



U.S. DEPARTMENT OF  
**ENERGY**

PNNL-24425

Prepared for the U.S. Department of Energy  
under Contract DE-AC05-76RL01830

# ARRA Interconnection Planning - Load Modeling Activities

DP Chassin  
Y Zhang  
P Etingov  
D James  
DI Hatley  
H Kirkham  
J Kueck (private consultant)  
X Li  
Y Huang  
C Chen

June 2015



**Pacific Northwest**  
NATIONAL LABORATORY

*Proudly Operated by **Battelle** Since 1965*

## DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes **any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.** Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST NATIONAL LABORATORY

*operated by*

BATTELLE

*for the*

UNITED STATES DEPARTMENT OF ENERGY

*under Contract DE-AC05-76RL01830*

Printed in the United States of America

Available to DOE and DOE contractors from the  
Office of Scientific and Technical Information,  
P.O. Box 62, Oak Ridge, TN 37831-0062;  
ph: (865) 576-8401  
fax: (865) 576-5728  
email: [reports@adonis.osti.gov](mailto:reports@adonis.osti.gov)

Available to the public from the National Technical Information Service  
5301 Shawnee Rd., Alexandria, VA 22312  
ph: (800) 553-NTIS (6847)  
email: [orders@ntis.gov](mailto:orders@ntis.gov) <<http://www.ntis.gov/about/form.aspx>>  
Online ordering: <http://www.ntis.gov>



This document was printed on recycled paper.

(8/2010)

# **ARRA Interconnection Planning - Load Modeling Activities**

DP Chassin  
Y Zhang  
P Etingov  
D James  
DI Hatley  
H Kirkham  
J Kueck (private consultant)  
X Li  
Y Huang  
C Chen

June 2015

Prepared for  
the U.S. Department of Energy  
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory  
Richland, Washington 99352



# Executive Summary

The performance of bulk power systems is analyzed using computer models that represent the systems' behavior under normal or abnormal conditions. As the load changes during the day, the generators follow, and the power flows can be calculated. However, for historical reasons, most load models are based on time-invariant, voltage-dependent polynomial load representations. The loads may be represented as constant impedance (Z), constant current (I), or constant power (P). It has been found recently that these models no longer provide a true representation of the dynamic response of the load, particularly in view of the increased penetration of residential air conditioners in recent years. The problem comes about because the load models do not capture the electromechanical behavior of the motors or the load protection in the moments after a fault occurs on the power system.

A Fault Induced Delayed Voltage Recovery (FIDVR) event is the phenomenon whereby system voltage remains at significantly reduced levels for several seconds after a transmission, subtransmission, or distribution fault has been cleared. The effect is thought to be caused by the stalling of highly concentrated induction motor loads with constant torque. These motors stall in response to low voltage. The stalled motors draw more reactive power from the grid, and that holds down the local voltage. A vicious circle is created. After several seconds of being stalled, motor protection devices begin to act and trip the motors to prevent them from overheating. As a result, there will be a large decrease in the load on the power system, with a potential secondary effect of high system voltage. That response is particularly likely if the protection response is slower than the voltage regulation response of the system.

The projects described in this report are the result of a multi-year effort by the U.S. Department of Energy to assist the Western Electricity Coordinating Council's (WECC's) Load Modeling Task Force (LMTF) as they attempt to address these modeling challenges. Although there are many tasks funded under the American Recovery and Reinvestment Act (ARRA) Interconnection Planning activities, this report updates Pacific Northwest National Laboratory's (PNNL's) progress on the following seven aspects: (1) Load Composition Model (LCM), (2) WECC support, (3) upgrade of commercial load composition; (4) aggregate motor protection model; (5) protection model of single-phase motors; (6) software tools to support WECC Joint Synchronized Information Subcommittee (JSIS) and Modeling and Validation Work Group (MVWG) activities; and (7) motor response and protection in commercial buildings. Some details are given below.

- **Load Composition Model:** PNNL developed the LCM and created a MATLAB version. The LCM is based on a component-based approach. The component-based load modeling approach is a bottom-up technique that consists of aggregating distribution loads according to standard load classes, specifying the types of devices comprised by those load classes, and then assigning the appropriate composition of the aggregated load to the various components of a suitable load model structure.
- **WECC support:** PNNL supported the WECC LMTF through the Phase 1 CMPLDW implementation. We were able to collect data from Bonneville Power Administration (BPA), the Salt River Project, Puget Sound Energy, Pacific Gas and Electric, and IdahoPower. This task included load composition and load shape analysis for these WECC members. We also developed a database for LCMs and utility data.
- **Upgrade of commercial load composition:** PNNL revised load composition data sets for commercial buildings that are temperature sensitive. A total of 96 simulations in EnergyPlus software

have been done for eight commercial building types in 12 climate zones. Commercial building data from the California Commercial End-Use Survey was upgraded by adding the HVAC load temperature sensitivity.

- **Aggregate load protection model:** PNNL developed an aggregated motor protection model for studying FIDVR events. The model considers motor behaviors in several different stages in sequence: pre-fault, fault, clear, reclose, recovery/trip, and restart. Different states, On, Off, Start, Stall, and Trip state, are used to describe motor responses in the voltage event. During FIDVR events, some fraction of the motors in each state transition to other states. The number of motors in each state changes depending on voltage level and the time duration in the fault. As a result, the aggregate power demand dynamically changes as the time increases.
- **Protection model of single-phase motor:** PNNL improved a single-phase motor model with motor protective device action. The model mimics contactor and thermal protection responses of motors, and captures the sensitivities of motor real and reactive power requirements to voltage and frequency.
- **Software tools to support WECC, JSIS, and MVWG activities:** PNNL has developed a Load Model Data Tool, Frequency Response Analysis Tool, and Power Plant Model Validation Tool in cooperation with BPA to support the WECC JSIS and MVWG.
- **Motor response and protection in commercial buildings:** PNNL developed building motor response tables for a given set of commercial building types with voltage variances and time frames of interest. We categorized motor protection and control responses for these voltage variances and times along with energy management system control logic restart times and motor protection trip delays. We identified “make and break” times of relays and contactors for the given voltage variances and recovery times. The results are shown in a set of tables giving our estimated motor response for the type of motor load, type of building, and level and duration of the voltage variance.

## **Acknowledgments**

We are particularly thankful to Joe Eto, Dmitry Kosterev, Steven Yang, Richard Bravo, Bernard Lesieutre, John Undrill, Donald Davies, and Ryan Quint for their support and contributions in these projects described in this report. We would like to give special thanks to Avtar Gill and Michael Gust for their review and comments on the motor protection in commercial buildings.





## Acronyms and Abbreviations

AMI	advanced metering infrastructure
AMR	automatic meter reading
ARRA	American Recovery and Reinvestment Act
BA	balancing authority
BPA	Bonneville Power Administration
CEUS	Commercial End-Use Survey
CMPLDW	Composite Load Model in PSLF
CMLD	Composite Load Model in PSS/E
COI	California-Oregon Intertie
DX	direct expansion
ELCAP	End-Use Load and Consumer Assessment Program
EMS	energy management system
FIDVR	Fault Induced Delayed Voltage Recovery
FRAT	Frequency Response Analysis Tool
FRM	frequency response measure
GE	General Electric
GUI	graphical user interface
HVAC	heating, ventilation, and air-conditioning
IEEE	Institute of Electrical and Electronics Engineers
JDBC	Java Database Connectivity
JSIS	Joint Synchronized Information Subcommittee
LCM	Load Composition Model
LMDT	Load Model Data Tool
LMTF	Load Modeling Task Force
MVWG	Modeling and Validation Work Group
NEMA	National Electrical Manufacturers Association
NERC	North American Electric Reliability Corporation
PG&E	Pacific Gas and Electric
PMU	phasor measurement unit
PNNL	Pacific Northwest National Laboratory
PPMV	Power Plant Model Validation Tool
PSE	Puget Sound Energy
RTU	roof top unit
SCADA	supervisory control and data acquisition
SCE	Southern California Edison
SRP	Salt River Project

TMY	typical meteorological year
VAV	variable air volume
VFD	variable frequency drive
WECC	Western Electricity Coordinating Council

# Contents

Executive Summary .....	iii
Acknowledgments.....	v
Acronyms and Abbreviations .....	vii
1.0 Background.....	1.1
2.0 Load Composition Modeling.....	2.1
2.1 WECC Load Composition Modeling .....	2.1
2.2 Load Composition Model Excel Version.....	2.5
2.3 Load Composition Model MATLAB version .....	2.7
2.4 Results of the Load Composition Model (MATLAB Version).....	2.16
2.4.1 Comparison and Validation.....	2.16
2.4.2 Climate-Zone Studies .....	2.19
3.0 WECC Support.....	3.1
3.1 Data Collection.....	3.1
3.2 Database Coordination System. ....	3.1
4.0 Update of Commercial Load Composition.....	4.1
4.1 Commercial Load.....	4.1
4.2 Temperature Sensitivity Method.....	4.2
4.2.1 Fix Temperature Sensitivity .....	4.2
4.2.2 Active Temperature Sensitivity.....	4.4
5.0 Aggregate Motor Protection Model.....	5.1
5.1 Aggregate Motor Protection Modeling .....	5.3
5.1.1 State Transition Modeling .....	5.3
5.1.2 State Transition Rate Specifications.....	5.7
5.2 Simulation Results.....	5.8
5.3 Conclusion.....	5.16
6.0 AC Motor Protection Model.....	6.1
6.1 Single-Phase Motor and Protection Modeling .....	6.1
6.2 Simulation Results.....	6.2
6.3 FIDVR Event Load Measurements Analysis and Its Methodologies .....	6.5
6.3.1 Background .....	6.7
6.3.2 Aggregate Motor Behavior.....	6.11
6.3.3 Event Analysis.....	6.13
7.0 Software Tools to Support WECC JSIS and MVWG Activities.....	7.1
7.1 Load Model Data Tool (LMDT) .....	7.1
7.1.1 System Requirements .....	7.3
7.1.2 Input Information Requirements .....	7.3

7.1.3	Generating Composite Model Using LMDT.....	7.6
7.1.4	Appending the Composite Load Models to the PSLF .dyd File.....	7.8
7.1.5	Appending the Composite Load Models to the PSS/E .dyr File .....	7.8
7.2	Frequency Response Analysis Tool (FRAT) .....	7.9
7.2.1	Main Features of FRAT .....	7.12
7.2.2	FR Tool User Interface.....	7.12
7.2.3	FRAT Requirements .....	7.26
7.2.4	Program Web Page.....	7.26
7.3	Power Plant Model Validation Tool (PPMV) .....	7.28
7.3.1	PPMV System Requirements .....	7.30
7.3.2	PPMV Prerequisites .....	7.30
8.0	Motor Response and Protection in Commercial Buildings .....	8.1
8.1	Introduction .....	8.1
8.2	Specific Motor Types and Applications.....	8.2
9.0	Conclusions .....	9.1
10.0	References .....	10.1
	Appendix A LCM Validation Results.....	A.1
	Appendix B SQL Code of Creating Database Schema.....	B.1
	Appendix C Database Entity Tables .....	C.1
	Appendix D Equations of the Single-Phase Motor Phasor Model.....	D.1
	Appendix E Temperature Sensitivity Table for Commercial .....	E.1
	Appendix F Load Composition Model - Climate Zone Study Results .....	F.1
	Appendix G Motor Dynamics Data Sample .....	G.1
	Appendix H Building Motor Response Tables .....	H.1

# Figures

Fig. 2-1. Composite load model.....	2.2
Fig. 2-2. Component-based load modeling.....	2.3
Fig. 2-3. Structure of the Load Composition Model.....	2.6
Fig. 2-4. Flowchart of the MATLAB version of the LCM .....	2.8
Fig. 2-5. An example of mode selection in the SetUp sheet in the INPUT file.....	2.11
Fig. 2-6. An example of city information in the SetUp sheet in the INPUT file .....	2.11
Fig. 2-7. An example of event data input format .....	2.12
Fig. 2-8. An example of climate zone inputs .....	2.13
Fig. 2-9. Basis of end-uses on weekdays/weekends and winter/summer.....	2.13
Fig. 2-10. Rules of association of the residential single-family.....	2.14
Fig. 2-11. An example of model parameters for residential load input .....	2.14
Fig. 2-12. An example of commercial load rules of association in the INPUT Excel file.....	2.15
Fig. 2-13. 24-h load shape for Portland .....	2.16
Fig. 2-14. Comparison results for BPA SCADA data, LCM v3.0, and LCM v5.0 .....	2.17
Fig. 2-15. Example load shape comparison for Portland .....	2.18
Fig. 2-16. An example load shape comparison for Boise .....	2.18
Fig. 2-17. An example load shape comparison for Phoenix .....	2.19
Fig. 3-1. Design of data storage and retrieval module .....	3.3
Fig. 3-2. Entity-relationship diagram.....	3.4
Fig. 3-3. Load shape results by extracting data from MySQL database .....	3.7
Fig. 4-1. Total building demand and HVAC demand for Portland small office building type.....	4.2
Fig. 4-2. HVAC load sensitivity for Portland small office .....	4.3
Fig. 4-3. Demonstration of HVAC load adding temperature sensitivities .....	4.5
Fig. 4-4. Example of HVAC load adding temperature sensitivities .....	4.5
Fig. 4-5. Examples of simulation results of single and multi family residential loads and the 1°F load difference: (a) Single Family Los Angeles; (b) Multi Family Los Angeles; (c) Single Family Portland; (d) Multi Family Portland .....	4.7
Fig. 5-1. Aggregated motor protection model.....	5.3
Fig. 5-2. Time series of main stages of aggregated motor protection model, showing system stage and motor states .....	5.5
Fig. 5-3. Motor distribution among the motor states .....	5.6
Fig. 5-4. P-V/Q-V curves.....	5.9
Fig. 5-5. Dynamic responses of aggregated motor protection model in case A .....	5.11
Fig. 5-6. Dynamic responses of aggregated motor protection model in cases B and C.....	5.12
Fig. 5-7. Dynamic responses of aggregated motor protection model in case D, scenario 1 .....	5.14
Fig. 5-8. Dynamic responses of aggregated motor protection model in case D, scenario 2 .....	5.15
Fig. 5-9. Dynamic responses with different conditions .....	5.16

Fig. 6-1. Behaviors of motor voltage, active power, reactive power, and motor state .....	6.3
Fig. 6-2. Active power and reactive power vs. voltage.....	6.3
Fig. 6-3. Behaviors of motor voltage, active power, reactive power, and motor state in a longer time scale .....	6.4
Fig. 6-4. Motor temperature.....	6.5
Fig. 6-5. Delayed voltage recovery following a 230 kV transmission fault in Southern California.....	6.6
Fig. 6-6. Induction motor equivalent circuits including losses (left) and ignoring losses (right) .....	6.7
Fig. 6-7. Power slip curves for typical induction motor .....	6.9
Fig. 6-8. Induction motor thermal trip curves (from IEEE Standard 620-1996) .....	6.13
Fig. 6-9. PQube voltage and power FIDVR event data .....	6.14
Fig. 6-10. Analysis of motor trips from event data.....	6.15
Fig. 6-11. Motor trip events (top) and motor sizes (bottom) based on event data .....	6.16
Fig. 7-1. LMDT graphical user interface .....	7.2
Fig. 7-2. LMDT settings .....	7.6
Fig. 7-3. LMDT output – generated composite load model.....	7.7
Fig. 7-4. LMDT error log.....	7.7
Fig. 7-5 Appending the composite load models to the PSLF .dyd file .....	7.8
Fig. 7-6. FRAT (Version 1.0) GUI .....	7.10
Fig. 7-7. FRAT (Version 2.0) GUI .....	7.11
Fig. 7-8. FRAT main GUI.....	7.13
Fig. 7-9. Float and hide function of the tool .....	7.14
Fig. 7-10. FRAT toolbar panel.....	7.14
Fig. 7-11. Events database screen .....	7.15
Fig. 7-12. Event characteristics screen.....	7.17
Fig. 7-13. Event plot screen .....	7.20
Fig. 7-14. Baseline plot screen.....	7.21
Fig. 7-15. Baseline plot range selector.....	7.21
Fig. 7-16. Statistical analysis of the interconnection FRM.....	7.22
Fig. 7-17. Event plot in “edit” mode.....	7.23
Fig. 7-18. Frequency response analysis report screen.....	7.25
Fig. 7-19. FRS 1 form.....	7.26
Fig. 7-20. FRAT repository (main Wiki page) .....	7.27
Fig. 7-21. FRAT documentation .....	7.27
Fig. 7-22. PPMV main screen GUI.....	7.29
Fig. 7-23. PPMV create new project screen.....	7.30
Fig. 8-1. Summary of specific type of motors .....	8.4
Fig. 8-2. Standard EMS equipment restart time.....	8.5

## Tables

Table 2-1. Facility types by customer class .....	2.5
Table 2-2. End-use load associations (single-family residential, Portland, Oregon).....	2.5
Table 2-3. Load mix on four types of feeders.....	2.10
Table 2-4. Code INPUT structure.....	2.10
Table 2-5. Code OUTPUT structure.....	2.10
Table 2-6. Residential, commercial, industrial, and agricultural load fractions .....	2.17
Table 2-7. Motor D percentage table from the climate zone studies .....	2.19
Table 3-1. The relationship between entities .....	3.6
Table 4-1. Climate zones and representative cities in the Load Composition Model.....	4.1
Table 4-2. Commercial building types in the Load Composition Model.....	4.1
Table 4-3. HVAC temperature sensitivity (kW/Ksqft/°F) for Seattle, WA, and Portland, OR .....	4.4
Table 5-1. Model parameters .....	5.9
Table 7-1. Default composite data specification.....	7.4
Table 7-2. Bus data specification.....	7.5
Table 7-3. Event characteristics columns definition.....	7.15

# 1.0 Background

The number of events known as Fault Induced Delayed Voltage Recovery (FIDVR) has been increasing in Southern California and Florida in the past several years. After a fault has been cleared, system voltage remains at significantly reduced levels for several seconds. Motor protective device action can cause significant load loss, resulting in a potential secondary effect of high system voltage [1]. The fact that FIDVR events are not well represented in power system studies has increased interest in load modeling, particularly loads with a high penetration of motors. A reason for this interest is that the dynamic load behavior profoundly influences the system dynamic response.

Most load models use stationary (that is, time-invariant), voltage-dependent polynomial load representation. The loads may be represented as constant impedance (Z), constant current (I), or constant power (P). These models do not provide a true representation of the dynamic response of the load, particularly in view of the increased penetration of residential air conditioners in recent years.

Ordinarily, modelers prefer to use the minimum number of load model components necessary to maintain fidelity of the model and capture the diversity in the dynamic characteristics of the relevant end-uses. For motors, the problem is challenging. The metrics for classifying direct-drive motor performance are (a) number of phases, (b) electrical characteristics, (c) load characteristics, (d) inertial behavior of combined motor and load, and (e) protection and controls. (Note that variable frequency drive [VFD] motors are classified as electronic loads.) It has been shown that the most important characteristic that distinguishes between motors is the kind of load driven, i.e., constant torque versus speed-dependent torque.

Motors that drive constant-torque loads (such as compressors) are much more susceptible to stalling than motors whose speeds increase when their mechanical load decreases (such as fans<sup>1</sup>). These constant-torque motors consequently have a more significant adverse impact on voltage stability and ultimately on the damping of inter-area power oscillations. Furthermore, the behavior of three-phase motors is quite different from single-phase motors, which have a higher propensity for stalling close to normal operating voltages. Finally, the combined inertia was found to a significant differentiating factor, particularly in situations where transmission faults are being considered.

Based on this analysis, the following four categories were identified as load components for motors:

- Motor A represents three-phase motors driving constant torque loads, such as commercial and industrial air-conditioning and refrigeration compressors.
- Motor B represents so-called “speed squared” motors with large inertia, such as fan motors.
- Motor C represents so-called “speed squared” motors with low inertia, such as water pumps.
- Motor D represents single-phase motors driving constant torque loads, such as residential air-conditioner, refrigerator, and heat pump compressors.

Motor D is of special interest because it can represent the behavior of residential air-conditioner compressors following a transmission system fault.

---

<sup>1</sup> For example, the reason a vacuum cleaner motor speeds up when the air intake is blocked is that the motor and fan are no longer moving any air, so the mechanical load is decreased.



Some while ago, the Western Electricity Coordinating Council (WECC) developed a composite load model [2] that considers Motors A, B, and C, represented by three-phase motor models, and Motor D, which is represented by a *performance* model. The performance model was derived from numerous motor test data. After that, Bernard C. Lesieutre, Dmitri Kosterev, and John Undrill developed a single-phase phasor induction motor model to represent a residential air-conditioner model (Motor D) [3].

More recently, WECC began developing a measurement-based approach to load modeling. A measurement-based approach is a top-down method in which an appropriate load model structure is defined and the component compositions (static and dynamic) and associated parameter values are estimated directly from disturbance measurements made in the field. Some form of optimization technique is needed to relate measured values to model parameters. Because the measurement-based approach means that the modeled load behavior is based on a measured response (rather than an assumed set of end-use devices and their individual compositions), results may be expected to be representative. The use of this kind of model allows load models to be updated periodically to reflect changes in load composition over time (or geography) as new measurements are obtained.

The component-based load modeling approach we used is a bottom-up technique. It consists of three major steps: (1) defining load classes to contain known load types, (2) specifying the types of devices comprised by those load classes, and then (3) finding a suitable load model mixture that reproduces the observed behavior. In this approach, a common load model structure and an associated set of parameter values are used throughout the system model. What is changed in the system model is the composition (e.g., percentage motor load versus static load) from bus to bus. This percentage composition may be kept constant throughout the system model because there is insufficient empirical data to justify changing it.

The bottom-up method for load composition estimation is based on end-use analysis results from building population surveys, building simulations, and end-use metering programs. It uses this kind of information to develop estimates for the fractions of different classes of load that are operating at any given time. Typically, the data collected is separated hierarchically by customer class, building type, and end-use type: residential, commercial, industrial, and agricultural loads are broken down in facility types.

The following sections of the report examine how our work has the potential to address problems related to load modeling and load composition data modeling, focusing primarily on the following:

1. Load Composition Model (LCM): Pacific Northwest National Laboratory (PNNL) developed the LCM and created a MATLAB version. The LCM is based on a component-based approach. The component-based load modeling approach is a bottom-up technique that consists of aggregating distribution loads according to standard load classes, specifying the types of devices comprised by those load classes, and then assigning the appropriate composition of the aggregated load to the components of a suitable load model structure.
2. WECC support: PNNL supported the WECC Load Modeling Task Force (LMTF) through the Phase 1 CMPLDW implementation. We were able to collect data from Bonneville Power Administration (BPA), the Salt River Project, Puget Sound Energy (PSE), Pacific Gas and Electric (PG&E), and IdahoPower. This task included load composition and load shape analysis for these WECC members. We also developed a database for LCMs and utility data.

3. Upgraded commercial load composition: PNNL revised load composition data sets for commercial buildings that are temperature sensitive. A total of 96 simulations in EnergyPlus software have been done for eight commercial building types in 12 climate zones. Commercial building data from the California Commercial End-Use Survey was upgraded by adding the heating, ventilation, and air-conditioning (HVAC) load temperature sensitivity.
4. Aggregate load protection model: PNNL developed an aggregated motor protection model for studying FIDVR events. The model considers motor behaviors in several different stages in sequence: pre-fault, fault, clear, reclose, recovery/trip, and restart. Different states, On, Off, Start, Stall, and Trip state, are used to describe motor responses in the voltage event. During FIDVR events, some fraction of the motors in each state transitions to other states. The number of motors in each state changes depending on voltage level and the time duration in the fault. As a result, the aggregate power demand dynamically changes as the time increases.
5. Protection model of single-phase motor: PNNL developed a protection model for a single-phase motor model. The model mimics contactor and thermal protection responses of motors, and captures the sensitivities of motor real and reactive power requirements to voltage and frequency. It reasonably predicts the stalling phenomena, and accurately represents motor current, and real and reactive power during the stalled state.
6. Software tools to support WECC, Joint Synchronized Information Subcommittee (JSIS), and Modeling and Validation Work Group (MVWG) activities: PNNL has developed a Load Model Data Tool (LMDT), Frequency Response Analysis Tool (FRAT), and Power Plant Model Validation Tool (PPMV) in cooperation with BPA to support the WECC JSIS and MVWG.
7. Motor response and protection in commercial buildings: PNNL developed building motor response tables for a given set of commercial building types with voltage variances and time frames of interest. We categorized motor protection and control responses for these voltage variances and times along with energy management system (EMS) control logic restart times and motor protection trip delays. We identified “make and break” times of relays and contactors for the given voltage variances and recovery times. The results are shown in a set of tables giving our estimated motor response for the type of motor load, type of building, and level and duration of the voltage variance.

## 2.0 Load Composition Modeling

### 2.1 WECC Load Composition Modeling

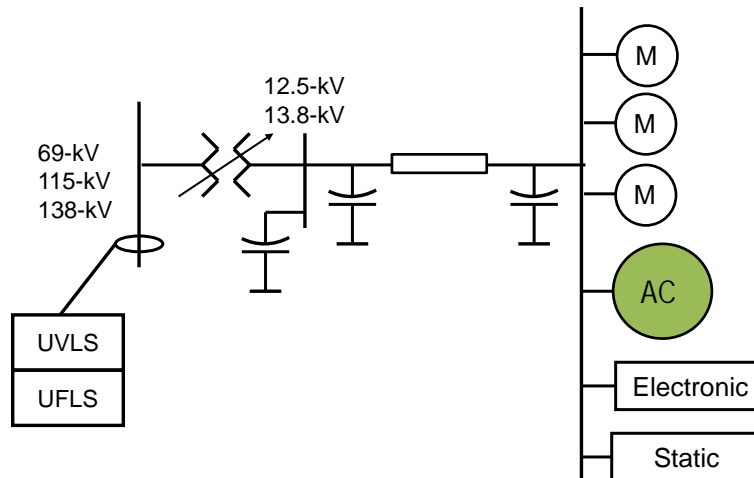
The BPA Energy Efficiency and Transmission Planning department/division/group/committee have been engaged in an extensive effort to update the End-Use Load and Consumer Assessment Program (ELCAP) data set sent to PNNL. They have been updating the load composition using new commercial and residential surveys and load monitoring programs. PNNL has been engaged with BPA in the effort to collect, analyze, and incorporate this new load composition data in the CMPLDW.

The WECC LMTF led the development and implementation of a composite load model to replace the much simpler models previously used. Currently, the load model is implemented in General Electric (GE) PSLE, Siemens PTI PSS/E, and PowerWorld grid simulators. A conceptually similar model is implemented in PowerTech's TSAT. The new model has been shown to be capable of capturing the phenomenon of fault-induced delayed voltage recovery and allowing a very good match of inter-area power oscillations in the West.

Load composition refers to process of determining the fraction of the total customer electric load that consists of different load components, such as motors, constant impedance/current/power, and electronic loads. The methodology used to compute the percentage of the load that is attributed to the installed capacity of each load component was developed initially for WECC in 2008 by the LMTF. The LMTF philosophy is to develop component-based load models, then validate and tune the models' performance using dynamic measurement. This was done in three major steps: (1) develop the structure of the composite load model, (2) obtain load model data, and (3) validate the load model through system performance studies.

The load model includes distribution feeder equivalent data (e.g., substation transformer characteristics, feeder equivalent impedances), load parameters (e.g., motor reactances, time constants, inertias, loads), and load fractions (e.g., motor, constant, electronic). The objective is to minimize the number of load components modeled while retaining fidelity to the diversity in dynamic characteristics of end-uses. Electric motors in particular require several distinct characteristics be preserved, specifically single- or three-phase supply, electrical characteristics, nature of the driven load, combined inertia of the motor and load, and motor protection and controls. Electronic load models must retain elements that identify the response of the power conversion system to voltage fluctuations, particularly with respect to decoupling of the primary and secondary sides.

Fig. 2-1 shows the composite model structure.



**Fig. 2-1.** Composite load model

Fig. 2-1 shows two particular features of the model:

- The model represents “electrical distance” from the transmission bus to the end-use bus by including a substation transformer and some type of a feeder equivalent.
- The model represents the diversity in characteristics of electrical end-uses by having four motor types, power electronic loads, and a static component.

The load components are:

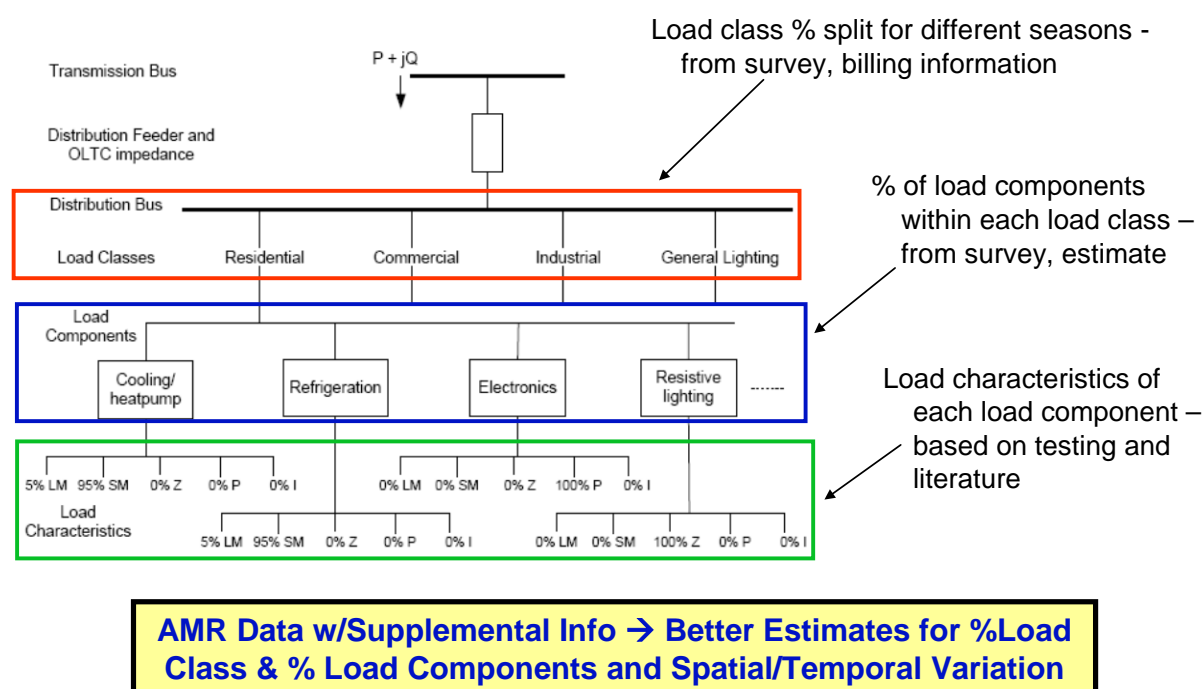
- Motor A – three-phase motor with constant torque load, representative of compressor motors found in commercial air-conditioners and refrigerators
- Motor B – high inertia motor with speed-dependent load, representative of motors driving fans
- Motor C – low inertia motor with speed-dependent load, representative of motors driving pumps
- Motor D – residential air-conditioners and heat pumps
- Power electronic loads, representative of VFDs and computing
- Static load, representative of lights, resistive space-heating, and water-heating

Obtaining load composition data is the most difficult part of this process. Load composition is affected by prevailing ambient conditions (temperature, humidity, and solar gains), the physical and thermal characteristics of buildings, the installed capacities of equipment, and human activities. In some areas, pronounced micro-climate and latitude affects must also be considered. The WECC LMTF opted to use a “bottom-up” approach to developing the load composition. For commercial buildings, the California Commercial End-Use Survey (CEUS) is used as the primary source for commercial load composition. For residential loads, estimates based on ELCAP data were developed.

WECC/LMTF does not recommend using advanced metering infrastructure (AMI) disaggregation techniques to attempt to reconstruct end-use load profiles. It has been suggested that the bottom-up approach could be augmented by using AMI data. The proposed enhancement relies on the fact that AMI data typically collects real or total power observations at 15 minute or hourly intervals. However, the data

is not suitable for a direct observation of the individual end-use loads or the composition, because the additional time-resolution of AMI does not provide any additional observability of the states of individual loads “behind” the meter. To date, the only known methods for measuring the states of end-use load are direct end-use meter and real-time pricing systems that employ end-use bidding strategies.

The overall methodology of the component-based load modeling approach is shown Fig. 2-2. The load at a distribution feeder can be categorized into different load classes and each load class can be represented by different load components. The existing practice is to collect information from survey or billing data for each load class and identify the load components’ percentages. There is a potential to use automatic meter reading (AMR) data to get better estimates of load classes as opposed to using customer survey information only to estimate the load components. The added benefit of using AMR data is that it will capture seasonal variations in the loads.



**Fig. 2-2.** Component-based load modeling

The load model affects two applications in particular: stability studies and planning studies. Good estimates of the load model fractions are essential for power system stability studies. Load composition is greatly affected by many factors, such as climate, feeder type, season, time of day, ambient conditions, and others. Because of this, load model fractions are among the most challenging pieces of the data to obtain.

Power system planning studies are done for a variety of seasonal system conditions, the most common are summer peak, super-peak and off-peak, shoulder peak and off-peak, and winter peak and off-peak. Specific conditions may be of interest for model validation studies. We expect the new Load Composition Model (LCM) to provide the load composition estimates for the variety of loading conditions.

The following information and data sources are used to derive load model fractions:

- The 2006 California CEUS is a detailed survey of commercial loads in California that provides load composition and shapes for various types of commercial buildings (office, grocery, retail, education, etc.) for 15 climate zones, including normal, hot, cold and weekend days.
- The 1983-1990 ELCAP provides an overview of residential consumption patterns in residential homes in the Pacific Northwest.
- The Florida Solar Energy Center provides research highlights from a 2002 large-scale residential monitoring study in a hot climate (FSEC-PF-369-02), including load shapes and load composition for residential homes in Florida.
- The 2002 Lawrence Berkeley National Laboratory report “Electricity Use in California: Past Trends and Present Usage Patterns” (LBL-47922) provides load shapes and composition for California for on-peak summer days.
- BPA data on residential load shape and HVAC data from Ashland, OR.
- 5-minute and hourly supervisory control and data acquisition (SCADA) data to verify the calculated load shapes.
- Residential and commercial load shapes published by Southern California Edison (SCE).

Traditionally, measurement-based approaches to load characterization have used a top-down method in which a load model structure is defined and the component compositions (static and dynamic) are estimated directly from disturbance measurements in the field.

The primary advantage of the measurement-based approach is that the load behavior is modeled from a directly measured response rather than an assumed set of end-use devices and their individual compositions. This allows load models to be updated to reflect changes in load composition over time and across geographic changes as measurements are obtained through the natural course of events.

The measurement-based approach is limited in the following respects:

- There is a limited amount of suitable disturbance data from which load model composition and parameters can be estimated.
- It is difficult to derive load model parameters where discontinuities in load response are observed during severe voltage sags, e.g., delayed voltage recovery due to motor load stalling or loss of load due to motor load (or other loads) tripping.
- There are sometimes multiple solutions to the optimization problem, yielding many sets of parameter values instead of one unique set.

The component-based load modeling approach is a bottom-up technique of three steps:

- Aggregating distribution loads according to standard load classes
- Specifying the types of devices comprised by those load classes
- Assigning the appropriate composition of the aggregated load to the various components of a suitable load model structure

This approach uses a common load model structure and associated set of parameter values throughout the system model. What is changed throughout the system model is the percentage composition (e.g., percentage motor load versus static load) from bus to bus. In most cases, even this percentage composition may be kept constant throughout the system model because of the lack of better knowledge.

The bottom-up method for load composition estimation uses results from building population surveys, building simulations, and end-use metering programs to develop estimates for the fractions of loads that are operating at any given time. Typically, the data collected is separated hierarchically by customer class, building type, and end-use type: residential, commercial, industrial, and agricultural loads are broken down in facility types, as illustrated in Table 2-1.

**Table 2-1.** Facility types by customer class

Residential	Commercial	Industrial	Agricultural
Single family	Small/Large office	Idiosyncratic	Idiosyncratic
Multi family	Retail/Lodging		
	Grocery/Restaurant		
	School/Health		

Each facility type has a fraction of end-use equipment associated with it, which is then associated with each load component, as illustrated in Table 2-2.

**Table 2-2.** End-use load associations (single-family residential, Portland, Oregon)

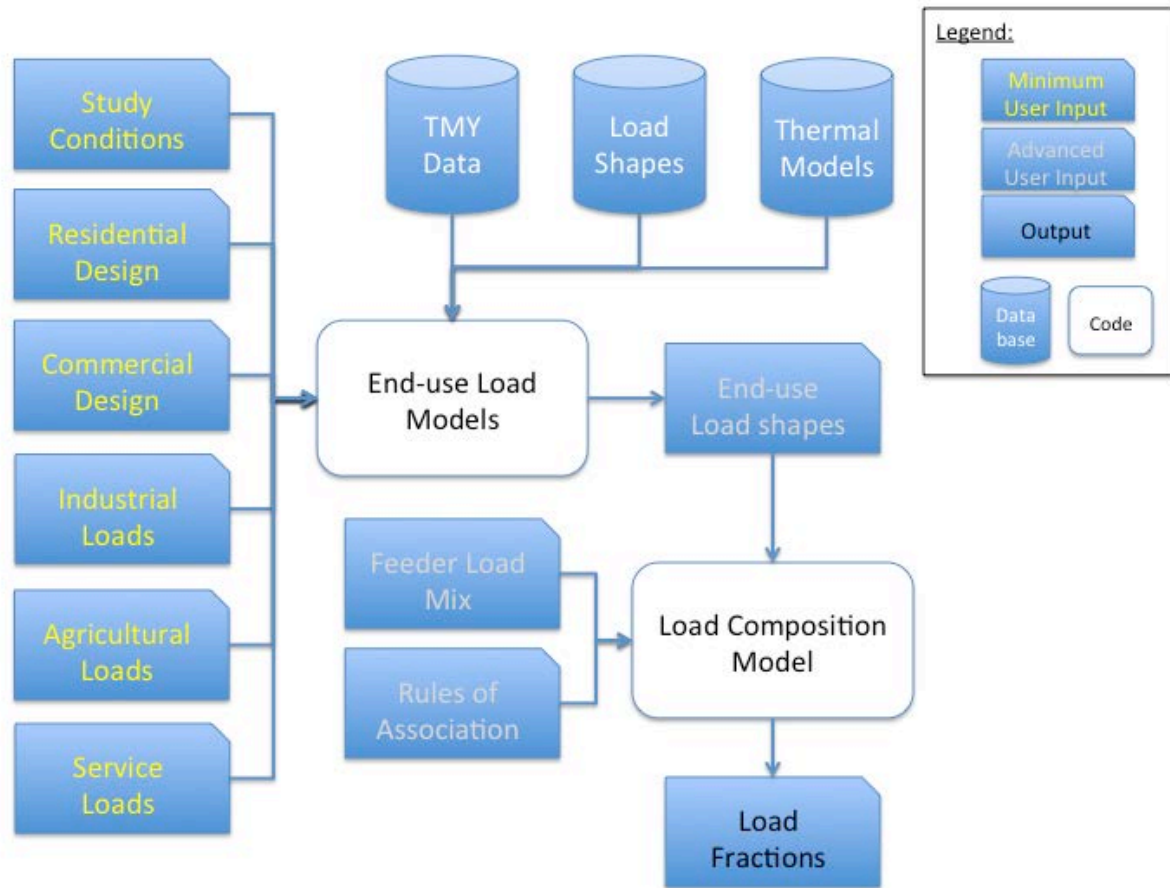
	Electronic	Motor				Z		I		P	
		A	B	C	D	Real	React.	Real	React.	Real	React.
Cooking	30%				10%	60%					
Hotwater						100%					
Lighting						90%		10%	-2%		
Plugs	90%					90%					
Washing					70%	30%					
Heating					20%	80%					
Cooling					100%						
Refrigeration	10%				90%						

Assumptions about gas versus electric cooking, space heating, and water heating are also generically applied to a region. In reality, these numbers can vary widely within a city depending on the construction year and the availability of natural gas or propane.

We incorporated the above information in the LCM using a bottom-up method. The Sections 2.2 through 2.4 present the LCM development and results.

## 2.2 Load Composition Model Excel Version

PNNL has developed the Excel version LCM. The structure of the LCM is shown in Fig. 2-3.



**Fig. 2-3. Structure of the Load Composition Model**

Given a known set of conditions, the bottom-up method can identify which end-uses are operating and, through a series of successive products, one can compute the final load component fractions. The challenge is thus to determine the prevailing usage of each load at the time being considered. Several factors affect which loads are operating at any given time and the amount of power they consume when operating, including:

- **Temperature** – outdoor air temperature principally affects the duty cycle and the efficiency of HVAC equipment. When the outdoor air temperature is near a building's balance point (the temperature at which all heat gains and heat losses balance), the duty cycle of the HVAC approaches zero. As the outdoor air approaches the heating or cooling design temperature, the duty cycle approaches unity. Furthermore, air-conditioning system and heat-pump heating system efficiency degrades as the temperature approaches the design temperature. Finally, many heat-pump heating systems have auxiliary heating modes that do not utilize a compressor, but instead use a resistance heating element.
- **Humidity** – relative humidity principally affects the latent heat load on air-conditioning systems. When the indoor air humidity is above about 50%, the latent load on the air-conditioner begins to rise. Near saturation, the latent heat load can be as high as 30% of the total load on the air-conditioning system.



- Solar – heat gain from insolation can significantly increase the cooling loads and significantly decrease the heating loads. This is especially true when the sun is close to the horizon and solar radiation is normal to the glazing surfaces buildings, such as in the early morning and late afternoon, or in northern latitudes.
- Occupancy – building occupancy can dramatically affect loads through the behavior of the people. Residential loads often peak once in the morning and once in the evening. This is normally determined by day of week and hour of day.
- Operations – commercial buildings undergo a morning setup load as the building is readied for weekday occupancy. Many residential thermostats have temperature setback schedules that can result in periods when the heating or cooling equipment is running 100% of the time, or not at all, depending on whether the temperature is floating to a new set point or being driven to the new set point.
- Design – the design, construction, and type of equipment use significantly affect the net electric load observed during various times of the year. In regions of the country where natural gas is readily available, the majority of homes use gas water heaters, cooking, and heating systems. In regions where electricity was historically inexpensive or gas is less accessible, electric water heating, cooking, and space heating is more common.

The most common approach to determining load composition is to examine end-use survey data, such as the ELCAP conducted by BPA between 1984 and 1994 in the Pacific Northwest region of the United States. However, the highly regional nature of this kind of data and the absence of current data makes it necessary to update existing data sets by making adjustments to account for climate variations, changes in construction quality and methods, changes in equipment performance and efficiency, and changes in consumption purchasing and evolving use habits of building occupants. A variety of approaches can be used to perform this task and results are generally mixed. One way to address the issue related to changing load devices is to actually test the behavior of specific load devices in a controlled laboratory environment. In fact, EPRI recently was engaged in work of this nature in testing several commercial air-conditioning units in the laboratory. One of the benefits of this type of “component” testing is the ability to better understand the discontinuous behavior of such load components and thus to be able to emulate the behavior in the modeling effort, e.g., actions such as motor contactor drop out and air-conditioner thermal overload relays.

Overall, bottom-up load composition methods remain difficult to implement generally and are only used when sufficient time and effort can be expended on modeling the loads in detail. The advantages of this approach include the following:

- Promotes correlation to the physical characteristic of end-use devices
- Utilizes load class data from individual substation, which is generally available

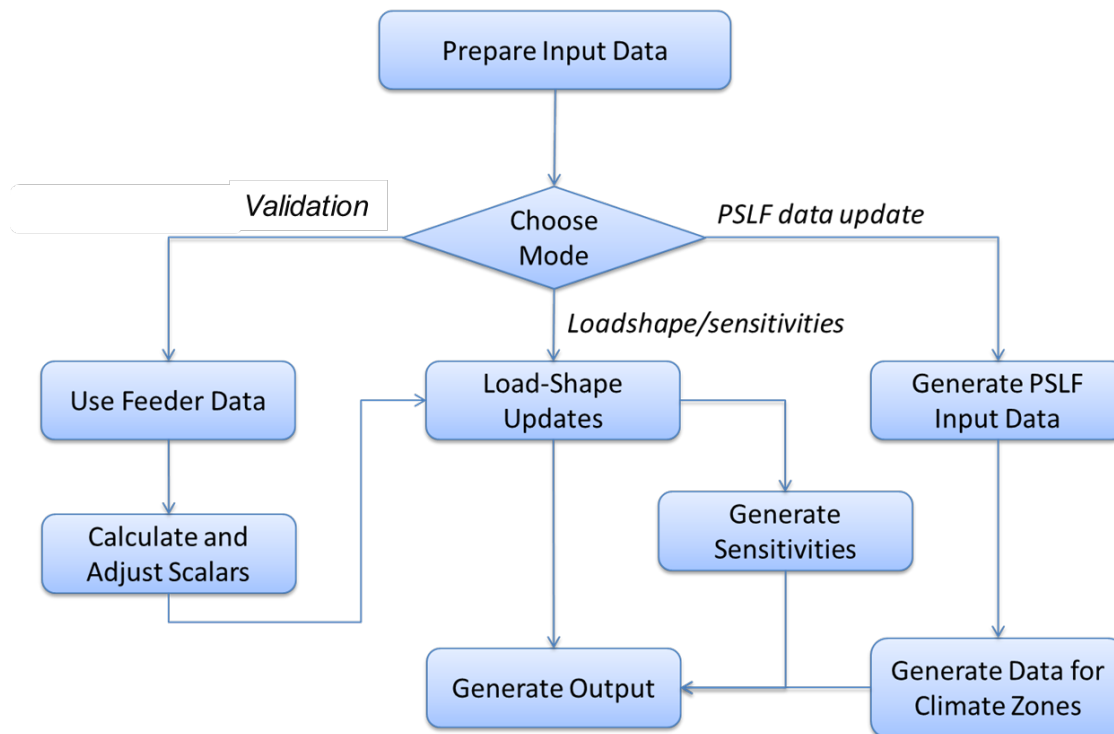
## **2.3 Load Composition Model MATLAB version**

PNNL has developed the LCM in MATLAB. The MATLAB version gives that developer more abilities to upgrade the LCM. Features of the MATLAB version of the LCM are:

1. Input study type and conditions

2. Residential, commercial, industrial, agriculture design
3. Fractions of motors, ZIP, and electronics
4. Output load shapes
5. Temperature sensitivity study
6. Given load percentage of R, C, I and A, ability to get scalars for RCIA
7. Curve fitting to find percentage of R, C, I and A
8. Make validation process easier
9. Input setting to determine what kind study you want to do
10. Choose one climate zone typical meteorological year (TMY) data manually
11. Automatically read though all climate zones' TMY data, and create output files

A flowchart of the MATLAB version of the LCM is shown in Fig. 2-4.



**Fig. 2-4.** Flowchart of the MATLAB version of the LCM

There are several MATLAB versions of the LCM:

1. Version 0.0: The original MATLAB version created according to “Load Composition Tool Prototype (EXCEL) v1.7.6”
2. Version 0.5: Modify calculation for residential part comparing to Version 0.0. Consider residential basis according to 12 different climate zones, additional residential basis data is needed as input.

3. Version 1.0: Add modified calculation for commercial part comparing to Version 0.5. Consider sensitivity data of eight commercial load sources, additional sensitivity data is needed as input (only for NWV Portland).
4. Version 2.0: Add commercial temperature sensitivity data for all 12 climate zones comparing to Version 1.0. Consider sensitivity data of eight commercial load sources, additional sensitivity data is needed as input.
5. Version 3.0: Take the hard-coded data out of MATLAB code to INPUT Excel file. User can easily modify data in the residential and commercial model design.
6. Version 4.0: Modify the input read function. Added time lag to the HVAC load of single family load to represent temperature delay in mass.
7. Version 5.0:
  - Updated cooking and hot water power densities (w/sqft).
  - Increased plug load fraction to account for rising base load.
  - Added commercial load temperature sensitivity for eight types of commercial building loads and for 12 climate zones.
  - Increased study types from three to five for climate zone studies.
  - Updated cooling to be a function of temperature for normal and cool summer.
  - Updated normal summer max temperature.
  - Updated cool summer max temperature.
  - Updated winter min temperature.

In the calculation process, there are several modes as described below.

- Basic Mode:
  - Calculate the 24-hour load shape for a single city with specified study conditions from input data.
- Sensitivity & Feeders Mode
  - Temperature Sensitivity
    - Calculate sensitivities of model results to temperature with 1 degree down in cooling season or 1 degree up in heating season.
  - Feeders
    - Calculate load compositions of  $3 \times 4 \times 3 = 36$  models
    - 3 study types: 1 = winter peak, 2 = typical, 3 = summer peak
    - 4 different hours (0 = midnight, ..., 12 = noon, ...): 1 = 6, 2 = 9, 3 = 15, 4 = 18
    - 3 different composition scalars: 1 = 100% Res, 2 = 50% Res 50% Com, 3 = 100% Com

- Validation process
  - Compare 24-hour observations of total power with the LCM model results by obtaining optimal customer composition scalars.
- Climate Zones
  - By using different types of load mix scalars, calculate load compositions for multiple climate zones (12 climate zone representative cities) with specified day type and hour.
  - 5 study types: 1 = normal summer, 2 = hot summer, 3 = cool summer, 4 = shoulder, 5 = winter

**Table 2-3.** Load mix on four types of feeders

Load Mix	Res	Com	Ind	Agr	Data	Service
RES	0.75	0.23	0	0	0	0.02
COM	0.2	0.73	0	0	0.05	0.02
MIX	0.45	0.48	0	0	0.05	0.02
RAG	0.4	0.2	0.15	0.25	0	0

**Table 2-4.** Code INPUT structure

Sheet Names		
1	Setup	Required (important)
2	CityInfo	Required
3	EventData	Optional
4	Residential	Required
5	Commercial	Required
6	Industrial	Required
7	Agricultural	Required
8	Composition	Required
9	ClimateZones	Optional
10	Basis	Required
11	Scommercial	Required
12	Model	Required

**Table 2-5.** Code OUTPUT structure

Sheet Names		
1	LoadShape	Required/Optional
2	Sensitivity	Optional
3	Feeders	Optional
4	Curve-Fit	Optional
5	ClimateZones	Optional

Several INPUT file examples are shown from Fig. 2-5 through Fig. 2-11:

1. Mode selection in the SetUp sheet in the INPUT file. Fig. 2-5 shows an example of Setup sheet in the INPUT file. We recommend that user only change the highlighted parts.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N															
1	This is the input file for WECC Load Composition Modeling (MATLAB)					Input data is marked by		, if there is no data, filled with 0.																					
2						Default value is marked by																							
3	Model Set-Up																												
4		0 = no	1 = yes			Comment:																							
5	If calculate sensitivity and output?	1				Calculate temperature sensitivities with 1 degree down in cooling season or 1 degree up in heating season.																							
6																													
7	If calculate feeders and output?	1				Calculate results for winter peak, typical shoulder, summer peak with 4 different hours and 3 different composition scalars.																							
8																													
9	If use default value for StudyType?	0			3	if B9 = 1, Use D9 - default StudyType	1=Winter peak, 2=Typical, 3=Summer peak, 4=Event																						
10				Study Type	4	if B9 = 0, Use D10 to input value.																							
11																													
12	If use default values for StudyMonth, StudyWeekdays, StudyHour?	0			7	if B12 = 0, Use D12-14 to input values.	1=Jan, ... 12=Dec																						
13				Study Month			1=Sun, ... 7=Sat, 8=Holiday																						
14				Study Weekdays	4		0=midnight, ..., 12=noon, ...																						
15				Study Hour	17																								
16																													
17																													
18	If perform parameter estimation to fit observations and output curve-fit?	0				if = 1, SCADA data in "EventData", will be used to compare total loads over 24h.	<table><tr><th colspan="4">Input Customer Composition</th><th>Percent</th></tr><tr><th>R</th><th>C</th><th>I</th><th>A</th><th></th></tr><tr><td>0.75</td><td>0.23</td><td>0.00</td><td>0.02</td><td>100%</td></tr></table>				Input Customer Composition				Percent	R	C	I	A		0.75	0.23	0.00	0.02	100%				
Input Customer Composition				Percent																									
R	C	I	A																										
0.75	0.23	0.00	0.02	100%																									
19	only works when Study Type = 4					G18-J18 will be used as RCIA's initial values.	Target load:	5.0	MW																				
20						if = 0, G18-J18 will be used as RCIA's fixed values.																							
21																													
22																													
23																													
24																													
25	If run Load Mix Model for Climate Zones and output?	0				if =1, all the other inputs in SET-UP are not used. LCM will be calculated due to different Load Mix and Climate Zones. Parameters are defined in sheet "ClimateZones" in INPUT files.																							
26																													
27																													
Introduction   Setup   CityInfo   EventData   Residential   Commercial   Industrial   Agricultural   Composition   ClimateZones   Basis   SCommercial   Model																													

Fig. 2-5. An example of mode selection in the SetUp sheet in the INPUT file

## 2. CityInfo:

This sheet shows the electricity usage fractions of end-uses over total energy usage.

Cities	Latitudes	City Index	Electric heat	Heat pumps	Electric hotwater	Electric cooking	Electric drying	Air-conditioning	Climate Zones	Climate Zone Index
TMV Data Names	1	2	3	4	5	6	7	8	9	10
Albuquerque NM	35.1	1	0.25	0.25	0.30	0.30	0.75	0.90	HID	12
Bakersfield CA	35.4	2	0.25	0.25	0.30	0.30	0.75	0.90	SCI	10
Barstow CA	34.3	3	0.25	0.25	0.30	0.30	0.75	0.90	0	0
Boise ID	43.6	4	0.75	0.25	0.70	0.70	0.75	0.75	NWI	3
Cheyenne WY	41.2	5	0.75	0.25	0.70	0.70	0.75	0.50	0	0
Denver CO	39.8	6	0.75	0.25	0.30	0.30	0.75	0.80	HID	12
Eugene OR	44	7	0.75	0.25	0.70	0.70	0.75	0.30	0	0
Eureka CA	40.9	8	0.25	0.50	0.70	0.70	0.75	0.20	0	0
Fresno CA	36.7	9	0.25	0.50	0.30	0.30	0.75	0.75	0	0
Helena MT	46.6	10	0.75	0.25	0.70	0.70	0.75	0.20	RMN	4
Las Vegas NV	36.2	11	0.25	0.75	0.30	0.30	0.75	0.95	DSW	11
Long Beach CA	33.8	12	0.50	0.50	0.30	0.30	0.75	0.50	0	0
Los Angeles CA	34.1	13	0.50	0.50	0.30	0.30	0.75	0.30	SCV	9
Medford OR	42.3	14	0.75	0.25	0.70	0.70	0.75	0.30	NCI	7
Phoenix AZ	33.4	15	0.25	0.50	0.30	0.30	0.75	0.95	DSW	11
Portland OR	45.5	16	0.50	0.25	0.30	0.30	0.75	0.60	NWV	2
Prince George BC	53.5	17	0.75	0.25	0.70	0.70	0.75	0.10	0	0
Redmond OR	44.3	18	0.50	0.25	0.30	0.30	0.75	0.75	0	0
Reno NV	39.5	19	0.50	0.25	0.70	0.70	0.75	0.90	HID	12
Richland WA	46.3	20	0.50	0.25	0.70	0.70	0.75	0.75	NWI	3
Sacramento CA	38.6	21	0.25	0.25	0.30	0.30	0.75	0.75	NCV	6
Salt Lake City UT	40.8	22	0.50	0.25	0.70	0.70	0.75	0.75	HID	12
San Diego CA	32.7	23	0.25	0.25	0.30	0.30	0.75	0.25	SCC	8
San Francisco CA	37.8	24	0.25	0.25	0.30	0.30	0.75	0.25	NCC	5
Santa Maria CA	35	25	0.25	0.25	0.30	0.30	0.75	0.50	0	0
Seattle WA	47.6	26	0.25	0.25	0.30	0.30	0.75	0.25	NWC	1
Spokane WA	47.7	27	0.75	0.25	0.70	0.70	0.75	0.60	NWI	3
Yakima WA	46.6	28	0.75	0.25	0.70	0.70	0.75	0.50	0	0

Fig. 2-6. An example of city information in the SetUp sheet in the INPUT file

## 3. Event Data:

Event Data		(Required only for study type 4)						
Hour		Temperature	Wind	Humidity	Clouds (%)	Diffuse solar	Direct solar	Load
		(F)	(mph)	(%)	(%)	(BTU/sf.h)	(BTU/sf.h)	SCADA
		1	2	3	4	5	6	(MWh/h)
0	1	80	0	62%	0%	0	0	11.0
1	2	79	5	58%	0%	0	0	9.6
2	3	78	4	64%	0%	0	0	8.7
3	4	77	0	74%	0%	0	0	8.1
4	5	76	0	76%	0%	0	0	7.9
5	6	76	0	84%	0%	10	55	8.2
6	7	76	0	76%	0%	20	156	8.5
7	8	77	0	66%	0%	28	210	9.3
8	9	83	5	56%	0%	35	241	11.7
9	10	84	6	51%	0%	41	259	12.5
10	11	86	6	43%	0%	44	270	13.9
11	12	90	6	37%	0%	46	275	14.9
12	13	93	7	28%	0%	47	277	15.6
13	14	96	13	23%	0%	45	274	16.8
14	15	97	12	22%	0%	43	267	17.4
15	16	98	12	20%	0%	38	254	17.2
16	17	99	9	20%	0%	32	232	17.5
17	18	100	13	20%	0%	24	193	17.2
18	19	101	12	22%	0%	16	121	17.2
19	20	101	9	24%	0%	5	16	16.9
20	21	99	7	36%	0%	0	0	16.3
21	22	91	6	45%	0%	0	0	15.9
22	23	86	9	46%	0%	0	0	15.1
23	24	83	5	62%	0%	0	0	13.0

Fig. 2-7. An example of event data input format

4. ClimateZone:

Load Mix	Res	Com	Ind	Agr	Data	Service
RES	0.75	0.23	0	0	0	0.02
COM	0.2	0.73	0	0	0.05	0.02
MIX	0.45	0.48	0	0	0.05	0.02
RAG	0.4	0.2	0.15	0.25	0	0
Enter Day Type 1=Winter peak, 2=Typical, 3=Summer Enter Hour (Pacific DLT) 1=midnight, ..., 13=noon, ...	3					
	16	17				
Zone names:						
Climate Zone	ID	Representative City	Other Cities	Hour Index	City Index	
Northwest Coast	NWC	Seattle WA	Vancouver BC	0	26	
Northwest Valley	NWV	Portland OR		0	16	
Northwest Inland	NWI	Spokane WA	Boise, Tri-Cities	0	27	
Rocky Mountain North	RMN	Helena MT	Calgary, Montana, Wyom	1	10	
Northern California Coast	NCC	San Francisco CA	Bay Area	0	24	
Northern California Valley	NCV	Sacramento CA		0	21	
Northern California Inland	NCI	Medford OR		0	14	
Southern California Coast	SCC	San Diego CA		1	23	
Southern California Valley	SCV	Los Angeles CA		1	13	
Southern California Inland	SCI	Bakersfield CA		1	2	
Desert Southwest	DSW	Phoenix AZ	Las Vegas, Riverside	1	15	
High Desert	HID	Reno NV	Salt Lake City, Albuquerque, Denve	1	19	
		City names must match the names in "CityInfo"				

Fig. 2-8. An example of climate zone inputs

5. Basis for ELCAP data:

NWC	NWV	NWI	RMN	NCC	NCV	NCI	SCC	SCV	SCI	DSW	HID
0.91	0.63	0.46	0.17	0.35	0.35	0.34	0.35	0.35	0.35	0.35	0.25
7.15	4.94	3.66	1.32	2.72	2.72	2.67	2.72	2.72	2.72	2.72	1.95
7.71	6.65	3.94	5.33	10.99	10.99	10.79	10.99	10.99	10.99	10.99	7.88
6.78	6.63	5.29	7.15	8.24	7.80	8.56	7.51	7.93	8.16	5.02	8.41
2.99	2.58	1.53	2.06	4.26	4.26	4.18	4.26	4.26	4.26	4.26	3.05
1.11	0.77	0.57	0.20	0.42	0.42	0.41	0.42	0.42	0.42	0.42	0.30
7.48	5.16	3.82	1.38	2.84	2.84	2.79	2.84	2.84	2.84	2.84	2.04
8.03	6.93	4.10	5.55	11.46	11.46	11.24	11.46	11.46	11.46	11.46	8.21
7.36	7.20	5.74	7.76	8.95	8.47	9.29	8.15	8.60	8.86	5.45	9.12
3.64	3.14	1.86	2.51	5.19	5.19	5.09	5.19	5.19	5.19	5.19	3.72
0.61	0.27	0.29	0.23	0.16	0.06	0.08	0.16	0.06	0.08	0.04	0.07
4.62	2.03	2.18	1.74	1.24	0.47	0.62	1.24	0.47	0.58	0.34	0.50
4.01	2.21	1.89	5.67	4.03	1.54	2.02	4.03	1.54	1.90	1.10	1.63
2.94	2.41	2.44	3.84	3.11	2.32	2.42	3.11	2.32	2.27	2.42	2.36
2.41	1.33	1.14	3.41	2.42	0.93	1.22	2.42	0.93	1.15	0.66	0.98
0.64	0.28	0.30	0.24	0.17	0.07	0.09	0.17	0.07	0.08	0.05	0.07
4.52	1.99	2.13	1.70	1.21	0.46	0.61	1.21	0.46	0.57	0.33	0.49
3.98	2.19	1.88	5.61	3.99	1.53	2.00	3.99	1.53	1.89	1.09	1.61
1.43	1.17	1.18	1.86	1.51	1.13	1.17	1.51	1.13	1.10	1.17	1.14
2.89	1.59	1.37	4.09	2.90	1.11	1.46	2.90	1.11	1.37	0.79	1.17

Fig. 2-9. Basis of end-uses on weekdays/weekends and winter/summer

## 6. Residential:

For residential loads, the end-use load shapes are based on ELCAP data and other data resources presented in Section 2.1. The single-family rules of association input example is shown in the following figure.

