NERC

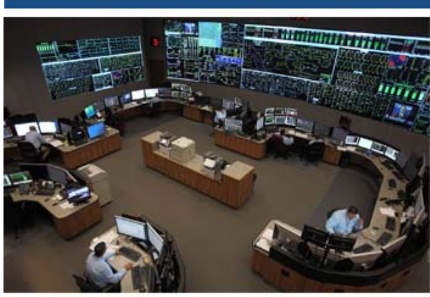
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Reliability Guideline

Developing Load Model Composition Data

March 2017

RELIABILITY | ACCOUNTABILITY




3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

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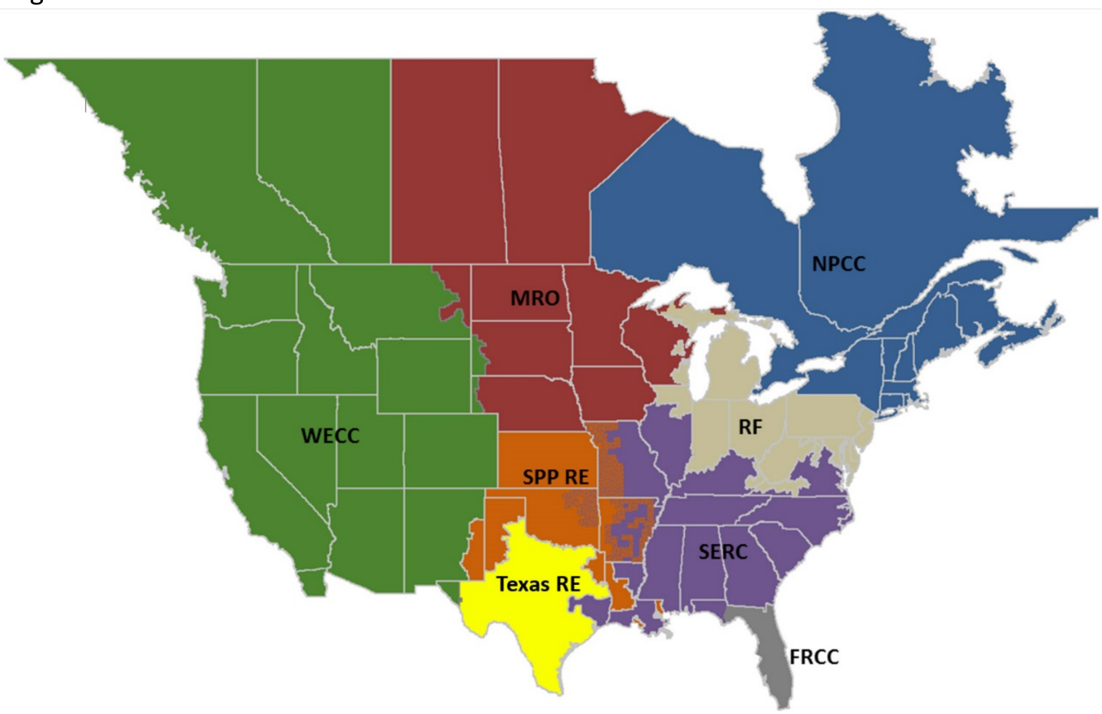
Preface

The North American Electric Reliability Corporation (NERC) is a not-for-profit international regulatory authority whose mission is to assure the reliability of the bulk power system (BPS) in North America. NERC develops and enforces Reliability Standards; annually assesses seasonal and long-term reliability; monitors the BPS through system awareness; and educates, trains, and certifies industry personnel. NERC's area of responsibility spans the continental United States, Canada, and the northern portion of Baja California, Mexico. NERC is the electric reliability organization (ERO) for North America, subject to oversight by the Federal Energy Regulatory Commission (FERC) and governmental authorities in Canada. NERC's jurisdiction includes users, owners, and operators of the BPS, which serves more than 334 million people.

The North American BPS is divided into eight Regional Entity (RE) boundaries as shown in the map and corresponding table below.



The North American BPS is divided into eight Regional Entity (RE) boundaries. The highlighted areas denote overlap as some load-serving entities participate in one Region while associated transmission owners/operators participate in another.

FRCC	Florida Reliability Coordinating Council
MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
SPP RE	Southwest Power Pool Regional Entity
Texas RE	Texas Reliability Entity
WECC	Western Electricity Coordinating Council

Preamble

It is in the public interest for NERC to develop guidelines that are useful for maintaining or enhancing the reliability of the Bulk Electric System (BES). The NERC Technical Committees—the Operating Committee (OC), the Planning Committee (PC), and the Critical Infrastructure Protection Committee (CIPC)—are authorized by the NERC Board of Trustees (Board) to develop Reliability (OC and PC) and Security Guidelines (CIPC) per their charters.[1] These guidelines establish a voluntary set of recommendations, considerations, and industry best practices on a particular topic for use by BES users, owners, and operators to assess and ensure BES reliability. These guidelines are coordinated by the technical committees and include the collective experience, expertise, and judgment of the industry.

The objective of reliability guidelines is to distribute key practices and information on specific issues related to maintaining the highest levels of BES reliability. Reliability guidelines are not to provide binding norms or create compliance type parameters similar to Reliability Standards that are monitored or enforced. Guideline practices are strictly voluntary and are designed to assist in reviewing, revising, or developing individual entity practices to achieve the highest levels of reliability for the BES. Further, these guidelines are not intended to take precedence over regional procedures or requirements.

NERC, as the FERC-certified Electric Reliability Organization (ERO),[2] is responsible for the reliability of the BES and has a suite of tools to accomplish this responsibility, including but not limited to the following: lessons learned, reliability and security guidelines, assessments and reports, the Event Analysis program, the Compliance Monitoring and Enforcement Program, and mandatory reliability standards. Each entity, as registered in the NERC compliance registry, is responsible and accountable for maintaining reliability and compliance with the mandatory standards to maintain the reliability of their portions of the BES. Entities should review this guideline in conjunction with a periodic review of their internal processes and procedures and make any needed changes based on their system design, configuration, and business practices.

[1] http://www.nerc.com/comm/OC/Related%20Files%20DL/OC%20Charter%2020131011%20(Clean).pdf
http://www.nerc.com/comm/CIPC/Related%20Files%20DL/CIPC%20Charter%20(2)%20with%20BOT%20approval%20footer.pdf
http://www.nerc.com/comm/PC/Related%20Files%202013/PC%20Charter%20-%20Board%20Approved%20November%202013.pdf
[2] http://www.ferc.gov/whats-new/comm-meet/072006/E-5.pdf

Purpose

End-use demand level and load composition are continuously changing elements of the BPS, and load model parameters are expected to reasonably represent a snapshot in time for a given set of conditions to reliably plan the BPS. The dynamic performance of end-use load is rapidly evolving due to energy efficiency and technology changes and industry should adapt their modeling practices to keep pace with these changes. This reliability guideline provides Transmission Planners (TPs) and Transmission Owners (TOs) with insights into end-use load behaviors and how to capture them in the composition of dynamic load models. Load composition aspects of dynamic load modeling are the primary focus but other aspects of dynamic load modeling such as motor performance, protection modeling, or performing sensitivity studies are also incorporated. Examples of how to develop aggregate load model composition data from various data sources, classify that data, and convert that information into suitable load model parameter values are provided for references. The guideline also provides technical guidance and reference material for how to apply the load composition data to develop reasonable and suitable dynamic load models used in stability simulations. Data can be collected from various data sources and implemented into different types of dynamic load models. The framework presented is applicable to varying levels of data availability and modeling capability.

The following topics are described in detail in this guideline to support the development of robust and representative end-use load composition data for dynamic load modeling purposes:

- Gathering applicable data sources for load classification
- Developing a process for classifying load data
- Determining a Rules of Association to convert classification information to model parameters
- Understanding the sensitivities of load composition on simulation results

The guideline does not provide binding norms or create parameters by which compliance to NERC Reliability Standards is monitored or enforced. The intent of the guideline is to provide insight into data and procedures that lead to reasonable modeling of load composition as may be necessary for compliance with such standards. The concepts are generic and can be adapted to fit the needs and specific implementations, systems, and processes of each entity. The approaches presented are among multiple suitable means of developing dynamic load composition data, and highlight aspects of different approaches.

The guideline applies primarily to TPs responsible for ensuring reasonable representation of the dynamic behavior of the end-use load being modeled, which includes a reasonable composition of end-use load components. In particular, this data is useful for the development of interconnection-wide powerflow and dynamics base cases as well as for more detailed local area studies.

Chapter 1: Dynamic Load Modeling Overview

The power grid consists of millions of electric end-use consumers who are independently receiving power from the BPS. System planners and operators use an aggregate model of the end-use loads that represent the total demand for an expected or actual point in time for steady state analysis. Further, in dynamic simulations the aggregate load response to disturbances is also modeled. The dynamic response should reflect the general behavior of aggregate load; it is not reasonable to understand or capture the individual response of each load for bulk power system studies. The representation of these aggregate loads, particularly the dynamic response of those loads, is the focus of this guideline.

Reasonable representation of the aggregate dynamic behavior of end-use loads is a critical aspect of BPS stability analysis. Load behavior has proved to have a significant effect on past disturbance events.[3] Simulation of these events for forensic analysis purposes may be unsuccessful or of limited success if the performance of induction motor loads and other types of loads sensitive to changes in grid frequency and voltage is overlooked. Figure 1.1 shows validation studies for a large N-3 event in the Western Interconnection. Oscillation damping sensitivity to motor load (*motorw* model[4]) was studied to better understand how load response affects BPS performance. It was determined that an increasing penetration of induction motor load can degrade the oscillation damping ratio, highlighting the importance of having representative dynamic load models for stability studies.

