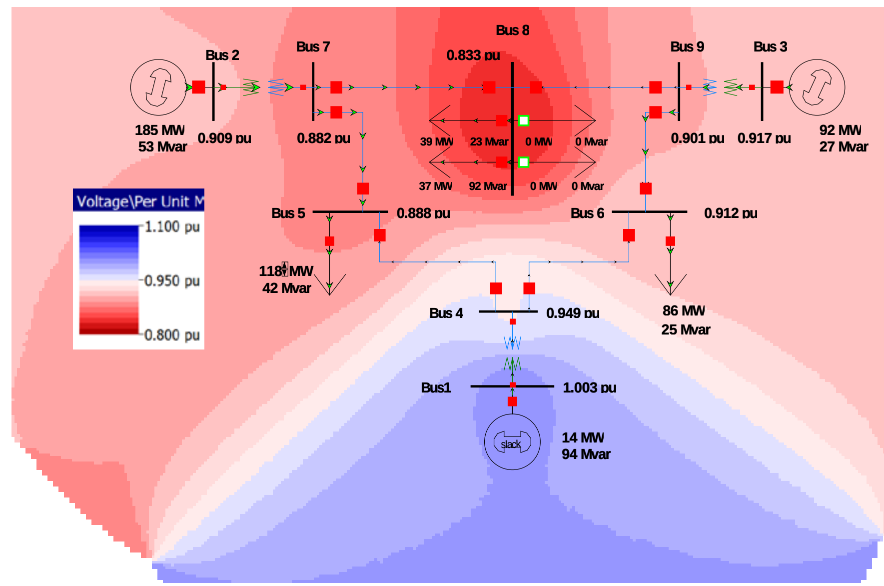
Motor Starting Example

- 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

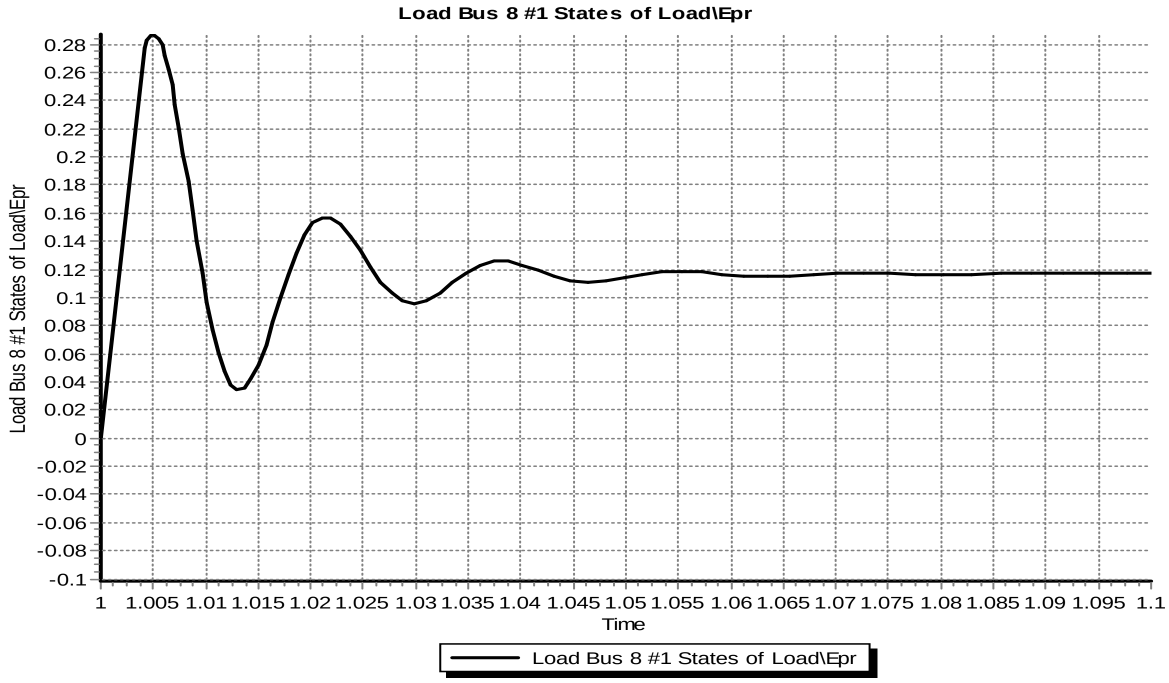
- Below graph shows the bus voltages for starting the four motors three seconds





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

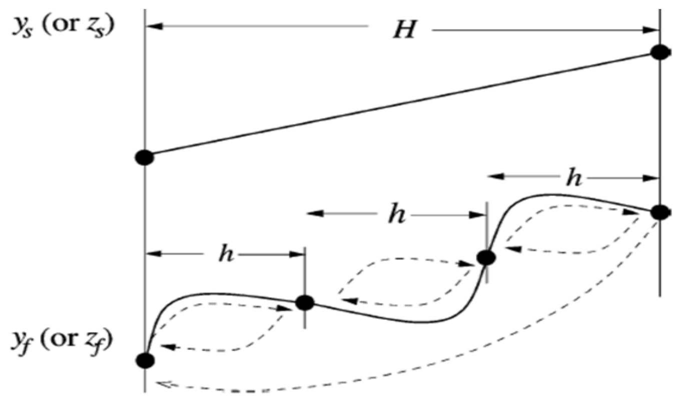
- These fast dynamics can be seen to vary with slip in the $\omega_s s$ term

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

- 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.

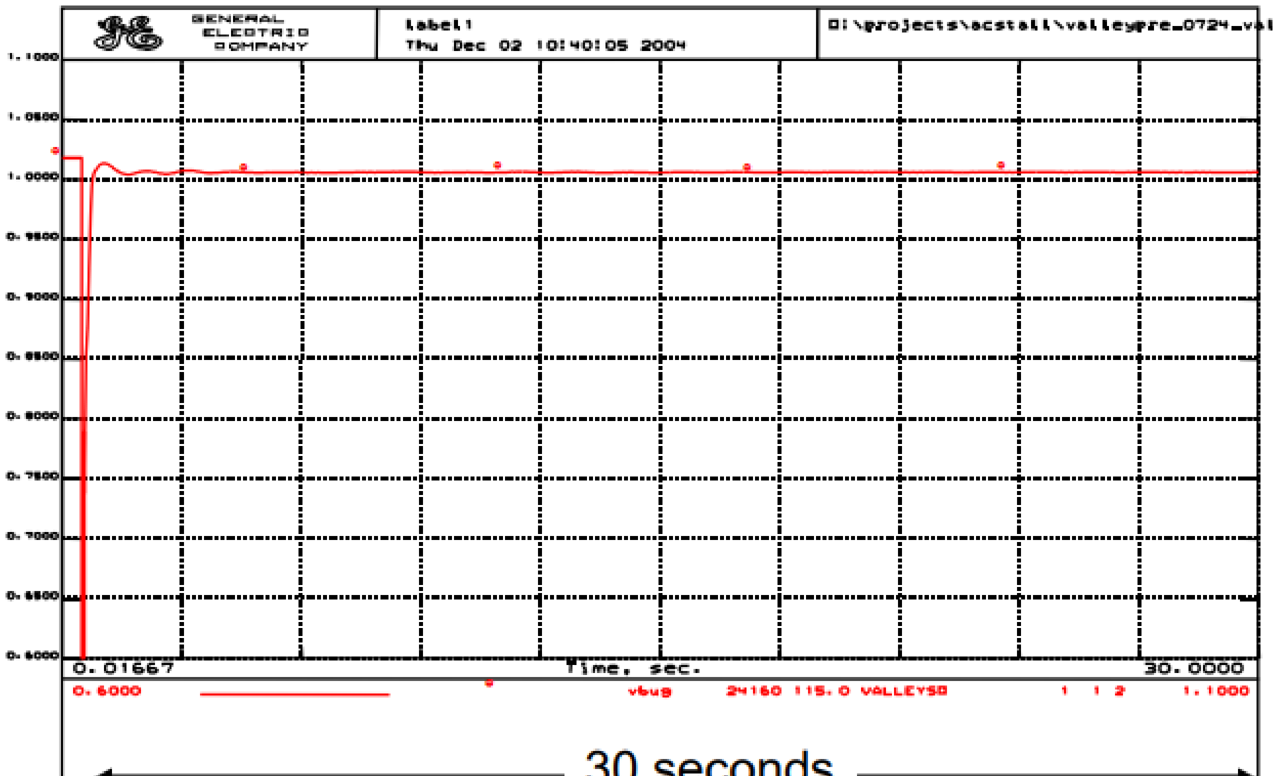
Need for Better Load Modeling: History of Load Modeling in WECC

- 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 down using the interim load model indicated would occur

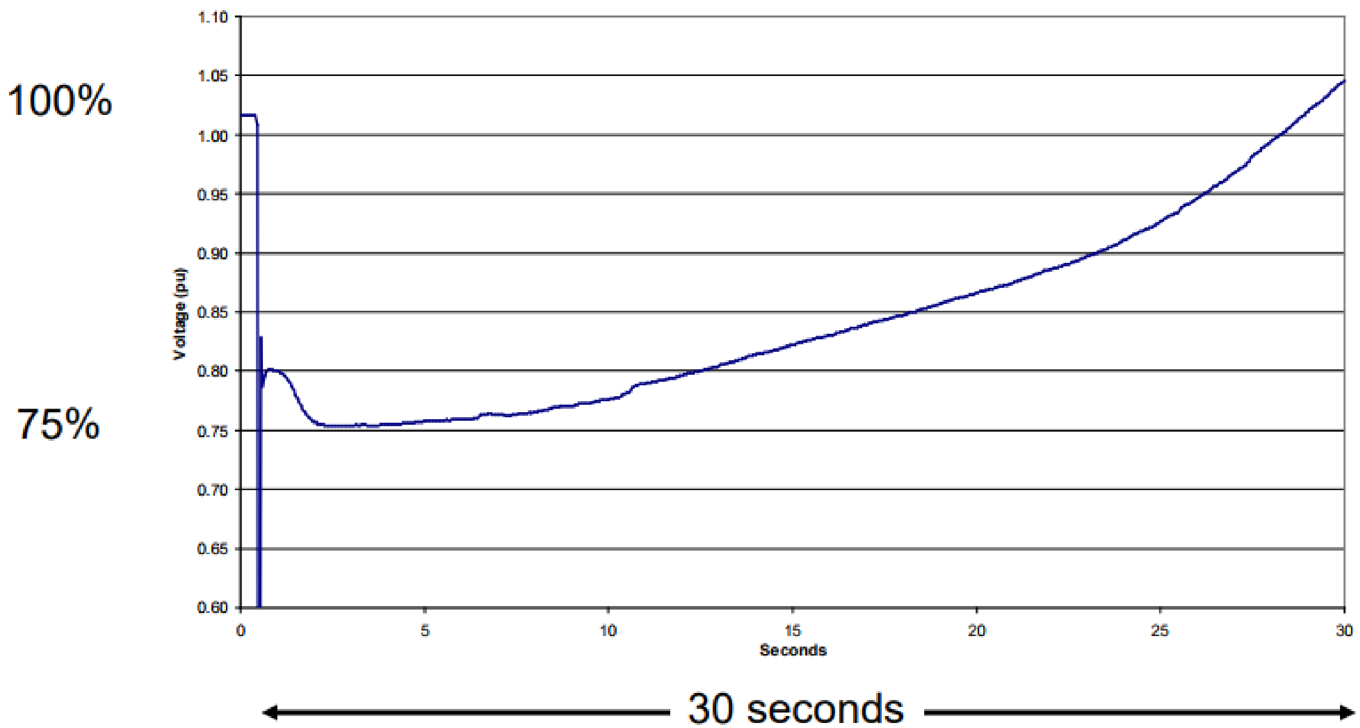


Vertical scale goes down to about 0.6 per unit

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



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
  - This is the model inside of “CMPLDW” and “CMLD” that allows the representation of FIDVR