		Electronic	Motor-A	Motor-B	Motor-C	Motor-D	ZIP Ip	ZIP Iq	ZIP Pp (P)	ZIP Pq (Q)	ZIP Zp (G)	ZIP Zq (B)	PF
		1	2	3	4	5	6	7	8	9	10	11	12
<b>Single-family loads</b>													
Cooking	1	0.000	0.000	0.150	0.000	0.000	0.000	0.000	0.000	0.000	0.850	0.000	1.00
Hotwater	2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	1.00
Lighting	3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	1.00
Plugs	4	0.550	0.000	0.250	0.075	0.000	0.000	0.000	0.000	0.000	0.125	0.000	1.00
Washing	5	0.200	0.000	0.000	0.300	0.000	0.000	0.000	0.000	0.000	0.500	0.000	1.00
Heating	6	0.000	0.000	0.000	0.000	0.300	0.000	0.000	0.000	0.000	0.700	0.000	1.00
Cooling	7	0.050	0.000	0.100	0.000	0.850	0.000	0.000	0.000	0.000	0.000	0.000	1.00
Refrigeration	8	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	1.00

**Fig. 2-10.** Rules of association of the residential single-family

## 7. Residential load model parameters

An example of model parameters is presented below.

<b>Single Family</b>			
ResSingleCoolingefficiency	11.5		SEER, must between 0~25
Installed capacity Lighting	1.0	W/sf	
Installed capacity Plugs	1.5	W/sf	
Installed capacity Washing	2.5	W/sf	
Installed capacity Refrigeration	0.2	W/sf	
Floor area	2200	sf	
Building height	10	ft	
Wall area	1990	sf	
Wall R-value	19	F.h/Btu.sf	Recommend using local code
Roof R-value	60	F.h/Btu.sf	Recommend using local code
Window-wall ratio	15%	%	Recommend using local code
Window R-value	3.5	F.h/Btu.sf	Recommend using local code
Thermostat setpoint	75	F	Should be between 55F and 85F
Thermostat deadband	1.5	F	
External shading	20%	%	
Overdesign temperature	20	F	Should be between ResSingleBalancetemperature and 150F
Mass-indoor air UA	8492	Btu/F.h	
Mass capacity	3784	Btu/F	

**Fig. 2-11.** An example of model parameters for residential load input



## 8. Commercial

For commercial buildings, the CEUS is used as the primary source for commercial load composition. The commercial building temperature sensitivities are discussed in Section 4.0 and the sensitivity table is shown in Appendix E.

Small office			Electronic	Motor-A	Motor-B	Motor-C	Motor-D	ZIP Ip	ZIP Iq	ZIP Pp (P)	ZIP Pq (Q)	ZIP Zp (G)	ZIP Zq (B)	PF	
			1	2	3	4	5	6	7	8	9	10	11	12	
	Heating	1	0.00	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.70	0.00	1.00	
	Cooling	2	0.15	0.75	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	
	Vent	3	0.30	0.00	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	
	WaterHeat	4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1.00	
	Cooking	5	0.05	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.00	1.00	
	Refrig	6	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	
	ExtLight	7	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	
	IntLight	8	0.00	0.00	0.00	0.00	0.00	1.00	0.26	0.00	0.00	0.00	0.09	0.94	
	OfficeEquip	9	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	
	Misc	10	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	
	Process	11	0.30	0.00	0.20	0.40	0.00	0.00	0.00	0.00	0.00	0.10	0.00	1.00	
	Motors	12	0.00	0.00	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	
	AirComp	13	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	
<b>Normalization basis</b>															
	Floorarea (ksf)	165	326	330	219	337	339	267	362	359	286	50	79	62	3180
<b>Load shape (kW)</b>															
	CEUScode	Heatir	Coolir	Vent	Water	Cookir	Refrig	ExtLig	IntLig	Office	Misc	Proce	Motor	AirCo	Total
	1101	14.68	7.521	27.54	8.775	0.504	22.66	77.65	47.41	52.23	16.12	0.026	3.155	1.121	279
	1102	17.29	7.359	29.81	8.765	0.502	22.66	77.49	46.51	52.23	16.08	0.026	3.124	1.101	283
	1103	20.29	7.032	31.52	8.768	0.511	22.67	75.63	46.41	52.35	16.13	0.026	3.134	1.109	286
	1104	22.56	7.097	33.24	8.802	0.578	22.71	73.22	47.55	53.04	16.5	0.026	3.243	1.181	290

**Fig. 2-12.** An example of commercial load rules of association in the INPUT Excel file

An output load shapes example is shown in Fig. 2-13.

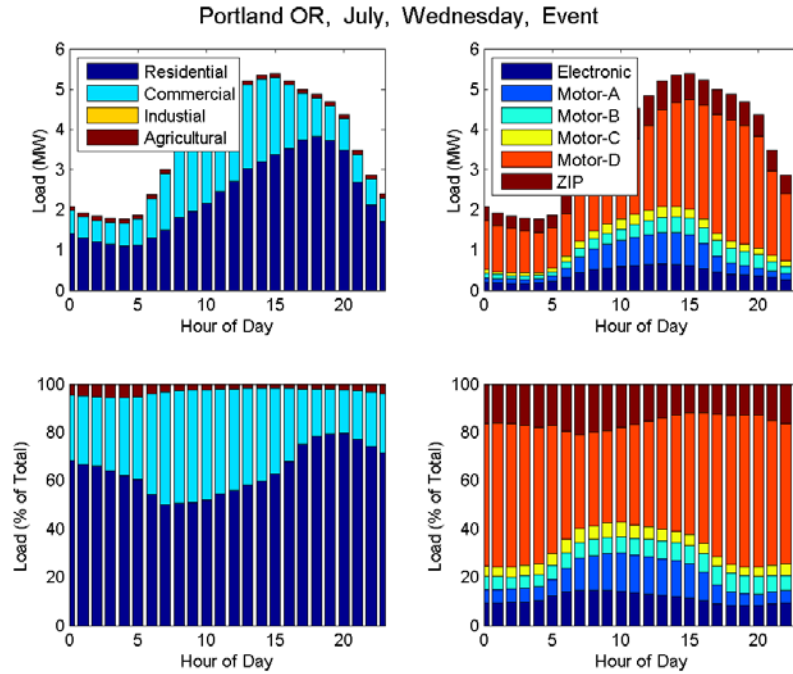
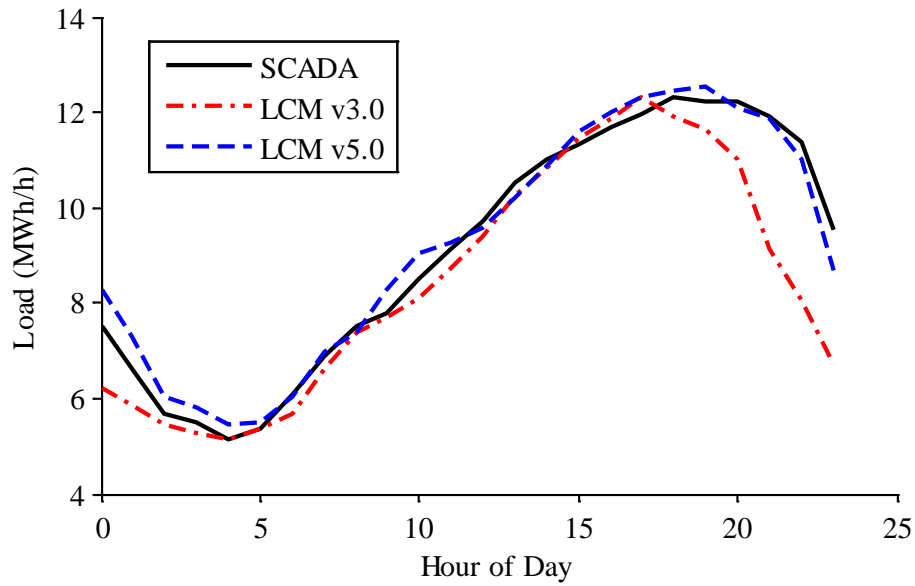


Fig. 2-13. 24-h load shape for Portland

## 2.4 Results of the Load Composition Model (MATLAB Version)

### 2.4.1 Comparison and Validation

This study is to validate the LCM based on the data sets from WECC utilities. The data is for summer 2009. A comparison of SCADA, LCM v3.0, and LCM v5.0 is shown in Fig. 2-14.



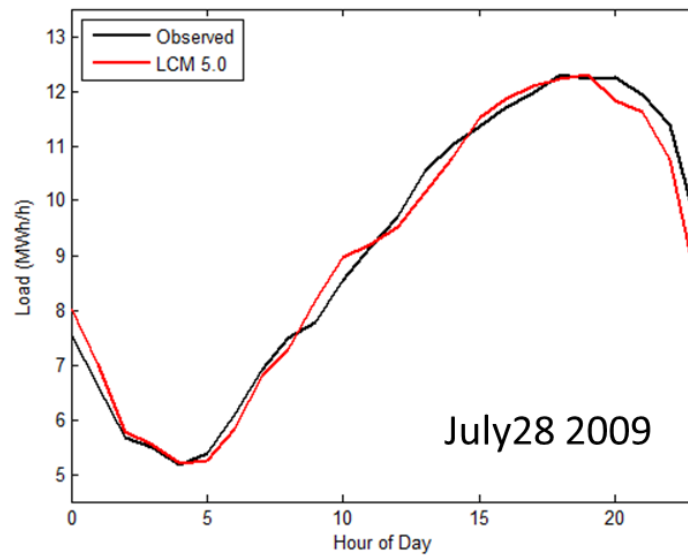
**Fig. 2-14.** Comparison results for BPA SCADA data, LCM v3.0, and LCM v5.0

The residential, commercial, industrial, and agricultural load fractions (R, C, I, A) values are shown in Table 2-6.

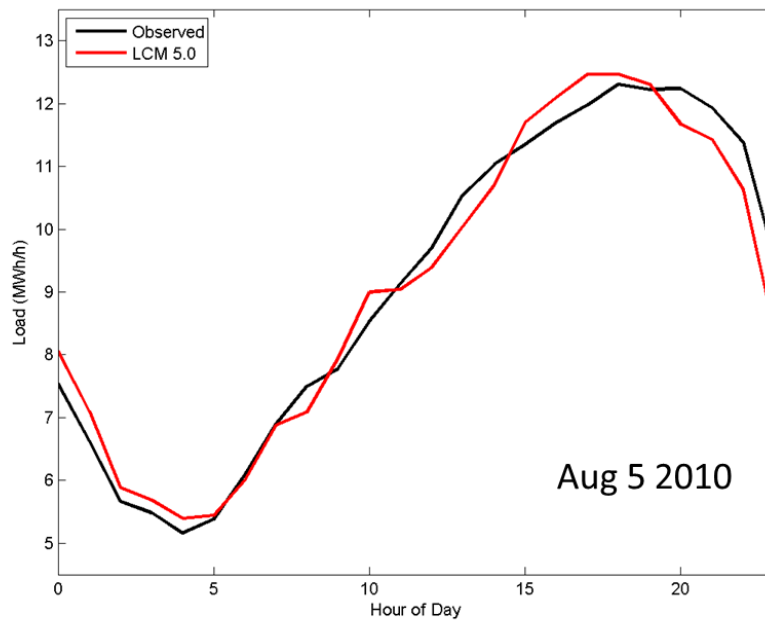
**Table 2-6.** Residential, commercial, industrial, and agricultural load fractions

	R	C	I	A
LCM v3.0	0.82	0.02	0.00	0.16
LCM v5.0	0.87	0.13	0.00	0.00

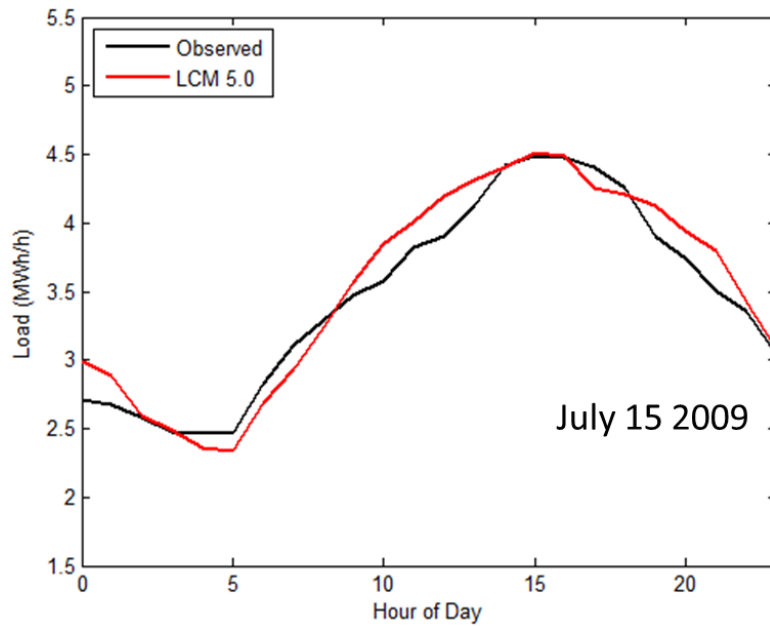
Based on the data we received, we tested the LCM load shape calculation. Three examples of load shape comparisons are presented for Portland, Boise, and Phoenix, respectively, in Fig. 2-15 through Fig. 2-17. These figures show the utility measurement; LCM 5.0 is the LCM load shape output. They are relatively close to observed load shapes. More results are presented in Appendix A. We validated the LCM by obtaining a better match between the LCM output and the real measurements. The latest version of LCM is more representative and generalized than previous versions.



**Fig. 2-15.** Example load shape comparison for Portland



**Fig. 2-16.** An example load shape comparison for Boise



**Fig. 2-17.** An example load shape comparison for Phoenix

## 2.4.2 Climate-Zone Studies

Load composition data sets have been updated using our updated LCM for all climate zones. A complete load composition data table is provided in Appendix F. It shows fractions of Motor A, B, C, D, power electronics, and active and reactive parts of ZIP. We compared the light LCM, V1.0 and V5 of the detailed LCM. Table 2-7 shows the minimum, average, and maximum Motor D percentages for 12 climate zones, for summer (hot, normal, cool), shoulder, and normal winter study types. They are extracted from the load composition data table in Appendix F. The fractions of Motor D increase in the load composition data in the latest LCM compared with previous versions.

**Table 2-7.** Motor D percentage table from the climate zone studies

Study	Motor D (%)								
	Minimum			Average			Maximum		
	Light	V 1.0	Ver 5.0	Light	V 1.0	V 5.0	Light	V 1.0	V 5.0
Hot	6	2	11	24	10	32	50	38	61
Normal	4	1	10	21	6	30	48	33	59
Cool	2	2	9	13	7	27	46	20	56
Shoulder	2	1	4	7	7	18	39	15	39
Winter	2	2	11	6	9	24	14	16	33

## **3.0 WECC Support**

### **3.1 Data Collection**

PNNL supports WECC LMTF through the Phase 1 CMPLDW implementation. This task includes load composition and load shape analysis for WECC members. WECC TSS announced in the August 2014 meeting that PNNL would be available to help. PNNL performed the support work described in Section 2.4.1 and Appendix A for BPA, the SRP, PSE and PG&E, and IdahoPower.

#### **BPA**

BPA sent two SCADA data sets. The resolution of the first BPA SCADA data set was hourly power data (megawatts), organized by feeder. The data represented the period from December 1, 2008, to September 4, 2009. Residential, commercial, and industrial feeders were included. The second data set was summer 2009 data, with both 5-min and 1-hour data.

#### **PSE**

PSE sent a file of 1-min 5-month substation data (megawatts). Both customer counts and monthly power (kilowatts) in 2008 for residential, commercial/industrial, and lighting were provided.

#### **SRP**

The Salt River Project sent 15-min data covering 4 months (June through September 2010) for rural, urban, residential, mixed, and commercial loads. Weather temperature data was also provided.

#### **PG&E**

PG&E sent 5-min data covering 3 months for urban, rural, residential, and commercial loads. Feeder voltage level was given from July to September 2010. A breakdown by urban, rural, residential, and commercial percentages was provided for each feeder.

#### **IdahoPower**

Idaho Power furnished hourly SCADA data giving power consumption from November 2009 to October 2010.

### **3.2 Database Coordination System.**

This section describes the development of a database that PNNL created for WECC load data from utilities and input data needed for LCM.

ARRA\_DATA is a database designed to manage data efficiently for building the LCM. It saves many types of data as well as their relationships.

In addition, a database module DSR is developed to (1) preprocess the utility data and store it in the database and (2) retrieve the desired data from the database to build LCM.

The ARRA\_DATA database is required to store the following data:

1. CityInfo: contains the information about the appliance electricity usage out of its total energy usage for cities whose data is used to build LCM (such as “electric heat,” “heat pumps,” “electric hotwater,” etc.).
2. EventData: contains the event data for 24 hours on a specified date for a city.
3. Residential: contains the load shapes in 24 hours for different periods (such as winter weekday, winter weekend) and for different load types (such as cooking, hot water).
4. Commercial: contains the rule of association of different types of commercial buildings, such as small office, large office, etc.
5. Industrial: contains the total electric power of industrial load.
6. Agricultural: contains the total electric power of agricultural load.
7. Composition: contains the substation composition between building types and categories, such as residential and commercial.
8. ClimateZones: contains the load mix, climate zones, and their representative cities.
9. Basis: contains the basis information for the residential power data
10. Scommercial: contains the  $k$ ,  $c$ ,  $T_k$  values for different cities.

Since some data is either unstructured or does not conform to the normalization form, it requires creating normalized tables to store these data; details about the design of these normalized tables can be found in the Design section.

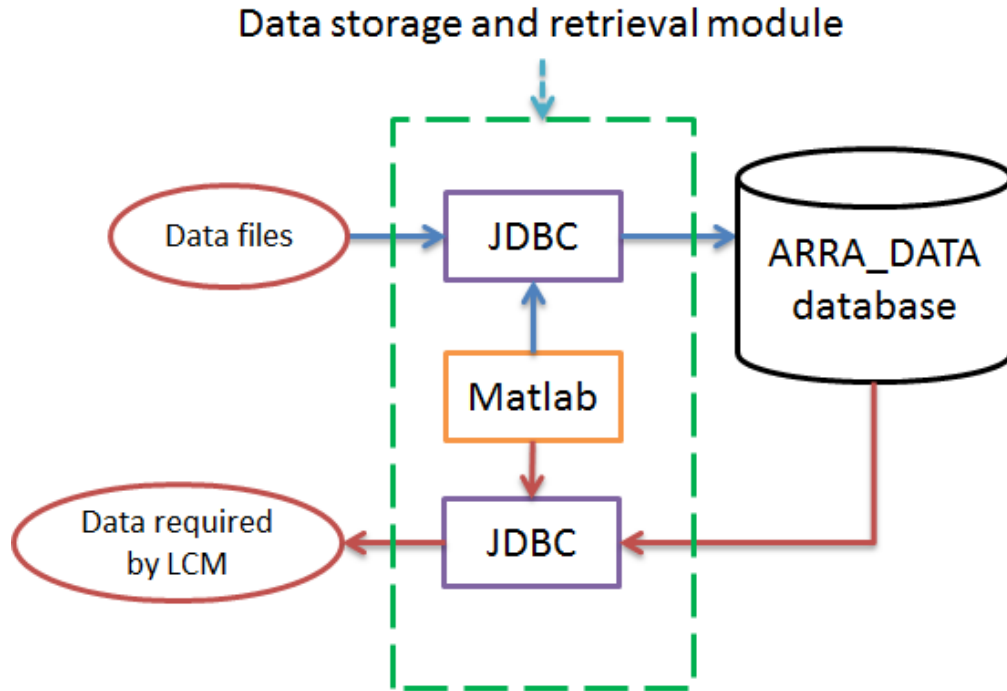
DSR is required to fulfill the following three functionalities:

1. Import the utility data into ARRA\_DATA.

A MATLAB script is used to load the data from Excel files, format the extracted data, and then store them in the MySQL databases.

2. Extract utility data from ARRA\_DATA and prepare input data for building LCM.

A MATLAB script is developed to prepare the input data in the right format for the LCM by extracting the correct data from the database and converting it into the format used by LCM.

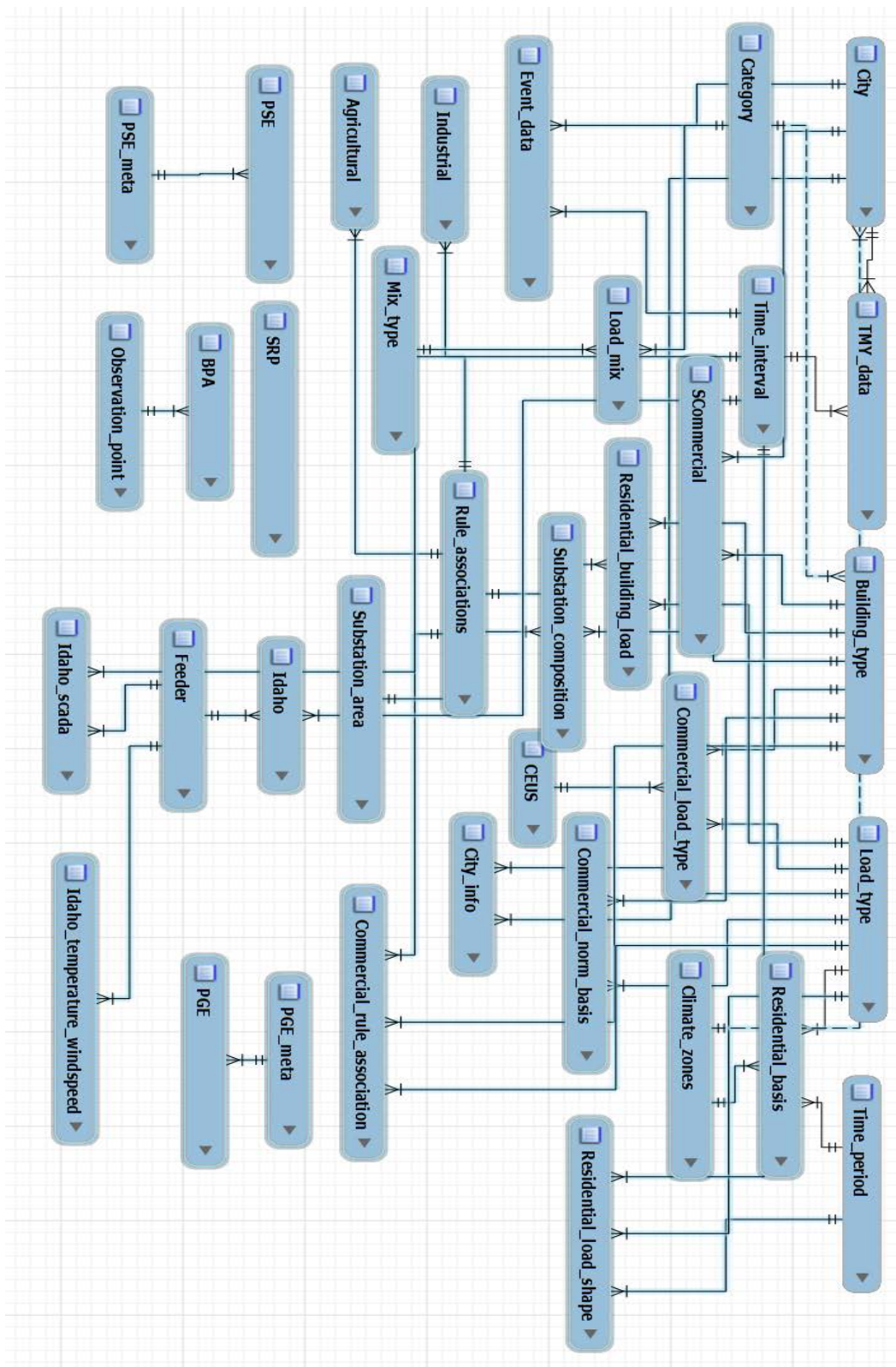


**Fig. 3-1.** Design of data storage and retrieval module

Fig. 3-1 shows the design of the DSR module. The module requires the ability to perform these two tasks:

1. **Data storage:** The DSR module loads the input data from a list of collected files into MATLAB, where the input data is normalized to be suitable for storage in the database using Java Database Connectivity (JDBC).
2. **Data retrieval:** The DSR module issues queries to the database and extracts desired input data for LCM via JDBC.





**Fig. 3-2.** Entity-relationship diagram

1. **Category:** represents category, such as “residential,” “commercial,” “agricultural,” etc.
2. **CEUS:** represents codes used in CEUS data.
3. **City:** represents the cities where the data are collected.
4. **Climate\_zones:** represents the climate zones where the cities are located.
5. **Building\_type:** represents building types, such as “small office,” “large office,” etc.
6. **Load\_type:** represents load types, such as “heating,” “cooling,” etc.
7. **Mix\_type:** represents the mixture types, such as “RES,” “COM,” “MIX,” etc.
8. **Rule\_associations:** represents the rule association types, such as “electronic,” “Motor-A,” etc.
9. **Substation\_area:** represents the substation areas. Currently these areas are numbered 1 to 8.
10. **Time\_interval:** represents the time interval of day. Currently there are 24 time intervals.
11. **Time\_period:** represents the period of a year, such as “Winter weekday,” “Summer weekend,” etc.
12. **Agricultural:** represents the power used by different rule association types in agriculture.
13. **City\_info:** represents the power information related to each city.
14. **Commercial\_load\_type:** represents the power data related to a certain load type, a CEUS code, and a certain commercial building type.
15. **Commercial\_norm\_basis:** represents the norm basis for a certain commercial building type, such as “small office,” etc.
16. **Commercial\_rule\_association:** represents the rule association for a commercial building type and a load type.
17. **Event\_data:** represents the event data related to a city within each time interval.
18. **Industrial:** represents the power used by different rule association types in industry.
19. **Load\_mix:** represents the distribution of categories for a certain mixture type.
20. **Residential\_basis:** represents the residential basis for different load types, time intervals and climate zones.
21. **Residential\_building\_Load:** represents the rule association of the residential power data in terms of different load types, building types, and rule associations.
22. **Residential\_Load\_shape:** represents the load shape of the residential power data in terms of different load types, time intervals, and time periods.
23. **SCommercial:** represents the temperature sensitivity of a city.
24. **Substation\_composition:** represents the composition of building types on different substation areas.
25. **TMY\_data:** represents the TMY data with regarding a certain type and location.
26. **BPA:** represents the BPA data.
27. **Feeder:** represents the feeder.
28. **Idaho:** represents the Idaho data.
29. **Idaho\_scada:** represents the SCADA data related to Idaho utility.
30. **Idaho\_temperature\_windspeed:** represents the temperature and wind speed info related to Idaho utility.
31. **Observation\_point:** represents the observation point.
32. **PGE:** represents the PGE data.
33. **PGE\_meta:** represents the metadata related to PGE data.
34. **PSE:** represents the PSE data.
35. **PSE\_meta:** represents the metadata related to PSE data.
36. **SRP:** represents the SRP data.

Entity tables are listed in Appendix C.

The relationships between entity tables are summarized in Table 3-1.

**Table 3-1.** The relationship between entities

Entity 1	Entity 2	Relationship
Agricultural	Rule_associations	Many-to-one
Building_type	Category	Many-to-one
City	Climate_zone	Many-to-one
City_info	Load_type	Many-to-one
City_info	City	Many-to-one
Commerical_load_type	Building_type	Many-to-one
Commerical_load_type	Load_type	Many-to-one
Commercial_load_type	CEUS	Many-to-one
Commercial_norm_basis	Building_type	Many-to-one
Commercial_norm_basis	Load_type	Many-to-one
Commercial_rule_association	Rule_associations	Many-to-one
Commercial_rule_association	Load_type	Many-to-one
Commercial_rule_association	Building_type	Many-to-one
Event_data	City	Many-to-one
Event_data	Time_interval	Many-to-one
Industrial	Load_type	Many-to-one
Load_mix	Mix_type	Many-to-one
Load_mix	Category	Many-to-one
Residential_basis	Time_period	Many-to-one
Residential_basis	Climate_zones	Many-to-one
Residential_basis	Load_type	Many-to-one
Residential_building_load	Rule_associations	Many-to-one
Residential_building_load	Load_type	Many-to-one
Residential_building_load	Building_type	Many-to-one
Residential_load_shape	Time_period	Many-to-one
Residential_load_shape	Load_type	Many-to-one
Residential_load_shape	Time_interval	Many-to-one
SCommercial	Building_type	Many-to-one
SCommercial	City	Many-to-one
Substation_composition	Building_type	Many-to-one
Substation_composition	Substation_area	Many-to-one
TMY_data	City	Many-to-one
TMY_data	Time_interval	Many-to-one
BPA	Observation_Point	Many-to-one
Idaho	Feeder	Many-to-one
Idaho	Time_interval	Many-to-one
Idaho_scada	Feeder	Many-to-one
Idaho_scada	Time_interval	Many-to-one
Idaho_temperature_windspeed	Feeder	Many-to-one
PGE	PGE_meta	Many-to-one
PSE	PSE_meta	Many-to-one

Load shapes for residential, commercial, industrial, and agricultural loads are shown in Fig. 3-3. The MATLAB version and Database version hourly power profiles match.

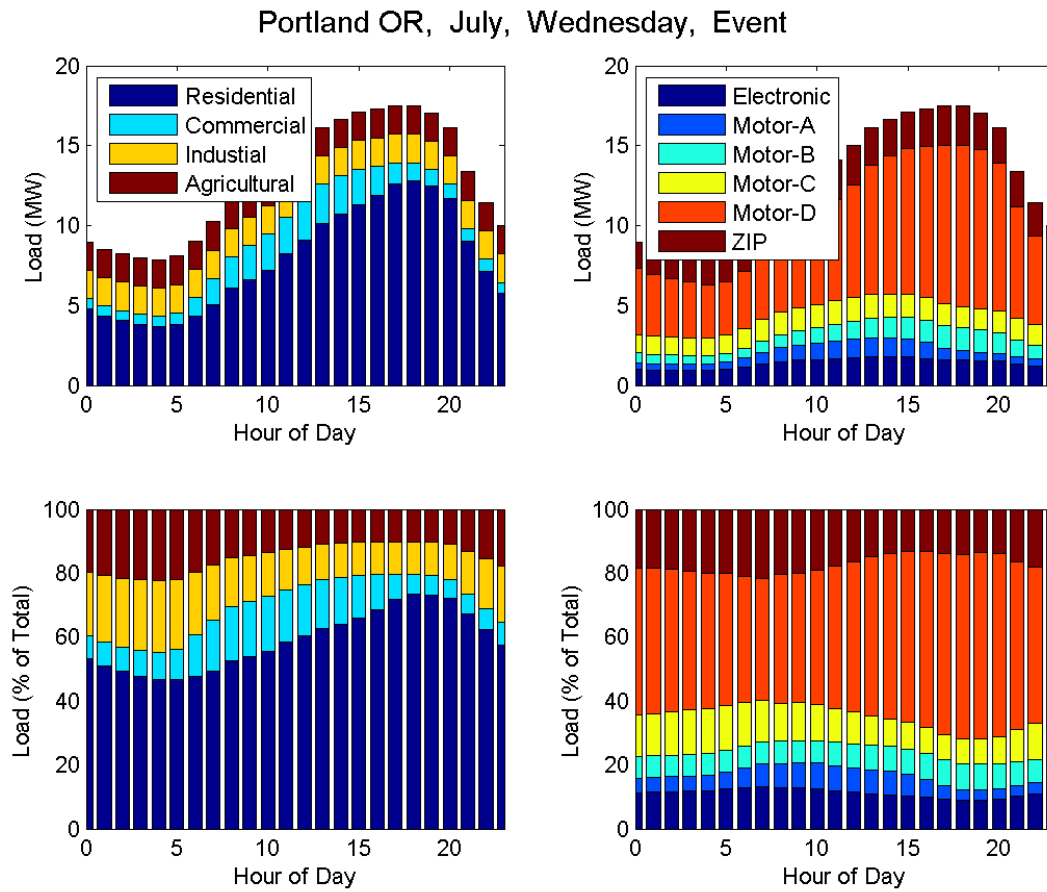


Fig. 3-3. Load shape results by extracting data from MySQL database

## 4.0 Update of Commercial Load Composition

This section describes revisions to load composition data sets for commercial buildings. The temperature sensitivities are added to the CEUS data of commercial buildings.

### 4.1 Commercial Load

A total of 96 simulations in EnergyPlus have been done for eight building types in 12 climate zones. After we add commercial building HVAC load temperature sensitivity in the LCM, the fractions of Motor D increase. Climate zones and representative cities are listed in Table 4-1. For each city, there are nine building types, which are listed in Table 4-2.

**Table 4-1.** Climate zones and representative cities in the Load Composition Model

Climate Zones	Representative Cities
NWC	Seattle, WA
NWV	Portland, OR
NWI	Spokane, WA
RMN	Helena, MT
NCC	San Francisco, CA
NCV	Sacramento, CA
NCI	Medford, OR
SCC	San Diego, CA
SCV	Los Angeles, CA
SCI	Bakersfield, CA
DSW	Phoenix, AZ
HID	Reno, NV

**Table 4-2.** Commercial building types in the Load Composition Model

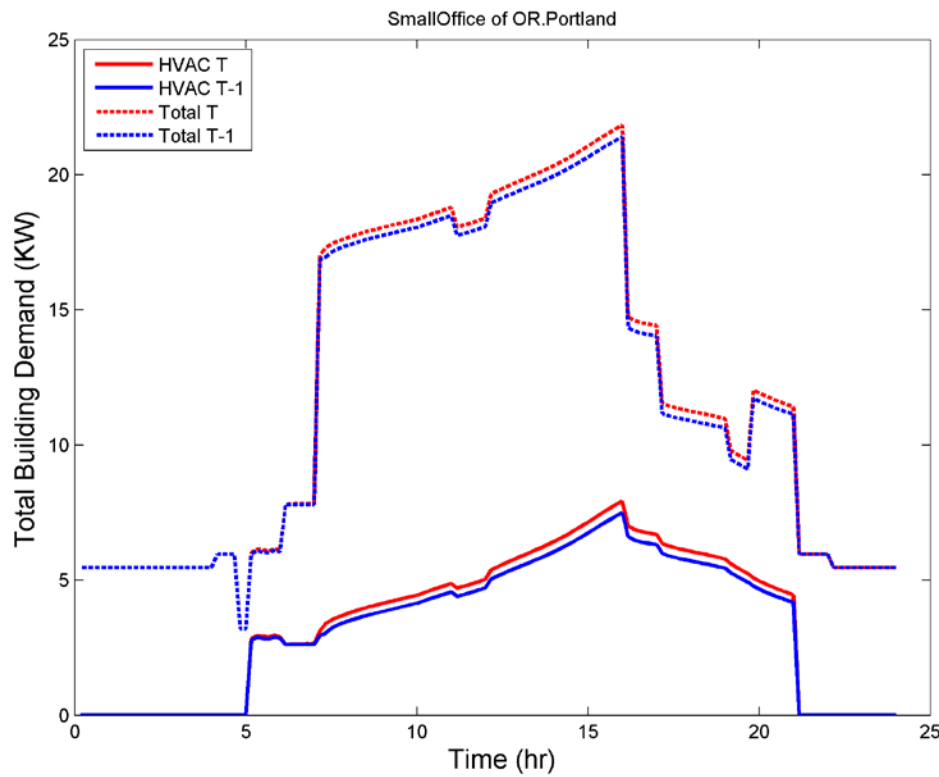
Building Type in LCM	Building Prototype	Heating	Cooling	Primary System	Secondary System
Small Office	Small Office	Heat pump	Unitary DX	Packaged CAV	No
Large Office	Medium Office	Gas furnace	Unitary DX	Packaged VAV	No
Retail	Standalone Retail	Gas furnace	Unitary DX	Packaged CAV	No
School	Secondary School	Boiler	Air-cooled chiller	VAV w/reheat	Packaged CAV
Hospital	Hospital	Boiler	Unitary DX	VAV w/reheat	Central CAV
Hotel	Large Hotel	Boiler	Air-cooled chiller	Fan-coil units	VAV w/reheat
Restaurant	Full-service Restaurant	Gas furnace	Unitary DX	Packaged CAV	No
Grocery	Supermarket	Gas furnace	DX	Packaged CAV	No

DX is direct expansion; CAV is constant air volume; VAV is variable air volume

## 4.2 Temperature Sensitivity Method

### 4.2.1 Fix Temperature Sensitivity

A set of simulations are carried out for all of the building types and all the cities with the peak day temperature profile in the Typical Meteorological Year 3 (TMY3) data. Another set of simulations used the peak day temperature profile minus 1°F. The total building and HVAC demands are shown in Fig. 4-1. Therefore, the HVAC demand differences of the two simulations are power difference per degrees Fahrenheit. Therefore, the HVAC load temperature sensitivity at the peak temperature (kW/Ksf. °F) can be approximately calculated. CEUS data used in commercial building is corrected by adding the HVAC load temperature sensitivity.



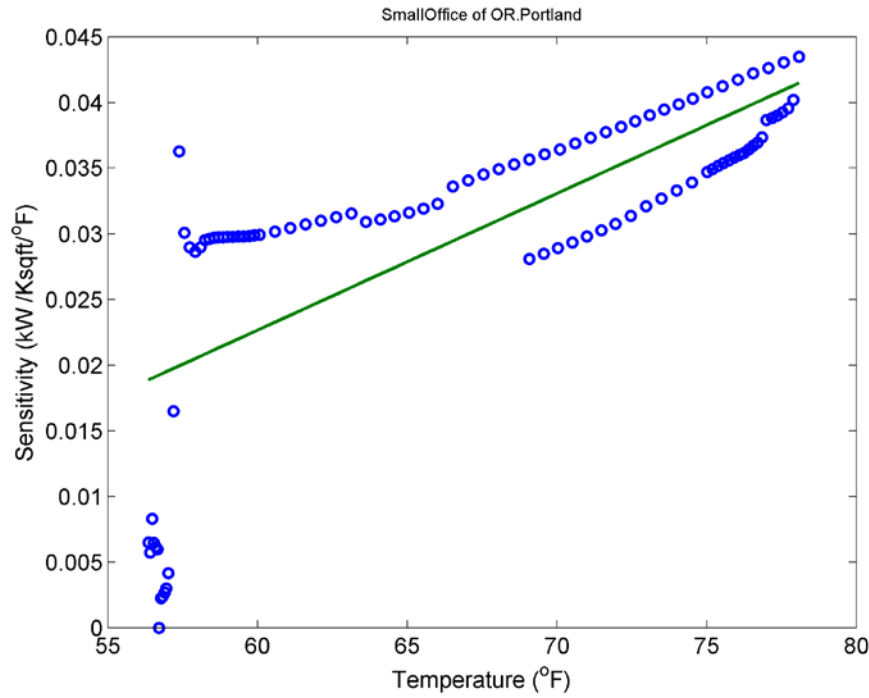
**Fig. 4-1.** Total building demand and HVAC demand for Portland small office building type

HVAC load temperature sensitivity of the Portland small office at 77°F is 40 kW/Msft. °F, which can be observed in Fig. 4-2. The straight line in Fig. 4-2 is written as  $y = K*(T-T_k)$ , where  $y$  is sensitivity and  $T$  is temperature. When  $y$  is 0,  $T$  is equal to  $T_k$  by solving the equation. Each figure of every building type for each representative city has a set of  $K$  and  $T_k$  values. They are put in a table. The table example for all the building types of Seattle, WA, and Portland, OR, is shown in Fig. 4-3. It can be achieved for all the other climate-zone-representative cities and all the building types in the same way. A complete HVAC load temperature sensitivity table is shown in Appendix E.

Since, in the equation  $y = K*(T-T_k)$ ,  $K$  and  $T_k$  can be found in the HVAC load temperature sensitivity table, the value  $y$  is added to CEUS cooling power data by finding corresponding  $K$  and  $T_k$  in this lookup

table. Here  $T$  is temperature in CEUS data or the temperature in the event data depending on the type of analysis.

Revisions are made to load composition data sets for commercial buildings with load temperature sensitivity. Load composition data sets have been updated using our updated LCM tool for all climate zones. A complete load composition data table is given in Appendix E. It shows fractions of Motors A, B, C, D, and power electronics. A big difference is the Motor D fraction compared with previous results. After we add HVAC load temperature sensitivity to the commercial building demand in LCM, the fractions of Motor D increase in the load composition data.



**Fig. 4-2.** HVAC load sensitivity for Portland small office

**Table 4-3.** HVAC temperature sensitivity (kW/Ksqft/°F) for Seattle, WA, and Portland, OR

	$y=K(T-T_k)$	$K*1000$	$T_k$
Seattle, WA	Small office	0.89	35.4
	Large office	-0.82	96.5
	Retail	1.92	56.4
	Lodging	-1.21	83.0
	Grocery	2.13	64.4
	Restaurant	2.30	43.3
	School	-4.01	98.4
	Health	1.58	91.4
Portland, OR	Small office	1.04	38.2
	Large office	-6.46	74.7
	Retail	4.11	58.7
	Lodging	-1.45	68.9
	Grocery	1.17	59.4
	Restaurant	7.15	58.1
	School	-4.83	82.2
	Health	-0.67	32.1

#### 4.2.2 Active Temperature Sensitivity

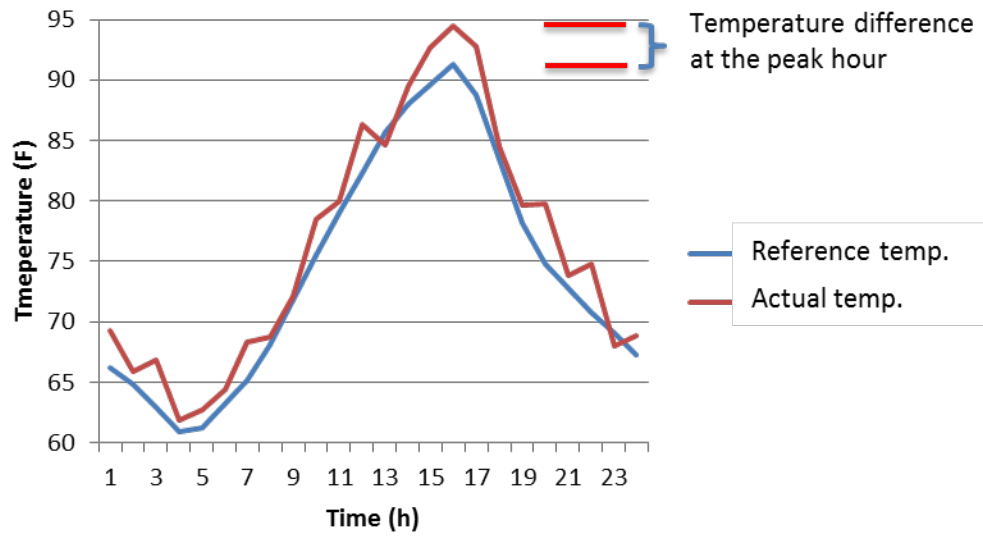
This is the second method we used to get active temperature sensitivities. Based on EnergyPlus simulations for a peak day from TMY (base temperature) and peak day temperature – 1, the difference of the two outputs is the active temperature sensitivity for a certain hour, as shown in Fig. 4-3 and Fig. 4-4. Therefore, the power output for a different day can be represented as:

$$Power_h = Shape_h + \Delta T_h \times \left( \frac{\Delta P}{\Delta T} \right)_h$$

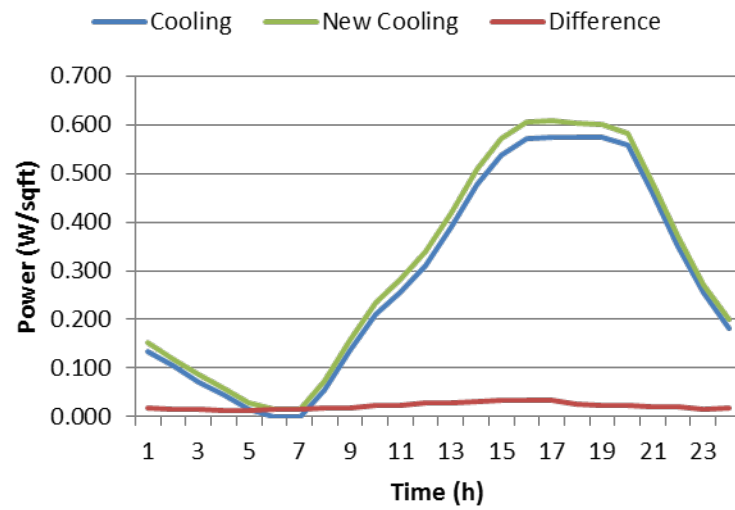
where  $h$  represents the hour from 0-23,  $\Delta T$  represent temperature difference between the actual temperature and the base temperature, power represents the actual load, and shape represent the base load shape.

Examples of simulation results of single and multi family residential loads and the 1°F load difference are shown in Fig. 4-5.



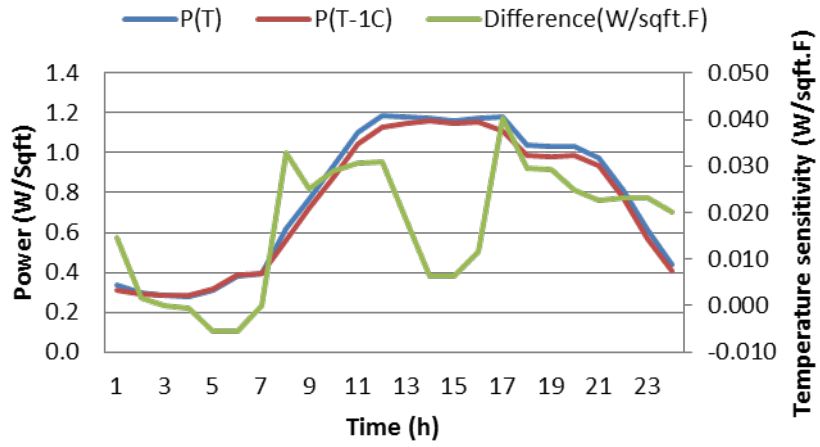


**Fig. 4-3.** Demonstration of HVAC load adding temperature sensitivities



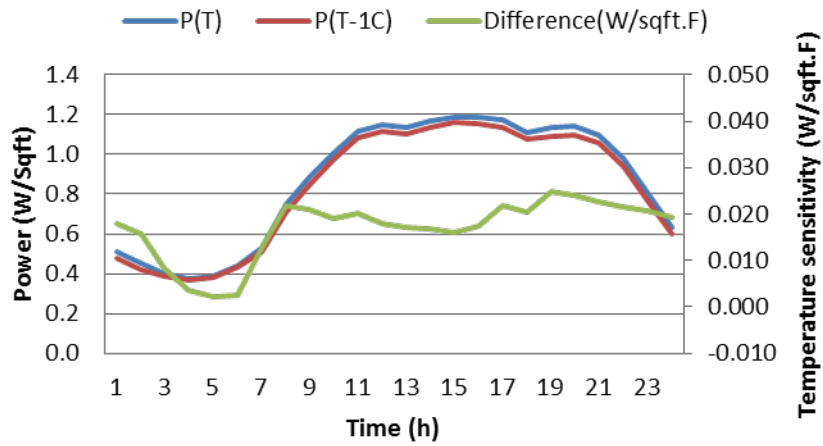
**Fig. 4-4.** Example of HVAC load adding temperature sensitivities

## Single-family Los Angeles

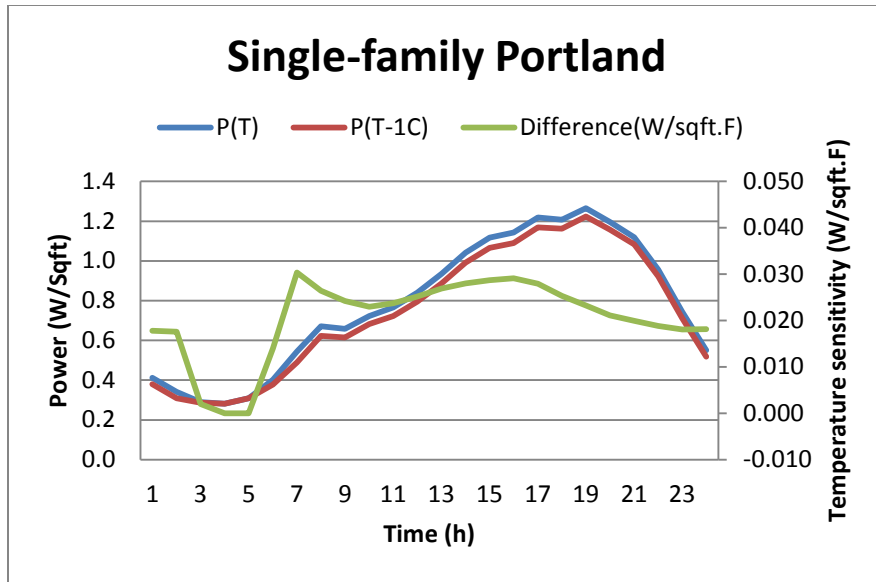


(a)

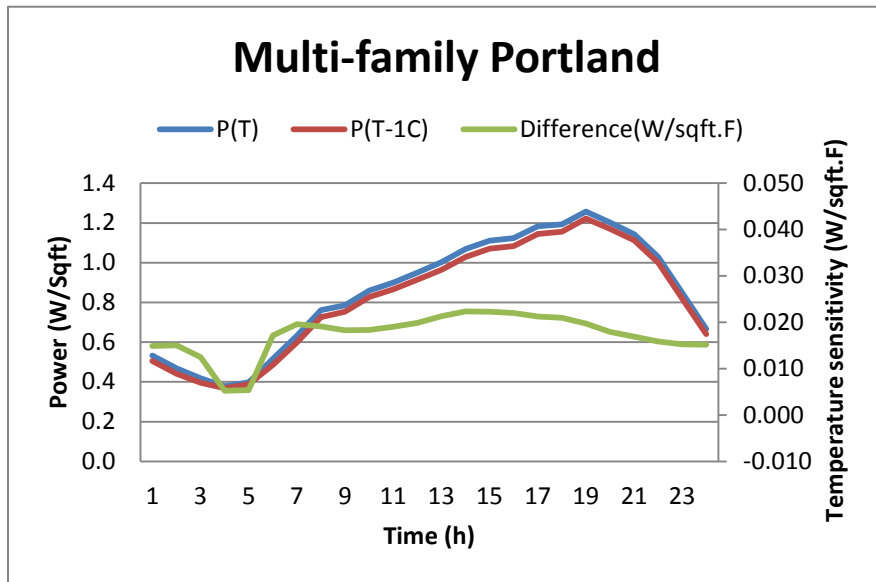
## Multi-family Los Angeles



(b)



(c)



(d)

**Fig. 4-5.** Examples of simulation results of single and multi family residential loads and the 1°F load difference: (a) Single Family Los Angeles; (b) Multi Family Los Angeles; (c) Single Family Portland; (d) Multi Family Portland

## 5.0 Aggregate Motor Protection Model

When the weather is such that air-conditioning is a large proportion of total load, induction motors are an important consideration. Induction motors play a significant role in the overall power system's dynamic simulations. Three-phase induction motor models are well known and have been implemented in available transient stability programs, such as PSS-E (now available from Siemens), PSLF (now available from GE), Power World, and others. However, there are likely to be many types of induction motors at any given bus, each having a different dynamic characteristic and each operating at a different steady-state condition. Rather than attempt to model each separately, it is generally more practical to model groups of induction motors.

Events such as the Swedish blackout of 1983 or ones in the U.S. Southwest in past years resulted in extensive aggregate load modeling research in the 1980s and 1990s [4]-[5]. The modelers employed induction motor steady-state equivalent circuits, and calculated equivalent parameters by using weighted averages based on the machines' power ratings [6]-[8]. Nozari *et al.* [8] developed models containing two induction motor models for aggregating induction motors in [7]-[8]. Two methods are described. The first method calculates each parameter of the aggregate motor as the weighted average of the respective parameter of individual motors in the group. The second method uses a weighted average of admittances. That method is same as connecting the branches in parallel and reducing them to a single equivalent branch. Three test cases represent a residential motor load, a commercial load, and a combination of residential and industrial motor loads. (The combination consists of motors such as those used in domestic refrigerators, freezers, dishwashers, clothes washers, and dryers, as well as industrial motors, large and small.)

More work has been done regarding to load modeling research [9]-[10]. Franklin [11] proposed another method based on an equivalent circuit connecting impedance branches in parallel. He estimated the aggregate motor inertia using physical arguments. In [12], Taleb *et al.* used the Thevenin theorem along with some transient characteristics of induction machines to calculate the parameters of the equivalent machine. Stankovic and Lesieutre [13][14] proposed a probabilistic approach to aggregate induction machines using a stochastic norm to describe a cluster of induction machines undergoing multiple simultaneous parametric variations.

In general, aggregate methods based on three-phase induction motor equivalent circuits did not consider changes in state. Such changes as motor stalling and motor protection are nevertheless the key issues in FIDVR.

Voltage dip depth, duration, and timing with respect to the waveform affect the motor behavior. The distance between the fault and the motors will affect the motor behavior as well, because voltage profiles along the line will be different. Therefore, in task 4, we are motivated to develop a model that considers the *state* of the load, and does so in a statistical sense. We consider different motor states, such as on, off, stalled, and starting, in a way that captures a sequence of motor behaviors during the voltage event. Our interest is particularly in the active and reactive power demand.

Static and electronic loads continue to be represented with polynomial models in this work. However, some three-phase electronic loads may disconnect briefly during voltage sags, depending on the design of inverter circuit. For such loads, the output active power and reactive power depend on the power

converters' control design. Usually the active power and reactive power are controlled separately. Some loads have low-voltage ride-through capability, meaning they can continue operation even with a low voltage on the input. However, not all equipment has this capability. For some kinds of loads, low-voltage operation can be damaging.

Electric equipment is typically protected from three principle causes of damage: overcurrent, overvoltage, and undervoltage. Overcurrent and overvoltage protection are usually implemented by sensing the relevant condition. However, undervoltage operation may be damaging because of overheating, and thermal protection is used for such loads, rather than electrical. Such a scheme can be more difficult to model because the delay between an undervoltage condition and a thermal trip is not easy to predict.

The undervoltage tolerance of computer equipment is approximately 50% to 80% of nominal voltage for no more than (say) 100 ms. Such equipment is sometimes provided with undervoltage protection that interrupts operation and performs a rapid data save. Some has enough inherent energy storage built in to allow the computer state to be completely saved. The tolerance to undervoltage of such equipment will depend on the power drawn by the load on the secondary supply, on the design capacity of the power supply, and on the pre-sag conditions of the primary power supply. In contrast, programmable logic controllers that support high-risk applications such as industrial control systems are provided with undervoltage protection that generally trips at about 75% voltage for just one cycle. Some controllers come equipped with DC bus capacitors that will allow for sags of up to 50% for 1/2 second or more.

Motor protection must account for the following three phenomena:

1. Motors can attempt to restart when the voltage returns following an interruption of power, but sometimes it is unsafe to restart the motor, or the application of the motor does not require a restart.
2. Excessive current consumption following an interruption of power can cause overheating damage to motors.
3. Depending on the mechanical load, motors can reverse direction before the fields collapse.

Automatic restart protection is usually determined by control requirements and typically is only implemented when the application requires it. Most residential and small commercial motor loads (such as residential air-conditioner compressors and fans) have no such protection: they will just try to restart after a voltage reduction. Notable exceptions are dryers and washing machines, which have a safety requirement to not restart after their cycle is interrupted without an explicit command from a human. Such loads should be removed from the load model after an undervoltage event sufficiently large to interrupt the operation of the load.

Three-phase motors used in large commercial and industrial applications usually are protected with overcurrent and thermal overload relays. All large motor loads (>600 V) used in large commercial and industrial applications can be expected to have undervoltage protection. Large induction motors use electronic protection. For electronically controlled motors, the protection is typically done with programmable controls that are configured by the equipment manufacturer. Voltage variance trip settings used by the manufacturer vary based on motor application and by vendor. This variance trip setting will be diverse due to the wide application range of industrial equipment.

For protection against thermal damage, most motors can be assumed to trip between 2 and 15 seconds after rotor lock. The population of trip time appears to have a long tail distribution, with many motors that can remain stalled for a sustained period.

Motor reversal is a likely outcome for single-phase motors when the undervoltage is within a critical range around the stall threshold. Although this is obviously a highly undesirable situation, there appears to be little concern among manufacturers about undervoltage protection systems to prevent this occurrence.

Motor reversal should be regarded as possible for low-inertia applications with non-constant mechanical loads (such as in some compressors). The electrical load may not return to its original value until external conditions stop the motors (e.g., air-conditioners stop because of ambient cooling rather than active cooling).

