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NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

A Look into Load Modeling: The Composite Load Model

Dynamic Load Modeling & FIDVR Workshop

September 30, 2015

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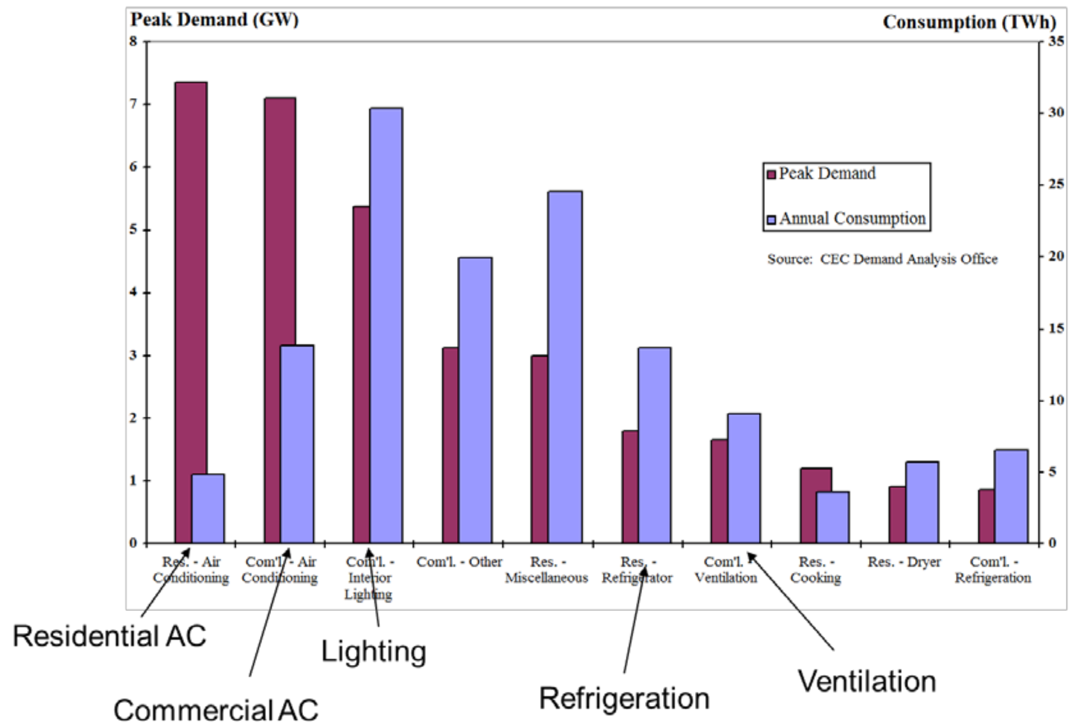
RELIABILITY | ACCOUNTABILITY




Let's Talk Loads

- Landscape
- Brief History
- Today's State of the Art
- Putting Context to the Comp Load Model
- A Look at Some Key Parameters
- Where We Are & Where We're Going

Summer peak vs. annual consumption in California



Our System Load

Resistive Cooking
Resistive Heating

Incandescent Lighting

Power Electronics

Distributed Generation

AC and Heat Pumps

Data Centers

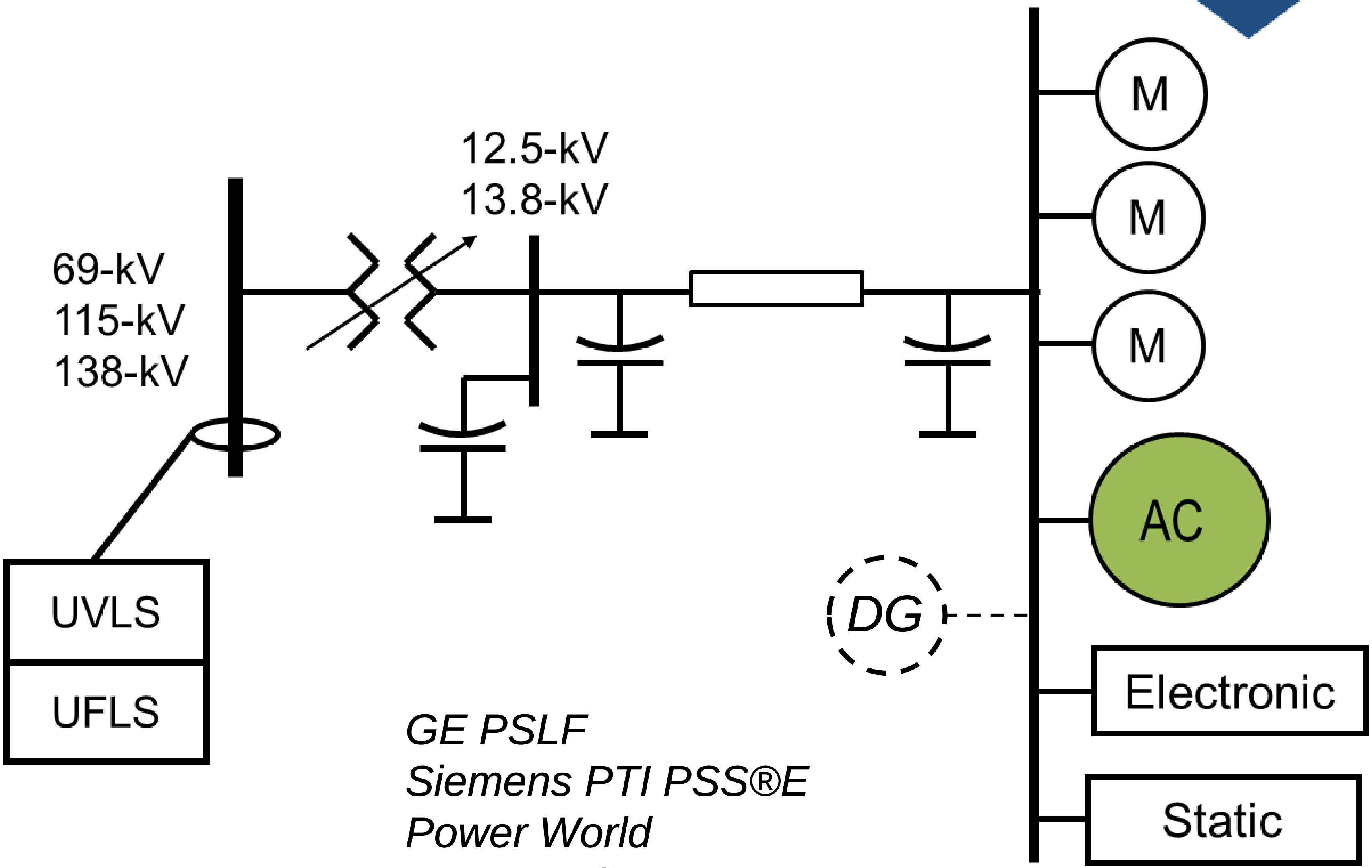
Electric Vehicles

Share of total system load

PTI PSS®E & GE PSLF Load Models

PSS®E Load Models	PSLF Load Models
CIM5 – Induction Motor Load	alwscc (b,w,z) – Load Voltage/Frequency Dependence Model
CIM6 – Induction Motor Load (WECC)	seccld1 (2,3) – Secondary Load Model with Tap Ration Reset
CIMW – Induction Motor Load	apfl (spfl) – Pump/Fan Driven Induction (Synchronous) Motor Load
CLOD – Complex Load Model	motorw/x – Single or Double Cage Induction Motor Model
EXTL – Extended-Term Reset Load	Ld1pac – Performance-based Model of Single Phase Air Conditioner
IEEL – IEEE Load Model	motorc – Phasor Model of Single Phase Air Conditioner
LDFR – Load Frequency Model	ldelec (rect) – Electronic (Rectifier) Load
ACMT – Single-Phase Air Conditioner	

