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Experience With A/C Stalling Behavior and Modeling it for Power System Studies

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BACKGROUND

- APS and SCE have had slow voltage recovery events
- This was attributed to a/c motor stalling
- EPRI Performed work for both utilities to model the phenomenon
- The objectives were to:
  - Test actual air-conditioning (a/c) units
  - Identify the physical behavior of these units
  - Use this information to develop a model
  - Test/Validate the approach against measured system events (simulate in GE PSLF™)

TESTING A/C UNITS IN THE LAB

- A survey was conducted of the typical types and sizes of a/c units in the South West
- 12 units were purchased from manufacturers
- A test plan was developed in collaboration with SCE
- SCE and BPA separately performed similar tests on multiple other units – the results from test by all three entities were quite similar

KEY FINDINGS OF LAB TESTS

- Main load (> 80%) is the a/c compressor motor
- Motor has a very light inertia (~0.03 kWs/kVA)
- Unit stalls in 3 cycles or less
- Stall voltage = 55 to 66%, depends on unit and outdoor temperature
- Motor contactor opens at = 40 to 55% voltage – independent of temperature, dependent on unit
- Single-Phase Motors
- Once voltage recovers, the contactor closes back in and the unit may then stall

KEY FINDINGS OF LAB TESTS

- All units have Thermal Overload (TOL) protection
- TOL operated between 2 to 20 seconds, depending on system voltage
- This is an I^2t phenomenon so the higher the voltage, the higher the current draw and the quicker the TOL operates
- When the unit stalls it draws as much as five times its steady-state current (real and reactive)
- Reciprocating compressors, once stalled they trip on TOL
- Scroll compressors can recover from stalling, without tripping on TOL, if the voltage recovers fast enough

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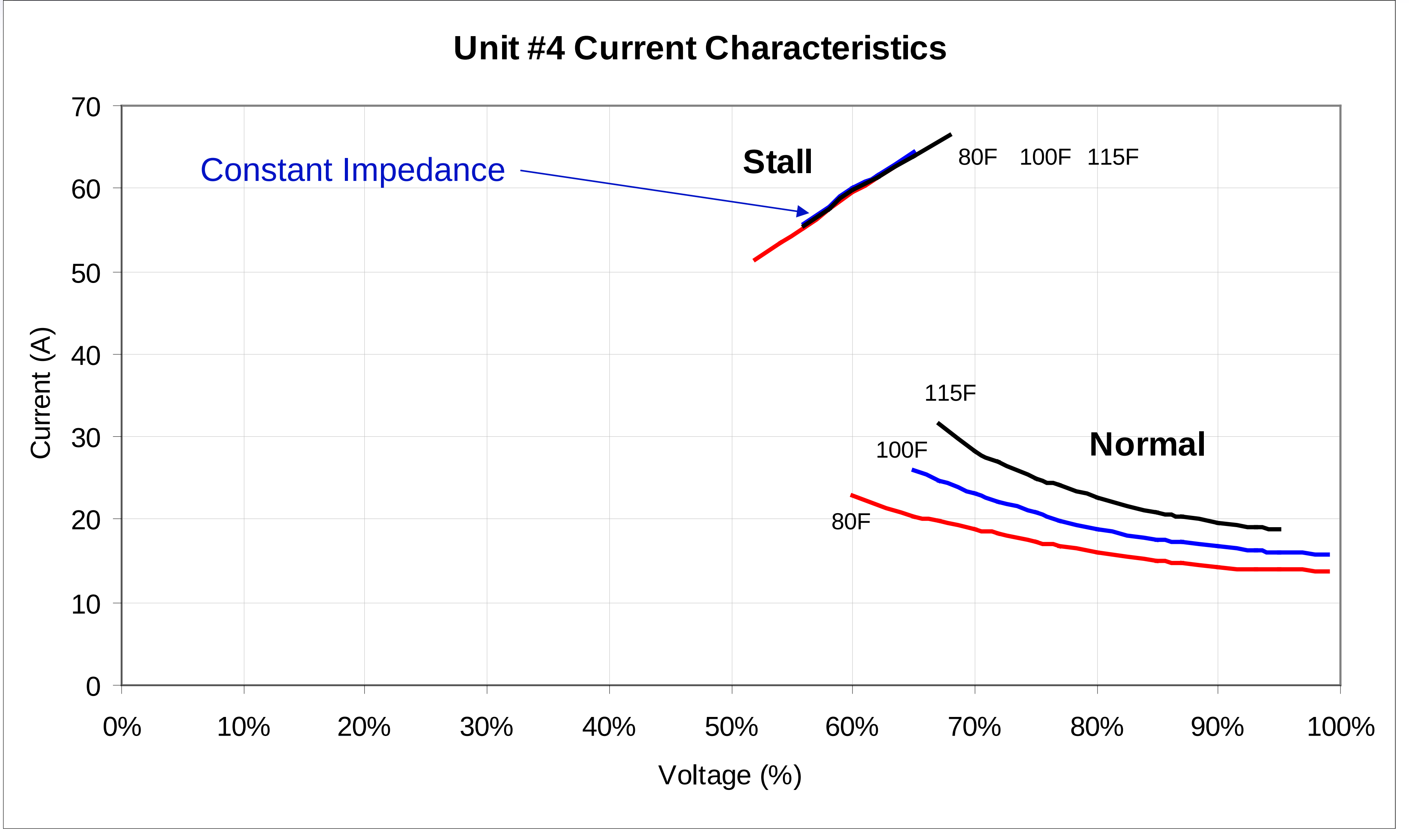
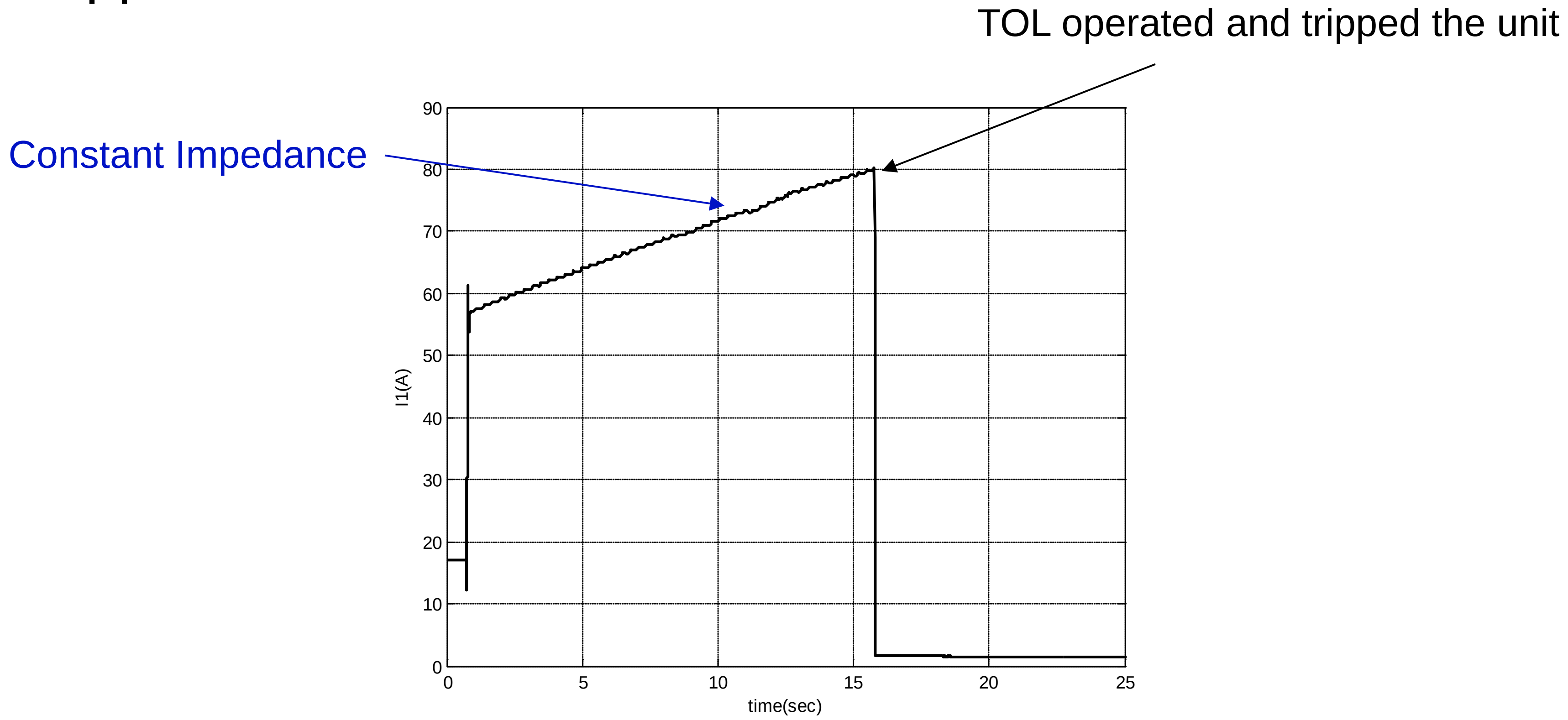
Current Characteristics of a Typical A/C Unit