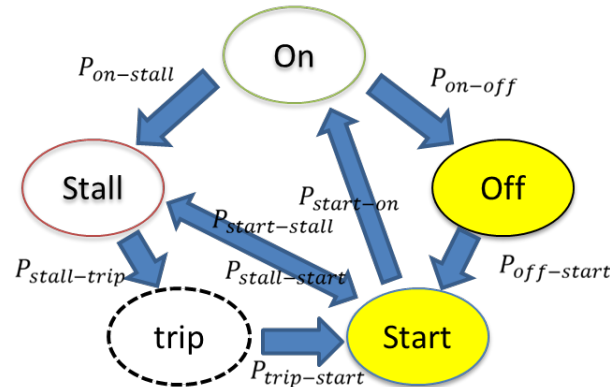
As a general rule, undervoltage motor protection schemes are designed to wait until fault-detecting relays have had a chance to clear faults. However, the time delay for undervoltage protection may not be satisfactory because contactors may drop out even before protection can engage. In addition, systems with fast automatic transfer switches may not be coordinated with undervoltage protection schemes. Finally, problems do arise because undervoltage protection schemes allow excessive inrush currents after interruption before thermal protection is engaged.

## 5.1 Aggregate Motor Protection Modeling

### 5.1.1 State Transition Modeling

Voltage sags or dips are brief reductions in voltage, typically lasting from a cycle to a second or so. Most voltage sags have a magnitude of around 80% and duration of 4 to 10 cycles [15]. Voltage sags are the main causes of disturbances, depending on the source, with an incidence between 61% and 87% [16]. The majority of voltage sags lasted 10 cycles or less, and were 20% to 30% in magnitude.

We developed an aggregate load protection model to represent the various behaviors of multiple motors during a voltage sag event (Fig. 5-1). The fractions  $P$  of motors in the different states will vary as the voltage changes for as long as the fault lasts, and during the post-fault recovery.



**Fig. 5-1.** Aggregated motor protection model

The model shows five states of an induction motor operation: *on*, *off*, *start*, *stall*, and *trip*. The system states (rather than the motor states) are, in time series, (a) prefault, (b) fault, (c) clear, (d) reclose, and (e) recovery. The *on* motor-state exists when a motor is in the normal running state. In system terms, this represents the prefault stage. The *off* motor-state begins when the motor is dropped by a contactor. The *start* state begins when the contactor recloses. From the system point of view, the motor starting represents the reclose and recovery stages.

The stall motor-state begins when the motor stalls. When this occurs with respect to the fault depends on a number of factors external to the motor, such as the proximity and severity of the fault, and the distance to the source. The trip motor-state occurs when the motor temperature is high enough to trigger the thermal protection. Usually, this thermal process is not rapid.

Consider Fig. 5-1. During the fault, motors that are *on* begin to transition to the *stall* state or the *off* state, so that the numbers in the *stall* and *off* states increase. Each transition is associated with a certain probability,  $P_{xx-yy}$ , the probability of a motor in (*xx*) state transiting from the (*xx*) state to the (*yy*) state at each time step. In general, we can write  $N_{xx}$  for the aggregate state occupancy, which is the fraction of the population of motors in the (*xx*) state at any given time. We can then see how that number changes. Thus, the number of motors in the *on* state changes as follows:

$$\frac{dN_{on}}{dt} = -P_{on-off}N_{on} - P_{on-stall}N_{on} \quad (5.1)$$

Note that this is a negative quantity.

After the fault is cleared, the motor contactors reclose, and some motors that are *off* will try to restart. If they are successful in restarting, that will tend to increase the number of motors in the *on* state. Equation (5.1) must thus be rewritten

$$T_m \frac{dN_{on}}{dt} = -P_{on-off}N_{on} - P_{on-stall}N_{on} + P_{start-on}N_{start} \quad (5.2)$$

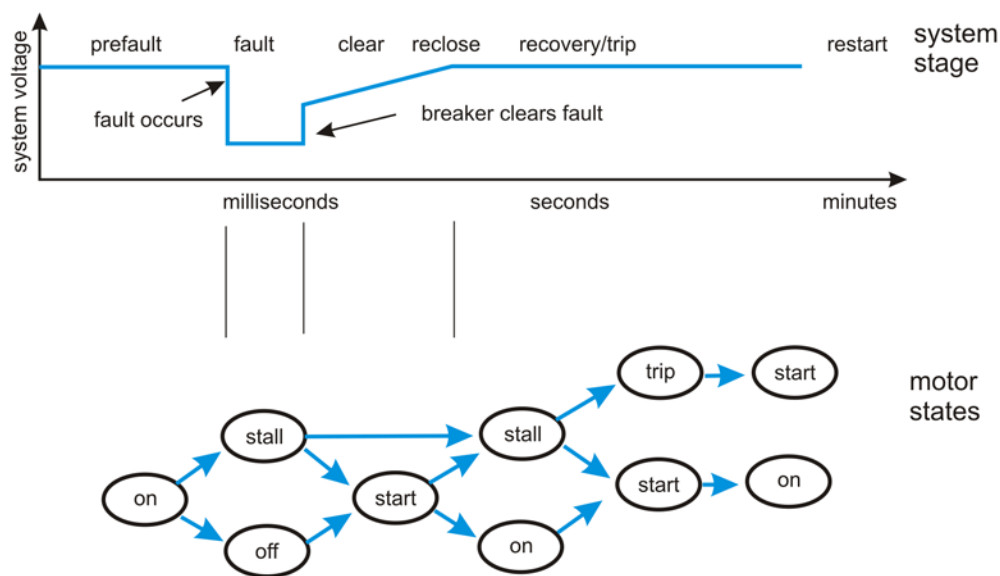
Similar equations can be written to describe the changes in the populations of the other four states, so that altogether we have

$$\begin{aligned} T_m \frac{dN_{on}}{dt} &= -P_{on-off}N_{on} - P_{on-stall}N_{on} + P_{start-on}N_{start} \\ T_m \frac{dN_{off}}{dt} &= -P_{off-start}N_{off} + P_{on-off}N_{on} \\ T_m \frac{dN_{start}}{dt} &= -(P_{start-stall} + P_{start-on})N_{start} + P_{off-start}N_{off} \\ &\quad + P_{trip-start}N_{trip} + P_{stall-start}N_{stall} \\ T_m \frac{dN_{stall}}{dt} &= -(P_{stall-trip} + P_{stall-start})N_{stall} \\ &\quad + P_{on-stall}N_{on} + P_{start-stall}N_{start} \\ T_m \frac{dN_{trip}}{dt} &= -P_{trip-start}N_{trip} + P_{stall-trip}N_{stall} \end{aligned} \quad (5.3)$$

In this set of equations, a dimensionless multiplier  $T_m$  has been added to allow for the effect of varying the time-step in the implementation of the model.

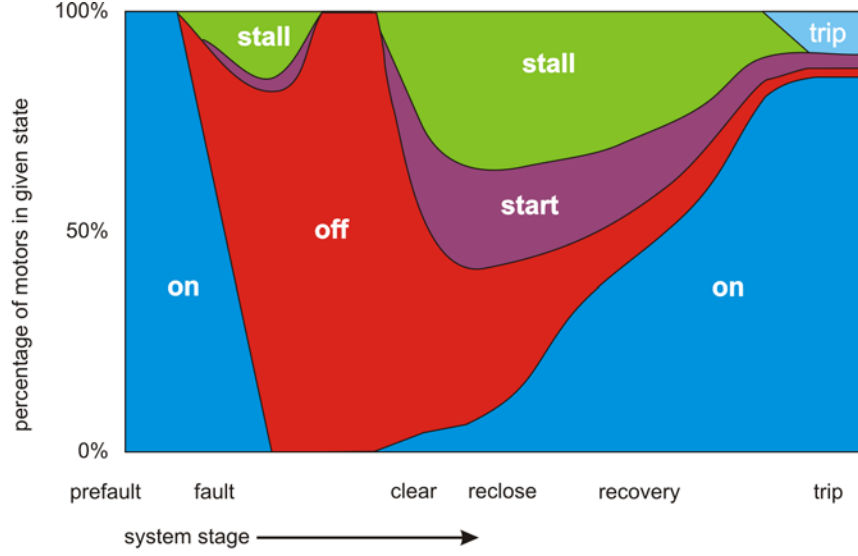
Some motors attempting to restart will stall. Whether they start or stall, during the system recovery condition, the dominant motor-state is either *on* or *stall*. The recovery period may last from several seconds to minutes after the fault.

A representative time series of the main stages of system behavior during a voltage sag event is shown in Fig. 5-2. The figure presents the predominant states and the motor state transitions during a voltage sag event. The time scale is deliberately vague: the fault may last from a few milliseconds up to 1 second. Fig. 5-3, based on our model calculations, gives a sense of the distribution of the machines in all the motor states.



**Fig. 5-2.** Time series of main stages of aggregated motor protection model, showing system stage and motor states





**Fig. 5-3.** Motor distribution among the motor states

We would benefit from an explanation:

After the fault occurs, the number of motors in the *on* state decreases rapidly (recall that the time scale is nonlinear). A few motors stall immediately, and the number of *stalled* motors increases. The number of contactors that drop out accounts for the fact that most of the motors go quickly to the *off* state. While some motors may try to restart, by the time the fault is cleared, most of the motors are *off*.

After the fault is cleared, the voltage starts to increase, but is held down by the relatively large number of motors in the *stalled* state.

In the *trip* state, the system may take a very long time to reconnect. However, in our study, we mainly focused on a shorter period, so only the *on*, *off*, *start*, and *stall* states are considered.

Therefore, the state-space model of the aggregate motor protection state transition model is derived as

$$\dot{x} = Ax \quad (5.4)$$

where

$$x = \begin{bmatrix} N_{on} & N_{off} & N_{start} & N_{stall} \end{bmatrix}^T \quad (5.5)$$

and

$$A = \frac{1}{T_{sys}} \begin{bmatrix} -P_{on-off} - P_{on-stall} & 0 & P_{start-on} & 0 \\ P_{on-off} & -P_{off-start} & 0 & 0 \\ 0 & P_{off-start} & -P_{start-stall} - P_{start-on} & P_{stall-start} \\ P_{on-stall} & 0 & P_{start-stall} & -P_{stall-start} \end{bmatrix} \quad (5.6)$$

If the state variable  $N_{xx}$  doesn't contribute 100% of the motor number in the state,  $(1-N_{xx})$  will stay in the  $xx$  state. Assuming that not all motors are in the transition process, the motor-state variable vector becomes

$$x' = \begin{bmatrix} N'_{on} & N'_{off} & N'_{start} & N'_{stall} \end{bmatrix}^T \quad (5.7)$$

For example, initially, if all motors are *on* and half of the motors will stay in the *on* state whether the voltage decreases or not, then  $N'_{off}$ ,  $N'_{start}$ , and  $N'_{stall}$  are 0, while  $N'_{on}$  is 50% of  $N_{on}$ .

### 5.1.2 State Transition Rate Specifications

$P_{on-off}$  represents the state transition rate of the motors in the *on* state transitioning to the *off* state. It describes a fraction of motors in the *on* state that are disconnected by contactor, thermal protection, etc., at each time step during fault. The probability (or rate) increases as the voltage decreases. It converges faster when the voltage decreases and time increases. As  $t$  goes from  $t_0$  to infinity,  $P_{on-off}$  changes from 0 to approximately  $a_1(1-V^\alpha)$ .  $t_0$  is the time when the fault occurs.  $V$  is the bus voltage.

$$P_{on-off} = a_1(1-V^\alpha) e^{-\frac{V^\beta}{T(t-t_0)}}, \quad a_1 + a_6 \leq 1 \quad (5.8)$$

$P_{off-start}$  represents the state transition rate of the motors in the *off* state transitioning to the *start* state. It describes that fraction of motors in the *off* state that are dropped by contactor and will restart at each time step. It starts from  $a_2$  to  $a_2V^\alpha$  with  $t$  increasing from  $t_0$  to infinity. It will converge  $a_2V^\alpha$  faster when the voltage is lower.

If  $V \geq V_{drop}$ , then

$$P_{off-start} = a_2 - a_2(1-V^\alpha) e^{-\frac{V^\beta}{T(t-t_0)}}, \quad a_2 \leq 1 \quad (5.9)$$

If  $V < V_{drop}$ , then no motors start, and  $P_{off-start} = 0$ .

$P_{start-stall}$  represents the state transition rate of the motors in the *start* state transitioning to the *stall* state. When  $t < t_0$ ,  $P_{start-stall} = 0$ ; during the fault

$$P_{start-stall} = a_3 \left( \frac{t-t_0}{T_{stall}} \right)^\gamma, \quad a_3 \leq 1 \quad (5.10)$$

After the fault, time lasts  $T_{stall}$ ,  $P_{start-stall} = a_3$ .

$T_{stall}$  is the duration from when the motor is interrupted (*off* state) until its angular kinetic energy decreases to  $E_0$ , when its torque is lower than the compressor torque, and thus is unable to drive it. Then the motor stalls. If  $a_3$  is less than 1, it means even after  $T_{stall}$ , a fraction of motors ( $a_3$ ) will stall at each time step.

$P_{start-on}$  describes the state transition rate of the motors in the *start* state transitioning to the *on* state. Note: If  $a_4$  is less than 1, it means a fraction of motors ( $1 - a_4$ ) stay in the *start* state at each time step. We set  $a_4$  to 1 in our study.

$$P_{start-on} = a_4 - a_3 \left( \frac{t - t_0}{T_{stall}} \right)^\gamma, \quad a_3 \leq a_4 \leq 1 \quad (5.11)$$

$P_{stall-start}$  represents the state transition rate of the motors in the *stall* state transitioning to the *start* state. The rate starts at  $a_5$  and converges to  $a_5 V^\alpha$ . If  $a_5$  is less than 1, it means a fraction of motors ( $1 - a_5$ ) will remain stalling at each time step.

$$P_{stall-start} = a_5 - a_5 \left( 1 - V^\alpha \right) e^{-\frac{V^\beta}{T(t-t_0)}}, \quad a_5 \leq 1 \quad (5.12)$$

$P_{on-stall}$  represents the state transition rate of the motors in the *on* state transitioning to the *stall* state.  $P_{on-stall}$  describes that a fraction of motors in normal operation mode (prefault) stall after the fault occurs.

$$P_{on-stall} = a_6 \left( 1 - V^\alpha \right) e^{-\frac{V^\beta}{T(t-t_0)}}, \quad a_1 + a_6 \leq 1 \quad (5.13)$$

$a_6$ : Assume when a fault occurs on the voltage wave, the probability that the voltage is close to zero.

If other parameters stay unchanged, the exponential term will converge faster with a smaller voltage.

Users can define  $T_{sys}$ ,  $a_1$ - $a_6$ ,  $\alpha$ ,  $\beta$ ,  $T$  in the equations.  $T$  affects the speed of the convergence of the exponential function.  $T_{sys}$  is the time constant of the system.

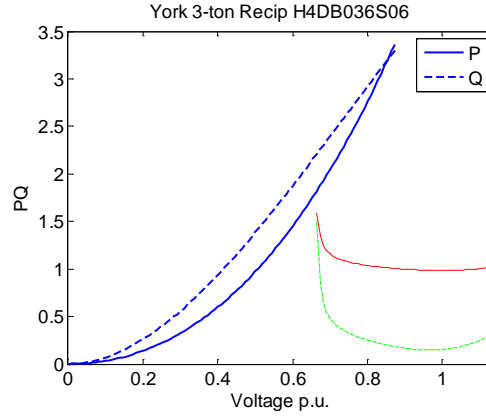
## 5.2 Simulation Results

In this the study, a short time scale is considered so that four states (*on*, *off*, *start*, and *stall*) are used. The *trip* state is not considered in this period. The active power and reactive power responses of induction motor loads are presented, with a sudden change in supply voltage magnitude.

Several assumptions are shown below:

- When a motor is in the *on* state, the active power is 1 p.u. and reactive power is 0.15 p.u.
- When a motor is in the *off* state, both the active and reactive power are 0.
- When a motor is in the *start* state, the active power is 3 p.u. and reactive power is 3.6 p.u.

- When a motor is in the *stall* state, a performance model is utilized. The active power and the reactive power follow the P-V and Q-V curves, which are the blue curves shown in Fig. 5-4. Details can be found in [17].



**Fig. 5-4.** P-V/Q-V curves

The model parameters in the simulations are listed in Table 5-1. They will change depending on different conditions, such as temperature and motor types.

**Table 5-1.** Model parameters

Parameters	Cases				
	A(1-2)	B	C	D(1)	D(2)
$T$	1	1	1	1	1
$T_{sys}$	0.1	0.1	0.1	0.1	0.1
$T_{stall}$	3	3	3	3	3
$A$	1	3.3	3.3	1	1
$B$	1	1	1	1	1
$a_1$	0.8	0.5	0.5	0.8	0.8
$a_2$	0	0	0	1	1
$a_3$	N/A	N/A	N/A	0.5	0.5
$a_4$	N/A	N/A	N/A	1	1
$a_5$	N/A	N/A	N/A	1	1
$a_6$	0	0	0	0.2	0.2

In cases A, B, and C, for large motors and large chiller motors that are over 250 HP, there is no stall, and no contactor drop in six cycles after the fault.

#### Case A

For case A, the motors either have *on* or *off* state. No *stall* or *restart*. The model parameters are listed in Table 5-1.

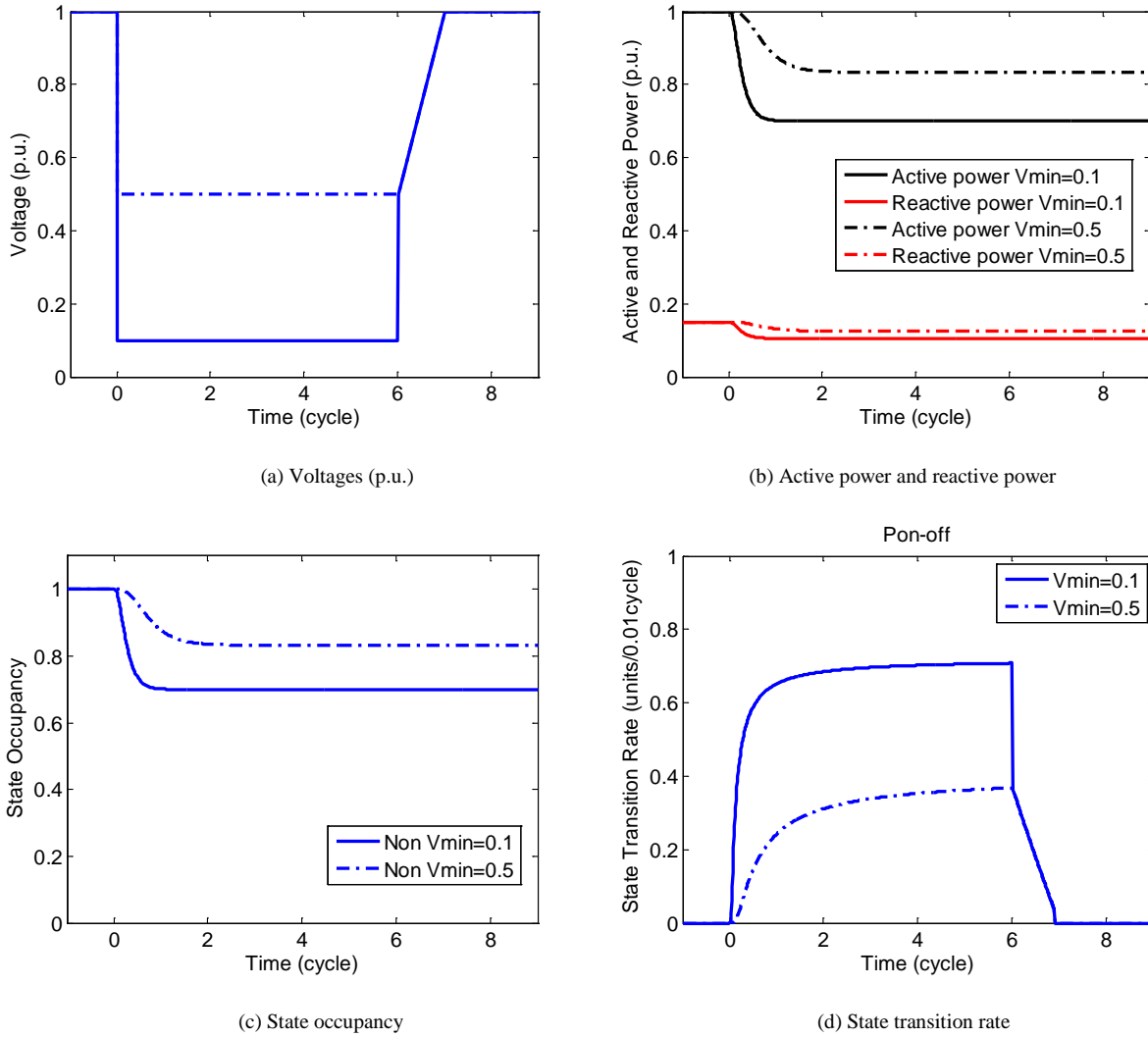
We assume in six cycles:

- 40% of motors are large motors over 250 HP.
- 10% of motors are three-phase motors under 250 HP.

- 90% of motors will trip in two cycles with the contact dropping out at perhaps 50% voltage.
- 30% of motors are large chiller motors, over 250 HP.
- 20% of motors are rooftop air conditioners.
- At 50% voltage, contactor drops out in one cycle.

Therefore, we further assume: in two cycles, 30% of motors will trip at 10% voltage and 15% of motors will trip at 50% voltage.

There are two voltage event profiles: (1) the bus voltage drops to 0.1; and (2) the bus voltage drops to 0.5. Both events last for six cycles, and recover at the sixth cycle and return to nominal voltage at the seventh cycle, which can be seen in Fig. 5-5(a). The number of the motors in the *state* transition depends on the minimum value of the voltage dip. The active and reactive powers are shown in Fig. 5-5(b). When the minimum voltage of the voltage profile is 0.1, nearly 30% power is reduced; while when it is 0.5, nearly 15% power is reduced. The *on*-state occupancy *Non* is presented in Fig. 5-5(c). The state transition rates from the *on* to *off* state for different voltage profiles are shown in Fig. 5-5(d). The minimum voltage of the voltage dip affects not only the number of motors in the state transition but also the state transition rates. Therefore, it demonstrates why the state occupancy decreases to 0.85 in two cycles when the minimum voltage is 0.5 while it decreases to nearly 0.7 in less than one cycle when the minimum voltage is 0.1.



**Fig. 5-5.** Dynamic responses of aggregated motor protection model in case A

### Cases B and C

For cases B and C, the motors either have *on* or *off* state. No *stall* or *restart*.

We assume in six cycles (0.1 s):

#### Case B

- 50% of motors are large motors over 250 HP.
- 50% of motors are three-phase motors under 250 HP.
  - 90% of motors will trip in two cycles with the contact dropping out at perhaps 50% voltage.

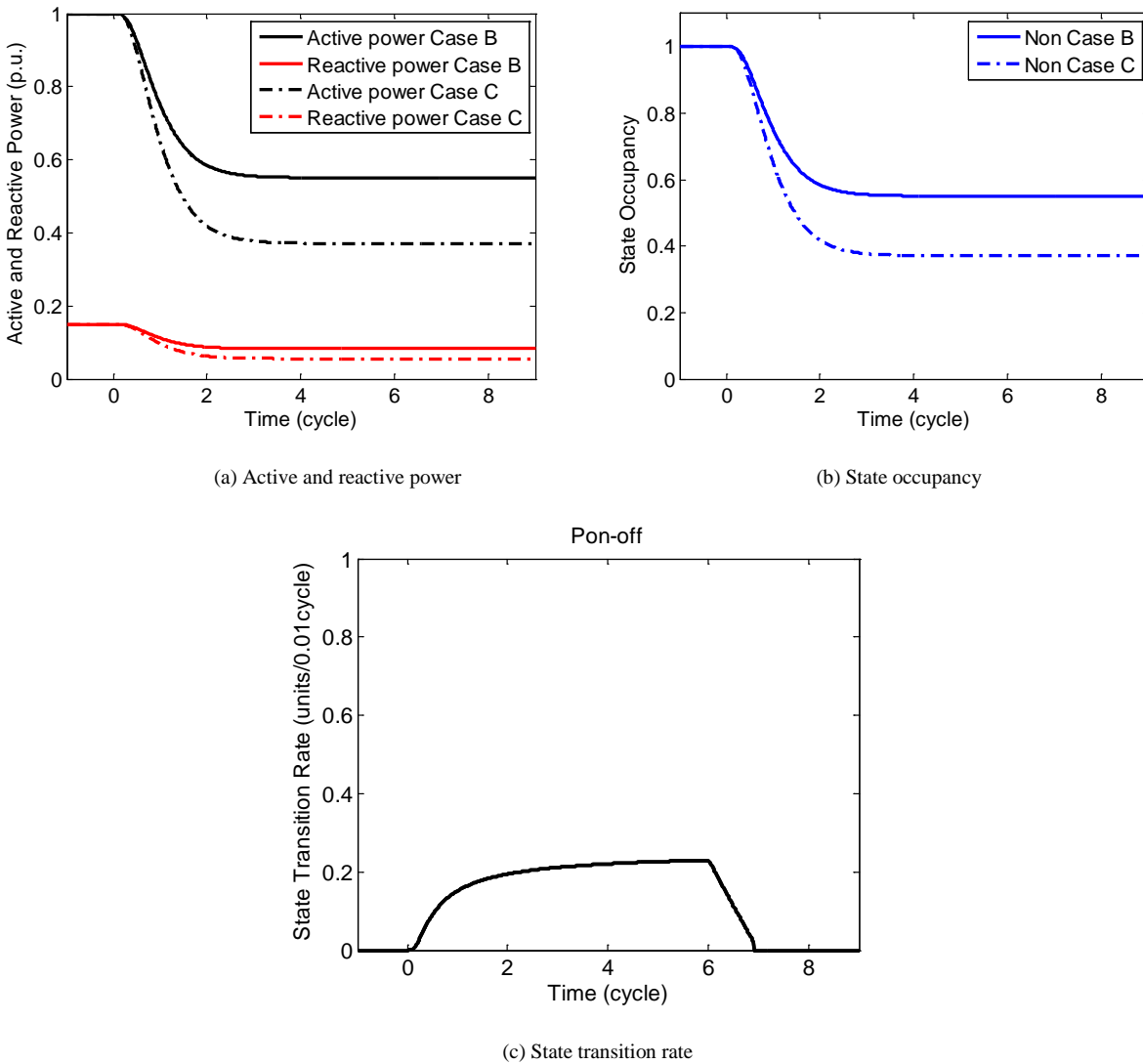
#### Case C

- 30% of motors are large motors over 250 HP.

- 70% of motors are three-phase motors under 250 HP.
  - 90% of motors will trip in two cycles with the contact dropping out at perhaps 50% voltage.

Therefore, we further assume in two cycles: 45% of motors will trip at 50% voltage in case B; 63% of motors will trip at 50% voltage in case C.

The model parameters are listed in Table 5-1. The voltage profile is the same as in the second scenario in case A. The minimum voltage of the voltage dip is 0.5. The simulation results for cases B and C are shown in Fig. 5-6. The active and reactive powers are shown in Fig. 5-6(a). The *on* state occupancy is shown in Fig. 5-6(b). In case B, the number of *on*-state motors decreases to about 55% in two cycles; while in case C it decreases to about 37% in two cycles. The state transition rates are the same for both cases shown in Fig. 5-6(c).



**Fig. 5-6.** Dynamic responses of aggregated motor protection model in cases B and C

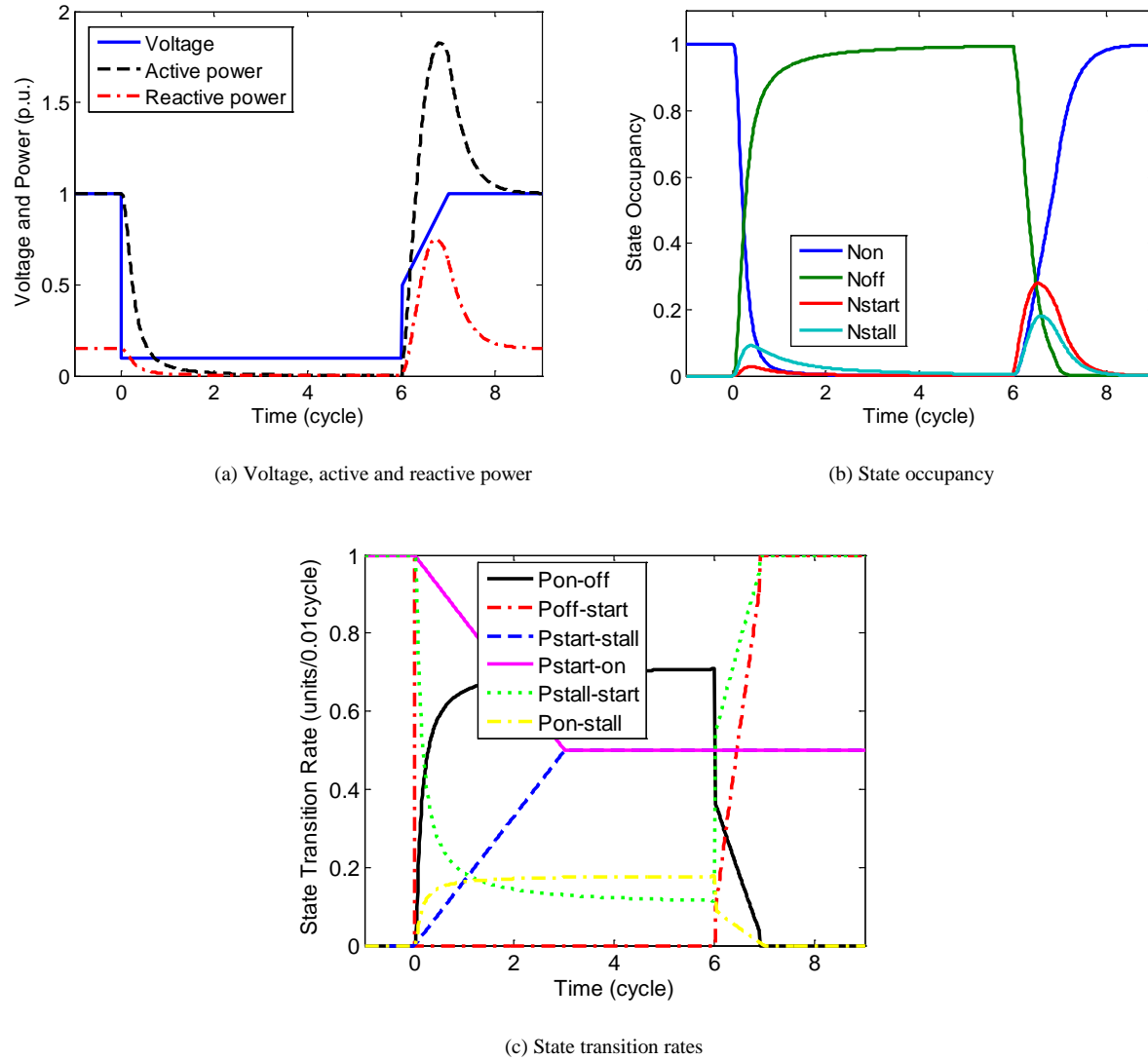
### ***Case D***

For case D, motors can stall and restart, so there are four states in the case D and there are two scenarios in this study. The model parameters are listed in Table 5-1. We assume when the voltage is below 0.5, the state transition rate,  $P_{off\_start}$ , goes to zero from *off* to *start* state.

- Scenario 1

The simulation results are shown in Fig. 5-7. The voltage, active power, and reactive power are shown in Fig. 5-7(a); state occupancy for *on*, *off*, *stall*, and *start* states are shown in Fig. 5-7(b); state transition rates are shown in Fig. 5-7(c). Fig. 5-7(b) indicates that after the voltage drops to 0.1, the *on*-state motors mainly transit to the *off* state and a small portion transitions to the *start* state. The voltage recovers after six cycles. At the beginning of the recovery, the numbers in the *start*, *stall*, and *on* states increase, and after about 0.6 more cycle the numbers in the *start* and *stall* state decrease while those in the *on* state still increase. The number in the *on* state gradually increases to 1, while those in the *off* and *stall* states decrease. The active and reactive power decreases at the beginning of the event, but increases in the recovery process. The peak of reactive power can be 5 times its base value.





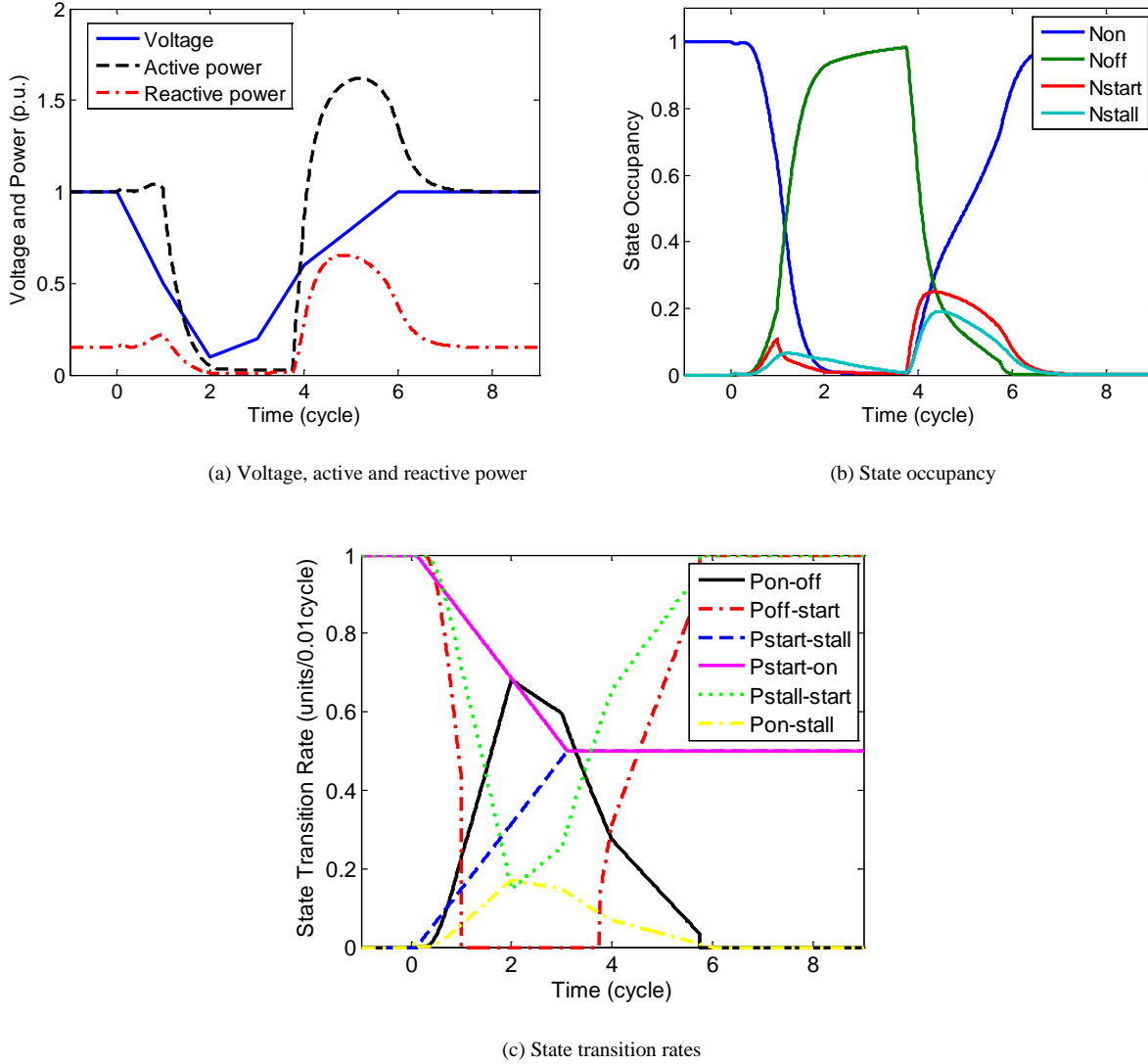
**Fig. 5-7.** Dynamic responses of aggregated motor protection model in case D, scenario 1

- Scenario 2

In this scenario, the bus voltage gradually decreases to 0.1 p.u. in two cycles and recovers to 1 p.u. within four more cycles. The voltage, active power, and reactive power are shown in Fig. 5-8(a); state occupancy for the *on*, *off*, *stall*, *start*, and *state* states is shown in Fig. 5-8(b); state transition rates are shown in Fig. 5-8(c).

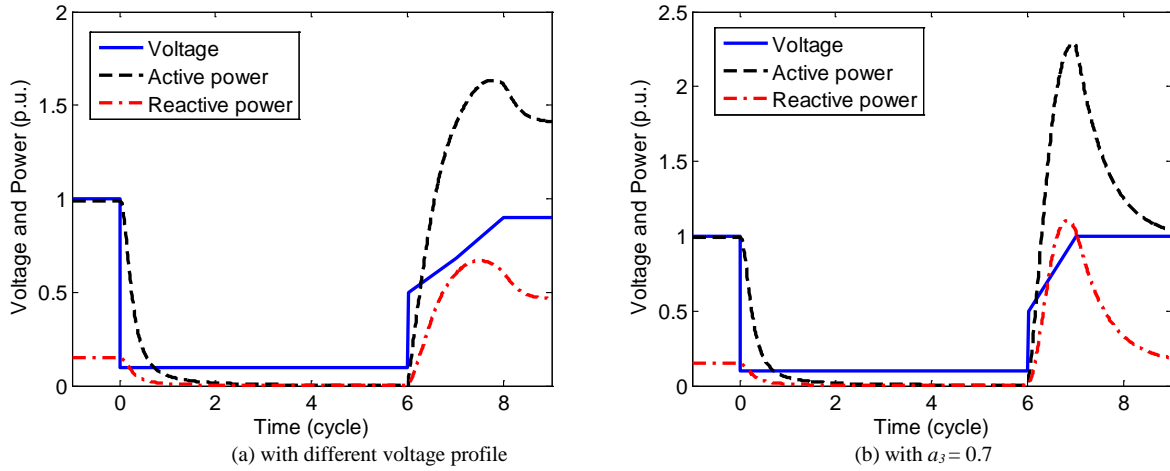
At the beginning of the voltage decrease, both active and reactive power increase, compared with scenario 1 in which they decrease. Thus, the model behaviors are affected by the voltage event. If the voltage dips gradually, some motors will stall and restart before contactors drop. This is why in scenario 2 the power increases in the first cycle of the voltage decrease. The power peaks appear at close to the seventh cycle after the event happens in scenario 1 but the fifth cycle in scenario 2. The power values are larger than the base values for a longer period in scenario 2, but the peak power values are larger in

scenario 1. This is because the voltage goes back to 0.5 before the fourth cycle and then the  $P_{off-start}$  increases from zero earlier in scenario 2.



**Fig. 5-8.** Dynamic responses of aggregated motor protection model in case D, scenario 2

Dynamic responses with different conditions are shown in Fig. 5-9. In Fig. 5-9(a), the voltage recovers to 0.9 and in Fig. 5-9(b), parameter  $a_3$  is 0.7 instead of 0.5. If we change the recovered voltage level, the voltage dip magnitude and rate, or state transition rate assumptions, formulas, and parameters, the active power and reactive power consumption of the aggregate motor model will be very different.



**Fig. 5-9.** Dynamic responses with different conditions

### 5.3 Conclusion

An aggregate motor protection model was developed based on state transition modeling. A state-space model of the aggregate motor protection state transition model was proposed. The *on*, *off*, *stall*, and *start* state occupancies were taken as state variables. State transition rate specifications were presented to represent the stochastic state transition process for each state and discuss a sequence of motor behaviors in time series.

In the short time scale simulations, we studied the A, B, C, and D cases. The results met our expectations on the Motor ABCD classification. Voltage profiles and the fault time durations affect the state occupancies and state transition rates, influencing the active power and reactive power consumption of the aggregate motor protection state transition model. Although the aggregate model is not based on the electromagnetic equations, it captures the main characteristics of the behaviors of a population of motors with protection, such as contactors dropping and motors stalling and restarting. In addition, the parameters play a key role in the results. We recommend feeder data be used to validate and calibrate the model.

## 6.0 AC Motor Protection Model

### 6.1 Single-Phase Motor and Protection Modeling

An induction motor stalls when the load torque exceeds a value of the motor torque known as the breakdown torque [18]- [21]. That causes its speed to decrease to zero, or to some stable operating point well below rated speed. This occurs when the applied shaft load is greater than the producing motor torque due to the suppression of the motor terminal voltage. Also, a stall condition can occur when an excessive mechanical load is applied beyond motor torque capability. This condition will develop motor current equal to or approaching locked-rotor current [22].

During the stalling process, the motor current will increase rapidly as the load torque increases (the current is called “inrush current”) until the breakdown torque is reached. Beyond breakdown torque, the motor current continues to increase, approaching locked-rotor current. Along with the increase in current, the speed of the motor decreases and the impedance of the motor approaches the locked-rotor impedance.

Two types of stall causes are identified in the Institute of Electrical and Electronics Engineers (IEEE) Guide for AC motor protection [22], as follows:

1. Excess shaft load torque prior to a motor startup (e.g., failure to open a pump’s discharge gate)
2. Sudden change of increased shaft load torque during normal operation (e.g., bearing failures)

Applied voltage sag will be another stall cause.

Stall detection for an induction motor is usually provided by an overcurrent relay. It will typically have an inverse time characteristic set to detect current above the breakdown torque level. Motor starting can result in a stall or locked-rotor condition, so this has to be protected against, too. This protection is usually done by setting the motor-starting relays above the motor-starting time-current curves and below the running and accelerating thermal limit for the motor. In cases where motors are applied to high-inertia loads, overcurrent protection may need to be combined with speed switches, distance relays, or additional rotor thermal protection.

National Electrical Manufacturers Association (NEMA) MG1-1998, Article 20.45, gives the conditions for motor operations. They are expected to operate at rated load with a voltage variation of  $\pm 10\%$ , or a frequency variation of  $\pm 5\%$ . They are also expected to operate with both voltage and frequency variations, provided the sum of the absolute values of the deviations does not exceed 10%. Variation in voltage or frequency, or both, usually results in an increase in stator winding temperature over that expected at rated nameplate conditions. Elevated temperature is usually considered to shorten the life of insulation. Within the NEMA-defined limits, the increase in operating temperature is permissible because it is characteristic of short duration and, therefore, is considered not damaging to the insulation. The motor can be protected against such overloads by devices that sense line current but are independent of frequency.

Failure of a motor to accelerate when its stator is energized can be caused by several types of abnormal conditions. Possibilities include mechanical failure of the motor or load bearings, low supply voltage, or an open circuit in one phase of a three-phase voltage supply. When a motor stator winding is energized with the rotor stationary, the motor performs like a transformer with resistance-loaded secondary winding. Stator winding currents may be as high as seven or so times the rated full-load value, depending on motor design and supply system impedance. The motor controller must be capable of interrupting this locked-rotor current.

Over-temperature can be prevented by sensing the line-current magnitude and interrupting the power when the starting time is excessive. Since motors require and can tolerate high current for a limited time during acceleration, an appropriate time delay must be incorporated in the current sensing device. To provide locked-rotor or failure-to-accelerate protection, the protective device must be set to disconnect the motor before the stator insulation suffers thermal damage, or the rotor conductors melt or suffer damage from repeated stress and deformation [22].

A contactor drops out when the field strength of the magnetic field becomes smaller, then the spring pressure tries to push the yoke away from the armature when the voltage falls to between 40% and 60% [23]-[25].

Single-phase induction motors in residential air conditioners are believed to tend to stall easily under voltage dips. The effect has been observed in the Southwest and Florida, and likely occurs elsewhere. This causes individual thermal protection to trip motors off line. It further results in delayed voltage recovery events. Developing a single-phase motor model is necessary because three-phase motor models in most of simulation packages or tools do not adequately represent all the observed behavior of single-phase motors.

The model with protective device actions is expected to mimic contactor and thermal protection responses, accurately capture the sensitivities of motor real and reactive power requirements as a function of its voltage and frequency, represent the motor impact on damping of low frequency inter-area oscillations, reasonably predict the stalling phenomenon, and accurately represent motor current, real, and reactive power during the stalled state.

We developed the protection model and used a dynamic phasor representation of a single phase motor model developed by [2] in Appendix D.

The protection device action models we developed have two parts:

1. When voltage decreases under trip voltage, the contactor drops.
2. When temperature increases to a critical value, thermal protection trips the motor. .

The user can define different motor parameters, voltage trip levels, motor temperature change rates, motor normal running temperatures, and thermal protection trip temperatures for the model.

## 6.2 Simulation Results

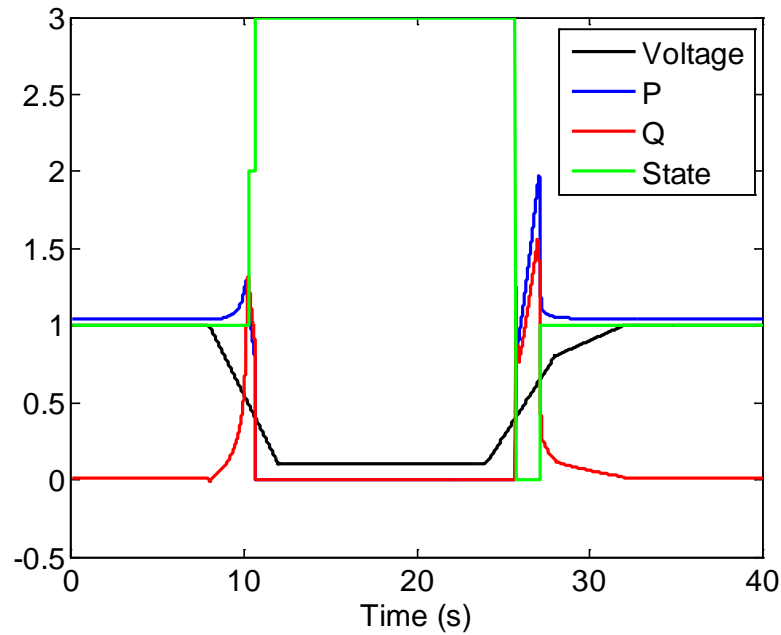
In this section, several simulation scenarios and case studies are carried out on a single-phase motor with contactor and thermal protection. Motor behaviors such as stall, start, contactor drop, and thermal protection trip are all modeled.

Scenario 1. Voltage dips to 0.1 p.u. and contactor drops when voltage decreases below 0.4 p.u.

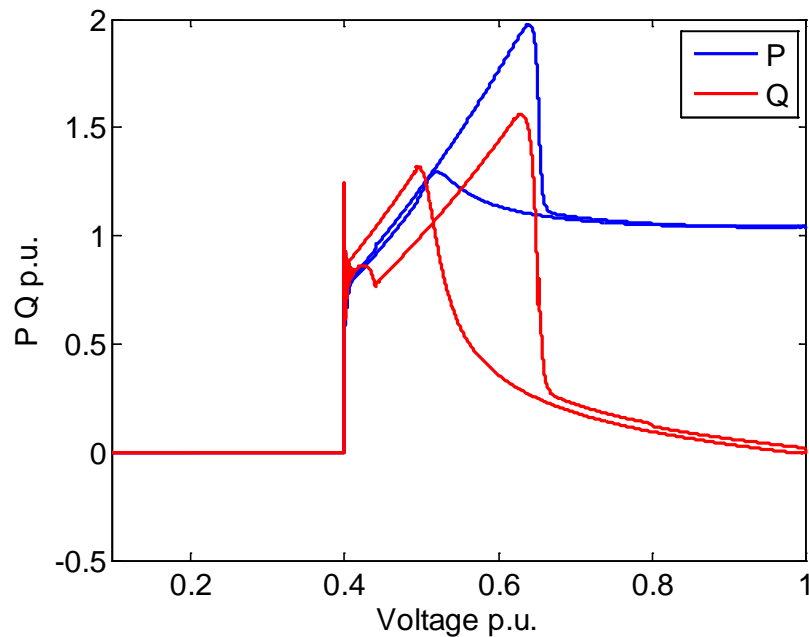
Behaviors of motor voltage, active power, reactive power, and motor state are shown in Fig. 6-1. The relation of active power, reactive power, and voltage is shown in Fig. 6-2. The State value of 1 indicates a motor is running normally; the State value of 2 indicates a motor stalls; the State value of 3 indicates contactor drops; the State value of 4 indicates thermal protection trips.

In pre-fault condition, voltage is 1 p.u., active power is about 1 p.u., reactive power is close to 0, and the State value is 1. In the event, when the voltage decreases to 0.5 and before it decreases to 0.4, active

power and reactive power increase as the motor stalls. When voltage reaches 0.4, the contactor drops out. The active power and reactive power requirement is thereafter zero. When voltage returns to 0.7, the motor restarts and operates normally afterward.



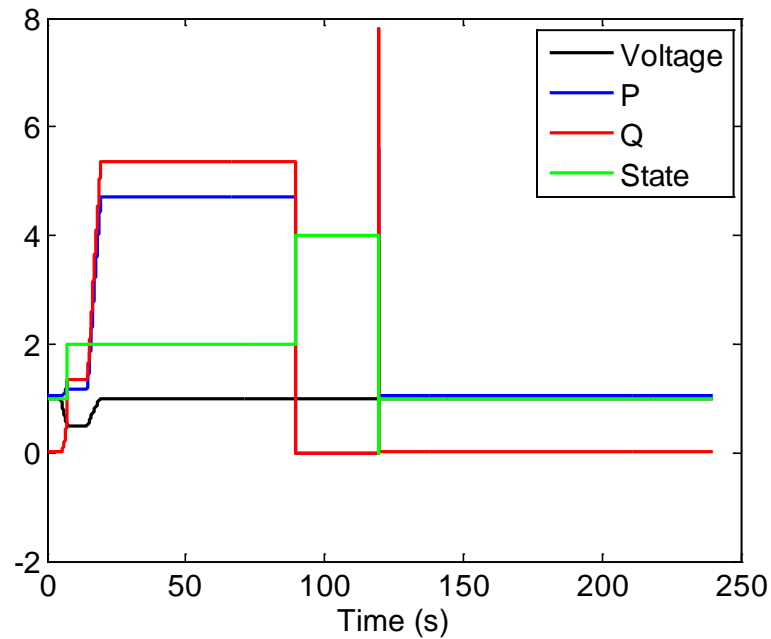
**Fig. 6-1.** Behaviors of motor voltage, active power, reactive power, and motor state  
(State=1: normal running; State=2: stalling; State=3: contactor drops; State=4: thermal protection)



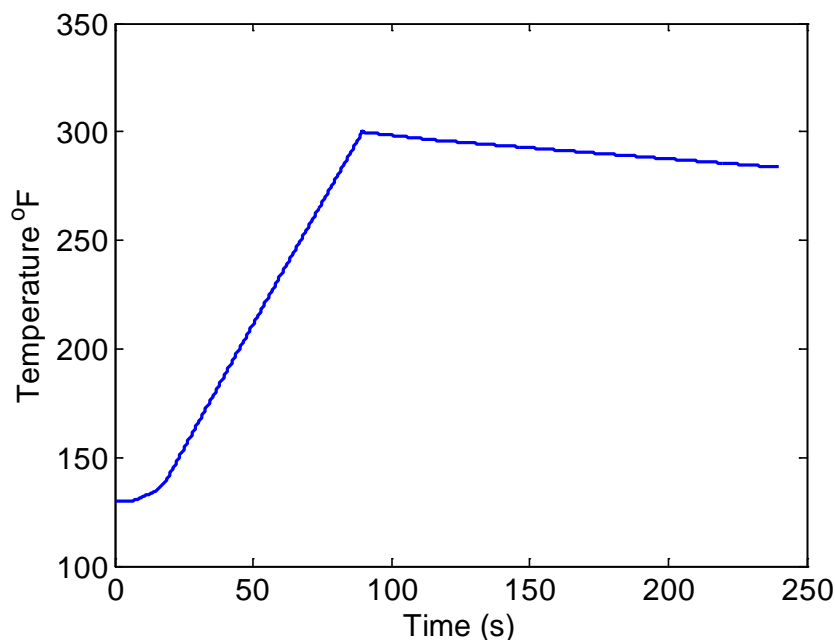
**Fig. 6-2.** Active power and reactive power vs. voltage

Scenario 2. This is a longer time scale simulation. In this event, voltage dips to 0.5 p.u. The trip temperature is 300°F.

Fig. 6-3 presents the behaviors of the applied voltage, the motor active power and reactive power, and the motor state over a period of 4 minutes. The motor temperature is shown in Fig. 6-4. When the temperature reaches 300°F, the motor is tripped. In this scenario, the motor's normal operating temperature is relatively higher and it increases and decreases more slowly than in previous cases. Motor heat gain is shown in Fig. 6-4. Because the heat gain is much higher when the motor stalls, compared to when the motor is in normal condition, the temperature increase rate is larger than its decrease rate. Heat is gained faster than it's removed.



**Fig. 6-3.** Behaviors of motor voltage, active power, reactive power, and motor state in a longer time scale  
(State=1: normal running; State=2: stalling; State=3: contactor drops; State=4: thermal protection)



**Fig. 6-4.** Motor temperature

### 6.3 FIDVR Event Load Measurements Analysis and Its Methodologies

This section describes a method for estimating the stalling and thermal protection characteristics of single-phase induction motors on a distribution circuit using data collected from field-deployment sensors during FIDVR events.

Bulk power transmission system planning requires accurate models of all the major generation, transmission, and load components of a bulk power system. Load has historically been the least accurate of these three components. Accurate load models are needed to evaluate the vulnerability of the bulk system to instability problems in the seconds after a major system event such as loss of a generation, transmission, or load component. These models are used to design and implement appropriate control responses and ensure that system operation satisfies the required contingency constraints.

IEEE provided initial guidance on load modeling in the early 1990s [26],[27]. After studying the 10 August 1996 outage and 4 August 2000 oscillations, the WECC identified the need for explicit representation of motor loads in power system studies and started development of an interim motor load model that was adopted for planning studies starting in 2002 [28]. This model addressed critical operational issues with the California-Oregon Intertie (COI) and improved the accuracy of planning models for events that involved north-south oscillations across the COI.

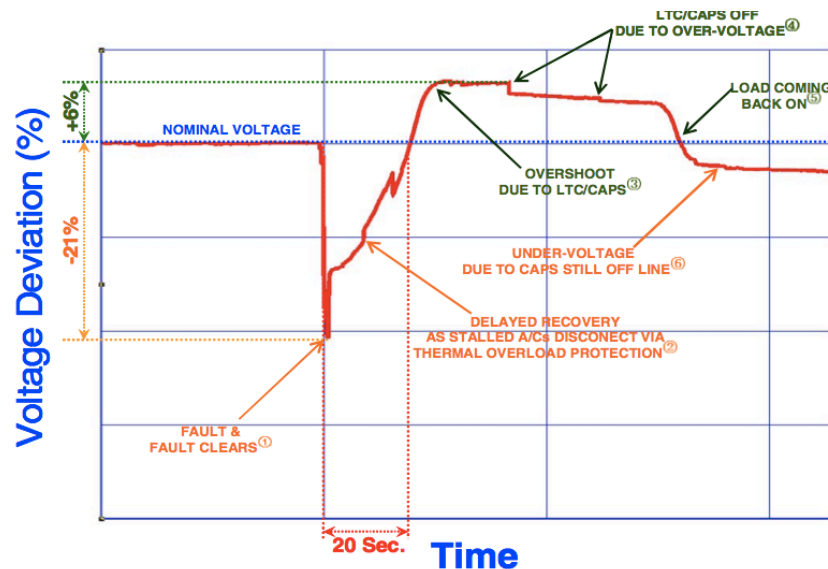
WECC continued to investigate models that could better represent the impact of load on damping of north-south power oscillations. Oscillations tended to be larger during summer on-peak conditions, when a larger percentage of air-conditioning motor loads were presented on the system. To address these and other issues, the WECC LMTF developed a composite load model for planning and operating studies [2]. The composite load model more accurately represents load response to voltage and frequency disturbances and offers more credible descriptions of load behavior following transmission faults.



A number of FIDVR incidents have been recorded in Southern California since 1990 [5]. Events were also reported by Florida Power and Light [30]. Confirming earlier reports [31], SCE and Florida Power & Light engineers concluded that the FIDVR load behavior is related to stalling of residential single-phase air conditioners in areas nearest the fault.

Beginning with the summer 2013 planning season, WECC performed dynamic voltage stability studies using the version 1 composite load model. These studies considered the effect of the dynamic behavior of loads in a manner that the interim load model could not. However, when motor stalling behavior was enabled, the models tended to over-represent FIDVR events caused by transmission faults. The version 1 composite load model showed very high sensitivity to motor thermal trip time and to the specific composition of motor. As a result, the 2013 studies were run with motor stalling behavior completely suppressed while the LMTF investigated the details of the model's behavior with respect to motor stalling and thermal tripping.

Fig. 6-5 shows a typical delayed voltage recovery profile as observed at a 230 kV transmission bus. Right after the fault, the voltage decreased to less than 80% of nominal voltage (point 1), before the fault was cleared. This dip in voltage caused some air-conditioning units to stall because the voltage on the distribution circuits was even lower. The air-conditioner motors drew significantly more power than when they were running; they kept the voltage from immediately recovering to nominal level (point 2). However, the excess power consumed caused the stalled motors' thermal overload protection to trip them after a few seconds. So the voltage gradually recovered but then overshot the nominal voltage by about 6% because the capacitor banks were still connected on the circuit (point 3). This over-voltage then caused the capacitor bank to trip off due to over-voltage (point 4). After the capacitors tripped off and the load-tripped air conditioners reset, the voltage went below the nominal voltage again (points 5 and 6).



**Fig. 6-5.** Delayed voltage recovery following a 230 kV transmission fault in Southern California

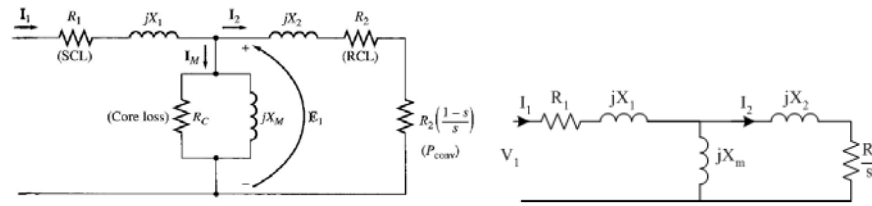
This sequence of events leaves the circuit more vulnerable to repeated events. Simulations of these events using the interim load model showed an instantaneous post-fault voltage recovery [32]. SCE studies also indicated that previously developed three-phase motor models [33], [34] did not reproduce air-conditioner stalling phenomenon during the simulated events, and SCE engineers proposed a hybrid modeling approach: A three-phase motor model to represent the running state and a constant impedance model representing a stalled motor [32]. The SCE study also demonstrated the need for a distribution

system equivalent to properly represent the voltage drop and real and reactive power losses in the distribution systems during the disturbances.

The WECC LMTF has recognized air-conditioners as a critical component of the composite load model [2], [28], completing the first phase of the composite load model development in 2012 and starting the second phase in 2013. During this phase, the LMTF, with support from SCE and the U.S. Department of Energy, began to collect and analyze FIDVR event data to validate and calibrate the composite load model. In addition, the task force considered proposals to enhance the composite load model to include more detailed aspects of motor protection and control. This paper reports on the use of distribution-level and customer premises data for the purpose of validating and calibrating the composite load model, as well as providing support information regarding further research and development needs on the composite load model.