The CMLD (CMPLDW) Model



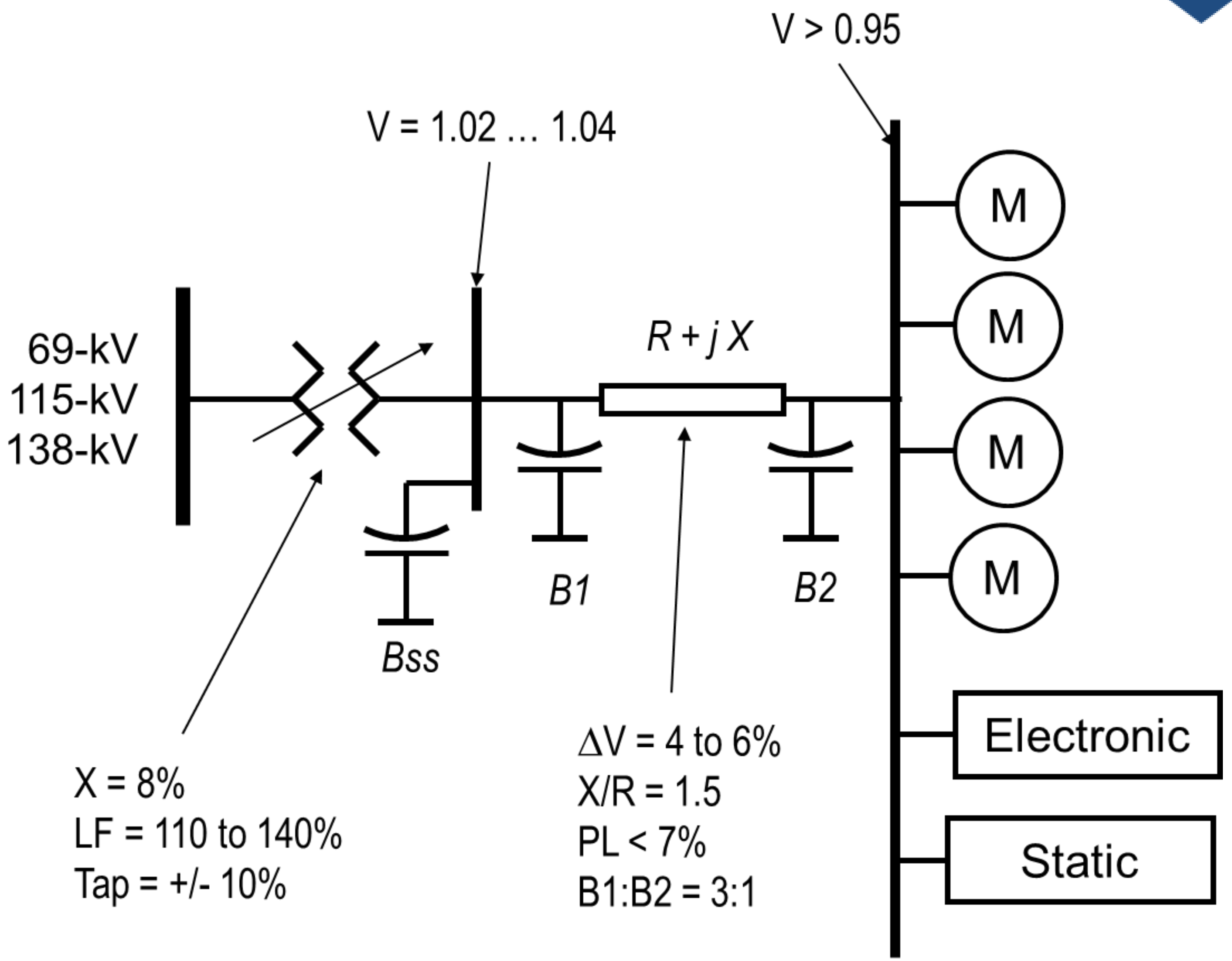
GE PSLF
Siemens PTI PSS®E
Power World
PowerTech TSAT

CMPLDW / CMLD Debunked

- Let us break down the 130+ parameters, contextualize their meaning; begins to come together cohesively.

```
"Bss"    0 "Rfdr" 0.04 "Xfdr" 0.04 "Fb" 0.75/
"Xxf" 0.08 "TfixHS" 1 "TfixLS" 1 "LTC" 0  "Tmin"   0.9 "Tmax" 1.1 "step" 0.00625 /
"Vmin"   1.025 "Vmax" 1.04 "Tdel" 30  "Ttap"   5 "Rcomp" 0 "Xcomp" 0 /
"Fma"   0.239538 "Fmb" 0.156309 "Fmc" 0.064766 "Fmd"   0.206375 "Fel"  0.116908  /
"PFel" 1 "Vd1" 0.7 "Vd2" 0.5 "Frcel" 0.8 /
"Pfs"   -0.994504 "P1e" 2 "P1c" 0.295212 "P2e" 1 "P2c"   0.704788 "Pfreq" 0 /
         "Q1e" 2 "Q1c" -0.5 "Q2e" 1 "Q2c"   1.5 "Qfreq" -1 /
"MtpA" 3  "MtpB" 3  "MtpC" 3  "MtpD" 1 /
"LfmA" 0.75 "RsA" 0.04 "LsA" 1.8 "LpA" 0.12 "LppA"   0.104 /
 "TpoA" 0.095 "TppoA" 0.0021 "HA"   0.1 "etrqA" 0 /
 "Vtr1A" 0.7 "Ttr1A" 0.02  "Ftr1A" 0.2 "Vrc1A" 1 "Trc1A" 99999 /
 "Vtr2A" 0.5 "Ttr2A" 0.02  "Ftr2A" 0.7 "Vrc2A" 0.7 "Trc2A" 0.1 /
"LfmB" 0.75 "RsB" 0.03 "LsB" 1.8 "LpB" 0.19 "LppB"   0.14 /
 "TpoB" 0.2 "TppoB" 0.0026 "HB"   0.5 "etrqB" 2 /
"Vtr1B" 0.6 "Ttr1B" 0.02  "Ftr1B" 0.2 "Vrc1B" 0.75 "Trc1B" 0.05 /
"Vtr2B" 0.5 "Ttr2B" 0.02  "Ftr2B" 0.3 "Vrc2B" 0.65 "Trc2B" 0.05 /
"LfmC" 0.75 "RsC" 0.03 "LsC" 1.8 "LpC" 0.19 "LppC"   0.14 /
"TpoC" 0.2 "TppoC" 0.0026 "HC"   0.1 "etrqC" 2 /
 "Vtr1C" 0.65 "Ttr1C" 0.02 "Ftr1C" 0.2 "Vrc1C" 1 "Trc1C" 9999 /
 "Vtr2C" 0.5 "Ttr2C" 0.02 "Ftr2C" 0.3 "Vrc2C" 0.65 "Trc2C" 0.1 /
"LfmD"  1 "CompPF" 0.98 /
"Vstall" 0.6 "Rstall" 0.1  "Xstall" 0.1 "Tstall" 0.03  "Frst" 0.2 "Vrst" 0.95 "Trst" 0.3 /
"fuvr" 0.1 "vtr1" 0.6 "ttr1" 0.02 "vtr2" 1 "ttr2" 9999 /
"Vc1off" 0.5 "Vc2off" 0.4 "Vc1on" 0.6 "Vc2on" 0.5 /
"Tth" 15 "Th1t" 0.7 "Th2t" 1.9 "tv" 0.025
```

The Distribution Equivalent Circuit



Motor A – Small Commercial

- Represents 3-phase compressor motors in commercial cooling and refrigeration systems
  - Typical of rooftop A/C – Walmart, Whole Foods, Malls, etc.
- Model data representative of 5-15 HP compressor motors
  - Special design motors (not NEMA)
  - Stall at about 40% voltage, restart at about 50-60% voltage
  - Constant torque load (on average)
  - Low inertia
- Motor protection & control:
  - Contactors trip when supply voltage drops to about 40% voltage, reclose at 45-55% voltage
  - Building EMS – no apparent reason to keep equipment out of service