Behavior of a Reciprocating Compressor Unit

- Example response of a reciprocating unit to delayed voltage recovery – stalled; TOL protection operated and tripped the unit



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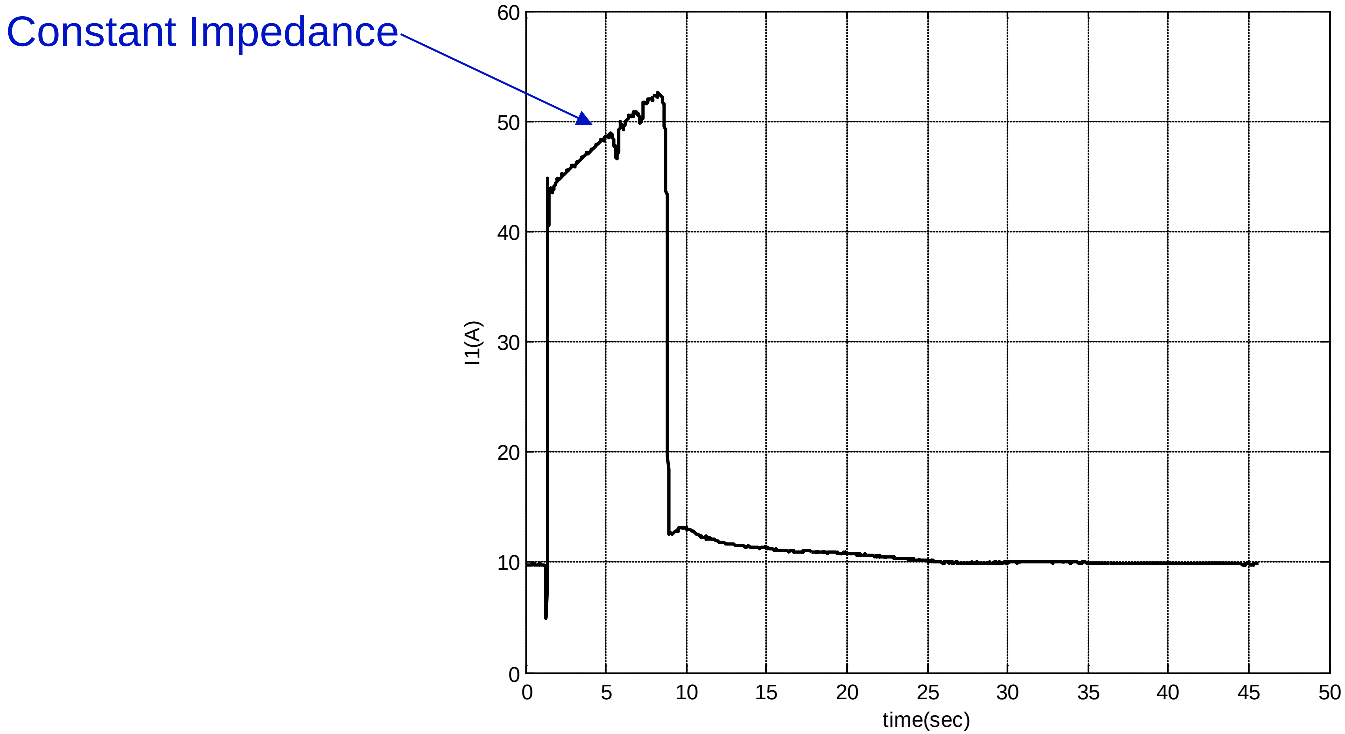
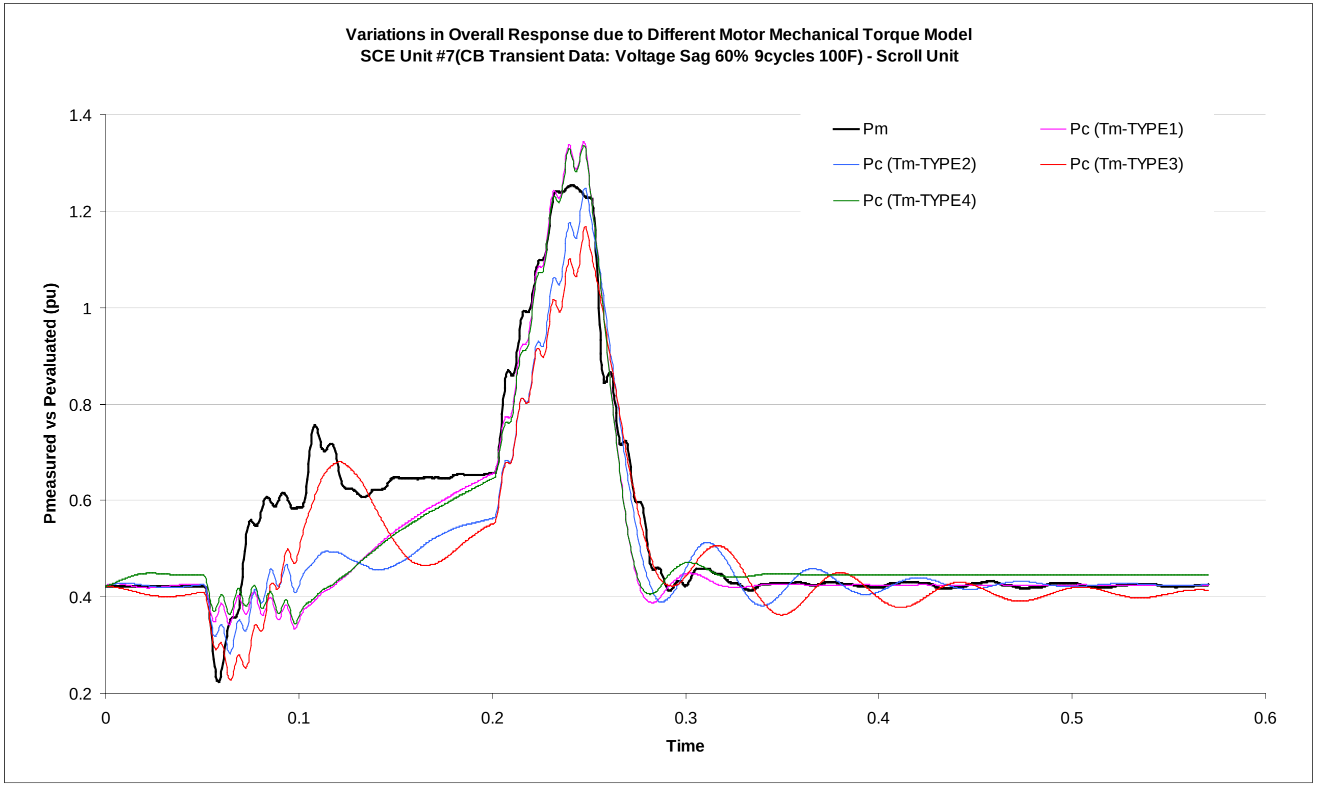
Behavior of a Scroll Compressor Unit