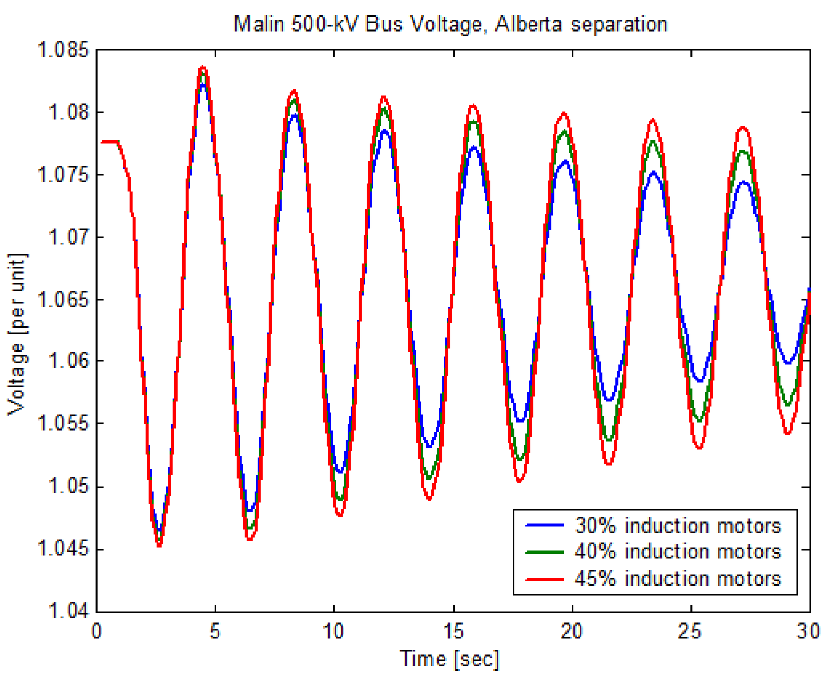


Figure 1.1: System Damping Sensitivity to Motor Load [Source: BPA]

Determining the amount of different types of loads, including induction motor load, requires understanding the composition of loads. This entails understanding the data sources for this information, the classification methods used by utilities, and the load model selected to represent the aggregate loads. Figure 1.2 illustrates the process of developing load composition information at a high level, including:

[3] B. Agrawal, D. Kosterev, "Model Validation Studies for a Disturbance Event That Occurred on June 14 2004 in the Western Interconnection," *IEEE PES General Meeting*, 2007, Tampa, FL, pp. 1-5.

[4] The *motorw* model represents an induction motor in dynamic simulations allowing for either a "one-cage" or "two-cage" model; however, it does not model magnetic saturation. The model is intended to represent aggregations of many motors across a distribution system.

- **End-Use Load Data:** Raw data relating to the composition of loads can come in various forms including billing data, regional load data, end-use surveys, energy efficiency programs, and historical SCADA load profiles. These raw data sources are often unique to the utility or entity compiling the information and usually are manipulated into a useable format such that information related to classification of these loads can be extracted.
- **Load Classification:** Often times, load information is classified by end-use load type and similar to the billing structures used by utilities. These classifications include residential, commercial, industrial, agricultural, etc. The classification data usually needs to be manipulated to relate the load class data to the model parameters.
- **Model Parameter Derivation:** The model parameters are based on the type of load model used, and often include composition fractions that relate the given load classification to various types of individual load components modeled in the dynamic load model structure. For example, model parameters related to composition often include types of induction motor loads, lighting, power electronic loads, and static load.

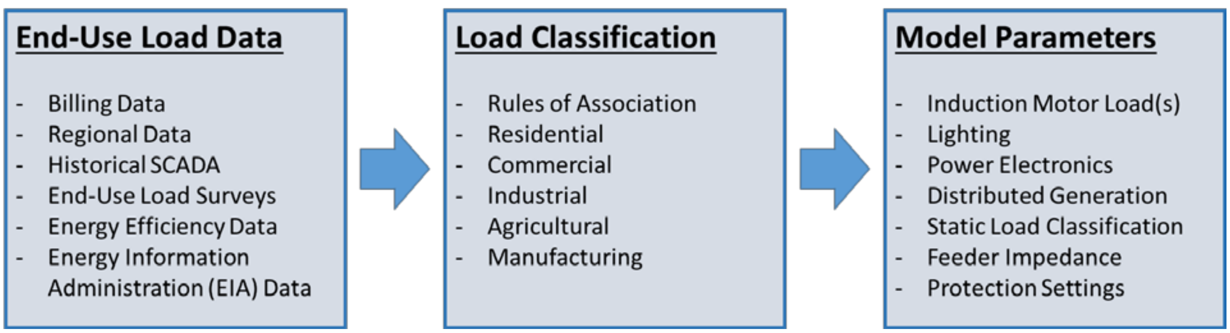


Figure 1.2: High-Level Process of Load Composition Data Development

The composite load model (CLM[5]) is referred to throughout the guideline as a useful example of how composition data is used for actual applications.[6] The structure of the CMLD model is shown in Figure 1.3. The model consists of the following components and features:

- Step-down distribution transformer including under-load tap changer (ULTC) controls
- Low-side distribution system bus and end-use load bus
- Distribution equivalent circuit represented by a series impedance and shunt compensation
- Induction motor models[7] representing:
    - Motor A: three-phase, constant-torque compressors used in air conditioning and refrigeration
    - Motor B: three-phase higher inertia fans whose torque is proportional to speed squared
    - Motor C: three-phase lower inertia pumps whose torque is proportional to speed squared
    - Motor D: single-phase compressors, often used in residential air conditioning

[5] The composite load model (CLM) is often referred to by its software implementation. For example, CMLD or CMPLDW (or CMPLDWG) refer to the same model and concept and are used interchangeably.

[6] The WECC Modeling and Validation Work Group (MVWG) led the development of the composite load model used in dynamic simulations of the BPS, and today the composite load model is implemented in most major positive sequence stability simulation programs. The model is an equivalent representation of the distribution system as well as the aggregate types of end-use loads. The composite load model has the greatest flexibility of existing models that are part of the standard model libraries used in many software simulation programs. In particular, the model can represent different types of feeders and compositions of end-use loads.

[7] The CLM often refer to these types of motor loads as Motor A, Motor B, Motor C, and Motor D, respectively.

- Power electronic load representing an aggregation of small electronic constant power loads
- Static load representing the remainder of unclassified aggregated loads
- Distributed energy resources (DER) connected at the end-use load bus to represent rooftop PV and other small-scale distributed[8] DER

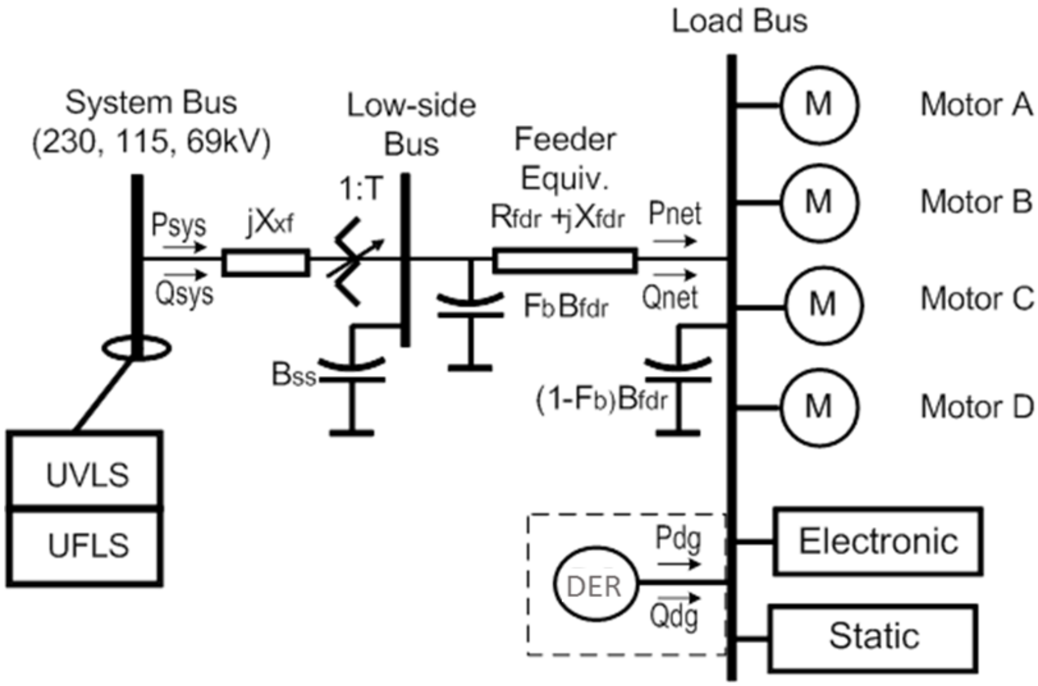


Figure 1.3: Composite Load Model Structure (CMPLDWG)

[8] Inclusion of DERs in dynamic load models is generally intended to capture the distributed resources rather than the utility-scale (either transmission or distribution level) resources directly connected to the utility bus.

Chapter 2: NERC Reliability Standard TPL-001-4

NERC Reliability Standard TPL-001-4, *Transmission System Planning Performance Requirements*, establishes Transmission system "performance requirements within the planning horizon to develop a BES that will operate reliably over a broad spectrum of System conditions and following a wide range of probable Contingencies." A key component to developing the models and study cases used to assess the performance of the BPS is understanding load composition and accurately modeling end-use load behavior. TPL-001-4 references "Load" and dynamic load modeling in the stability analysis as part of the following Requirements:

- **R2.4.1:** "…System peak Load levels shall include a Load model which represents the expected dynamic behavior of Loads that could impact the study area, considering the behavior of induction motor Loads. An aggregate System Load model which represents the overall dynamic behavior of the Load is acceptable."
- **R2.4.3:** "…sensitivity case(s) shall be utilized to demonstrate the impact of changes to the basic assumptions used in the model… the Planning Assessment must vary one or more of the following conditions by a sufficient amount to stress the System within a range of credible conditions… [that includes] Load level, Load forecasts, or dynamic Load model assumptions."