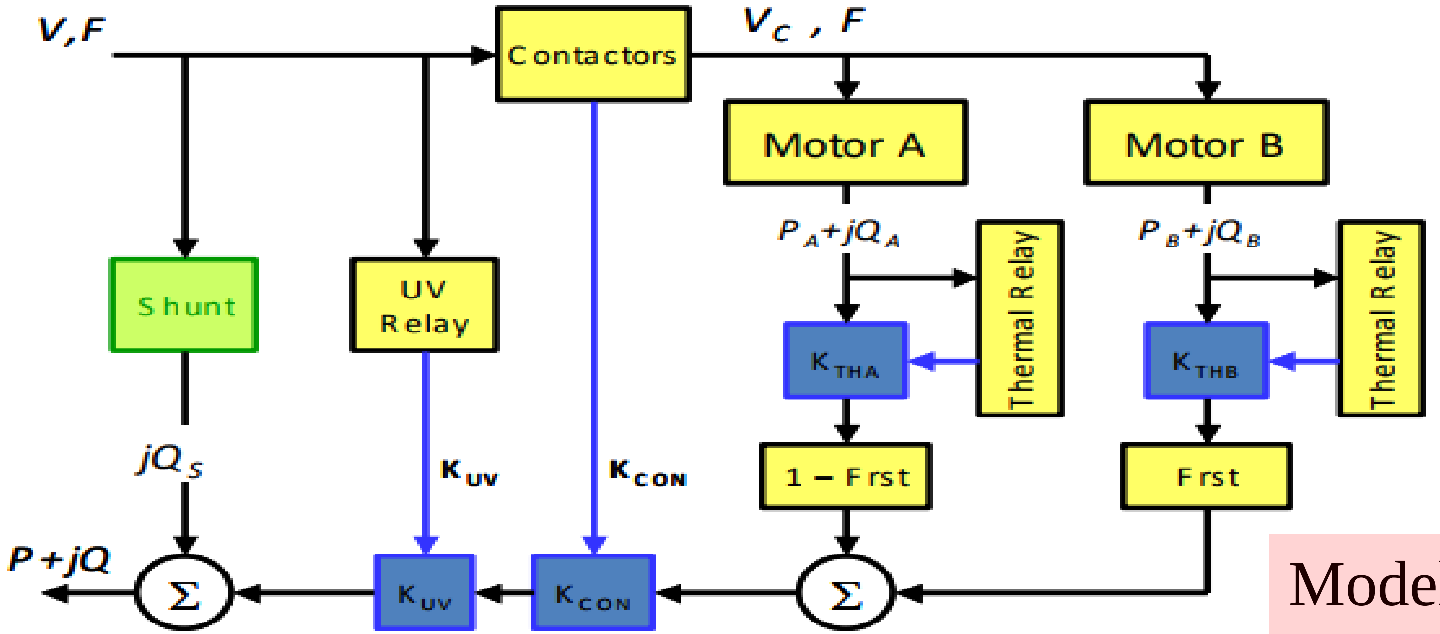
What is LD1PAC

- 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 concrete
  - 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 <u>*steady-state*</u> 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*.

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

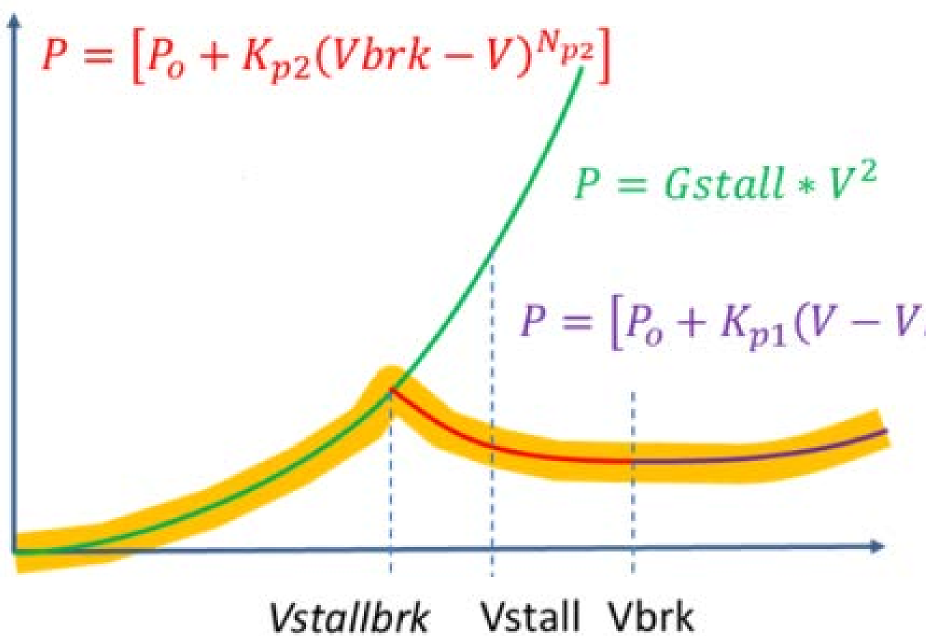
Model is mostly algebraic, but with stalling behavior

"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 goest 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)

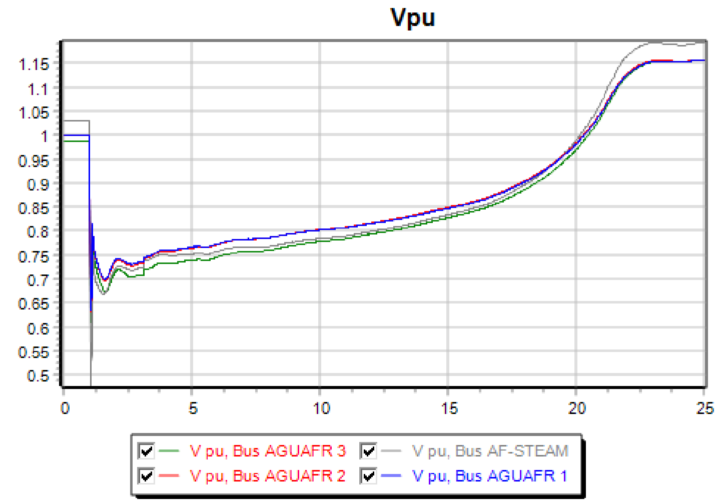


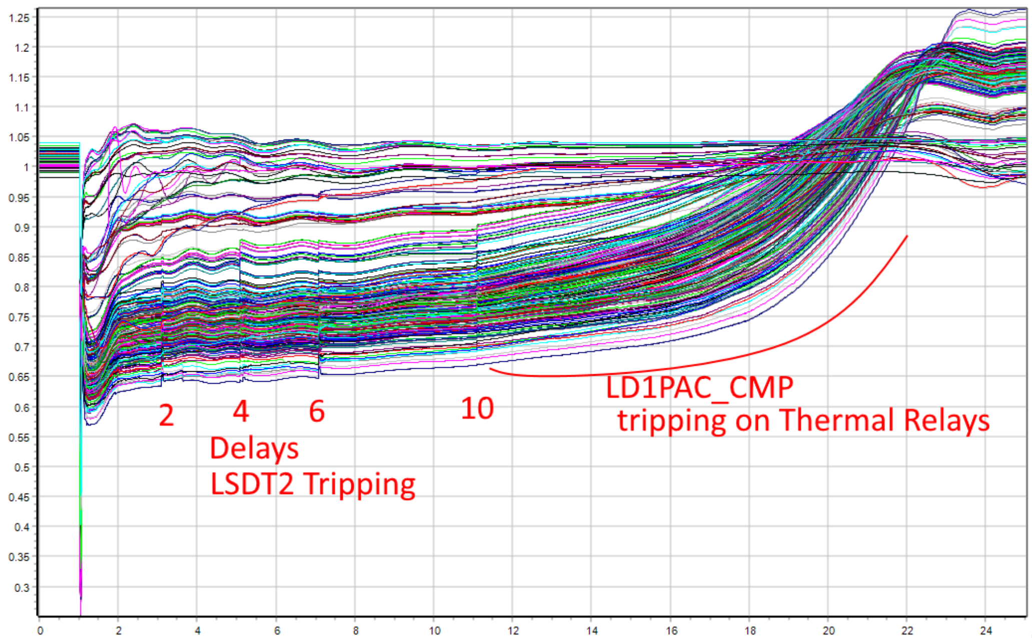
Transition between the "Operating" and "Stall" Curves

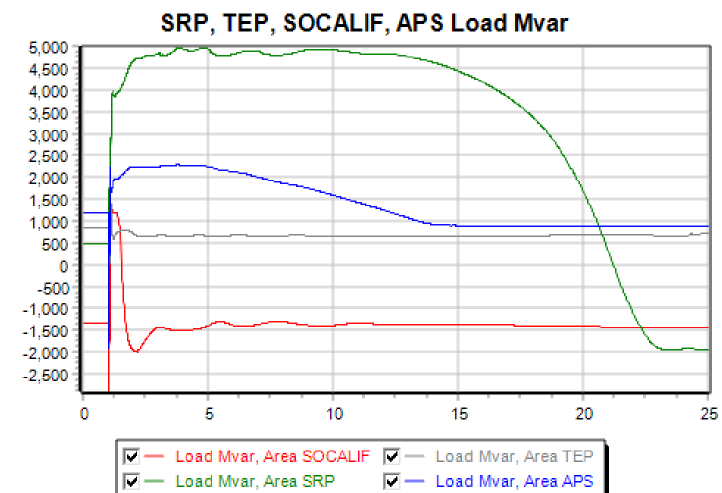
- In existing LD1PAC and CMPLDW/CMLD models this transition is defined simply as
  - If Voltage < Vstall for more than Tstall seconds, then immediately flip to the green stall curve
  - The "Motor A" fraction of the model will remain there until the thermal relay trips it
  - The "Motor B" fraction of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







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)

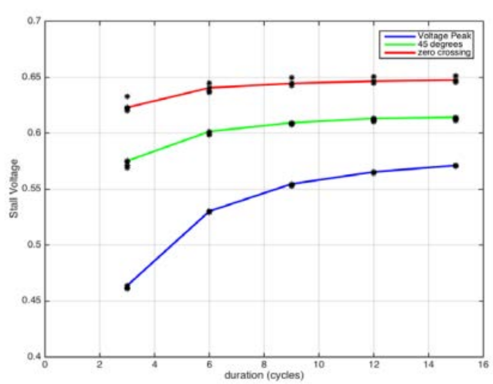
https://www.osti.gov/servlets/purl/1183173

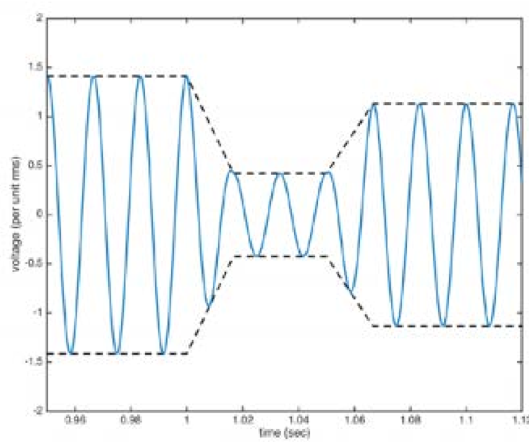
- They found that when stalling happened it happened extremely quickly (the motors are very small and have very little inertia)

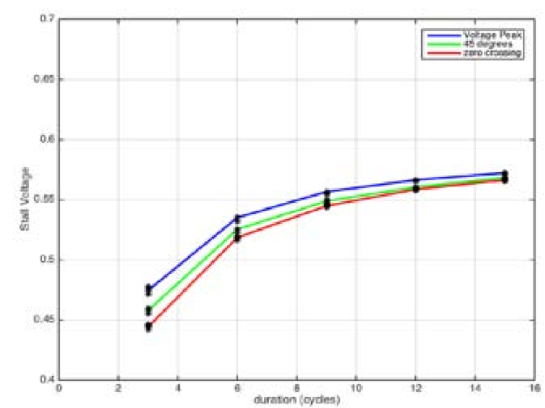
https://gig.lbl.gov/sites/all/files/6b-quint-composite-load-model-data.pdf