- Example response of a scroll unit to delayed voltage recovery – stalled but recovered once voltage recovered.

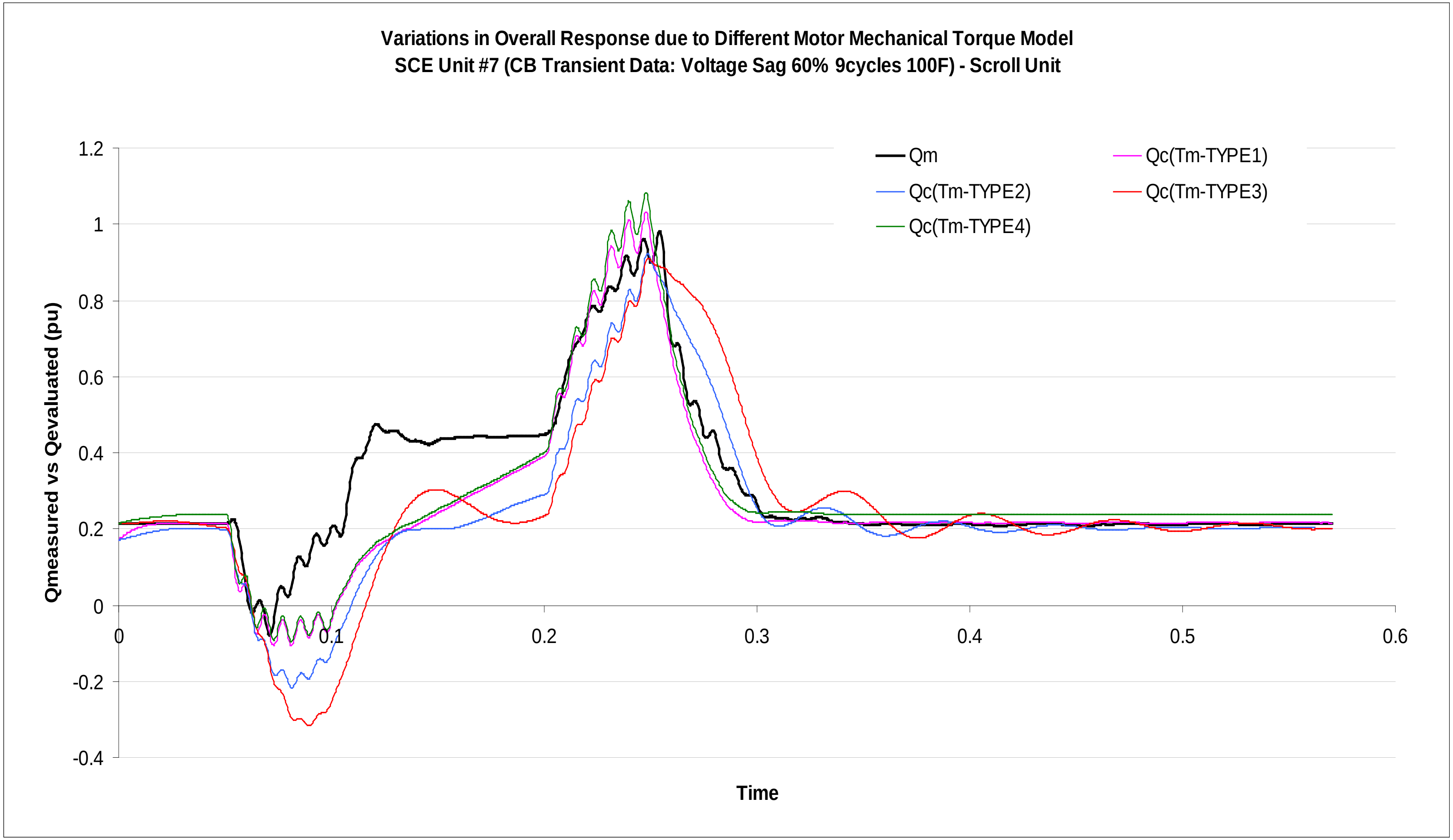


MODELING THE A/C UNIT (NORMAL CONDITION)

- Under normal (not stalled) operation a/c compressor may be reasonably represented as a standard 3-phase positive sequence induction motor model
- Graph shows the fit for various mechanical torque models for a normal circuit breaker clearing transient (measured is black curve – real power is shown)



MODELING THE A/C UNIT (NORMAL CONDITION) – REACTIVE POWER



MODELING THE A/C UNIT - INERTIA

Full-Load Running Speed (RPM)	Motor Rotor Mass (kg)	Watts	Width (inches)	Weight (lb)	Height (inches)	Rotor Radius (cm)	H (Ws/VA)
3500	3.67	1780	9.567	66	15.6	3.20	0.08
3500	3.67	2230	9.567	67	15.6	3.20	0.06
3500	3.67	2520	9.567	48.6	15.6	3.20	0.05
3500	3.80	3620	9.567	69	16.14	3.20	0.04
3500	4.30	5050	9.71	90	17.75	3.25	0.03
3500	8.66	9750	11.69	200	24.65	3.91	0.05
3500	8.97	8300	11.69	200	24.65	3.91	0.06
3500	3.67	1130	9.567	66	15.6	3.20	0.12
3500	3.67	1410	9.567	67	15.6	3.20	0.09
3500	3.67	1670	9.567	48.6	15.6	3.20	0.08
3500	3.80	2410	9.567	69	16.14	3.20	0.06
3500	4.30	3520	9.71	90	17.75	3.25	0.05
3500	8.66	6800	11.69	200	24.65	3.91	0.07
3500	8.66	5850	11.69	200	24.65	3.91	0.08
3500	3.59	1100	9.565	66	15.275	3.20	0.12
3500	3.59	1660	9.565	66	15.275	3.20	0.08
3500	3.98	2250	9.565	66	16.93	3.20	0.06
3500	3.29	800	9.3	43.6	14.82	3.11	0.14

Rough estimates:

Manufacturers Could Really Help Us to Better Understand Inertia

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HYBRID MODEL FOR POWER SYSTEM SIMULATIONS

- The modeling approach is based on a hybrid approach (similar to [1] but fully automated)
  - Assume that the positive sequence 3-phase IM model is adequate for capturing the single-phase compressor IM for normal operation (i.e. not stalled)
  - Use a constant impedance model to represent the stall condition

[1] G. L. Chinn, "Modeling Stalled Induction Motors", IEEE T&D Conference, May 2006.