TPL-001-4 requires that the system peak load levels be studied as part of the near-term transmission planning horizon portion of the stability analysis as a part of the overall planning assessment. The peak load level case, as per Requirement R2.4.1, includes the dynamic behavior of loads while considering induction motor loads.

While the standard mentions induction motor load in R2.4.1, TPs should consider the effects of motor load as well as other types of end-use load. In addition, TPs should consider the impacts these types of loads may have on BPS dynamic performance in off-peak load conditions as well as in the long-term transmission planning horizon. The dynamic behavior of the end-use loads has proven to have a significant effect on the dynamic behavior of the interconnected BPS at all times of operation. For example, the increased penetration of constant power loads (i.e., electronically connected loads) has shown to impacts post-contingency oscillatory and voltage stability in some interconnections or parts of interconnections (see Figure 2.1). System modelers and planners should consider how load composition changes between operating conditions and whether load response plays a critical role to reliability during these conditions.

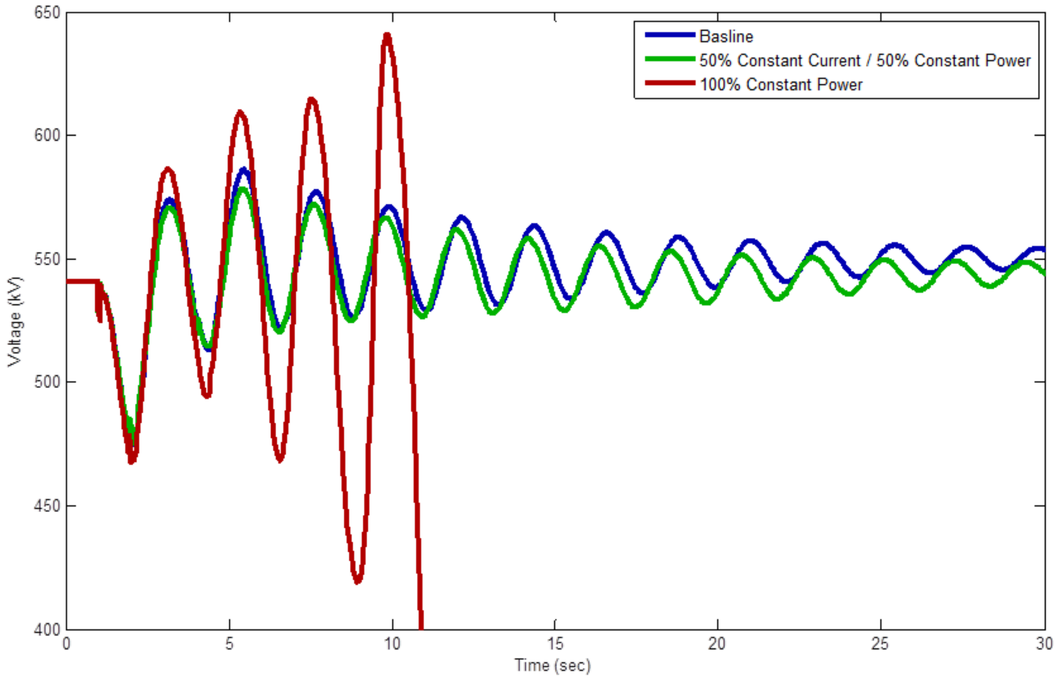


Figure 2.1: Impact of Constant Power Load on Oscillatory Stability [Source: WECC]

Chapter 3: Load Model Classification

Loads are generally classified into different categories typically for purposes such as customer billing used by utilities for ratepayer differentiation[9] or simply for record keeping. These classifications identify loads that generally behave similarly and can therefore be aggregated for use in BPS planning studies. The composition of each load classification identifies load types and is used to derive load model parameters. Examples of end-use loads and the classification of these loads that is commonly used is shown in Table 3.1 as a reference.

<table>
<tr><th colspan="2">Table 3.1: Load Classification Examples</th></tr>
<tr><td colspan="2">Residential: residential households may include a variety of dwellings including single-family and small multi-family units.</td></tr>
<tr><td colspan="2">Load Composition:
- Single-phase air conditioners
- Refrigerators
- Heat pumps
- Pool pumps
- Electric vehicle battery chargers
- Water heaters
- Air compressors
- Consumer electronics
- Space heaters (resistive)
- Ceiling and floor fans
- Incandescent and LED lighting</td></tr>
<tr><td colspan="2">Commercial: commercial includes a vast array of load types and is often separated into two distinct classifications:</td></tr>
<tr><td>Small Commercial: these units may include small retail spaces such as strip malls, big-box retailers, small apartment buildings, office parks, etc. These types of load are often found intermixed with residential communities and suburban neighborhoods.</td><td>Large Commercial: these units may include larger retail spaces and buildings such as large malls, large downtown office buildings/skyscrapers, etc.</td></tr>
<tr><td>Load Composition:
- Rooftop air conditioners
- Refrigerators
- Pumps
- Power electronics
- Fluorescent lighting</td><td>Load Composition:
- Air handling systems
- Refrigerators
- Pumps
- Power electronics
- Variable frequency drives (VFD)[10]
- Electronically commutated motors (ECM)[11]
- Lighting</td></tr>
</table>

[9] Electricity tariffs may vary by customer type.

[10] VFDs are adjustable-speed drives controlling AC motor speed and torque by motor input voltage magnitude and frequency.

[11] ECMs are high-efficiency DC motors connected through a power electronic inverter, commonly used in fan applications.

Table 3.1: Load Classification Examples

Industrial: industrial facilities[12] are usually process-oriented such as paper mills, oil refineries, chemical processing plants, etc. Their composition will often be based on the process being driven and should be considered uniquely based on an understanding of the general industry being served and purpose for the facility.

Load Composition:

- Conveyor belts
- Pumps
- Lighting
- Cooling systems
- VFDs and ECMs
- Power electronics

Power Plant Auxiliary Loads: loads within large power plants such as gas, coal, and nuclear power plants that drive all the equipment used to generate the electric power.

Load Composition:

- Feed water pumps
- Compressors
- VFDs and ECMs
- Lubrication pumps
- Pulverizers
- Cooling systems
- Power electronics
- Lighting
- Induction draft fans

Agricultural: in some regions agricultural loads are a significant part of the load composition and can be identified separately. These loads are often electric pumps or other unique composition.

Load Composition:

- Irrigation pumps
- Power electronics
- VFDs and ECMs

[12] A list of typical values for load composition for various industrial facilities is provided in Appendix A.

Chapter 4: Factors Affecting Load Composition

The constant variation of end-use load presents a challenge to developing a representative composition of that load under potential future system conditions. However, developing a representation of the expected performance of the end-use load that captures the general shape of the response provides more engineering insight than using models such as the ZIP[13] representation. Estimating the compositions for each load classification may be based on engineering judgment and benchmarking to past system events. The following considerations highlight the challenge in developing load composition information and should be accounted for:

- It is an insurmountable task to know with certainty the precise composition of the connected end-use load in a large utility at any given time in the future due to the tremendously large number of individual end-use load components[14].
- The connected end-use loads vary over time on a continuous basis in a stochastic nature with noticeable variations based on time of day, day of the week, and season.
- Different types of loads will peak at different times; for example, three-phase motors in commercial buildings may peak at their highest usage during the work-day while residential air conditioning load may peak later in the afternoon as people return home from work.
- The classification of the load (e.g., residential, commercial, industrial) may drive the types of loads used in these settings based on different motivations such as energy efficiency (e.g., compact fluorescent lighting (CFL) and variable speed drives (VFDs) used in commercial offices and industrial facilities on large installations).
- The dynamic nature of the end-use load is changing and should be accounted for in the characterization of these aggregate loads, particularly as the availability and penetration of newer technologies (e.g., electric vehicles and battery storage systems) continues to increase.
- Increasing penetration of distributed energy resources (DERs) across many areas of the BPS will play a key role in the dynamic response of the aggregate load and should be accounted for appropriately. The NERC Distributed Energy Resources Task Force (DERTF) and Load Modeling Task Force (LMTF) are developing technical guidance materials to help utilities account for these types of resources in power system models and reliability studies.
- Even with an "accurate" load composition and representation, non-linear behaviors[15] of many end-use loads during system events make capturing the exact nature of the aggregate load response a challenge. This requires differentiation between the tuning of models to recreate historical events in detail versus developing a best guess of the aggregate dynamic performance of models using engineering judgment. This highlights the need for sensitivity analysis.

The following sub-sections provide examples of various types of factors that affect the load composition to illustrate how these can be accounted for when developing composition data if applicable.

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[13] "ZIP" refers to modeling the load as some fraction of constant impedance (Z), constant current (I), and constant power (P). The utility industry has, over the past many years, adopted a "rule of thumb" representation of the load as a constant current real power, constant impedance reactive power load characteristic primarily due to the computational limitations at the time these models were developed. However, this is no longer acceptable (as described in TPL-001-4) given observations in WECC and many other regions of the inability of these simplistic load models to accurately represent the actual system response reasonably.

[14] Such as the number of lighting circuits online in a residential household or the number of motors online in a large commercial office building.

[15] Such as single-phase induction motor load stalling, end-use load or building energy management system protection, and power electronic load tripping.

Time of Day

The time of day will have a significant impact on the composition of end-use loads on the system. In the middle of the night and early morning, commercial, industrial, and residential load demand is at a minimum. As the morning progresses, load demand increases as various residential and commercial loads come online. There is often a mid-day drop in overall demand as the load composition on the system shifts to more commercial and industrial and less residential. In the afternoon, load demand increases as more residential load comes online and load composition predominantly includes all load classes: residential, commercial, and industrial. As ambient temperatures increase, residential (and commercial) air conditioner load can increase the composition of these types of loads substantially in some areas and can dominate the load characteristic.

