Load Modeling in Grid Simulations and System Performance Issues

Presentation at DOE Workshop

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Delayed Voltage Recovery Event

Main Grid Voltage

- Fault
- AC stall
- AC thermal trip
- LTCs / Shunt Capacitors
- AC re-start

20 – 25 %

8 – 15 %

20 – 30 sec

~ 2 minutes
Our primary interest is the fast dynamic response of loads, not projections of future demand.
Load Modeling in WECC

• Load Model Structure:
  – Composite load model in WECC production programs
  – Explicit load representation

• Load Model Data

• System Impact Studies:
  – Sensitivity, Validation, System Performance
WECC Composite Load Model

Initial development is done in GE PSLF
Load Model Structure

• WECC developed EPCL routines for explicit load representation in PSLF program in 2004–05:
  – Add Transformer
  – Add Feeder Equivalent
  – Create Load Composition

• WECC developed a user-defined model of single-phase residential air-conditioners

• WECC is working with GE on developing a composite load model in PSLF program
  – Specifications are developed in March 2006
  – Several releases have been tested since April 2007
  – Final version is expected in Q1 of 2009
Single-Phase A/C Compressor Motor Model
A/C Compressor Motor

1-phase motor has 2 windings
### Single-Phase Motors – Steady-State

(a) Compressor motor in a 3-ton air-conditioning unit

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Main</th>
<th>Auxiliary(*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real Power, W</td>
<td>3180</td>
<td>1910</td>
<td>1270</td>
</tr>
<tr>
<td>Reactive Power, VAR</td>
<td>730</td>
<td>1645</td>
<td>-915</td>
</tr>
<tr>
<td>Power Factor, Per Unit</td>
<td>0.974</td>
<td>0.758</td>
<td>-0.81</td>
</tr>
</tbody>
</table>

(b) Compressor motor in a 3.5-ton air-conditioning unit

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Main</th>
<th>Auxiliary(*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real Power, W</td>
<td>3790</td>
<td>2500</td>
<td>1290</td>
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<tr>
<td>Reactive Power, VAR</td>
<td>800</td>
<td>2000</td>
<td>-1200</td>
</tr>
<tr>
<td>Power Factor, Per Unit</td>
<td>0.978</td>
<td>0.781</td>
<td>-0.732</td>
</tr>
</tbody>
</table>

Notice high power factor
Single-Phase Motors – Steady-State

Compressor Power vs. Ambient Temperature

Ambient Temperature (F)

Power (W)

3-ton compressor motor
Compressor Motor Tests – Motor Inertia

H = 0.03 – 0.05 seconds

E.g. 3.5-ton compressor motor: Weight: 4.6 kg
Notice motor non-symmetric behavior becomes more pronounced as voltage ramps down.
Compressor Motor Tests – Power-Voltage Trajectories

Notice that stall voltage increases with temperature
1φ – AC Motor Tests

• Compressor motor is 1-phase capacitor-run motor, has 2 windings

• Nominal power factor is relatively high 0.95 – 0.97

• Compressor load and stall voltage increase with temperature

• Compressor motor inertia is very low (~0.05 sec)

• Compressor motor is non-symmetric, non-symmetry becomes more pronounced as voltage declines

• Once the motor stalls it is likely to remain stalled until coolant pressure is equalized, very few motors can re-start
Single-Phase Motor Models

• Three-phase motor models cannot represent behavior of single-phase motors:
  – Stalling phenomenon (3-phase motor model usually stalls at much lower voltages)
  – Real and reactive power when stalled
  – Steady-state sensitivities of real and reactive power with respect to voltage and frequency

• Single-phase motor models exist but require point-of-wave simulations
  – Not acceptable for positive-sequence grid simulators which use ¼ cycle time step
Single-Phase Motor Models

- Phasor Models
- Performance-Type Models
  - Several variations
- Hybrid model
  - Originally developed by SCE, enhanced by EPRI

- Single-Phase Waveform Conversion
Phasor Model*

* This model was developed by Bernard Lesieutre at LBNL, and his research was funded by California Energy Commission’s Public Energy Research Program, WA# MR-049, through the California Institute for Energy and Environment, Award Number MTX-060-1.
Phasor Model

• Can be simulated with $\frac{1}{4}$ cycle time step used in the grid simulators

• Uses differential equations to represent motor dynamics

• Matches well most tests:
  – Voltage steps, ramp, oscillations
  – Frequency steps
  – Correctly identifies faults when compressor motor stalls from the faults when compressor motor re-accelerates
Phasor Model

• Outstanding research issues:
  – Torque model: Simulated inertia had to reduced to about $\frac{1}{2}$ of the measured to reproduce motor stalling. This may be because of torque of a reciprocating compressor is not modeled appropriately when motor stalls. Higher inertia fits well with the oscillation tests. Bernie plans to repeat the tests for a scroll compressor.