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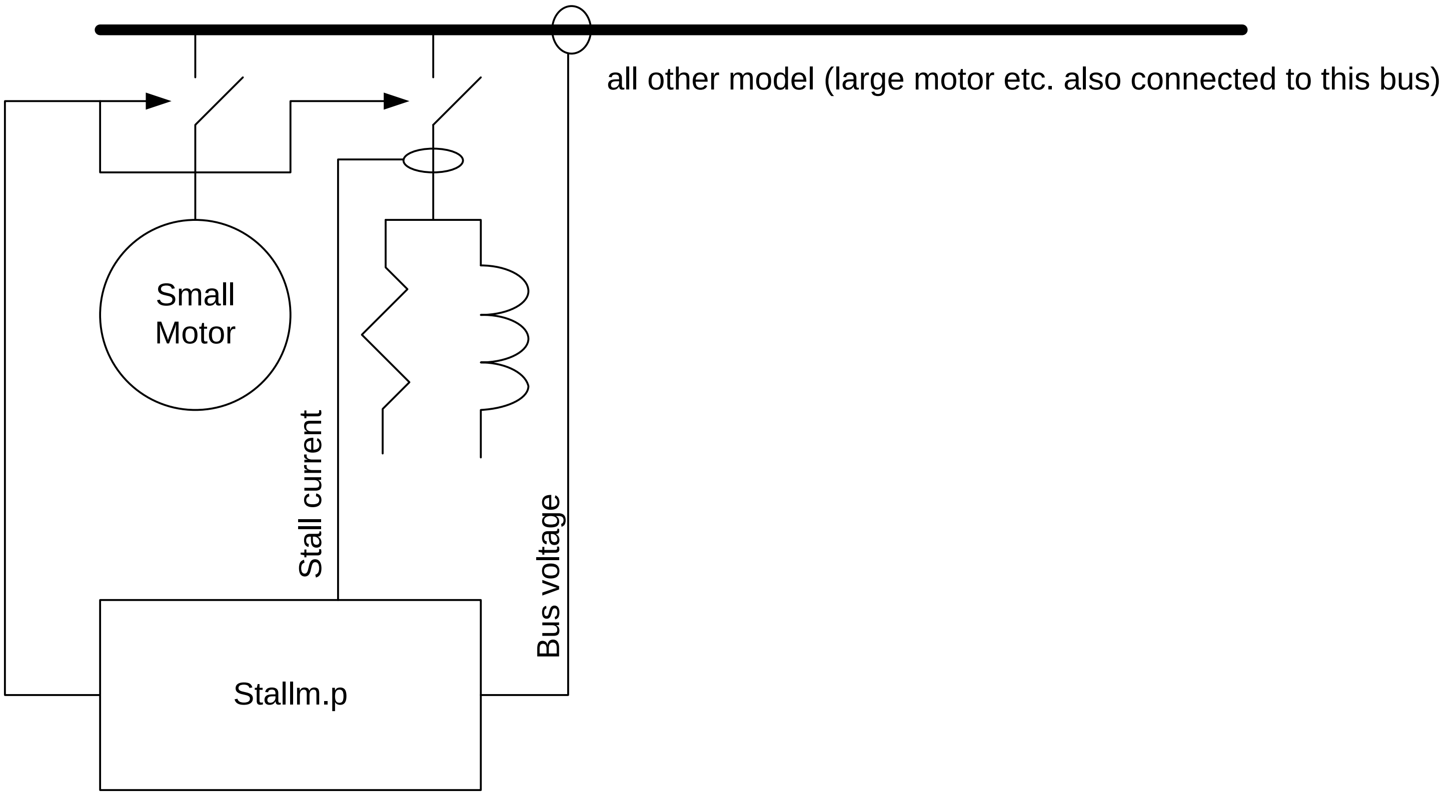
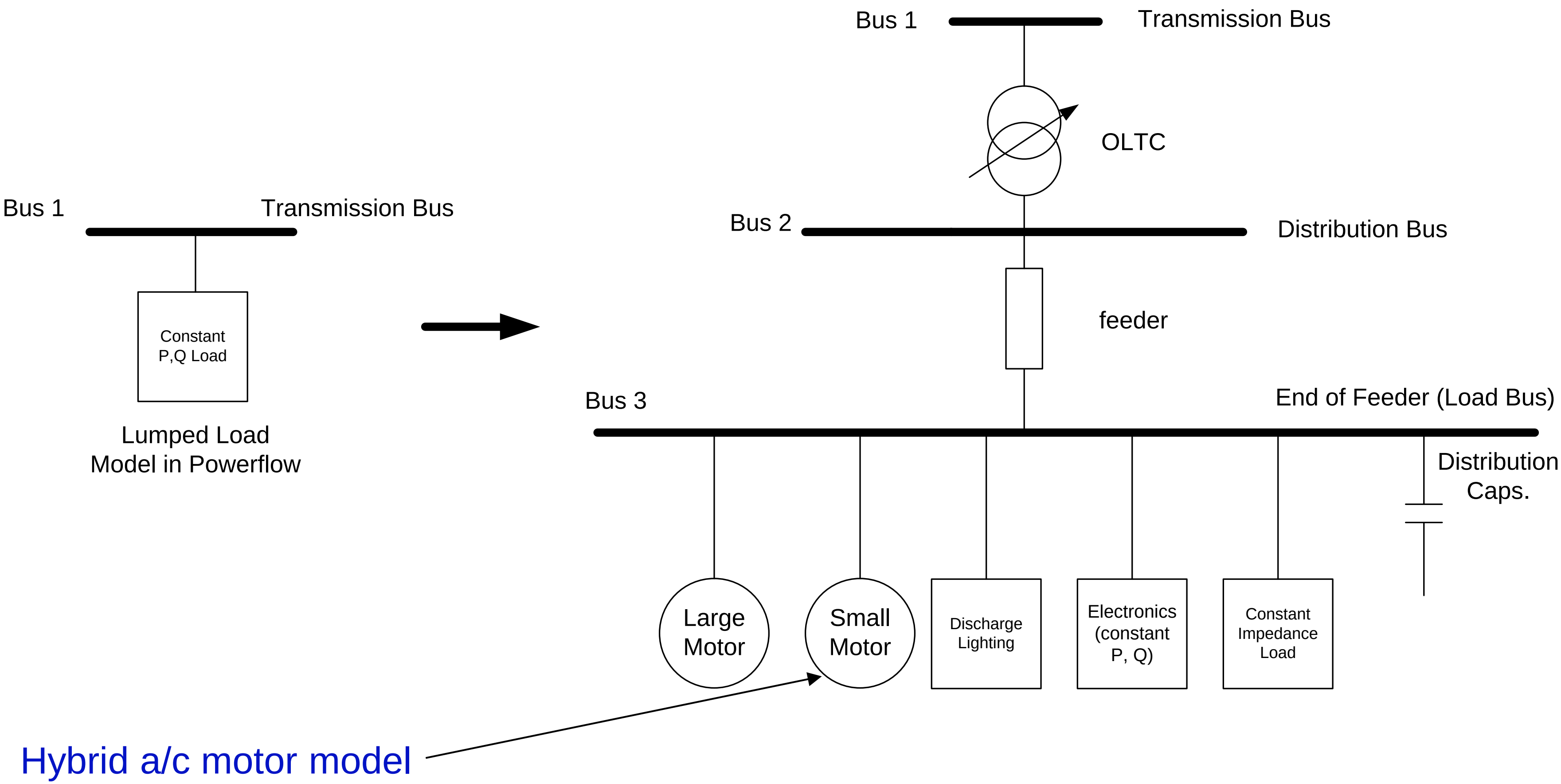
HYBRID-MODEL