### 6.3.1 Background

The analysis of FIDVR event load telemetry in the context of the composite load model requires a detailed representation of the expected electrical behavior of a motor as it transitions from nominal operating speed to stalled (or near stalled) speed. A typical induction motor circuit is shown in Fig. 6-6, where  $N_{ph}$  is the number of connected phases,  $R_1$  is the stator resistance,  $X_1$  is the stator reactance,  $X_m$  is the core reactance,  $R_2$  is the rotor resistance,  $X_2$  is the rotor reactance, and  $s$  is the motor slip.



**Fig. 6-6.** Induction motor equivalent circuits including losses (left) and ignoring losses (right)

The Thevenin equivalent values are

$$\begin{aligned}
 Z_e &= jX_m \frac{R_1 + jX_1}{R_1 + j(X_1 + X_m)} \\
 R_e &= R[Z_e] \\
 X_e &= I[Z_e] \\
 V_e &= \left| V_1 \frac{jX_m}{R_1 + j(X_1 + X_m)} \right|
 \end{aligned} \tag{6.1}$$

Motor speed determines the amount of real and reactive power consumed. Speed (measured in RPM) is related to slip  $s$  as

$$RPM = \frac{120f}{n}(1-s) \tag{6.2}$$

where  $f$  is the system frequency (measured in Hz) and  $n$  is the number of poles on the motor. The total power consumed is

$$S = NV_e \left[ \frac{sV_e}{(Z_e + jX_2)s + R_2} \right]^* \quad (6.3)$$

where  $N$  is the number of phases. The real and reactive powers are

$$\begin{aligned} P = R[S] &= \frac{NV_1^2 s(R_e s + R_2)}{(R_e + R_2)^2 + (X_2 + X_e)^2} \\ Q = I[S] &= \frac{NV_1^2 s(X_2 + X_e)}{(R_e + R_2)^2 + (X_2 + X_e)^2 s^2} \end{aligned} \quad (6.4)$$

We observe that  $P^2(s) + [Q(s) - P_{\max}]^2$  describes a circle of radius  $P_{\max}$  centered about the point  $S = jP_{\max}$ , so that we have

$$P^2(s) + [Q(s) - P_{\max}]^2 = P_{\max}^2 \quad (6.5)$$

which simplifies to

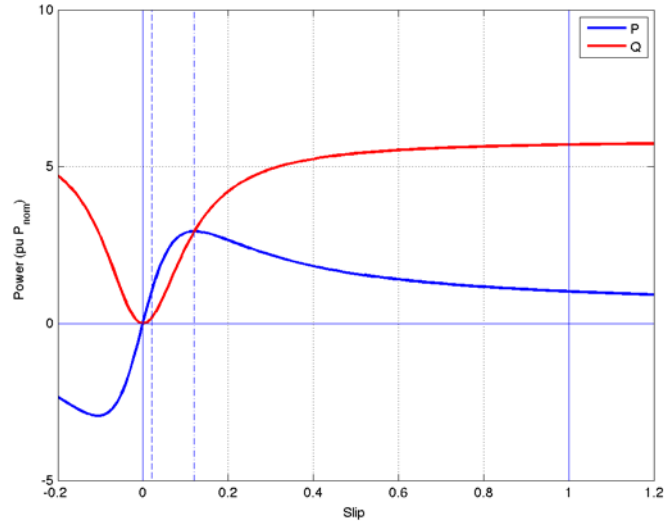
$$P_{\max} = \frac{NV_1^2}{2(X_2 + X_e)} \quad (6.6)$$

and corresponds to the maximum torque

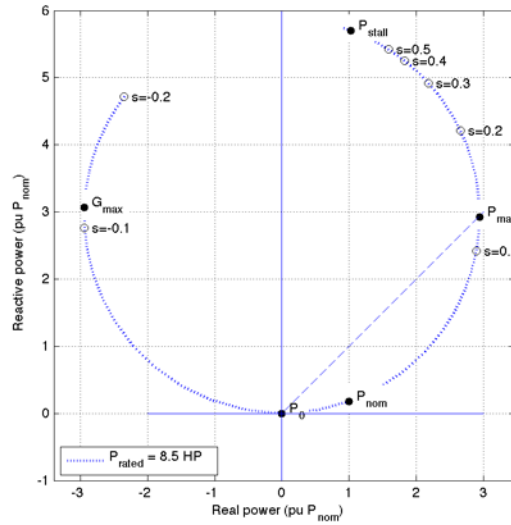
$$T_{\max} = \frac{NV_1^2}{2\omega_s \left[ R_e + \sqrt{R_e^2 + (X_2 + X_e)^2} \right]} \quad (6.7)$$

when we ignore losses. This circular relationship between real and reactive power is shown in Fig. 6-7, with powers shown per unit of nominal power.

The electrical characteristics of motors as a function of speed illustrated in Fig. 6-7 for slips ranging from -0.2 to +1.2 allow us to make some useful observations about steady state induction motor power consumption at various speeds. These will be helpful in performing aggregate parameter identification from FIDVR event data when motors trip on thermal protection. The real and reactive power reduction on the circuit when a motor trips corresponds to the real and reactive power consumed by the motor immediately before the trip, when it is presumably stalled and at steady state. (We ignore all event data for which either real or reactive power increases corresponding to the second quadrant, i.e., generation, and lower half-plane when reactive power is negative.)



(a) P/Q



(b) complex

**Fig. 6-7.** Power slip curves for typical induction motor

1. As motor speed varies, the real and reactive powers plotted in the complex plane form a circle centered on the point  $P = 0$  and  $Q = P$ .
2. Each point in the right-hand side corresponds to a unique combination of motor rated power and slip: there is only one circle that is centered on a point on the positive imaginary axis that also intersects both the origin and an arbitrary point in the first quadrant. Thus, for each real/reactive power drop, observation corresponds a unique point in the first quadrant for which there can be one and only one associated motor size.
3. Nominal power conditions are those very near the real axis in the first quadrant with  $P \gg Q$ . Observations near the real axis are most likely not thermal trips and probably normal motor duty-cycle operation.

4. The maximum torque is developed when the real and reactive power are approximately equal to  $P$ . As motor size increases, these points form a line extending from the origin at  $45^\circ$ . Although the maximum torque slips may vary with motor design, the relationship of real and reactive power is invariant for the maximum torque condition.
5. Stalled power conditions can only exist when  $Q > P$  for NEMA Design B motors. For motors with large starting torque as a fraction of maximum torque,  $Q$  is expected to be only slightly larger than  $P$ . Motors with very low starting torques may have  $Q > 10P$ . Recall that higher starting torque is typical of reciprocating compressors and low starting torque may be more common with scroll compressors.
6. Reactive power asymptotically approaches the value  $Q = 2P$  when the motor is running in reverse. Observations of conditions where  $P \rightarrow 0$  and  $Q \rightarrow 2P$  correspond either to motors running backwards or stalled low-starting-torque motors.

### Motor D Parameter Estimation

For the planning studies, the aggregate motor parameters should be provided for each bus in the planning model. While the aggregate motor parameters do not literally represent an individual motor, they are designed to represent the behavior of the population of motors with the understanding that the model is only an approximation. Nonetheless, the aggregate motor parameters are based on a single motor's parameters as described above, with a linear ramp from stalled to tripped state, which is determined by the thermal protection time constant. With the exception of the thermal protection time constant, the standard procedure for estimating induction motor parameters is usually as follows [35]:

1. No load test: Determines rotational losses and estimates magnetizing current by applying normal power with no mechanical torque.
2. DC test: Determines the stator resistance  $R$  by applying a zero-frequency voltage to the stator terminals.
3. Locked rotor test: Determines the rotor copper losses by applying a low-voltage AC signal at reduced frequency to simulate rotor slip during normal operation.

Unfortunately, for a large population of motors on a circuit, it is impossible to perform these tests in a systematic and cost-effective way. In principle, it is possible to observe the normal operating power for an individual motor by observing the voltage and current change on the circuit when the motor is disconnected, provided that the motor being disconnected represents a significant fraction of the total load on the circuit to overcome the background noise on the circuit and the instrument combined. For small motors that have a higher propensity to stall, this is impractical.

The only other condition that can be observed is during a FIDVR event when single-phase air-conditioner motors may undergo thermal trips. If one assumes that such motors are close to or at steady state when the thermal trip occurs, then the change in real and reactive power observed on the circuit will correspond to a point in figure that is associated with a single motor size (based on rated or nominal power). Using the distribution of motor sizes and the times to trip, the remaining motor parameters can be derived for aggregate equivalent Motor D required by the composite load model.

### 6.3.2 Aggregate Motor Behavior

This section presents a simplified method of estimating the distribution of Motor D parameters for a population of motors on a circuit using thermal trip voltage and current measurements in the seconds following a FIDVR event.

The composite load model simplifies the representation of motors on feeder circuits by classifying motors according to electrical and mechanical loading characteristics.

- **Motor A:** Motors with constant torque typical of compressor motors found in commercial air-conditioning systems and large-scale refrigeration systems. These motors are not considered vulnerable to undervoltage stalling because they typically come with undervoltage protection built in to the control circuits.
- **Motor B:** High inertia motors with speed-dependent loads typical of fans. These motors are not considered vulnerable to undervoltage stalling because of their high inertia.
- **Motor C:** Low inertia motors with speed-dependent loads typical of pumps. These motors are not considered vulnerable to undervoltage stalling because they typically come with undervoltage protection built in to the control circuits.
- **Motor D:** Motors with low starting torques typical of residential air-conditioning units and heat pumps. These motors are particularly vulnerable to undervoltage stalling and are provided with a thermal protection circuit breaker in the rotor. FIDVR data can be expected to include the effect of both Motor D stalls and rotor thermal protection.
- **Electronic drive:** Motors with electronic speed controls are generally grouped with other electronic loads even though such motors do not necessarily respond like other electronic loads such as compact fluorescents and consumer electronics. Motor drives are designed with either double feed or simple rectifiers, the former having the ability to regenerate when the DC bus voltage is higher than terminal voltage and the latter “disappearing” from the circuit when the DC bus voltage exceeds the voltage at the terminals. Regardless of the drive type, electronic motors are not generally vulnerable to undervoltage stalling because the electric drive control provides the necessary undervoltage protection.

Of these motor types, only Motor D behavior can be expected to show up in data collected in the seconds after a FIDVR event, as evidenced by the following.

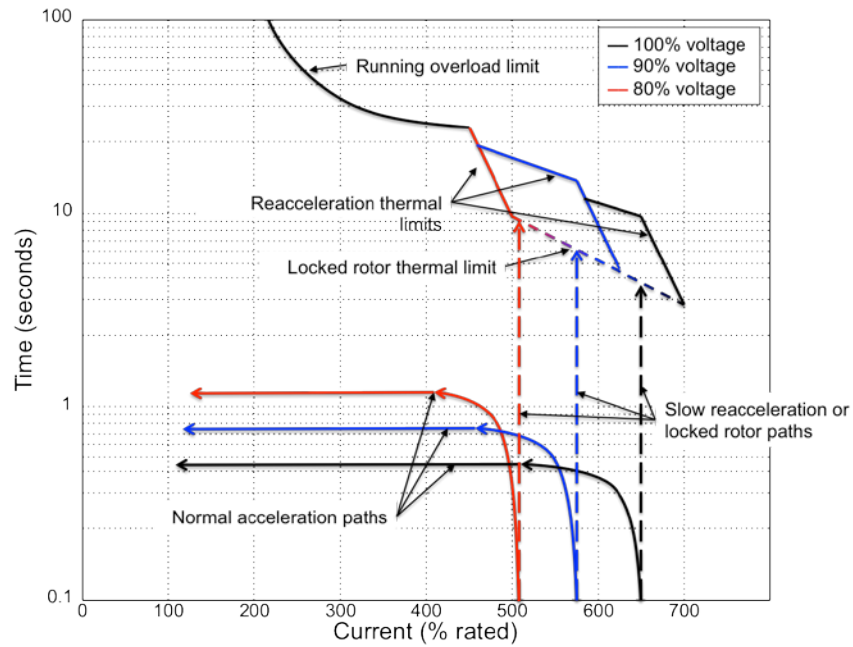
1. **Initial response:** During the few cycles immediately after the fault is cleared, all motors begin reaccelerating, with more current than before the fault. The amount of reactive power drawn will depend on how much the motor has slowed during the fault, which depends on the motor’s overall inertia considering the driven load. In the presence of full compressor backpressure, Motor D can be expected to slow a great deal and is very likely to stop completely. Compressors are typically either reciprocating, in which case the motor has substantial starting torque capabilities, or scroll compressors, in which case the motor most likely has lower starting torque. In either case, for NEMA B motors, the motor is expected to stall if the voltage falls too far below 0.8 pu.V.
2. **Stalling:** Motors that fail to reaccelerate enter a stalled state, during which the reactive power draw increases significantly relative to its pre-fault state. It is typical for reactive power to increase to about 5 times the nominal real power. (For very efficient motors with nominal power factors of 0.97, this can represent a 10-fold or greater increase in reactive power relative to pre-fault reactive power.) Motors with relatively high starting torques, such as those used to drive reciprocating compressors, typically

stall using only slightly more reactive power than real power. However, motors with relatively low starting torques, such as those used to drive scroll compressors, can be expected to have significantly higher reactive power draw than real power when stalled. The stalled power draw will be converted to heat in the rotor and continue to do so until the voltage increases enough to restart the motor or the thermal protection of the rotor opens the rotor circuit.

3. **Restarting:** As the voltage on the circuit increases, some motors may resume operation because the starting torque developed becomes sufficient to overcome the remaining compressor backpressure, which began dropping as soon as the compressor stopped. These motors will return to normal operation and their real and reactive power will return to nominal values.
4. **Tripping:** For motors that do not restart, the time required for the thermal protection to open the rotor circuit is an inverse function of the total power consumed by the motor. Scroll-type compressor motors are somewhat less prone to stalling, but if stalled they can be expected to trip much sooner than reciprocating compressor motors.
5. **Thermal lag:** It is worth noting that even when the motor resumes normal operation after voltage recovery, there is certain amount of thermal lag that can cause the thermal protection to open the rotor circuit anyway. This delayed tripping can result in motor load loss when the voltage is above 1.0 p.u. V, which is a potentially undesirable condition in the moments after a FIDVR event.

### **Characteristics of Motor Trip Events**

Model D motors can be expected to stall when the voltage drops below 0.8 p.u. V. Once a motor slows down, it must have sufficiently high starting torque to quickly reaccelerate and overcome the normal compressor backpressure before the thermal protection opens the rotor circuit. If the motor slip increases above the critical slip required to overcome the backpressure before the voltage is restored, the motor will stall. Motors that approach the critical slip may have delayed reacceleration and also be subjected to a thermal protection event as shown in Fig. 6-8. If thermal protection occurs, the motor is assumed to be at steady state and the interrupted power will be characteristic of the motor size and state. Thus, the measured real and reactive power will show a joint step the magnitudes of which is uniquely associated with a motor size and the slip at the instant the thermal protection operated.

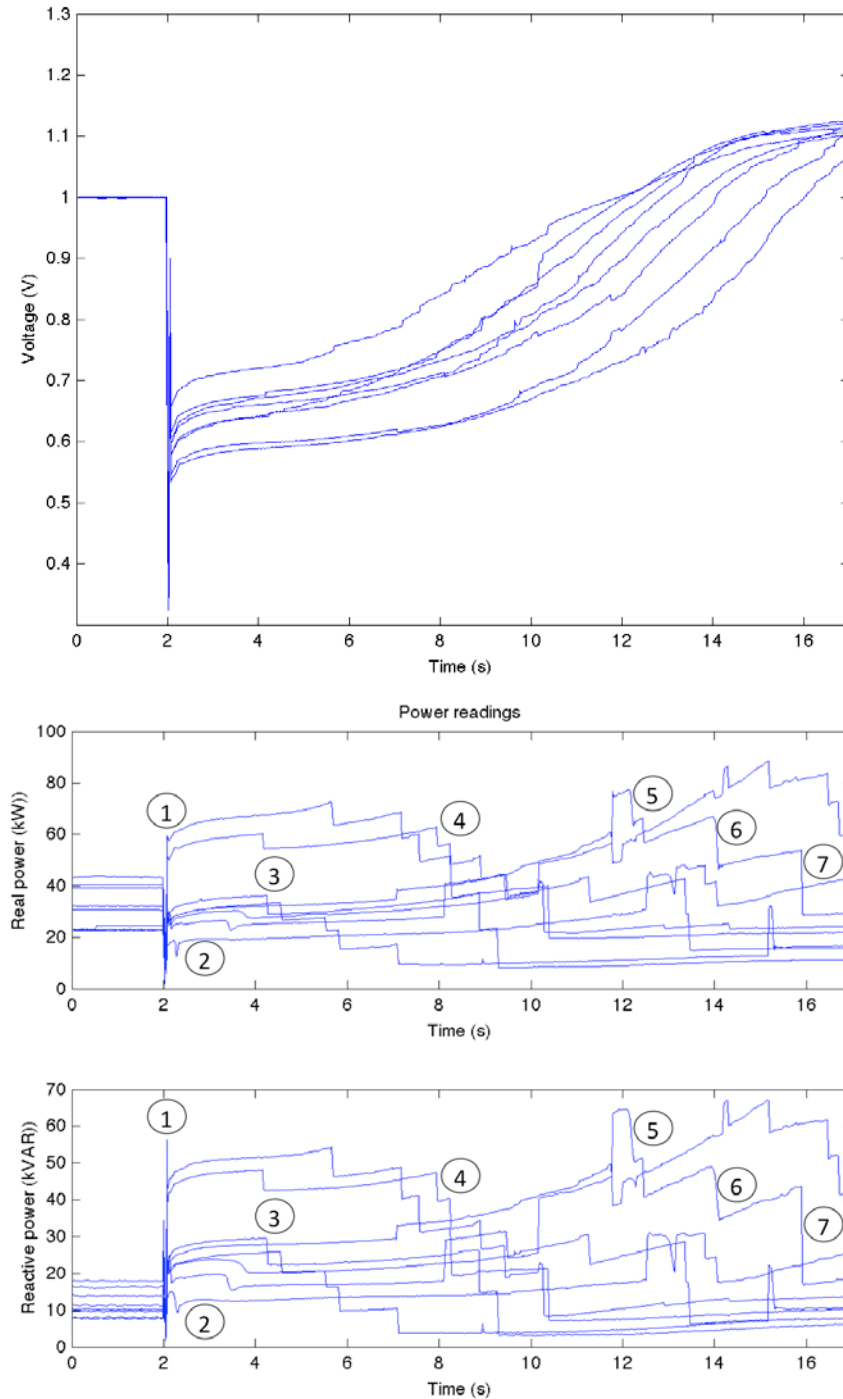


**Fig. 6-8.** Induction motor thermal trip curves (from IEEE Standard 620-1996)

### 6.3.3 Event Analysis

This section examines the data from a FIDVR event recorded by SCE on 12 August 2012. The voltage and power time-series are shown in Fig. 6-9. As with all FIDVR events, the voltage drops well below 0.8 puV during the fault and fails to return to above 0.9 puV immediately after the fault is cleared. This voltage recovery failure immediately initiates a FIDVR event, and both real and reactive power consumed increase significantly (point 1). In the second or so immediately after the initial event, we can observe a few motors with slow reacceleration (point 2). Approximately 2 seconds after the event, we observe the first of a series of abrupt steps down in power corresponding to motor trips (point 3). The first few trips correspond to motors with much higher reactive power than real power and are smaller than the later steps. These can be presumed to be either small, low-starting-torque motors that are stalled or small motors that are running backwards, both of which would consume very large amounts of reactive power under such conditions.





**Fig. 6-9.** PQube voltage and power FIDVR event data

After about 5 seconds, the remaining stalled motors are those that consume relatively less reactive power (but still more than real power), such as high-starting-torque motors. These begin tripping and continue to do so for some time (point 4).

About 12 seconds after the event, we observe abrupt increases in power followed shortly by a rounded drop-off. The increase in power is most likely motor starting. The sustained high power draw is most likely

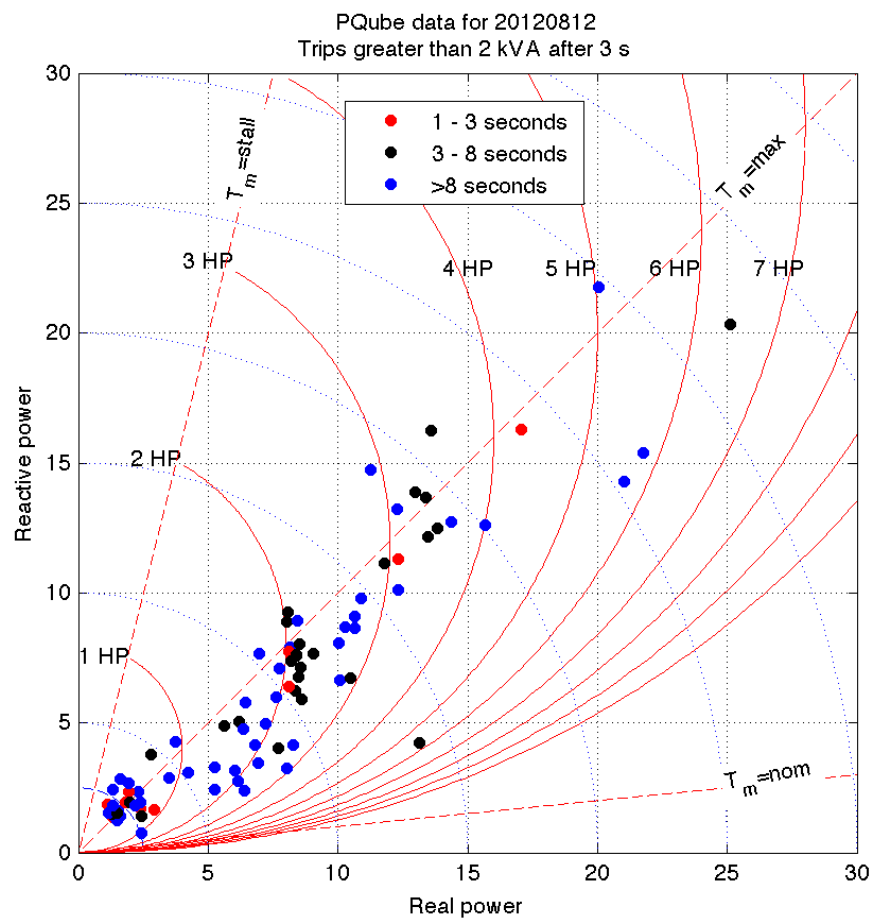
a slow acceleration, suggesting that the motor is not starting normally and perhaps is a larger motor restarting after undervoltage protection reset. The rounded drop-off within less than a second would seem to confirm this conjecture. In addition, we observe some motor restarts that appear to be from stalled condition (point 6).

Finally, we observe some abrupt drop characteristics of thermal trips on a larger motor well after the voltage has returned above 1.0 puV (point 7). This suggests that motor thermal protection can continue operating even though all motors are presumably operating normally, perhaps due to thermal lag in the rotor.

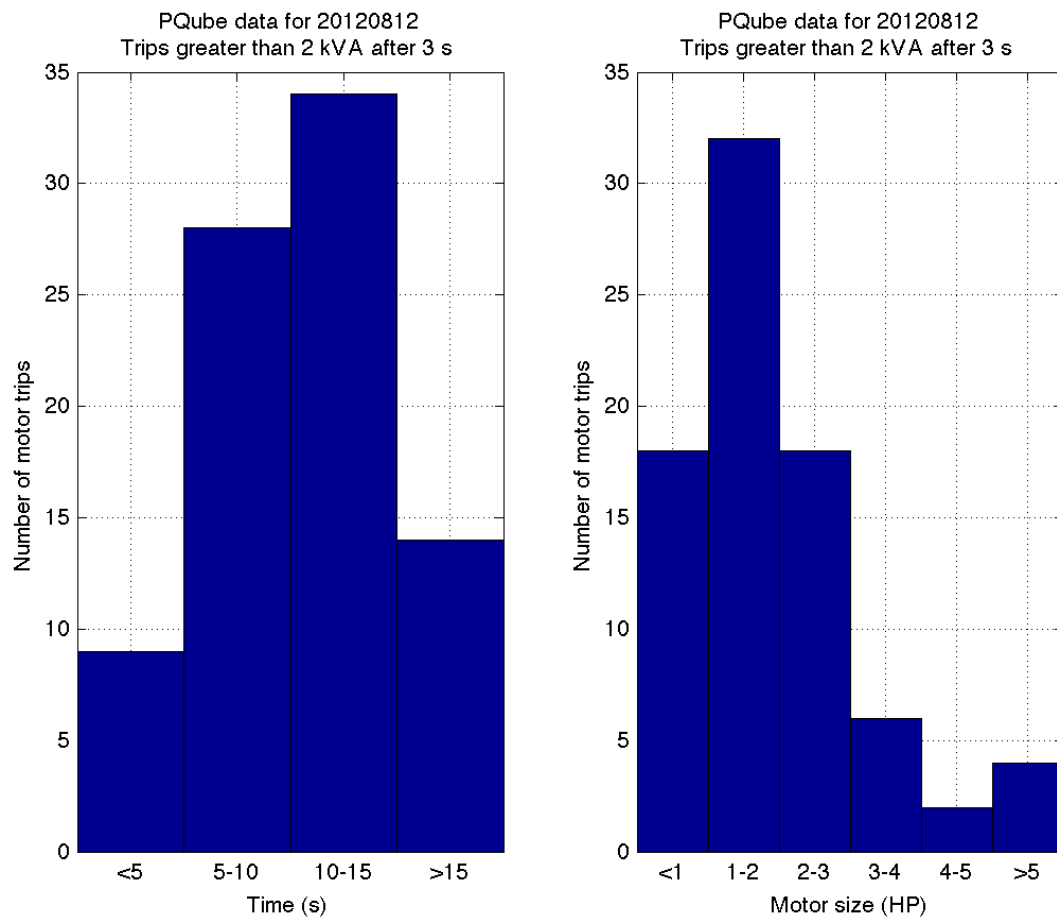
Fig. 6-10 shows the results of mapping the trip events in the data shown in Fig. 6-9 onto the motor curves on the complex plane. As discussed above, the various motor slip curves are used to generate isolating curves shown in red. The approximate nominal, maximum, and stall torque margins are shown by the dashed red lines.

Fig. 6-11 (right) shows the summary statistics for the motor sizes and thermal protection trip times.

Fig. 6-11 (left) shows the events captured by this analysis on the original voltage traces. We can see that a number of trips occur on distribution circuits after the voltage has substantially recovered, suggesting that thermal lag in the rotor may play in a role in tripping motors, hence reducing load when the voltage is already too high.



**Fig. 6-10.** Analysis of motor trips from event data



**Fig. 6-11.** Motor trip events (top) and motor sizes (bottom) based on event data

## **7.0 Software Tools to Support WECC JSIS and MVWG Activities**

A set of the software tools has been developed in cooperation with BPA to support the WECC JSIS and MVWG.

- **Load Model Data Tool (LMDT)**

The Load Model Data Tool automates the process of the load composite model data preparation in the format supported by major power system software vendors (GE PLSF and Siemens PSSE).

Tool website: <https://svn.pnl.gov/LoadTool>

- **Frequency Response Analysis Tool (FRAT)**

The Frequency Response Analysis Tool automates the power system frequency response analysis process. The tool can help to estimate the frequency response characteristics based on the phasor measurement unit (PMU) measurements, and collect and process statistical information on the frequency response characteristics. The tool can also represent the information using advanced visualization techniques.

Tool website: <https://svn.pnl.gov/FRTTool>

- **Power Plant Model Validation Tool (PPMV)**

The PPMV validates power plant dynamic models. The model validation is based on the PMU measurements.

Tool website: <https://svn.pnl.gov/PPMV>

Currently, these tools are used by the WECC members and other electrical utilities. The tools received very positive feedback from WECC JSIS and MVWG members.

All programs are stand-alone MS Windows applications implemented in VB.NET (Microsoft Visual Studio 2012) and released under an open source license.

### **7.1 Load Model Data Tool (LMDT)**

The LMDT software automates load composite model data preparation in the format supported by major power system software vendors (GE and Siemens).

Proper representation of the load composite model in power system dynamic analysis is very important. Software tools for power system simulation like GE PSLF and Siemens PSSE already include algorithms for load composite modeling. However, these tools require that the input information on composite load be provided in custom formats. Preparation of this data is time-consuming and requires multiple manual operations. The LMDT software automates this process.



### 7.1.1 System Requirements

The LMDT software is a stand-alone MS Windows application. The tool installation package can be downloaded from <https://svn.pnl.gov/LoadTool>. To install the program, download the “LMDT\_install.zip” file, unzip it, and run “setup.exe”

- Operating system: Windows XP or later
- Prerequisites: Microsoft .Net 4.0 Framework
- Processor, memory, HDD: no special requirements

### 7.1.2 Input Information Requirements

To generate a composite load model, three components need to be provided:

- Load composition default data
- Motor dynamic information
- Power flow bus data

The data sample can be found in “CSV” folder of the installation package: LMTF Data.csv – load composition model; Motordata.csv – motor data; Loads.csv – power flow bus data.

#### 7.1.2.1 Load Composition Default Data

Default load composition data specification is given in Table 7-1. Default load composition data should be provided for each climate zone and feeder type based on season and hour of the day.

The user needs to adjust the AC stall voltage in Column “Vac\_stall” based on the study conditions. The default data is for normal summer conditions during on-peak hours. For shoulder season and off-peak hours, set “Vac\_stall” to 0.5 per unit.

**Table 7-1.** Default composite data specification

Column #	Column Name	
1	#AREA	Climate zone and substation type identifier (LID)
2	Tx_Lf	Distribution transformer model data
3	Tx_X	
4	Tx_HS	
5	Tx_LS	
6	TX_LTC	
7	Tx_TapMax	
8	Tx_TapMin	
9	Tx_TapStep	
10	Tx_Vmax	
11	Tx_Vmin	
12	Tx_Rcomp	
13	Tx_Xcomp	
14	Tx_Ttap	
15	Tx_Tdelay	
16	B_sub	Substation shunt capacitor
17	Fdr_DeltaV	Feeder model data
18	Fdr_Vmin	
19	Fdr_Vmax	
20	R_fdr	
21	X_fdr	
22	Fdr_LoadPF	
23	Fdr_ShSplit	
24	Fdr_Plossmax	Motor model identifiers
25	ID_MotorA	
26	ID_MotorB	
27	ID_MotorC	
28	ID_MotorD	
29	ID_PwrElec	
30	ID_DG	
31	Lc_MotorA	Load composition data
32	Lc_MotorB	
33	Lc_MotorC	
34	Lc_MotorD	
35	LC_PwrElec	
36	Lc_DG	
37	Lc_StatPF	
38	Lc_Zp	
39	Lc_Ip	
40	Lc_Pp	
41	Lc_Zq	
42	Lc_Iq	
43	Lc_Qq	
44	Lc_Pf	
45	Lc_Qf	
46	Report	Reporting level
47	Vac_stall	Voltage at which residential air-conditioners stall

### 7.1.2.2 Motor Dynamic Information

The motor dynamic dataset includes motor parameters and protection data. A sample of motor information input file is given in Appendix G.

Motor models include:

- MA – three-phase motor model representative of commercial compressors (5 to 20 hp)
- MB – motor model representative of small fans (less than 50 hp)
- MC – motor model representative of pumps (less than 50 hp)
- IA – industrial compressors
- IB – large industrial fans
- IC – large industrial pumps

Air conditioner models:

- AC – air-conditioners, air-conditioner stall voltage “Vstall” is increased with ambient temperature

Electronic load:

- PE – power electronic load data (mostly commercial and residential)
- PI – dive and electronic load in industrial facilities

### 7.1.2.3 Power Flow Bus Data

The power flow bus data specification is presented in Table 7-2. The dataset includes bus information based on the power flow solution case.

**Table 7-2.** Bus data specification

Column #	Column Name	Description
1	Bus_Number	Bus number
2	Bus_Name	Bus name
3	Base_kV	Bus rated voltage
4	Load_ID	Load ID
5	Area	Area ID
6	Zone	Zone ID
7	Owner	Owner ID
8	P	Active Power
9	Q	Reactive Power
10	Voltage	Voltage
11	LID	Long ID



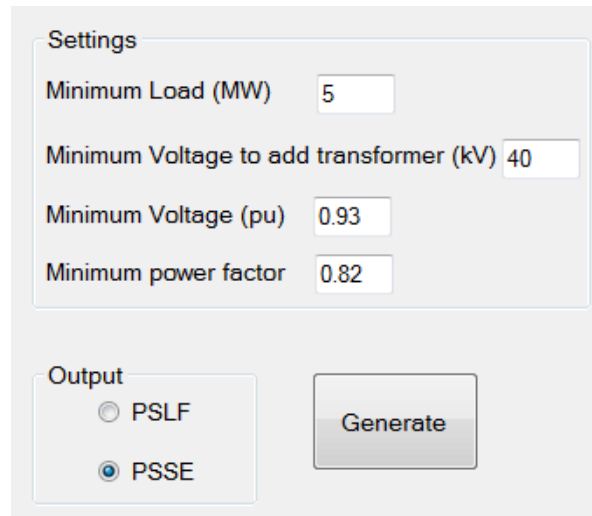
### 7.1.3 Generating Composite Model Using LMDT

Run “Load Model Data Tool.exe”:

1. Click the “Open load composition data” button and select load composition data file.
2. Click the “Open motor data” button and select motor data file.
3. Click the “Open power flow bus data” button and select bus data file.
4. Specify the tool output (PSLF or PSSE).

Users also can specify additional parameters (Fig. 7-2), including:

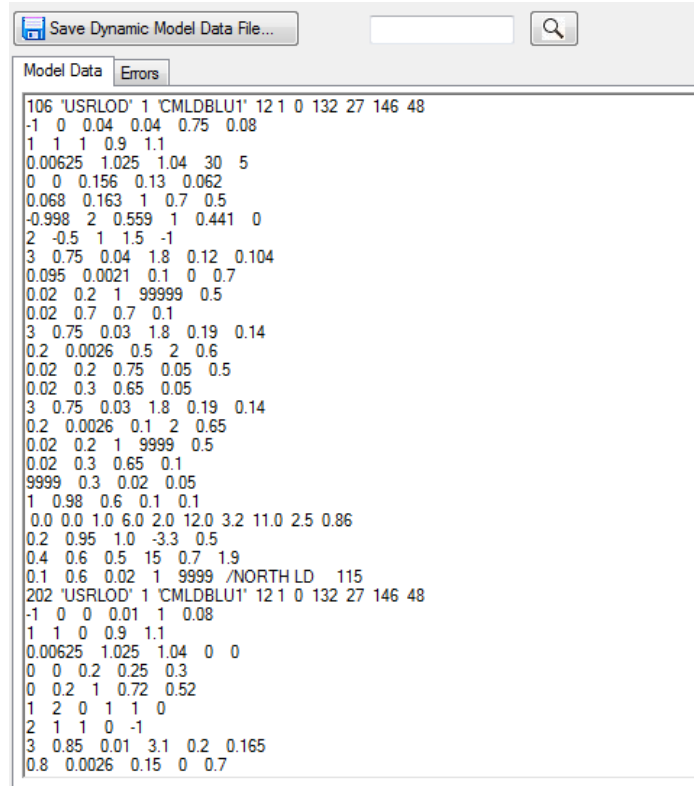
- Minimum load to be included in the composite model
- Minimum voltage to add transformer
- Minimum load bus voltage to be included in the composite model
- Minimum power factor to be included in the composite model



The screenshot shows a software window titled "Settings". Inside, there are four labeled input fields: "Minimum Load (MW)" with the value "5", "Minimum Voltage to add transformer (kV)" with the value "40", "Minimum Voltage (pu)" with the value "0.93", and "Minimum power factor" with the value "0.82". Below these is an "Output" section with two radio buttons: "PSLF" and "PSSE". The "PSSE" radio button is selected. To the right of the "Output" section is a "Generate" button.

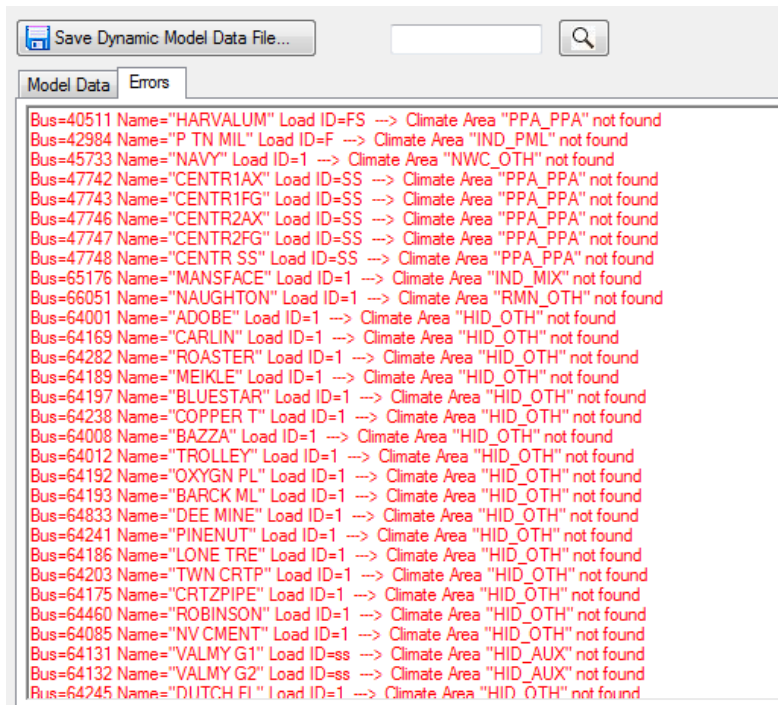
**Fig. 7-2.** LMDT settings

5. Click the “Generate” button. The tool will generate LCM data (Fig. 7-3) in PSLF (CMPLDW load composition data) or PSS/E format (CMLDBLU1 load composition data).



**Fig. 7-3.** LMDT output – generated composite load model

The Errors log tab contains any data errors detected by the LMDT during composite load generation process. (Fig. 7-4)



**Fig. 7-4.** LMDT error log

- Click the “save output file” button and save the output information to the file (.dyd for PSLF or .dyr for PSS/E).

### 7.1.4 Appending the Composite Load Models to the PSLF .dyd File

The dynamic data file may include the “motorw” and “blwsc” records associated with an interim load model (Fig. 7-5).

- Remove “motorw” records associated with the interim load model from dyd file.
- Remove “blwsc” records from .dyd file.
- You can either:
  - Add composite load model data to the end of the modified dynamic data file.
  - Read the modified dynamic data file and the composite load model file sequentially.

To combine the .dyd records into one file, append the composite load model records to the end of the master dynamics file.

	<b>lodrep</b>
<b>Remove</b>	<b>motorw 31551 "TRINTY " 60.0 "1 " : #1 mva=0.0000 0.200000 3.6000 ....</b>
<b>“motorw” records</b>	<b>...</b>
	<b>...</b>
<b>Keep “alwsc”</b>	<b>alwsc 10005 "ALCAZAR " 12.50 "1 " : #9 10.0000 ...</b>
<b>records</b>	<b>alwsc 11002 "ALA 5 " 115.00 "1 " : #9 11.0000 ...</b>
	<b>....</b>
<b>Remove “blwsc”</b>	<b>blwsc 24406 "ACTON SC" 66.00 "1 " : #9 0.050000 0.340000 0.340000 ...</b>
<b>records</b>	<b>...</b>
	<b>...</b>
	<b>models</b>
	<b>genrou 10394 "LEF_G1" 18.00 "1 " : #9 mva=234.0000 "tpdo" 9.0000 ...</b>
	<b>...</b>
<b>Add “cmpldw”</b>	<b>lodrep</b>
<b>records</b>	<b>cmpldw 31551 "TRINTY " 60.00 "1 " : #1 mva=-1.1 "Bss" 0 "Rfdr" 0.03 ...</b>
	<b>...</b>

Fig. 7-5 Appending the composite load models to the PSLF .dyd file

### 7.1.5 Appending the Composite Load Models to the PSS/E .dyr File

Besides the CMLD WECC Composite Load Model, PSS/E has a number of dynamic load models, including:

- Single-Phase Air Conditioner Motor Model – ACMT
- Induction Motor Load Model – CIMB5, CIMB6
- Induction Motor Load Model (WECC) – CIMW
- Complex Load Model – CLOD

- Extended-Term Load Reset Model – EXTL
- IEEE Load Model – IEEL
- Load Frequency Model – LDFR

These load models should be removed prior to simulation using the CMLD load model.

The dynamic data resides either in a saved snapshot file (.snp) or in the dynamic model data file (.dyr). Use the option below that best fits.

If using a .snp file to load dynamic data:

1. Ensure any of the above-mentioned models have been removed from the .snp file.
2. Load .dyr file using “Add Dynamics Model Data” sequentially after loading .snp file.

If using a .dyr file to load dynamic data:

1. Ensure any of the above-mentioned models have been removed from the .dyr file.
2. Option 1: Sequentially load the standard .dyr file and .dyr file with CMLD models.
3. Option 2: Append the composite load models to the end of the standard .dyr file.

## 7.2 Frequency Response Analysis Tool (FRAT)

Electrical interconnection must be operated within a secure frequency range to maintain a continuous balance between the system demand, interchange, and generation. Interconnection frequency deviation could cause significant negative impacts on system reliability and control performance.

The Federal Energy Regulatory Commission states in [35]: “Frequency response is a measure of an Interconnection’s ability to stabilize frequency immediately following the sudden loss of generation or load, and is a critical component of the reliable operation of the power system, particularly during disturbances and recoveries.” Frequency response has received much attention in recent years at the national level, culminating in the development and approval of the North American Electric Reliability Corporation (NERC) BAL-003-1 Frequency Response and Frequency Bias Setting Reliability Standard [36]. The standard determines the amount of frequency response required in each interconnection and the allocation of frequency response obligation among balancing authorities. The standard is largely based on technical work done in the NERC Frequency Response Initiative [37] and Lawrence Berkeley National Laboratory-led work on frequency response metrics [38].

The WECC has a long history of frequency response monitoring. WECC made several attempts to develop its own regional frequency responsive reserve standard or criteria [39], well before the NERC standard. WECC’s objectives were to (a) ensure that an adequate amount and quality of frequency responsive reserves are carried in the interconnection, and (b) achieve even distribution of frequency response across the interconnection to mitigate the frequency response impacts on transmission paths. WECC has used synchrophasor data to monitor frequency response in the Western Interconnection.

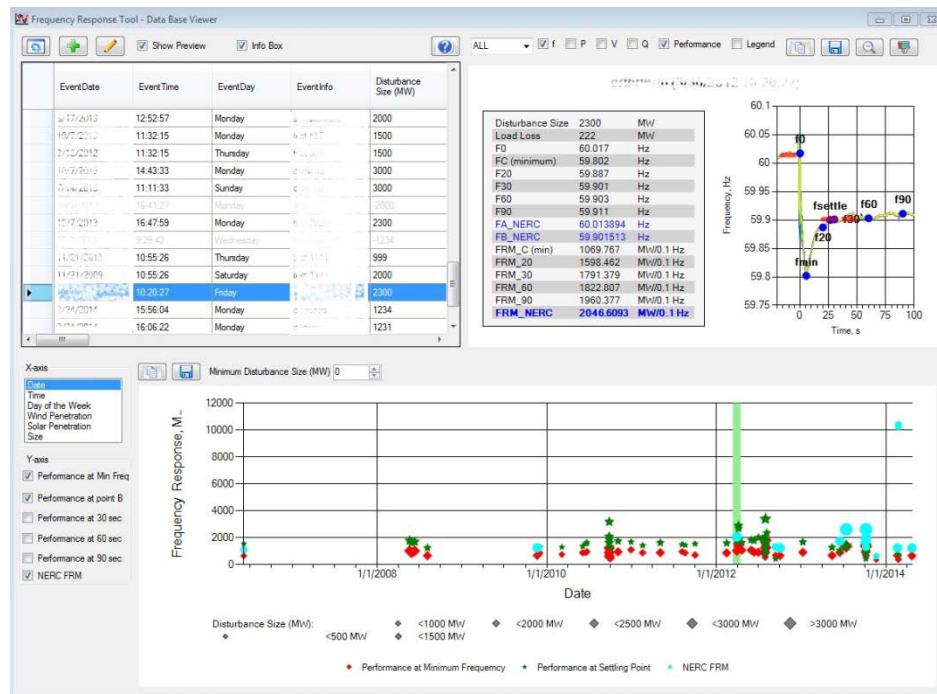
BPA implemented the practice of using synchrophasor data for governor response validation [41]. These efforts greatly improved the accuracy of frequency response representation in power system studies, as evident from a number of system-wide validation studies.

PNNL, in collaboration with BPA and WECC JSIS, developed a tool to automate the analysis of interconnection frequency response [42]. The tool can help estimate the frequency response characteristics based on the PMU and SCADA measurements, and collect and process statistical information on the frequency response characteristics. The tool can also represent the information using advanced visualization techniques.

The first version of FRAT (Version 1.0) was released under open source license in 2013. A screenshot of the FRAT 1.0 GUI is shown in Fig. 7-6.

FRAT 1.0 has the following main features:

- Automation of frequency response analysis process
- Calculation of the interconnection frequency response measure (FRM) using PMU and SCADA data
- Initial estimation of the frequency response parameters (initial frequency, minimum frequency, settling point, etc.)
- Visual inspection and manual adjustment of system parameters
- Archiving of the historical events and baselining of the interconnection performance
- Automatic generation of reports in MS Word format
- User friendly GUI

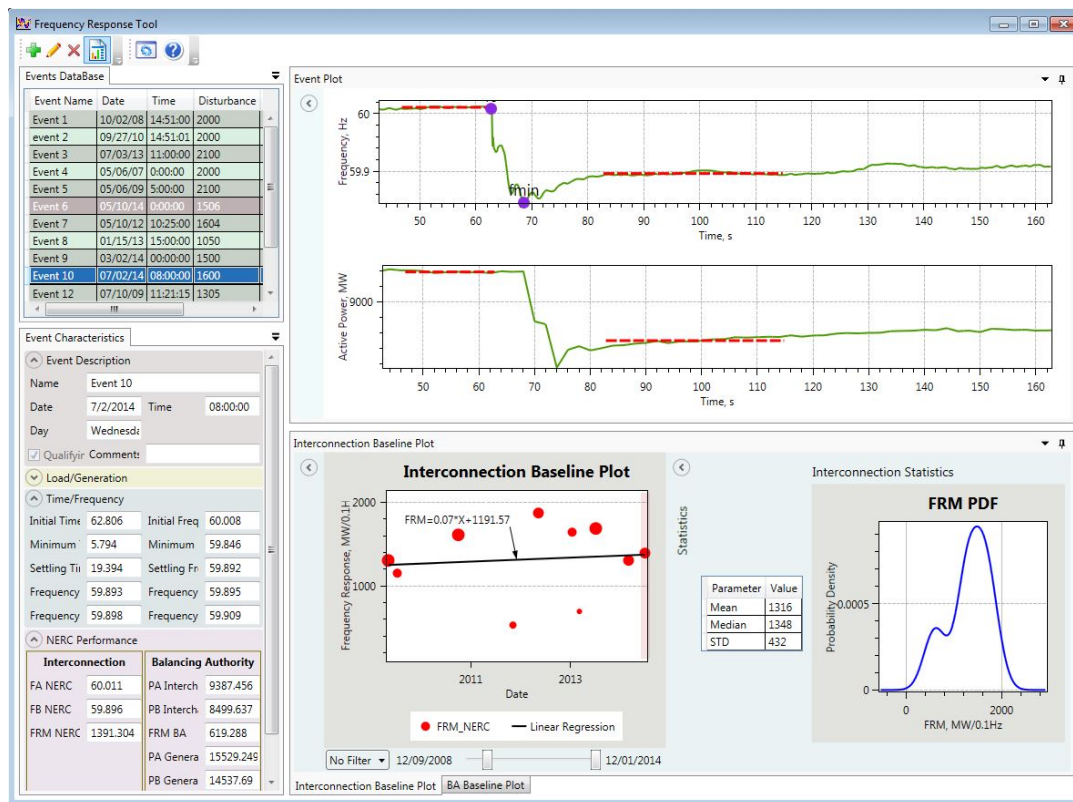


**Fig. 7-6. FRAT (Version 1.0) GUI**

Based on feedback from industry partners, a new version of the tool (FRAT 2.0) was developed and released under an open source license in August 2014. The FRAT 2.0 GUI is shown in Fig. 7-7. The new version of the tool includes all features from the previous version as well as new functionality requested by the users and an improved GUI.

The new FRAT features include:

- New analytical functions, including:
  - Calculation of the interconnection and balancing authority (BA) FRM according to the NERC BAL-003-01 Standard
  - Statistical analysis
- Completely redesigned user interface
- New advanced visualization
- New reporting capabilities
- Support for different data sources



**Fig. 7-7. FRAT (Version 2.0) GUI**

### 7.2.1 Main Features of FRAT

Power system frequency response estimation can be based on the retrospective analysis of the PMU measurements recorded during the system disturbances. To estimate frequency response of the system, the pre- and post-fault conditions are analyzed. It is necessary to analyze large a number of events in the system to collect sufficient statistical information about system frequency response characteristics.

Currently, the process of collecting and analyzing this information is not automated and requires a lot of manual work. The purpose of the FRAT tool is to automate the power system frequency response analysis process. The FRAT can help to estimate the frequency response characteristics based on the PMU measurements and collect and process statistical information on the frequency response characteristics. The tool can also represent the information using advanced visualization techniques.

The purpose of the FRAT tool is to automate the BA and interconnection frequency response analysis process. The tool estimates the frequency response characteristics according to the NERC BAL-003-01 Standard using SCADA and PMU measurements. FRAT also can visualize frequency response information using different types of plots and perform statistical analysis. Reports (FRS forms) can be automatically generated.

FRAT is a standalone Windows application. It has a user friendly interface. FRAT has been developed using Microsoft Visual Studio 2012. FRAT features include:

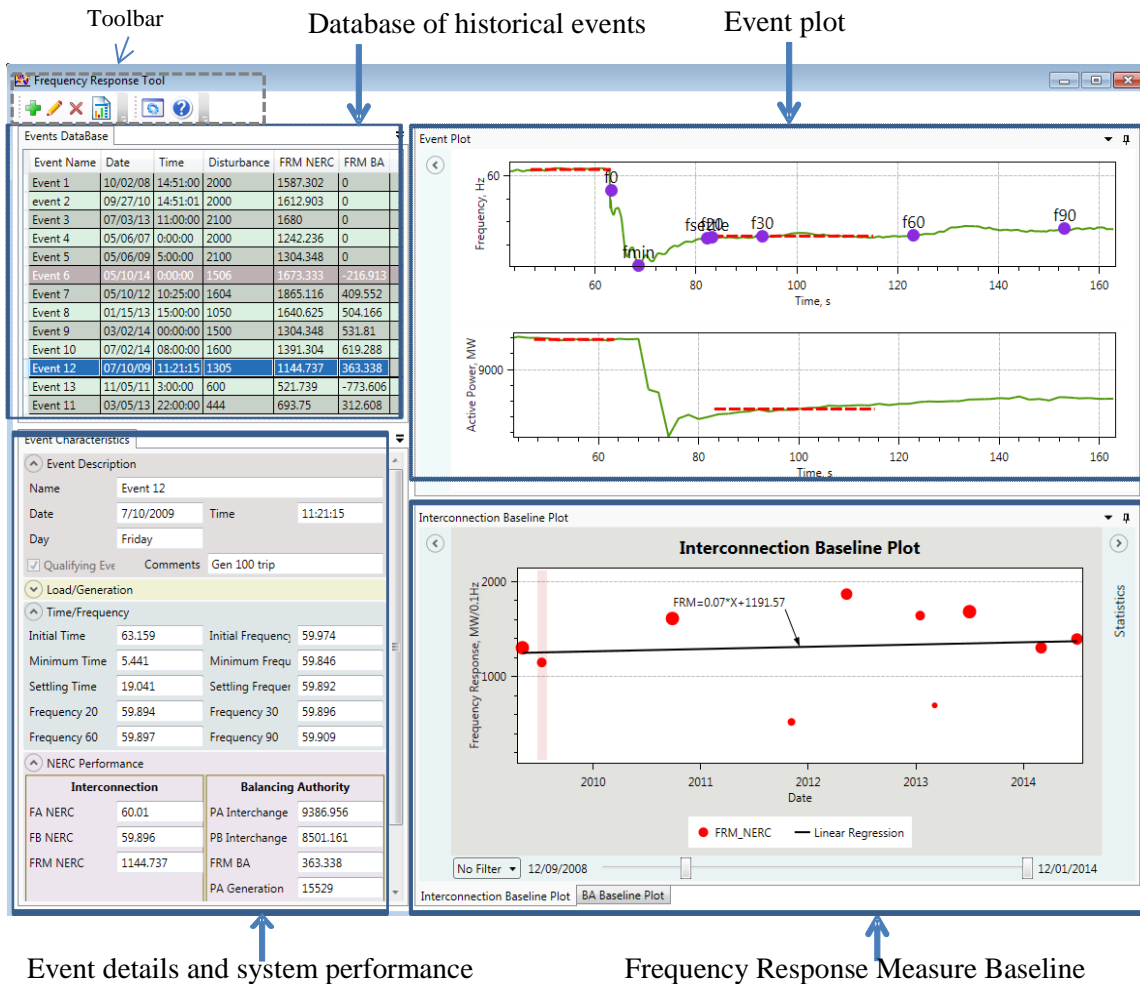
- Calculating system mean frequency based on user-specified PMU measurements.
- Performing initial estimation of the system FR parameters (initial frequency, minimum frequency, settling point, etc.).
- Allow visual inspection and adjustment of initial estimation of FR parameters.
- Calculation of FR performance characteristics according to NERC BAL-003-01 Standard (MW/0.1 Hz at point B), as well as additional performance metrics: FRM at minimum frequency (point C), 30 sec, 60 sec, 90 sec, etc.).
- Archiving the historical events into internal database and baselining the system performance.
- Performing statistical analysis (linear regression, basic descriptive statistics)
- Visualizing FR performance using different plots (depending on date, time, day of the week, wind/solar generation penetration).
- Allow all graphs produced by the tool to be copied into clipboard or into file (.jpg or .emf formats).
- Automatically generating reports (including FRS 1 form) in Word format.

### 7.2.2 FR Tool User Interface

Fig. 7-8 shows an interactive display of FRAT (Version 2.0). The GUI consists of a toolbar and four major panels (screens):

- Event database screen – shows the list of frequency events and basic information about these events.

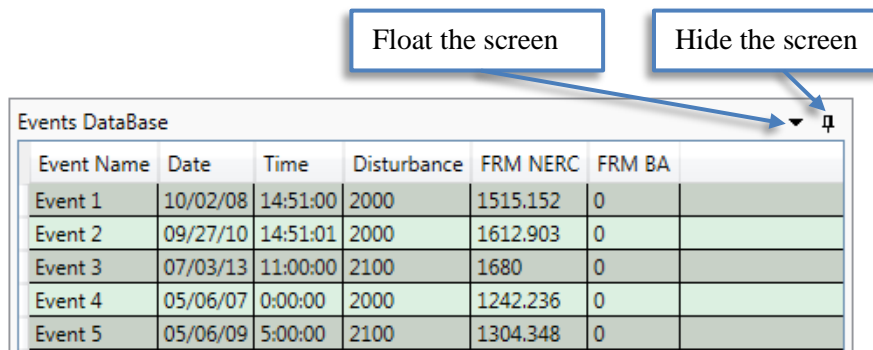
- Event details and system performance screen – shows the event details (initial frequency, settling frequency, minimum frequency, etc.), interconnection/BA information (generation, load, generation by type of units, etc.), FR characteristics (BA FRM, interconnection FRM, etc.)
- Event plot – graphically displays the event. This screen consists from three subplots for frequency, active power, and voltage.
- FRM baseline and analysis screen – shows the FR performance baseline and statistical analysis of the events.



**Fig. 7-8.** FRAT main GUI

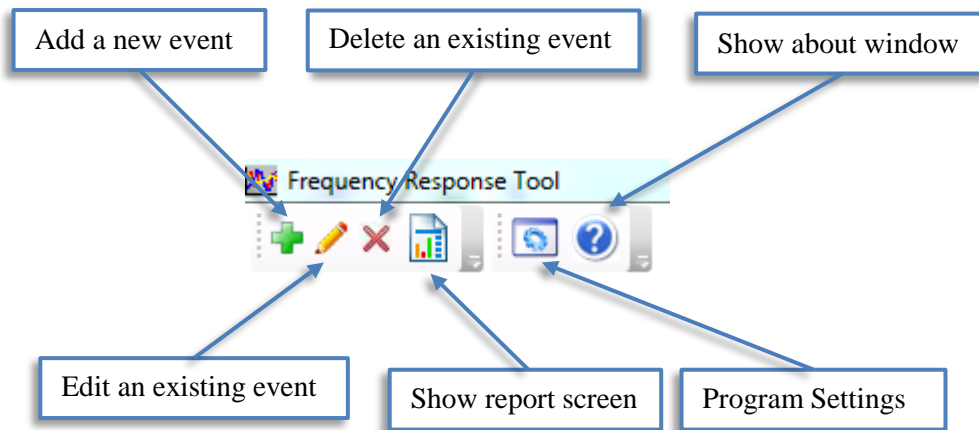
All of these screens can float and be rearranged by the user, or be hidden if not needed. Fig. 7-9 shows how to close or hide the panel.





**Fig. 7-9.** Float and hide function of the tool

The FRAT toolbar consists of several buttons to add/edit/delete events, specify the program settings, and get program help (Fig. 7-10).



**Fig. 7-10.** FRAT toolbar panel

### 7.2.2.1 Event Database Panel

The events database screen is used to view the information about all frequency events available for analysis (Fig. 7-11). Non-qualifying events are highlighted gray and are not used for system baselining or statistical analysis. When a user selects an event from the list of event characteristics panel, the event plot panel is updated automatically to display detailed information about the event. The selected event is also highlighted at the baselining plot.

Event Name	Date	Time	Disturbance	FRM NERC	FRM BA
Event 1	10/02/08	14:51:00	2000	1587.302	0
event 2	09/27/10	14:51:01	2000	1612.903	0
Event 3	07/03/13	11:00:00	2100	1680	0
Event 4	05/06/07	0:00:00	2000	1242.236	0
Event 5	05/06/09	5:00:00	2100	1304.348	0
Event 6	05/10/14	0:00:00	1506	1673.333	-216.913
Event 7	05/10/12	10:25:00	1604	1865.116	409.552
Event 8	01/15/13	15:00:00	1050	1640.625	504.166
Event 9	03/02/14	00:00:00	1500	1304.348	531.81
Event 10	07/02/14	08:00:00	1600	1391.304	619.338
Event 12	07/10/09	11:21:15	1305	1144.737	363.338
Event 13	11/05/11	3:00:00	600	521.739	-773.606
Event 11	03/05/13	22:00:00	444	693.75	312.608

Non qualifying event (gray)

Selected event (blue)

**Fig. 7-11.** Events database screen


FRAT archives all information in the frequency events database. The .csv file is used to store frequency events information. The structure of the database is given in Table 7-3.