• Outstanding implementation issues:
  – John Undrill is working on “motorc” model in GE PSLF. Still, need to reconcile Bernie’s MATLAB model and John’s “motorc” model
Phasor Model

• The model has been useful in developing understanding of single-phase motors. The model will be a valuable addition to grid simulators as a stand-alone model to study specific motor behavior.

• The model, however, may not be the best choice for grid-level studies, as the model precision is lost when representing an aggregate behavior of multiple motors in a feeder.
AC Motor Model

• Grid-simulation model
  – Simulation of the impact of air-conditioning loads on the grid dynamic performance

• Equipment model
  – Gain the insight in the dynamic behavior of air-conditioning units

• Coordination and cross-calibration of the models
Performance-Type Models

• The model has two states: running and stalled

• The transition from running to stalled state is done based on the motor voltage

• Running state is represented with static exponential models

• Stalled state is represented with an equivalent impedance \( R_{STALL} + j X_{STALL} \)
Characteristics and stall voltage are adjusted depending on the motor load factor
Performance Model

- Easy to implement
- Model provides good representation of the motor real and reactive power for slow variations of voltage and frequency
- Model does not capture well voltage and frequency dynamics above 0.7 Hz.
- Model is “happier” to stall than the actual motor
- Model captures well motor current, real and reactive power during the stall condition
1φ - AC Unit Model

Model Includes:

- Compressor Motor Model
- Thermal Relay Model
- Under-Voltage Relay (proposed by SCE) Model
- Condensing Unit Controls / Contactors

Model Does NOT Include:

- Indoor and Outdoor fans are modeled separately
Thermal Relay Characteristic

Time (sec)

Current (Per Unit)

Model:
- Trane
- Carrier 38TKB036
- York - H4DB040
- York - H4DB036
Thermal Protection

Current (Amps)

- stall
- thermal trip
- thermal re-close
- thermal trip

Compressor Pressure

Pressure (Psi)

Time (sec)
Thermal Protection

Current

Compressor Pressure

Time [sec]

Pressure [psi]
WECC Status

• AC-Motor Model Development:
  – Include “performance” – type AC compressor model in a WECC composite load model
  – Continue development of the “motorc” model as a stand-alone model in power system simulators
  – WECC is preparing a detailed report on 1-φ compressor testing and modeling

• Composite load model is expected to be done in Q1 2009:
  – Prototype is currently available in GE PSLF 16.1
  – Outstanding development – 1-phase motors, connect to UVLS and UFLS data records
  – Model acceptance tests and system performance studies
  – Load composition data
Load Model Studies
Load Model Studies

Explicit load representation

“Performance” model for 1-phase A/C units

Simulations done by Robert Tucker, SCE
System Studies

• AC Units Stall:
  – A grid fault turns into a “wide-area” fault
  – Represents a risk to voltage stability
    • Risk of generator reducing reactive power by OEL
    • Risk of operation of Zone 3 protection
  – Need to disconnect stalled AC units from the grid
  – Need to contain the affected area

• AC Units are disconnected:
  – “Your risks can change rapidly”
  – Risk of major over-voltages, equipment damage and protective tripping
  – Dynamic reactive resources help
Studies of Solutions

3-phase fault
Hassayampa – Palo Verde
Normal clearing

Explicit load representation

“Performance” A/C model

Residential AC is 30% of load

Baseline simulation
20% of a/c tripped by UV relay
30% of a/c tripped by UV relay
60% of a/c tripped by UV relay
Our Viewpoint

• Large metro areas:
  – Increasing amount of air-conditioning load
  – Limited dynamic voltage support – generators are remote and VARS do not travel well
  – Prone to dynamic voltage stability problems

• BPA view of the risks:
  – Risk of voltage collapse developing in a metro area
  – Risk of voltage collapse cascading outside metro area
  – Risk of extreme over-voltages

• Solutions:
  – Equipment-level solutions
  – System solutions – dynamic VARs are needed
  – Special Protection Schemes to prevent outage spread
Acknowledgement

• WECC composite load model is a collaborative development of many researchers, including
  – Bill Price and John Undrill, retired from General Electric
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  – Peter Mackin, Navigant Consulting

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  – BPA Technology Innovation Office