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



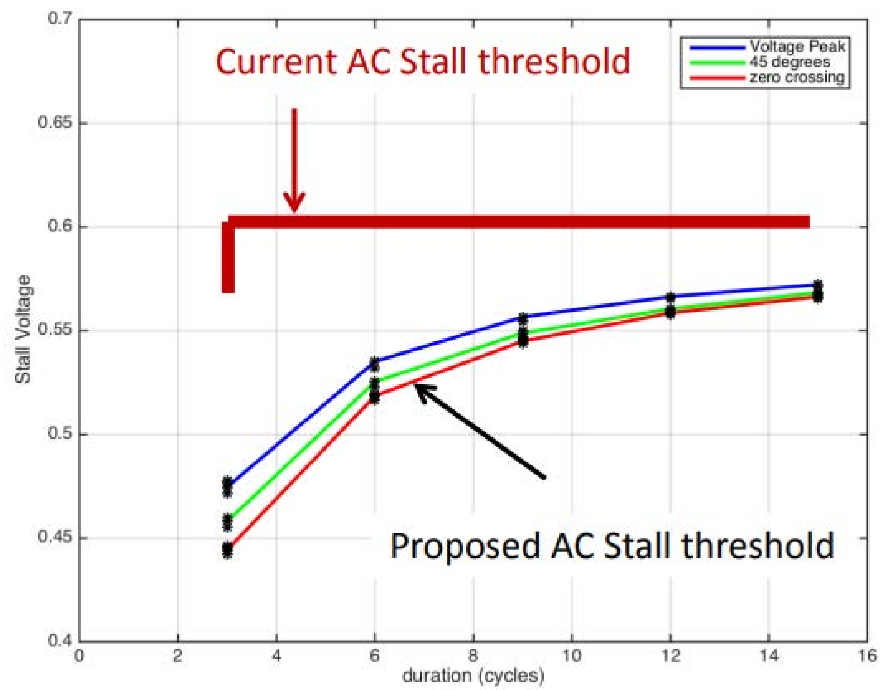




https://gig.lbl.gov/sites/all/files/6b-quint-composite-load-model-data.pdf

This is still being discussed within industry group: WECC and NERC

- In the short-term (by early 2020), we may convert this to an indefinite time decision
  - Lower voltages would cause transition to stall faster
  - Slightly higher voltage seen for a longer time would also stall
  - We have modified the LD1PAC model so that Tstall < 0 means a hard-code curve

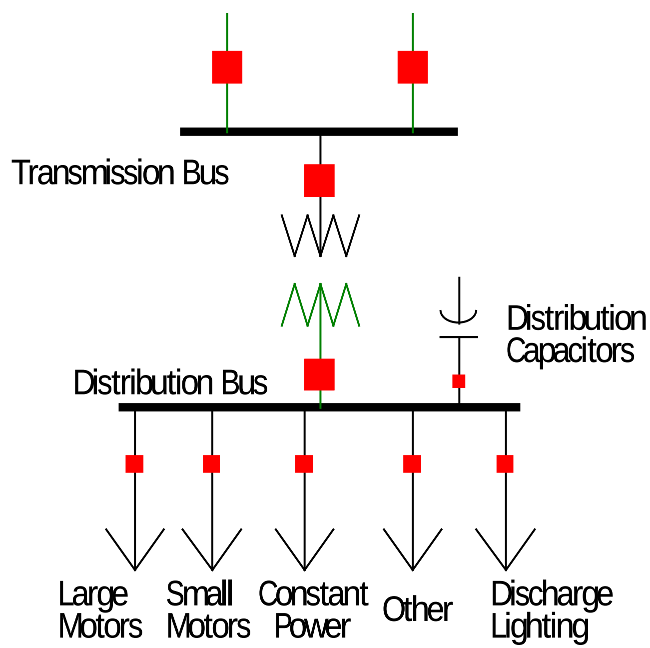


Composite Load Models

- 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

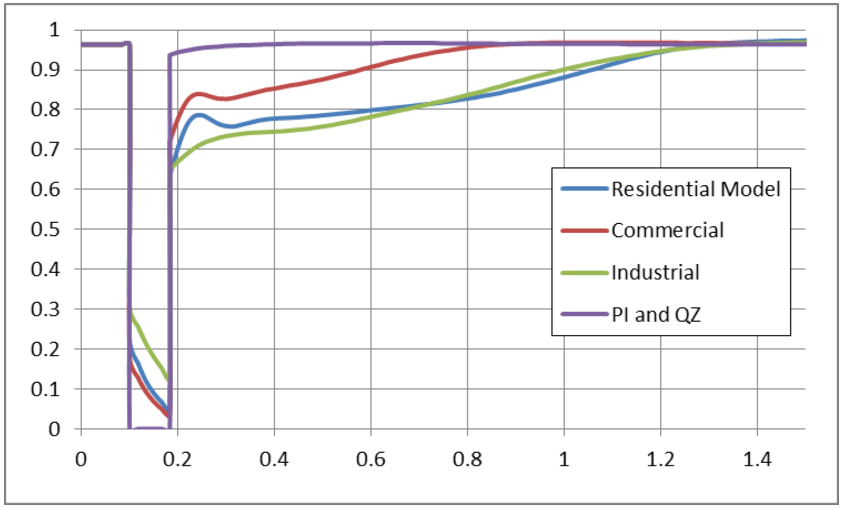
- The CLOD model represents the load as a combination of large induction motors, small induction motors, constant power, discharge lighting, and other



CLOD Model

- Different load classes can be defined

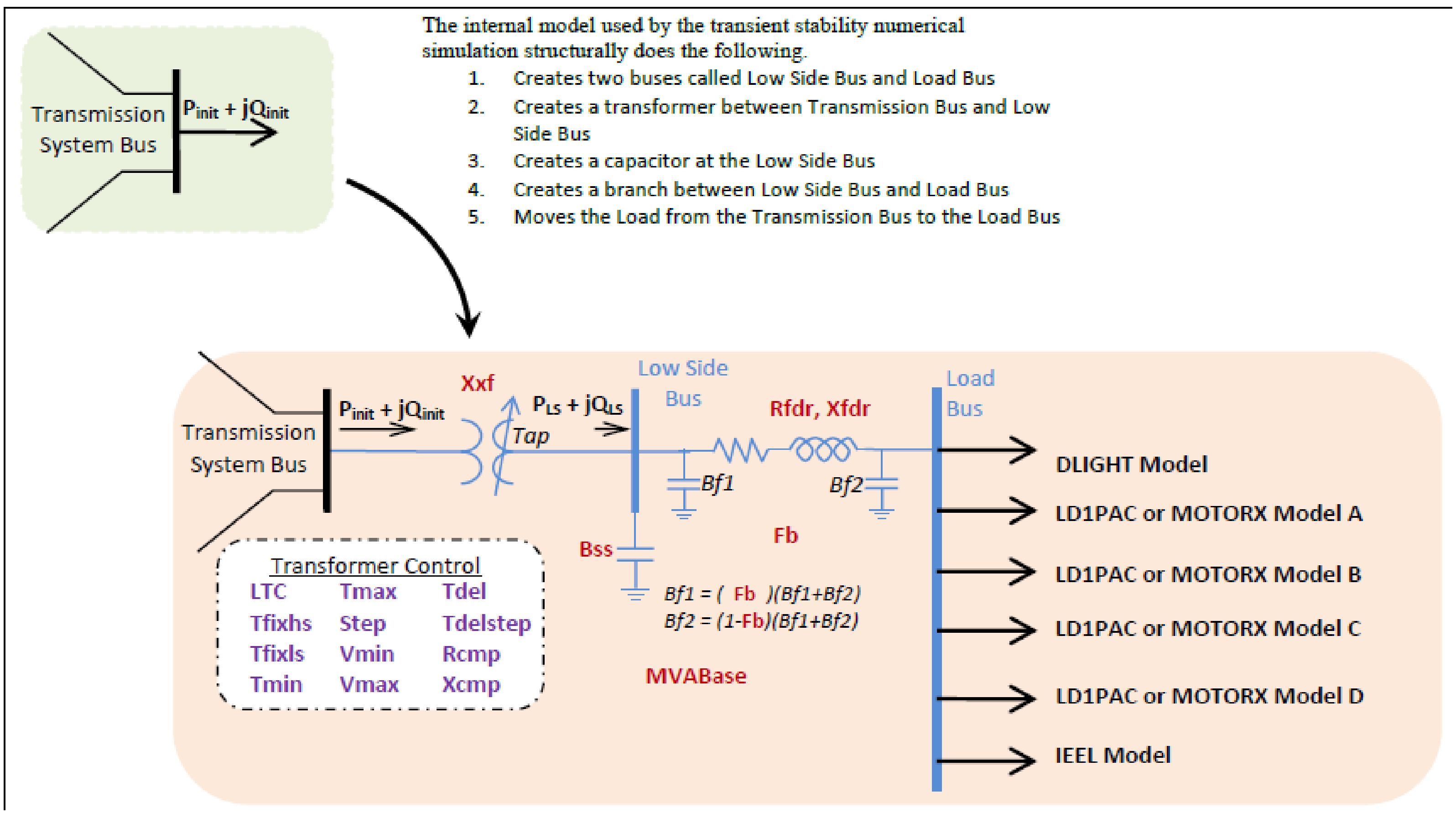
Customer Class	Large Motor	Small Motor	Discharge Lighting	Constant Power	Remaining (PI, QZ)
Residential	0.0	64.4	3.7	4.1	27.8
Agriculture	10.0	45	20	4.5	19.5
Commercial	0.0	46.7	41.5	4.5	7.3
Industrial	65.0	15.0	10.0	5.0	4.0



Comparison of voltage recovery for different model types

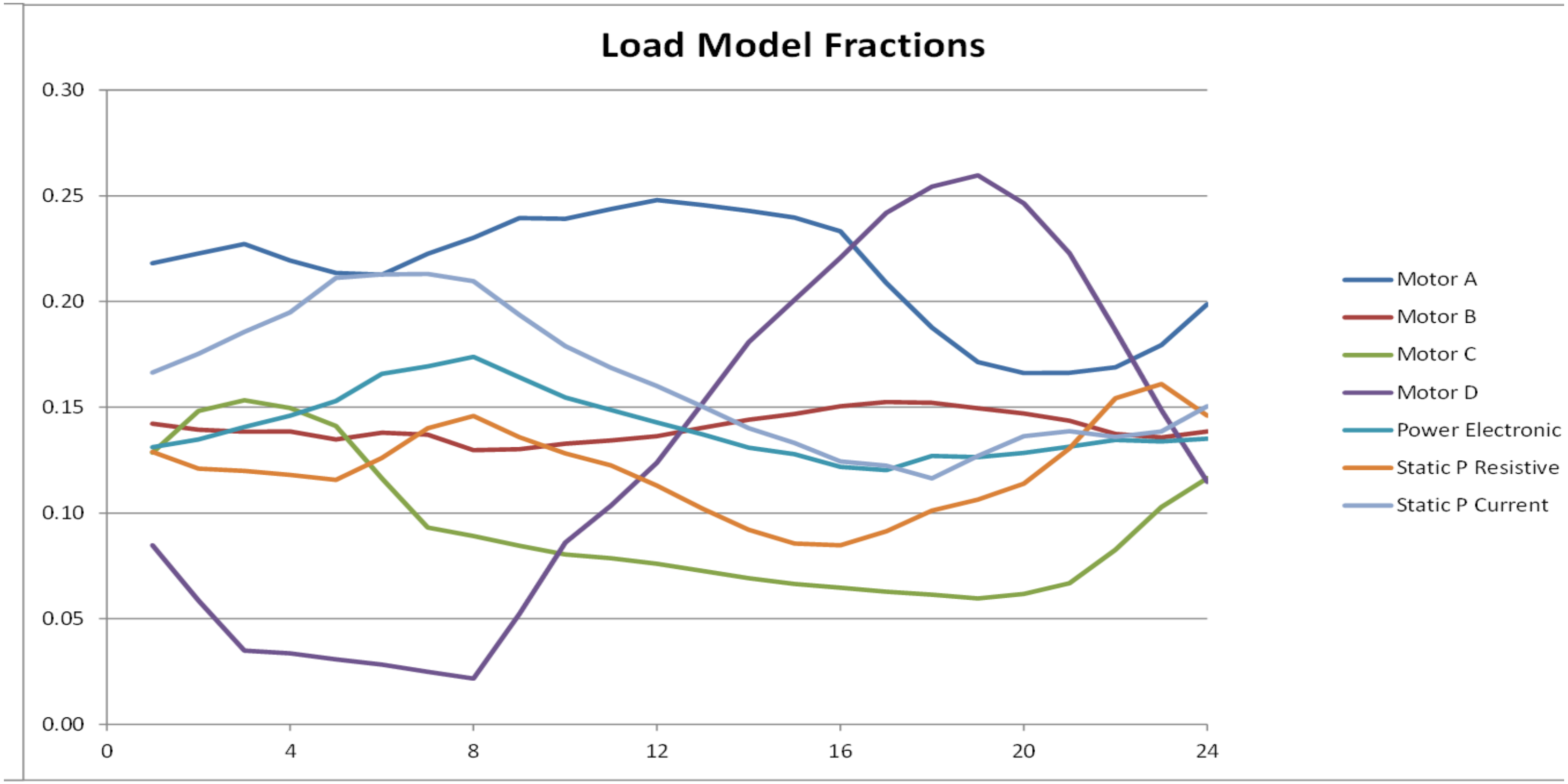
WECC Composite Load Model

- Contains up to four motors or single phase



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 a huge 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.