**Table 7-3.** Event characteristics columns definition

	Column Name	Definition
Event Description	Name	Event name
	Date	Event date
	Time	Event time
	Day	Day of week
	Qualifying event	Qualifying event (Yes or No)
Load/ Generation	Generation loss	Generation loss
	Load loss time	Load loss time
	Load loss	Load loss
	Total generation	Total generation
	Thermal generation	Thermal generation
	Hydro generation	Hydro generation
	Wind generation	Wind generation
	BA generation loss	BA generation loss
	BA generation	BA generation
	BA thermal generation	BA thermal generation
	BA hydro generation	BA hydro generation
	BA wind generation	BA wind generation
Time/ Frequency	Initial time	Initial time
	Minimum time	Minimum time
	Settling time	Settling time
	Initial frequency	Initial frequency
	Minimum frequency	Minimum frequency

NERC Performance	Settling frequency	Settling frequency
	Frequency 20	Frequency at 20 seconds
	Frequency 30	Frequency at 30 seconds
	Frequency 60	Frequency at 60 seconds
	Frequency 90	Frequency at 90 seconds
	FA NERC	Frequency at point A
	FB NERC	Frequency at point B
	FRM NERC	Interconnection frequency response measure (MW/0.1Hz)
	PA Interchange	Interchange at point A
	PB Interchange	Interchange at point B
	FRM BA	Frequency response measure of the balancing authority (MW/0.1Hz)
	PA Generation	Generation power at point A
	PB Generation	Generation power at point B
	FR Gen BA	FRM calculated using balancing authority generation
Additional Performance Indexes	FRM Min	Interconnection FRM at point C (minimum point)
	FRM B	Interconnection FRM at point B
	FRM 20	Frequency response measurement at 20 seconds
	FRM 30	Frequency response measurement at 30 seconds
	FRM 60	Frequency response measurement at 60 seconds
	FRM 90	Frequency response measurement at 90 seconds

### 7.2.2.2 Event Characteristics Panel

The event characteristics panel displays information about a frequency event (Fig. 7-12). This information is arranged in several groups. Each group can be collapsed or expanded to save the screen space using the expand/collapse button .

#### Event Description Group

The event description group includes information on event name, event date, and time. Day of the week is identified automatically based on the date of event. The user also can add comments to the event. The event description provides information on the status of the event (qualifying/non-qualifying) using a check box.

Event Characteristics

Event Description

Name
Event 12

Date
7/10/2009
Time
11:21:15

Day
Friday

☒ Qualifying Event
Comments
Gen XXX trip

Load/Generation

Interconnection		Balancing Authority	
Generation Loss	1300	BA Generation Loss	1300
Load Loss Time			
Load Loss			
Total Generation	60000	BA Generation	15532.8
Thermal Generation	50000	BA Thermal Generation	1607
Hydro Generation	15000	BA Hydro Generation	9913.399
Wind Generation	5000	BA Wind Generation	4011

Time/Frequency

Initial Time	63.159	Initial Frequency	59.974
Minimum Time	5.441	Minimum Frequency	59.846
Settling Time	19.041	Settling Frequency	59.892
Frequency 20	59.894	Frequency 30	59.896
Frequency 60	59.897	Frequency 90	59.909

NERC Performance

Interconnection		Balancing Authority	
FA NERC	60.01	PA Interchange	9386.956
FB NERC	59.896	PB Interchange	8501.161
FRM NERC	1140.351	FRM BA	363.338
		PA Generation	15529
		PB Generation	14540.264
		FR Gen BA	273.039

Additional Performance Indexes

FRM Min	1015.625		
FRM B	1585.366		
FRM 20	1625	FRM 30	1666.667
FRM 60	1688.312	FRM 90	2000

**Fig. 7-12.** Event characteristics screen

## Load/Generation Group

The load/generation group includes information on interconnection and BA generation/load, including:

- Generation loss
- Load loss size and time
- Total generation
- Thermal generation

- Hydro generation
- Wind generation



*These three parameters are not part of the NERC BAL-003-01 Standard*

### **Time/Frequency Group**

The time/frequency group includes information on the interconnection frequency, including:

- Initial time and frequency
- Minimum time and frequency
- Settling time and frequency
- Frequency at time  $t_0+20$ ,  $t_0+30$ ,  $t_0+60$ , and  $t_0+90$

### **NERC Performance Group**

The NERC performance group includes information on interconnection frequency values, BA interchange values, and interconnection/BA FRM indexes:

- Point A frequency
- Point B frequency
- Point A interchange value
- Point B interchange value
- Interconnection FRM
- BA FRM
- Point A BA generation
- Point B BA generation
- BA FRM based on generation


### **Additional Performance Indexes Group**

The additional performance indexes group includes information on additional interconnection indexes calculated by FRAT, including:

- FRM at minimum point
- FRM at settling point
- FRM at time  $t_0+20$ ,  $t_0+30$ ,  $t_0+60$ , and  $t_0+90$

#### **7.2.2.3 Event Plot Panel**

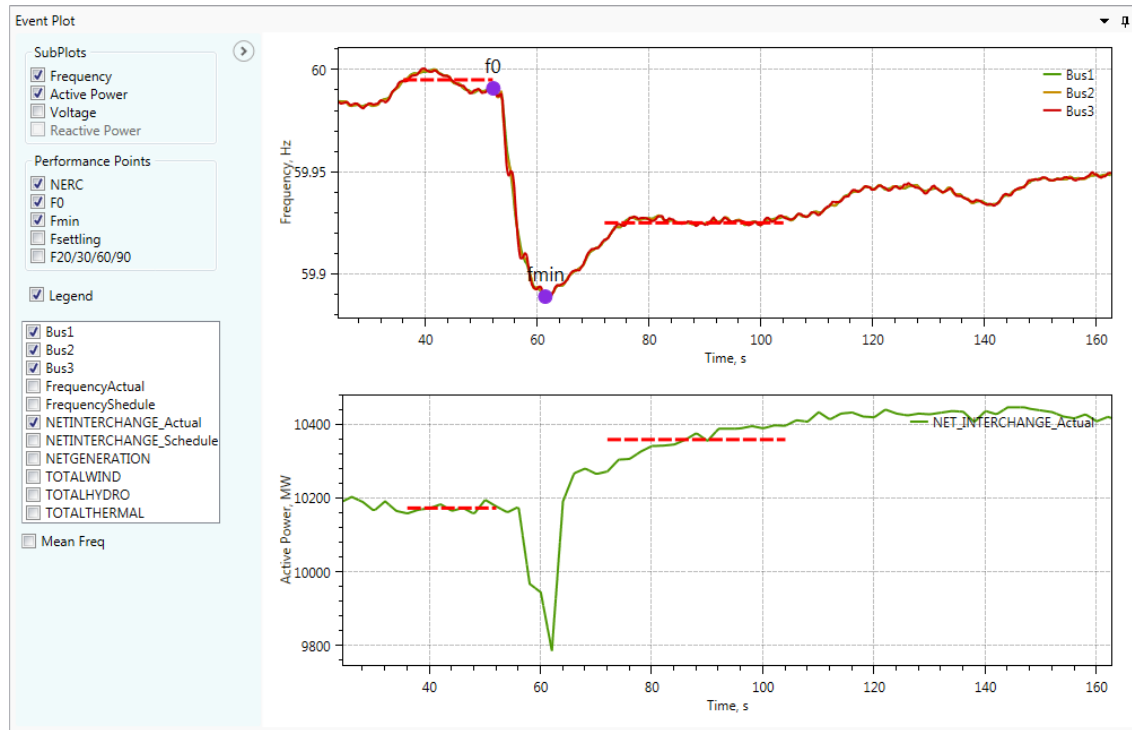
The event plot panel displays the event graph (Fig. 7-13). It consists from several subplots to display frequency, active power, and voltage graphs. Additional panels with graph settings can be collapsed or

expanded on the left side of the screen using expand/collapse button . Graph settings include a set of checkboxes to:

- Turn on and off frequency, active power and voltage subplots
- Turn on and off performance points
  - NERC points A and B (red horizontal dashed lines)
  - Initial point ( $F_0$ )
  - Minimum point ( $F_{\min}$ )
  - Settling point ( $F_{\text{settling}}$ )
  - Frequency at time  $t_0+20$ ,  $t_0+30$ ,  $t_0+60$ , and  $t_0+90$
- Turn on and off the legend
- Select PMU and SCADA measurements to be displayed
- Turn on and off the mean frequency curve calculated based on the selected frequency signals


The user can pan and zoom in and out on the plot as well as copy it to clipboard. The plot can be controlled using the following actions:

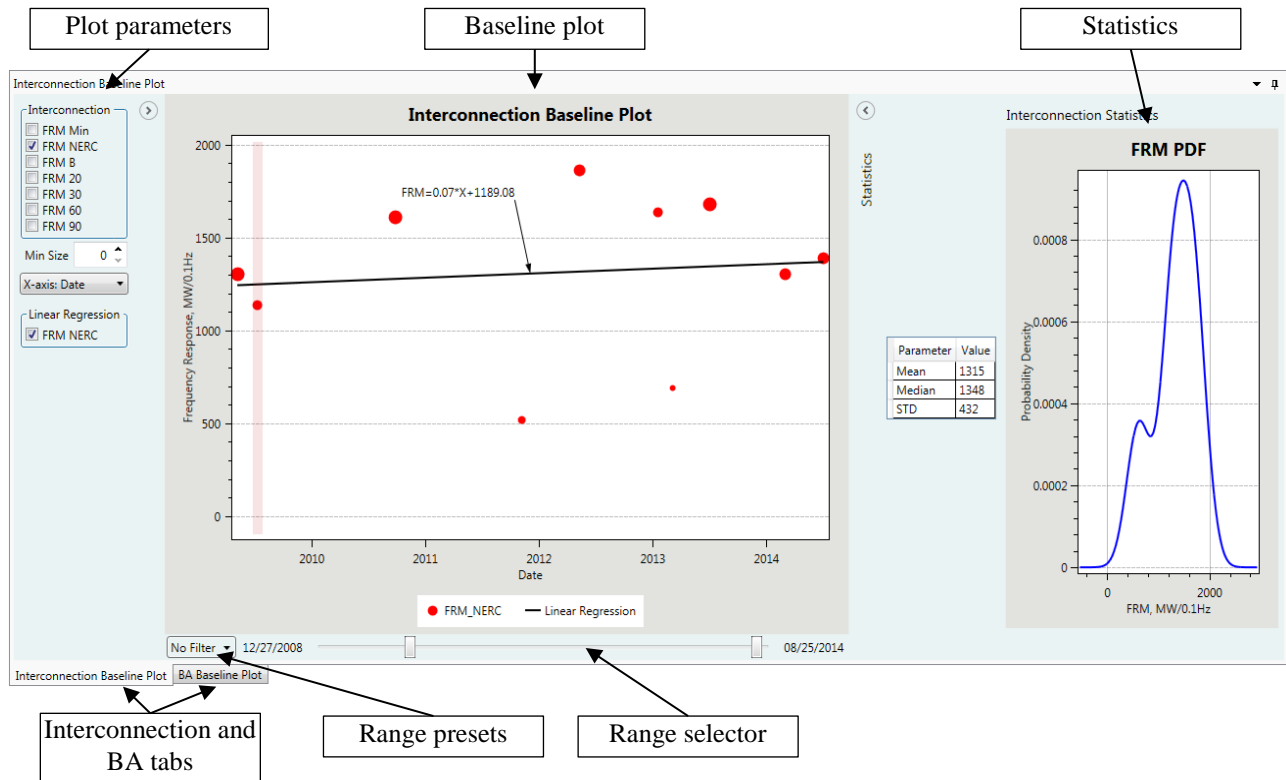
- Mouse wheel – to zoom in and out on the plot
- Mouse wheel over an axis – to zoom only selected axis
- Hold left mouse button and move the mouse to pan the plot
- Press “A” button to reset the plot to initial (auto) ranges
- Press Ctrl+C to copy the plot to clipboard
- Hold Ctrl + right mouse button to select an area to display



**Fig. 7-13.** Event plot screen

#### 7.2.2.4 FRM Baseline and Statistical Analysis Screen

The baselining panel displays the FRM baseline plot for interconnection and BA (Fig. 7-14). The screen consists of two tabs: one for interconnection analysis and the other for BA analysis. The right side of the screen also includes the statistical analysis panel that can be collapsed or expanded using the expand/collapse button . The plot settings panel is on the left side of the screen and also can be expanded.



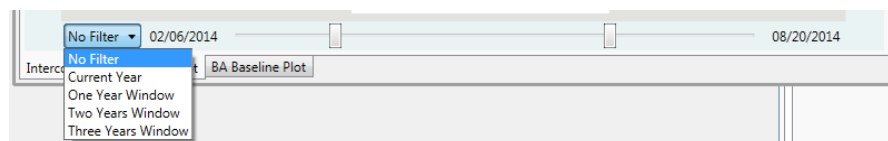
**Fig. 7-14.** Baseline plot screen

## Baseline Plot

Based on the statistical information collected in the database, FRAT can generate different types of plots illustrating system frequency response characteristics. The baselining plot shown in Fig. 7-14 illustrates changing of interconnection FRM (MW/0.1 Hz) from the selected time range. The size of points in the baselining plot depends on the size of the disturbance. The different types of plot are also available. For example, FRAT can correlate FRM metrics with the size of event or with generation mix (hydro, thermal, wind, and solar generation).

The user can select any dot on the baseline plot to get information about that event. The information and graphs at the event characteristics and event plot panels are updated automatically when a user clicks on the event at the baseline plot.

At the bottom of the baseline plot there is a range selector to select the studied range (see Fig. 7-15). There is also a drop-down list with range. For example, only the current year or 1 year window can be selected.



**Fig. 7-15.** Baseline plot range selector

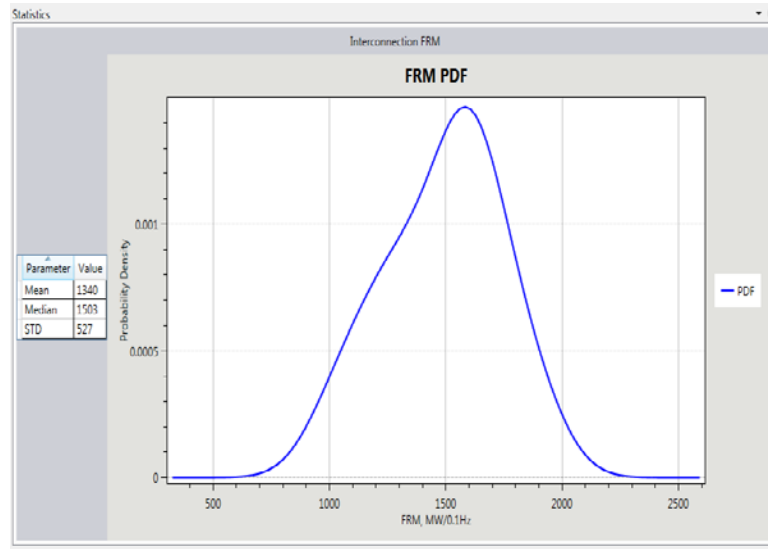


The baseline plot settings panel includes the following elements:

- Check boxes to select performance metrics to display (FRM at minimum point, FRM at point B, FRM at settling point, FRM at time t0+20, etc.)
- Plot X-axis type (date, time, disturbance size, generation mix, etc.)
- Turn on/off linear regression curve

## FRM Statistical Analysis

The statistical analysis screen includes FRM probability density function (PDF) plot and information on the FRM statistical parameters (mean value, median value, and standard deviation) for the selected range (Fig. 7-16).



**Fig. 7-16.** Statistical analysis of the interconnection FRM

FRAT also performs linear regression analysis to estimate the FRM time trend. A linear regression equation is a statistical model to describe the relationship between time and FRM. The equation can be expressed as follows:

$$FRM = A * Time + B \quad (7.1)$$

where *FRM* is the frequency response measurement value (MW/0.1Hz).

Time variable represents a time that could be years, months, days, hours, minutes, and seconds. *A* is the slope of the regression line and *B* is the intercept of the regression line.


To calculate parameters *A* and *B*, the error between the regression line and the real data should be minimized.

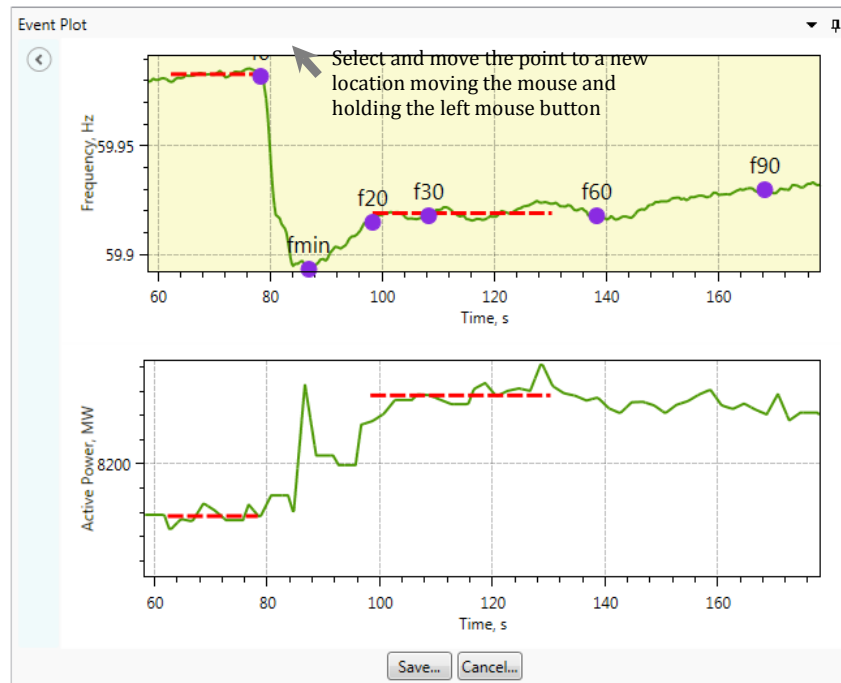
$$\min \sum_{i=1}^N (y_i - \tilde{y}_i) \quad (7.2)$$

where  $y_i$  is the  $i^{\text{th}}$  FRM data and  $\tilde{y}_i = Ax_i + B$ ,  $x_i$  is the  $i^{\text{th}}$  time data and  $N$  is the total number of data.

The linear regression problem is solved using a least squares method. Details on this method can be found in the NERC Frequency Response Initiative Report [38].


### 7.2.2.5 Editing Event Database

To edit an event in the database, the user should select this event in the “events database” screen and then click the “edit” button . After FRAT switches to the “edit” mode, the background of the frequency plot is changed to yellow (Fig. 7-17). In edit mode, the user can manually adjust the values of the initial, minimum, and other points. To manually adjust the location (value) of the point, select it using the mouse. Then, to move the selected point, press and hold the left mouse button. Drag the point to a new location. When the initial point is adjusted, the values of  $t_0+20$ ,  $t_0+30$ ,  $t_0+60$ , and  $t_0+90$  points are updated automatically. FRAT also recalculates FRM values every time the FR performance points are modified.



**Fig. 7-17.** Event plot in “edit” mode

In edit mode, the user also can change the values generation/load loss, generation production, and other parameters at the event characteristics screen. The name of event can be also changed. To save the modified information in the database, click the “save” button.

To delete an event, select this event and then click the “delete” button .

### 7.2.2.6 Adding New Event

To add a new event, click the “add event” button . The user will be asked to select the input file with the SCADA and/or PMU information.

FRAT provides the initial estimates of the following parameters:

- Initial point:  $f_0$  – pre-fault frequency
- Point A frequency (average frequency at interval  $t_{0-16}$  to  $t_0$ )
- Minimum point:  $f_{\min}$  – minimum frequency value (frequency nadir)
- Settling point:  $f_{\text{settle}}$  – settling frequency value
- Point B frequency (average frequency at interval  $t_{0+20}$  to  $t_{0+52}$ )
- Frequency at time  $t_0+20\text{s}$ :  $f_{20}$
- Frequency at time  $t_0+30\text{s}$ :  $f_{30}$
- Frequency at time  $t_0+60\text{s}$ :  $f_{60}$
- Frequency at time  $t_0+90\text{s}$ :  $f_{60}$

At the next step, the user can visually inspect the results of estimation and adjust estimated points if necessary. The points’ adjustment procedure is similar to the editing process explained in the previous section (Section 7.2.2.5).



The user also should provide the size of event (generation loss), specify the date and time of event, and enter the name of event.

After the user confirms that parameters estimation is correct and enters the size of disturbance, the tool calculates frequency response performance characteristics:

- FRM at point B according to the NERC BAL-003-01 Standard
- FRM at minimum point, MW/0.1 Hz
- FRM at settling point, MW/0.1 Hz
- FRM at time 20 sec, MW/0.1 Hz
- FRM at time 30 sec, MW/0.1 Hz
- FRM at time 60 sec, MW/0.1 Hz
- FRM at time 90 sec, MW/0.1 Hz

The FRM metrics are calculated for the interconnection and for the BA. To save the new event in the database, click the “save” button. After the new event is entered to the database, the baseline plot is updated automatically.

### 7.2.2.7 FRAT Report Generation

To open the report window, click the “show report” button . The report screen is shown in Fig. 7-18. To generate the report, click the “FR report” button. To include event plots in the report, select the “add event plot” checkbox. Fig. 7-18 shows an example of the report automatically generated by FRAT. The generated report can be copied to the clipboard or saved as an MS Word file by clicking the “save”  button.

To generate the FRS 1 form, click the “NERC FRS1” button. An example of FRS 1 form report is given in Fig. 7-19.



Fig. 7-18. Frequency response analysis report screen

Report

☐ Add Event Plot    FR Report    NERC FRS1

Balancing Authority: DEMO    NERC FRS FORM 1

Event Number	UTC Date/Time	Prevailin g Date/Time	Prevailin g zone	BA Date/Time	BA zone	Del Freq	BA Time	BA Bias	Relay Limit R1	Value NAI	A Value Adj	A Value NAI	B Value Adj	B FRM Bias	for FRM R1	for Exclude
1	1/10/2014 1:00:00 PM	1/10/2014 6:00:00 AM	MST	1/10/2014 5:00:00 AM	PST	-0.128	5:00:00	0	59.5	0	0	0	-100	78.125	-	N
2	4/22/2014 8:10:00 PM	4/22/2014 2:10:00 PM	MST	4/22/2014 1:10:00 PM	PST	-0.07	13:10:00	0	59.5	10172.605	0	10358.453	-0	265.497	-	N
3	11/20/2013 8:00:00 AM	11/20/2013 1:00:00 AM	MST	11/20/2013 12:00:00 AM	PST	-0.07	0:00:00	0	59.5	10172.605	0	10358.453	-1200	1979.783	-	N
4	7/6/2014 7:00:00 AM	7/6/2014 1:00:00 AM	MST	7/6/2014 12:00:00 AM	PST	-0.068	00:00:00	0	59.5	10172.954	0	10359.792	-1300	2186.526	-	N

Fig. 7-19. FRS 1 form

### 7.2.3 FRAT Requirements

- Operating system: Windows XP or higher
- Prerequisites: Microsoft .Net 4.0 Framework
- Hardware requirements: should meet Microsoft .NET 4.0 system requirements

### 7.2.4 Program Web Page

The FRAT repository is: <https://svn.pnl.gov/FRTool>.

The repository is based on Trac technology. Trac is a web-based software project management and bug/issue tracking system. It also provides an integrated Wiki, an interface to version control systems (Fig. 7-20).

Registered users can access the latest version of the tool, contribute to the program source code, manuals (using integrated Wiki), and create new tickets (in case of bugs/issues detected). Program documentation is also available (Fig. 7-21); it is automatically generated using a Doxygen document generator.<sup>1</sup>

<sup>1</sup> <http://www.stack.nl/~dimitri/doxygen/index.html>

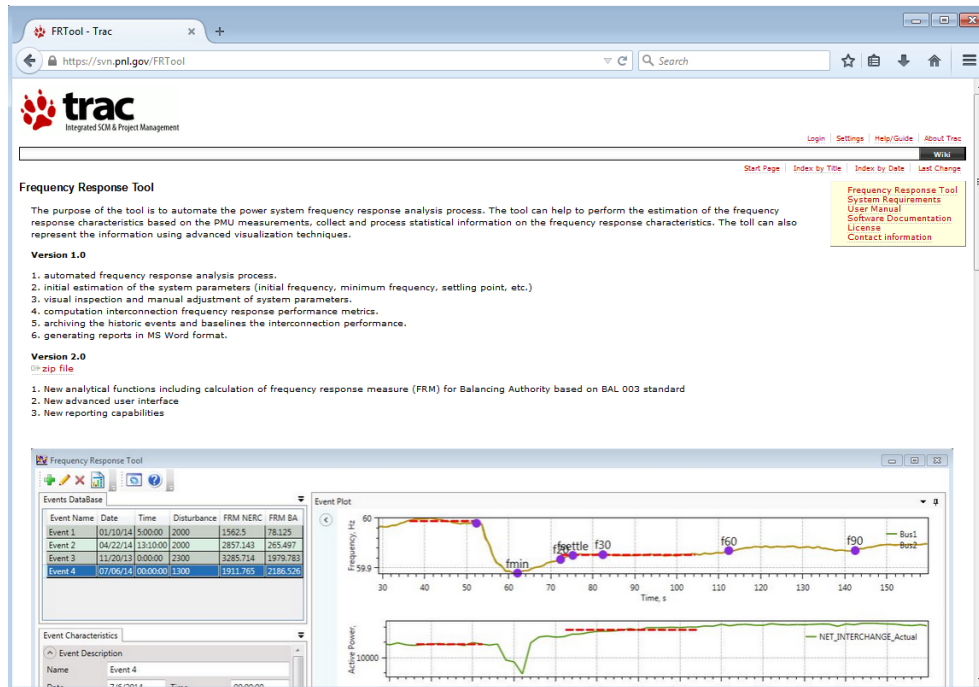


Fig. 7-20. FRAT repository (main Wiki page)

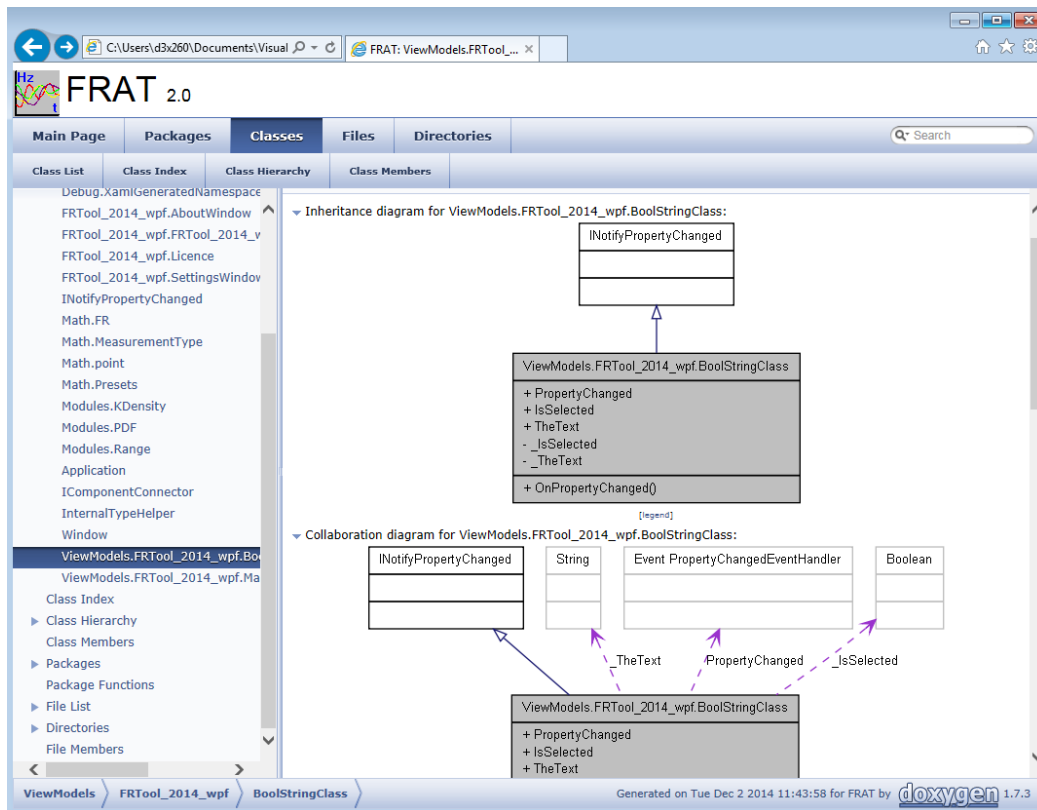


Fig. 7-21. FRAT documentation

### 7.3 Power Plant Model Validation Tool (PPMV)

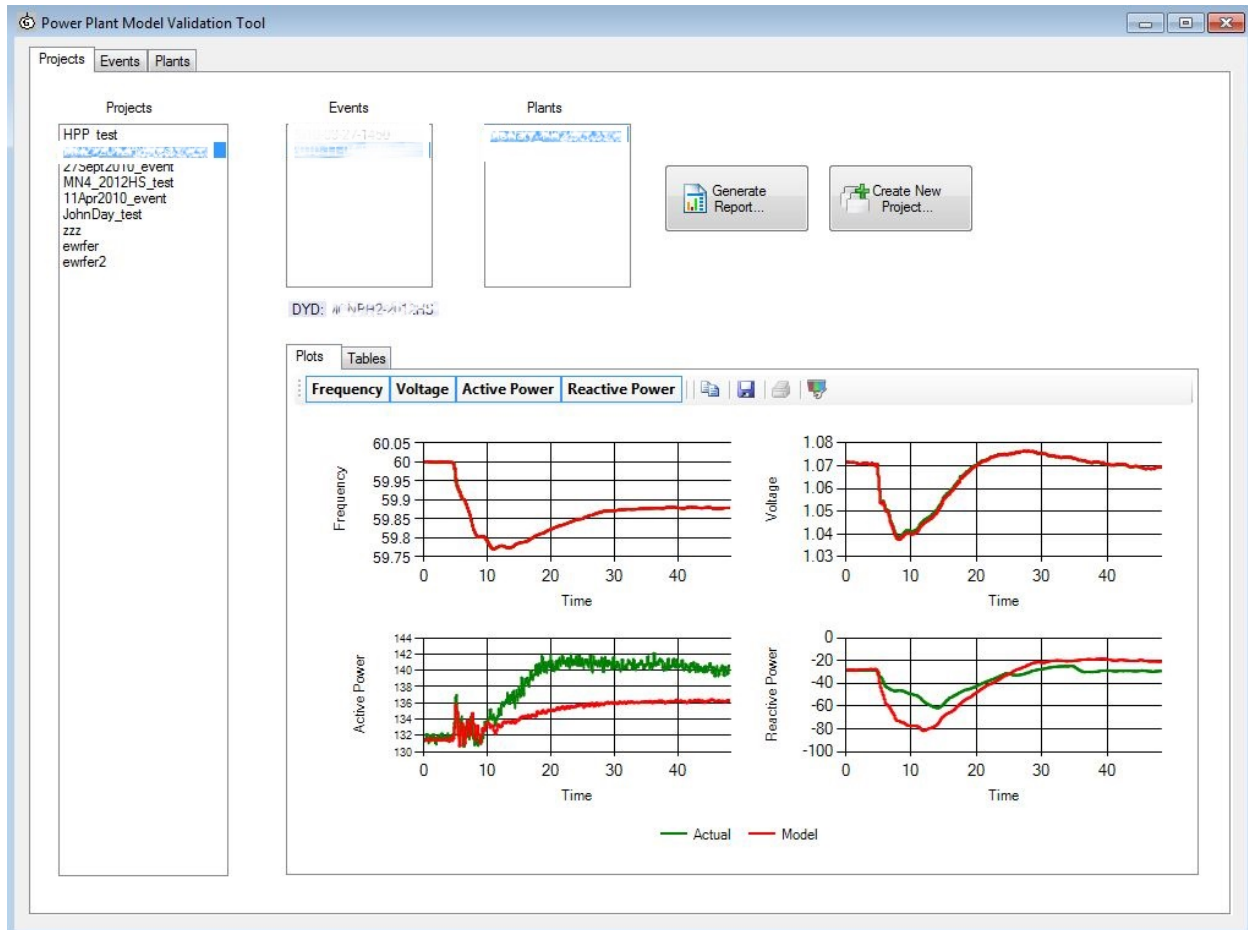
Validation of power system models for power flow and dynamic studies is very important for ensuring that these models are accurate and up to date. Disturbance recordings, especially PMU measurements, are very helpful for dynamic model verification.

The GE PSLF software package has built-in features for model validation using disturbance recordings. A set of PSLF scripts (written in EPCL language) was developed by BPA to facilitate the model validation process. However, the process of power plant model validation is still time consuming and requires multiple manual runs of different tools and manual modification of different script files.

The PPMV tool enables automatic processing of power plant model validation using disturbance recordings. The tool uses PMU and SCADA measurements as input information. The tool automatically adjusts all required EPCL scripts and calls PSLF in the batch mode.

The PPMV tool is a standalone Windows application with a user friendly interface.

Fig. 7-22 shows a screenshot of the main PPMV tool window. It shows a list of available projects created by the user (on the left side of the screen). Each project consists of a set of different events (disturbances) and different power plants. The tool also displays actual system response (green lines) vs. simulated system response (red lines).



**Fig. 7-22.** PPMV main screen GUI

Fig. 7-23 shows the “create new project” screen. The user can create two types of project:

- Analysis by event
- Analysis by plant

After the user defines a new project, the PPMV tool automatically updates all script files and performs validation analysis. The validation process consists from three steps:

- State estimation
- Model validation
- Extracting information from PSLF channel file



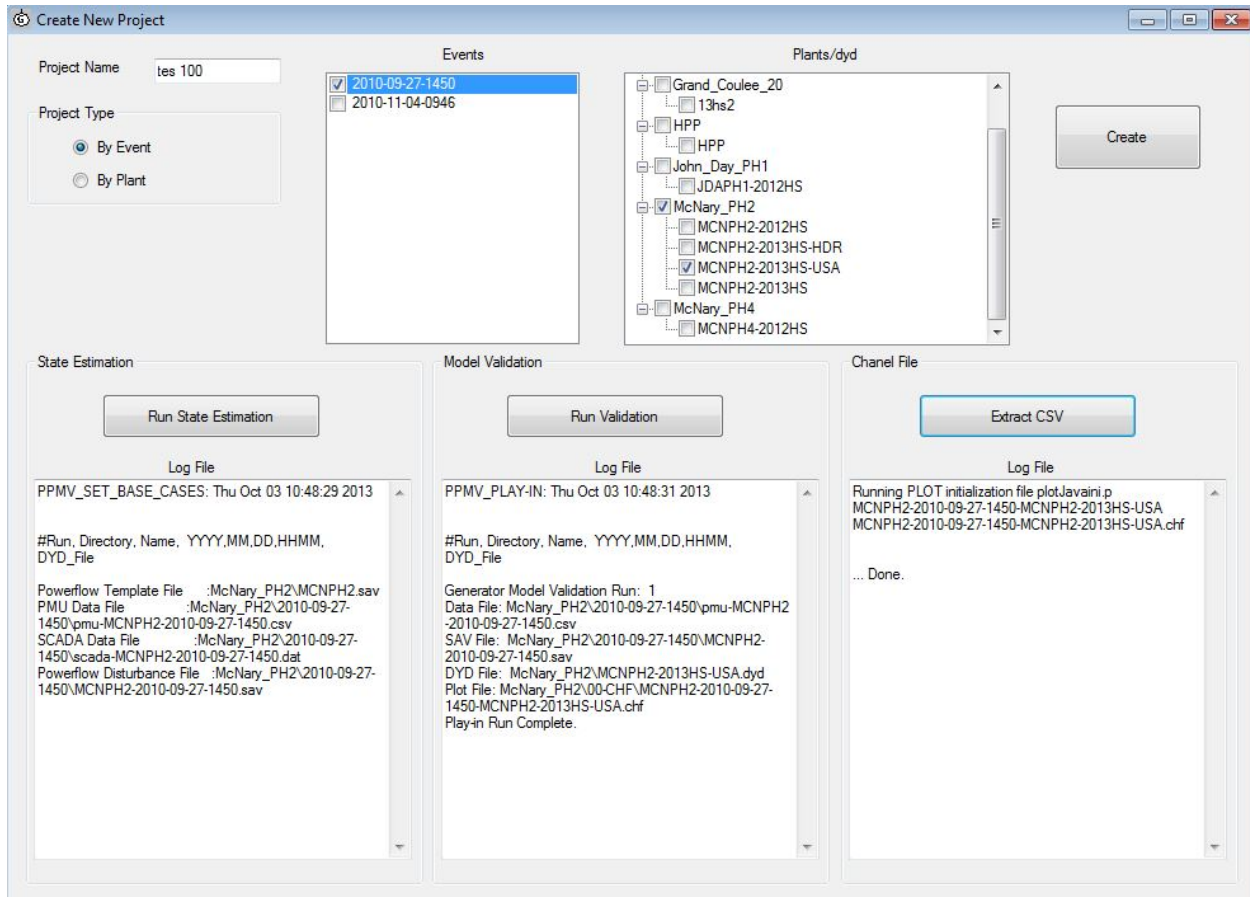


Fig. 7-23. PPMV create new project screen

### 7.3.1 PPMV System Requirements

- Operating system: Windows XP or later
- Processor, memory, HDD: no special requirements

### 7.3.2 PPMV Prerequisites

- Microsoft .Net 4.0 Framework
- GE PSLF 18.0 or later

## 8.0 Motor Response and Protection in Commercial Buildings

### 8.1 Introduction

This section along the tables in Appendix H provides details on voltage responses of typical motor loads found in commercial buildings. Depending of the magnitude and duration of the voltage sag, motors may ride through, trip, or stall. When voltages recover, motors may immediately reenergize and reaccelerate, or delay for a few minutes, or stay stalled. The estimated motor response is given for both the voltage sag magnitude and voltage sag duration. These response estimates are based on experience and available test data. Good data is available for voltage sag response for many components such as relays and contactors, but little data is available for both voltage sag and recovery response. The tables in Appendix H include data from recent voltage sag and recovery tests performed by SCE and BPA on air conditioners and energy management systems. The response of the motor can vary greatly depending on the type of protection and control. The time duration for the voltage sag consists of those times that are of interest for bulk power system modelers. The times of interest are 5, 10, and 20 cycles, 2 seconds, and 3 minutes.

In the Appendix H, tables are prepared in two categories of voltage drop: voltage drop that ranges from 75% to 100% of nominal and drop that ranges from 50% to 75% of nominal. In general, most motor control equipment will ride through sags down to 75%. In some cases, for larger motors, under voltage protection will trip motors for sags to 80% of nominal for 2 seconds.

The types of commercial buildings that have been considered are as follows:

- Food Service (Fast Food) (McDonalds)
- Supermarket (Albertson's)
- Other (Hotels, Residential Care)
- Office
  - 20k – 100k sf office building motor response
  - 100k – 1m sf office building motor response
- Retail (Both Big and Small, by square feet)
  - 5k – 15k sf retail building motor table (service station)
  - 15k – 40k sf retail building motor response (strip mall)
  - 40k – 100k sf retail building motor response (big box stores)
- Warehouse

The tables in Appendix H provide columns for equipment, motors, protection, and controls. This gives the reader an understanding of the type of motor, what equipment it is used in, how it is usually protected, and what type of control system is normally used.

The commercial office building tables are broken down by square foot to indicate which of the following apply:

- Larger, high-rise office buildings usually have an EMS that senses outdoor temperature, planned building occupancies, day of week, etc., to operate the chillers, boilers, fans, and pumps most efficiently. The mechanical engineer and architect dictate the complexity of the mechanical systems that are present.
- Larger office buildings have variable air volume or VAV systems that also modulate the conditioned air flow throughout the building to optimize efficiency. VAV systems generally have some type of building automation system or BAS, the more complex the HVAC system the more it benefits from advanced control. Sequencing of the air handlers and optimizing that with the heating/cooling needed from the chillers and boilers sometimes makes for a complex control system. The more different mechanical systems that need to be sequenced together the more complex things can become. Small office buildings can sometimes get away with very simple thermostat controls and time clocks; in these cases a computerized control system may not be used.
- The tables have a range of square feet that is the typical size for each building type.
- The Commercial Building Management Survey showed that 41% of commercial office buildings use some sort of EMS. In preparation of the tables, we have adjusted this by commercial building type and size to show that essentially 100% of some commercial building types use an EMS, and other types do not use them.

Some restaurant chains, like McDonald's, have done extensive energy efficiency studies and use EMSs in the restaurants, but typically, and for simplicity, we assume EMS is not used in food service buildings. Large retail stores such as Super Walmart or Costco that also sell groceries and have refrigeration equipment loads are in the category of grocery. Stores that sell primarily dry goods are in the category of retail.

Plug loads generally include coffee makers, copiers, computers, printers, ATMs, etc. In general, plug loads will ride through sags down to 75% of nominal for 2 seconds. Below this voltage, they drop out, and computer-based loads will go through a reboot sequence on voltage recovery.

The 3-minute column is really just for interest. Three minutes is ancient history in planning for automatic response to power system transients. The 3-minute column estimates what the motor load would be doing at this point.

## 8.2 Specific Motor Types and Applications

The following is a discussion of specific equipment types given in the Appendix H tables, providing specific background and detail that may be of interest.

### • **Roof Top Unit (RTU) Air Conditioner Compressor Motor**

RTU compressors motors are typically three-phase and include a dedicated local solid state control board. The motor contactors drop out at 58% to 61% voltage, which is higher than the stall voltage of about 50%. Thus, it is unlikely that the three-phase motors will be stalling during transients, unlike the

single-phase compressor motors. However, for unbalanced sags, stall may occur because the contactor voltage may stay near normal when the contactor is supplied by the voltages phases that are remaining near nominal voltage. SCE testing has shown that for both balanced and unbalanced voltages, after the contactor had dropped out due to low voltage, it would not reclose after voltage recovery for several minutes. Some RTUs may be equipped with manufacturer low voltage protection that operates after 2 seconds at 80% voltage (SCE RTU test, page 36, 53).

- **Single-Phase Air-Conditioning Unit Compressor Motor**

Recent testing of single-phase (split-phase motor type) air conditioning units by SCE found that these units typically stall between 60% and 70% nominal voltage well before they are disconnected because their power contactors drop out at about 50% to 60% voltage. It was also discovered that these single-phase compressor motors begin stalling rather quickly, normally within 3 cycles. This verifies the FIDVR theory that large numbers of single-phase air conditioning compressor motors may be stalling when voltage is between 70% and 50% of nominal. Single-phase compressor motors typically will not restart after tripping until a time delay of perhaps 3 minutes or more.

- **Local Solid State Control Board**

Reach-in and walk-in freezers, chillers, boiler elevators, and many other complex individual loads are also controlled by a local solid state control board. The board may be controlled by a local thermostat or by the EMS.

- **Variable Frequency Drives**

Variable Frequency Drives are typically programmed to ride through short duration voltage sags by current limiting the motor. In cases where only one phase is sagging, and the motor is being operated at partial load, the motor can run for several seconds or more. In the Appendix H tables, we assume that, for 60% voltage and 5, 10, and 20 cycles, the VFD should be able to ride through by current limiting the motor. The VFD cannot ride through a 2-second or 3-minute loss of voltage unless it is equipped with energy storage. In testing, VFDs were noted to ride through sags of up to 2 seconds, or more, in duration, then trip after voltage recovery.

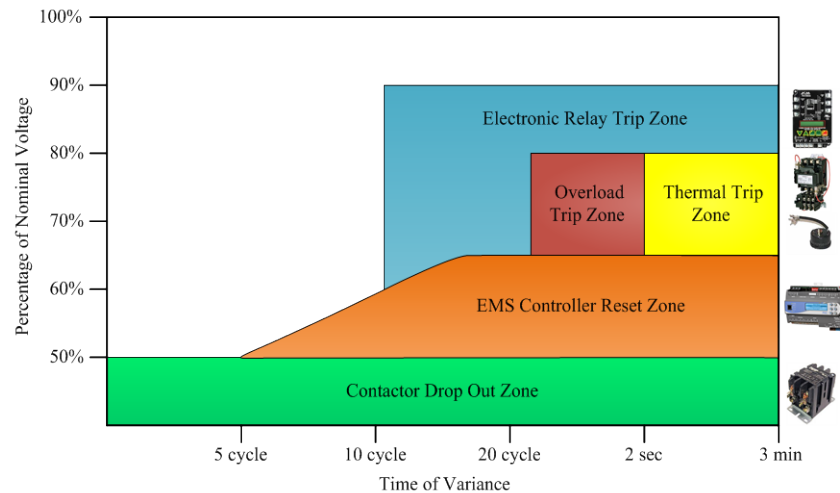
- **Chiller Motors**

Large chiller motors in the range of 100 to 700 HP typically have their own proprietary local control board with voltage, overcurrent, and unbalance protection. Manufacturer undervoltage protection is typically set at 90% of nominal voltage for 2 seconds and 80% of nominal voltage for 0.1 seconds. If the motor is de-energized on under voltage, until the built in anti-cycle timers minimum off delay expires.

- **Contactors**

Contactors, in general, will drop out within 5 cycles at 50% voltage. In some cases, voltage may sag to 40% before the contactor drops, and in some cases, it may be 60%, but 50% is a good estimate. When the voltage recovers, at 70% of nominal voltage the BPA test shows the contactor reclosed after two cycles. At 65%, it took 8.5 cycles to reclose. At 62% it never pulled in, even after multiple seconds.

The following graphic Fig. 8-1 represents reasonable estimates based on voltage sag and time; exact component trip points will be determined further by point on wave, motor load, control transformer load, ambient temperature. This graphic is for quick reference only, for more definitive parameters please see the Appendix H.



**Fig. 8-1.** Summary of specific type of motors

- **Energy Management System**

Testing at BPA has shown that the EMS can ride through severe voltage sags down to 65% of nominal voltage, the EMS will drop out 2 to 3 seconds after the event and then takes 3 seconds to reset. This occurred even with a battery-backed EMS. If there are batteries in controllers that control the outputs to the equipment, it's typically just to keep the internal clock/calendar operating while power is not available. The internal batteries are not usually used to maintain normal operation during voltage dips or loss. It will be assumed for the tables in Appendix H assume that for voltage sag down to 65% of nominal, the EMS will ride through but not reset. For sags below 65%, the EMS will ride through the initial event but will reset 2 seconds after the event, dropping the load until the programmed sequences in the controller has run from the beginning. Some loads and motors will be started relatively quickly while others may take several minutes to reengage the loads. Sometimes the controllers have built in restart programs that delay startup of equipment. If an entire building were to lose power and then have it reapplied, having everything startup at once could cause issues. So the controllers are often set to delay at varying period so that restarting all the equipment won't cause any demand surcharges or other load issues. Testing revealed that the EMS controllers tripped less at voltages above 60% when the control transformer secondary supplying power the controller was under 50% of its max VA capacity. EMS controllers did not trip on voltages above 65% when the loading of the transformer was at 80%, which is the max allowable by the National Electrical Code. In general, testing showed that voltage variances below 60% resulted in the EMS controller resetting regardless of transformer loading. All EMS controllers that were tested showed no reaction to 5-cycle events even when the nominal voltage went to 0%.

Fig. 8-2 reflects industry standard equipment start-up timing and sequencing in energy management systems. This does not reflect custom equipment start-up timing and sequencing for unique buildings or

mechanical systems designated by a design engineer or equipment not controlled by an EMS. This graphic is for quick reference only; for more exact reset times please see the Appendix H.

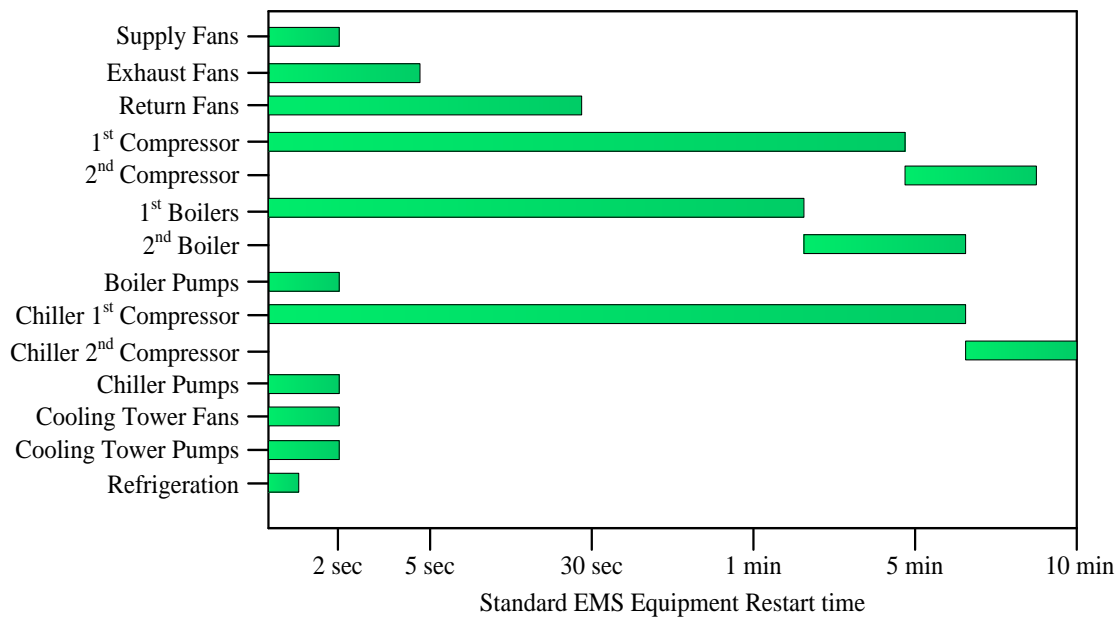


Fig. 8-2. Standard EMS equipment restart time

## 9.0 Conclusions

This *ARRA Interconnection Planning - Load Modeling Activities* report presented the multi-year effort on load modeling related work to assist and support WECC LMTF, MVWG, and JSJS activities. It primarily presented the load composition modeling, motor protection modeling, software tools development, and survey and testing related work. In summary, this report demonstrates the following aspects:

1. Load Composition Model: PNNL developed the LCM and created a MATLAB version. The LCM is based on a component-based approach. The component-based load modeling approach is a bottom-up technique that consists of aggregating distribution loads according to standard load classes, specifying the types of devices comprised by those load classes, and then assigning the appropriate composition of the aggregated load to the various components of a suitable load model structure.
2. WECC support: PNNL supported the WECC LMTF through the Phase 1 CMPLDW implementation. We were able to collect data from BPA, the SRP, PSE, PG&E, and IdahoPower. This task included load composition and load shape analysis for these WECC members. We also developed a database for LCMs and utility data.
3. Upgrade of commercial load composition: PNNL revised load composition data sets for commercial buildings that are temperature sensitive. A total of 96 simulations in EnergyPlus software have been done for eight commercial building types in 12 climate zones. Commercial building data from the California CEUS was upgraded by adding the HVAC load temperature sensitivity.
4. Aggregate load protection model: PNNL developed an aggregated motor protection model for studying FIDVR events. The model considers motor behaviors in several different stages in sequence: pre-fault, fault, clear, reclose, recovery/trip, and restart. Different states, On, Off, Start, Stall, and Trip state, are used to describe motor responses in the voltage event. During FIDVR events, some fraction of the motors in each state transition to other states. The number of motors in each state changes depending on voltage level and the time duration in the fault. As a result, the aggregate power demand dynamically changes as the time increases.
5. Protection model of single-phase motor: PNNL developed a protection model for a single-phase motor model. The model mimics contactor and thermal protection responses of motors, and captures the sensitivities of motor real and reactive power requirements to voltage and frequency. It reasonably predicts the stalling phenomena, and accurately represents motor current, and real and reactive power during the stalled state.
6. Software tools to support WECC, JSIS, and MVWG activities: PNNL has developed a Load Model Data Tool, Frequency Response Analysis Tool, and Power Plant Model Validation Tool in cooperation with BPA to support the WECC JSIS and MVWG.
7. Motor response and protection in commercial buildings: PNNL developed building motor response tables for a given set of commercial building types with voltage variances and time frames of interest. We categorized motor protection and control responses for these voltage variances and times along with EMS control logic restart times and motor protection trip delays. We identified “make and break” times of relays and contactors for the given voltage variances and recovery times. The results are

shown in a set of tables giving our estimated motor response for the type of motor load, type of building, and level and duration of the voltage variance.

In the future, we may continue to work on the load composition modeling and tools development, and incorporate the findings from the motor protection surveys into the load modeling work.



## 10.0 References

- [1] NERC Planning Committee White Paper on Delayed Voltage Recovery, [Online]. Available: [http://www.nerc.com/docs/pc/tis/White\\_Paper\\_on\\_Delayed\\_Voltage\\_Recovery\\_R16.pdf](http://www.nerc.com/docs/pc/tis/White_Paper_on_Delayed_Voltage_Recovery_R16.pdf).
- [2] Dmitry Kosterev, Anatoliy Meklin, John Undrill, Bernard Lesieutre, William Price, David Chassin, Richard Bravo, Steve Yang, "Load Modeling in Power System Studies:WECC Progress Update", IEEE PES General meeting General Meeting, Conversion and Delivery of Electrical Energy in the 21st Century, 2008.
- [3] B. C. Lesieutre, D. Kosterev, and J. Undrill, "Phasor modeling approach for single phase A/C Motors," *IEEE PES General meeting*, 2008.
- [4] Walve, K. "Modeling of Power System Components at Severe Disturbances," CIGRE paper 38-18, 1986.
- [5] B. R. Williams, W. R. Schmus, and D. C. Dawson, "Transmission Voltage Recovery Delayed by Stalled Air Conditioner Compressors," *IEEE Transactions on Power Systems*, vol.7, no.3, pp.1173-1181, August 1992.
- [6] L. Y. Taylor and S. M. Hsu "Transmission Voltage Recovery Following a Fault Event in the Metro Atlanta Area," Power Engineering Society Summer Meeting, 2000 IEEE.M. M. Abdel Hakim and G. J. Berg, "Dynamic Single Unit Representation of Induction Motor Groups," *IEEE Trans. on Power Apparatus and Systems*, vol. 95, no. 1, pp. 9-14, 1976.
- [7] K. O. Abledu and A. A. Mahmoud, "Equivalent Load Model of Induction Machines," *Electric Machines and Power Systems*, vol. 9, pp.435-452, 1984.
- [8] F. Nozari, M. D. Kankam, and W. W. Price, "Aggregation of Induction Motors for Transient Stability Load Modeling," *IEEE Trans. on Power Systems*, vol. 2, no. 4, pp. 1096-1102, 1987.
- [9] KW. Louie, J.R. Marti and H.W Dommel, "Aggregation of Induction Motors in a Power System Based on Some Special Operating Conditions," *Canadian Conference on Electrical and Computer Engineering*, pp.1429-1432, 2007.
- [10] D. J. Hill, "Nonlinear Dynamic Load Models with Recovery for Voltage Stability Studies," *IEEE Trans. on Power Systems*, vol. 8, no. 1, pp. 166-176, 1993.
- [11] D. C. Franklin and A. Morelato, "Improving Dynamic Aggregation of Induction Motor Models," *IEEE Trans. on Power Systems*, vol. 9, no. 4, pp. 1934-1941, 1994.
- [12] M. Taleb, A. Akbaba, E. A. Abdullah, "aggregation of induction machines for power systems dynamic studies," *IEEE Trans. on Power Systems*, vol. 9, no. 4, pp. 2042-2048, 1994.
- [13] A. M. Stankovic and B. C. Lesieutre, "A Probabilistic Approach to Aggregate Induction Machine Modeling", *IEEE Trans. on Power Systems*, vol. 11, no. 4, pp. 1982-1989, 1996.
- [14] A. M. Stankovic, B. C. Lesieutre, and T. Aydin, "Modeling and Analysis of Single-Phase Induction Machines with Dynamic Phasors", *IEEE Trans. on Power Systems*, vol. 14, no. 1, pp. 9-14, 1999.
- [15] E. W. Gunther and H. Mehta, "A survey of distribution system power quality—Preliminary results," *IEEE Trans. Power Delivery*, vol. 10, pp.322–329, Jan. 1995.

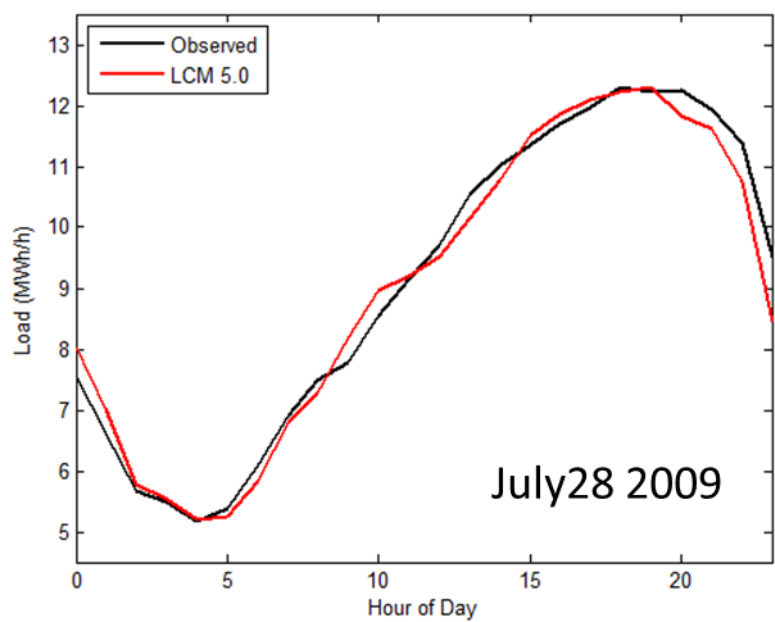
- [16] J. C. Gomez, M. M. Morcos, C. A. Reineri, and G. N. Campetelli, "Behavior of Induction Motor Due to Voltage Sags and Short Interruptions," *IEEE Trans. on Power Delivery*, vol. 17, no. 2, pp. 434-440, 2002.
- [17] N Lu, YL Xie, and Z Huang, "Air Conditioner Compressor Performance Model", PNNL-17796, Pacific Northwest National Laboratory, Richland, WA, August 2008.
- [18] H. Bai, P. Zhang, and V. Ajjarapu, "A Novel Parameter Identification Approach via Hybrid Learning for Aggregate Load Modeling," *IEEE Trans. on Power Systems*, vol. 24, no. 3, pp. 1145-1154, 2009.
- [19] J. W. Shaffer, "Air Conditioner Response to Transmission Faults," *IEEE Trans. on Power Systems*, vol. 12, no. 2, pp. 614-621, 1997.
- [20] V. Stewart and E. H. Camm, "Modeling of Stalled Motor Loads for Power System Short-Term Voltage Stability Analysis," IEEE PES General Meeting, vol.2, pp. 1887-1892, 2005.
- [21] C. D. Vournas and G. A. Manos, "Modelling of Stalling Motors during Voltage Stability Studies," *IEEE Trans. on Power Systems*, vol. 13, no. 3, pp. 775-781, 1998.
- [22] *IEEE Guide for AC Motor Protection*, IEEE Standard C37.96-2000
- [23] IT De Villiers, "The behaviour of contactors during voltage dips," [Online]. Available: [http://www.measurlogic.com/Resources/Paper4\\_book.pdf](http://www.measurlogic.com/Resources/Paper4_book.pdf).
- [24] S. Z. Djokic', J. V. Milanovic', and D. S. Kirschen, "Sensitivity of AC Coil Contactors to Voltage Sags, Short Interruptions, and Undervoltage Transients," *IEEE Transactions on Power Delivery*, vol. 19, no. 3, pp. 1299-1307, 2004.
- [25] A. E. Turner and E. R. Collins, Jr., "The Performance of AC Contactors During Voltage Sags," Proceedings of the 1996 International Conference on Harmonics and Quality of Power (ICHQP), Las Vegas NV, October 1996.
- [26] IEEE Task Force on Load Representation for Dynamic Performance, "Load Representation for Dynamic Performance Analysis," *IEEE Transactions on Power Systems*, vol. 8, no. 2, May 1993, pp. 472-482.
- [27] IEEE Task Force on Load Representation for Dynamic Performance, "Standard Models for Power Flow and Dynamic Performance Simulation," *IEEE Transactions on Power Systems*, vol. 10, no. 3, August 1995, pp. 1302-1313.
- [28] Pereira L., D.N. Kosterev, P. Mackin, D. Davies, J. Undrill, W. Zhu, "An Interim Dynamic Induction Motor Model for Stability Studies in WSCC," *IEEE Transactions on Power Systems*, vol. 17, no.4, November 2002, pp. 1108-1115.
- [29] John Shaffer, "Air Conditioner Response to Transmission Faults", *IEEE Transactions on Power Systems*, vol.12, no.2, May 1997, pp.614-621.
- [30] North American Electric Reliability Council, 1987 System Disturbances, p. 19, July 1988.
- [31] Garry Chinn, "Modeling Stalled Induction Motors," presented at the IEEE Transmission and Distribution Conference, Dallas TX, May 2006.