Throughout the day, there are various "static loads" which are not generally classifiable and lumped into this static class with a generalized response. Entities should use engineering judgment to capture dynamic loads to the extent possible and minimize the use of static load unless directly accounting for specific types of end-use loads, when applicable.[16]

Figure 4.1 shows an example of the fractional composition of different load components used by WECC. These fractional values are used to generate hourly load composition data for each climate zone they classify (Figure 4.4). This allows the model to be based on 1) a climate zone, and 2) hour of day, to develop a load composition quantity.

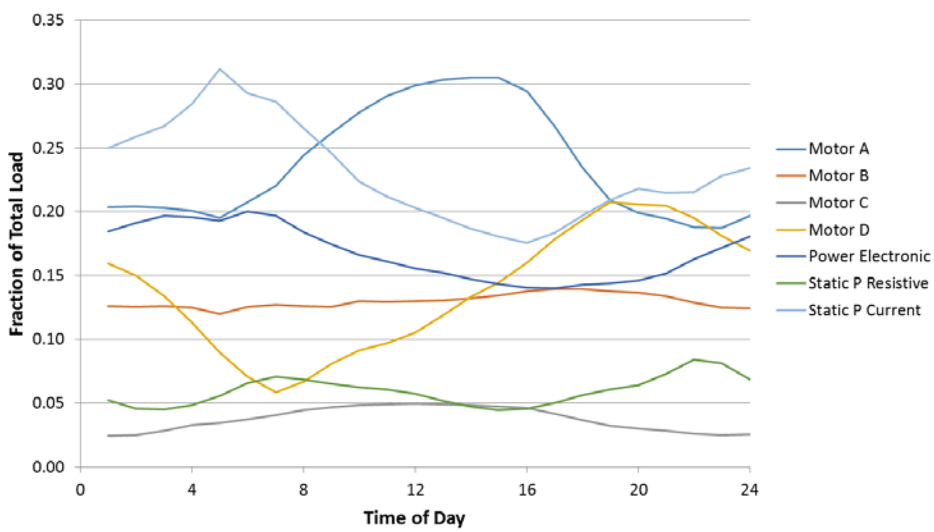

Figure 4.1: Load Fraction based on Time of Day [Source: WECC]

BPA performed testing and measurement of residential feeders and residences to understand the percentage of air conditioning load on the system based on time of day and for various seasons (summer season shown below). This was tested over a range of end-users during multiple days of the season. Figure 4.2 (left plot) shows an illustration of multiple households and the percentage of load the air conditioner represented throughout the day for each residence. That data was aggregated to create an average percentage of load (right plot) that could be used to create summer peak system cases.

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[16] If the load responds similar to a static load representation (e.g., resistive cooking or heating load) then this is an appropriate form of load classification.

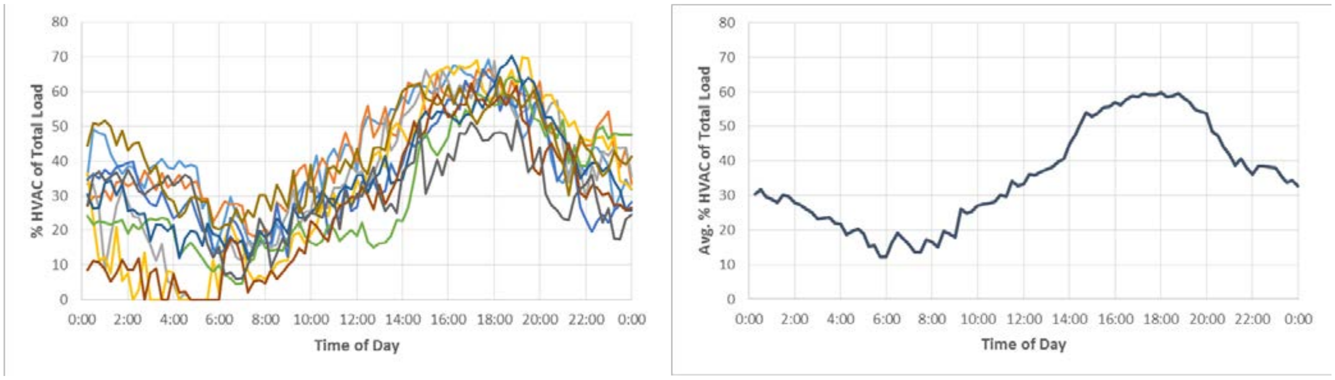

Figure 4.2: Percentage HVAC to Total Load (Multiple Days (left) and Average (right)) [Source: BPA]

Geographic Region and Climate Zone

The geographic region and climate zone associated with that region can play a very important role in the composition of load. The granularity of classifying these zones or regions can occur at any level. For example, the U.S. Department of Energy (DOE) funded development of a guide[17] for determining climate regions[18] by county and characterized the U.S. into eight climates (Figure 4.3). The regions are based on heating degree days, average temperatures, and precipitation. The survey was developed for home building; however the regions are useful for understanding possible classification of high-level regional zones for developing load composition data as well, particularly for motor loads.

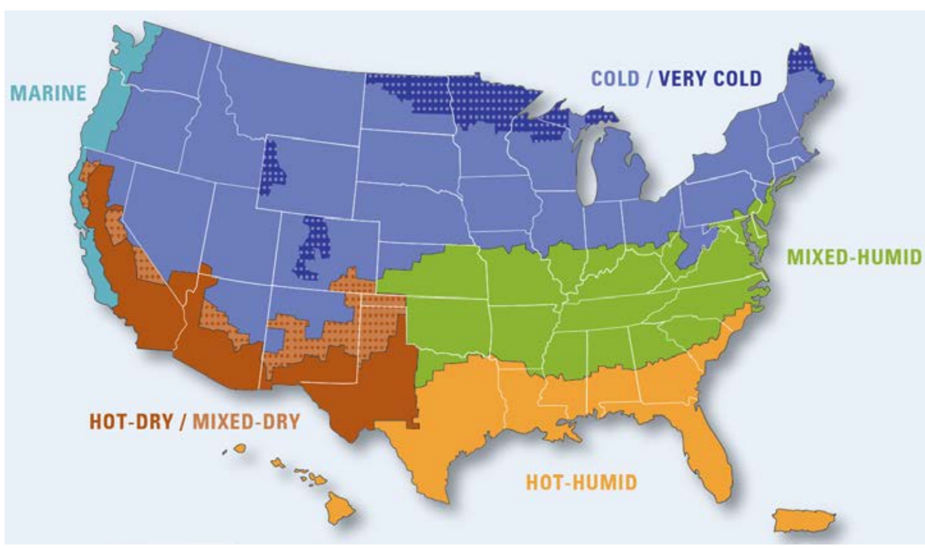

Figure 4.3: Climate Regions from US DOE Classification [Source: DOE]

WECC has also developed twelve climate zones for their specific system based on detailed analysis funded and performed by the WECC Load Modeling Task Force over the years (see Figure 4.4). These climate zones differentiate the end-use load shapes, characteristics, and modeled load types. It is clear there are similarities to

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[17] Pacific Northwest National Laboratory, Oak Ridge National Laboratory, "Building America Best Practices Series for High-Performance Technologies: Determining Climate Regions," prepared for U.S. Department of Energy, December 2007. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/climate_region_guide.pdf.

[18] These regions are defined in the DOE-funded guide, and provided here for reference. Refer to the DOE guide for more information.

the DOE classification based on humidity, temperature, location, etc. with some additional granularity where WECC members felt it was necessary to differentiate.[19]

ID	Climate Zone	Representative City
NWC	Northwest Coast	Seattle, Vancouver BC
NWV	Northwest Valley	Portland OR
NWI	Northwest Inland	Boise, Tri-Cities, Spokane
RMN	Rocky Mountain North	Calgary, Montana, Wyoming
NCC	Northern California Coast	Bay Area
NCV	Northern California Valley	Sacramento
NCI	Northern California Inland	Fresno
SCC	Southern California Coast	LA, San Diego
SCV	Southern California Valley	LA, San Diego
SCI	Southern California Inland	LA, San Diego
DSW	Desert Southwest	Phoenix, Riverside, Las Vegas
HID	High Desert	Salt Lake City, Albuquerque, Denver, Reno

Figure 4.4: WECC Climate Zones [Source: WECC]

Demographics and Tolerance

The demographics of the end-use loads are closely linked to the region and climate zone of the loads. For example, many southern regions rely on air conditioners as a necessity to keep indoor temperatures to a safe level during summer months. On the other hand, northern regions may not even have air conditioners or they may be considered a luxury rather than a necessity. Similarly, communities with larger residences may use two air conditioners for each single-family home (one for each story) while other communities may rely on floor fans or open windows to cool down individual rooms. These aspects are hard to quantify but can be used to make engineering judgments about load composition.

Regional Industries & Processes

Regional industries can play an important role in load composition particularly for industrial load. In general, it is recommended to distinguish between the types of industrial processes at some level. The type of process will affect the types of motors used within the facility (e.g., conveyer belts vs. liquid pumps vs. air handlers), and will also impact the composition of loads captured in the models used. Refer to Appendix A for more information about recommended settings for different types of industrial loads.

Temperature

Ambient temperature affects both total demand and load composition, particularly for residential loads classes. Temperature is affected by many things including climate zone, season of the year, etc. Figure 4.5 shows the load profile for (1) a newer construction suburban residential feeder (left), and (2) a commercial feeder (right) for three distinctly different ambient temperatures (warm (blue), hot (green), extreme (red)) for the region. The active and reactive power plots show a clear relationship between increasing ambient temperature and residential feeder peak demand while that same relationship is not observed in the commercial load class. Increased peak demand for the residential feeder can be attributed to increased power consumption and usage of residential air conditioners. While commercial load will have some ambient effect, the majority of that load class is not air

[19] This is a good example of how practices can be adopted to different areas.

conditioning. In this example, residential load can increase by 100 percent between the 75 °F and 103 °F days while commercial load increases by only about 30 percent. The TP used this observation to confirm the hypothesis that similar residential feeders can consist of up to 40–60 percent air conditioning load during summer peak conditions.