LD1PAC Stalling/Restarting

- Again, this is an aggregate model meant to represent 1000s individual motors
  - A meager attempt is made to model motor stalling and restarting
  - I say meager, because you basically model it like you have 2 motors and allow 1 to restart
- Also try to several other phenomena
  - Thermal tripping
  - Under voltage tripping
  - Contactor tripping

Current Research

- Current topics for load modeling research include assessment of how much the load model maters
- Another issue is how to determine the load model parameters – which ones are observable under what conditions
  - For example, motor stalling can not be observed except during disturbances that actually cause the motors to stall
  - Not important to precisely determine parameters that ultimately do not have much influence on the final problem solution; of course these parameters would be hard to observe
- Correctly modeling embedded distribution level generation resources, such as PV, is important

Coordinated Initialization of the Load Distribution Equivalent, Load Characteristic, and Load Distributed Generation Models

PowerWorld Corporation
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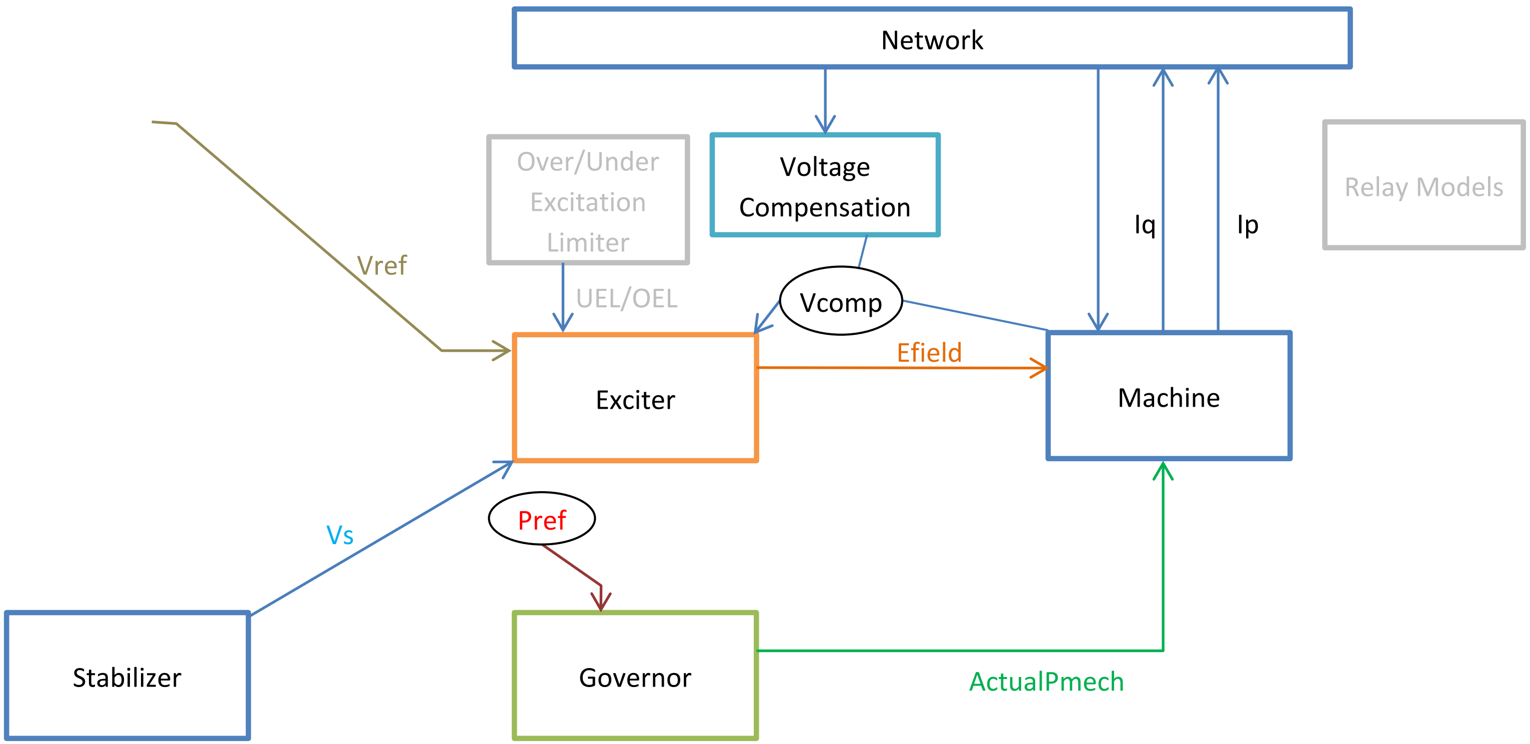
Champaign, IL 61820
http://www.powerworld.com
info@powerworld.com
217 384 6330

Coordinated Initialization of Generator Models

- Generators have included a modular structure for several decades (1970s and onward)
- Synchronous generators needed up to 8 separate modules with coordinated initialization
  - Machine (Generator/Converter Model)
  - Exciter (P and Q controller)
  - Governor (Drive Train)
  - Stabilizer (Pitch Control)
  - Under Excitation Limiter
  - Over Excitation Limiter
  - Compensator Model
  - Relay Model

8 Synchronous Generator Modules

- We have always done this with Generators

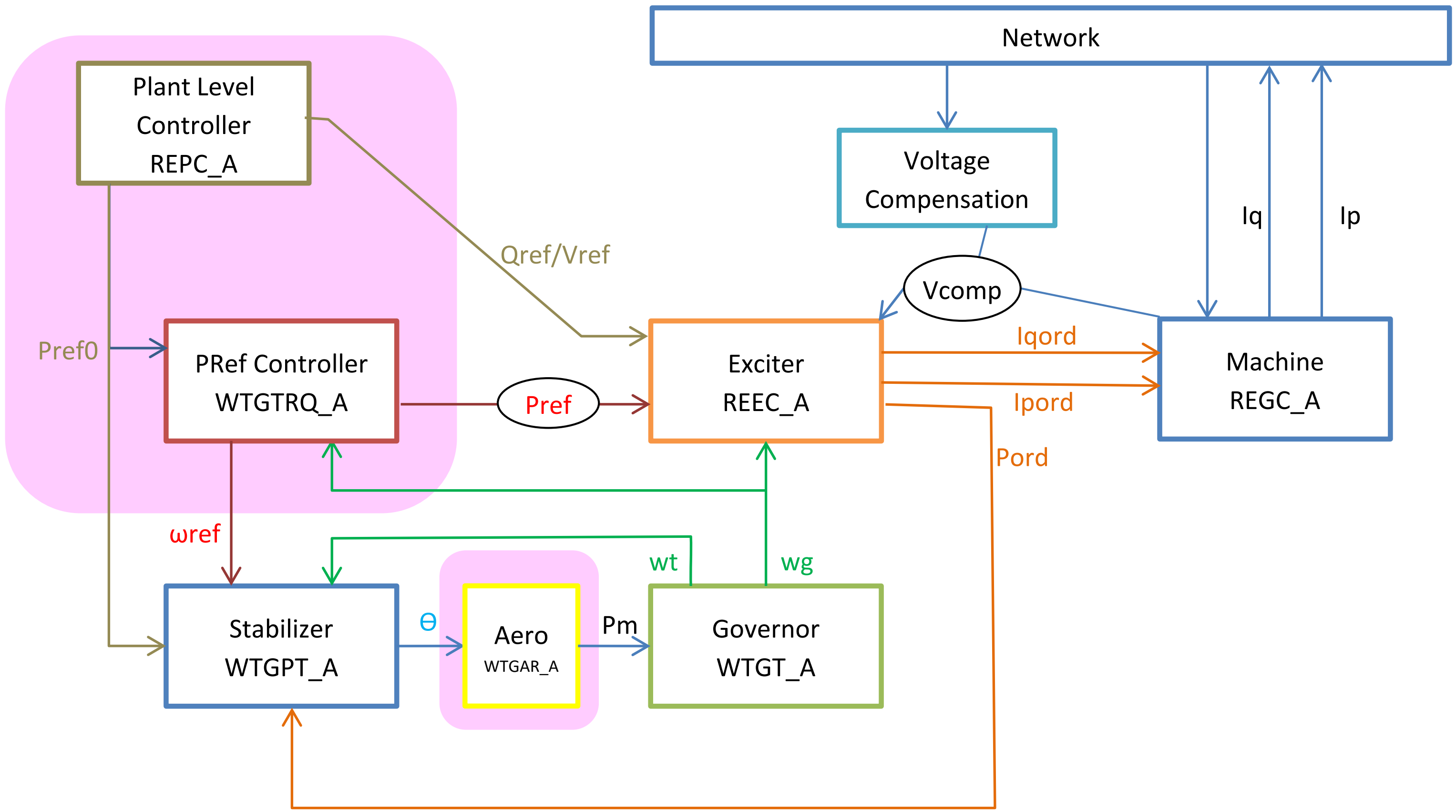


Generator Modules Continue to Grow

- In past several years even more modules have been added
  - Aerodynamic Model (Type 3 Wind)
  - Pref Controller (Type 3 wind and LCFB1)
  - Plant Controller (renewable models)
  - AGC Controller (Implemented in Version 19 of PowerWorld Simulator)