Roof-Top Direct Expansion HVAC
10-25 hp compressor motors

Motor A – Large Commercial

- Large commercial buildings have central cooling systems
- Chiller compressors are large motors 200-500 HP
- Motor protection & control:
  - Chillers are sensitive equipment
  - Once tripped, probably require manual restart

Central Cooling System
Chiller 200-250 hp compressors

Motor A Model Data

- High initial torque motor
- H = 0.1 sec
- Constant torque load
- 70% of motors trip at 50% voltage, restart at 70% voltage (representing 10-25 HP motors)
- 20% of motors trip at 70% voltage, remain disconnected (representing large chillers)

Motor B

- Represents fan motors used in residential and commercial buildings
  - Ventilation fans in buildings, air-handler fans
- Model data is representative of 5-25 HP fan motors
  - Usually NEMA B design motors
  - Torque load proportional to speed squared
  - High inertia (0.25 to 1 seconds)
- Motor protection and control:
  - Contactors trip: ~ 40% voltage; Reclose: ~ 45-55% voltage
  - Building EMS – no apparent reason to keep equipment out of service
- Current trend: Fan motors are being replaced with Electronically Commutated Motors (ECMs)
  - Energy Efficiency Upgrade – DC motors, controllable speed
- Stall at very low voltages

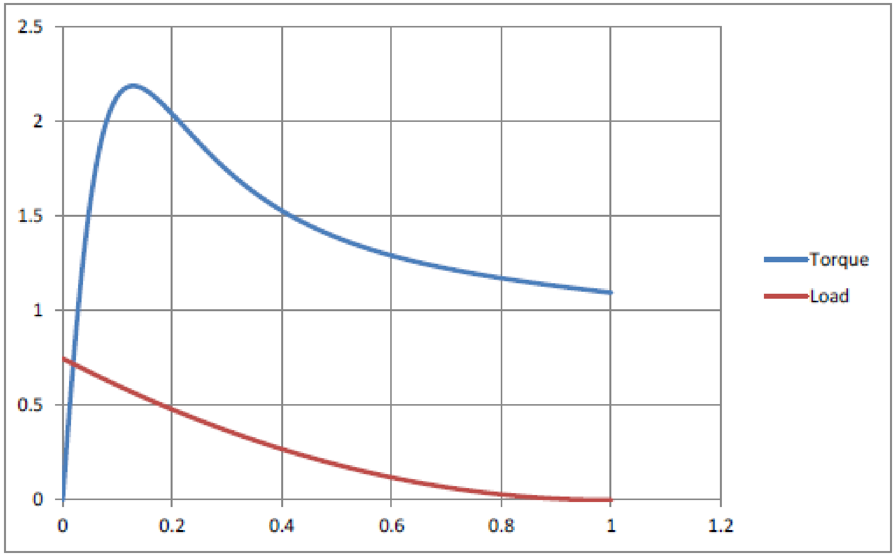
Motor C

- Represents direct-connected pump motors used in commercial buildings
  - Water circulating pumps in central cooling systems
- Same as Motor B, but with low inertia
- Model data is representative of a 5-25 HP pump motor
  - Usually NEMA B design motors
  - Torque load proportional to speed squared
  - Lower inertia (0.1 to 0.2 seconds)
- Motor protection and control:
  - Contactors trip: ~ 40% voltage; Reclose: ~ 45-55% voltage
  - Building EMS – no apparent reason to keep equipment out of service
- Current trend: Pump motors are being replaced with Variable Frequency Drives (VFDs)
  - EE Upgrade – AC motors, controllable speed

Motor B and C Model Data

- NEMA B Design Motor
- H = 0.5 sec for fan, H = 0.1 sec for pump
- Load torque proportional to speed squared

L	1.80
L'	0.19
L"	0.15
T'	0.19
T"	0.0026
D	2
H (fan)	0.5
H (pump)	0.15



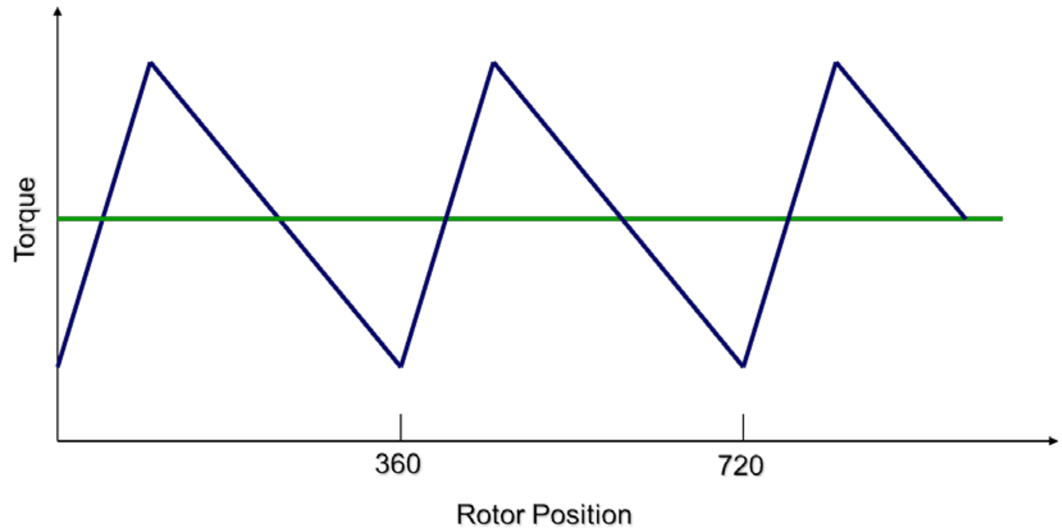
Motor D – Residential Air Conditioner

Motor D

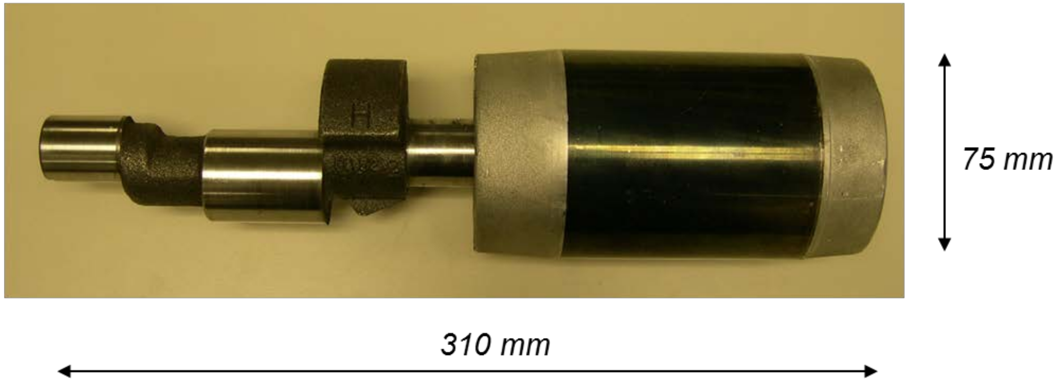
- Single-phase compressor motors in residential and small commercial cooling and refrigeration
- Model data representative of 3-5 HP compressor motors
  - Special design motors (not NEMA)
  - Stall at about 45-60% voltage
  - Constant torque load (on average)
  - Low inertia
- Motor protection and control:
  - Contactors trip: ~ 40-50% voltage; Reclose: ~ 45-55% voltage

Motor D – Performance

- Compressor Load Torque is very cyclical
- Very possible that motor stalls on next compression cycle