- [32] Williams, B., W. Schmus, D. Dawson, "Transmission Voltage Recovery Delayed by Stalled Air Conditioner Compressors," IEEE Transactions on Power Systems, vol. 7, no. 3, pp. 1173-1181, August 1992.
- [33] Shaffer, J., "Air Conditioner Response to Transmission Faults", IEEE Transactions on Power Systems, vol. 12, no. 2, May 1997, pp. 614-621.
- [34] EEEB344 Electromechanical Devices
- [35] Federal Energy Regulatory Commission, Docket RM13-11, Frequency Response and Frequency Bias Setting Reliability Standard, 144 FERC ¶ 61,057 (July 18, 2013) (NOPR).
- [36] North American Electric Reliability Corporation. 2014. "NERC BAL-003-1 Frequency Response and Frequency Bias Setting Reliability Standard", Atlanta, GA.
- [37] North American Electric Reliability Corporation, "NERC Frequency Response Initiative Report" (2012), Atlanta, GA. October 2012, Available: <http://www.nerc.com/docs/pc/FRI%20Report%209-16-12%20Draft.pdf>.
- [38] Eto J. et al. 2010. "Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation." LBNL-4142E, Lawrence Berkeley National Laboratory, Berkeley, CA. Available: <http://www.ferc.gov/industries/electric/indus-act/reliability/frequencyresponsemetrics-report.pdf>.
- [39] Western Electricity Coordinating Council. 2004. "WECC White Paper on Frequency Response Standard", Salt Lake City, UT. Available: [http://www.wecc.biz/Standards/Development/wecc0044/Shared%20Documents/Posted%20for%20OCC%20Approval/FRR%20White%20Paper%20v12\\_Tables\\_8-9.doc](http://www.wecc.biz/Standards/Development/wecc0044/Shared%20Documents/Posted%20for%20OCC%20Approval/FRR%20White%20Paper%20v12_Tables_8-9.doc).
- [40] Federal Energy Regulatory Commission, Docket AD13-8. 2013. "Market Implications of Frequency Response and Frequency Bias Setting Requirements" (144 FERC ¶ 61,058, July 18, 2013).
- [41] Kosterev D. 2004. "Hydro-Turbine Model Validation in Pacific Northwest." IEEE Transactions on Power Systems, vol.19, no. 2, May 2004, pages 1144–1149.
- [42] Kosterev D., D. Davies, P. Etingov, A. Silverstein, and J. Eto. 2014. "Using Synchrophasors for Frequency Response Analysis in Western Interconnection." CIGRE Grid of the Future Symposium, Houston, TX, USA, October 19 - 21, 2014.

# Appendix A LCM Validation Results

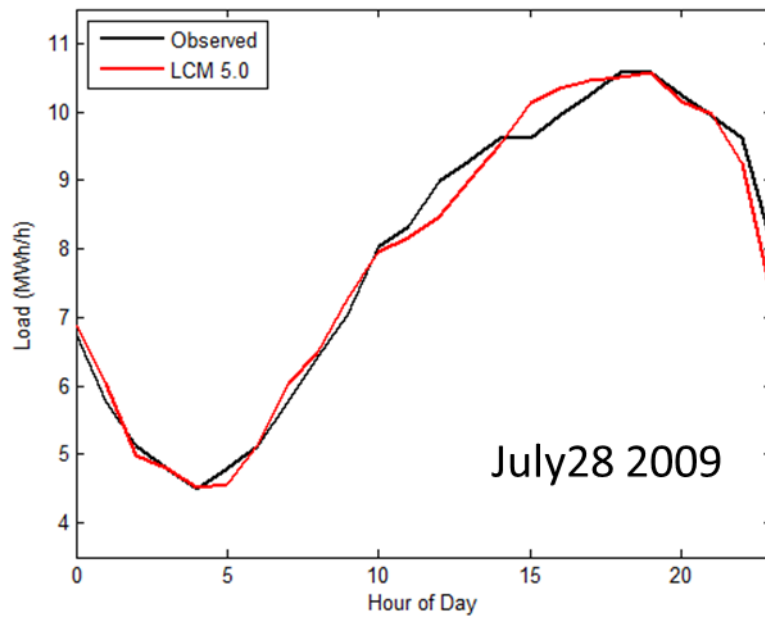
This appendix presents the results of the LCM validation that was performed using data received from utilities.

Portland Sub1:



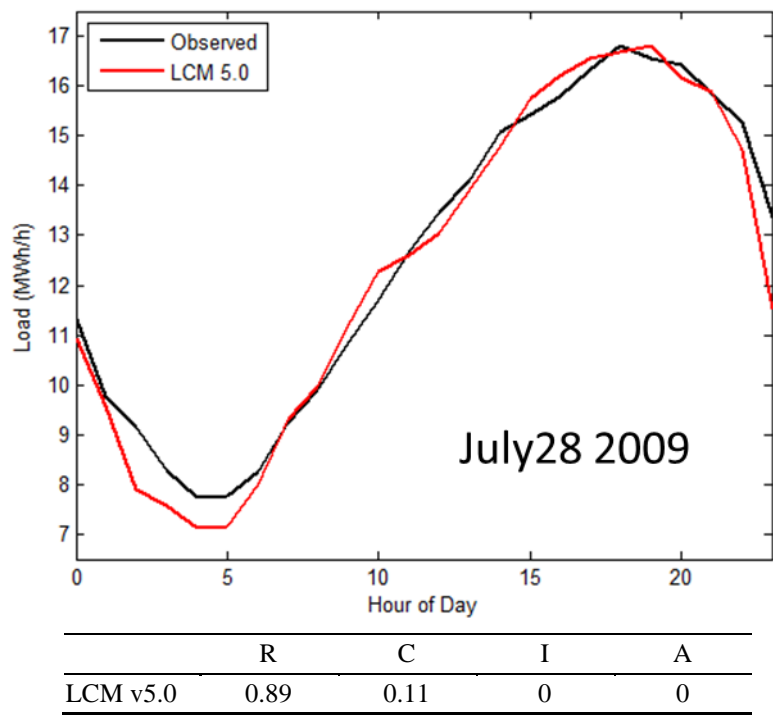
	R	C	I	A
LCM v5.0	0.9	0.1	0	0

Portland Sub2:



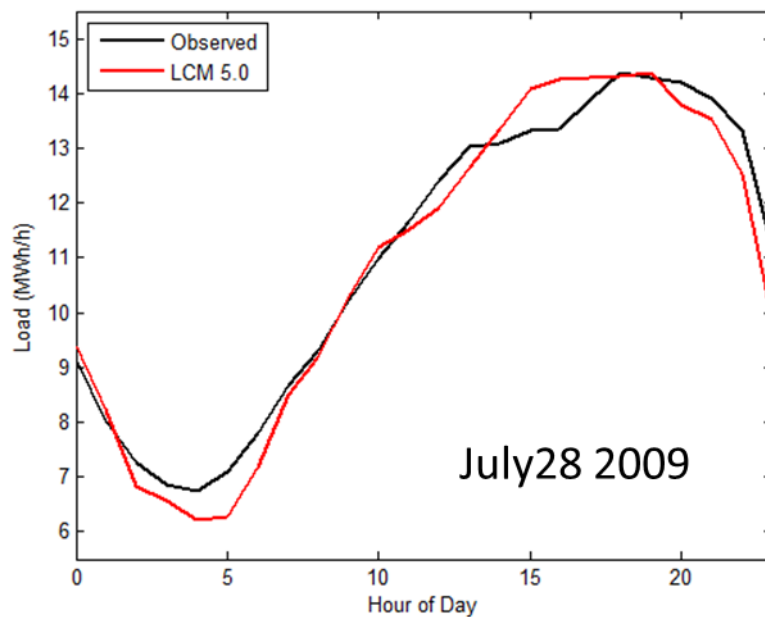
	R	C	I	A
LCM v5.0	0.88	0.12	0	0

	Climate Zone	Load Mix	Hour	Res	Com	Ind	Agr	E	MA	MB	MC	MD	ZIP
Default	NWV	RES	16	0.75	0.23	0	0.02	0.09	0.08	0.07	0.04	0.59	0.04
Calibrated	NWV	RES	19	0.88	0.12	0	0	0.10	0.04	0.09	0.03	0.64	0.11



	Climate Zone	Load Mix	Hour	Res	Com	Ind	Agr	E	MA	MB	MC	MD	ZIP
Default	NWV	RES	16	0.75	0.23	0	0.02	0.09	0.08	0.07	0.04	0.59	0.04
Calibrated	NWV	RES	19	0.89	0.11	0	0	0.10	0.03	0.09	0.03	0.65	0.11

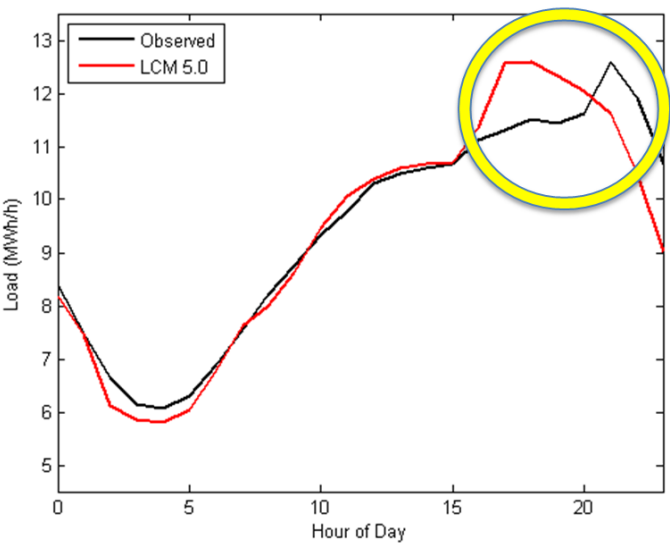
# Portland Sub4



	R	C	I	A
LCM v5.0	0.86	0.14	0	0

	Climate Zone	Load Mix	Hour	Res	Com	Ind	Agr	E	MA	MB	MC	MD	ZIP
Default	NWV	RES	16	0.75	0.23	0	0.02	0.09	0.08	0.07	0.04	0.59	0.04
Calibrated	NWV	RES	19	0.86	0.14	0	0	0.10	0.04	0.09	0.03	0.62	0.12

Seattle Sub Residential King



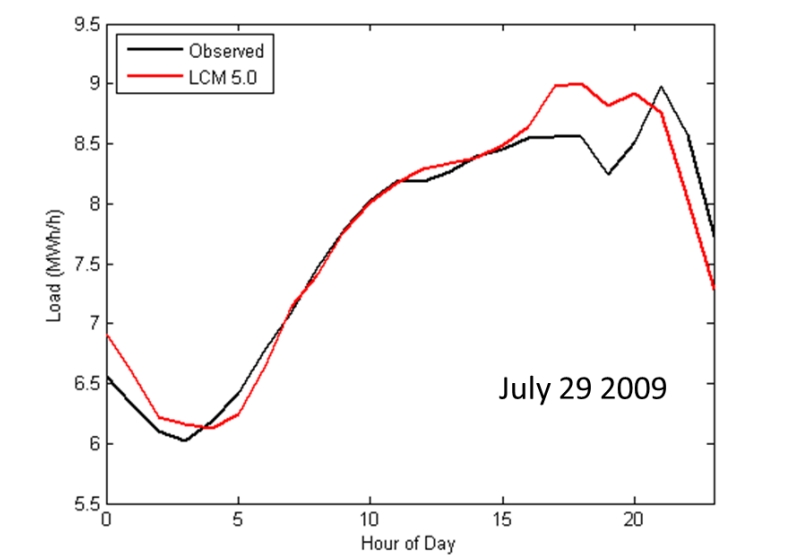
AC control saturation

	R	C	I	A
Data (Energy)	0.77	0.23	0	0
LCM v5 (Power)	1	0	0	0

	Climate Zone	Load Mix	Hour	Res	Com	Ind	Agr	E	MA	MB	MC	MD	ZIP
Default	NWC	RES	16	0.75	0.23	0	0.02	0.10	0.09	0.05	0.06	0.50	0.2
Calibrated	NWC	RES	18	1	0	0	0	0.10	0.00	0.07	0.05	0.56	0.21



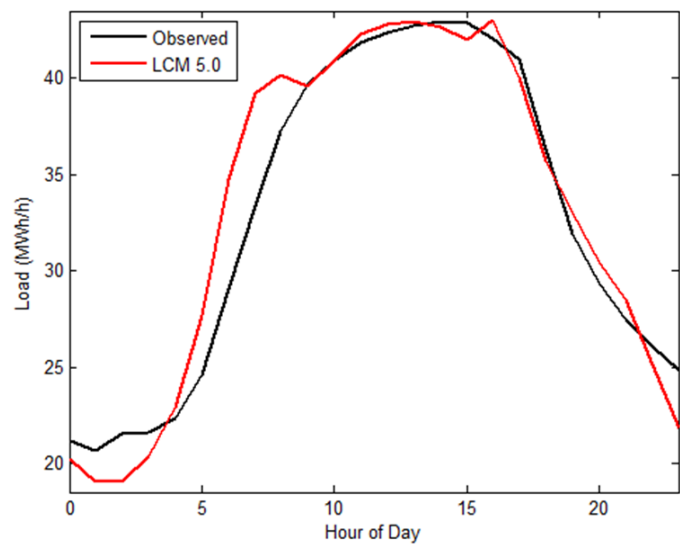
Seattle Sub Residential Skagit



Is this a data center?

	R	C	I	A
Data (Energy)	0.69	0.31	0	0
LCM v5 (Power)	0.58	0.04	0.38	0

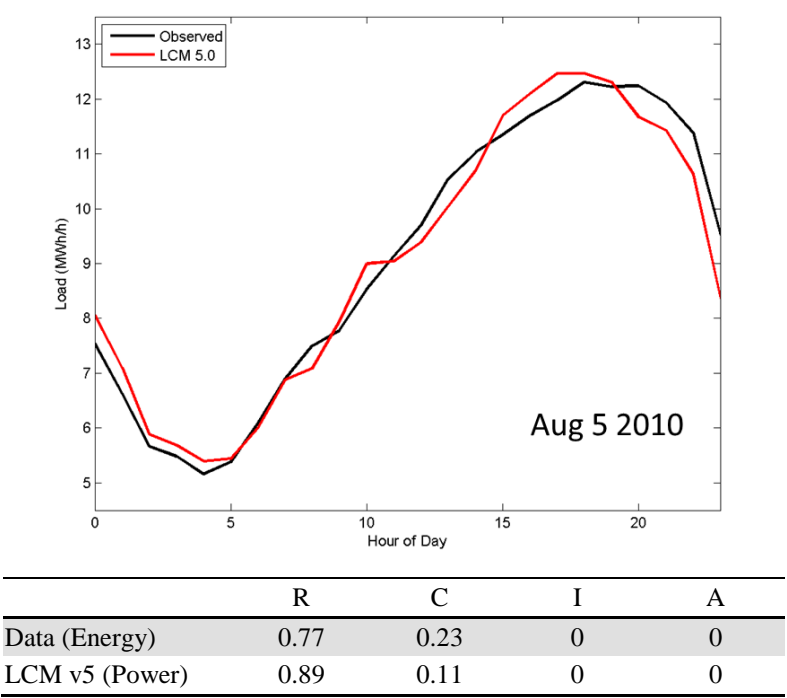
Seattle Sub Downtown King



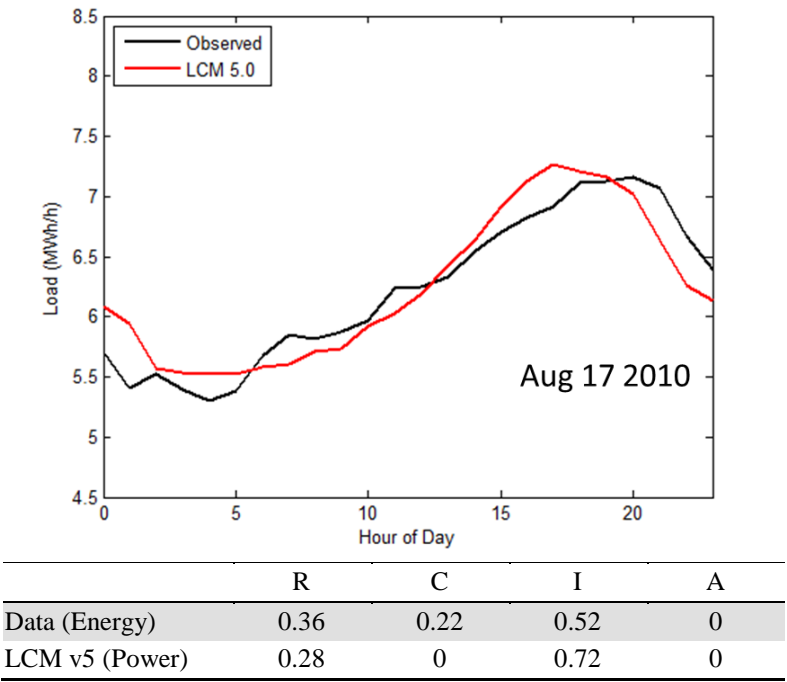
Large office ramp is not defined correctly (but it’s not on peak anyway).

	R	C	I	A
Data (Energy)	0.08	0.92	0	0
LCM v5 (Power)	0.34	0.66	0	0

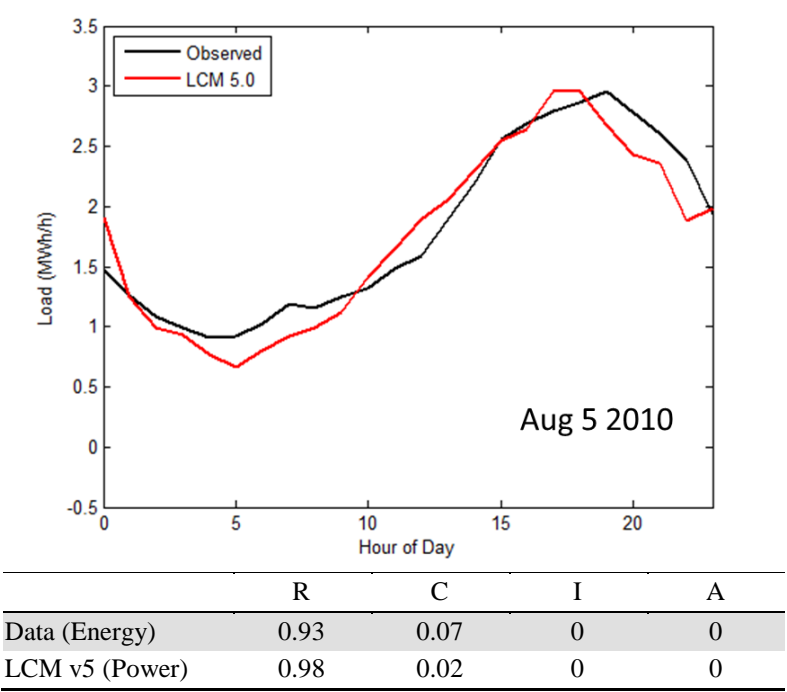
	Climate Zone	Load Mix	Hour	Res	Com	Ind	Agr	E	MA	MB	MC	MD	ZIP
Default	NWC	Com	16	0.2	0.73	0.05	0.02	0.19	0.30	0.08	0.08	0.13	0.22
Calibrated	NWC	Com	13	0.34	0.66	0	0	0.13	0.26	0.12	0.10	0.20	0.19



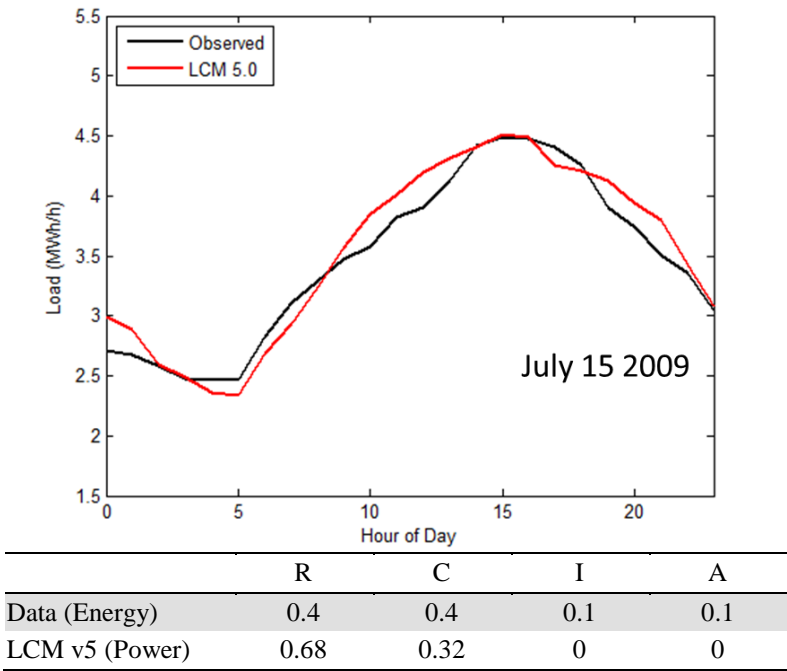
	Climate Zone	Load Mix	Hour	Res	Com	Ind	Agr	E	MA	MB	MC	MD	ZIP
Default	NWI	RES	16	0.75	0.23	0	0.02	0.09	0.09	0.07	0.04	0.59	0.12
Calibrated	NWI	RES	19	0.89	0.11	0	0	0.09	0.03	0.09	0.02	0.67	0.10



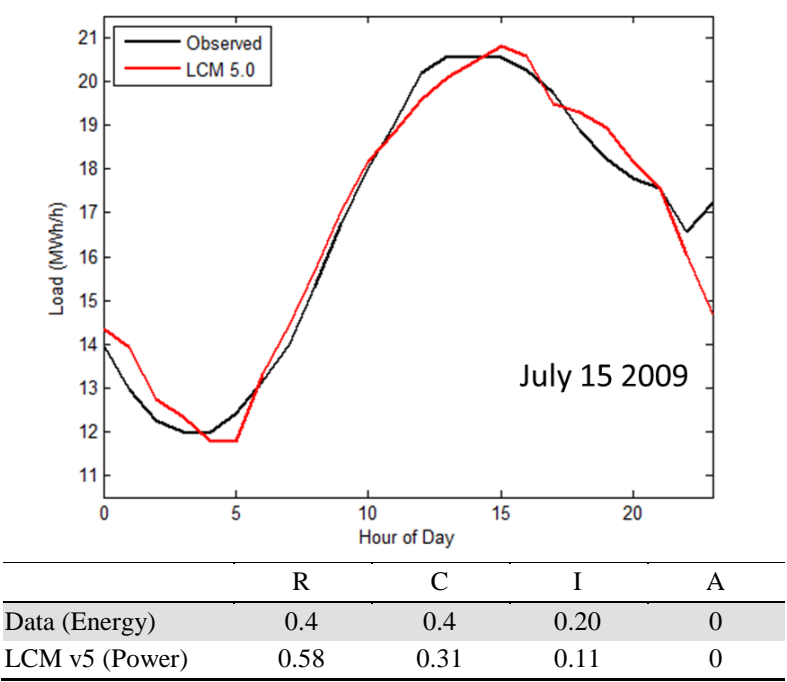
	Climate Zone	Load Mix	Hour	Res	Com	Ind	Agr	E	MA	MB	MC	MD	ZIP
Default	NWC	RAG	16	0.4	0.2	0.15	0.25	0.14	0.10	0.08	0.15	0.32	0.21
Calibrated	NWC		19	0.29	0	0.71	0	0.16	0.00	0.03	0.29	0.21	0.31



	Climate	Load											
	Zone	Mix	Hour	Res	Com	Ind	Agr	E	MA	MB	MC	MD	ZIP
Default	NWI	RES	16	0.75	0.23	0	0.02	0.09	0.09	0.07	0.04	0.59	0.12
Calibrated	NWI	RES	18	0.98	0.02	0	0	0.07	0.01	0.09	0.02	0.72	0.09

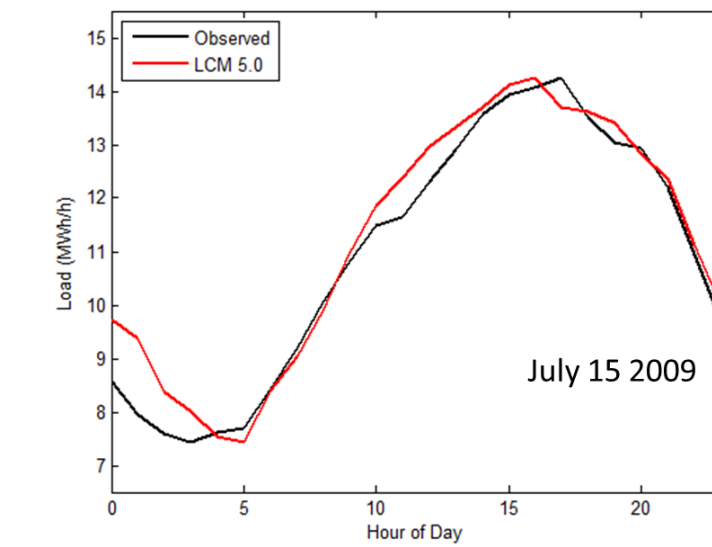


	Climate Zone	Load Mix	Hour	Res	Com	Ind	Agr	E	MA	MB	MC	MD	ZIP
Default	DSW	RAG	17	0.4	0.2	0.15	0.25	0.14	0.09	0.08	0.15	0.34	0.2
Calibrated	DSW	Rural	16	0.68	0.32	0	0	0.12	0.11	0.09	0.03	0.55	0.1



	Climate Zone	Load Mix	Hour	Res	Com	Ind	Agr	E	MA	MB	MC	MD	ZIP
Default	DSW	MIX	17	0.45	0.48	0.05	0.02	0.14	0.18	0.09	0.05	0.37	0.17
Calibrated	DSW	MIX	16	0.59	0.31	0.11	0	0.13	0.12	0.11	0.05	0.48	0.12

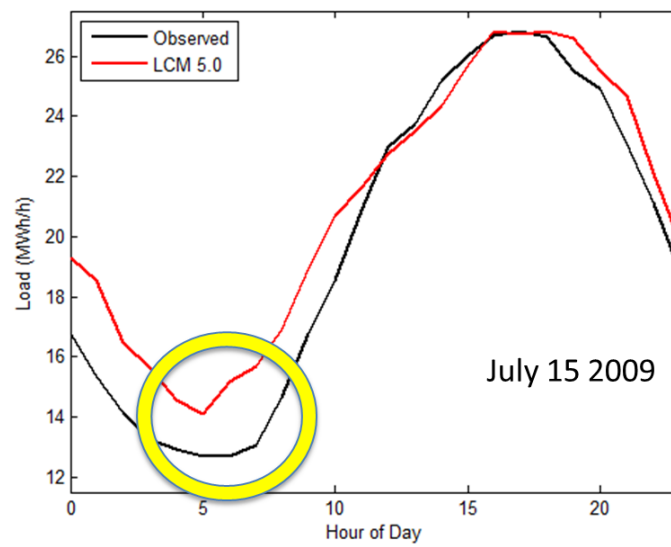
# Phoenix\_Urban



	R	C	I	A
Data (Energy)	0.5	0.5	0	0
LCM v5 (Power)	0.72	0.28	0	0

	Climate Zone	Load Mix	Hour	Res	Com	Ind	Agr	E	MA	MB	MC	MD	ZIP
Default	DSW	RES	17	0.75	0.23	0	0.02	0.09	0.08	0.09	0.03	0.63	0.08
Calibrated	DSW	Urban	16	0.72	0.28	0	0	0.11	0.09	0.09	0.02	0.59	0.09

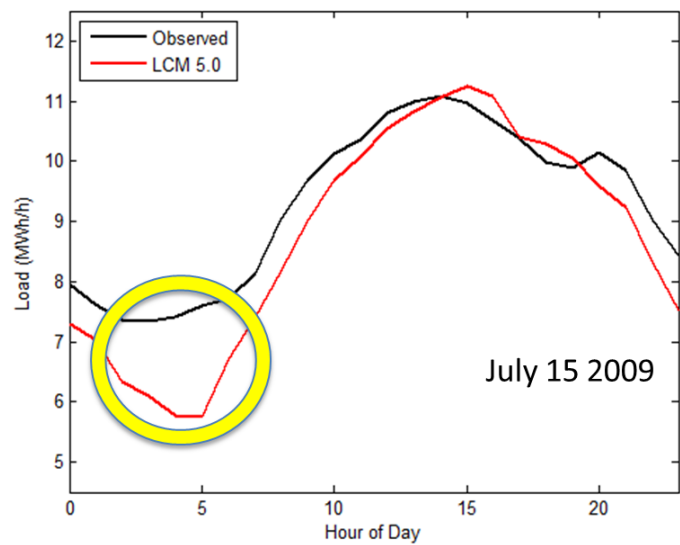




More nighttime AC in model than actual data?

	R	C	I	A
Data (Energy)	0.8	0.2	0	0
LCM v5 (Power)	0.83	0.17	0	0

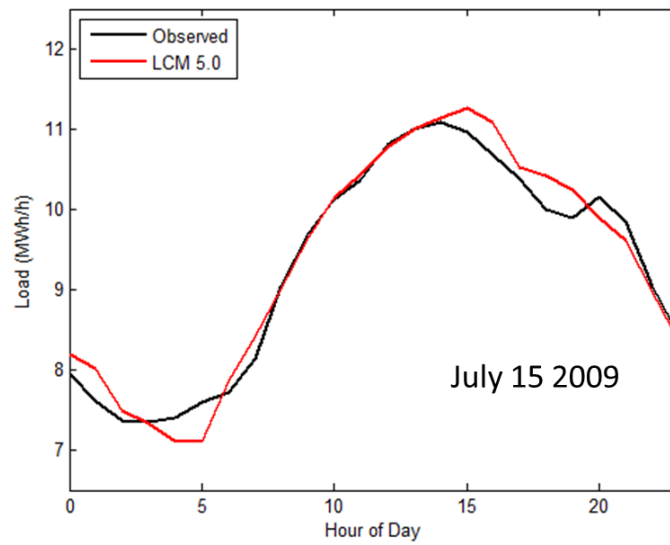
	Climate Zone	Load Mix	Hour	Res	Com	Ind	Agr	E	MA	MB	MC	MD	ZIP
Default	DSW	RES	17	0.75	0.23	0	0.02	0.09	0.08	0.09	0.03	0.63	0.08
Calibrated	DSW	RES	16	0.83	0.17	0	0	0.09	0.06	0.09	0.02	0.68	0.06



Is this a data center?

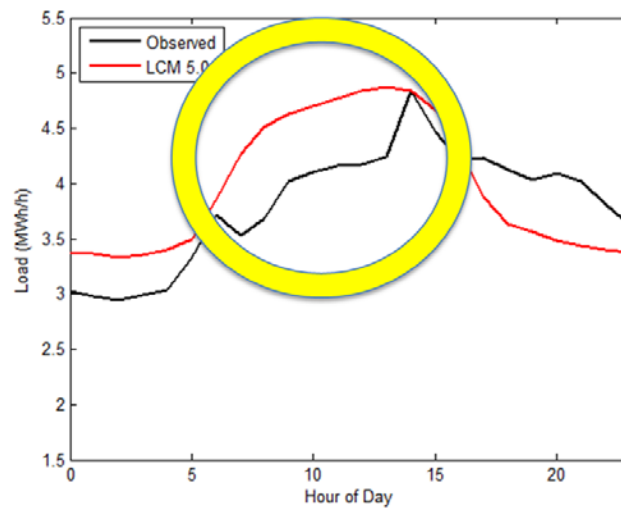
	R	C	I	A
Data (Energy)	0.2	0.8	0	0
LCM v5 (Power)	0.65	0.35	0	0

	Climate Zone	Load Mix	Hour	Res	Com	Ind	Agr	E	MA	MB	MC	MD	ZIP
Default	DSW	COM	17	0.2	0.73	0.05	0.02	0.19	0.25	0.1	0.07	0.17	0.22
Calibrated	DSW	COM	16	0.65	0.35	0	0	0.12	0.12	0.09	0.03	0.53	0.11



	R	C	I	A
Data (Energy)	0.2	0.8	0	0
LCM v5 (Power)	0.47	0.28	0.25	0

San Francisco\_Com



The third-party weather data may not be from the same location as the feeder.

Was a DR program in effect that day?

	R	C	I	A
Data (Energy)	0.16	0.76	0.06	0
LCM v5 (Power)	0	0.41	0.59	0

## Appendix B

### SQL Code of Creating Database Schema

```
SET @OLD_UNIQUE_CHECKS=@@UNIQUE_CHECKS, UNIQUE_CHECKS=0;
```

```
SET @OLD_FOREIGN_KEY_CHECKS=@@FOREIGN_KEY_CHECKS,  
FOREIGN_KEY_CHECKS=0;
```

```
SET @OLD_SQL_MODE=@@SQL_MODE, SQL_MODE='TRADITIONAL';
```

```
CREATE SCHEMA IF NOT EXISTS `ARRA_DATA` DEFAULT CHARACTER SET latin1 COLLATE  
latin1_swedish_ci ;
```

```
USE `ARRA_DATA` ;
```

```
-----  
-- Table `ARRA_DATA`.`Climate_zones`  
-----
```

```
CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Climate_zones` (
```

```
  `climate_zone_id` INT NOT NULL ,
```

```
  `climate_zone_name` VARCHAR(45) NULL ,
```

```
  `abbr_id` VARCHAR(45) NULL ,
```

```
  `hour_index` INT NULL ,
```

```
  PRIMARY KEY (`climate_zone_id`))
```

```
ENGINE = InnoDB;
```

```
-----  
-- Table `ARRA_DATA`.`City`
```

```

-----

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`City` (

  `city_id` INT NOT NULL ,

  `city_name` VARCHAR(45) NULL ,

  `latitude` DOUBLE NULL ,

  `state` VARCHAR(45) NULL ,

  `climate_zone_id` INT NULL ,

  `representative_flag` CHAR(1) NULL ,

  PRIMARY KEY (`city_id`) ,

  INDEX `fk_city_climate_zone_id` (`climate_zone_id` ASC) ,

  CONSTRAINT `fk_city_climate_zone_id`

    FOREIGN KEY (`climate_zone_id` )

      REFERENCES `ARRA_DATA`.`Climate_zones` (`climate_zone_id` )

    ON DELETE NO ACTION

    ON UPDATE NO ACTION)

ENGINE = InnoDB;

```

```

-----

-- Table `ARRA_DATA`.`Load_type`

```

```

-----

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Load_type` (

  `load_type_id` INT NOT NULL ,

  `load_type_name` VARCHAR(45) NULL ,

  PRIMARY KEY (`load_type_id` )

ENGINE = InnoDB;

```

```

-----
-- Table `ARRA_DATA`.`City_info`
-----

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`City_info` (
  `city_id` INT NOT NULL ,
  `load_type_id` INT NOT NULL ,
  `value` DOUBLE NULL ,
  PRIMARY KEY (`city_id`, `load_type_id`),
  INDEX `fk_city_info_city_id` (`city_id` ASC),
  INDEX `fk_city_info_load_type_id` (`load_type_id` ASC),
  CONSTRAINT `fk_city_info_city_id`
    FOREIGN KEY (`city_id`)
      REFERENCES `ARRA_DATA`.`City` (`city_id`)
    ON DELETE NO ACTION
    ON UPDATE NO ACTION,
  CONSTRAINT `fk_city_info_load_type_id`
    FOREIGN KEY (`load_type_id`)
      REFERENCES `ARRA_DATA`.`Load_type` (`load_type_id`)
    ON DELETE NO ACTION
    ON UPDATE NO ACTION)
ENGINE = InnoDB;

```

```

-----
-- Table `ARRA_DATA`.`Time_interval`
-----

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Time_interval` (
  `time_interval_id` INT NOT NULL ,

```

```

`begin_time` VARCHAR(45) NULL ,

`end_time` VARCHAR(45) NULL ,

PRIMARY KEY (`time_interval_id`))

ENGINE = InnoDB;

```

```

-----

-- Table `ARRA_DATA`.`Event_data`

-----

```

```

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Event_data` (

  `city_id` INT NOT NULL ,

  `time_interval_id` INT NOT NULL ,

  `record_date` DATE NOT NULL ,

  `temperature` DOUBLE NULL ,

  `wind` DOUBLE NULL ,

  `humidity` DOUBLE NULL ,

  `clouds` DOUBLE NULL ,

  `diffuse_solar` DOUBLE NULL ,

  `direct_solar` DOUBLE NULL ,

  `load_scada` DOUBLE NULL ,

  PRIMARY KEY (`city_id`, `time_interval_id`, `record_date`),

  INDEX `fk_event_data_city_id` (`city_id` ASC),

  INDEX `fk_event_data_time_interval_id` (`time_interval_id` ASC),

  CONSTRAINT `fk_event_data_city_id`

    FOREIGN KEY (`city_id`)

      REFERENCES `ARRA_DATA`.`City` (`city_id`)

    ON DELETE NO ACTION

    ON UPDATE NO ACTION,

```

```

CONSTRAINT `fk_event_data_time_interval_id`

FOREIGN KEY (`time_interval_id` )

REFERENCES `ARRA_DATA`.`Time_interval` (`time_interval_id` )

ON DELETE NO ACTION

ON UPDATE NO ACTION)

ENGINE = InnoDB;

```

```

-----

-- Table `ARRA_DATA`.`Time_period`

-----

```

```

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Time_period` (

  `time_period_id` INT NOT NULL ,

  `time_period_name` VARCHAR(45) NULL ,

  PRIMARY KEY (`time_period_id` )

ENGINE = InnoDB;

```

```

-----

-- Table `ARRA_DATA`.`Residential_load_shape`

-----

```

```

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Residential_load_shape` (

  `time_period_id` INT NOT NULL ,

  `load_type_id` INT NOT NULL ,

  `time_interval_id` INT NOT NULL ,

  `load_value` DOUBLE NULL ,

  PRIMARY KEY (`time_period_id`, `load_type_id`, `time_interval_id`),

  INDEX `fk_residential_load_shape_time_period_id` (`time_period_id` ASC),

```



```

INDEX `fk_residential_load_shape_load_type_id` (`load_type_id` ASC) ,
INDEX `fk_residential_load_shape_time_interval_id` (`time_interval_id` ASC) ,
CONSTRAINT `fk_residential_load_shape_time_period_id`
    FOREIGN KEY (`time_period_id` )
    REFERENCES `ARRA_DATA`.`Time_period` (`time_period_id` )
    ON DELETE NO ACTION
    ON UPDATE NO ACTION,
CONSTRAINT `fk_residential_load_shape_load_type_id`
    FOREIGN KEY (`load_type_id` )
    REFERENCES `ARRA_DATA`.`Load_type` (`load_type_id` )
    ON DELETE NO ACTION
    ON UPDATE NO ACTION,
CONSTRAINT `fk_residential_load_shape_time_interval_id`
    FOREIGN KEY (`time_interval_id` )
    REFERENCES `ARRA_DATA`.`Time_interval` (`time_interval_id` )
    ON DELETE NO ACTION
    ON UPDATE NO ACTION)
ENGINE = InnoDB;

```

```

-----
-- Table `ARRA_DATA`.`Rule_associations`
-----

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Rule_associations` (
    `rule_association_id` INT NOT NULL ,
    `rule_association_name` VARCHAR(45) NULL ,
    PRIMARY KEY (`rule_association_id` )
ENGINE = InnoDB;

```

```

-----

-- Table `ARRA_DATA`.`Category`
-----

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Category` (
  `category_id` INT NOT NULL ,
  `category_name` VARCHAR(45) NULL ,
  PRIMARY KEY (`category_id`) )
ENGINE = InnoDB;

-----

-- Table `ARRA_DATA`.`Building_type`
-----

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Building_type` (
  `building_type_id` INT NOT NULL ,
  `building_type_name` VARCHAR(45) NOT NULL ,
  `category_id` INT NULL ,
  PRIMARY KEY (`building_type_id`) ,
  INDEX `fk_building_category_id` (`category_id` ASC) ,
  CONSTRAINT `fk_building_category_id`
    FOREIGN KEY (`category_id` )
    REFERENCES `ARRA_DATA`.`Category` (`category_id` )
    ON DELETE NO ACTION
    ON UPDATE NO ACTION)
ENGINE = InnoDB;

```

```

-----
-- Table `ARRA_DATA`.`Commercial_rule_association`
-----

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Commercial_rule_association` (
  `building_type_id` INT NOT NULL ,
  `load_type_id` INT NOT NULL ,
  `rule_association_id` INT NOT NULL ,
  `value` DOUBLE NULL ,
  PRIMARY KEY (`building_type_id`, `load_type_id`, `rule_association_id`),
  INDEX `fk_commercial_rule_association_building_type_id` (`building_type_id` ASC),
  INDEX `fk_commercial_rule_association_load_type_id` (`load_type_id` ASC),
  INDEX `fk_commercial_rule_association_rule_association_id` (`rule_association_id` ASC),
  CONSTRAINT `fk_commercial_rule_association_building_type_id`
    FOREIGN KEY (`building_type_id`)
    REFERENCES `ARRA_DATA`.`Building_type` (`building_type_id`)
    ON DELETE NO ACTION
    ON UPDATE NO ACTION,
  CONSTRAINT `fk_commercial_rule_association_load_type_id`
    FOREIGN KEY (`load_type_id`)
    REFERENCES `ARRA_DATA`.`Load_type` (`load_type_id`)
    ON DELETE NO ACTION
    ON UPDATE NO ACTION,
  CONSTRAINT `fk_commercial_rule_association_rule_association_id`
    FOREIGN KEY (`rule_association_id`)
    REFERENCES `ARRA_DATA`.`Rule_associations` (`rule_association_id`)
    ON DELETE NO ACTION
    ON UPDATE NO ACTION)

```

```
ENGINE = InnoDB;
```

```
-- Table `ARRA_DATA`.`CEUS`
```

```
CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`CEUS` (
```

```
  `ceus_id` INT NOT NULL ,
```

```
  `ceus_code` INT NULL ,
```

```
  PRIMARY KEY (`ceus_id`))
```

```
ENGINE = InnoDB;
```

```
-- Table `ARRA_DATA`.`Commercial_load_type`
```

```
CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Commercial_load_type` (
```

```
  `building_type_id` INT NOT NULL ,
```

```
  `load_type_id` INT NOT NULL ,
```

```
  `ceus_id` INT NOT NULL ,
```

```
  `value` DOUBLE NULL ,
```

```
  PRIMARY KEY (`building_type_id`, `load_type_id`, `ceus_id`),
```

```
  INDEX `fk_commercial_load_type_building_type_id` (`building_type_id` ASC),
```

```
  INDEX `fk_commercial_load_type_load_type_id` (`load_type_id` ASC),
```

```
  INDEX `fk_commercial_load_type_ceus_id` (`ceus_id` ASC),
```

```
  CONSTRAINT `fk_commercial_load_type_building_type_id`
```

```
    FOREIGN KEY (`building_type_id` )
```

```
    REFERENCES `ARRA_DATA`.`Building_type` (`building_type_id` )
```

```

ON DELETE NO ACTION

ON UPDATE NO ACTION,

CONSTRAINT `fk_commercial_load_type_load_type_id`

FOREIGN KEY (`load_type_id` )

REFERENCES `ARRA_DATA`.`Load_type` (`load_type_id` )

ON DELETE NO ACTION

ON UPDATE NO ACTION,

CONSTRAINT `fk_commercial_load_type_ceus_id`

FOREIGN KEY (`ceus_id` )

REFERENCES `ARRA_DATA`.`CEUS` (`ceus_id` )

ON DELETE NO ACTION

ON UPDATE NO ACTION)

ENGINE = InnoDB;

```

```

-----

-- Table `ARRA_DATA`.`Commercial_norm_basis`

-----

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Commercial_norm_basis` (

  `building_type_id` INT NOT NULL ,

  `load_type_id` INT NOT NULL ,

  `floor_area` DOUBLE NULL ,

  PRIMARY KEY (`building_type_id`, `load_type_id`),

  INDEX `fk_commercial_norm_basis_building_type_id` (`building_type_id` ASC),

  INDEX `fk_commercial_norm_basis_load_type_id` (`load_type_id` ASC),

  CONSTRAINT `fk_commercial_norm_basis_building_type_id`

    FOREIGN KEY (`building_type_id` )

    REFERENCES `ARRA_DATA`.`Building_type` (`building_type_id` )

```

```

ON DELETE NO ACTION

ON UPDATE NO ACTION,

CONSTRAINT `fk_commercial_norm_basis_load_type_id`

FOREIGN KEY (`load_type_id` )

REFERENCES `ARRA_DATA`.`Load_type` (`load_type_id` )

ON DELETE NO ACTION

ON UPDATE NO ACTION)

ENGINE = InnoDB;

```

```

-----

-- Table `ARRA_DATA`.`Industrial`

-----

```

```

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Industrial` (

`rule_association_id` INT NOT NULL ,

`power` DOUBLE NULL ,

PRIMARY KEY (`rule_association_id` ) ,

INDEX `fk_industrial_rule_association_id` (`rule_association_id` ASC) ,

CONSTRAINT `fk_industrial_rule_association_id`

FOREIGN KEY (`rule_association_id` )

REFERENCES `ARRA_DATA`.`Rule_associations` (`rule_association_id` )

ON DELETE NO ACTION

ON UPDATE NO ACTION)

ENGINE = InnoDB;

```

```

-----

-- Table `ARRA_DATA`.`Agricultural`

-----

```

```

-----
CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Agricultural` (
  `rule_association_id` INT NOT NULL ,
  `power` DOUBLE NULL ,
  PRIMARY KEY (`rule_association_id`),
  INDEX `fk_agricultural_rule_association_id` (`rule_association_id` ASC),
  CONSTRAINT `fk_agricultural_rule_association_id`
    FOREIGN KEY (`rule_association_id` )
      REFERENCES `ARRA_DATA`.`Rule_associations` (`rule_association_id` )
    ON DELETE NO ACTION
    ON UPDATE NO ACTION)
ENGINE = InnoDB;

```

```

-----
-- Table `ARRA_DATA`.`Residential_building_load`
-----

```

```

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Residential_building_load` (
  `load_type_id` INT NOT NULL ,
  `rule_association_id` INT NOT NULL ,
  `building_type_id` INT NOT NULL ,
  `value` DOUBLE NULL ,
  PRIMARY KEY (`load_type_id`, `rule_association_id`, `building_type_id`),
  INDEX `fk_residential_building_load_load_type_id` (`load_type_id` ASC),
  INDEX `fk_residential_building_load_rule_association_id` (`rule_association_id` ASC),
  INDEX `fk_residential_building_load_building_type_id` (`building_type_id` ASC),
  CONSTRAINT `fk_residential_building_load_load_type_id`
    FOREIGN KEY (`load_type_id` )

```

```

REFERENCES `ARRA_DATA`.`Load_type` (`load_type_id` )

ON DELETE NO ACTION

ON UPDATE NO ACTION,

CONSTRAINT `fk_residential_building_load_rule_association_id`

FOREIGN KEY (`rule_association_id` )

REFERENCES `ARRA_DATA`.`Rule_associations` (`rule_association_id` )

ON DELETE NO ACTION

ON UPDATE NO ACTION,

CONSTRAINT `fk_residential_building_load_building_type_id`

FOREIGN KEY (`building_type_id` )

REFERENCES `ARRA_DATA`.`Building_type` (`building_type_id` )

ON DELETE NO ACTION

ON UPDATE NO ACTION)

ENGINE = InnoDB;

```

```

-- -----

-- Table `ARRA_DATA`.`Substation_area`

-- -----

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Substation_area` (

  `substation_area_id` INT NOT NULL ,

  `substation_area_name` VARCHAR(45) NULL ,

  PRIMARY KEY (`substation_area_id`))

ENGINE = InnoDB;

```

```

-- -----

-- Table `ARRA_DATA`.`Substation_composition`

```



```

-----

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Substation_composition` (

  `substation_area_id` INT NOT NULL ,

  `building_type_id` INT NOT NULL ,

  `value` DOUBLE NULL ,

  PRIMARY KEY (`substation_area_id`, `building_type_id`),

  INDEX `fk_substation_composition_substation_area_id` (`substation_area_id` ASC),

  INDEX `fk_substation_composition_building_type_id` (`building_type_id` ASC),

  CONSTRAINT `fk_substation_composition_substation_area_id`

    FOREIGN KEY (`substation_area_id` )

      REFERENCES `ARRA_DATA`.`Substation_area` (`substation_area_id` )

        ON DELETE NO ACTION

        ON UPDATE NO ACTION,

  CONSTRAINT `fk_substation_composition_building_type_id`

    FOREIGN KEY (`building_type_id` )

      REFERENCES `ARRA_DATA`.`Building_type` (`building_type_id` )

        ON DELETE NO ACTION

        ON UPDATE NO ACTION)

ENGINE = InnoDB;

```

```

-----

-- Table `ARRA_DATA`.`Mix_type`

-----

```

```

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Mix_type` (

  `mix_type_id` INT NOT NULL ,

  `mix_type_name` VARCHAR(45) NULL ,

  PRIMARY KEY (`mix_type_id`))

```

```
ENGINE = InnoDB;
```

```
-- Table `ARRA_DATA`.`Load_mix`
```

```
CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Load_mix` (  
  `mix_type_id` INT NOT NULL ,  
  `category_id` INT NOT NULL ,  
  `value` VARCHAR(45) NULL ,  
  PRIMARY KEY (`mix_type_id`, `category_id`),  
  INDEX `fk_load_mix_mix_type_id` (`mix_type_id` ASC) ,  
  INDEX `fk_load_mix_category_id` (`category_id` ASC) ,  
  CONSTRAINT `fk_load_mix_mix_type_id`  
    FOREIGN KEY (`mix_type_id` )  
    REFERENCES `ARRA_DATA`.`Mix_type` (`mix_type_id` )  
    ON DELETE NO ACTION  
    ON UPDATE NO ACTION,  
  CONSTRAINT `fk_load_mix_category_id`  
    FOREIGN KEY (`category_id` )  
    REFERENCES `ARRA_DATA`.`Category` (`category_id` )  
    ON DELETE NO ACTION  
    ON UPDATE NO ACTION)  
ENGINE = InnoDB;
```

```
-- Table `ARRA_DATA`.`Residential_basis`
```

```

-----
CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Residential_basis` (
  `time_period_id` INT NOT NULL ,
  `load_type_id` INT NOT NULL ,
  `climate_zone_id` INT NOT NULL ,
  `value` DOUBLE NULL ,
  PRIMARY KEY (`time_period_id`, `load_type_id`, `climate_zone_id`),
  INDEX `fk_residential_basis_time_period_id` (`time_period_id` ASC),
  INDEX `fk_residential_basis_load_type_id` (`load_type_id` ASC),
  INDEX `fk_residential_basis_climate_zone_id` (`climate_zone_id` ASC),
  CONSTRAINT `fk_residential_basis_time_period_id`
    FOREIGN KEY (`time_period_id`)
      REFERENCES `ARRA_DATA`.`Time_period` (`time_period_id`)
      ON DELETE NO ACTION
      ON UPDATE NO ACTION,
  CONSTRAINT `fk_residential_basis_load_type_id`
    FOREIGN KEY (`load_type_id`)
      REFERENCES `ARRA_DATA`.`Load_type` (`load_type_id`)
      ON DELETE NO ACTION
      ON UPDATE NO ACTION,
  CONSTRAINT `fk_residential_basis_climate_zone_id`
    FOREIGN KEY (`climate_zone_id`)
      REFERENCES `ARRA_DATA`.`Climate_zones` (`climate_zone_id`)
      ON DELETE NO ACTION
      ON UPDATE NO ACTION)
ENGINE = InnoDB;

```

```
-- Table `ARRA_DATA`.`SCommercial`
```

```
CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`SCommercial` (  
  `city_id` INT NOT NULL ,  
  `building_type_id` INT NOT NULL ,  
  `temperature_sensitivity` DOUBLE NULL ,  
  `zero_sensitivity_temperature` DOUBLE NULL ,  
  PRIMARY KEY (`city_id`, `building_type_id`),  
  INDEX `fk_scommercial_city_id` (`city_id` ASC) ,  
  INDEX `fk_building_type_id` (`building_type_id` ASC) ,  
  CONSTRAINT `fk_scommercial_city_id`  
    FOREIGN KEY (`city_id` )  
      REFERENCES `ARRA_DATA`.`City` (`city_id` )  
    ON DELETE NO ACTION  
    ON UPDATE NO ACTION,  
  CONSTRAINT `fk_building_type_id`  
    FOREIGN KEY (`building_type_id` )  
      REFERENCES `ARRA_DATA`.`Building_type` (`building_type_id` )  
    ON DELETE NO ACTION  
    ON UPDATE NO ACTION)  
ENGINE = InnoDB;
```

```
-- Table `ARRA_DATA`.`TMY_data`
```

```
CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`TMY_data` (
```

```

`city_id` INT NOT NULL ,

`year` INT NOT NULL ,

`month` INT NOT NULL ,

`day` INT NOT NULL ,

`time_interval_id` INT NOT NULL ,

`direct_normal_radiation` DOUBLE NULL ,

`diffuse_horizontal_radiation` DOUBLE NULL ,

`dry_bulb_temperature` DOUBLE NULL ,

`opaque_sky_cover` DOUBLE NULL ,

`relative_humidity` DOUBLE NULL ,

`wind_speed` DOUBLE NULL ,

PRIMARY KEY (`city_id`, `year`, `month`, `day`, `time_interval_id`),

INDEX `fk_TMY_data_city_id` (`city_id` ASC),

INDEX `fk_TMY_data_time_interval_id` (`time_interval_id` ASC),

CONSTRAINT `fk_TMY_data_city_id`

    FOREIGN KEY (`city_id`)

    REFERENCES `ARRA_DATA`.`City` (`city_id`)

    ON DELETE NO ACTION

    ON UPDATE NO ACTION,

CONSTRAINT `fk_TMY_data_time_interval_id`

    FOREIGN KEY (`time_interval_id`)

    REFERENCES `ARRA_DATA`.`Time_interval` (`time_interval_id`)

    ON DELETE NO ACTION

    ON UPDATE NO ACTION)

ENGINE = InnoDB;

```

-----

-- Table `ARRA\_DATA`.`SRP`

-----

CREATE TABLE IF NOT EXISTS `ARRA\_DATA`.`SRP` (

  `record\_date` DATETIME NOT NULL ,

  `rural` DOUBLE NULL ,

  `rural\_qc` CHAR(1) NULL ,

  `urban` DOUBLE NULL ,

  `urban\_qc` CHAR(1) NULL ,

  `residential` DOUBLE NULL ,

  `residential\_qc` CHAR(1) NULL ,

  `mixed` DOUBLE NULL ,

  `mixed\_qc` CHAR(1) NULL ,

  `commercial` DOUBLE NULL ,

  `commercial\_qc` CHAR(1) NULL ,

  `corblrecmair\_temperature` DOUBLE NULL ,

  `corblrecmair\_temperature\_qc` CHAR(1) NULL ,

  PRIMARY KEY (`record\_date`))

ENGINE = InnoDB;

-----

-- Table `ARRA\_DATA`.`Observation\_point`

-----

CREATE TABLE IF NOT EXISTS `ARRA\_DATA`.`Observation\_point` (

  `observation\_point\_id` INT NOT NULL ,

  `point\_id` INT NULL ,

  `station\_name` VARCHAR(45) NULL ,

  `description` VARCHAR(45) NULL ,

```

`voltage` VARCHAR(45) NULL ,
`device_type` VARCHAR(45) NULL ,
`unit` VARCHAR(45) NULL ,
PRIMARY KEY (`observation_point_id`)
ENGINE = InnoDB;

```

```

-----
-- Table `ARRA_DATA`.`BPA`
-----

```

```

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`BPA` (
  `record_date` DATETIME NOT NULL ,
  `observation_point_id` INT NOT NULL ,
  `value` VARCHAR(45) NULL ,
  PRIMARY KEY (`record_date`, `observation_point_id`),
  INDEX `fk_obs_point` (`observation_point_id` ASC),
  CONSTRAINT `fk_obs_point`
    FOREIGN KEY (`observation_point_id`)
      REFERENCES `ARRA_DATA`.`Observation_point` (`observation_point_id`)
    ON DELETE NO ACTION
    ON UPDATE NO ACTION)
ENGINE = InnoDB;

```

```

-----
-- Table `ARRA_DATA`.`Feeder`
-----

```

```

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Feeder` (

```

```

`feeder_id` INT NOT NULL ,

`feeder_name` VARCHAR(45) NULL ,

`rate` VARCHAR(45) NULL ,

PRIMARY KEY (`feeder_id` )

ENGINE = InnoDB;

```

```

-----
-- Table `ARRA_DATA`.`Idaho`
-----

```

```

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Idaho` (

`feeder_id` INT NOT NULL ,

`record_date` DATE NOT NULL ,

`time_interval_id` INT NOT NULL ,

`irr_kwh` DOUBLE NULL ,

`irr_count` INT NULL ,

`lcom_kwh` DOUBLE NULL ,

`lcom_count` INT NULL ,

`scom_kwh` DOUBLE NULL ,

`scom_count` INT NULL ,

`res_kwh` DOUBLE NULL ,

`res_count` INT NULL ,

`lighting_kwh` DOUBLE NULL ,

`lighting_count` INT NULL ,

PRIMARY KEY (`feeder_id`, `record_date`, `time_interval_id`),

INDEX `fk_feeder_id` (`feeder_id` ASC),

INDEX `fk_time_interval_id` (`time_interval_id` ASC),

CONSTRAINT `fk_feeder_id`

```



```

FOREIGN KEY (`feeder_id` )
REFERENCES `ARRA_DATA`.`Feeder` (`feeder_id` )
ON DELETE NO ACTION
ON UPDATE NO ACTION,
CONSTRAINT `fk_time_interval_id`
FOREIGN KEY (`time_interval_id` )
REFERENCES `ARRA_DATA`.`Time_interval` (`time_interval_id` )
ON DELETE NO ACTION
ON UPDATE NO ACTION)
ENGINE = InnoDB;

```

```

-----
-- Table `ARRA_DATA`.`PGE_meta`
-----

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`PGE_meta` (
  `pge_id` INT NOT NULL ,
  `pge_type` VARCHAR(45) NULL ,
  `pge_type_id` VARCHAR(45) NULL ,
  `voltage` VARCHAR(45) NULL ,
  PRIMARY KEY (`pge_id` )
ENGINE = InnoDB;

```

```

-----
-- Table `ARRA_DATA`.`PGE`
-----

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`PGE` (

```

```

`pge_id` INT NOT NULL ,

`record_date_time` VARCHAR(45) NOT NULL ,

`amp_a` DOUBLE NULL ,

`amp_b` DOUBLE NULL ,

`amp_c` DOUBLE NULL ,

`power` DOUBLE NULL ,

PRIMARY KEY (`pge_id`, `record_date_time`),

INDEX `fk_pge_id` (`pge_id` ASC),

CONSTRAINT `fk_pge_id`

FOREIGN KEY (`pge_id` )

REFERENCES `ARRA_DATA`.`PGE_meta` (`pge_id` )

ON DELETE NO ACTION

ON UPDATE NO ACTION)

ENGINE = InnoDB;

```

```

-----

-- Table `ARRA_DATA`.`PSE_meta`

-----

```

```

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`PSE_meta` (

`pse_id` INT NOT NULL ,

`pse_name` VARCHAR(45) NULL ,

PRIMARY KEY (`pse_id`))

ENGINE = InnoDB;

```

```

-----

-- Table `ARRA_DATA`.`PSE`

```

```

-----
CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`PSE` (
  `pse_id` INT NOT NULL ,
  `record_date_time` VARCHAR(45) NOT NULL ,
  `xfmr` DOUBLE NULL ,
  `temperature` DOUBLE NULL ,
  PRIMARY KEY (`pse_id`, `record_date_time`),
  INDEX `fk_pse_id` (`pse_id` ASC),
  CONSTRAINT `fk_pse_id`
    FOREIGN KEY (`pse_id`)
      REFERENCES `ARRA_DATA`.`PSE_meta` (`pse_id`)
    ON DELETE NO ACTION
    ON UPDATE NO ACTION)
ENGINE = InnoDB;

```

```

-----
-- Table `ARRA_DATA`.`Idaho_scada`
-----

```

```

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Idaho_scada` (
  `feeder_id` INT NOT NULL ,
  `record_date` VARCHAR(45) NOT NULL ,
  `time_interval_id` INT NOT NULL ,
  `scada_data` DOUBLE NULL ,
  PRIMARY KEY (`feeder_id`, `record_date`, `time_interval_id`),
  INDEX `fk_idaho_scada_feeder_id` (`feeder_id` ASC),
  INDEX `fk_idaho_time_interval_id` (`time_interval_id` ASC),
  CONSTRAINT `fk_idaho_scada_feeder_id`

```

```

FOREIGN KEY (`feeder_id` )
REFERENCES `ARRA_DATA`.`Feeder` (`feeder_id` )
ON DELETE NO ACTION
ON UPDATE NO ACTION,
CONSTRAINT `fk_idaho_time_interval_id`
FOREIGN KEY (`time_interval_id` )
REFERENCES `ARRA_DATA`.`Time_interval` (`time_interval_id` )
ON DELETE NO ACTION
ON UPDATE NO ACTION)
ENGINE = InnoDB;

```

```

-----
-- Table `ARRA_DATA`.`Idaho_temperature_windspeed`
-----

CREATE TABLE IF NOT EXISTS `ARRA_DATA`.`Idaho_temperature_windspeed` (
  `feeder_id` INT NOT NULL ,
  `record_date` VARCHAR(45) NOT NULL ,
  `temperature` DOUBLE NULL ,
  `windspeed` DOUBLE NULL ,
  PRIMARY KEY (`feeder_id`, `record_date`),
  INDEX `fk_idaho_temp_wind_feeder` (`feeder_id` ASC),
  CONSTRAINT `fk_idaho_temp_wind_feeder`
    FOREIGN KEY (`feeder_id` )
    REFERENCES `ARRA_DATA`.`Feeder` (`feeder_id` )
    ON DELETE NO ACTION
    ON UPDATE NO ACTION)
ENGINE = InnoDB;

```

```
SET SQL_MODE=@OLD_SQL_MODE;  
SET FOREIGN_KEY_CHECKS=@OLD_FOREIGN_KEY_CHECKS;  
SET UNIQUE_CHECKS=@OLD_UNIQUE_CHECKS;
```

## Appendix C

### Database Entity Tables

**Table C-1.** Entity Category

Attributes	Explanation
category_id	ID of a category
category_name	The name of a category

**Table C-2.** Entity CEUS

Attributes	Explanation
ceus_id	ID of a CEUS code
ceus_code	The code of CEUS

**Table C-3.** Entity City

Attributes	Explanation
city_id	ID of a city
city_name	The name of a city, such as Seattle
latitude	The latitude of a city
state	The state where a city is located
climate_zone_id	The ID of a climate zone that the city is located
representative_flag	The city is a representative city of that climate zone or not

**Table C-4.** Entity Climate\_zones

Attributes	Explanation
climate_zone_id	ID of a climate zone
climate_zone_name	The name of a climate zone
abbr_id	The abbreviation ID of a climate zone
hour_index	The hour index of a climate zone

**Table C-5. Entity Building\_type**

Attributes	Explanation
building_type_id	ID of a building type
building_type_name	The name of a building type, such as small office
category_id	The category of a building type

**Table C-6. Entity Load\_type**

Attributes	Explanation
load_type_id	ID of a load type
load_type_name	The name of a load type, such as cooking, plugs, etc.