Type 3 Wind Turbine model added 3 new modules

- Pref Controller, Plant Controller, Aero



Load Models have not kept up

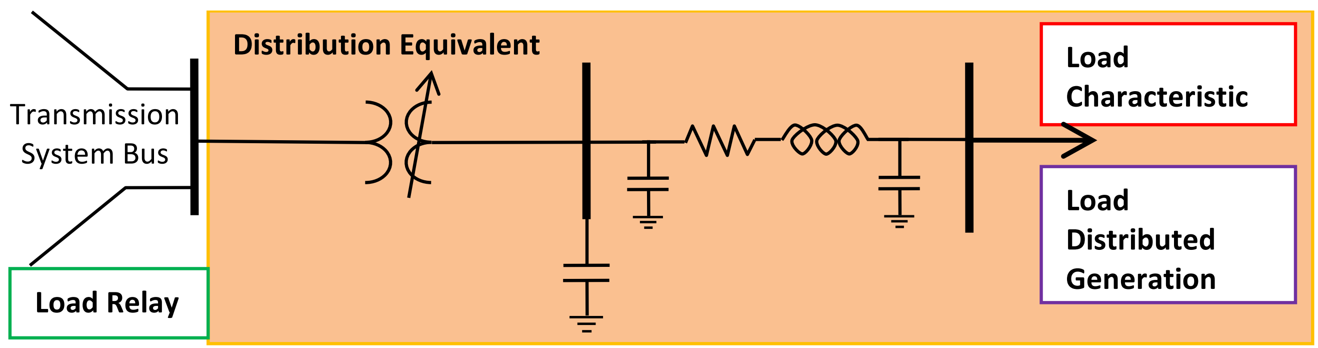
- Load Models have been stuck with only two modules
  - Load characteristic
  - Load relay
- The MOTORW model introduced in PSLF in the 1990s was a step in the right direction
  - MOTORW included a parameter indicating what percentage of the load was a motor
  - This meant we now had 3 modules
    - Dynamic Model
    - Algebraic Model
    - Relay Model
  - No longer required you to split the power flow load record to permit a load model split
- Relay model is always simple, but so is MOTORW
  - Does not require any coordination in the initialization of the models. Algebraic and Dynamic model just get split

Initial Implementation of Distribution Equivalent

- Composite load model (CMPLDW) was designed within the WECC LMTF in the mid 2000s
  - The distribution equivalent is stuck inside the load characteristic
  - Has meant that new load models are gravitating toward being smashed into the CMPLDW framework
- Load Distributed Generation (Roof-top Solar for example)
  - WECC LMTF is now pushing us toward getting the Load Distributed Generation model out of the CMPLDW

It is Time to Modularize: Just like Generators

- Natural for a load record to have 4 modules associated with transient stability
  - **Load Characteristic** (can also split algebraic/dynamic)
  - **Relay Model**
  - **Distribution Equivalent**
    - Added in PowerWorld Simulator Version 17 in January 2013
  - **Load Distributed Generation Model**
    - Added in PowerWorld Simulator Version 19 in November 2015



- Initialization of this model must be fully documented though

Load Record: Distributed Generation

- Discussed in WECC LMTF for a few years and decision was made in 2014 to model with three new user input fields with each Load Record
  - **Dist MW Input**: the user entered MWs of distributed generation at the load
  - **Dist Mvar Input**: the user entered Mvars of distributed generation at the load
  - **Dist Status**: The status of the distributed generation (Open or Closed)
- Available in PowerWorld Simulator 19 now

	Number of Bus	Name of Bus	Area Name of Load	Zone Name of Load	ID	Status	MW	Mvar	MVA	S MW	S Mvar	Dist Status	Dist MW Input	Dist Mvar Input	Dist MW	Dist Mvar	Net Mvar	Net MW
1	2	Two	Top	1	1	Closed	80.00	20.00	82.46	80.00	20.00	Closed	40.00	0.00	40.000	0.000	20.000	40.000
2	3	Three	Top	1	1	Closed	220.00	40.00	223.61	220.00	40.00	Open	110.00	0.00	0.000	0.000	40.000	220.000
3	4	Four	Top	1	1	Closed	160.00	30.00	162.79	160.00	30.00	Closed	80.00	0.00	80.000	0.000	30.000	80.000
4	5	Five	Top	1	1	Closed	260.00	40.00	263.06	260.00	40.00	Open	130.00	0.00	0.000	0.000	40.000	260.000
5	6	Six	Left	1	1	Closed	400.00	0.00	400.00	400.00	0.00	Closed	200.00	0.00	200.000	0.000	0.000	200.000
6	7	Seven	Right	1	1	Closed	400.00	0.00	400.00	400.00	0.00	Closed	200.00	0.00	200.000	0.000	0.000	200.000

Other Load Record Fields

- **Dist MW**, **Dist Mvar**: this is the actual MWs being seen by the power flow solution
  - This will be 0.0 if **DistStatus** = Open
  - This will be reduced if the voltage falls below the minimum voltage for constant power load
- **Net MW**: this is equal to the subtraction of the fields **MW – Dist MW**

	Number of Bus	Name of Bus	Area Name of Load	Zone Name of Load	ID	Status	MW	Mvar	MVA	S MW	S Mvar	Dist Status	Dist MW Input	Dist Mvar Input	Dist MW	Dist Mvar	Net Mvar	Net MW
1	2	Two	Top	1	1	Closed	80.00	20.00	82.46	80.00	20.00	Closed	40.00	0.00	40.000	0.000	20.000	40.000
2	3	Three	Top	1	1	Closed	220.00	40.00	223.61	220.00	40.00	Open	110.00	0.00	0.000	0.000	40.000	220.000
3	4	Four	Top	1	1	Closed	160.00	30.00	162.79	160.00	30.00	Closed	80.00	0.00	80.000	0.000	30.000	80.000
4	5	Five	Top	1	1	Closed	260.00	40.00	263.06	260.00	40.00	Open	130.00	0.00	0.000	0.000	40.000	260.000
5	6	Six	Left	1	1	Closed	400.00	0.00	400.00	400.00	0.00	Closed	200.00	0.00	200.000	0.000	0.000	200.000
6	7	Seven	Right	1	1	Closed	400.00	0.00	400.00	400.00	0.00	Closed	200.00	0.00	200.000	0.000	0.000	200.000

Treatment of Distributed Generation in Power Flow

- Summary Information with Areas, Zones, Substations, etc…
  - Dist MW is separate summation from Load MW

	Area Num	Area Name	AGC Status	Gen MW	Load MW	Dist MW	Shunt MW	Tot Sched MW	Int MW	ACE MW	Lambda	Loss MW
1	1	Top	ED	367.42	720.00	120.000		0.00	-359.54	-359.54	0.00	6.96
2	2	Left	ED	199.52	400.00	200.000		0.00	-200.82	-200.82	0.00	0.34
3	3	Right	ED	400.99	400.00	200.000		0.00	0.36	0.36	0.00	0.64

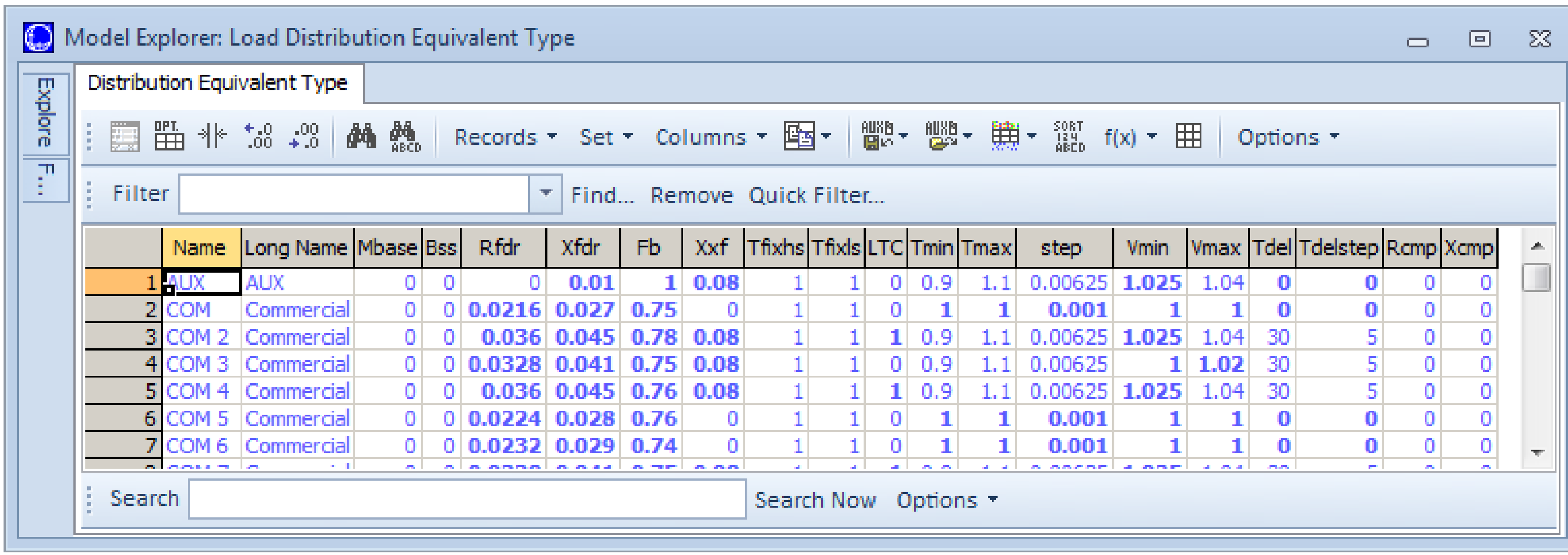
- Injection Group Treatment
  - Injected MW = Gen MW – Load MW – Dist Gen MW
- Contingency Actions
  - "Set, Change, Move" actions only act on Load portion
  - Open and Close actions also open the distributed gen

Load Distribution Equivalent

- Supplementary model that defines an equivalent of the distribution system's transformer, capacitors, and feeder
- Created independently of the load characteristic models
- Can be used with any load characteristic model
- Design assumes small number of Load Distribution Equivalent Types with many different loads assigned to each

Load Distribution Equivalent

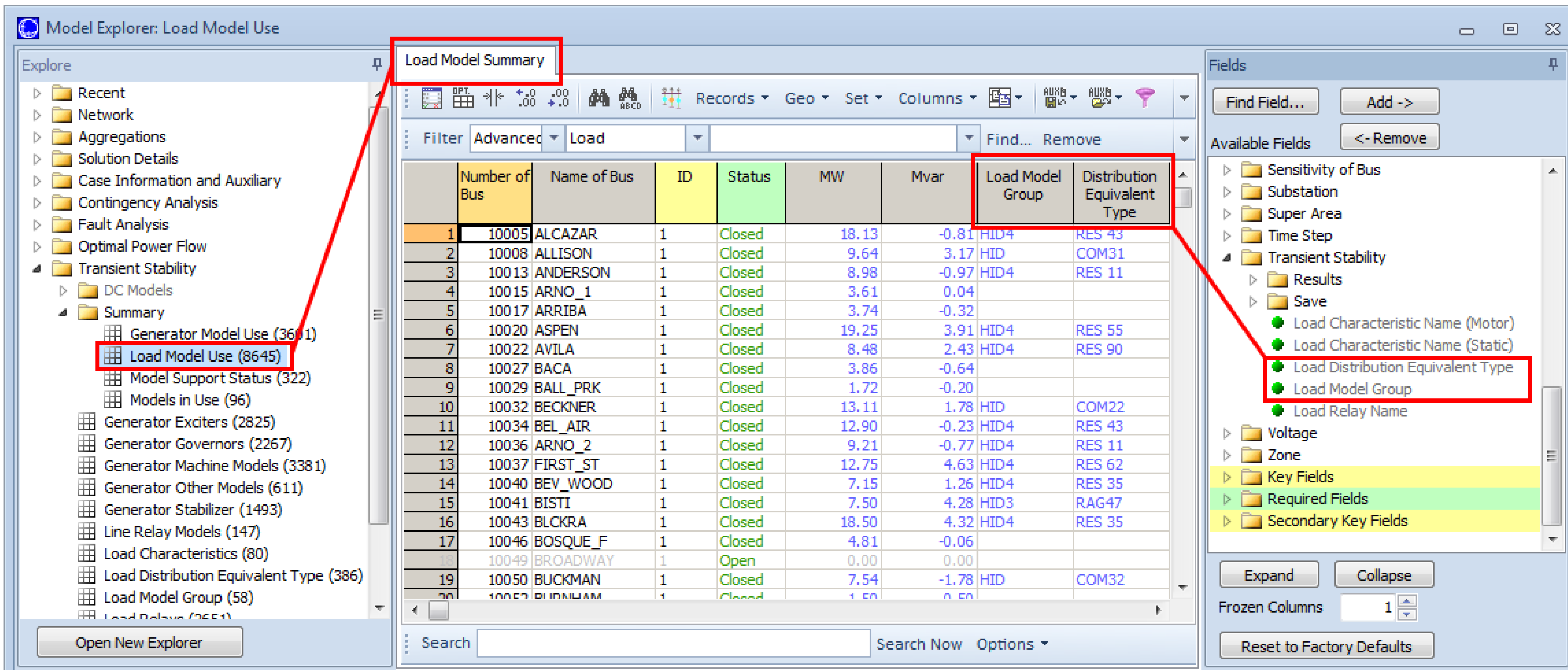
- First 17 parameters of the CMPLDW load characteristic model along with MVA base