E.g. 3.5-ton compressor motor: *Weight: 4.6 kg*



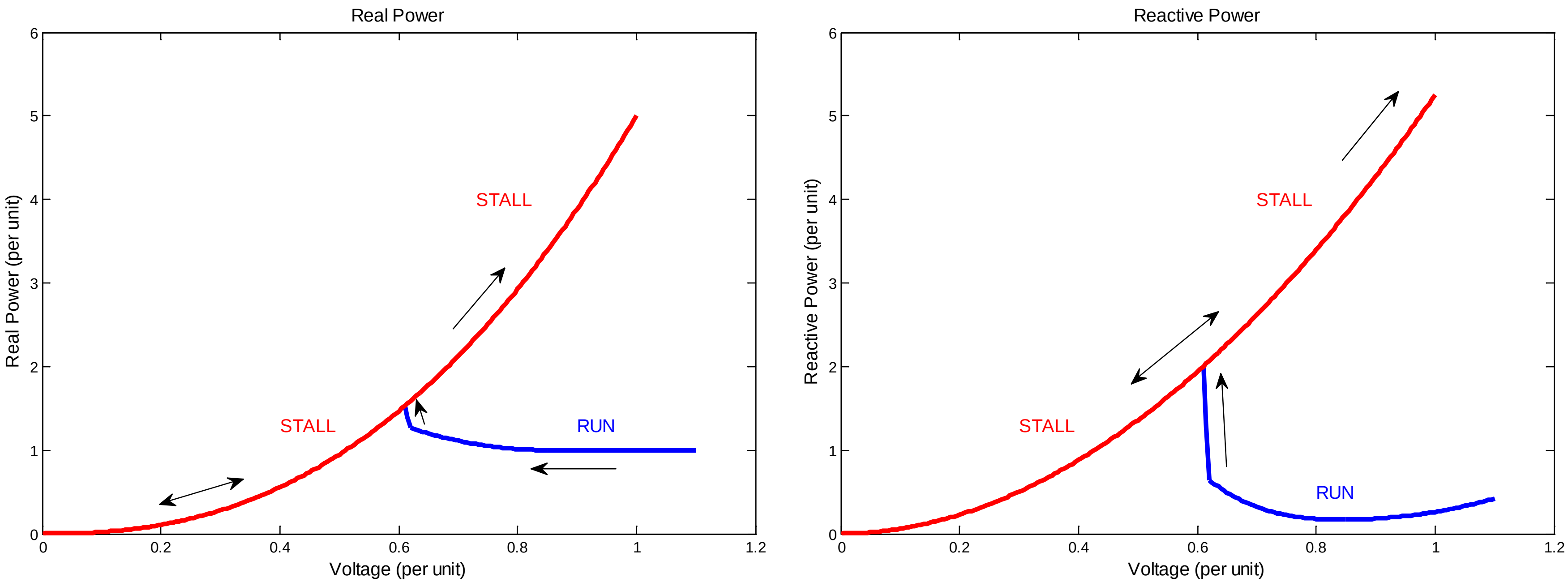
- Compressor Motor Inertia is very low
  - H = 0.03 – 0.05 sec
- Physically small

Motor D Model Representation

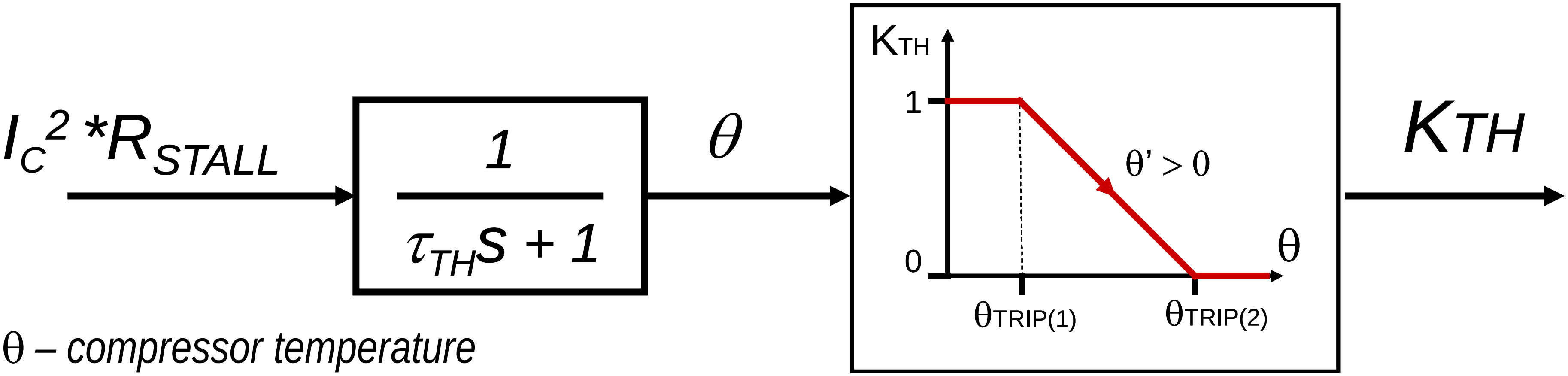
- Three-phase motor models cannot represent behavior of single-phase motors with the same datasets
  - Stalling phenomena – 3-phase motors usually stall at much lower voltages
  - P and Q consumption during stalling
- Single-phase models exist, but not in positive sequence models
  - Research is looking into sensitivities of single-phase motors
    - Point-on-wave
    - Electrical impedance
    - Voltage rate-of-change
    - Voltage and duration

Motor D Performance Model

- Motors stall when voltage drops below Vstall for duration Tstall
- Fraction Frst of aggregate motor can restart when voltage exceeds Vrst for duration Trst

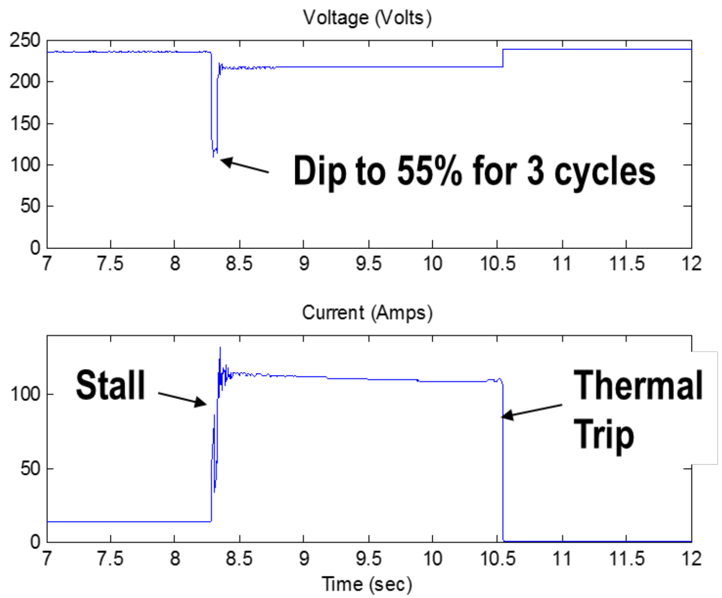


Thermal Relay Model



θ – compressor temperature

K_{TH} – fraction of motors that remain connected



- Thermal trip constant varies by manufacturer, protection requirements
- Thermal relay model accounts for this in linear tripping mechanism

Motor D

- Electrical response is represented with performance model
  - "Run" and "stall" states based on Vstall and Tstall
  - Fraction of motors allowed to restart (usually scroll compressors)
  - Manufacturers believe scroll-type represents 10-20% of A/C motors
- Thermal protection
  - I^2t characteristic used – a range is used to capture diverse settings
- Contactors
  - Load reduced linearly at 40-50% voltage, reconnect at 50-60% voltage
- Energy Efficiency standards driving greater penetration of scroll compressors – higher efficiency
  - SEER 12 very hard to meet with reciprocating units
- Newer A/C units have power-electronic VFDs – generally smaller ones popular in Europe/Japan for single-room cooling

Closing Remarks

- The CMPLDW/CMLD model is NOT the "WECC" Model
  - It is generic, and can be used across the interconnections
  - Can provide detailed representation of dynamic load behavior, including induction motor loads
  - Advancements in model structure greatly simplify utilization
  - Must perform sensitivity studies to better understand model parameter impacts on performance
  - Can disable A/C motor stalling by setting Tstall to 9999 (WECC Phase 1)
    - More work to understand software implementation of this
  - Tools available to generate load model records effectively
- These types of models will never capture the level of accuracy of generator modeling. But they're a big step in the right direction.
  - Can be tuned to accurately reproduce and explain historical events
  - Seek to predict future events ***in principle***, not in full fidelity