**Table C-7. Entity Mix\_type**

Attributes	Explanation
mix_type_id	ID of a mixture type
mix_type_name	The name of a mixture type, such as RES, COM, etc.

**Table C-8. Entity Rule\_associations**

Attributes	Explanation
rule_association_id	ID of a rule association
rule_association_name	The type of a rule association

**Table C-9. Entity Substation\_area**

Attributes	Explanation
substation_area_id	ID of a substation area
substation_area_name	The name of a substation area

**Table C-10. Entity Time\_interval**

Attributes	Explanation
time_interval_id	ID of a time interval
begin_time	The start time of a time interval
end_time	The end time of a time interval

**Table C-11. Entity Time\_period**

Attributes	Explanation
time_period_id	ID of a time period
time_period_name	The name of a time period

**Table C-12.** Entity Agricultural

Attributes	Explanation
rule_association_id	ID of a load type
power	The power of a load type in agriculture

**Table C-13.** Entity City\_info

Attributes	Explanation
city_id	ID of a city
load_type_id	ID of a load type
value	The value of a load type for a city

**Table C-14.** Entity Commercial\_load\_type

Attributes	Explanation
building_type_id	ID of a building type
load_type_id	ID of a load type
ceus_id	ID of a CEUS code
value	The value of data for a building type, load type, and a CEUS code

**Table C-15.** Entity Commercial\_norm\_basis

Attributes	Explanation
building_type_id	ID of a building type
load_type_id	ID of a load type
floor_area	The floor area of a load type for a certain building type

**Table C-16.** Entity Commercial\_rule\_association

Attributes	Explanation
building_type_id	ID of a building type
load_type_id	ID of a load type
rule_association_id	ID of a rule association
value	The value of rule association regarding a certain load type and building type



**Table C-17.** Entity Event\_data

Attributes	Explanation
city_id	ID of a city
time_interval_id	ID of a time interval
record_date	The date of the event
temperature	The temperature property of the event
wind	The wind property of the event
humidity	The humidity property of the event
clouds	The cloud property of the event
diffuse_solar	The diffuse_solar property of the event
direct_solar	The direct_solar property of the event
load_scada	The load_scada property of the event

**Table C-18.** Entity Industrial

Attributes	Explanation
rule_association_id	ID of a rule association
Power	The power of the corresponding load type

**Table C-18.** Entity Load\_mix

Attributes	Explanation
mix_type_id	ID of the mixture type
category_id	ID of the category
value	The proportion of each category for a mixture type

**Table C-20.** Entity Residential\_basis

Attributes	Explanation
time_period_id	ID of a time period
load_type_id	ID of a load type
climate_zone_id	ID of a climate zone
value	The value of residential basis for a time period with a certain load type and a climate zone

**Table C-21.** Entity Residential\_building\_load

Attributes	Explanation
load_type_id	ID of a load type
rule_association_id	ID of a rule association
building_type_id	ID of a building type
Value	The value for a load type with regarding to a rule association and a building type

**Table C-22.** Entity Residential\_Load\_Shape

Attributes	Explanation
time_period_id	ID of a time period
load_type_id	ID of a load type
time_interval_id	ID of a time interval
load_value	The load value for a load type at a certain time interval during a certain time period

**Table C-23.** Entity SCommercial

Attributes	Explanation
city_id	ID of a city
building_type_id	ID of a building type
temperature_sensitivity	The slope of temperature T
zero_sensitivity_temperature	The current temperature of T with zero sensitivity

**Table C-24.** Entity Substation\_composition

Attributes	Explanation
substation_area_id	ID of a substitution area
building_type_id	ID of a building type
Value	The value of a building type in a certain substitution area

**Table C-25.** Entity TMY\_data

Attributes	Explanation
city_id	ID of a city
year	The year information of the TMY data
month	The month information of the TMY data
day	The day information of the TMY data
time_interval_id	ID of a time interval
direct_normal_radiation	Direct normal radiation [Wh/m <sup>2</sup> ]
diffuse_horizontal_radiation	Diffuse horizontal radiation [Wh/m <sup>2</sup> ]
dry_bulb_temperature	Dry bulb temperature [1/10 °C]
opaque_sky_cover	Opaque sky cover
relative_humidity	Relative humidity [%]
wind_speed	Wind speed

**Table C-26. Entity Observation\_Point**

Attributes	Explanation
observation_point_id	ID of an observation_point
point_id	ID of a point
station_name	The name of the observation station
description	The description of the observation station
voltage	The voltage related to the observation station
device_type	The type of the device
unit	The unit used by the observation points

**Table C-27. Entity BPA**

Attributes	Explanation
record_date	The date of the observation
observation_point_id	ID of an observation point
value	The value of power load on a specified date for an observation_point_id

**Table C-28. Entity Feeder**

Attributes	Explanation
feeder_id	ID of a feeder
feeder_name	The name of a feeder
Rate	The rate associated with a feeder

**Table C-29. Entity Idaho**

Attributes	Explanation
feeder_id	ID of a feeder
record_date	The record date of the utility data
time_interval_id	ID of a time interval
irr_kwh	irr value of the utility data
irr_count	The count of irr
lcom_kwh	lcom value of the utility data
lcom_count	The count of lcom
scom_kwh	scom value of the utility data
scom_count	The count of scom
res_kwh	res value of the utility data
res_count	The count of res
lighting_kwh	Lighting value of the utility data
lighting_count	The count of lighting

**Table C-30. Entity Idaho\_scada**

Attributes	Explanation
feeder_id	ID of a feeder
record_date	The record date of the utility data
time_interval_id	ID of a time interval
scada_data	The SCADA data related to Idaho utility data

**Table C-31. Entity Idaho\_temperature\_windspeed**

Attributes	Explanation
feeder_id	ID of a feeder
record_date	The record date of the utility data
temperature	The temperature of the utility data
windspeed	The wind speed of the utility data

**Table C-32. Entity PGE**

Attributes	Explanation
pge_id	ID of pge
record_date_time	The record date and time of the PGE data
amp_a	amp_a value of the PGE data
amp_b	amp_b value of the PGE data
amp_c	amp_c value of the PGE data
Power	Power of the PGE data

**Table C-33. Entity PGE\_meta**

Attributes	Explanation
pge_id	ID of pge
pge_type	The type of pge data
page_type_id	The id of the pge type
voltage	The voltage related to the pge

**Table C-34. Entity PSE**

Attributes	Explanation
pse_id	ID of pse
record_date_time	The record date and time of the pse data
xfmr	xfmr of the pse data
temperature	The temperature of the pse data

**Table C-35.** Entity PSE\_meta

Attributes	Explanation
pse_id	ID of pse
pse_name	The name of pse

**Table C-36.** Entity SRP

Attributes	Explanation
record_date	The record date of srp data
rural	The power of rural part of srp data
rural_qc	The quality of rural
urban	The power of urban part of srp data
urban_qc	The quality of urban
residential	The power of residential part of srp data
residential_qc	The quality of residential
mixed	The power of mixed part of srp data
mixed_qc	The quality of mixed
commercial	The power of commercial part of srp data
commercial_qc	The quality of commercial
corblrecmair_temperature	The power of corblrecmair_temperature part of srp data
corblrecmair_temperature_qc	The quality of corblrecmair_temperature

## Appendix D

### Equations of the Single-Phase Motor Phasor Model

Equations of the single-phase motor phasor model [2]:

$$\begin{aligned}
 |V_s| &= \left( r_{ds} + j \frac{\omega_s}{\omega_b} X'_{ds} \right) (I_{ds}^R + j I_{ds}^I) + j \frac{\omega_s X_m}{\omega_b X_r} (\Psi_{dr}^R + j \Psi_{dr}^I) \\
 |V_s| &= \left( r_{qs} + j \frac{\omega_s}{\omega_b} X'_{qs} + j \frac{\omega_b}{\omega_s} X_c \right) (I_{qs}^R + j I_{qs}^I) + j \frac{n \omega_s X_m}{\omega_b X_r} (\Psi_{qr}^R + j \Psi_{qr}^I) \\
 \begin{bmatrix} \Psi_f^R + j \Psi_f^I \\ \Psi_b^R + j \Psi_b^I \end{bmatrix} &= \frac{1}{2} \begin{bmatrix} 1 & -j \\ 1 & j \end{bmatrix} \begin{bmatrix} \Psi_{dr}^R + j \Psi_{dr}^I \\ \Psi_{qr}^R + j \Psi_{qr}^I \end{bmatrix} \\
 \begin{bmatrix} \Psi_{dr}^R + j \Psi_{dr}^I \\ \Psi_{qr}^R + j \Psi_{qr}^I \end{bmatrix} &= \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix} \begin{bmatrix} \Psi_f^R + j \Psi_f^I \\ \Psi_b^R + j \Psi_b^I \end{bmatrix} \\
 \begin{bmatrix} I_f^R + j I_f^I \\ I_b^R + j I_b^I \end{bmatrix} &= \frac{1}{2} \begin{bmatrix} 1 & -jn \\ 1 & jn \end{bmatrix} \begin{bmatrix} I_{ds}^R + j I_{ds}^I \\ I_{qs}^R + j I_{qs}^I \end{bmatrix} \\
 \begin{bmatrix} I_{ds}^R + j I_{ds}^I \\ I_{qs}^R + j I_{qs}^I \end{bmatrix} &= \begin{bmatrix} 1 & 1 \\ \frac{j}{n} & -\frac{j}{n} \end{bmatrix} \begin{bmatrix} I_f^R + j I_f^I \\ I_b^R + j I_b^I \end{bmatrix} \\
 T_0' \frac{d}{dt} (\Psi_f^R + j \Psi_f^I) &= X_m (I_f^R + j I_f^I) - (sat(\Psi_f, \Psi_b) + j(\omega_s - \omega_r) T_0') (\Psi_f^R + j \Psi_f^I) \\
 (\Psi_b^R + j \Psi_b^I) &= \frac{X_m (I_b^R + j I_b^I)}{(sat(\Psi_f, \Psi_b) + j(\omega_s + \omega_r) T_0')} \\
 \frac{2H}{\omega_b} \frac{d\omega_r}{dt} &= \frac{2X_m}{X_r} (I_f^R \Psi_f^R - I_f^I \Psi_f^I - I_b^I \Psi_b^R + I_b^R \Psi_b^I) - T_{mech} \\
 I_s &= \left[ (I_{ds}^R + j I_{ds}^I) + (I_{qs}^R + j I_{qs}^I) \right] e^{j\phi} \\
 \Psi &= \sqrt{(\Psi_f^R)^2 + (\Psi_f^I)^2 + (\Psi_b^R)^2 + (\Psi_b^I)^2} \\
 sat(\Psi_f, \Psi_b) &= \begin{cases} 1 & \text{if } \Psi \leq b_{sat} \\ 1 + A_{sat} (\Psi - b_{sat})^2 & \text{if } \Psi > b_{sat} \end{cases}
 \end{aligned}$$

where:

Variable	Definition
$v_{as}$	stator main winding voltage
$v_{bs}$	stator auxiliary winding voltage
$i_{as}$	stator main winding current
$i_{bs}$	stator auxiliary winding current
$\lambda_{as}$	stator main winding flux
$\lambda_{bs}$	stator auxiliary winding flux
$i_{ar}$	rotor main winding current
$i_{br}$	rotor auxiliary winding current
$\lambda_{ar}$	rotor main winding flux
$\lambda_{br}$	rotor auxiliary winding flux
$\theta$	rotor angle
$\omega_r$	rotor speed
$\omega_s$	frequency of the applied voltage
$\omega_b$	base speed
$I_f$ or $I_b$	forward and backward rotating field components of the current
$\Psi_f$ or $\Psi_b$	forward and backward rotating field components of the flux

## Appendix E

### Temperature Sensitivity Table for Commercial

	$y=k(T-T_k)$	$k*1000$	$T_k$
Seattle, WA	Small office	0.89	35.4
	Large office	-0.82	96.5
	Retail	1.92	56.4
	Lodging	-1.21	83.0
	Grocery	2.13	64.4
	Restaurant	2.30	43.3
	School	-4.01	98.4
	Health	1.58	91.4
Portland, OR	Small office	1.04	38.2
	Large office	-6.46	74.7
	Retail	4.11	58.7
	Lodging	-1.45	68.9
	Grocery	1.17	59.4
	Restaurant	7.15	58.1
	School	-4.83	82.2
	Health	-0.67	32.1
Spokane, WA	Small office	0.37	-30.9
	Large office	-0.87	109.8
	Retail	1.19	38.4
	Lodging	-1.79	93.6
	Grocery	2.50	70.8
	Restaurant	0.63	-57.8
	School	-3.01	111.5
	Health	0.43	102.2
Helena, MT	Small office	0.15	73.8
	Large office	-2.49	96.0
	Retail	1.28	56.4
	Lodging	-0.36	105.7
	Grocery	1.20	65.4
	Restaurant	2.55	53.4
	School	-1.88	105.9
	Health	0.54	115.2



	$y=k(T-T_k)$	$k*1000$	$T_k$
San Francisco, CA	Small office	1.17	37.6
	Large office	-0.41	102.5
	Retail	2.79	61.1
	Lodging	0.34	72.4
	Grocery	2.86	68.7
	Restaurant	3.35	53.2
	School	-8.21	93.9
	Health	1.68	88.2
Sacramento, CA	Small office	1.42	42.2
	Large office	0.29	59.1
	Retail	3.14	60.5
	Lodging	-2.59	86.7
	Grocery	3.10	69.2
	Restaurant	4.88	56.3
	School	-5.34	106.3
	Health	1.11	95.5
Medford, OR	Small office	0.67	15.1
	Large office	-0.12	150.2
	Retail	1.32	42.2
	Lodging	-0.81	103.6
	Grocery	2.40	69.3
	Restaurant	1.39	10.3
	School	-4.68	108.0
	Health	0.91	102.1
San Diego CA	Small office	0.48	-13.1
	Large office	0.30	78.7
	Retail	3.12	60.7
	Lodging	-5.26	80.8
	Grocery	2.91	71.4
	Restaurant	4.28	51.2
	School	1.93	68.5
	Health	1.64	88.1
Los Angeles, CA	Small office	1.10	40.1
	Large office	-0.63	97.9
	Retail	2.44	58.2
	Lodging	-1.09	81.4
	Grocery	2.64	65.9
	Restaurant	3.17	48.8
	School	-1.93	116.0
	Health	0.90	101.0
Bakersfield, CA	Small office	0.43	-34.9
	Large office	0.18	71.1
	Retail	0.91	7.7
	Lodging	-1.35	97.8
	Grocery	2.97	75.7
	Restaurant	3.95	55.9
	School	0.11	-306.6
	Health	0.62	104.1

	$y=k(T-T_k)$	$k*1000$	$T_k$
Phoenix, AZ	Small office	0.76	24.2
	Large office	0.14	60.6
	Retail	0.02	-3086.6
	Lodging	0.05	-165.5
	Grocery	2.59	74.1
	Restaurant	1.23	-24.4
	School	-0.90	147.8
	Health	0.30	114.0
Reno, NV	Small office	0.57	19.6
	Large office	-2.29	99.3
	Retail	2.00	59.7
	Lodging	-1.05	89.4
	Grocery	2.07	68.0
	Restaurant	3.09	48.1
	School	-3.03	105.6
	Health	0.18	192.2

## Appendix F

### Load Composition Model - Climate Zone Study Results

Load Composition Model Climate- Zone Studies Results for PSLF input:

Climate Zone	Load Mix	Res	Com	Ind	Agr	Study Type	Hour	PSLF LID	Motor A	Motor B	Motor C	Motor D	Power Electronic	DG	Static PF	Static P Re-sistive	Static P Current	Static P Power	Static Q Re-actance	Static Q Current	Static Q Power	Check P Total
NWC	RES	0.74	0.24	0.00	0.02	1	15	NWC_RES	0.10	0.07	0.07	0.44	0.14	0.00	1.00	0.13	0.05	0.00	0.00	0.01	0.00	1.00
NWC	COM	0.19	0.74	0.05	0.02	1	15	NWC_COM	0.30	0.09	0.08	0.12	0.20	0.00	0.98	0.07	0.14	0.00	0.01	0.03	0.00	1.00
NWC	MIX	0.44	0.49	0.05	0.02	1	15	NWC_MIX	0.20	0.08	0.08	0.26	0.17	0.00	0.99	0.10	0.10	0.00	0.01	0.02	0.00	1.00
NWC	RAG	0.39	0.20	0.15	0.25	1	15	NWC_RAG	0.10	0.07	0.17	0.23	0.17	0.00	1.00	0.09	0.16	0.00	0.00	0.01	0.00	1.00
NWV	RES	0.73	0.25	0.00	0.02	1	15	NWV_RES	0.09	0.08	0.05	0.53	0.13	0.00	0.99	0.07	0.06	0.00	0.00	0.01	0.00	1.00
NWV	COM	0.18	0.74	0.05	0.02	1	15	NWV_COM	0.27	0.09	0.07	0.13	0.20	0.00	0.98	0.06	0.17	0.00	0.01	0.04	0.00	1.00
NWV	MIX	0.43	0.50	0.05	0.02	1	15	NWV_MIX	0.18	0.09	0.06	0.31	0.17	0.00	0.98	0.06	0.12	0.00	0.01	0.02	0.00	1.00
NWV	RAG	0.38	0.21	0.16	0.26	1	15	NWV_RAG	0.10	0.08	0.16	0.27	0.17	0.00	1.00	0.05	0.17	0.00	0.00	0.01	0.00	1.00
NWI	RES	0.73	0.24	0.00	0.02	1	15	NWI_RES	0.10	0.08	0.04	0.54	0.12	0.00	0.99	0.07	0.05	0.00	0.00	0.01	0.00	1.00
NWI	COM	0.19	0.74	0.05	0.02	1	15	NWI_COM	0.31	0.09	0.08	0.14	0.20	0.00	0.98	0.05	0.15	0.00	0.01	0.03	0.00	1.00
NWI	MIX	0.43	0.50	0.05	0.02	1	15	NWI_MIX	0.21	0.09	0.06	0.32	0.16	0.00	0.98	0.06	0.10	0.00	0.01	0.02	0.00	1.00
NWI	RAG	0.38	0.21	0.15	0.26	1	15	NWI_RAG	0.11	0.08	0.16	0.28	0.16	0.00	1.00	0.05	0.16	0.00	0.00	0.01	0.00	1.00
RMN	RES	0.74	0.24	0.00	0.02	1	16	RMN_RES	0.09	0.07	0.08	0.40	0.15	0.00	1.00	0.16	0.06	0.00	0.00	0.01	0.00	1.00
RMN	COM	0.19	0.74	0.05	0.02	1	16	RMN_COM	0.28	0.09	0.08	0.10	0.20	0.00	0.97	0.06	0.18	0.00	0.01	0.04	0.00	1.00
RMN	MIX	0.44	0.49	0.05	0.02	1	16	RMN_MIX	0.19	0.09	0.08	0.24	0.18	0.00	0.99	0.11	0.12	0.00	0.01	0.03	0.00	1.00
RMN	RAG	0.39	0.20	0.15	0.26	1	16	RMN_RAG	0.10	0.08	0.17	0.21	0.17	0.00	1.00	0.10	0.17	0.00	0.00	0.01	0.00	1.00
NCC	RES	0.74	0.24	0.00	0.02	1	15	NCC_RES	0.10	0.07	0.07	0.46	0.15	0.00	1.00	0.11	0.05	0.00	0.00	0.01	0.00	1.00
NCC	COM	0.19	0.74	0.05	0.02	1	15	NCC_COM	0.30	0.09	0.08	0.12	0.20	0.00	0.98	0.07	0.14	0.00	0.01	0.03	0.00	1.00
NCC	MIX	0.44	0.49	0.05	0.02	1	15	NCC_MIX	0.20	0.08	0.08	0.27	0.18	0.00	0.99	0.09	0.10	0.00	0.01	0.02	0.00	1.00
NCC	RAG	0.39	0.20	0.15	0.26	1	15	NCC_RAG	0.10	0.07	0.17	0.24	0.17	0.00	1.00	0.08	0.16	0.00	0.00	0.01	0.00	1.00
NCV	RES	0.73	0.24	0.00	0.02	1	15	NCV_RES	0.09	0.08	0.04	0.57	0.12	0.00	0.99	0.04	0.05	0.00	0.00	0.01	0.00	1.00
NCV	COM	0.19	0.74	0.05	0.02	1	15	NCV_COM	0.29	0.09	0.08	0.15	0.20	0.00	0.98	0.05	0.14	0.00	0.01	0.03	0.00	1.00
NCV	MIX	0.43	0.50	0.05	0.02	1	15	NCV_MIX	0.20	0.09	0.06	0.33	0.16	0.00	0.98	0.05	0.10	0.00	0.01	0.02	0.00	1.00
NCV	RAG	0.38	0.21	0.15	0.26	1	15	NCV_RAG	0.10	0.08	0.16	0.30	0.16	0.00	1.00	0.04	0.16	0.00	0.00	0.01	0.00	1.00
NCI	RES	0.74	0.24	0.00	0.02	1	15	NCI_RES	0.10	0.08	0.05	0.54	0.13	0.00	0.99	0.06	0.05	0.00	0.00	0.01	0.00	1.00
NCI	COM	0.19	0.74	0.05	0.02	1	15	NCI_COM	0.30	0.09	0.08	0.14	0.20	0.00	0.98	0.05	0.14	0.00	0.01	0.03	0.00	1.00
NCI	MIX	0.44	0.49	0.05	0.02	1	15	NCI_MIX	0.20	0.09	0.07	0.32	0.17	0.00	0.99	0.06	0.10	0.00	0.01	0.02	0.00	1.00

Climate Zone	Load Mix	Res	Com	Ind	Agr	Study Type	Hour	PSLF LID	Motor A	Motor B	Motor C	Motor D	Power Elec- tronic	DG	Static PF	Static P Re- sistive	Static P Cur- rent	Static P Power	Static Q Re- actance	Static Q Cur- rent	Static Q Power	Check P Total
NCI	RAG	0.39	0.20	0.15	0.26	1	15	NCI_RAG	0.10	0.08	0.16	0.28	0.16	0.00	1.00	0.05	0.16	0.00	0.00	0.01	0.00	1.00
SCC	RES	0.74	0.24	0.00	0.02	1	16	SCC_RES	0.08	0.07	0.07	0.43	0.15	0.00	1.00	0.13	0.06	0.00	0.00	0.01	0.00	1.00
SCC	COM	0.19	0.74	0.05	0.02	1	16	SCC_COM	0.26	0.10	0.08	0.11	0.20	0.00	0.98	0.08	0.17	0.00	0.01	0.04	0.00	1.00
SCC	MIX	0.44	0.49	0.05	0.02	1	16	SCC_MIX	0.18	0.09	0.08	0.26	0.18	0.00	0.99	0.10	0.12	0.00	0.01	0.03	0.00	1.00
SCC	RAG	0.39	0.20	0.15	0.26	1	16	SCC_RAG	0.09	0.08	0.17	0.23	0.18	0.00	1.00	0.09	0.17	0.00	0.00	0.01	0.00	1.00
SCV	RES	0.73	0.25	0.00	0.02	1	16	SCV_RES	0.10	0.08	0.05	0.50	0.14	0.00	0.99	0.08	0.05	0.00	0.00	0.01	0.00	1.00
SCV	COM	0.19	0.74	0.05	0.02	1	16	SCV_COM	0.30	0.09	0.08	0.13	0.20	0.00	0.98	0.06	0.15	0.00	0.01	0.03	0.00	1.00
SCV	MIX	0.43	0.50	0.05	0.02	1	16	SCV_MIX	0.21	0.09	0.07	0.29	0.17	0.00	0.99	0.07	0.11	0.00	0.01	0.02	0.00	1.00
SCV	RAG	0.38	0.21	0.16	0.26	1	16	SCV_RAG	0.11	0.08	0.16	0.26	0.17	0.00	1.00	0.06	0.16	0.00	0.00	0.01	0.00	1.00
SCI	RES	0.73	0.25	0.00	0.02	1	16	SCI_RES	0.08	0.09	0.04	0.56	0.12	0.00	0.99	0.05	0.06	0.00	0.00	0.01	0.00	1.00
SCI	COM	0.19	0.74	0.05	0.02	1	16	SCI_COM	0.26	0.10	0.07	0.14	0.20	0.00	0.98	0.06	0.17	0.00	0.01	0.04	0.00	1.00
SCI	MIX	0.43	0.50	0.05	0.02	1	16	SCI_MIX	0.18	0.10	0.06	0.33	0.16	0.00	0.98	0.06	0.12	0.00	0.01	0.02	0.00	1.00
SCI	RAG	0.38	0.21	0.16	0.26	1	16	SCI_RAG	0.09	0.08	0.16	0.29	0.16	0.00	1.00	0.05	0.17	0.00	0.00	0.01	0.00	1.00
DSW	RES	0.74	0.24	0.00	0.02	1	16	DSW_RES	0.08	0.09	0.03	0.59	0.11	0.00	0.99	0.03	0.06	0.00	0.00	0.01	0.00	1.00
DSW	COM	0.19	0.74	0.05	0.02	1	16	DSW_COM	0.26	0.10	0.07	0.15	0.19	0.00	0.98	0.06	0.17	0.00	0.01	0.04	0.00	1.00
DSW	MIX	0.43	0.50	0.05	0.02	1	16	DSW_MIX	0.17	0.10	0.06	0.35	0.16	0.00	0.98	0.05	0.12	0.00	0.01	0.02	0.00	1.00
DSW	RAG	0.38	0.21	0.15	0.26	1	16	DSW_RAG	0.09	0.09	0.15	0.31	0.15	0.00	1.00	0.04	0.17	0.00	0.00	0.01	0.00	1.00
HID	RES	0.73	0.25	0.00	0.02	1	16	HID_RES	0.10	0.09	0.04	0.57	0.11	0.00	0.99	0.04	0.05	0.00	0.00	0.01	0.00	1.00
HID	COM	0.18	0.75	0.05	0.02	1	16	HID_COM	0.31	0.09	0.07	0.14	0.19	0.00	0.98	0.04	0.15	0.00	0.01	0.03	0.00	1.00
HID	MIX	0.42	0.51	0.05	0.02	1	16	HID_MIX	0.21	0.09	0.06	0.33	0.16	0.00	0.98	0.04	0.11	0.00	0.01	0.02	0.00	1.00
HID	RAG	0.37	0.21	0.16	0.26	1	16	HID_RAG	0.11	0.08	0.16	0.29	0.16	0.00	1.00	0.04	0.17	0.00	0.00	0.01	0.00	1.00
NWC	RES	0.75	0.23	0.00	0.02	2	15	NWC_RES	0.09	0.07	0.06	0.46	0.14	0.00	1.00	0.13	0.05	0.00	0.00	0.01	0.00	1.00
NWC	COM	0.20	0.73	0.05	0.02	2	15	NWC_COM	0.30	0.09	0.08	0.12	0.20	0.00	0.98	0.07	0.14	0.00	0.01	0.03	0.00	1.00
NWC	MIX	0.45	0.48	0.05	0.02	2	15	NWC_MIX	0.20	0.08	0.08	0.27	0.17	0.00	0.99	0.10	0.10	0.00	0.01	0.02	0.00	1.00
NWC	RAG	0.40	0.20	0.15	0.25	2	15	NWC_RAG	0.10	0.07	0.17	0.24	0.17	0.00	1.00	0.09	0.16	0.00	0.00	0.01	0.00	1.00
NWV	RES	0.75	0.23	0.00	0.02	2	15	NWV_RES	0.08	0.08	0.04	0.55	0.12	0.00	0.99	0.06	0.05	0.00	0.00	0.01	0.00	1.00
NWV	COM	0.20	0.73	0.05	0.02	2	15	NWV_COM	0.26	0.09	0.07	0.15	0.20	0.00	0.98	0.06	0.16	0.00	0.01	0.04	0.00	1.00
NWV	MIX	0.45	0.48	0.05	0.02	2	15	NWV_MIX	0.18	0.09	0.06	0.33	0.17	0.00	0.98	0.06	0.11	0.00	0.01	0.02	0.00	1.00
NWV	RAG	0.40	0.20	0.15	0.25	2	15	NWV_RAG	0.09	0.08	0.15	0.29	0.16	0.00	1.00	0.05	0.16	0.00	0.00	0.01	0.00	1.00
NWI	RES	0.75	0.23	0.00	0.02	2	15	NWI_RES	0.09	0.08	0.04	0.56	0.12	0.00	0.99	0.06	0.05	0.00	0.00	0.01	0.00	1.00
NWI	COM	0.20	0.73	0.05	0.02	2	15	NWI_COM	0.30	0.09	0.07	0.15	0.19	0.00	0.98	0.05	0.14	0.00	0.01	0.03	0.00	1.00
NWI	MIX	0.45	0.48	0.05	0.02	2	15	NWI_MIX	0.20	0.09	0.06	0.33	0.16	0.00	0.98	0.06	0.10	0.00	0.01	0.02	0.00	1.00
NWI	RAG	0.40	0.20	0.15	0.25	2	15	NWI_RAG	0.10	0.08	0.15	0.30	0.16	0.00	1.00	0.05	0.16	0.00	0.00	0.01	0.00	1.00
RMN	RES	0.75	0.23	0.00	0.02	2	16	RMN_RES	0.08	0.07	0.07	0.42	0.14	0.00	1.00	0.15	0.06	0.00	0.00	0.01	0.00	1.00
RMN	COM	0.20	0.73	0.05	0.02	2	16	RMN_COM	0.27	0.09	0.08	0.11	0.20	0.00	0.97	0.06	0.18	0.00	0.01	0.04	0.00	1.00
RMN	MIX	0.45	0.48	0.05	0.02	2	16	RMN_MIX	0.18	0.09	0.08	0.25	0.17	0.00	0.99	0.11	0.12	0.00	0.01	0.03	0.00	1.00
RMN	RAG	0.40	0.20	0.15	0.25	2	16	RMN_RAG	0.10	0.08	0.17	0.22	0.17	0.00	1.00	0.10	0.17	0.00	0.00	0.01	0.00	1.00
NCC	RES	0.75	0.23	0.00	0.02	2	15	NCC_RES	0.09	0.07	0.07	0.47	0.14	0.00	1.00	0.11	0.05	0.00	0.00	0.01	0.00	1.00
NCC	COM	0.20	0.73	0.05	0.02	2	15	NCC_COM	0.30	0.09	0.08	0.13	0.20	0.00	0.98	0.06	0.14	0.00	0.01	0.03	0.00	1.00
NCC	MIX	0.45	0.48	0.05	0.02	2	15	NCC_MIX	0.20	0.08	0.08	0.28	0.17	0.00	0.99	0.09	0.10	0.00	0.01	0.02	0.00	1.00
NCC	RAG	0.40	0.20	0.15	0.25	2	15	NCC_RAG	0.10	0.07	0.17	0.25	0.17	0.00	1.00	0.08	0.16	0.00	0.00	0.01	0.00	1.00
NCV	RES	0.75	0.23	0.00	0.02	2	15	NCV_RES	0.09	0.09	0.04	0.59	0.12	0.00	0.99	0.04	0.05	0.00	0.00	0.01	0.00	1.00
NCV	COM	0.20	0.73	0.05	0.02	2	15	NCV_COM	0.29	0.09	0.07	0.16	0.19	0.00	0.98	0.05	0.14	0.00	0.01	0.03	0.00	1.00
NCV	MIX	0.45	0.48	0.05	0.02	2	15	NCV_MIX	0.19	0.09	0.06	0.35	0.16	0.00	0.98	0.05	0.10	0.00	0.01	0.02	0.00	1.00
NCV	RAG	0.40	0.20	0.15	0.25	2	15	NCV_RAG	0.10	0.08	0.15	0.31	0.16	0.00	1.00	0.04	0.16	0.00	0.00	0.01	0.00	1.00
NCI	RES	0.75	0.23	0.00	0.02	2	15	NCI_RES	0.09	0.08	0.04	0.55	0.13	0.00	0.99	0.06	0.05	0.00	0.00	0.01	0.00	1.00
NCI	COM	0.20	0.73	0.05	0.02	2	15	NCI_COM	0.30	0.09	0.08	0.15	0.20	0.00	0.98	0.05	0.14	0.00	0.01	0.03	0.00	1.00

Climate Zone	Load Mix	Res	Com	Ind	Agr	Study Type	Hour	PSLF LID	Moto r A	Motor B	Motor C	Motor D	Power Elec- tronic	DG	Static PF	Static P	Static P	Static P Power	Static Q	Static Q	Static Q	Check P Total
																Re- sistive	Cur- rent		Re- actance	Cur- rent	Power	
NCI	MIX	0.45	0.48	0.05	0.02	2	15	NCI_MIX	0.20	0.09	0.06	0.33	0.16	0.00	0.99	0.06	0.10	0.00	0.01	0.02	0.00	1.00
NCI	RAG	0.40	0.20	0.15	0.25	2	15	NCI_RAG	0.10	0.08	0.15	0.29	0.16	0.00	1.00	0.05	0.16	0.00	0.00	0.01	0.00	1.00
SCC	RES	0.75	0.23	0.00	0.02	2	16	SCC_RES	0.08	0.07	0.07	0.45	0.15	0.00	1.00	0.13	0.06	0.00	0.00	0.01	0.00	1.00
SCC	COM	0.20	0.73	0.05	0.02	2	16	SCC_COM	0.26	0.10	0.08	0.12	0.20	0.00	0.98	0.08	0.17	0.00	0.01	0.04	0.00	1.00
SCC	MIX	0.45	0.48	0.05	0.02	2	16	SCC_MIX	0.17	0.09	0.08	0.27	0.18	0.00	0.99	0.10	0.12	0.00	0.01	0.02	0.00	1.00
SCC	RAG	0.40	0.20	0.15	0.25	2	16	SCC_RAG	0.09	0.08	0.17	0.24	0.17	0.00	1.00	0.09	0.16	0.00	0.00	0.01	0.00	1.00
SCV	RES	0.75	0.23	0.00	0.02	2	16	SCV_RES	0.09	0.08	0.05	0.52	0.14	0.00	0.99	0.07	0.05	0.00	0.00	0.01	0.00	1.00
SCV	COM	0.20	0.73	0.05	0.02	2	16	SCV_COM	0.30	0.09	0.08	0.14	0.19	0.00	0.98	0.06	0.15	0.00	0.01	0.03	0.00	1.00
SCV	MIX	0.45	0.48	0.05	0.02	2	16	SCV_MIX	0.20	0.09	0.07	0.31	0.17	0.00	0.99	0.06	0.10	0.00	0.01	0.02	0.00	1.00
SCV	RAG	0.40	0.20	0.15	0.25	2	16	SCV_RAG	0.10	0.08	0.16	0.28	0.17	0.00	1.00	0.06	0.16	0.00	0.00	0.01	0.00	1.00
SCI	RES	0.75	0.23	0.00	0.02	2	16	SCI_RES	0.08	0.09	0.04	0.58	0.11	0.00	0.99	0.05	0.06	0.00	0.00	0.01	0.00	1.00
SCI	COM	0.20	0.73	0.05	0.02	2	16	SCI_COM	0.25	0.10	0.07	0.15	0.19	0.00	0.98	0.06	0.17	0.00	0.01	0.04	0.00	1.00
SCI	MIX	0.45	0.48	0.05	0.02	2	16	SCI_MIX	0.17	0.10	0.06	0.35	0.16	0.00	0.98	0.05	0.11	0.00	0.01	0.02	0.00	1.00
SCI	RAG	0.40	0.20	0.15	0.25	2	16	SCI_RAG	0.09	0.09	0.15	0.31	0.16	0.00	1.00	0.04	0.16	0.00	0.00	0.01	0.00	1.00
DSW	RES	0.75	0.23	0.00	0.02	2	16	DSW_RES	0.08	0.09	0.03	0.61	0.11	0.00	0.99	0.03	0.06	0.00	0.00	0.01	0.00	1.00
DSW	COM	0.20	0.73	0.05	0.02	2	16	DSW_COM	0.25	0.10	0.07	0.16	0.19	0.00	0.98	0.06	0.17	0.00	0.01	0.04	0.00	1.00
DSW	MIX	0.45	0.48	0.05	0.02	2	16	DSW_MIX	0.17	0.10	0.05	0.36	0.15	0.00	0.98	0.05	0.11	0.00	0.01	0.02	0.00	1.00
DSW	RAG	0.40	0.20	0.15	0.25	2	16	DSW_RAG	0.09	0.09	0.15	0.32	0.15	0.00	1.00	0.04	0.16	0.00	0.00	0.01	0.00	1.00
HID	RES	0.75	0.23	0.00	0.02	2	16	HID_RES	0.09	0.09	0.03	0.59	0.11	0.00	0.99	0.04	0.05	0.00	0.00	0.01	0.00	1.00
HID	COM	0.20	0.73	0.05	0.02	2	16	HID_COM	0.30	0.09	0.07	0.16	0.19	0.00	0.98	0.04	0.15	0.00	0.01	0.03	0.00	1.00
HID	MIX	0.45	0.48	0.05	0.02	2	16	HID_MIX	0.20	0.09	0.06	0.36	0.15	0.00	0.98	0.04	0.10	0.00	0.01	0.02	0.00	1.00
HID	RAG	0.40	0.20	0.15	0.25	2	16	HID_RAG	0.10	0.08	0.15	0.32	0.15	0.00	1.00	0.04	0.16	0.00	0.00	0.01	0.00	1.00
NWC	RES	0.72	0.26	0.00	0.02	3	15	NWC_RES	0.10	0.07	0.07	0.41	0.15	0.00	1.00	0.14	0.05	0.00	0.00	0.01	0.00	1.00
NWC	COM	0.18	0.75	0.05	0.02	3	15	NWC_COM	0.31	0.09	0.08	0.10	0.20	0.00	0.98	0.07	0.15	0.00	0.01	0.03	0.00	1.00
NWC	MIX	0.41	0.51	0.05	0.02	3	15	NWC_MIX	0.21	0.08	0.08	0.24	0.18	0.00	0.99	0.10	0.11	0.00	0.01	0.02	0.00	1.00
NWC	RAG	0.36	0.21	0.16	0.26	3	15	NWC_RAG	0.11	0.07	0.17	0.21	0.18	0.00	1.00	0.09	0.17	0.00	0.00	0.01	0.00	1.00
NWV	RES	0.68	0.29	0.00	0.03	3	15	NWV_RES	0.10	0.08	0.05	0.47	0.14	0.00	0.99	0.08	0.07	0.00	0.00	0.01	0.00	1.00
NWV	COM	0.15	0.78	0.05	0.02	3	15	NWV_COM	0.28	0.09	0.08	0.10	0.21	0.00	0.98	0.06	0.17	0.00	0.01	0.04	0.00	1.00
NWV	MIX	0.37	0.55	0.06	0.02	3	15	NWV_MIX	0.20	0.09	0.07	0.25	0.18	0.00	0.98	0.07	0.13	0.00	0.01	0.03	0.00	1.00
NWV	RAG	0.32	0.23	0.17	0.28	3	15	NWV_RAG	0.10	0.08	0.17	0.22	0.18	0.00	1.00	0.06	0.18	0.00	0.00	0.01	0.00	1.00
NWI	RES	0.69	0.28	0.00	0.02	3	15	NWI_RES	0.11	0.08	0.05	0.49	0.13	0.00	0.99	0.08	0.06	0.00	0.00	0.01	0.00	1.00
NWI	COM	0.16	0.77	0.05	0.02	3	15	NWI_COM	0.32	0.09	0.08	0.11	0.20	0.00	0.98	0.05	0.15	0.00	0.01	0.03	0.00	1.00
NWI	MIX	0.38	0.54	0.06	0.02	3	15	NWI_MIX	0.23	0.09	0.07	0.27	0.17	0.00	0.98	0.06	0.11	0.00	0.01	0.02	0.00	1.00
NWI	RAG	0.34	0.22	0.17	0.28	3	15	NWI_RAG	0.11	0.08	0.17	0.24	0.17	0.00	1.00	0.06	0.17	0.00	0.00	0.01	0.00	1.00
RMN	RES	0.72	0.26	0.00	0.02	3	16	RMN_RES	0.10	0.07	0.08	0.36	0.16	0.00	1.00	0.17	0.07	0.00	0.00	0.01	0.00	1.00
RMN	COM	0.17	0.76	0.05	0.02	3	16	RMN_COM	0.28	0.09	0.08	0.09	0.21	0.00	0.97	0.07	0.18	0.00	0.01	0.04	0.00	1.00
RMN	MIX	0.41	0.52	0.05	0.02	3	16	RMN_MIX	0.20	0.08	0.09	0.20	0.18	0.00	0.99	0.11	0.13	0.00	0.01	0.03	0.00	1.00
RMN	RAG	0.36	0.21	0.16	0.27	3	16	RMN_RAG	0.10	0.07	0.18	0.18	0.18	0.00	1.00	0.11	0.18	0.00	0.00	0.01	0.00	1.00
NCC	RES	0.71	0.26	0.00	0.02	3	15	NCC_RES	0.10	0.07	0.08	0.42	0.16	0.00	1.00	0.12	0.06	0.00	0.00	0.01	0.00	1.00
NCC	COM	0.17	0.76	0.05	0.02	3	15	NCC_COM	0.31	0.09	0.08	0.10	0.21	0.00	0.98	0.07	0.15	0.00	0.01	0.03	0.00	1.00
NCC	MIX	0.40	0.52	0.05	0.02	3	15	NCC_MIX	0.21	0.08	0.08	0.24	0.18	0.00	0.99	0.09	0.11	0.00	0.01	0.02	0.00	1.00
NCC	RAG	0.36	0.21	0.16	0.27	3	15	NCC_RAG	0.11	0.07	0.18	0.21	0.18	0.00	1.00	0.08	0.17	0.00	0.00	0.01	0.00	1.00
NCV	RES	0.70	0.28	0.00	0.02	3	15	NCV_RES	0.11	0.08	0.04	0.53	0.13	0.00	0.99	0.05	0.06	0.00	0.00	0.01	0.00	1.00
NCV	COM	0.16	0.76	0.05	0.02	3	15	NCV_COM	0.30	0.09	0.08	0.12	0.20	0.00	0.98	0.05	0.15	0.00	0.01	0.03	0.00	1.00
NCV	MIX	0.39	0.53	0.06	0.02	3	15	NCV_MIX	0.22	0.09	0.07	0.30	0.17	0.00	0.98	0.05	0.11	0.00	0.01	0.02	0.00	1.00
NCV	RAG	0.34	0.22	0.16	0.27	3	15	NCV_RAG	0.11	0.08	0.17	0.26	0.17	0.00	1.00	0.04	0.17	0.00	0.00	0.01	0.00	1.00
NCI	RES	0.71	0.26	0.00	0.02	3	15	NCI_RES	0.10	0.08	0.05	0.51	0.14	0.00	0.99	0.07	0.06	0.00	0.00	0.01	0.00	1.00

Climate Zone	Load Mix	Res	Com	Ind	Agr	Study Type	Hour	PSLF LID	Motor A	Motor B	Motor C	Motor D	Power Elec- tronic	DG	Static PF	Static P Re- sistive	Static P Cur- rent	Static P Power	Static Q Re- actance	Static Q Cur- rent	Static Q Power	Check P Total
NCI	COM	0.17	0.76	0.05	0.02	3	15	NCI_COM	0.31	0.09	0.08	0.12	0.20	0.00	0.98	0.05	0.15	0.00	0.01	0.03	0.00	1.00
NCI	MIX	0.40	0.52	0.05	0.02	3	15	NCI_MIX	0.21	0.09	0.07	0.29	0.17	0.00	0.99	0.06	0.11	0.00	0.01	0.02	0.00	1.00
NCI	RAG	0.36	0.21	0.16	0.27	3	15	NCI_RAG	0.11	0.08	0.17	0.25	0.17	0.00	1.00	0.05	0.17	0.00	0.00	0.01	0.00	1.00
SCC	RES	0.71	0.27	0.00	0.02	3	16	SCC_RES	0.09	0.07	0.08	0.39	0.16	0.00	1.00	0.15	0.06	0.00	0.00	0.01	0.00	1.00
SCC	COM	0.17	0.76	0.05	0.02	3	16	SCC_COM	0.27	0.10	0.08	0.09	0.21	0.00	0.98	0.08	0.17	0.00	0.01	0.04	0.00	1.00
SCC	MIX	0.40	0.52	0.05	0.02	3	16	SCC_MIX	0.19	0.09	0.08	0.22	0.19	0.00	0.99	0.11	0.13	0.00	0.01	0.03	0.00	1.00
SCC	RAG	0.35	0.22	0.16	0.27	3	16	SCC_RAG	0.10	0.07	0.18	0.19	0.18	0.00	1.00	0.09	0.18	0.00	0.00	0.01	0.00	1.00
SCV	RES	0.68	0.29	0.00	0.03	3	16	SCV_RES	0.12	0.07	0.06	0.44	0.16	0.00	0.99	0.09	0.06	0.00	0.00	0.01	0.00	1.00
SCV	COM	0.15	0.77	0.05	0.02	3	16	SCV_COM	0.31	0.09	0.08	0.10	0.20	0.00	0.98	0.06	0.15	0.00	0.01	0.03	0.00	1.00
SCV	MIX	0.37	0.55	0.06	0.02	3	16	SCV_MIX	0.23	0.08	0.08	0.24	0.18	0.00	0.99	0.07	0.12	0.00	0.01	0.02	0.00	1.00
SCV	RAG	0.32	0.23	0.17	0.28	3	16	SCV_RAG	0.11	0.08	0.18	0.21	0.18	0.00	1.00	0.06	0.18	0.00	0.00	0.01	0.00	1.00
SCI	RES	0.69	0.28	0.00	0.02	3	16	SCI_RES	0.10	0.09	0.04	0.52	0.13	0.00	0.99	0.06	0.07	0.00	0.00	0.01	0.00	1.00
SCI	COM	0.16	0.77	0.05	0.02	3	16	SCI_COM	0.27	0.10	0.07	0.12	0.20	0.00	0.98	0.06	0.18	0.00	0.01	0.04	0.00	1.00
SCI	MIX	0.38	0.54	0.06	0.02	3	16	SCI_MIX	0.19	0.10	0.07	0.29	0.17	0.00	0.98	0.06	0.13	0.00	0.01	0.03	0.00	1.00
SCI	RAG	0.34	0.22	0.17	0.28	3	16	SCI_RAG	0.10	0.08	0.17	0.25	0.17	0.00	1.00	0.05	0.18	0.00	0.00	0.01	0.00	1.00
DSW	RES	0.70	0.28	0.00	0.02	3	16	DSW_RES	0.09	0.09	0.04	0.56	0.12	0.00	0.99	0.04	0.07	0.00	0.00	0.01	0.00	1.00
DSW	COM	0.16	0.76	0.05	0.02	3	16	DSW_COM	0.26	0.10	0.07	0.13	0.20	0.00	0.98	0.06	0.17	0.00	0.01	0.04	0.00	1.00
DSW	MIX	0.39	0.53	0.06	0.02	3	16	DSW_MIX	0.19	0.10	0.06	0.31	0.16	0.00	0.98	0.05	0.13	0.00	0.01	0.03	0.00	1.00
DSW	RAG	0.34	0.22	0.16	0.27	3	16	DSW_RAG	0.10	0.09	0.16	0.27	0.16	0.00	1.00	0.04	0.18	0.00	0.00	0.01	0.00	1.00
HID	RES	0.66	0.31	0.00	0.03	3	16	HID_RES	0.12	0.08	0.05	0.50	0.13	0.00	0.99	0.05	0.07	0.00	0.00	0.01	0.00	1.00
HID	COM	0.14	0.78	0.05	0.02	3	16	HID_COM	0.32	0.09	0.08	0.11	0.20	0.00	0.98	0.05	0.16	0.00	0.01	0.03	0.00	1.00
HID	MIX	0.35	0.57	0.06	0.02	3	16	HID_MIX	0.24	0.09	0.07	0.27	0.17	0.00	0.98	0.05	0.12	0.00	0.01	0.02	0.00	1.00
HID	RAG	0.30	0.23	0.17	0.29	3	16	HID_RAG	0.12	0.08	0.17	0.23	0.17	0.00	1.00	0.04	0.18	0.00	0.00	0.01	0.00	1.00
NWC	RES	0.73	0.24	0.00	0.03	4	15	NWC_RES	0.09	0.06	0.09	0.34	0.17	0.00	1.00	0.19	0.06	0.00	0.00	0.01	0.00	1.00
NWC	COM	0.18	0.72	0.07	0.03	4	15	NWC_COM	0.28	0.09	0.09	0.08	0.22	0.00	0.98	0.07	0.17	0.00	0.01	0.04	0.00	1.00
NWC	MIX	0.42	0.49	0.07	0.03	4	15	NWC_MIX	0.19	0.08	0.09	0.19	0.19	0.00	0.99	0.12	0.12	0.00	0.01	0.03	0.00	1.00
NWC	RAG	0.33	0.18	0.18	0.31	4	15	NWC_RAG	0.09	0.07	0.20	0.15	0.19	0.00	1.00	0.11	0.19	0.00	0.00	0.01	0.00	1.00
NWV	RES	0.65	0.31	0.00	0.04	4	15	NWV_RES	0.08	0.07	0.08	0.34	0.19	0.00	0.99	0.14	0.10	0.00	0.01	0.02	0.00	1.00
NWV	COM	0.13	0.76	0.08	0.03	4	15	NWV_COM	0.21	0.10	0.08	0.07	0.24	0.00	0.97	0.06	0.24	0.00	0.02	0.06	0.00	1.00
NWV	MIX	0.33	0.55	0.09	0.03	4	15	NWV_MIX	0.16	0.09	0.08	0.17	0.22	0.00	0.98	0.09	0.18	0.00	0.01	0.04	0.00	1.00
NWV	RAG	0.24	0.19	0.21	0.35	4	15	NWV_RAG	0.08	0.08	0.21	0.13	0.20	0.00	1.00	0.08	0.23	0.00	0.00	0.01	0.00	1.00
NWI	RES	0.59	0.36	0.00	0.04	4	15	NWI_RES	0.14	0.07	0.07	0.32	0.18	0.00	0.99	0.14	0.09	0.00	0.01	0.02	0.00	1.00
NWI	COM	0.11	0.79	0.07	0.03	4	15	NWI_COM	0.31	0.09	0.08	0.06	0.22	0.00	0.97	0.05	0.19	0.00	0.01	0.04	0.00	1.00
NWI	MIX	0.28	0.60	0.08	0.03	4	15	NWI_MIX	0.24	0.09	0.09	0.15	0.20	0.00	0.98	0.08	0.15	0.00	0.01	0.03	0.00	1.00
NWI	RAG	0.21	0.21	0.21	0.36	4	15	NWI_RAG	0.11	0.07	0.21	0.11	0.19	0.00	1.00	0.07	0.22	0.00	0.00	0.01	0.00	1.00
RMN	RES	0.65	0.33	0.00	0.03	4	16	RMN_RES	0.12	0.07	0.09	0.29	0.17	0.00	1.00	0.18	0.08	0.00	0.01	0.02	0.00	1.00
RMN	COM	0.13	0.79	0.06	0.02	4	16	RMN_COM	0.30	0.09	0.08	0.06	0.21	0.00	0.97	0.06	0.19	0.00	0.02	0.05	0.00	1.00
RMN	MIX	0.33	0.58	0.06	0.02	4	16	RMN_MIX	0.22	0.09	0.09	0.15	0.20	0.00	0.99	0.11	0.15	0.00	0.01	0.03	0.00	1.00
RMN	RAG	0.29	0.24	0.18	0.30	4	16	RMN_RAG	0.11	0.07	0.20	0.13	0.19	0.00	1.00	0.10	0.20	0.00	0.00	0.01	0.00	1.00
NCC	RES	0.78	0.20	0.00	0.03	4	15	NCC_RES	0.05	0.06	0.10	0.36	0.18	0.00	1.00	0.19	0.07	0.00	0.00	0.01	0.00	1.00
NCC	COM	0.22	0.67	0.08	0.03	4	15	NCC_COM	0.19	0.09	0.09	0.10	0.23	0.00	0.98	0.08	0.21	0.00	0.02	0.05	0.00	1.00
NCC	MIX	0.48	0.42	0.07	0.03	4	15	NCC_MIX	0.12	0.08	0.10	0.22	0.20	0.00	0.99	0.13	0.14	0.00	0.01	0.03	0.00	1.00
NCC	RAG	0.35	0.15	0.19	0.31	4	15	NCC_RAG	0.07	0.07	0.20	0.17	0.19	0.00	1.00	0.11	0.19	0.00	0.00	0.01	0.00	1.00
NCV	RES	0.66	0.30	0.00	0.05	4	15	NCV_RES	0.08	0.06	0.09	0.34	0.19	0.00	0.99	0.14	0.10	0.00	0.01	0.02	0.00	1.00
NCV	COM	0.14	0.74	0.09	0.04	4	15	NCV_COM	0.21	0.10	0.09	0.07	0.24	0.00	0.97	0.06	0.24	0.00	0.02	0.05	0.00	1.00
NCV	MIX	0.34	0.53	0.10	0.04	4	15	NCV_MIX	0.15	0.09	0.09	0.18	0.22	0.00	0.98	0.09	0.18	0.00	0.01	0.04	0.00	1.00
NCV	RAG	0.23	0.17	0.23	0.38	4	15	NCV_RAG	0.08	0.07	0.22	0.12	0.20	0.00	1.00	0.07	0.23	0.00	0.00	0.01	0.00	1.00