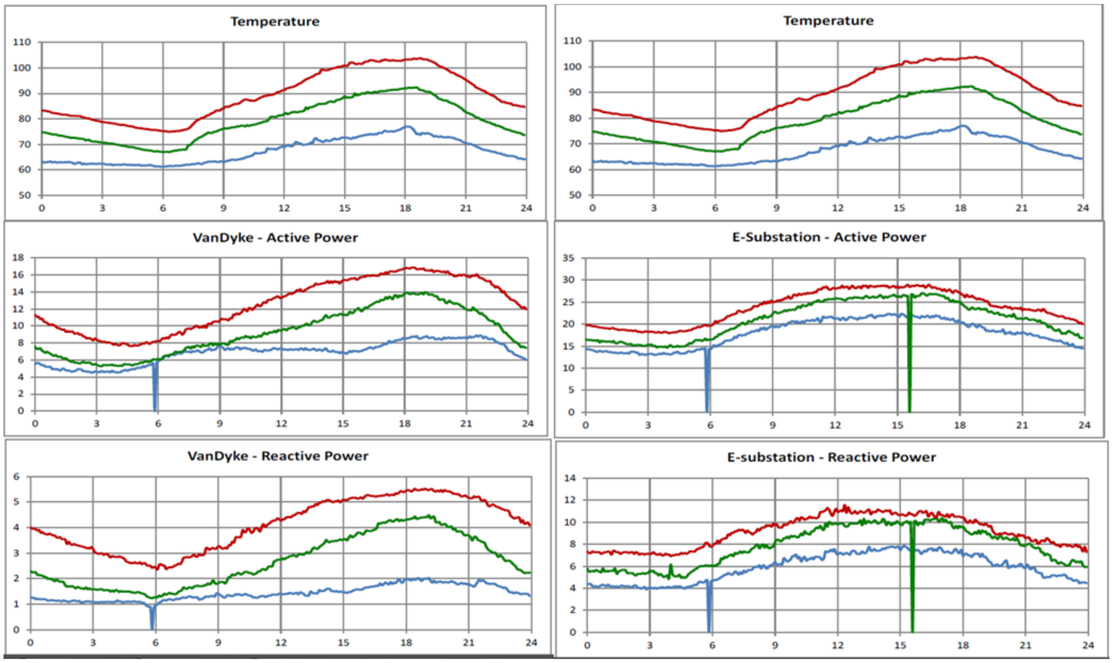

Figure 4.5: Load (Residential and Commercial) Response to Temperature

Chapter 5: Load Model Data Sources

To begin any exercise of classifying load for the purposes of developing load composition and load model parameters, each entity should consider the data sources available to them. The vast amount of data that classifies end-use loads at the distribution level for purposes of billing can be a daunting concept for modelers and planners. Yet the selection of load composition is critical[20] to study results and steps can be taken to minimize the complexity of aggregating this data to a manageable level.[21] Regardless, the TP will need to develop some representative load model based on data collected from the Distribution Provider (DP), available data sources, and engineering judgment.

Engineering Judgment

Given the uncertain nature of any load model parameters developed, the TP can improve the quality of the resultant model parameters by keeping in mind some fundamental questions:

- How should the loads be classified and how does geographic region, weather zone, demographics, etc., affect the load composition of each load classification?
- How can a reasonably accurate representation of the impedances (e.g., transformer and feeders) between the load and the transmission level bus to which that load is connected be obtained?
- For each classified load type, how much of that load can be expected to trip and how much can be expected to stall during a voltage event and at what voltage levels?
- How much time and resources are available to identify and obtain relevant load data and convert that data into model parameters.

This last question recognizes the reality that developing robust and representative dynamic load models and load composition information will be an iterative process. In some cases, a "one size fits all" set of default parameters may need to be used based on engineering judgment that can be supplemented with actual data when available. DPs and TPs should develop processes to derive the load classification on a substation basis, or however loads are represented in the base case for each planning entity, and consider the deployment of a myriad of technologies to gather data for improving load model fidelity.

Progressing from an approximate load model to a more accurate model will take time. Given this reality, the first three questions focus more on some of the parameters in the model that can have higher sensitivity[22] to the study results and may not be based so much on composition values. Nevertheless, they should be accounted for in coordination with load composition information to develop a more representative model.

Simple classification of aggregate loads into demographic, geographic, and/or climatological regions has been shown to provide a significant improvement in simulation credibility and reasonability. Differentiating between industrial compared with residential and/or commercial load types is an important division. Additionally, differentiating between urban and rural load types can be a further refinement.

- Urban loads have a higher percentage of larger three-phase induction motor loads due to hotels, high-rise office buildings, convention centers, and similar buildings with the presence of large, centralized motor equipment. It is often important to differentiate between motor type such as compressors, fans,

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[20] An overly optimistic choice of parameters may mask potential voltage stability issues, compromising reliability. An overly pessimistic choice of parameters may indicate voltage stability issues where none exist, prompting unnecessary mitigation measures.

[21] For example, feeder- or bus-level aggregations are commonly used and recommended for BPS modeling. Other options include area- or zonal-based methods when more aggregate data is not available or deemed unnecessary based on engineering judgment.

[22] As in, study results are most sensitive to these parameter choices.

and pumps due to the torque-speed response each motor has and the impact that response can have on grid performance.

- Rural and suburban loads with mostly residential and small commercial buildings have a higher percentage of smaller single-phase and some three-phase induction motor loads (e.g., rooftop air conditioning, small-scale refrigeration, etc.). These smaller motors likely have different performance characteristics and simpler protection that will change their dynamic response when subjected to grid disturbances.

Useful Resources

Potential resources that may provide insight for use in developing composition and parameter values for dynamic load models include:

- **Transmission-Distribution Transformer Data:** Specification and test reports and relay setting records generally include this data. Most utilities use a standard set of transformer sizes, which can be a useful source for typical data. Both newer specs and older specs should be considered since the installed population of these transformers vary in age.
- **Distribution Transformer Impedance Data:** Typical distribution transformer impedances (e.g., distribution voltage to 480/240/120 V transformers) may be estimated from utility and/or manufacturer specifications for these transformers.
- **Distribution Equivalent Impedance Data:** Typical distribution feeder lengths and conductor types, along with the impedance parameters, are generally available from utility distribution planning or modeling groups.
- **Electronically Coupled Loads:** Power quality engineers often have insight regarding larger customer loads and the penetration of electronically coupled loads such as VFDs. VFDs are commonly replacing older direct-drive induction motors due to efficiency.
- **Distribution Provider or Distribution Planning Engineers:** Distribution planners are an excellent source of data regarding load classification and the processes used to classify these loads. These job functions are often done on a regional basis within each utility, so obtaining area-specific load characteristics may be possible.
- **Customer Billing Data:** Customer billing data is often the most granular data available for creating load composition information. The billing can be separated into a number of different classifications, but there are often categories that can be used to separate the amount of load on each feeder[23] such as large commercial, small commercial, residential, industrial, etc.
- **Gas Availability Data:** Data regarding gas availability can help characterize summer/winter load shifts resulting from different winter heating sources in one area versus another.

Feeder Information

The utilization voltage of loads is either in the medium voltage range (e.g., 13.2 kV, 7.2 kV, 4160 V, etc.) or the low voltage range (e.g., 480, 240, 120, etc. V). As such, there is necessarily an appreciable impedance between the transmission level bus, the distribution level bus, and the end use load. This should be accounted for in dynamic load models to capture the electrical impedance, and hence a voltage difference across the feeder.[24]

[23] Separated by each feeder or other separating method for modeling in the power flow case.

[24] The dynamic load models generally use an equivalent impedance that represents an average impedance to the equivalent end-use loads.

- For industrial loads, the impedance of the high voltage transformer may be sufficient as it may be the only significant impedance between the load and the system. This may provide suitable results for general study purposes.
- Other more distributed loads should include some average or typical distribution feeder impedance,[25] which may or may not include impedance associated with the pad-mount or pole-mount transformer-fed loads. In addition, a transmission-distribution (T-D) transformer impedance should also be included with any load tap changing (LTC) controls, as applicable. Stand-alone voltage regulator operation can be approximated by the LTC control in the model. The T-D transformer data is fairly easy to obtain since it is often owned by the TO and the interface between the TO and DP; however, an average or typical transformer impedance is also generally suitable.

End-Use Load Tripping and Protection

Different types of end-use equipment will have different protection settings based on the load they are serving. Accurately modeling the protection and controls associated with this equipment is essential for representing the dynamic response of the aggregate load, particularly for voltage sags caused by distribution or transmission system faults. It is important to understand the end-use equipment being represented in the model and have an idea of how this equipment is protected. For example:

- Simple contactors that will likely trip within a couple cycles for a severe voltage sag and re-energize as the voltage recovers
- Building energy management systems for process-oriented drives and motors may trip at higher voltage levels and generally not reconnect for a period of time
- Process-oriented drives that may have voltage-ride through technology to keep the motors connected for voltage sags
- Large commercial or industrial drives that will trip on supervisory protection and may require manual reconnection
- Sensitive loads (e.g., data centers, government buildings, or hospitals) that may have sensitive protection that will switch to local uninterruptible power supply (UPS) and disconnect from the grid
- Single-phase air conditioners that may stall prior to tripping on contactor dropout, resulting in increased reactive consumption

The protection and control settings used in the model should reflect the composition of the load being modeled. For example, load model parameters for small motors used in retail or residential applications should include basic protection for tripping and reconnection; load model parameters for industrial and large commercial motors should have associated trip settings and only a fraction of these motors may reconnect.