Questions and Answers

Appendix: Supplemental Material

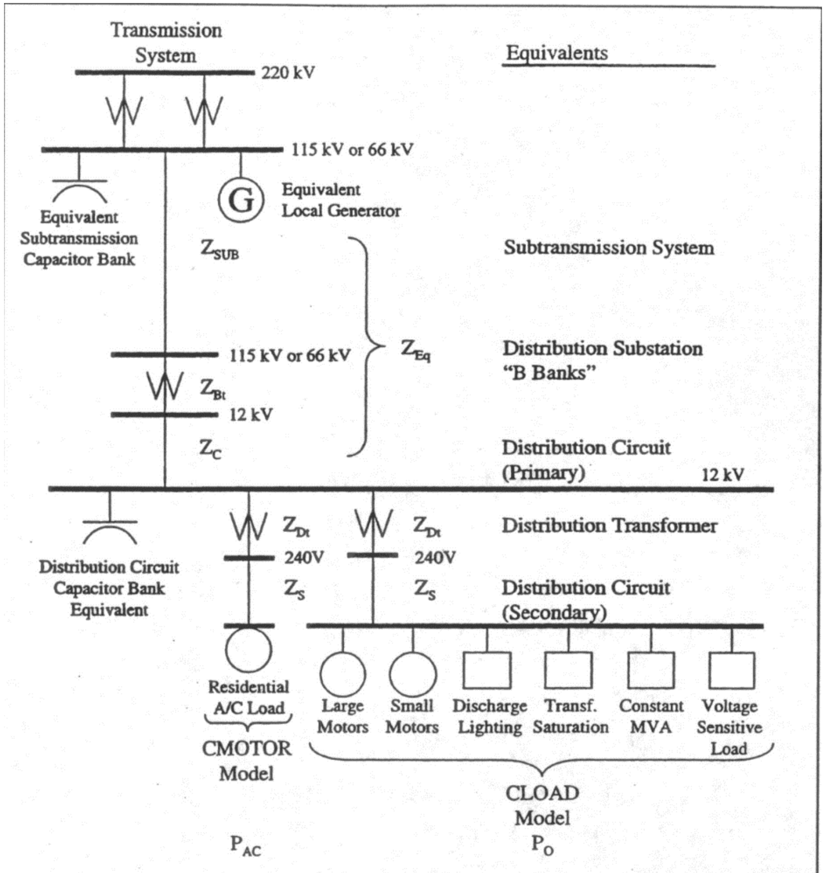
History of Load Modeling (in WECC)

- 1980s: Constant current real, constant impedance reactive models connected at transmission-level bus
  - ***Limitation of computing technology for that time***
- 1990s: EPRI Loadsyn (static polynomial characteristic to represent load), IEEE Task Force recommends dynamic load modeling
  - ***Failed to get much traction in industry***
- 1996: BPA model validation study for August 10 1996 outage
  - ***Demonstrated need for motor load representation*** in dynamic load models to capture oscillations and voltage instability

History of Load Modeling (in WECC)

- 2000-2001 – WECC “Interim” Load Model
  - 20% induction motor, remaining static load
  - Was only practical option in 2001
  - Intended as a temporary ‘fix’ to model oscillatory behavior observed at the California-Oregon Intertie (COI)
  - Model limitations were recognized and need for a better model was clear
  - ***Model was used for 10+ years to plan and operate the Western Interconnection***
  - ***…Many utilities are choosing to use the CLOD model, which is similar to this approach from 2001…!***

SCE's Observations and Modeling



Model was used in Southern California for special studies using PTI PSS®E simulator

- Late 1980s – Southern California Edison observes delayed voltage recovery events, attributed to stalling of residential air conditioners
  - Tested residential A/C units in laboratory, developed empirical AC models
- 1997 – SCE model validation effort of Lugo event
  - ***Illustrated need to represent distribution equivalent***
  - ***Illustrated need to have special models for air conditioning load***

The East Joins the Party

- 1994 – Florida Power published an IEEE paper, using a similar load model
- 1998 – Delayed voltage recovery event in Atlanta area in Southern Company territory
  - Events were observed, analyzed, modeled, and benchmarked to recreate event
- FPL and Southern Co. used, in principle, similar approaches to SCE and the eventual WECC model

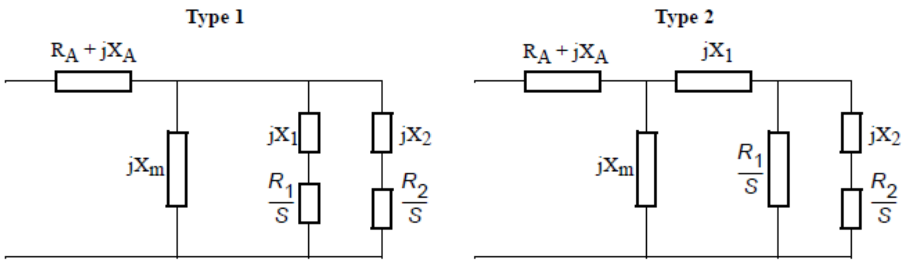
- *These models were used for special studies of local areas, but beginning to get traction*

WECC Load Modeling Task Force

- 2005 – WECC developed ‘explicit’ model
  - Included distribution equivalent, induction motor and static loads
  - Numerical stability in Interconnection-wide study
    - ***This was a big step 10 years ago. Still unavailable in the East.***
- 2007 – First version of the composite load model in PSLF
  - Three phase motor models only, no single phase represented
- 2006-2009 – EPRI/BPA/SCE testing of residential air conditioners and development of models
- 2009 – 1ϕ air conditioner model added to composite load model
- 2011 – WECC adopts phased approach for composite load model, starts system impact studies
- 2013 – TPL-001-4 requires modeling induction motor load
- 2013-Current – WECC approved use of Phase I composite load models for planning and operational studies

PTI PSS®E Load Models

- **CIM5 – Induction Motor Load Model**
  - Load Torque represented by $T_{LOAD} = T_{NOM}(1 + n)^D$
  - Single- or double-cage induction motors, including rotor flux dynamics
  - Captures motor start-up

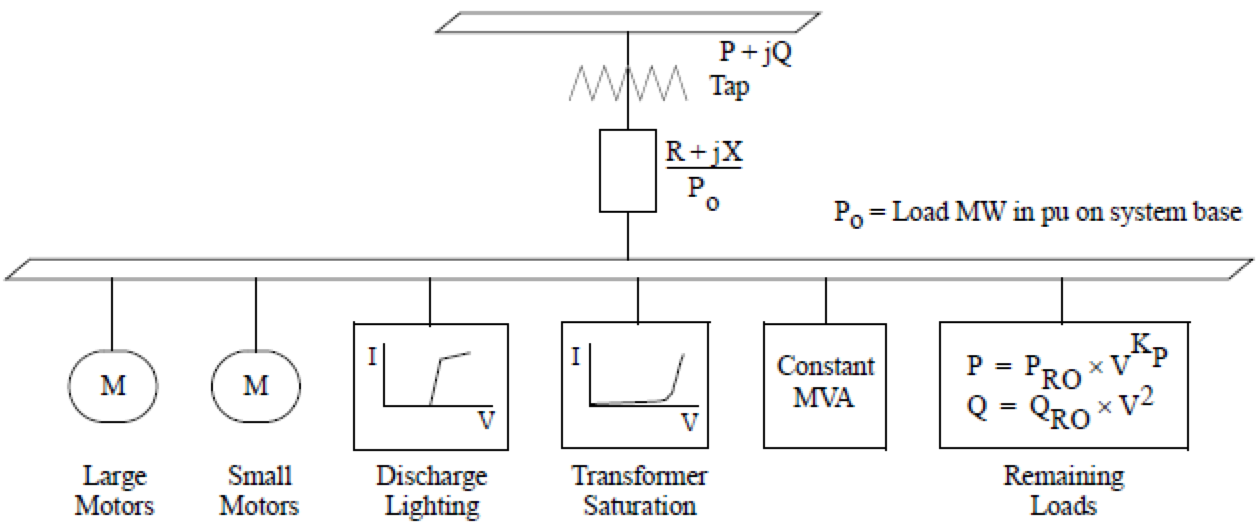


- **CIMW – Induction Motor Load Model (WECC)**
  - Motor load including electromagnetic dynamics (single- or double cage)
  - Load Torque represented by $T_{LOAD} = T_0(A\omega^2 + B\omega + C_0 + D\omega^e)$
- **CIM6 – Induction Motor Load Model**
  - Detailed load torque representation of CIMW
  - Motor starting capability of CIM5

PSS®E Model Library, Version 32.0.5, Revised October 2010.