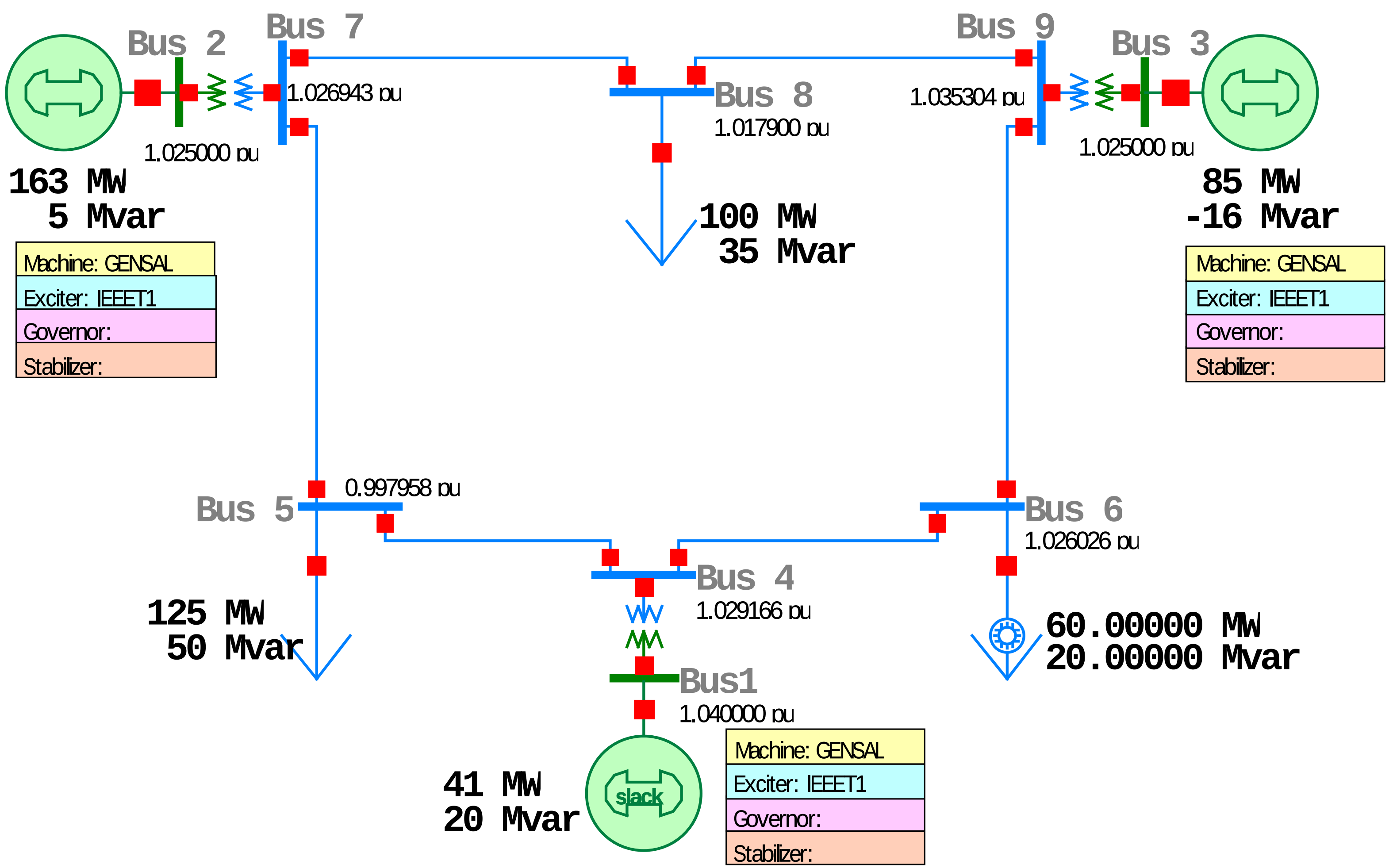
	Name	Long Name	Mbase	Bss	Rfdr	Xfdr	Fb	Xxf	Tfixhs	Tfixls	LTC	Tmin	Tmax	step	Vmin	Vmax	Tdel	Tdelstep	Rcmp	Xcmp
1	AUX	AUX	0	0	0	0.01	1	0.08	1	1	0	0.9	1.1	0.00625	1.025	1.04	0	0	0	0
2	COM	Commercial	0	0	0.0216	0.027	0.75	0	1	1	0	1	1	0.001	1	1	0	0	0	0
3	COM 2	Commercial	0	0	0.036	0.045	0.78	0.08	1	1	1	0.9	1.1	0.00625	1.025	1.04	30	5	0	0
4	COM 3	Commercial	0	0	0.0328	0.041	0.75	0.08	1	1	0	0.9	1.1	0.00625	1	1.02	30	5	0	0
5	COM 4	Commercial	0	0	0.036	0.045	0.76	0.08	1	1	1	0.9	1.1	0.00625	1.025	1.04	30	5	0	0
6	COM 5	Commercial	0	0	0.0224	0.028	0.76	0	1	1	0	1	1	0.001	1	1	0	0	0	0
7	COM 6	Commercial	0	0	0.0232	0.029	0.74	0	1	1	0	1	1	0.001	1	1	0	0	0	0

Assigning Load Distribution Equivalent Models

- Each Load record is assigned to a Distribution Equivalent



What does this look like?

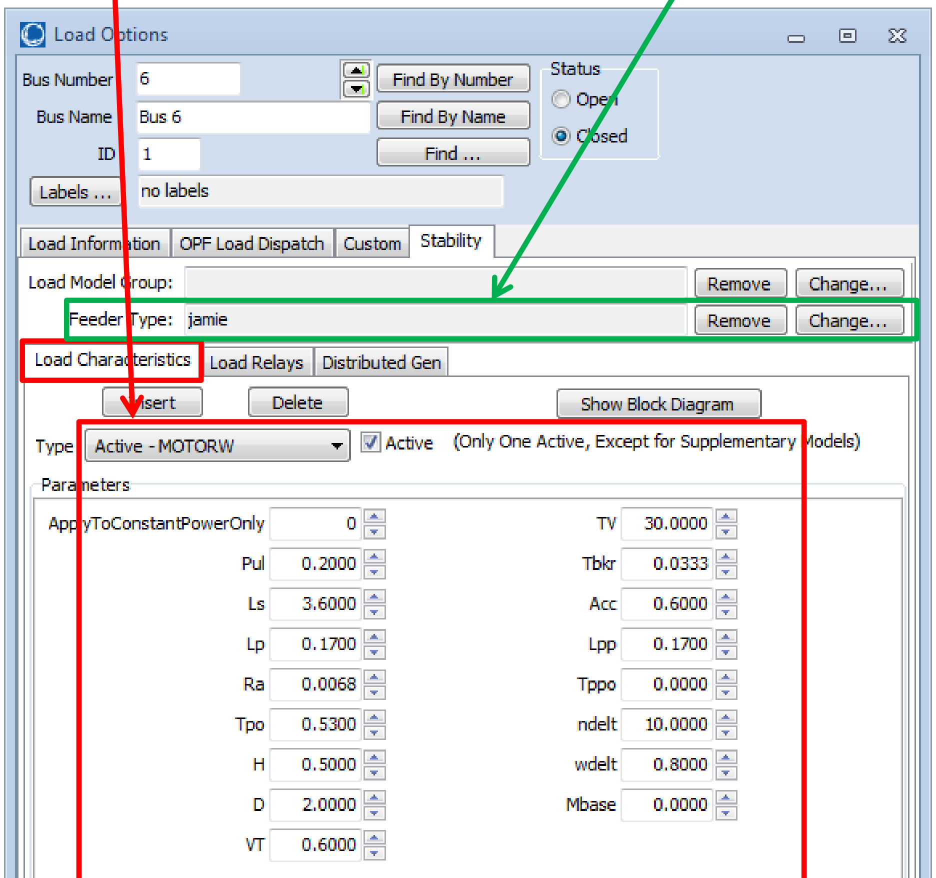


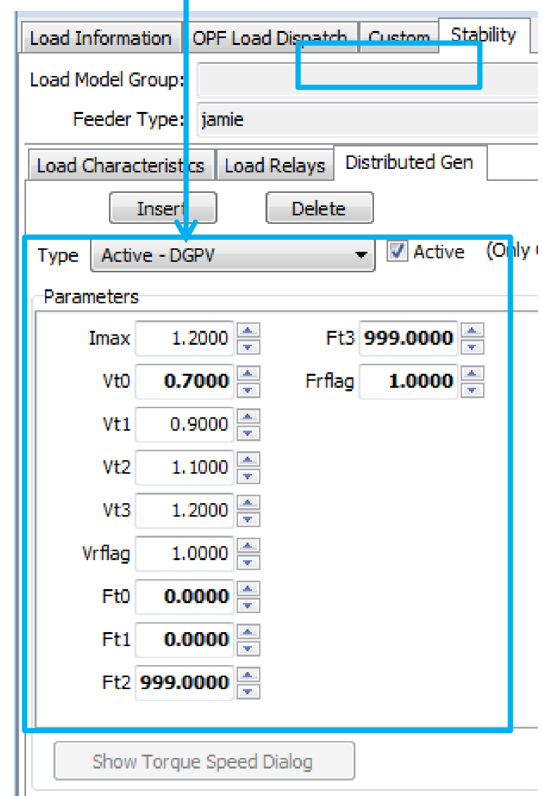
Load Record has Modules

Load Characteristic

Distribution Equivalent

Distributed Generation





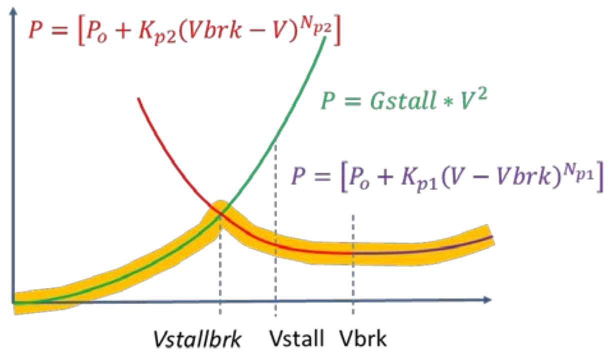
Initialization

- When using a software model the fundamental details of the model should be known to the user
  - Equipment affects everyone as it is connected to a grid
  - Others need to model your equipment
  - This often means pseudo-code is needed
- Describing how a model is initialized is part of this
  - *Software vendor secret*: the hardest thing to do with transient stability models is to initialize them
  - Also some arbitrary decisions are sometimes made about a model during initialization → need pseudo-code
- Before we discuss coordinated initialization of these models → consider initialization of
  - Single Phase Air Conditioner → LD1PAC
  - Induction Motors → MOTORW, CIM5, MOTOR1, etc..

LD1PAC Model: Algebraic Performance Model

- LD1PAC follows algebraic P/Q Curves
  - If *V* > *Vbrk* then
    - $P = \left[P_o + K_{p1}(V - Vbrk)^{N_{p1}}\right][1 + CmpKpf * \Delta f]$
    - $Q = \left[Q_o + K_{q1}(V - Vbrk)^{N_{q1}}\right][1 + CmpKqf * \Delta f]$
  - If *V* < *Vbrk* and *V* > *Vstallbrk* then
    - $P = \left[P_o + K_{p2}(Vbrk - V)^{N_{p2}}\right][1 + CmpKpf * \Delta f]$
    - $Q = \left[Q_o + K_{q2}(Vbrk - V)^{N_{q2}}\right][1 + CmpKqf * \Delta f]$
  - If *V* < *Vstallbrk* then
    - $P = Gstall * V^2$
    - $Q = Bstall * V^2$
- Important somewhat arbitrary decision
  - What is *Vstallbrk* ? Must fully document this stuff!