End-Use Data Surveys

End-use surveys provide a more comprehensive understanding of specific sectors of the energy industry and their respective electric usage. These surveys often support broad energy initiatives related to demand forecasting, energy efficiency, and clean energy. The studies provide extensive information on end-use consumption of electric energy, summary information on load composition by load type, and load classification for developing baseline load composition information for the dynamic load models.

[25] The impedance captures the electrical impedance between the distribution bus and the aggregate end-use load consumption point(s).

The California Commercial End-Use Survey (CEUS) was developed to support the California energy demand forecasting activities and focus on select electric service areas and the collection of commercial building characteristics. Detailed analysis of operating schedules, equipment stocks, efficiency levels, etc. were all incorporated in the analysis to derive the composition of end-use loads. Figure 5.1 shows an example from the survey detailing the breakdown of electricity usage by end-use load type for commercial load class.

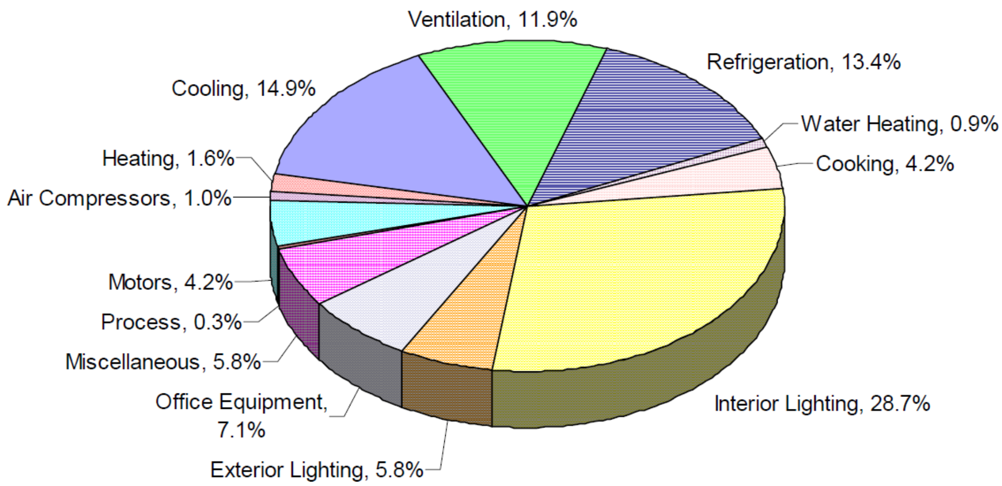

Figure 5.1: CEUS Electric Use by End Use Survey Results[26] [Source: CEC]

The U.S. DOE sponsored a project to develop load composition data for the New England region.[27] The comprehensive study used a "bottom-up" approach using available data from the Energy Information Administration (EIA) along with additional sources on energy usage. These sources included residential consumption surveys, energy efficiency program data, data on miscellaneous and electronics loads, and lighting consumption information. The study determined the amount of each of the major end use load components (e.g., refrigerators, pool pumps, lighting, etc.) and used that information to compile the state-based composition of loads. A conversion to load model parameters was used to get the classification data to model parameters used in the composite load model. Figure 5.2 shows the regional breakdown of end-use load percentages and Figure 5.3 the regional breakdown of load model composition data used in the model.

[26] *California Commercial End-Use Survey*. Itron, Inc., Report CEC-400-2006-005, March 2006. http://www.energy.ca.gov/2006publications/CEC-400-2006-005/CEC-400-2006-005.PDF

[27] W. Gifford, et al., "End-Use Data Development for Power System Load Model in New England – Methodology and Results," DNV-GL Energy, 2014. Available: https://certs.lbl.gov/sites/all/files/data-development-for-ne-end-use-load-modeling.pdf.

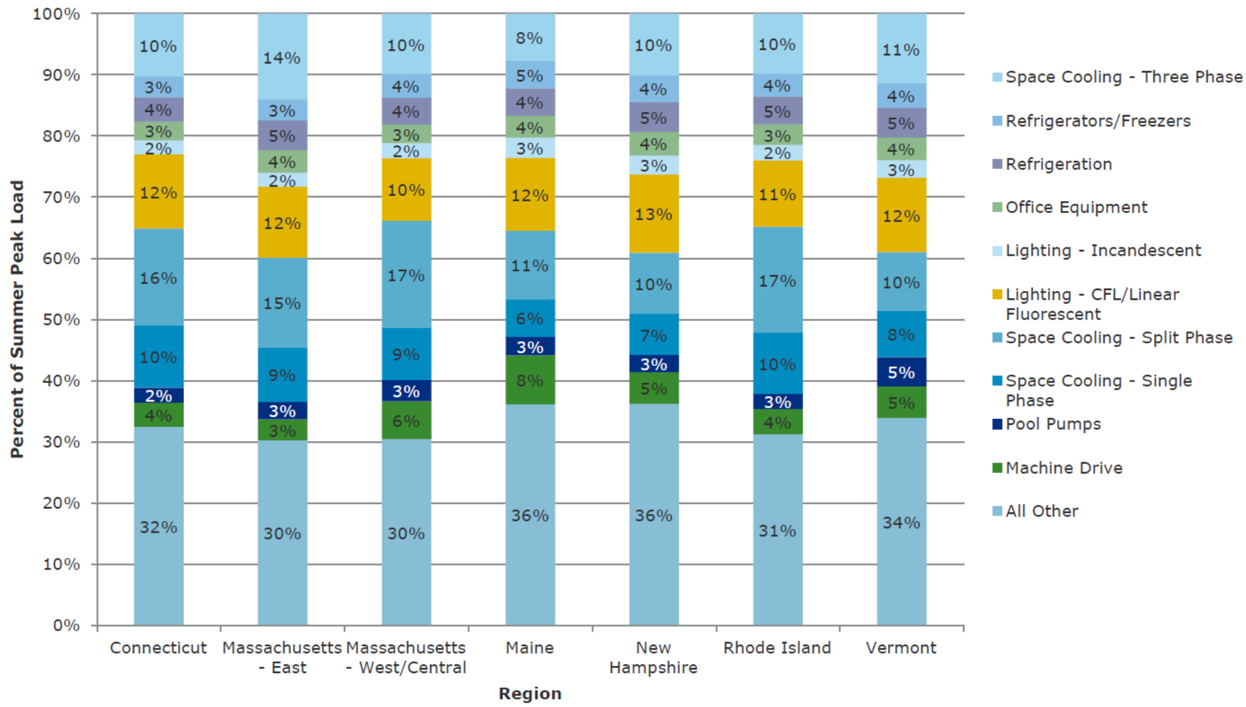

Figure 5.2: ISO-NE Electric Use by End Use Survey Results [Source: CERTS]

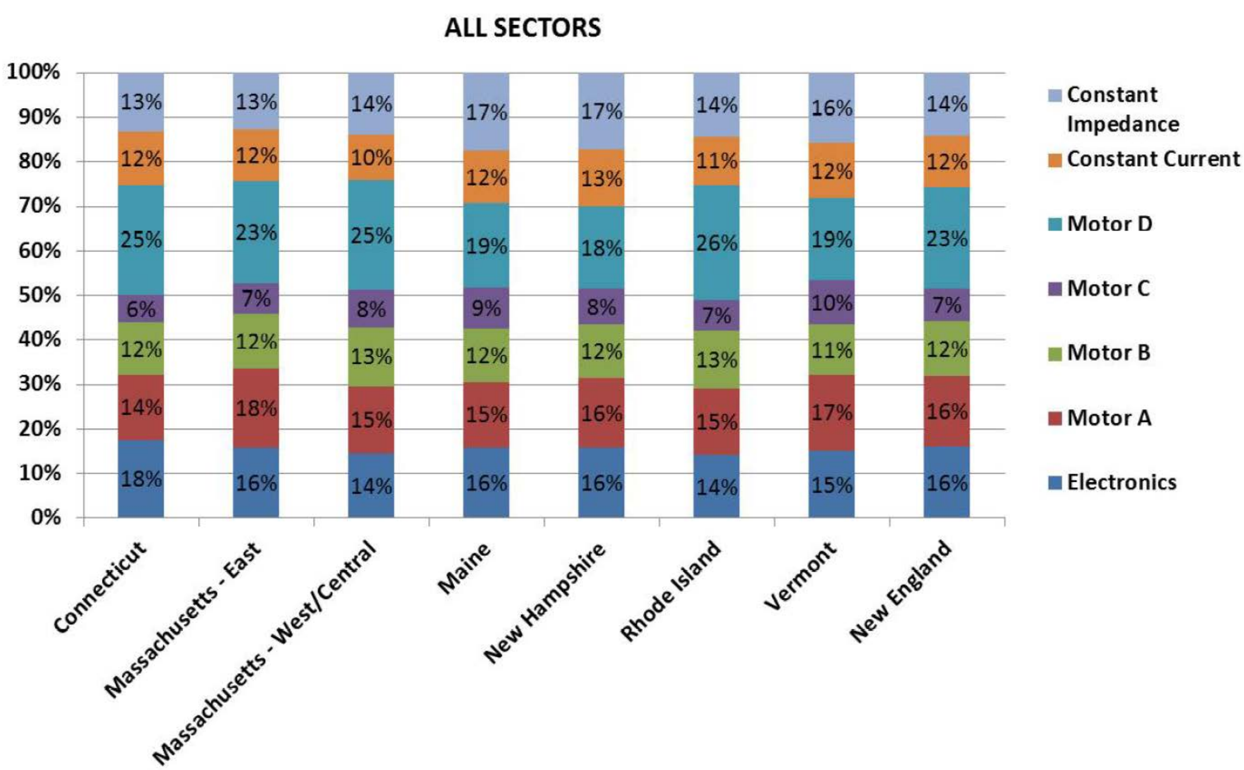

Figure 5.3: ISO-NE Motor Parameter Breakdown from Survey Results [Source: CERTS]

Data from the DP

The TP should work with the DP and neighboring TPs, if applicable, to obtain the necessary information in order to reasonably model the distribution loads. This is particularly important if the TP does not have adequate data or access to such data regarding load characteristics. Distribution utilities may use different methods to classify their loads that can affect the information provided back to the TP. It is important that the TP understand the methods used by the DP to provide this information regarding classification. The methods described below have been used by DPs for classification. To explain the methods, the following example is provided to use as a reference.