PTI PSS®E Load Models

- **CLOD – Complex Load Model**
  - Distribution (transformer & circuit) impedance
  - Large & Small 3-ϕ induction motors
  - Discharge lighting
  - Transformer saturation
  - Assumed 0.98 pu loads – tap calculation to obtain V at load bus



PSS®E Model Library, Version 32.0.5, Revised October 2010.

PTI PSS®E Load Models

- **EXTL – Extended-Term Load Reset Model**
  - Simulates general effects of loads being reset to constant MWMVAR in steady-state without specifically modeling equipment (taps, caps, etc.)
- **IEEL – IEEE Load Model**
  - Algebraic representation of load

$$P = P_{load}\left(a_1 v^{n_1} + a_2 v^{n_2} + a_3 v^{n_3}\right)(1 + a_7 \Delta f)$$

$$Q = Q_{load}\left(a_4 v^{n_4} + a_5 v^{n_5} + a_6 v^{n_6}\right)(1 + a_8 \Delta f)$$

- **LDFR – Load Frequency Model**
  - Constant P and constant I components sensitive to system frequency

$$P = P_o\left(\frac{\omega}{\omega_o}\right)^m$$

$$Q = Q_o\left(\frac{\omega}{\omega_o}\right)^n$$

$$I_p = I_{po}\left(\frac{\omega}{\omega_o}\right)^r$$

$$I_q = I_{qo}\left(\frac{\omega}{\omega_o}\right)^s$$

- **ACMT – Single-Phase Air Conditioner Motor Model**
  - Aggregate representation of single-phase A/C load
    - Compressor motor, thermal relay, U/V relays, contactors
  - Representation based on "*Performance Model for Representing Single-Phase Air-Conditioner Compressor Motors in Power System Studies*" developed by WECC Load Model Task Force (LMTF)
  - This is the 1-ϕ A/C motor representation in the CMLD model

PSS®E Model Library, Version 32.0.5, Revised October 2010.

GE PSLF Load Models

- **Aggregate Load**
  - alwscc (b,w,z) – Load Voltage/Frequency Dependence Model
  - Secld1(2,3) – Secondary Load Model with Reset of Tap Ratio
- **Induction Motor Load**
  - apfl (spfl) – Pump/Fan Driven Induction (Synchronous) Motor Load Model
  - motorw/x – Single or Double Cage Induction Motor Model
- **Single-phase Air Conditioner Load**
  - Ld1pac – Performance-based Model of 1-ϕ Air Conditioner Load
  - motorc – Phasor Model of 1-ϕ Air Conditioner Load
- **Other Loads**
  - Ldelec (rect) – Electronic (Rectifier) Load Model

PSLF, PSLF User's Manual, Version 19.0_01, Revised July 2015.

Substation & Feeder Parameters

```
"Bss"   0 "Rfdr" 0.04 "Xfdr" 0.04 "Fb" 0.75/
"Xxf" 0.08 "TfixHS" 1 "TfixLS" 1 "LTC" 0  "Tmin"   0.9 "Tmax" 1.1 "step" 0.00625 /
"Vmin"   1.025 "Vmax" 1.04 "Tdel" 30  "Ttap"   5 "Rcomp" 0 "Xcomp" 0 /
```

Parameter	Default	Reason
Load MVA Base	-1.0 to -1.25	If (-), MVA base = Load MW/Value Specified
Bss	0.0	Assumed no shunt compensation at bus
Rfdr	0.04	4% impedance on load MVA base; 1:1 distribution feeder impedance X:R ratio
Xfdr	0.04	
Fb	0.0	No shunt compensation, so N/A
Xxf	0.08	8% impedance on load MVA base
TfixHS	1.0	Assumed 1:1 T:D transformer turns ratio
TfixLS	1.0	

T:D Transformer Parameters

```
"Bss"    0 "Rfdr" 0.04 "Xfdr" 0.04 "Fb" 0.75/
"Xxf" 0.08 "TfixHS" 1 "TfixLS" 1 "LTC" 0  "Tmin"   0.9 "Tmax" 1.1 "step" 0.00625 /
"Vmin"   1.025 "Vmax" 1.04 "Tdel" 30  "Ttap"   5 "Rcomp" 0 "Xcomp" 0 /
```

Parameter	**Default**	**Reason**
LTC	1 or 0	Based on whether LTC action enabled
Tmin	0.9	Based on common ULTC configuration: • 32 steps • +/- 0.1 tap • +/- 1.25% voltage operation bounds
Tmax	1.1	
step	0.00625	
Vmin	0.9875	
Vmax	1.0125	
Tdel	30-75	Depends on utility practice for LTC action delay
Ttap	5	Time duration of LTC adjustment, commonly 5 seconds
Rcomp	0	Resistance and reactance compensation for LTC; Generally no considered
Xcomp	0	

Load Composition Parameters

```
"Fma"   0.239538 "Fmb" 0.156309 "Fmc" 0.064766 "Fmd"   0.206375 "Fel"  0.116908  /
```

Parameter	Default	Reason
Fma	Varies	These parameters are solely dependent on the load composition at the given bus. Many utilities use zonal or regional data when bus-level or feeder-level data is not available. Exact values depend on many factors – season, regional economies, industries, load type, etc. For example, heavy summer case parameters could = A: 25%, B: 15%, C: 5%, D: 15%, PE: 10%. But this is solely dependent on the load composition at the bus.
Fmb	Varies	
Fmc	Varies	
Fmd	Varies	
Fel	Varies	

Power Electronic Load Parameters

```
"PFel" 1 "Vd1" 0.7 "Vd2" 0.5 "Frcel" 0.8 /
```

Parameter	Default	Reason
Pfel	1.0	Assumed power electronic load at unity power factor
Vd1	0.7	Assume electronic load starts tripping at 70% voltage
Vd2	0.5	Assume all electronic load is tripped by 50% voltage
Frcel	0.8	Assumed 80% of electronic load will automatically reconnect upon acceptable voltage return

Static Real Load Parameters

```
"Pfs"   -0.994504 "P1e" 2 "P1c" 0.295212 "P2e" 1 "P2c"   0.704788 "Pfreq" 0 /
          "Q1e" 2 "Q1c" -0.5 "Q2e" 1 "Q2c"   1.5 "Qfreq" -1 /
```

Parameter	Default	Reason
Pfs	-0.995	Rather than specify shunt compensation, assume slight capacitive power factor for static load to account for shunt compensation at substation and on feeder
P1e	2.0	$P=P_0*(P_{1c}*V/V_0^{P1e} + P_{2c}*V/V_0^{P2e} + P_3) * (1 + P_{frq} * D_f)$ Assume one component varies with square of voltage; 50% remaining static load assigned to this component
P1c	0.5	
P2e	1.0	$P=P_0*(P_{1c}*V/V_0^{P1e} + P_{2c}*V/V_0^{P2e} + P_3) * (1 + P_{frq} * D_f)$ Assume one component varies linearly with voltage; 50% remaining static load assigned to this component
P2c	0.5	
Pfreq	0.0	Assume real power not frequency dependent