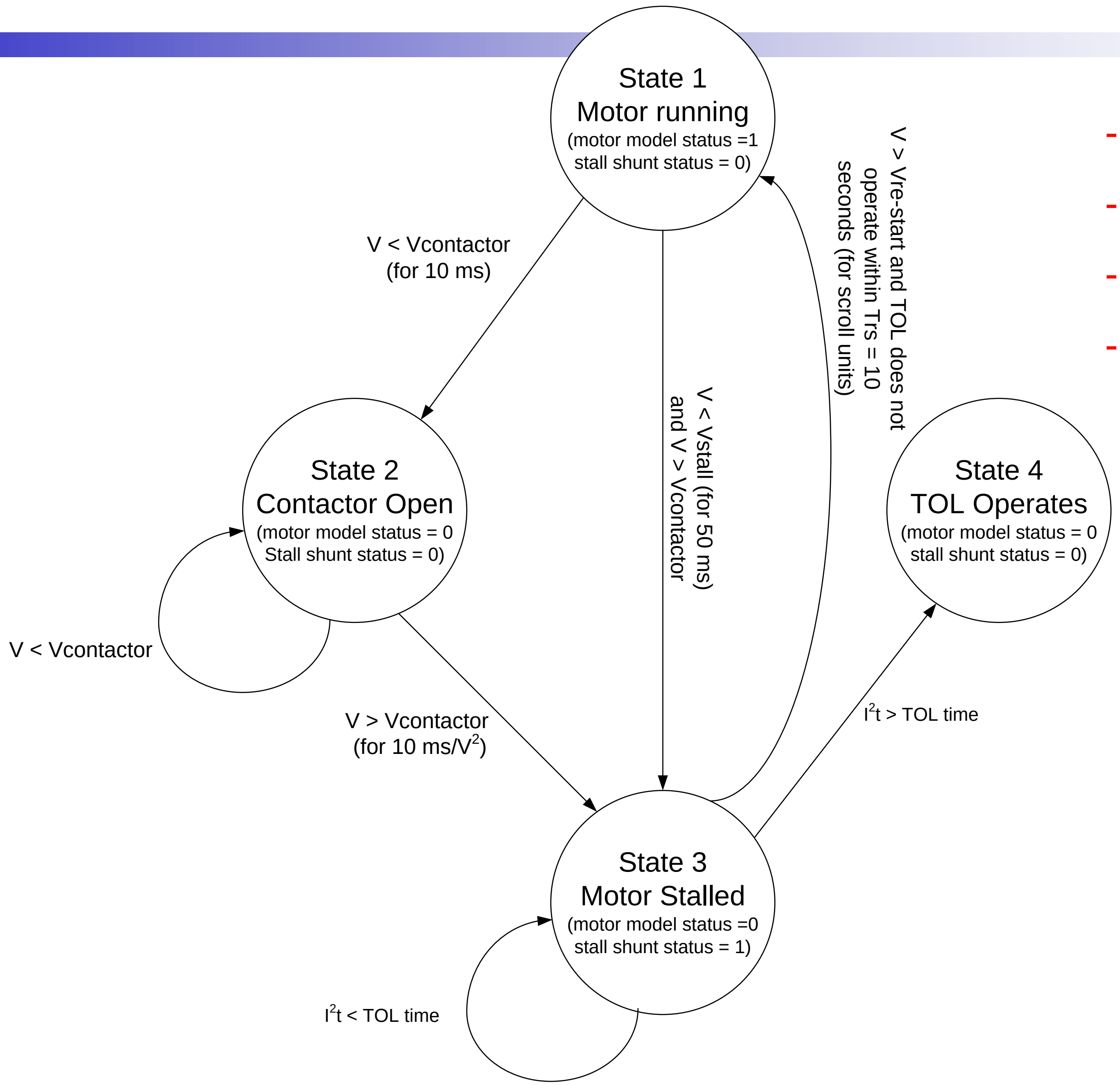


COMPOSITE MODEL STRUCTURE

- Convert all loads through an automated user-written *EPCL*

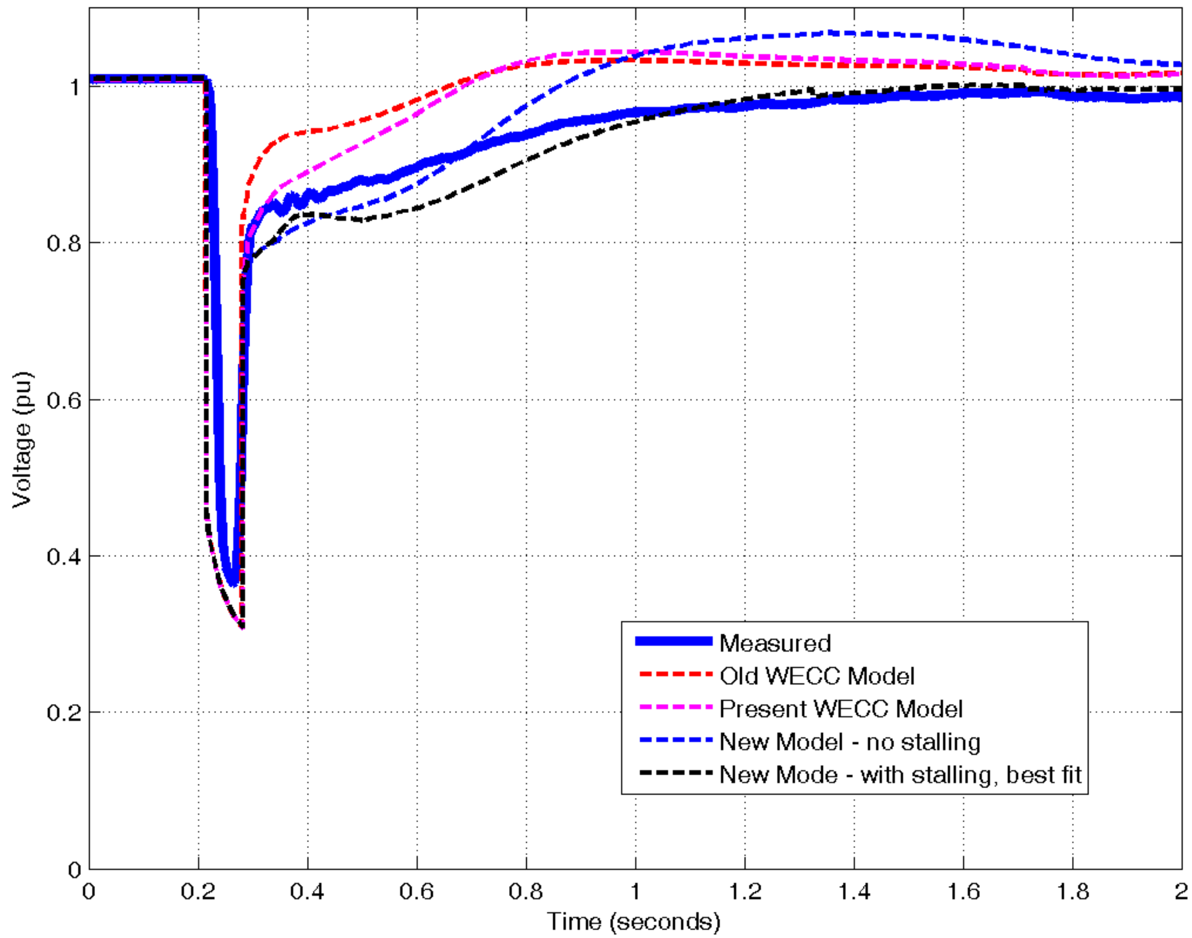


STATE TRANSITION DIAGRAM FOR HYBRID MODEL



- Motor
- Stalling
- Contactor
- TOL (I-squared t)

APS EVENT – Hassayampa, 28th July, 2003



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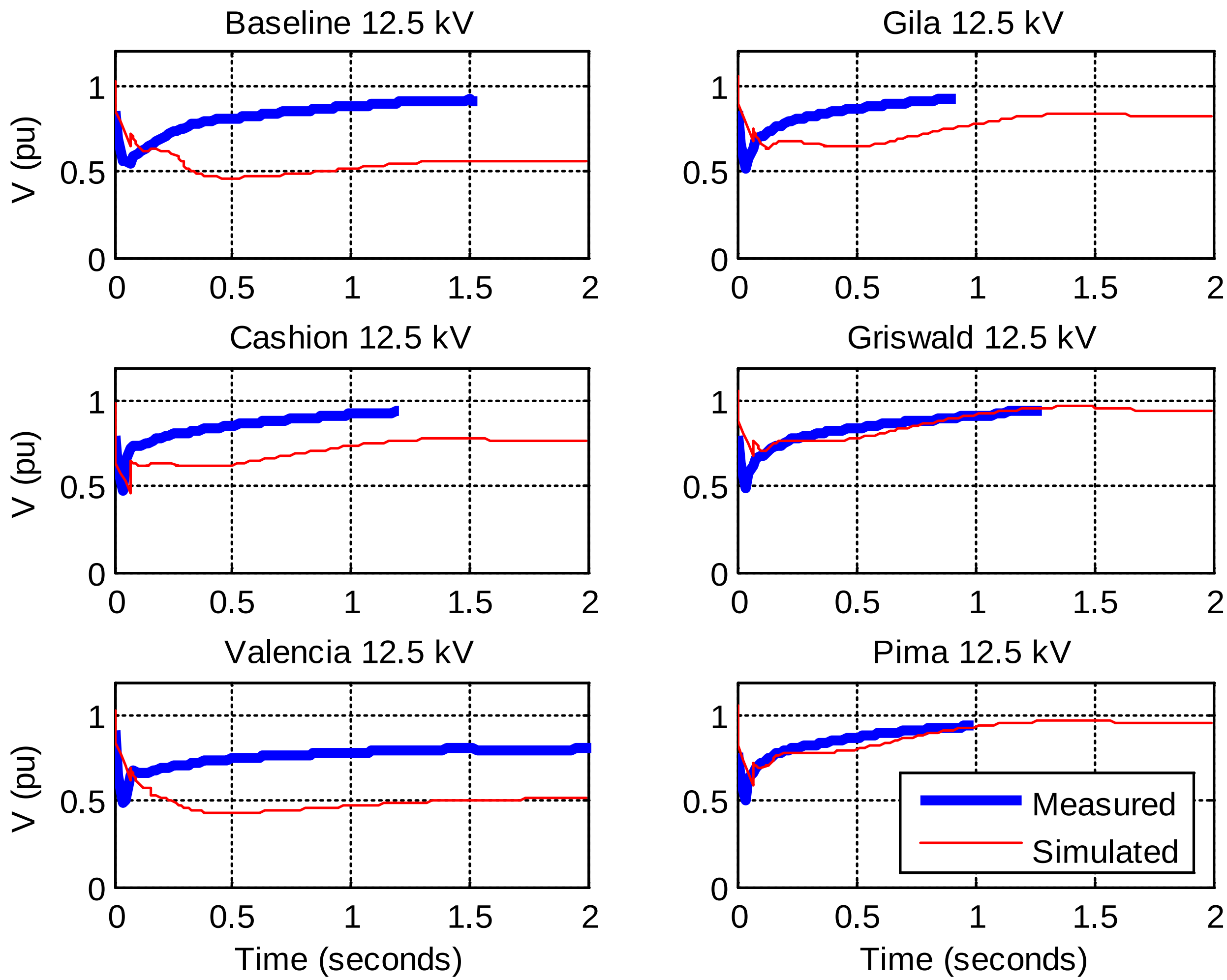
APS EVENT – Feeder Voltages



APS EVENT – System Response

- Over a 20 second period roughly 400 to 600 MW of air-conditioning loads tripped.
- The I^2t TOL results in this behavior
- They started tripping at around 2.6 seconds and stopped tripping at around 29 seconds.
- This is quite indicative of actual system behavior.
- The trace of recorded APS load shows a dip of roughly 500 MW in the first minute following the disturbance.

APS EVENT – Sensitivity Analysis

- A large number of sensitivity runs were performed
- The intent was to show the relative sensitivity of results to load model parameters
- In order of most sensitive to least sensitive:
  - Load composition (% motor, % of static loads)
  - V-stall of stalling motor
  - H of stalling motor
  - Load torque of motors
  - All others (feeder impedance, machine electrical parameters etc.) – much less sensitive
- Most of the stalling happened after the fault cleared