Figure 5.4 shows a single distribution meter point serving four customers, three residential households,[28] and one commercial building. The three residential households are served from a single 1 MVA distribution transformer and the commercial department store is served from two parallel 1 MVA distribution transformers. Table 5.1 shows the load data in tabular form.

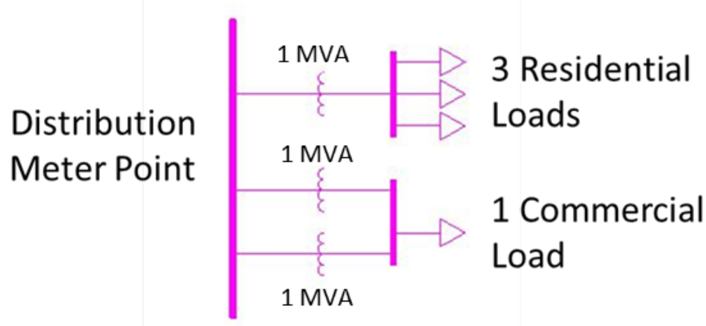

Figure 5.4: Simple Example of Load Classification

Table 5.1: Example Load Composition Data and Classification Methods

Classification / Load Metric	Residential	Commercial
# Customers	3	1
Peak Active Power Demand (kW)	5	15
Total Peak Energy (kWh)	2,000	10,000
Total Transformer Capacity (MVA)	1	2

- **Method 1–Percent Number of Customers:** This method uses a physical count of the different types (e.g., residential, commercial, industrial) of customers to determine the composition for a given load bus. In the example, the load would be classified as three-quarters (75 percent) residential and one-quarter (25 percent) commercial. This method poses concerns for accurate classification of load for dynamics modeling purposes. It does not account for the total demand of each customer classification and simply uses the number of customers regardless of size.
- **Method 2–Percent MW of Load:** Each residential customer has a load of 5 kW and the department store peak load is 15 kW, totaling 30 kW. The load at the metered point using this method is classified as 50%[29] residential and 50 percent[30] commercial. This method works well for allocating load models on peak cases.

[28] The load characteristics for the residential customers are assumed to be identical in these scenarios.
[29] 3 * 5 kW / 30 kW = 50%
[30] 1 * 15 kW / 30 kW = 50%

However, in off-peak cases the load percentages may shift dramatically. For example, in a shoulder or off peak case large industrial customers or commercial loads may consume near the same amount as peak load while residential customers only a fraction of peak load. In these off peak cases, the assumption of percent commercial and industrial load should be re-evaluated and possibly increased from what is provided.

- **Method 3–Percent MWh of Load:** Total energy usage over a given period (e.g., peak month of the last year) is recorded for each customer. Customer load class percentages are determined using this total energy. In the example, each residential customers consumes 2,000 kWh while the commercial customer consumes 10,000 kWh during the peak month of the last year. The percent classifications would be 37.5 percent[31] for the residential and 62.5 percent[32] for the commercial customer. This method provides an average for the year, but may not accurately represent specific periods of interest (e.g., summer peak conditions).
- **Method 4–Percent kVA Distribution Transformers:** The three residential households are served from a 1 MVA distribution transformer and the department store is served from two parallel 1 MVA distribution transformers, totaling three transformers each 1 MVA in size (3 MVA total capacity). The load at that metered point is classified as 33.3 percent[33] residential and 66.7 percent[34] commercial. This method may have an advantage to LSEs because data management is much easier (fewer transformers than customers); however, this method has similar problems to Method 2 because transformer capacities are sized for peak loads, which will skew results because transformers are oversized in anticipation of future growth or to accommodate for contingencies.

Each classification method that may be used by DPs produces a unique representation of the composition of the load that should be accounted for and coordinated with the TP so they understand how the classification information is compiled. Many TPs and PCs advocate for Method 2 since it most accurately reflects the end-use load in terms of MW value on the peak conditions. Adjustment factors can be used to shift the load classifications (residential, commercial, etc.) for off-peak hours. For example, using hourly shapes for various types of loads can help with determining these adjustments. Other methods can be used and the chosen method is based on the granularity and availability of data used for this type of analysis.

Distributed Energy Resources

As the penetration of distributed energy resources (DERs) continues to increase across North America, it should also be more accurately accounted for in steady-state and dynamic simulations of the BPS. DERs can have a substantial impact on the performance of the BPS based on their protection, ride-through, and control strategies.

- **Net Load Reduction:** Regardless of the capacity of DERs, it is not recommended to simply reduce the net load for increasing DERs. This approach does not account for the dynamic response of these resources and also offsets the dynamic response of actual loads, including induction motor load. While small amounts of DERs may not have a substantive impact on grid performance, the aggregate behavior of DERs does have a substantial impact. Further, for higher penetration areas accounting for DERs is critical for understanding performance to grid events.
- **Installed Capacity:** The total installed capacity of DERs should be accounted for and represented in dynamic load models. This capacity may be aggregated on a bus-level or load-level approach based on the granularity of the data available; however, the total amount of DERs should be understood and modeled to get an appropriate dynamic response.

[31] 3 * 2,000 kWh / 16 kWh = 37.5%
[32] 10 kWh / 16 kWh = 62.5%
[33] 1 MVA / 3 MVA = 33.3%
[34] 2 MVA / 3 MVA = 66.7%

- **Types of DERs and Controls:** Performance requirements for different sizes and types of DERs may be different based on utility practices and technology capabilities. For example, older distributed solar rooftop PV installations may be connected to the grid with simple unity power factor, no frequency response capability, and limited ride-through capability. However, larger commercial or solar PV plants connected to the distribution utility bus, for example, may have more stringent requirements that could include dynamic voltage support, frequency response, and ride-through. These could be based on vintage of the resources and the requirements that were in place as the technology continued to evolve and penetration increased. For these situations, it may be important to differentiate some amount of DERs as one technology or control capability and other amounts as other technologies or control capabilities (e.g., "smart" vs. "advanced" controls) and may be accounted for and modeled separately in the dynamic load models.

Chapter 6: Hierarchical Modeling Strategy

Dynamic load models can often be implemented using a modeling hierarchy that is based on the granularity of load classification information available to the modeler. The application of the model includes:

- **Bus:** Bus-level representation captures each load separately and is suited for utilities with detailed information about load composition for each feeder or load in their system. Information is often available from billing data. It is recommended to use as much detail as available and reasonable to the planner; tools are available to simplify data compilation into suitable model parameters.
- **Owner:** This classification is often used when a utility or equipment owner has general information for the loads within their footprint. All loads defined with the identified owner have the same load model representation. This is suitable for situations where minimal or no load composition information is known at the bus-level; however, this can be a large generalization that will skew results. The composition should be based on engineering judgment and understanding of the loads in that owner footprint.
- **Zone:** A zonal approach to load modeling is useful to capture relative geographical areas of parts of the electrical system that are similar in terms of load composition. This includes major load centers such as downtown or highly urban areas where the load is predominantly commercial. It is also useful for representing predominantly residential rural areas. Typically these zones are used in the power flow case to represent a certain area that aligns somewhat with the load modeling.
- **Area:** Area-based approaches are a high-level, simplistic representation of the end-use load and should only be used when very little or no information is known about the loads being modeled. It is known that the load does not exhibit the same composition on a wide-area basis, and that mixture of residential, commercial, industrial, etc., drives a diverse range of compositions. Therefore, this method is not recommended when more detailed forms of data are available.

Modelers can combine these methods using a hierarchy. It is recommended that load composition be represented to the best available data available. If information for industrial loads are available, those loads should be explicitly represented. In addition, if bus-level information is available for some buses but not all, bus-level applications can be used to represent those loads while a broader zonal- or area-based model can be overlaid to account for feeders with unknown load composition.

Chapter 7: Rules of Association

Load model Rules of Association (RoA) are often used to convert load classification data regarding the type of end-use loads to a set of Model Parameters based on the dynamic load model used for system studies. This requires some knowledge of the end-use load equipment at the distribution level. The RoA relies on sound engineering judgment, surveys, and research efforts. There are three steps in going from the system load to developing parameters in a selected load model (see Figure 7.1). The first step, discussed in the preceding sections, is obtaining load class information. This is specific to each utility and the given snapshot in time that is to be studied (e.g., system peak). The next two steps are what is referred to here as the RoA:

1. Determine the types and percentage of end-use components (e.g., air conditioning, computers, compact fluorescent lights, etc.) in each of the load composition classes (Figure 7.1 illustrates residential class). This step is often based on detailed surveys and research performed to identify the make-up of various load classes, and will vary from region to region based on climate, demographics, etc.
2. Convert the components to specific parameters in the final load model structure (Figure 14 illustrates *cmpldw* fractions). This can again be based on surveys, research, and engineering judgment. For example, collective research has developed an understanding of the behavior of residential air conditioners, forming the basis for the percentage[35] of residential A/C load and the actual parameters used in the CLM.