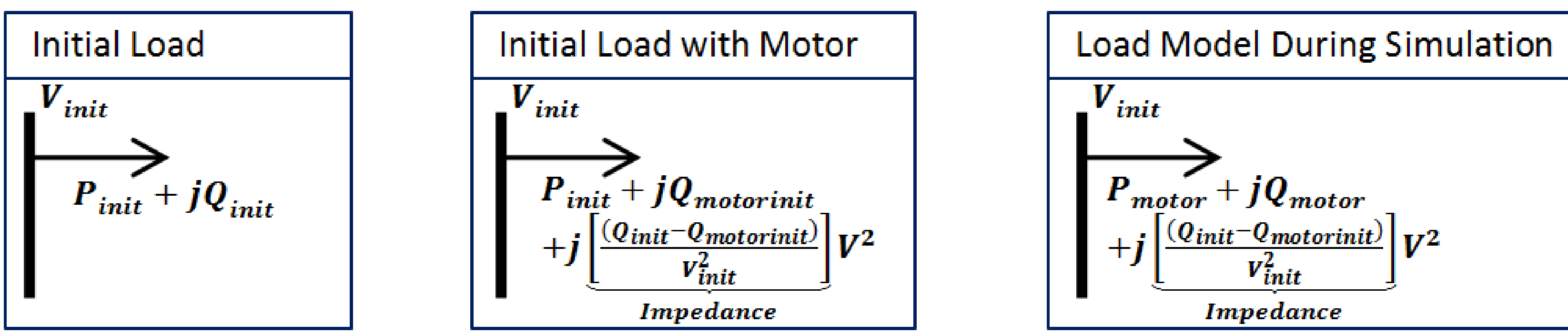
P_o, Q_o, and Vstallbrk



- $P_o = P_{init} - K_{p1}(V_{init} - Vbrk)^{N_{p1}}$
- *Vstallbrk* = intersection of the power stall curve and the power curve defined by Kp2 and Np2.
  - PowerWorld determines this to a tolerance of 0.0001 per unit voltage.
- $Q_o = P_{init}\left(\frac{\sqrt{1 - CompPF^2}}{CompPF}\right) - K_{p1}(1.0 - Vbrk)^{N_{p1}}$
- As long as the motor is not stalled (Below *Vstall* for more than *Tstall* seconds), then the algebraic P and Q values following this yellow highlighted curves

Induction Motor Initialization

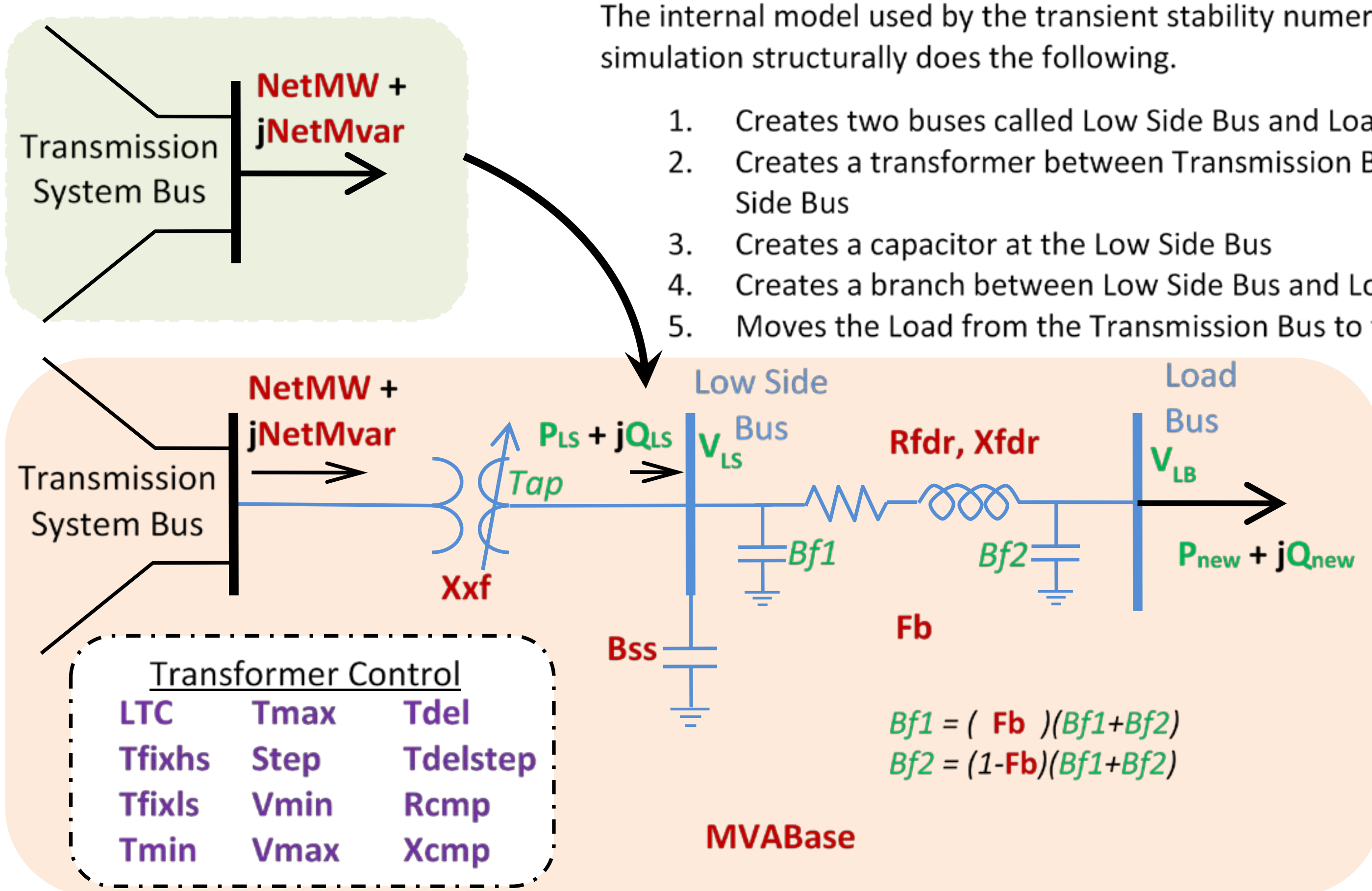
- Mvar of an induction motor at initialization (steady state) is <u>*dependent*</u> on the terminal voltage and MW of the motor.
- There will be a mismatch between
  - Motor Mvar
  - Load Flow Record Initial Mvar
- Handled by including a shunt admittance as part of the load model to match the initial condition
  - These will be called ExtraMvars in this document



Coordinated Initialization with Distribution Equivalent

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



Important: Input Data Validation Check

- The **NetMW** and **NetMvar** of the load can potentially exceed the maximum power transfer of the Distribution Equivalent
  - Calculation of DistEquivMVABase
    - MVABase > 0 means DistEquivMVABase = MVABase
    - MVABase < 0 means DistEquivMVABase = Abs(**NetMW**/MVABase)
    - MVABase = 0 means DistEquivMVABase = **NetMW**/0.8
  - Notice that MVABase is a function of **NetMW** for MVABase <=0
- Problem for loads with extremely poor power factor
  - What if load is 1.2 MW and 30 Mvar? Impedances are based on base proportional to 1.2, but 30 Mvars across this may be too much.
- Software Solution: Add a validation error
  - Check if Estimate of Real Power I^2R losses exceeds the **NetMW**
  - Clearly bad input data if

$$\underbrace{\left[\frac{NetMW^2 + NetMvar^2}{Vpu^2}\right]}_{Current\ Squared} * \underbrace{\left[Rfdr\frac{SystemMVABase}{DistEquivMVABase}\right]}_{R\ on\ system\ MVABase} > NetMW$$

Important: Related Validation Check

- A lot of these weird validation errors actually occur with extremely small loads
  - How about MW = 0.001 and Mvar = 0.020
  - This kind of thing happens a lot when you get a real-time state estimation case → just noise from measurements and the state estimator solution
- PowerWorld Simulator has a hard-coded threshold
  - Any MW Load < 0.001 per unit (0.1 MW for 100 MVABase system) is never modeled with anything but an algebraic load model
  - Silly to model motors this small anyway
  - You will see warning messages inside Simulator indicating this is occurring

Initialization Process

- Goal of Initialization is to calculate Tap, Bf1, Bf2, VLS, PLS, QLS, VLB, Pnew, and Qnew. (Also might change **Bss**, **Rfdr**, and **Xfdr**)
- If you want the same results you need to define the rules precisely
  - It is quite likely that multiple values of Tap will get you inside the **Vmin** and **Vmax** range specified in the distribution equivalent
  - How you split Bf1, Bf2, and **Bss** might change results
  - How to reduce the **Rfdr** and **Xfdr** when the load bus voltage falls below 0.95 matters
- Define "precisely" → means psuedo-code

Initialization Steps 1 – 2: Impedance Base Conversion

- Step 1: Calculation of DistEquivMVABase
  - MVABase > 0 means DistEquivMVABase = MVABase
  - MVABase < 0 means DistEquivMVABase = Abs(**NetMW**/MVABase)
  - MVABase = 0 means DistEquivMVABase = Abs(**NetMW**/0.8)
  - Note: This is a function of NetMW, so that means MW – DistMW of the distributed generation
- Step 2: Impedance parameters are given on this DistEquivMVABase base, so convert them to the SystemMVABase
  - **Xxf** = **Xxf** * *SystemMVABase*/ *DistEquivMVABase*.
    Rfdr = **Rfdr** * *SystemMVABase*/ *DistEquivMVABase*.
    Xfdr = **Xfdr** * *SystemMVABase*/ *DistEquivMVABase*.
    Rcmp = **Rcmp** * *SystemMVABase*/ *DistEquivMVABase*.
    Xcmp = **Xcmp** * *SystemMVABase*/ *DistEquivMVABase*.
    Bss = **Bss** / *SystemMVABase** *DistEquivMVABase*.

Initialization Steps 3 – 4: Transformer Setup

- Step 3: Convert Transformer Tap values and impedances to the SystemMVABase
  - Variable tab is on the low side bus
  - **Xxf** = **Xxf** * (**Tfixhs**)^2
  - **Step** = **Step**/**Tfixhs**
  - **Tmin** = (**Tmin** + **Tfixls** - 1)/**Tfixhs**
  - **Tmax** = (**Tmax** + **Tfixls** - 1)/**Tfixhs**
- Step 4: Set tap ratio (Tap) needed.
  - Sending end flow is Net values so (Load – DistGen)
  - Calculate exact tap ratio needed to give Low Side Bus Voltage of (**Vmin** + **Vmax**)/2 (arbitrary decision)
    - See Section 3.2.1 of companion PDF document for exact equations
  - Round to nearest discrete step and enforce **Tmin** and **Tmax**

There are likely a few Tap values which get you inside Vmin and Vmax

Initialization Steps 5 – 7:

- Step 5: Calculate the Low Side Bus Voltage (VLS) and the Low Side Bus P and Q flow *exactly* (PLS, QLS)
  - See Section 3.2.2 of companion PDF document for exact equations
- Step 6: Initialize Bf1 and Bf2 to zero
- Step 7: If VLS < 0.95 then automatically set **Rfdr** and **Xfdr** to minimum value
  - **Rfdr** = 0.0000001 per unit
  - **Xfdr** = 0.00001 per unit

- This is where things get complicated
  - Calculation Load Bus Voltage (VLB) depends on Bf1
  - As mentioned in induction motor initialization, there are ExtraVars that come from that initialization which depends on VLB
  - The distribution equivalent model specifies that these ExtraVars be split between the from and to end of the feeder according to **Fb** input option
    - *Bf1* = (**Fb**)(*Bf1* + *Bf2*)
    - *Bf2* = (1-**Fb**)(*Bf1* + *Bf2*)
  - But Bf1 is used to calculate VLB

If Fb = 0, things are a LOT easier!