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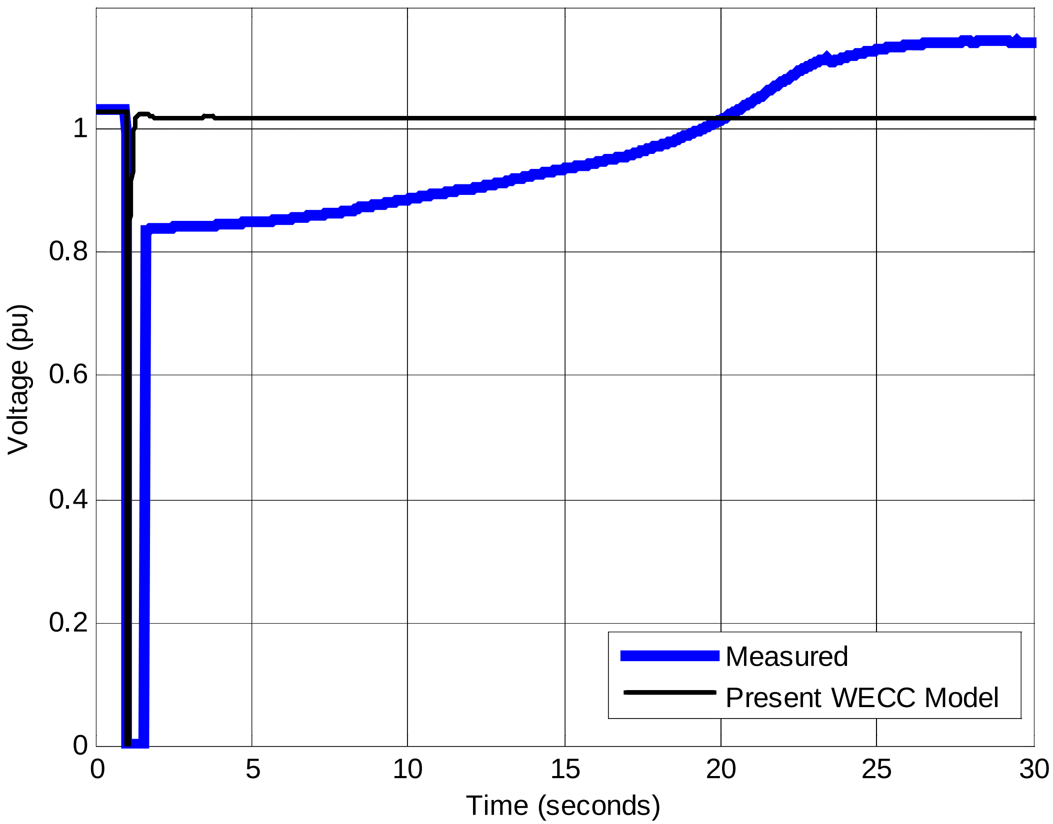
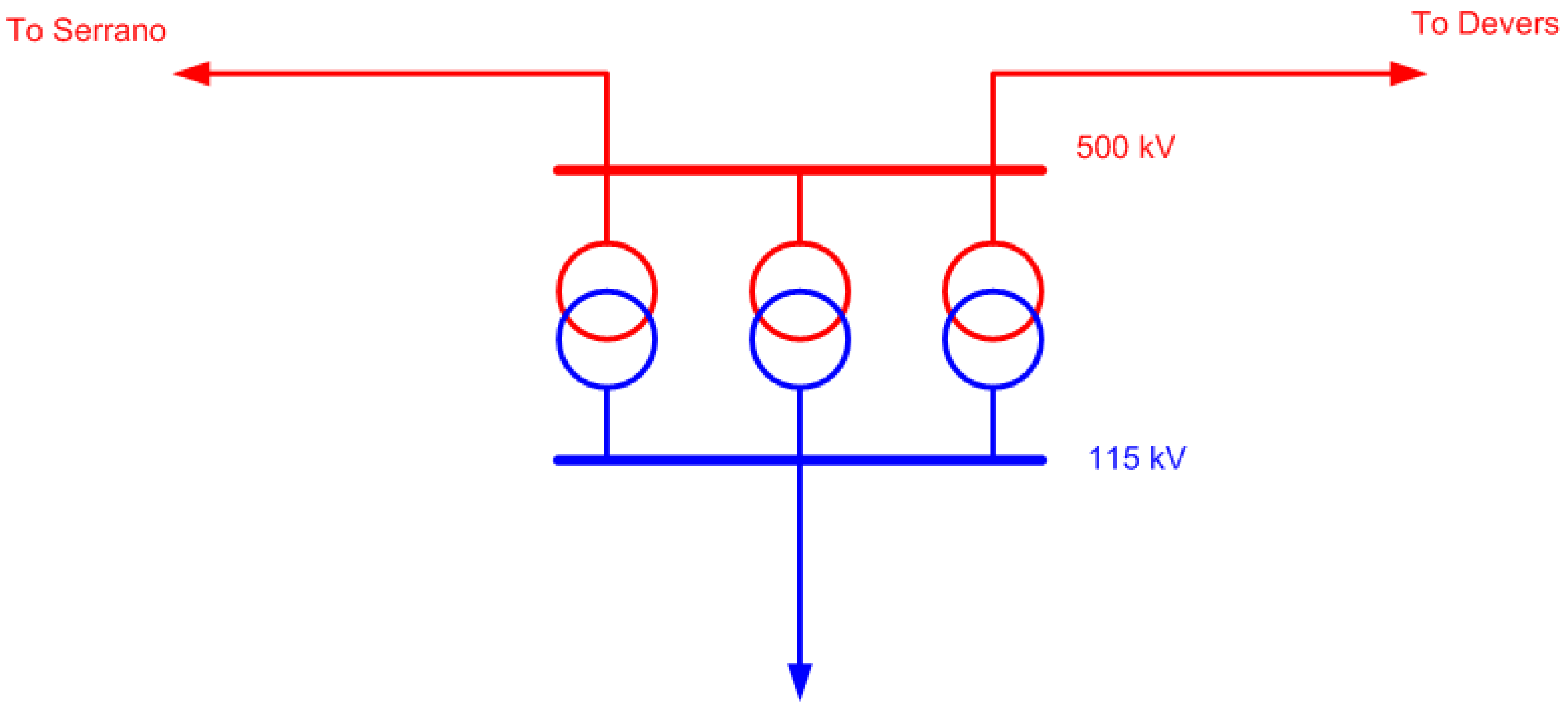
SCE EVENT – Valley, July 2006



SCE EVENT – The Challenge With Modeling

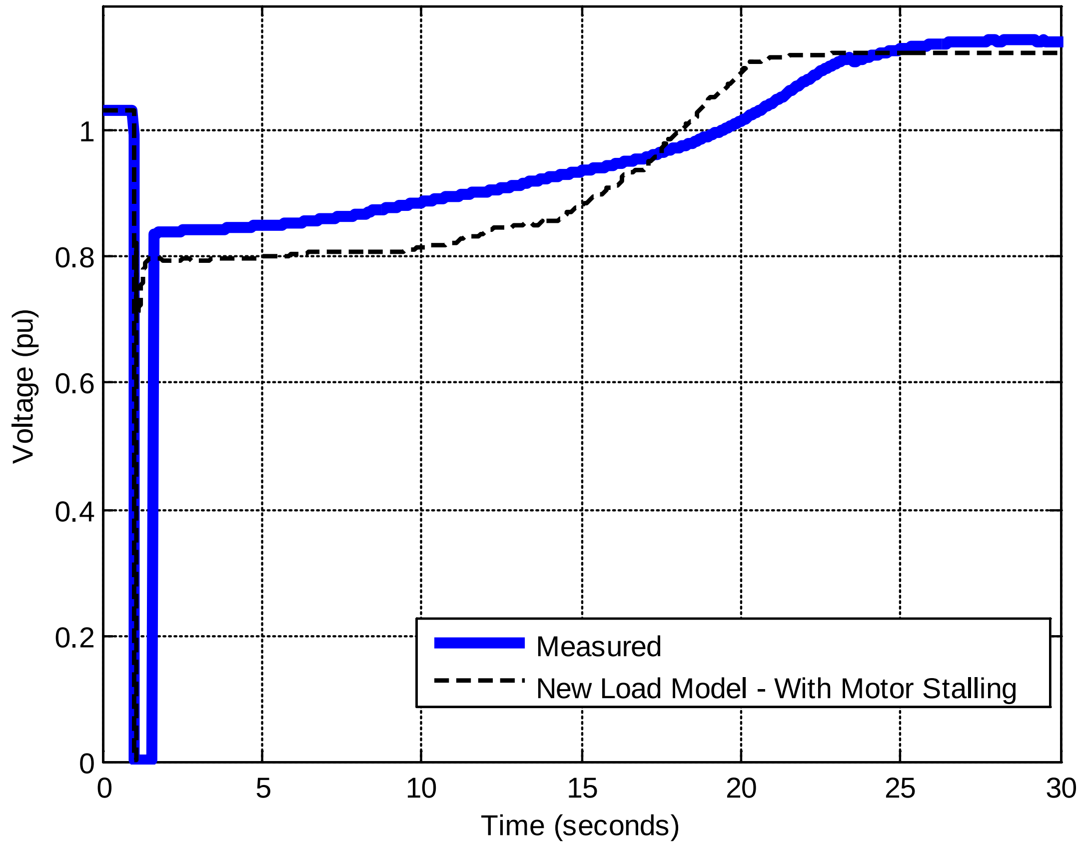
- Large, radial fed, load with no source near the load