Static Reactive Load Parameters

```
"Pfs"    -0.994504 "P1e" 2 "P1c" 0.295212 "P2e" 1 "P2c"   0.704788 "Pfreq" 0 /
          "Q1e" 2 "Q1c" -0.5 "Q2e" 1 "Q2c"   1.5 "Qfreq" -1 /
```

Parameter	Default	Reason
Q1e	2.0	$Q = Q_0 * (Q_{1c} * V/V_0^{Q1e} + Q_{2c} * V/V_0^{Q2e} + Q_3) * (1 + Q_{frq} * D_f)$ Assume one component varies with square of voltage; 50% remaining static load assigned to this component; Inversely related to voltage relationship
Q1c	-0.5	
Q2e	1.0	$Q = Q_0 * (Q_{1c} * V/V_0^{Q1e} + Q_{2c} * V/V_0^{Q2e} + Q_3) * (1 + Q_{frq} * D_f)$ Assume one component varies linearly with voltage.
Q2c	1.5	
Qfreq	-1.0	Assume Q inversely frequency dependent

Motor Type Definition Parameters

```
"MtpA" 3  "MtpB" 3  "MtpC" 3  "MtpD" 1 /
```

Parameter	Default	Reason
MtpA	3	Constant torque loads (e.g. commercial air conditioners and refrigerators)
MtpB	3	Torque speed squared loads with high inertia (fans)
MtpC	3	Torque speed squared loads with low inertia (pumps)
MtpD	1	Single-phase induction motors (residential A/C)

Motor A Model Parameters

```
"LfmA" 0.75 "RsA" 0.04 "LsA" 1.8 "LpA" 0.12 "LppA"   0.104 /
 "TpoA" 0.095 "TppoA" 0.0021 "HA"   0.1 "etrqA" 0 /
 "Vtr1A" 0.7 "Ttr1A" 0.02  "Ftr1A" 0.2 "Vrc1A" 1 "Trc1A" 99999 /
 "Vtr2A" 0.5 "Ttr2A" 0.02  "Ftr2A" 0.7 "Vrc2A" 0.7 "Trc2A" 0.1 /
```

Parameter	Default	Reason
LfmA	0.75	Load MVA = MW/MVA Rating
RsA	0.04	These are 'generic' motor parameters for this type of load, based on laboratory testing
LsA	1.8	
LpA	0.12	
LppA	0.104	
TpoA	0.095	
TppoA	0.0021	
HA	0.1	Majority of these motors are small – low inertia
etrqA	0*	$T_{mech} = T_{mech,0} * \omega^{Etrq}$ - Constant Torque

**3φ motors driving constant torque loads (commercial air conditioner compressors and refrigeration)*

Motor A Protection Parameters

```
"LfmA" 0.75 "RsA" 0.04 "LsA" 1.8 "LpA" 0.12 "LppA"   0.104 /
 "TpoA" 0.095 "TppoA" 0.0021 "HA"   0.1 "etrqA" 0 /
 "Vtr1A" 0.7 "Ttr1A" 0.02  "Ftr1A" 0.2 "Vrc1A" 1 "Trc1A" 99999 /
 "Vtr2A" 0.5 "Ttr2A" 0.02  "Ftr2A" 0.7 "Vrc2A" 0.7 "Trc2A" 0.1 /
```

Parameter	Default	Reason
Vtr1A	0.7	Assumed performance of these motors: • This set represents the higher performance motors – large commercial building chillers/air handlers • First trip level at 0.70 pu voltage, trip time < 2 cycles • 20% of these motors have this type of protection • Manual reconnection
Ttr1A	0.02	
Ftr1A	0.2	
Vrc1A	1.0	
Trc1A	9999	
Vtr2A	0.5	Assumed performance of these motors: • This set represents the majority of ‘brute’ motors – standard design, rugged, automated • Trip level at 0.50 pu voltage, trip time < 2 cycles • 70% of these motors have this type of protection • Auto-reconnect – 0.7 pu within 100 ms.
Ttr2A	0.02	
Ftr2A	0.7	
Vrc2A	0.7	
Trc2A	0.1	

Motor B Model Parameters

```
"LfmB" 0.75 "RsB" 0.03 "LsB" 1.8 "LpB" 0.19 "LppB"   0.14 /
 "TpoB" 0.2 "TppoB" 0.0026 "HB"   0.5 "etrqB" 2 /
"Vtr1B" 0.6 "Ttr1B" 0.02  "Ftr1B" 0.2 "Vrc1B" 0.75 "Trc1B" 0.05 /
"Vtr2B" 0.5 "Ttr2B" 0.02  "Ftr2B" 0.3 "Vrc2B" 0.65 "Trc2B" 0.05 /
```

Parameter	**Default**	**Reason**
LfmB	0.75	Load MVA = MW/MVA Rating
RsB	0.03	These are 'generic' motor parameters for this type of load, based on laboratory testing
LsB	1.8	
LpB	0.19	
LppB	0.14	
TpoB	0.2	
TppoB	0.0026	
HB	0.5	Large inertia commercial/industrial fan motor loads
etrqB	2*	$T_{mech} = T_{mech,0} * \omega^{Etrq}$ - Torque ∝ Speed-Squared

**3φ motors driving load proportional to speed-squared relationship with high inertia (large fans)*

Motor B Protection Parameters

```
"LfmB" 0.75 "RsB" 0.03 "LsB" 1.8 "LpB" 0.19 "LppB"   0.14 /
 "TpoB" 0.2 "TppoB" 0.0026 "HB"   0.5 "etrqB" 2 /
"Vtr1B" 0.6 "Ttr1B" 0.02  "Ftr1B" 0.2 "Vrc1B" 0.75 "Trc1B" 0.05 /
"Vtr2B" 0.5 "Ttr2B" 0.02  "Ftr2B" 0.3 "Vrc2B" 0.65 "Trc2B" 0.05 /
```

<table>
<tr><th>Parameter</th><th>Default</th><th>Reason</th></tr>
<tr><td>Vtr1B</td><td>0.6</td><td rowspan="5">Assumed performance of these motors:
• First trip level at 0.60 pu voltage, trip time < 2 cycles
• 20% of these motors have this type of protection
• Auto-reconnect – 0.75 pu voltage within 50 ms</td></tr>
<tr><td>Ttr1B</td><td>0.02</td></tr>
<tr><td>Ftr1B</td><td>0.2</td></tr>
<tr><td>Vrc1B</td><td>0.75</td></tr>
<tr><td>Trc1B</td><td>0.05</td></tr>
<tr><td>Vtr2B</td><td>0.5</td><td rowspan="5">Assumed performance of these motors:
• Trip level at 0.50 pu voltage, trip time < 2 cycles
• 30% of these motors have this type of protection
• Auto-reconnect – 0.65 pu within 50 ms
• Emulates staggered tripping and reconnection – diversity of motor load</td></tr>
<tr><td>Ttr2B</td><td>0.02</td></tr>
<tr><td>Ftr2B</td><td>0.3</td></tr>
<tr><td>Vrc2B</td><td>0.65</td></tr>
<tr><td>Trc2B</td><td>0.05</td></tr>
</table>

Motor C Model Parameters

```
"LfmC" 0.75 "RsC" 0.03 "LsC" 1.8 "LpC" 0.19 "LppC"   0.14 /
"TpoC" 0.2 "TppoC" 0.0026 "HC"   0.1 "etrqc" 2 /
 "Vtr1C" 0.65 "Ttr1C" 0.02 "Ftr1C" 0.2 "Vrc1C" 1 "Trc1C" 9999 /
 "Vtr2C" 0.5 "Ttr2C" 0.02 "Ftr2C" 0.3 "Vrc2C" 0.65 "Trc2C" 0.1 /
```