Initialization Steps 8 – 9

- Step 8: Using present values of Bf1 and Bf2, estimate both the Load Bus Voltage (VLB) and the flow reaching the Load Bus (Pnew, Qnew)
  - See Section 3.2.2 of companion PDF document for exact equations
- Step 9: If magnitude of VLB < 0.95 then the feeder impedances are reduced by a factor such that VLB = 0.95 (exactly) and update Pnew, Qnew
  - See Section 3.2.3 of companion PDF document for exact equations

Initialization Steps 10 – 11

- Step 10: Using Values of VLB, Pnew, Qnew initialize the dynamic load characteristic models
  - If Distributed Generation Model is present, then the Load Characteristic Models will use (Pnew + DistMW) and (Qnew + DistMvar)
  - Part of Load Characteristic initialization will result in ExtraMvars
- Step 11: If we have reduced **Rfdr** and **Xfdr** to minimum value already, then Exit Initialization and leave ExtraMvars with Load Bus

Initialization Steps 12
ExtraMvars → Bf1, Bf2

- Step 12: Allocate ExtraMvars to Bf1 and Bf2
  - If (ExtraMvars < 1E-4 per unit) OR (**Fb** < 0.001), then stick them all at the Load Bus
    - *Bf2* = *Bf2* + ExtraMvars/(VLB^2)
    - *ExitShortly* = True
  - Else
    - *Bf1* = *Bf1* + **Fb***ExtraMvars/(VLS^2)
    - *Bf2* = *Bf2* + (1 – **Fb**)*ExtraMvars/(VLB^2)
    - *ExitShortly* = False

Initialization Steps 13: Coordinate Bf1, Bf2 with **Bss**

- Step 13: If *Bf1* and *Bf2* are negative and **Bss** > 0 then reduce **Bss** toward zero to cancel out *Bf1* and *Bf2*.
  - *ExitShortly* = False
  - Bf1var = *Bf1* * VLS ^{2}
  - Bf2var = *Bf2* * VLB ^{2}
  - Bssvar = **Bss** * VLS ^{2}
  - If abs(Bf1var + Bf2Var) > Bssvar then
    - tempVar = BssVar
    - **Bss** = 0

    // Set Bss=0 and reduce magnitude of Bf1 and Bf2
  - If **Fb** = 1 then
    - tempVar = abs(Bf1Var)
    - **Bss** = **Bss** – tempVar / VLS ^{2}

    // Reduce Bss by Bf1Var and reallocate Mvars to *Bf1* and *Bf2*
  - Else
    - tempVar = abs(Bf2var) / (1 – **Fb**)
    - **Bss** = **Bss** – tempVar / VLS ^{2}

    // attempt to push Bf2 toward zero
  - *Bf1* = *Bf1* + **Fb** * tempVar / VLS ^{2}
  - *Bf2* = *Bf2* + (1 – **Fb**) * tempVar / VLS ^{2}

Initialization Steps 14: Finish Off

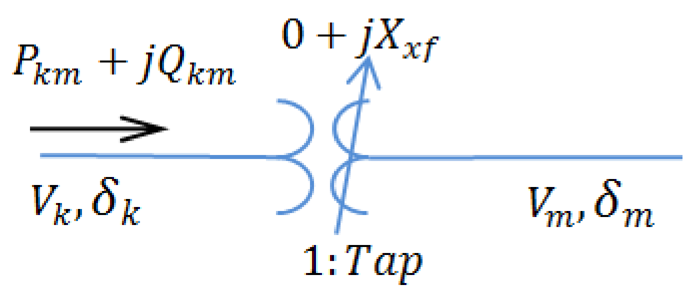
- Step 14:
  - If (ExitShortly) then Exit Initialization
    Else go back to Step 8 and repeat

Summary

- Transparency of stability models is vital if you want to share models
  - Need good documentation
  - Often need some psuedo-code as block diagrams aren't enough
    - Various ways to implement non-windup PI limits
    - Algebraic models get weird (Bf1, Bf2, **Bss** coordination of distribution equivalent)
    - Calculation of *Vstallbrk* on LD1PAC
- Good examples of how to share model specifications
  - H6B governor model from John Undrill and implemented in PSLF https://www.wecc.biz/Reliability/H6b-Governor-Model-Specification.pdf
    - I implemented this in PowerWorld Simulator in February 2014 very quickly because documentation was excellent
    - Psuedo-code was important because of unique non-windup PI limit
  - Colstrip Acceleration Trend Relay from Jamie Weber implemented in PowerWorld Simulator http://www.powerworld.com/WebHelp/Content/TransientModels_PDF/Generator/Others/Relay%20Model%20ATRRELAY.pdf
  - Generic Wind and Solar Models
    - However, input units on which MVABase is still not clear on a few of these models…
    - Psuedo-code would have made that more clear

Tap Calculation Equation (Section 3.2.1 of PDF)

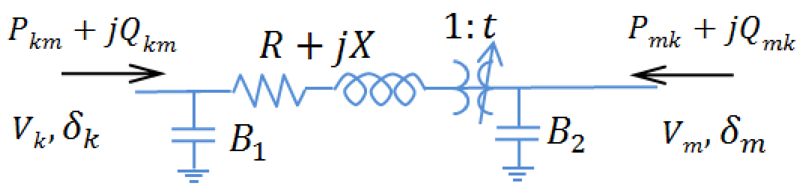
- Initial condition and the input parameters $P_{km}, Q_{km}, V_k,$ and X_{xf}.



- We use $V_m = \frac{V_{min}+V_{max}}{2}$
- PDF document shows derivation of required Tap.
- $Tap = \sqrt{\frac{(V_k V_m)^2}{(Q_{km}X_{xf} - V_k^2)^2 + (X_{xf}P_{km})^2}}$

Calculation of Far Bus Complex Voltage and PQ Flows (Section 3.2.2)

- General Network as Follows



$$g_{kk} = \frac{R}{(R^2+X^2)} \qquad b_{kk} = \frac{-X}{(R^2+X^2)} + B_1 \qquad g_{km} = g_{mk} = \frac{-R}{(R^2+X^2)t}$$

$$g_{mm} = \frac{R}{(R^2+X^2)t^2} \qquad b_{mm} = \frac{-X}{(R^2+X^2)t^2} + B_2 \qquad b_{km} = b_{mk} = \frac{X}{(R^2+X^2)t}$$

- Calculate Complex Vm

$$\begin{bmatrix} e_k g_{km} + f_k b_{km} & | & -e_k b_{km} + f_k g_{km} \\ f_k g_{km} - e_k b_{km} & | & -f_k b_{km} - e_k g_{km} \end{bmatrix} \begin{bmatrix} e_m \\ f_m \end{bmatrix} = \begin{bmatrix} P_{km} - e_k^2 g_{kk} - f_k^2 g_{kk} \\ Q_{km} + f_k^2 b_{kk} + e_k^2 b_{kk} \end{bmatrix}$$

- Calculate far end flows

$$P_{mk} = +e_m^2 g_{mm} + e_m e_k g_{mk} - e_m f_k b_{mk} + f_m^2 g_{mm} + f_m f_k g_{mk} + f_m e_k b_{mk}$$
$$Q_{mk} = -f_{km}^2 b_{mm} + f_m e_k g_{mk} - f_m f_k b_{mk} - e_m^2 b_{mm} - e_m f_k g_{mk} - e_m e_k b_{mk}$$

Section 3.2.2 Admittance Values Transformer and Feeder Branch

For our Transformer branch the admittance parameters are as follows.

$$g_{kk} = 0 \qquad b_{kk} = -\frac{1}{X_{xf}} \qquad g_{km} = g_{mk} = 0$$

$$g_{mm} = 0 \qquad b_{mm} = -\frac{1}{X_{xf}Tap^2} \qquad b_{km} = b_{mk} = \frac{1}{X_{xf}Tap}$$

For our Feeder branch the admittance parameters are as follows.

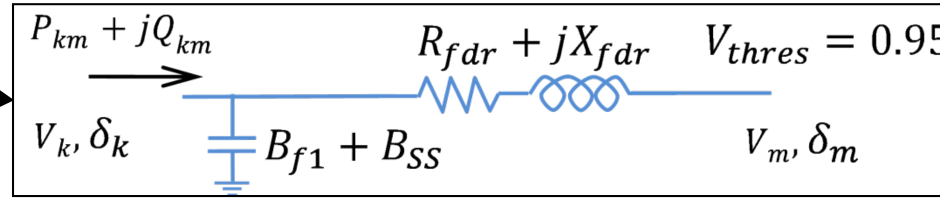
(Note: the capacitors are lumped into the feeder admittances for calculation purposes here.)

$$g_{kk} = \frac{R_{dfr}}{R_{fdr}^2 + X_{fdr}^2} \qquad b_{kk} = \frac{-X_{dfr}}{R_{fdr}^2 + X_{fdr}^2} + B_{f1} + B_{ss} \qquad g_{km} = g_{mk} = \frac{-R_{dfr}}{R_{fdr}^2 + X_{fdr}^2}$$

$$g_{mm} = \frac{R_{dfr}}{R_{fdr}^2 + X_{fdr}^2} \qquad b_{mm} = \frac{-X_{dfr}}{R_{fdr}^2 + X_{fdr}^2} + B_{f2} \qquad b_{km} = b_{mk} = \frac{X_{dfr}}{R_{fdr}^2 + X_{fdr}^2}$$

Calculation of Far Bus Values with a Voltage Constraint

- Feeder Network at this point is



- Group the Bss and Bf1 terms in Q flow and define

$$g_{kk} = \frac{R_{dfr}}{R_{fdr}^2 + X_{fdr}^2} \qquad b_{kk} = \frac{-X_{dfr}}{R_{fdr}^2 + X_{fdr}^2}$$

$$g_{km} = \frac{-R_{dfr}}{R_{fdr}^2 + X_{fdr}^2} \qquad b_{km} = \frac{X_{dfr}}{R_{fdr}^2 + X_{fdr}^2}$$

- The solve following three nonlinear equations using Newton's method

$$P_{km} - MULT \begin{pmatrix} +e_k^2 g_{kk} + e_k e_m g_{km} - e_k f_m b_{km} \\ +f_k^2 g_{kk} + f_k f_m g_{km} + f_k e_m b_{km} \end{pmatrix} = 0$$

$$[Q_{km} + (B_{SS} + B_{f1})V_k^2] - MULT \begin{pmatrix} -f_k^2 b_{kk} + f_k e_m g_{km} - f_k f_m b_{km} \\ -e_k^2 b_{kk} - e_k f_m g_{km} - e_k e_m b_{km} \end{pmatrix} = 0$$

$$e_m^2 + f_m^2 - V_{thres}^2 = 0$$

- Convergence Tolerance of
  - P and Q equation 1E-5
  - Voltage equation 1E-8
- Jacobian Matrix

$$\begin{bmatrix} -MULT\begin{pmatrix} e_k g_{km} \\ +f_k b_{km} \end{pmatrix} & -MULT\begin{pmatrix} -e_k b_{km} \\ +f_k g_{km} \end{pmatrix} & -\begin{pmatrix} +e_k^2 g_{kk} + e_k e_m g_{km} - e_k f_m b_{km} \\ +f_k^2 g_{kk} + f_k f_m g_{km} + f_k e_m b_{km} \end{pmatrix} \\ -MULT\begin{pmatrix} f_k g_{km} \\ -e_k b_{km} \end{pmatrix} & -MULT\begin{pmatrix} -f_k b_{km} \\ -e g_{km} \end{pmatrix} & -\begin{pmatrix} -f_k^2 b_{kk} + f_k e_m g_{km} - f_k f_m b_{km} \\ -e_k^2 b_{kk} - e_k f_m g_{km} - e_k e_m b_{km} \end{pmatrix} \\ 2e_m & 2f_m & 0 \end{bmatrix}$$