Climate Zone	Load Mix	Res	Com	Ind	Agr	Study Type	Hour	PSLF LID	Motor A	Motor B	Motor C	Motor D	Power Elec- tronic	DG	Static PF	Static P Re- sistive	Static P Cur- rent	Static P Power	Static Q Re- actance	Static Q Cur- rent	Static Q Power	Check P Total
NCI	RES	0.72	0.24	0.00	0.04	4	15	NCI_RES	0.06	0.06	0.09	0.36	0.18	0.00	1.00	0.17	0.08	0.00	0.01	0.02	0.00	1.00
NCI	COM	0.18	0.71	0.08	0.03	4	15	NCI_COM	0.20	0.10	0.08	0.09	0.23	0.00	0.97	0.07	0.22	0.00	0.02	0.05	0.00	1.00
NCI	MIX	0.41	0.47	0.08	0.03	4	15	NCI_MIX	0.14	0.09	0.09	0.20	0.21	0.00	0.99	0.11	0.16	0.00	0.01	0.03	0.00	1.00
NCI	RAG	0.30	0.16	0.20	0.34	4	15	NCI_RAG	0.07	0.07	0.21	0.15	0.20	0.00	1.00	0.09	0.21	0.00	0.00	0.01	0.00	1.00
SCC	RES	0.76	0.22	0.00	0.03	4	16	SCC_RES	0.05	0.06	0.10	0.34	0.18	0.00	1.00	0.20	0.07	0.00	0.01	0.02	0.00	1.00
SCC	COM	0.21	0.70	0.07	0.03	4	16	SCC_COM	0.19	0.10	0.08	0.09	0.23	0.00	0.97	0.08	0.22	0.00	0.02	0.05	0.00	1.00
SCC	MIX	0.46	0.45	0.07	0.03	4	16	SCC_MIX	0.12	0.09	0.09	0.21	0.20	0.00	0.99	0.14	0.15	0.00	0.01	0.03	0.00	1.00
SCC	RAG	0.36	0.17	0.18	0.30	4	16	SCC_RAG	0.07	0.07	0.20	0.16	0.19	0.00	1.00	0.11	0.19	0.00	0.00	0.01	0.00	1.00
SCV	RES	0.77	0.20	0.00	0.03	4	16	SCV_RES	0.05	0.06	0.08	0.39	0.17	0.00	1.00	0.17	0.07	0.00	0.01	0.02	0.00	1.00
SCV	COM	0.22	0.68	0.08	0.03	4	16	SCV_COM	0.18	0.10	0.08	0.11	0.23	0.00	0.97	0.08	0.22	0.00	0.02	0.05	0.00	1.00
SCV	MIX	0.47	0.43	0.07	0.03	4	16	SCV_MIX	0.12	0.09	0.09	0.24	0.20	0.00	0.99	0.12	0.15	0.00	0.01	0.03	0.00	1.00
SCV	RAG	0.35	0.15	0.19	0.31	4	16	SCV_RAG	0.07	0.07	0.20	0.18	0.19	0.00	1.00	0.10	0.20	0.00	0.00	0.01	0.00	1.00
SCI	RES	0.59	0.37	0.00	0.05	4	16	SCI_RES	0.09	0.07	0.09	0.29	0.19	0.00	0.99	0.14	0.12	0.00	0.01	0.03	0.00	1.00
SCI	COM	0.10	0.78	0.08	0.03	4	16	SCI_COM	0.21	0.11	0.08	0.05	0.24	0.00	0.97	0.06	0.25	0.00	0.02	0.06	0.00	1.00
SCI	MIX	0.27	0.60	0.09	0.04	4	16	SCI_MIX	0.17	0.10	0.09	0.14	0.22	0.00	0.98	0.09	0.20	0.00	0.02	0.04	0.00	1.00
SCI	RAG	0.20	0.20	0.23	0.38	4	16	SCI_RAG	0.09	0.08	0.22	0.10	0.20	0.00	1.00	0.07	0.24	0.00	0.01	0.02	0.00	1.00
DSW	RES	0.47	0.47	0.00	0.06	4	16	DSW_RES	0.10	0.08	0.08	0.24	0.21	0.00	0.98	0.11	0.17	0.00	0.01	0.04	0.00	1.00
DSW	COM	0.07	0.82	0.08	0.03	4	16	DSW_COM	0.18	0.11	0.07	0.04	0.26	0.00	0.97	0.05	0.28	0.00	0.02	0.07	0.00	1.00
DSW	MIX	0.19	0.66	0.10	0.04	4	16	DSW_MIX	0.15	0.11	0.08	0.10	0.24	0.00	0.97	0.08	0.24	0.00	0.02	0.06	0.00	1.00
DSW	RAG	0.14	0.22	0.24	0.41	4	16	DSW_RAG	0.08	0.08	0.23	0.07	0.21	0.00	1.00	0.06	0.27	0.00	0.01	0.02	0.00	1.00
HID	RES	0.57	0.38	0.00	0.05	4	16	HID_RES	0.10	0.07	0.08	0.29	0.19	0.00	0.99	0.13	0.13	0.00	0.01	0.03	0.00	1.00
HID	COM	0.10	0.78	0.09	0.03	4	16	HID_COM	0.21	0.11	0.08	0.05	0.24	0.00	0.97	0.06	0.25	0.00	0.02	0.06	0.00	1.00
HID	MIX	0.26	0.60	0.10	0.04	4	16	HID_MIX	0.17	0.10	0.09	0.13	0.22	0.00	0.98	0.09	0.20	0.00	0.02	0.05	0.00	1.00
HID	RAG	0.18	0.19	0.24	0.39	4	16	HID_RAG	0.08	0.08	0.23	0.09	0.20	0.00	1.00	0.07	0.25	0.00	0.00	0.01	0.00	1.00
NWC	RES	0.97	0.02	0.00	0.01	5	15	NWC_RES	0.01	0.02	0.03	0.33	0.05	0.00	1.00	0.56	0.01	0.00	0.00	0.00	0.00	1.00
NWC	COM	0.71	0.19	0.07	0.03	5	15	NWC_COM	0.07	0.05	0.06	0.24	0.11	0.00	1.00	0.42	0.06	0.00	0.00	0.01	0.00	1.00
NWC	MIX	0.88	0.07	0.04	0.02	5	15	NWC_MIX	0.03	0.03	0.04	0.29	0.07	0.00	1.00	0.51	0.03	0.00	0.00	0.00	0.00	1.00
NWC	RAG	0.69	0.03	0.10	0.17	5	15	NWC_RAG	0.02	0.03	0.11	0.23	0.09	0.00	1.00	0.41	0.09	0.00	0.00	0.00	0.00	1.00
NWV	RES	0.96	0.04	0.00	0.01	5	15	NWV_RES	0.01	0.01	0.02	0.31	0.03	0.00	1.00	0.61	0.01	0.00	0.00	0.00	0.00	1.00
NWV	COM	0.64	0.29	0.05	0.02	5	15	NWV_COM	0.05	0.05	0.04	0.21	0.11	0.00	1.00	0.43	0.11	0.00	0.01	0.02	0.00	1.00
NWV	MIX	0.85	0.11	0.03	0.01	5	15	NWV_MIX	0.02	0.03	0.03	0.28	0.06	0.00	1.00	0.55	0.04	0.00	0.00	0.01	0.00	1.00
NWV	RAG	0.73	0.05	0.08	0.14	5	15	NWV_RAG	0.02	0.03	0.08	0.24	0.07	0.00	1.00	0.47	0.08	0.00	0.00	0.00	0.00	1.00
NWI	RES	0.97	0.02	0.00	0.01	5	15	NWI_RES	0.00	0.01	0.01	0.31	0.02	0.00	1.00	0.65	0.01	0.00	0.00	0.00	0.00	1.00
NWI	COM	0.75	0.20	0.04	0.01	5	15	NWI_COM	0.03	0.04	0.03	0.24	0.08	0.00	1.00	0.52	0.07	0.00	0.01	0.02	0.00	1.00
NWI	MIX	0.90	0.07	0.02	0.01	5	15	NWI_MIX	0.01	0.02	0.01	0.29	0.03	0.00	1.00	0.61	0.03	0.00	0.00	0.01	0.00	1.00
NWI	RAG	0.81	0.03	0.06	0.10	5	15	NWI_RAG	0.01	0.02	0.06	0.26	0.05	0.00	1.00	0.55	0.06	0.00	0.00	0.00	0.00	1.00
RMN	RES	0.96	0.03	0.00	0.00	5	16	RMN_RES	0.01	0.01	0.01	0.30	0.02	0.00	1.00	0.64	0.01	0.00	0.00	0.00	0.00	1.00
RMN	COM	0.70	0.27	0.02	0.01	5	16	RMN_COM	0.06	0.04	0.03	0.22	0.09	0.00	1.00	0.48	0.09	0.00	0.01	0.02	0.00	1.00
RMN	MIX	0.88	0.10	0.01	0.01	5	16	RMN_MIX	0.02	0.02	0.01	0.27	0.04	0.00	1.00	0.59	0.04	0.00	0.00	0.01	0.00	1.00
RMN	RAG	0.85	0.05	0.04	0.07	5	16	RMN_RAG	0.02	0.02	0.04	0.26	0.04	0.00	1.00	0.57	0.05	0.00	0.00	0.00	0.00	1.00
NCC	RES	0.96	0.02	0.00	0.01	5	15	NCC_RES	0.01	0.02	0.06	0.32	0.08	0.00	1.00	0.50	0.01	0.00	0.00	0.00	0.00	1.00
NCC	COM	0.68	0.20	0.09	0.04	5	15	NCC_COM	0.06	0.05	0.08	0.23	0.14	0.00	1.00	0.37	0.07	0.00	0.00	0.01	0.00	1.00
NCC	MIX	0.86	0.07	0.05	0.02	5	15	NCC_MIX	0.02	0.04	0.07	0.29	0.10	0.00	1.00	0.45	0.03	0.00	0.00	0.00	0.00	1.00
NCC	RAG	0.64	0.03	0.13	0.21	5	15	NCC_RAG	0.02	0.04	0.15	0.21	0.12	0.00	1.00	0.34	0.11	0.00	0.00	0.00	0.00	1.00
NCV	RES	0.91	0.07	0.00	0.02	5	15	NCV_RES	0.01	0.02	0.05	0.31	0.08	0.00	1.00	0.50	0.03	0.00	0.00	0.01	0.00	1.00
NCV	COM	0.45	0.42	0.09	0.04	5	15	NCV_COM	0.07	0.08	0.07	0.16	0.17	0.00	0.99	0.28	0.16	0.00	0.01	0.04	0.00	1.00
NCV	MIX	0.72	0.20	0.06	0.02	5	15	NCV_MIX	0.04	0.05	0.06	0.25	0.12	0.00	1.00	0.41	0.08	0.00	0.01	0.02	0.00	1.00

Climate Zone	Load Mix	Res	Com	Ind	Agr	Study Type	Hour	PSLF LID	Motor A	Motor B	Motor C	Motor D	Power Elec- tronic	DG	Static PF	Static P Re- sistive	Static P Cur- rent	Static P Power	Static Q Re- actance	Static Q Cur- rent	Static Q Power	Check P Total
NCV	RAG	0.52	0.07	0.15	0.26	5	15	NCV_RAG	0.03	0.05	0.16	0.18	0.13	0.00	1.00	0.30	0.15	0.00	0.00	0.01	0.00	1.00
NCI	RES	0.96	0.03	0.00	0.01	5	15	NCI_RES	0.00	0.01	0.02	0.31	0.04	0.00	1.00	0.60	0.01	0.00	0.00	0.00	0.00	1.00
NCI	COM	0.68	0.26	0.05	0.02	5	15	NCI_COM	0.04	0.05	0.04	0.22	0.11	0.00	1.00	0.44	0.10	0.00	0.01	0.02	0.00	1.00
NCI	MIX	0.87	0.10	0.03	0.01	5	15	NCI_MIX	0.02	0.03	0.03	0.28	0.06	0.00	1.00	0.55	0.04	0.00	0.00	0.01	0.00	1.00
NCI	RAG	0.74	0.04	0.08	0.14	5	15	NCI_RAG	0.02	0.03	0.09	0.24	0.08	0.00	1.00	0.47	0.08	0.00	0.00	0.00	0.00	1.00
SCC	RES	0.87	0.12	0.00	0.01	5	16	SCC_RES	0.02	0.03	0.06	0.31	0.10	0.00	1.00	0.43	0.04	0.00	0.00	0.01	0.00	1.00
SCC	COM	0.35	0.57	0.06	0.02	5	16	SCC_COM	0.12	0.08	0.07	0.13	0.20	0.00	0.99	0.20	0.20	0.00	0.02	0.05	0.00	1.00
SCC	MIX	0.64	0.30	0.04	0.02	5	16	SCC_MIX	0.07	0.06	0.06	0.23	0.14	0.00	1.00	0.32	0.11	0.00	0.01	0.03	0.00	1.00
SCC	RAG	0.54	0.12	0.13	0.21	5	16	SCC_RAG	0.04	0.05	0.14	0.20	0.14	0.00	1.00	0.28	0.14	0.00	0.00	0.01	0.00	1.00
SCV	RES	0.91	0.08	0.00	0.01	5	16	SCV_RES	0.02	0.03	0.04	0.32	0.07	0.00	1.00	0.50	0.03	0.00	0.00	0.01	0.00	1.00
SCV	COM	0.47	0.46	0.05	0.02	5	16	SCV_COM	0.10	0.07	0.06	0.16	0.17	0.00	0.99	0.27	0.16	0.00	0.01	0.04	0.00	1.00
SCV	MIX	0.74	0.21	0.04	0.01	5	16	SCV_MIX	0.05	0.04	0.05	0.26	0.11	0.00	1.00	0.41	0.08	0.00	0.01	0.02	0.00	1.00
SCV	RAG	0.63	0.09	0.11	0.18	5	16	SCV_RAG	0.03	0.04	0.12	0.22	0.11	0.00	1.00	0.36	0.11	0.00	0.00	0.01	0.00	1.00
SCI	RES	0.86	0.12	0.00	0.02	5	16	SCI_RES	0.02	0.03	0.05	0.29	0.09	0.00	1.00	0.46	0.05	0.00	0.00	0.01	0.00	1.00
SCI	COM	0.33	0.55	0.08	0.03	5	16	SCI_COM	0.09	0.09	0.07	0.11	0.20	0.00	0.99	0.23	0.20	0.00	0.02	0.04	0.00	1.00
SCI	MIX	0.61	0.30	0.07	0.03	5	16	SCI_MIX	0.05	0.06	0.06	0.21	0.14	0.00	1.00	0.35	0.11	0.00	0.01	0.02	0.00	1.00
SCI	RAG	0.44	0.10	0.17	0.28	5	16	SCI_RAG	0.04	0.06	0.17	0.15	0.15	0.00	1.00	0.26	0.17	0.00	0.00	0.01	0.00	1.00
DSW	RES	0.88	0.09	0.00	0.03	5	16	DSW_RES	0.02	0.02	0.05	0.31	0.08	0.00	1.00	0.48	0.03	0.00	0.00	0.00	0.00	1.00
DSW	COM	0.37	0.43	0.14	0.06	5	16	DSW_COM	0.13	0.08	0.09	0.13	0.20	0.00	1.00	0.24	0.13	0.00	0.01	0.02	0.00	1.00
DSW	MIX	0.64	0.22	0.10	0.04	5	16	DSW_MIX	0.07	0.06	0.07	0.22	0.13	0.00	1.00	0.37	0.08	0.00	0.00	0.01	0.00	1.00
DSW	RAG	0.38	0.06	0.21	0.35	5	16	DSW_RAG	0.05	0.06	0.20	0.13	0.15	0.00	1.00	0.23	0.18	0.00	0.00	0.00	0.00	1.00
HID	RES	0.91	0.08	0.00	0.01	5	16	HID_RES	0.02	0.02	0.02	0.29	0.04	0.00	1.00	0.59	0.03	0.00	0.00	0.01	0.00	1.00
HID	COM	0.47	0.46	0.05	0.02	5	16	HID_COM	0.10	0.07	0.05	0.15	0.15	0.00	0.99	0.32	0.16	0.00	0.01	0.04	0.00	1.00
HID	MIX	0.74	0.21	0.04	0.01	5	16	HID_MIX	0.05	0.04	0.03	0.24	0.08	0.00	1.00	0.48	0.08	0.00	0.01	0.02	0.00	1.00
HID	RAG	0.64	0.09	0.10	0.17	5	16	HID_RAG	0.03	0.04	0.10	0.21	0.09	0.00	1.00	0.42	0.11	0.00	0.00	0.01	0.00	1.00



## Appendix G

### Motor Dynamics Data Sample

**Table G-1.** Motor dynamics data sample

#	Type	ID	L.F.	P.F.	Ls	Lps	Lpps	Ra	Tpo	Tppo	H	Etrq	Vtr1	Ttr1	Ftr1	Vrc1	Trc1	Vtr2	Ttr2	Ftr2	Vrc2	Trc2	
M3	MA		0.75	0.78	1.8	0.12	0.104	0.04	0.095	0.0021	0.1	0	0.7	0.02	0.2	1	99999	0.5	0.02	0.7	0.7	0.1	Three-phase compressor
M3	MB		0.75	0.78	1.8	0.19	0.14	0.03	0.2	0.0026	0.5	2	0.6	0.02	0.2	0.75	0.05	0.5	0.02	0.3	0.65	0.05	Fan
M3	MC		0.75	0.78	1.8	0.19	0.14	0.03	0.2	0.0026	0.1	2	0.65	0.02	0.2	1	9999	0.5	0.02	0.3	0.65	0.1	Pump
M3	IA		0.85	0.89	3.1	0.2	0.165	0.01	0.8	0.0026	0.15	0	0.7	0.05	1	1	9999	0.6	0.02	0	1	99999	Industrial compressor
M3	IB		0.85	0.89	3.1	0.2	0.165	0.01	0.8	0.0026	1	2	0.7	0.05	0.3	1	9999	0.6	0.02	0.5	0.75	0.25	Industrial fan
M3	IC		0.85	0.89	3.1	0.2	0.165	0.01	0.8	0.0026	0.2	2	0.7	0.05	0.3	1	9999	0.6	0.02	0.5	0.75	0.25	Industrial pump
M3	PA		0.85	0.89	3.1	0.2	0.165	0.01	0.8	0.0026	0.15	0	0.7	0.1	1	1	9999	0.6	0.1	0	1	99999	Industrial compressor
M3	PB		0.85	0.89	3.1	0.2	0.165	0.01	0.8	0.0026	1	2	0.7	0.1	0.4	1	9999	0.6	0.1	0.5	0.75	0.25	Industrial fan
M3	PC		0.85	0.89	3.1	0.2	0.165	0.01	0.8	0.0026	0.2	2	0.7	0.1	0.4	1	9999	0.6	0.1	0.5	0.75	0.25	Industrial pump
#	Type	ID	L.F.	P.F.	Vstall	Tstall	Rstall	Xstall	Frst	Vrst	Trst	Tth	Th1t	Th2t	Fuvr	Vuvr1	Tuvr1	Vuvr2	Tuvr2	Vc1off	Vc1on	Vc2off	Vc2on
AC	AC		1	0.98	0.6	9999	0.1	0.1	0.2	0.95	0.3	15	0.7	1.9	0.1	0.6	0.02	1	9999	0.5	0.6	0.4	0.5
#	Type	ID	L.F.	P.F.	Vd1	Vd2	Frcel																
PE	PE		1	1	0.7	0.5	1																
PE	PI		1	1	0.72	0.52	1																
PE	PP		1	1	0.6	0.5	1																

## **Appendix H**

### **Building Motor Response Tables**

## H.1 Building Motor Response Tables for Voltage Sags down to 75% of Nominal Voltage

Supermarket Building Load Table

Square feet: 50,000

Voltages above 75% of nominal

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
Refrigeration and freezers	1-ph or 3-ph compressor	Fuse and thermal	Line voltage with contactor	Motor continues to run.				Extended sag may have caused the thermal protection to trip. Auto restart <b>after</b> manufacturer solid state controller restart sequence of 3 to 5 min.
HVAC roof top units ( <b>RTUs</b> )	3-ph compressor motors	Fuse	Low voltage thermostat with contactor	Motors operate through voltage variance.			Manufacturer control board may have under voltage trip. If tripped at 2 seconds, motor will Auto restart. Extended sag may have caused the thermal protection to trip.	
	3-ph indoor fans motors	Fuse						
	1-ph fractional condenser and induced draft motors	Fuse and thermal						
Misc plug loads, computers, vending, ATMs	Exhaust fans and compressor motors, single phase, fractional HP	Thermal and fuse	Local relay	Motors operate through voltage variance.				

# Fast Food Building Load Table

Square feet: 2,500

Voltages above 75% of nominal

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
Walk-in refrigeration and freezers	1-ph or 3-ph compressors	Fuse and thermal	Line voltage with contactor	Motors operate through voltage variance.			Manufacturer control board may have under voltage trip. If tripped at 2 seconds, motor will Auto restart. Extended sag may have caused the thermal protection to trip.	
	1-ph fractional evaporator and condenser fan motors	Fuse and thermal	Line voltage with contactor	Motors operate through voltage variance.			Manufacturer control board may have under voltage trip. If tripped at 2 seconds, motor will Auto restart. Extended sag may have caused the thermal protection to trip.	
HVAC RTUs	3-ph compressors motors	Fuse and thermal	Low voltage thermostat with contactor	Motors operate through voltage variance.			Manufacturer control board may have under voltage trip. If tripped at 2 seconds, motor will Auto restart. Extended sag may have caused the thermal protection to trip.	
	3-ph indoor fans motors	Fuse	Low Voltage Thermostat with contactor	Motors operate through voltage variance.			Manufacturer control board may have under voltage trip. If tripped at 2 seconds, motor will Auto restart	
	1-ph fractional condenser and induced draft motors	Fuse and thermal	Low voltage thermostat with contactor	Motors operate through voltage variance.			Manufacturer control board may have under voltage trip. If tripped at 2 seconds, motor will Auto restart. Extended sag may have caused the thermal protection to trip.	
HVAC make-up air unit (MAU) and exhaust fan	3-ph motors exhaust and supply fan motors	Fuse and thermal	Line voltage start/stop switch with contactor	Motors operate through voltage variance.			Extended sag may have caused the thermal protection to trip.	
	1-ph fractional hp induced draft motors	Fuse and thermal	Low voltage thermostat with contactor	Motors operate through voltage variance.			Manufacturer control board may have under voltage trip. Extended sag may have caused the thermal protection to trip.	
Ice Machines	1-ph motor compressor	Thermal	Solid-state with contactor	Motors operate through voltage variance.			Manufacturer control board may have under voltage trip Auto restart after solid-state reboot and program restart sequence.	
	1-ph fractional condenser fan and water pump motors	Thermal	Solid-state with relay from control board	Motors operate through voltage variance.			Manufacturer control board may have under voltage trip Auto restart after solid-state reboot and program restart sequence.	
Soft Serve Ice Cream Machine	1-ph 3-ph motor compressor	Thermal	Line voltage with contactor	Motors operate through voltage variance.			Manufacturer control board may have under voltage trip Auto restart after solid-state reboot and program restart sequence.	
	1-ph fractional condenser fan and pump motors	Thermal	Line voltage with contactor	Motors operate through voltage variance.			Manufacturer control board may have under voltage trip Auto restart after solid-state reboot and program restart sequence.	

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
Reach-in Refrigeration and freezers	1-ph fractional compressor condenser and evaporator fan motors	Thermal	Solid-state with relay from control board	Motors operate through voltage variance.			Manufacturer control board may have under voltage trip Auto restart after solid-state reboot and program restart sequence.	

Office Building Load Table  
10,000 sf through 100,000 sf  
Voltages above 75% of nominal

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
Custom DX-AHUs or AHUs with air cooled chillers	3-ph fan motors	Over voltage, phase imbalance, over current, current limiting or fuse and thermal	EMS with VFD or equipment manufacturer solid state control tied into ems	EMS remains in control. Motors operate through voltage variance.				Auto restart after EMS controller and VFD reboot and program restart sequence
	3-ph compressor motors	Electronic Phase Monitor Fused And Thermal	EMS or equipment manufacturer solid state control tied into EMS	EMS remains in control. Motors operate through voltage variance.				Manufacturer control board may have under voltage trip Auto restart after controller reboot and program restart sequence
Fan powered VAVs	1-ph fractional fan motors	Fuse and Thermal	EMS with contactor	EMS remains in control. Motors operate through voltage variance.				Auto restart after EMS controller and VFD reboot and program restart sequence
Fan coil units	1-ph Fractional HP Fan Motors	Thermal	EMS with contactor	EMS remains in control. Motors operate through voltage variance.				Auto restart after EMS controller and VFD reboot and program restart sequence
Building general exhaust fans	1 and 3-ph fan motors	Over voltage, Phase imbalance, over current, and current limiting or fuse and thermal	EMS with VFD or line voltage thermostats or manual start/stop switch	EMS and VFD remains in control. Motors operate through voltage variance.				EMS controller and VFD reboot and program restart sequence / or restart instantaneously
CRAC computer room air conditioner	1-ph or 3-ph compressor	Over voltage, phase imbalance, over current, or fuse and thermal	Manufacturer solid-state with contactor or low voltage standalone thermostats	Manufacturer solid-state remains in control. Motors operate through voltage variance.				Manufacturer control board may have under voltage trip Auto restart after manufacturer solid state controller restart sequence / or restart after start-up delay

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
	1-ph or 3-ph fan motor	Over voltage, phase imbalance, over current, or fuse and thermal		Manufacturer solid-state remains in control. Motors operate through voltage variance.				Manufacturer control board may have under voltage trip Auto restart after manufacturer solid state controller restart sequence / or restart instantaneously
Boilers	1-ph induced draft motor	Fuse and thermal	Manufacturer Solid-state with contactor	Manufacturer solid-state remains in control. Motors operate through voltage variance.				Manufacturer control board may have under voltage trip Auto restart after manufacturer solid state controller restart sequence
	3-ph motors	Over voltage, phase imbalance, over current, and current limiting	EMS with VFD	EMS and VFD remains in control. Motors operate through voltage variance.				Auto restart after EMS controller and VFD reboot and program restart sequence
Domestic hot water pumps	1-ph fractional motor	Circuit breaker and thermal	EMS with relay / or Manual switch	EMS remains in control. Operate through voltage variance.				Auto restart after EMS controller reboot and program restart sequence
Other plug loads	Elevators, computers, refrigeration, includes small delis and vending equipment, ATMs, telecommunications equipment.							

Office Building Load Table  
Square feet: 100,000 to 1,000,000  
Voltages above 75% of nominal

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
AHUs	3-ph fan motors	Over voltage, phase imbalance, over current, and current limiting	EMS with VFD	EMS and VFD remains in control Motors operate through voltage variance.				Auto restart <b>after</b> EMS controller and VFD reboot and program restart sequence
Fan powered VAVs	1-ph fan motors	Fuse and thermal	EMS with contactor	EMS remains in control Motors operate through voltage variance.				Auto restart <b>after</b> EMS controller and VFD reboot and program restart sequence
<b>(DOAS)</b> dedicated outside air system	3-ph fan motors	Over voltage, phase imbalance, over current, and current limiting	EMS with VFD	EMS and VFD remains in control Motors operate through voltage variance.				Auto restart <b>after</b> EMS controller and VFD reboot and program restart sequence
Chillers	3-ph compressor motors	Over voltage, phase imbalance, over current	Manufacturer solid-state controller tied into EMS	Manufacturer Solid-state remains in control Compressor operates through voltage variance.			May trip offline due to under voltage protection. Auto restart <b>after</b> manufacturer solid state controller restart sequence	
	3-ph pump motors	Over voltage, phase imbalance, over current, and current limiting	EMS with VFD	EMS and VFD remain in control. Motors operate through voltage variance.				Auto restart <b>after</b> EMS controller and VFD reboot and program restart sequence
Boilers	1-ph induced draft motor	Fuse and Thermal	Manufacturer Solid-state with contactor	EMS remains in control. Motors operate through voltage variance.			May trip offline due to under voltage protection. Auto restart <b>after</b> manufacturer solid state controller restart sequence	
	3-ph motors	Over voltage, Phase Imbalance, over current, and current limiting	EMS with VFD	EMS remains in control. Motors operate through voltage variance.				Auto restart <b>after</b> EMS controller and VFD reboot and program restart sequence
Cooling towers	3-ph fan motor	Over voltage, Phase Imbalance, over current, and current limiting	EMS with VFD	EMS and VFD remain in control. Motors operate through voltage variance.				Auto restart <b>after</b> EMS controller and VFD reboot and program restart sequence
Fan coil units	1-ph fractional fan motors	Fuse and Thermal	EMS with Contactor	EMS remains in control. Motors operate through voltage variance.				Auto restart <b>after</b> EMS controller and VFD reboot and program restart sequence



Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
Building general exhaust fans	1 and 3-ph fan motors	Over voltage, Phase Imbalance, over current, and current limiting <b>or</b> fuse and thermal	EMS with VFD or Line voltage thermostat / <b>or</b> manual start/stop switch	EMS and VFD remain in control. Motors operate through voltage variance.				Auto restart <b>after</b> EMS controller and VFD reboot and program restart sequence
(CRAC) computer room air conditioner	1-ph or 3-ph compressor motor	Over voltage, phase imbalance, over current, <b>or</b> fuse and thermal	Manufacturer solid-state with contactor / <b>or</b> low voltage standalone thermostats	Manufacturer solid-state remains in control. Compressors operate through voltage variance.			May trip offline due to under voltage protection. Auto restart <b>after</b> manufacturer solid state controller restart sequence	
	1-ph or 3-ph fan motor	Over voltage, phase imbalance, over current, <b>or</b> fuse and thermal		Manufacturer solid-state remains in control. Motors operate through voltage variance.			May trip offline due to under voltage protection. Auto restart <b>after</b> manufacturer solid state controller restart sequence	
Domestic cold water pumps	3-ph pump motor	Over voltage, phase imbalance, over current, and current limiting	Manufacturer solid-state with VFD	Manufacturer solid-state remains in control. Motors operate through voltage variance.			May trip offline on voltage imbalance. Auto restart with equipment staging delay	
Domestic hot water pumps	1-ph fractional pump motor	Circuit breaker and thermal	EMS with relay / <b>or</b> manual switch	Manufacturer solid-state remains in control. Motors operate through voltage variance.				May trip offline due to under voltage protection. Auto restart <b>after</b> manufacturer solid state controller restart sequence
Sewage rejection	3-ph pump motor	Fused with current overload	Line voltage mag-starter start/stop level switch	Motors operate through voltage variance.				
Other loads	Elevators, computers, refrigeration, cooking includes small delis and vending equipment, ATMs, telecommunications equipment, medical equipment, and manufacturing performed in commercial buildings.							

Retail Building Load Table  
Square feet: 5,000 and under  
Voltage above 75%

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
HVAC RTUs	3-ph compressor motors	Fuse	Manufacturer solid state <b>or</b>	Manufacturer control continues to operate.				If tripped offline by under voltage or over current, auto restart <b>after</b> manufacturer solid state controller restart sequence  Extended sag may have caused the thermal protection to trip. Auto restart
	3-ph indoor fans motors	Fuse	Low voltage standalone thermostats					
	1-ph fractional condenser and induced draft motors	Fuse and thermal	manufacturer solid state <b>or</b> Low voltage standalone thermostats					
Exhaust fans	1-ph fractional motor	Circuit breaker and thermal	Manual switch	Motors operate through voltage variance.				Extended sag may have caused the thermal protection to trip. Auto restart
Walk-in refrigeration and freezers	1-ph or 3-ph compressors	Fuse and thermal	Line voltage with contactor	Manufacturer control continues to operate. Motors operate through voltage variance.				Extended sag may have caused the thermal protection to trip. Auto restart
	1-ph fractional evaporator and condenser fan motors	Fuse and thermal	Line voltage with contactor					Extended sag may have caused the thermal protection to trip. Auto restart
Reach-in refrigeration and freezers	1-ph fractional compressor motors	Fuse and thermal	Manufacturer solid-state with contactor	Manufacturer solid-state remains in control. Motors operate through voltage variance.				If tripped by thermal, auto restart <b>after</b> manufacturer solid state controller restart sequence

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
	1-ph fractional condenser and evaporator fan motors	Fuse and Thermal		Manufacturer solid-state remains in control. Motors operate through voltage variance.				If tripped offline by thermal, auto restart <b>after</b> manufacturer solid state controller restart sequence
Other plug loads	Gas pumps, refrigerated display cases, ice bins, TVs and monitors, cooking equipment							

Retail Building Load Table  
Square feet: 15,000 to 40,000  
Voltages above 75% of nominal

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
HVAC RTUs	3-ph compressor motors	Fuse	EMS with VFD <b>or</b> Manufacturer solid state tied into	EMS and VFD remains in control. Motors operate through voltage variance.				If tripped offline by under voltage or thermal protection, auto restart <b>after</b> EMS controller reboot and program restart sequence / <b>or</b> restart instantaneously  Extended sag may have caused the thermal protection to trip. Auto restart
	3-ph indoor fans motors	Fuse						
	1-ph fractional condenser and induced draft motors	Fuse and thermal	EMS with contactors <b>or</b> Low voltage standalone thermostats					
Exhaust fans	1-ph fractional horsepower motor	Circuit breaker and thermal	EMS with relay / <b>or</b> manual switch	Motors operate through voltage variance Extended sag may have caused the thermal protection to trip. Auto restart				
Other plug loads	Elevators, computers, refrigeration, cooking includes small delis and vending equipment, ATMs, telecommunications equipment							

Retail Building Load Table  
Square feet: 15,000 to 100,000  
Voltages above 75% of nominal

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
RTUs	3-ph fan motors	Over voltage, phase imbalance, over current, current limiting or fuse and thermal	EMS with VFD <b>or</b> Manufacturer solid state tied into EMS with contactors <b>or</b> Low voltage standalone thermostats	EMS and VFD remains in control Motors operate through voltage variance				If tripped offline auto restart <b>after</b> EMS controller reboot and program restart sequence / <b>or</b> restart instantaneously
	3-ph compressor motors	Fused and thermal	EMS with contactors <b>or</b> Manufacturer solid state tied into EMS <b>or</b> Low voltage standalone thermostats	EMS remains in control Compressor operates through voltage variance				If tripped offline by thermal or under voltage, auto restart <b>after</b> EMS controller reboot and program restart sequence
Exhaust fans	1-ph fractional fan motor	Circuit breaker and thermal	EMS with relay / <b>or</b> manual switch	EMS remains in control Motors operate through voltage variance				If tripped offline, auto restart <b>after</b> EMS controller reboot and program restart sequence / <b>or</b> restart instantaneously
Other plug loads	Elevators, escalators, computers, refrigeration, cooking includes small delis and vending equipment, ATMs, telecommunications equipment							

Warehouse Building Load Table  
Square Feet 20,000  
Voltages above 75% of nominal

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
Gas fired unit heaters	1-ph fractional fan motors	Thermal	Low voltage thermostat switch with contactor	Motors operate through voltage variance				Thermostat reboot and program restart sequence
Exhaust fans	1-ph fan motors	Thermal	Line voltage start/stop switch with contactor	Motors operate through voltage variance Extended sag may have caused the thermal protection to trip. Auto restart				
Paddle fans	1-ph fan motors	Thermal	Manual start/stop switch	Motors operate through voltage variance Extended sag may have caused the thermal protection to trip. Auto restart				
Other plug loads	Electric forklift charging, TV and monitors, computers, copiers, fax, printers, refrigerators, microwaves, box fans. Ride through.							

## H.2 Building Motor Response Tables for Voltage Variance Range of 75 to 50% of Nominal

Supermarket Building Load Table

Square feet: 50,000 (Albertson's)

Voltages between 75% and 50% of nominal

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
RTUs	3-ph indoor fan motors	Fused <b>possibly</b> voltage monitored <b>possibly</b> overload relays	EMS with contactors <b>or</b> Manufacturer solid state tied into EMS with contactors <b>or</b> Low voltage standalone thermostats	EMS remains in control  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event	EMS and VFD drop out 2 seconds after event below 65% V, but will automatically restart with voltage recovery. First fan starts within 5 seconds, second fan if applicable restarts at 30 seconds.  Contactors operate through voltage variance, but drop out when EMS drops offline 2 seconds after event. Or, if the voltage dips below 50% V, the contactor will drop and reenergize 1 to 8 cycles after event, and then drop out again when the EMS drops 2 seconds later.  <b>Possible</b> overload trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
	3-ph compressor motors	Fused and thermal <b>possibly</b> voltage monitored	EMS with contactors <b>or</b> Manufacturer solid state tied into EMS <b>or</b> Low voltage standalone thermostats		EMS drops out 2 seconds after event below 65% V, but will automatically restart with voltage recovery; 270 seconds first compressor, 150-second interstaging delay for each additional compressor if applicable.  Contactors operate through voltage variance but drop out when EMS drops offline 2 seconds after event. Or, if the voltage dips below 50% V, the contactor will drop and reenergize 1 to 8 cycles after event, and then drop out again when the EMS drops 2 seconds later.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
	1-ph fractional condenser and induced draft motors	Fused and thermal <b>possibly</b> voltage monitored	EMS with contactors <b>or</b> Manufacturer solid state tied into EMS <b>or</b> Low voltage standalone thermostats		EMS and VFD drop out 2 seconds after event below 65% V, but will automatically restart. 270 seconds with the first compressor, 150-second interstaging delay for each additional compressor if applicable.  Contactors operate through voltage variance but drop out when EMS drops offline 2 seconds after event. Or, if the voltage dips below 50% V, the contactor will drop and reenergize 1 to 8 cycles after event, and then drop out again when the EMS drops 2 seconds later.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
Refrigeration and freezers	1-ph or 3-ph compressor motors	Fuse and Thermal	Line voltage with contactor	Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event	Automatically restart. 300 seconds for compressor and all associated 1-ph fans.			
Misc plug loads	Exhaust fans and compressor motors, single phase, fractional HP drop out at 50% to 60% voltage, time delay on restart of computer-based loads.							

# Fast Food Building Load Table

Square feet: 2,500

Voltages between 75% and 50% of nominal

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
Walk-in refrigeration and freezers	1-ph or 3-ph compressors	Fuse and thermal	Line voltage with contactor	Contactor drops out at 50% V.	Automatically restart. 300 seconds for compressor and all associated 1-phase fans.  <b>Possible</b> thermal trip if the voltage variance is longer than 2 to 3 seconds and above 50% V.			
	1-ph fractional evaporator and condenser fan motors	Fuse and thermal	Line voltage with contactor	Reenergizes after 1 to 8 cycles after event.				
RTUs	3-ph indoor fan motors	Fused <b>Possibly</b> Overload relays	Low voltage thermostat with contactor	Thermostat remains in control.	Thermostat will drop out below 65% V, but will automatically restart. Fan starts within 30 seconds.			
	3-ph compressor motors	Fuse and thermal	Low voltage thermostat with contactor	Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	<b>Possible</b> overload trip if the voltage variance is long enough and above 65%. Thermostat will drop out below 65% V, but will automatically restart the compressor within 300 seconds.			
	1-ph fractional condenser and induced draft motors	Fuse and thermal	Low voltage thermostat with contactor		Thermostat will drop out below 65% V, but will automatically restart the fans with the compressor within 300 seconds.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
HVAC make-up air unit MAU and exhaust fan	3-ph motors exhaust and supply fan motors	Fused <b>possibly</b> overload relays	Line voltage start/stop switch with contactor	Contactor drops out at 50% V. Reenergizes after 1 to 8 cycles after event.	<b>Possible</b> overload trip if the voltage variance is long enough and above 50%.			
	1-ph fractional HP induced draft motors	Fuse and thermal	Low voltage thermostat with contactor	Thermostat remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	Thermostat will drop out below 65% V, but will automatically restart the Induced draft motors.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V			
Ice machines	1-ph motor compressor	Thermal	Solid-state with contactor	Control board remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	Solid-state control board will drop out below 65% V. Manual reset needed.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
	1-ph fractional condenser fan and water pump motors	Thermal	Solid-state with relay from control board	Motor will continue to operate through voltage variance.	Solid-state control board will drop out below 65% V. Manual reset needed.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			



Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
Soft serve ice cream machine	1-ph motor compressor	Thermal	Solid-state with contactor	Control board remains in control.	Solid-state control board will drop out below 65% V. Manual reset needed.			
	1-ph fractional condenser fan and water pump motors	Thermal	Solid-state with contactor	Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	<p><b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.</p> <p>Solid-state control board will drop out below 65% V. Manual reset needed.</p> <p><b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.</p>			
Reach-in refrigeration and freezers	1-ph fractional compressor condenser and evaporator fan motors	Thermal	Solid-state with relay from control board	Motor will continue to operate through voltage variance.	<p>Solid-state control board will drop out below 65% V. Manual reset needed.</p> <p><b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.</p>			

Office Building Load Table  
Square feet: 10,000 through 100,000  
Voltages above 75% of nominal

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
Custom DX-AHUs or AHUs with air cooled chillers	3-ph fan motors	Over voltage, phase imbalance, over current, or fuse and thermal	EMS with VFD or equipment manufacturer solid state control tied into EMS	EMS remains in control.	EMS and VFD operate through event then drop out 2 seconds after event below 65% V, but will automatically restart. First fan starts within 5 seconds, second fan if applicable restarts at 30 seconds.			
	3-ph compressor motors	Electronic phase monitor fused and thermal	EMS or equipment manufacturer solid state control tied into EMS	EMS remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	EMS drops out 2 seconds after event below 65% V, but will automatically restart. 270 to 300 seconds first compressor, 150 to 240 second interstaging delay for each additional compressor if applicable.  Contactors operate through voltage variance, but drop out when EMS drops offline 2 seconds after event. Or, if the voltage dips below 50% V, the contactor will drop and reenergize 1 to 8 cycles after event, and then drop out again when the EMS drops 2 seconds later.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
Fan powered VAVs	1-ph fractional fan motors	Fuse and thermal	EMS with contactor	EMS remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	EMS drops out 2 seconds after event below 65% V, but will automatically restart. Fan starts within 5 seconds.  Contactors operate through voltage variance, but drop out when EMS drops offline 2 seconds after event. Or, if the voltage dips below 50% V, the contactor will drop and re-energize 1 to 8 cycles after event, and then drop out again when the EMS drops 2 seconds later.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
Fan coil units	1-ph fractional fan motors	Thermal	EMS with contactor	EMS remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	EMS drops out 2 seconds after event below 65% V, but will automatically restart. Fan starts within 5 seconds,  Contactors operate through voltage variance, but drop out when EMS drops offline 2 seconds after event. Or, if the voltage dips below 50% V, the contactor will drop and re-energize 1 to 8 cycles after event, and then drop out again when the EMS drops 2 seconds later.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
Building general exhaust fans	1 and 3-ph fan motors	Over voltage, phase imbalance, over current, or fuse and thermal	EMS with VFD or line voltage thermostats / or manual start/stop switch	EMS remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	EMS and VFD drop out 2 seconds after event below 65% V, but will automatically restart. First fan starts within 5 seconds, second fan if applicable restarts at 30 seconds.  Contactors operate through voltage variance, but drop out when EMS drops offline 2 seconds after event. Or, if the voltage dips below 50% V, the contactor will drop and re-energize 1 to 8 cycles after event, and then drop out again when the EMS drops 2 seconds later			

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
<b>CRAC</b> Computer Room Air Conditioner	1-ph or 3-ph compressor	Over voltage, phase imbalance, over current, <b>or</b> fuse and thermal	Manu- facturer Solid-state with contactor / <b>or</b> low voltage standalone thermostats	Manu- facturer solid-state control board remains in control.	Manufacturer solid-state control board drops out below 65% V, but will automatically restart. 270 to 300 seconds first compressor, 150 to 240 second interstaging delay for each additional compressor if applicable.  <b>Possible</b> thermal trip if the voltage variance is longer than 3 to 4 seconds and above 65% V.			
	1-ph or 3-ph fan motor	Over voltage, phase imbalance, over current, <b>or</b> fuse and thermal		Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	Manufacturer solid-state control board drops out 2 seconds after event below 65% V, but will automatically restart. Fan starts within 5 seconds  <b>Possible</b> thermal trip if the voltage variance is longer than 3 to 4 seconds and above 65% V.			
Boilers	1-ph induced draft motor	Fuse and thermal	Manu- facturer solid-state with contactor	Control Board remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	Manufacturer solid-state control board drops out below 65% V, but will automatically restart. 120 seconds first boiler, 240 seconds interstaging delay for each additional boiler if applicable.  <b>Possible</b> thermal trip if the voltage variance is longer than 3 to 4 seconds and above 65% V.			
	3-ph pump motor	Over voltage, phase imbalance, over current, and current limiting	EMS with VFD	EMS and VFD remain in control.	EMS and VFD operate through event, then drop out 2 seconds after event below 65% V, but will automatically restart. Pump starts within 90 seconds.			
Domestic hot water pumps	1-ph fractional motor	Circuit breaker and thermal	EMS with relay / <b>or</b> Manual switch	EMS remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	EMS drops out 2 seconds after event below 65% V, but will automatically restart within 10 seconds.  Contactors operate through voltage variance, but drop out when EMS drops offline 2 seconds after event. Or, if the voltage dips below 50% V, the contactor will drop and reenergize 1 to 8 cycles after event, and then drop out again when the EMS drops 2 seconds later.  <b>Possible</b> thermal trip if the voltage variance is longer than 2 to 4 seconds and above 65% to 50% V.			
Other plug loads	Elevators, computers, includes small delis and vending equipment, ATMs, telecommunications equipment, drop out at 50%, and computer based loads will go through a reboot sequence on voltage recovery.							

# Office Building Load Table

Square feet: 100,000 to 1,000,000

Voltages between 75% and 50% of nominal

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
AHUs	3-ph fan motors	Over voltage, phase imbalance, over current	EMS with VFD	EMS remains in control.	EMS and VFD operate through event, then drop out 2 seconds after event below 65% V, but will automatically restart. First fan starts within 5 seconds, second fan if applicable restarts at 30 seconds.			
Fan powered VAVs	1-ph fractional fan motors	Fuse and thermal	EMS with contactor	EMS remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	EMS drops out 2 seconds after event below 65% V, but will automatically restart. Fan starts within 5 seconds.  Contactors operate through voltage variance, but drop out when EMS drops offline 2 seconds after event. Or, if the voltage dips below 50% V, the contactor will drop and reenergize 1 to 8 cycles after event, and then drop out again when the EMS drops 2 seconds later.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
<b>(DOAS)</b> dedicated outside air system	3-ph fan motors	Over voltage, phase imbalance, over current	EMS with VFD	EMS remains in control.	EMS and VFD operate through event, then drop out 2 seconds after event below 65% V, but will automatically restart. First fan starts within 5 seconds, second fan if applicable restarts at 30 seconds.			
Chillers	3-ph compressor motors	Over voltage, phase imbalance, over current	Manufacturer solid-state controller tied into EMS	Control board remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	Manufacturer solid-state control board drops out below 65% V, but will automatically restart. 300 to 500 seconds first chiller, 600-second interstaging delay for each additional chiller if applicable.			
	3-ph pump motors	Over voltage, phase imbalance, over current	EMS with VFD	EMS and VFD remain in control.	EMS and VFD operate through event, then drop out 2 seconds after event below 65% V, but will automatically restart. Pump soft starts within 90 seconds.			
Boilers	1-ph induced draft motor	Fuse and thermal	Manufacturer solid-state with contactor, EMS	Control board remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	Manufacturer solid-state control board drops out below 65% V, but will automatically restart. 120 seconds first boiler, 240-second interstaging delay for each additional boiler if applicable.  <b>Possible</b> thermal trip if the voltage variance is long enough and above 65% for 2 to 3 seconds.			
	3-ph motors	Over voltage, phase imbalance, over current, and current limiting	EMS with VFD	EMS and VFD remain in control.	EMS and VFD operate through event, then drop out 2 seconds after event below 65% V, but will automatically restart. Pump starts within 90 seconds.			
Cooling towers	3-ph fan motor	Over voltage, phase imbalance, over current, and current limiting	EMS with VFD	EMS and VFD remain in control.	EMS and VFD operate through event, then drop out 2 seconds after event below 65% V, but will automatically restart. First fan starts within 5 seconds, second fan if applicable restarts at 30 seconds.			

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
Fan coil units	1-ph fractional fan motors	Thermal	EMS with contactor	EMS remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	EMS drops out 2 seconds after event below 65% V, but will automatically restart. Fan starts within 5 seconds.  Contactors operate through voltage variance, but drop out when EMS drops offline 2 seconds after event. Or, if the voltage dips below 50% V, the contactor will drop and reenergize 1 to 8 cycles after event, and then drop out again when the EMS drops 2 seconds later.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
Building general exhaust fans	1 and 3-ph fan motors	Over voltage, phase imbalance, over current, <b>or</b> fuse and thermal	EMS with VFD or line voltage thermostats / <b>or</b> manual start/stop switch	EMS remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	EMS and VFD drops out 2 seconds after event below 65% V, but will automatically restart. First fan starts within 5 seconds, second fan if applicable restarts at 30 seconds.  Contactors operate through voltage variance, but drop out when EMS drops offline 2 seconds after event. Or, if the voltage dips below 50% V, the contactor will drop and reenergize 1 to 8 cycles after event, and then drop out again when the EMS drops 2 seconds later.			
<b>CRAC</b>	1-ph or 3-ph compressor	Over voltage, phase imbalance, over current, <b>or</b> fuse and thermal	Manufacturer solid-state with contactor / <b>or</b> low voltage standalone thermostats	Manufacturer solid-state control board remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	Manufacturer solid-state control board drops out below 65% V, but will automatically restart. 270 to 300 seconds first compressor, 150 to 240 seconds interstaging delay for each additional compressor if applicable.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
	1-ph or 3-ph fan motor	Over voltage, phase imbalance, over current, <b>or</b> fuse and thermal			Manufacturer solid-state control board drops out 2 seconds after event below 65% V, but will automatically restart. Fan starts within 5 seconds.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
Domestic cold water pumps	3-ph pump motor	Over voltage, phase imbalance, over current	Manufacturer solid-state with VFD	Manufacturer solid-state control board remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	Manufacturer solid-state control board drops out 2 seconds after event below 65% V, but will automatically restart. Pumps soft start within 5 seconds.			
Domestic hot water pumps	1-ph fractional motor	Circuit breaker and thermal	EMS with relay / <b>or</b> manual switch	EMS remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	EMS drops out 2 seconds after event below 65% V, but will automatically restart within 10 seconds.  Contactors operate through voltage variance, but drop out when EMS drops offline 2 seconds after event. Or, if the voltage dips below 50% V, the contactor will drop and reenergizes 1 to 8 cycles after event, and then drop out again when the EMS drops 2 seconds later.  <b>Possible</b> thermal trip if the voltage variance is longer than 3 to 4 seconds and above 65% V.			
Sewage rejection	3-ph pump motor	Fused with current overload	Line voltage mag-starter start/stop level switch	Contactor drops out at 50% V. Reenergizes after 1 to 8 cycles after event.			Contactor drops out at 50% V. Reenergizes after 1 to 8 cycles after event.  <b>Possible</b> overload trip if the voltage variance is long enough and above 50% V.	

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
Other loads	Elevators, computers, includes small delis and vending equipment, ATMs, telecommunications equipment, drop out at 50%, and computer based loads will go through a reboot sequence on voltage recovery.							

Retail Building Load Table  
Square feet: 5,000 and under  
Voltage between 75% and 50% of nominal

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
RTUs	3-ph indoor fan motors	Fused <b>possibly</b> overload relays	Low voltage thermostat with contactor	Thermostat remains in control.	Thermostat will drop out below 65% V, but will automatically restart. Fan starts within 30 seconds.			
	3-ph compressor motors	Fuse and thermal	Low voltage thermostat with contactor	Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	<b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
	1-ph fractional condenser and induced draft motors	Fuse and thermal	Low voltage thermostat with contactor		Thermostat will drop out below 65% V, but will automatically restart the compressor within 300 seconds.			
Walk-in refrigeration and freezers	1-ph or 3-ph compressors	Fuse and thermal	Line voltage with contactor	Contactor drops out at 50% V. Reenergizes after 1 to 8 cycles after event.	Thermostat will drop out below 65% V, but will automatically restart the fans with the compressor within 300 seconds.			
	1-ph fractional evaporator and condenser fan motors	Fuse and thermal	Line voltage with contactor		<b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
Exhaust fans	1-ph fractional motor	Circuit breaker and thermal	Manual switch	Contactor drops out at 50% V. Reenergizes 1 to 8 cycles after event.	Automatically restart. 300 seconds for compressor and all associated 1-phase fans.		Automatically restart. 300 seconds for compressor and all associated 1-phase fans.	
					<b>Possible</b> thermal trip if the voltage variance is longer than 2 to 3 seconds and above 50% V.		<b>Possible</b> thermal trip if the voltage variance is longer than 2 to 3 seconds and above 50% V.	
Exhaust fans	1-ph fractional motor	Circuit breaker and thermal	Manual switch	Contactor drops out at 50% V. Reenergizes 1 to 8 cycles after event.			Contactor drops out at 50% V. Reenergizes after 1 to 8 cycles after event.	
							<b>Possible</b> Thermal trip if the voltage variance is long enough and above 50% V.	
Reach-in refrigeration and freezers	1-ph fractional compressor condenser and evaporator fan motors	Thermal	Solid-state with relay from control board	Motor will continue to operate through voltage variance.	The solid-state control board will drop out below 65% V. Manual reset needed.			
					<b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
Other plug loads	Gas pumps, refrigerated display cases, ice bins, TVs and monitors, cooking equipment drop out at 75% voltage and computer based loads will restart after reboot sequence.							

# Retail Building Load Table

Square feet: 15,000 to 40,000

Voltages between 75% and 50% of nominal

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
RTUs	3-ph indoor fan motors	Fused <b>possibly</b> overload relays	EMS <b>or</b> Manufacturer solid state tied into ems with contactors <b>or</b> Low voltage standalone thermostats	Thermostat remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	EMS or thermostat will drop out below 65% V, but will automatically restart. Fan starts within 30 seconds.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
	3-ph compressor motors	Fuse and thermal			EMS or thermostat will drop out below 65% V, but will automatically restart the compressor within 300 seconds.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
	1-ph fractional condenser and induced draft motors	Fuse and thermal			EMS or thermostat will drop out below 65% V, but will automatically restart the fans with the compressor within 300 seconds.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
Exhaust fans	1-ph fractional motor	Circuit breaker and thermal	Manual switch	Contactor drops out at 50% V. Reenergizes after 1 to 8 cycles after event.			Contactor drops out at 50% V. Reenergizes after 1 to 8 cycles after event.  <b>Possible</b> thermal trip if the voltage variance is long enough and above 50% V.	
Other plug loads	Elevators, computers, refrigeration, cooking includes small delis and vending equipment, ATMs, telecommunications equipment drop out at 75% voltage, and recover immediately with voltage recovery except for computer-based load with a reboot sequence.							



# Retail Building Load Table

Square feet: 15,000 to 100,000

Voltages between 75% and 50% of nominal

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
RTUs	3-ph indoor fan motors	Fused <b>possibly</b> overload relays	EMS <b>or</b> Manufacturer solid state tied into EMS with contactors <b>or</b> Low voltage standalone thermostats	Thermostat remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	EMS or thermostat will drop out below 65% V, but will automatically restart. Fan starts within 30 seconds.  <b>Possible</b> thermal trip if the voltage variance is longer than 4-5 seconds and above 65% V.			
	3-ph compressor motors	Fuse and thermal			EMS or thermostat will drop out below 65% V, but will automatically restart the compressor within 300 seconds.  <b>Possible</b> thermal trip if the voltage variance is longer than 4-5 seconds and above 65% V.			
	1-ph fractional condenser and induced draft motors	Fuse and thermal			EMS or thermostat will drop out below 65% V, but will automatically restart the fans with the compressor within 300 seconds.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
Exhaust fans	1-ph fractional motor	Circuit breaker and thermal	Manual switch	Contactor drops out at 50% V. Reenergizes after 1 to 8 cycles after event.			Contactor drops out at 50% V. Reenergizes after 1 to 8 cycles after event.  <b>Possible</b> thermal trip if the voltage variance is long enough and above 50% V.	
Other plug loads	Elevators, escalators, computers, refrigeration, vending equipment, ATMs, telecommunications equipment drops out at 75% voltage and restarts with voltage recovery, except for computer-based, which must go through reboot sequence.							

# Warehouse Building Load Table

Square feet: 20,000

Voltages between 75% and 50% of nominal

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
Gas fired unit heaters	1-ph fractional fan motors	Thermal	Low voltage thermostat with contactor	Thermostat remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	EMS or Thermostat will drop out below 65% V. but will automatically restart. Fan starts within 30 seconds.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
Exhaust fans	1-ph fractional motor	Thermal	Manual switch	Contactor drops out at 50% V. Reenergizes after 1 to 8 cycles after event.	Contactor drops out at 50% V. Reenergizes after 1 to 8 cycles after event.  <b>Possible</b> thermal trip if the voltage variance is long enough and above 50% V.			
Paddle fans	1-ph fractional motor	Thermal	Manual switch	Contactor drops out at 50% V. Reenergizes after 1 to 8 cycles after event.	Contactor drops out at 50% V. Reenergizes after 1 to 8 cycles after event.  <b>Possible</b> thermal trip if the voltage variance is long enough and above 50%.			
Other plug loads	Electric forklift charging, TV and monitors, computers, copiers, fax, printers, refrigerators, microwaves, box fans will drop off at 75% and restart with voltage recovery. Computer-based loads will go through reboot sequence.							

Other Building Load Table  
 Voltages between 75% and 50% of nominal

Equipment	Motors	Protection	Controls	5 cycle	10 cycle	20 cycle	2 second	3 minute
Single phase heat pumps	1-ph fractional HP motors	Fuse and thermal	Low voltage thermostat with contactor	Stall between 60% and 70%. Disconnect at 50%. Do not restart for 3 to 5 minutes.	Thermostat will drop out below 65% V, but will automatically restart. Fan starts within 30 seconds.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
	1-ph compressor motor	Fuse and thermal	Battery backed low voltage thermostat with contactor	Drop out at 50% V and restart at 90% V.	Thermostat will drop out below 65% V, but will automatically restart the compressor within 300 seconds.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
RTUs	3-ph indoor fan motors	Fused <b>possibly</b> overload relays	EMS <b>or</b> Manufacturer solid state tied into EMS with contactors <b>or</b> Low voltage standalone thermostats	Thermostat remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	Thermostat will drop out below 65% V, but will automatically restart. Fan starts within 30 seconds.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
	3-ph compressor motors	Fuse and thermal			Thermostat will drop out below 65% V, but will automatically restart the compressor within 300 seconds.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
	1-ph fractional condenser and induced draft motors	Fuse and thermal			Thermostat will drop out below 65% V, but will automatically restart the fans with the compressor within 300 seconds.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
Electric heat fan motors	1-ph fractional fan motors	Thermal	Low voltage thermostat with contactor	Thermostat remains in control.  Contactor drops out at 50% V and reenergizes after 1 to 8 cycles after event.	EMS or thermostat will drop out below 65% V, but will automatically restart. Fan starts within 30 seconds.  <b>Possible</b> thermal trip if the voltage variance is longer than 4 to 5 seconds and above 65% V.			
Misc. plug loads, computers, vending, ATMs	Exhaust fans and compressor motors, single phase, fractional HP	Thermal and fuse	Local relay	Battery-backed devices remain on. Others drop out at 50% V. 1-minute delay on voltage recovery.				

## Distribution

### **No. of Copies**

# Name  
Organization  
Address  
City, State and ZIP Code

# Organization  
Address  
City, State and ZIP Code  
Name  
Name  
Name  
Name (#)

# Name  
Organization  
Address  
City, State and ZIP Code

### **No. of Copies**

#### **# Foreign Distribution**

# Name  
Organization  
Address  
Address line 2  
COUNTRY

#### **# Local Distribution**

Pacific Northwest National Laboratory  
Name Mailstop  
Name Mailstop  
Name Mailstop  
Name Mailstop  
Name (PDF)





*Proudly Operated by **Battelle** Since 1965*

902 Battelle Boulevard  
P.O. Box 999  
Richland, WA 99352  
1-888-375-PNNL (7665)

[www.pnl.gov](http://www.pnl.gov)



U.S. DEPARTMENT OF  
**ENERGY**