Parameter	**Default**	**Reason**
LfmC	0.75	Load MVA = MW/MVA Rating
RsC	0.03	These are ‘generic’ motor parameters for this type of load, based on laboratory testing
LsC	1.8	
LpC	0.19	
LppC	0.14	
TpoC	0.2	
TppoC	0.0026	
HC	0.1	Large inertia commercial/industrial pump motor loads
etrqC	2*	$T_{mech} = T_{mech,0} * \omega^{Etrq}$ - Torque ∝ Speed-Squared

**3φ motors driving load proportional to speed-squared relationship with low inertia (pump loads)*

Motor C Protection Parameters

```
"LfmC" 0.75 "RsC" 0.03 "LsC" 1.8 "LpC" 0.19 "LppC"   0.14 /
"TpoC" 0.2 "TppoC" 0.0026 "HC"   0.1 "etrqc" 2 /
 "Vtr1C" 0.65 "Ttr1C" 0.02 "Ftr1C" 0.2 "Vrc1C" 1 "Trc1C" 9999 /
 "Vtr2C" 0.5 "Ttr2C" 0.02 "Ftr2C" 0.3 "Vrc2C" 0.65 "Trc2C" 0.1 /
```

Parameter	Default	Reason
Vtr1C	0.65	Assumed performance of these motors: • First trip level at 0.65 pu voltage, trip time < 2 cycles • 20% of these motors have this type of protection • Manual reconnection
Ttr1C	0.02	
Ftr1C	0.2	
Vrc1C	1.0	
Trc1C	9999	
Vtr2C	0.5	Assumed performance of these motors: • Trip level at 0.50 pu voltage, trip time < 2 cycles • 30% of these motors have this type of protection • Auto-reconnect – 0.65 pu within 100 ms
Ttr2C	0.02	
Ftr2C	0.3	
Vrc2C	0.65	
Trc2C	0.1	

Motor D Model Parameters

```
"LfmD"  1 "CompPF" 0.98 /
"Vstall" 0.6 "Rstall" 0.1  "Xstall" 0.1 "Tstall" 0.03  "Frst" 0.2 "Vrst" 0.95 "Trst" 0.3 /
"fuvr" 0.1 "vtr1" 0.6 "ttr1" 0.02 "vtr2" 1 "ttr2" 9999 /
"Vc1off" 0.5 "Vc2off" 0.4 "Vc1on" 0.6 "Vc2on" 0.5 /
"Tth" 15 "Th1t" 0.7 "Th2t" 1.9 "tv" 0.025
```

Parameter	**Default**	**Reason**
LfmD	1.0	Load MVA = MW/MVA Rating
CompPF	0.98	Assumed slightly inductive motors load
Vstall	0.60	Stall voltage (range) based on laboratory testing
Rstall	0.1	Based on laboratory testing results of residential air-conditioners
Xstall	0.1	
Tstall	0.03	Stall time (range) based on laboratory testing
Frst	0.2	Captures diversity in load; also based on testing.
Vrst	0.95	Reconnect when acceptable voltage met
Trst	0.3	Induction motor restart time is relatively short

**1φ induction motor load (residential air-conditioner compressors)*

Motor D Protection Parameters

```
"LfmD"  1 "CompPF" 0.98 /
"Vstall" 0.6 "Rstall" 0.1  "Xstall" 0.1 "Tstall" 0.03  "Frst" 0.2 "Vrst" 0.95 "Trst" 0.3 /
"fuvr" 0.1 "vtr1" 0.6 "ttr1" 0.02 "vtr2" 1 "ttr2" 9999 /
"Vc1off" 0.5 "Vc2off" 0.4 "Vc1on" 0.6 "Vc2on" 0.5 /
"Tth" 15 "Th1t" 0.7 "Th2t" 1.9 "tv" 0.025
```

Parameter	Default	Reason
fuvr	0.1	Assumed most A/C units have undervoltage relaying
vtr1	0.6	Undervoltage relay
ttr1	0.02	
vtr2	1	No second level undervoltage tripping specified.
ttr2	9999	
Vc1off	0.5	Stall time (range) based on laboratory testing
Vc2off	0.4	Based on laboratory testing results
Vc1on	0.6	Reconnect when acceptable voltage met
Vc2on	0.5	Induction motor restart time is relatively short

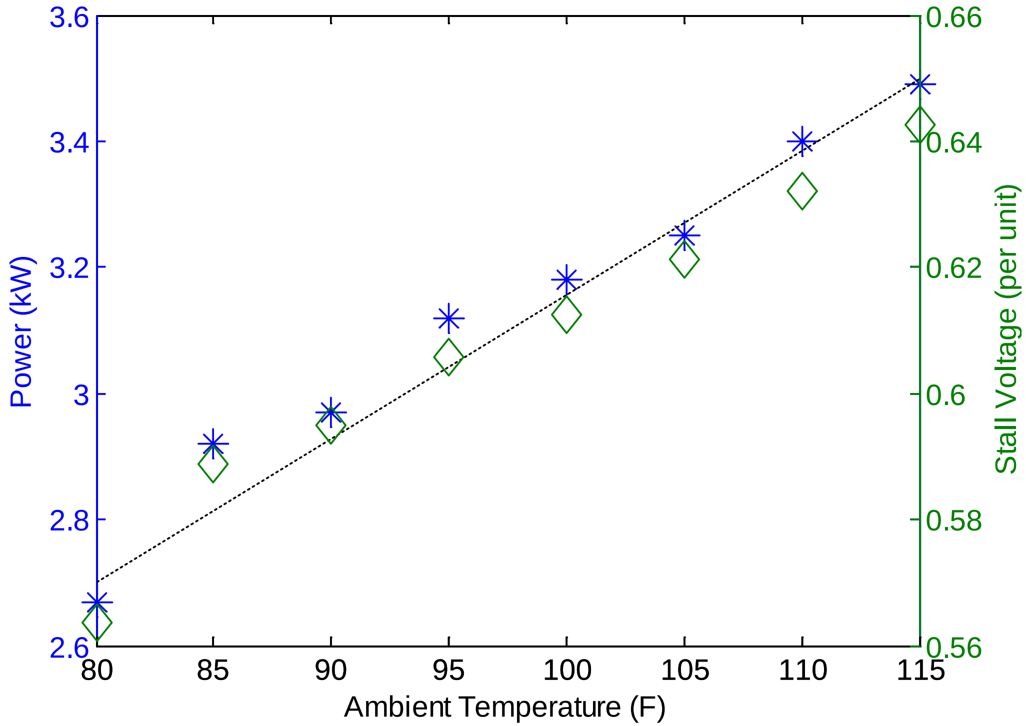
Motor D Protection Parameters

```
"LfmD"  1 "CompPF" 0.98 /
"Vstall" 0.6 "Rstall" 0.1  "Xstall" 0.1 "Tstall" 0.03  "Frst" 0.2 "Vrst" 0.95 "Trst" 0.3 /
"fuvr" 0.1 "vtr1" 0.6 "ttr1" 0.02 "vtr2" 1 "ttr2" 9999 /
"Vc1off" 0.5 "Vc2off" 0.4 "Vc1on" 0.6 "Vc2on" 0.5 /
"Tth" 15 "Th1t" 0.7 "Th2t" 1.9 "tv" 0.025
```

Parameter	Default	Reason
Tth	15	Varies based on manufacturer – sensitivity analysis required; based on range of external factors
Th1t	0.7	Assumed tripping starting at 70% temperature, with all tripped at 190% temperature
Th2t	1.9	
tv	0.025	Assumed generic transducer time lag

Motor D – Sensitivity to Ambient Temp

- Compressor loading and stall voltage depend on ambient temperature
- Compressor motors have high power factor when running
  - Approximately 0.97 pf



Current R&D Efforts

- Point-on-wave sensitivity
- Voltage sag rate-of-change sensitivity
  - Distribution recordings show sag is not instantaneous
  - At least 1 cycle for voltage to sag – motor back-feed
  - Vstall numbers lower than previously thought