SCE EVENT – Modeling

- In original model – single lumped load
- Split it into tens of smaller portions
- Vary feeder impedance between maximum to minimum value
- Details of distribution network not readily available – to emulate variations in TOL pickup and voltage recovery, set TOL time based on normal random distribution with 4 second standard deviation

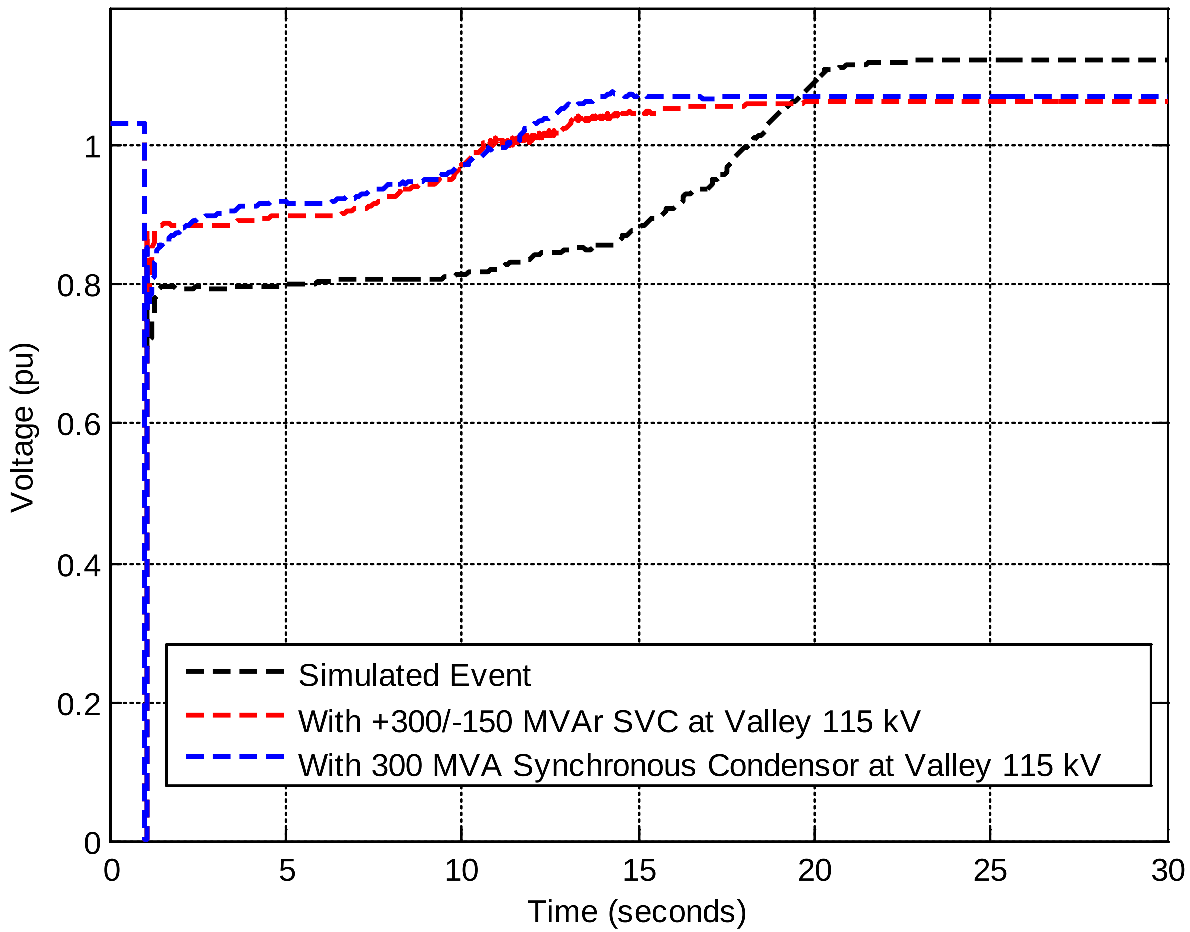
SCE EVENT – Valley, July 2006



SCE EVENT - Sensitivity

- Load composition - % motor load
- Variations in inertia of the a/c load not as important
  - Units light enough that they stall quickly
- Because the load is served radially and there are no short circuit sources (generation) below the 115 kV level, thus when we have a fault, if the voltage falls low enough, all a/c units stall.
- The response is really governed by:
  - the nature of the remaining connected load,
  - the effective impedance from the source to the load,
  - the thermal overload tripping time, and
  - the effective stall impedance (motor current draw).
- MOTORS STALL DURING THE FAULT - The stall voltage is a key factor

CURSORY LOOK AT TRANSMISSION SOLUTIONS



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THE ISSUES

- What can you do about it now?
- What should we be doing?
  - Minimize risk of cascading
  - This requires boosting voltage on transmission as quickly and as much as possible
- Cannot stop all the stalling – it happens too fast
- Can reduce stalling:
  - Faster clearing of faults (where practical)
  - Increasing system short circuit (where practical)
- Fixes at the a/c units themselves may take years to impact a critical mass → Transmission solutions are needed

SOLUTIONS MOVING FORWARD

- Put sources closer to the load
- Put protection on the a/c units – might lead to overvoltage due to large blocks tripping
- Internationals (e.g. Japan) have full-converter drives on a/c units → shutdown at low voltage and smooth start; much more expensive.
- Put smoothly controlled reactive compensation at the transmission bus:
  - Reduces risk of cascading
  - Controls under- and over-voltage
- Reduce impedance between source and load (build more lines or series compensation)
- Really need combination transmission and load side solutions

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CONCLUSIONS

- We can reasonably replicate the system behavior with new models
- The results are highly sensitive to:
  - The amount of motor load and other static load components
  - The stall voltage of motors (voltage below which air-conditioner motors stall)
  - The effective inertia of motors
  - The characteristics of the mechanical load on the motors
  - The stall impedance
- One focus from this point on should be on <u>Sensitivity Analysis</u> with credible bounds
- <u>Solutions</u> likely need to be pursued both <u>at the system and component level</u>