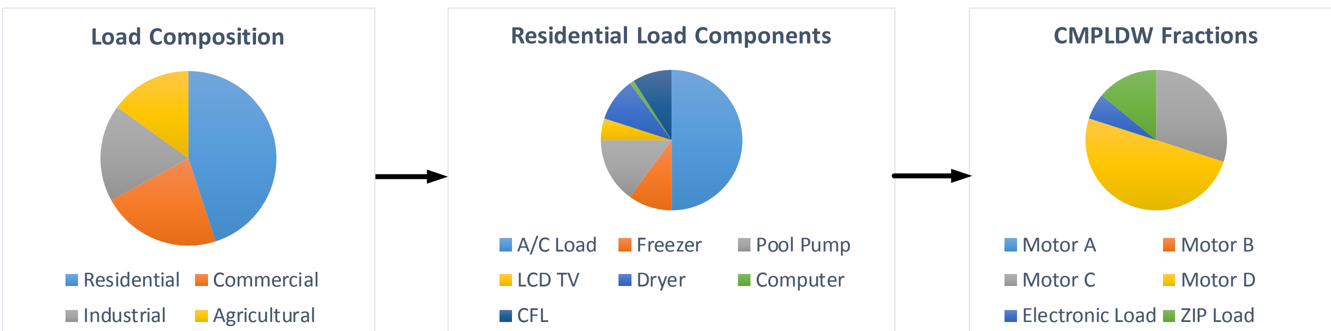

Figure 7.1: Illustrative Example of Load Composition to Model Parameters [Source: EPRI]

RoA derived from actual analysis of end-use load data can improve the accuracy of the rules, particularly for categories that account for a large proportion of the demand, such as cooling, lighting, and industrial drives and motors. This information can often be pulled from other sources of research, such as end-use metering or energy efficiency programs. The RoA can be developed for an aggregate set of loads (Load Classifications) or individual load types (e.g., single-family residential, low-rise commercial, etc.).

[35] This work determined that for a typical residential A/C unit, 80–87% of the power is consumed by the compressor motor, 10–12% by the indoor fan, and 3–5% by the outdoor fan. Thus, the majority of that load type is assigned to the Motor D fraction of the CLM.

Rules of Association for End-Use Load Data

If information relating to the end-use loads are available, a set of RoA logic can be determined for each type of building or load aggregate (e.g., lodging, healthcare, grocery, etc.). Table 7.1 shows an example[36] of converting end-use load information into a set of load composition values for the CLM. Note that information was available for the end-use loads within a given load classification (e.g., retail) and the RoA is converting those loads to a set of Model Parameters. In this example, two forms of ZIP load are used: one represents lighting loads and another represents other loads such as resistive heating or cooking.

Table 7.1: End-Use Load RoA

Load Type	End-Use Load	Motor A	Motor B	Motor C	Motor D	Power Elect.	ZIP A	ZIP B
Small Commercial	Heating	0.7			0.2			0.1
	Cooling	1.0						
	Ventilation		0.7			0.3		
	Water Heating						0.1	
	Cooking		0.2			0.2		0.6
	Refrigeration	0.8			0.1	0.1		
	Exterior Lighting						1.0	
	Interior Lighting						1.0	
	Office Equipment					1.0		
	Miscellaneous		0.5	0.5				
	Process		0.5	0.5				
	Motors	0.3	0.4	0.3				
	Air Compression	1.0						

Rules of Association for Load Classification Data

The RoA can also be applied to load classification data if end-use load data is not available. The load types are simply aggregated up one level from the component-based to the classification-based approach. This is common for entities with information pertaining to load classification (e.g., billing information) but no knowledge of the equipment within those load classifications. Table 4 shows an example of the RoA created for a multi-region utility in the Eastern Interconnection applied to the CLOD model in PSS®E. The load classifications (rows) were determined based on the customer billing data available. The model parameters are based on the model being used (CLOD). It was determined that for this implementation, the feeder equivalent impedance data would be held constant for all loads in the area since more detailed information was not available at the time. The RoA logic in the table is based on engineering judgment and reasonable estimations of load composition for each load classification.

[36] https://certs.lbl.gov/sites/all/files/data-development-for-ne-end-use-load-modeling.pdf

Table 4: Rules of Association Example for CLOD Model								
Building Type	% Large-Motor	% Small-Motor	% Discharge Lighting	% Constant Power	% TX Exciting Current	Kp of Remaining	Branch R	Branch X
Church	0	0.4	0.1	0.1	0	1.25	0.04	0.12
State Building	0.2	0.4	0.2	0.1	0	1.25	0.04	0.12
County Municipal	0.2	0.4	0.2	0.1	0	1.25	0.04	0.12
Industrial	0.8	0.1	0.1	0	0	1.25	0.04	0.12
Large Commercial	0.5	0.2	0.1	0.1	0	1.25	0.04	0.12
Large Comm./Industrial	0.5	0.4	0.1	0	0	1.25	0.04	0.12
Small Commercial	0.3	0.4	0.2	0.1	0	1.25	0.04	0.12
Region 1 Residential	0	0.7	0	0.1	0	1.25	0.04	0.12
Region 2 Residential	0	0.6	0	0.2	0	1.25	0.04	0.12
Lighting Only	0	0	1	0	0	1.25	0.04	0.12
Flat Load	0.15	0.45	0.2	0.1	0	1.25	0.04	0.12
Resale	0	0.6	0	0.2	0	1.25	0.04	0.12

To put the RoA example into context for this load classification example, the following judgments were made based on the data available and knowledge of the end-use loads:

- Residential and Church load are mainly small-motor load, lighting, and power electronics (constant power); County, State, and Small Commercial load are very similar in nature with some large motors, mainly small motors, lighting, and power electronics.
- Industrial differs from Large Commercial in that there are more large motors in industrial facilities compared with large commercial buildings and multi-storied buildings.
- Residential was broken into two regions based on distinct locations and load behavior in those regions; this was used to differentiate the amount of small-motor load (assumed to be single-phase air conditioner load).
- Flat Load and Resale loads were given “default” values since information about these loads was not well known (resale power customers).
- It was assumed that a new load classification of Data Center would be introduced to represent a growing composition of the load in select regions.

Chapter 8: Modeling Thresholds

While each load has its own dynamic behavior, the aggregate response of these loads is what needs to be captured reasonably by the load models applied. Load modeling thresholds are often applied in the model to assure numerical robustness and to focus on the loads that have most impact on the performance of the BPS. The following thresholds are recommended when applying dynamic load models to the dynamics case:

- **Minimum Ratio of Active to Reactive Power (Power Factor):** Because the MVA Base used for calculation of the load model parameters are often based on the active power (MW) load modeled in the base case, numerical instability can exist when the model is applied to loads with poor power factor (or ratio of P/Q). The maximum power transfer equation is violated, resulting in potential initialization problems or errors. Therefore, dynamic load models should not be applied to loads where the ratio of P/Q is greater than a defined threshold value.[37] Common practice is to use a default value for minimum P/Q ratio of 4.0. This comes out to a power factor of 0.86; the absolute value of this number can be reduced based on local sensitivity analysis to ensure proper initialization. The P/Q ratio is commonly used over the power factor for simplification of users since it does not require a calculation of power factor and its ease of use by engineers running studies.
- **Voltage Magnitude:** The dynamic load models introduce an equivalent impedance between the end-use load bus and the low-side bus of the transmission-distribution (T/D) transformer. If the high-side bus of the T/D transformer is abnormally low in the power flow base case, this will cause the end-use load bus created to potentially have very low bus voltage and cause voltage collapse upon initialization. For this reason, a voltage magnitude threshold should be used when applying the dynamic load model[38]. Common practice is to use a default value of 0.9-0.95 pu voltage with local sensitivity analysis to reduce that number further.
- **MW Demand:** Small loads generally do not have a substantive impact on the dynamic performance of the BPS. For this reason, the dynamic load model is generally not applied to small loads. Rather, the “default” or “standard” load model is applied to these buses; however, based on TPL-001-4 requirements, it is recommended to ensure that some form of induction motor load be applied to these loads as well. This may include, for example, applying an area- or zone-based dynamic load model with more detailed models where available. Common practice is to use a default value of 5-10 MW for interconnection-wide case creation and studies; local studies should consider using a lower threshold for detailed modeling.

These modeling thresholds are especially important when applying a dynamic load model to state estimator snapshot cases. Many state estimators use pseudo loads to achieve solution convergence. These loads do not reflect actual system loads; rather, they drive the solution mismatch towards zero for a more robust solution. The power factor of these loads can be any value and often with poor power factor. Blanket load models (e.g., area-, zonal-, or owner-based) may not consider these thresholds and may have trouble initializing. It is recommended that entities analyze loads with poor voltage or power factor loads more carefully and modify the base case accordingly if those changes are warranted. In some cases where loads should be modeled with bad power factor or bus voltage magnitude, these loads will have to be accounted for specifically.

[37] It is recommended that these loads be analyzed closely to determine if the correct power factor is applied to the aggregate load, which could lead to improved power factor for each load and therefore the dynamic load model actually applied to that load. Not modeling poor power factor loads on a wider area could lead to potential voltage-related issues that could be missed without applying the correct load model to those buses.

[38] Voltage magnitudes should be modified in the base case using available reactive devices to attain reasonable high-side bus voltages for the Transmission-Distribution transformer such that a dynamic load model can be applied correctly.

Chapter 9: Sensitivity Analysis

The complexity in gathering end-use load data and uncertainties in developing parameters of the load model necessitate some form of sensitivity analysis to understand the impact it has on reliability. These uncertainties can be categorized broadly as:

- Constant variability in load composition and demand level due to temporal, geographic, and technological changes in the load. A load model can be tuned to match historical events for a particular snapshot in time; and "default" or "representative" load models used for studying future states should capture the general expected performance of the load under those conditions, but will inherently have some uncertainty associated with it.
- Aspects of the load model that cannot be captured in large scale positive-sequence simulation tools, such as point-on-wave at which a fault/voltage dip occurs affecting motor load stalling, and voltage tripping and reconnection levels.
- The process of aggregation that is necessary since BPS planning models cannot represent the full details of distribution systems. Thus, load is aggregated to the substation level. Load models used for analysis of the BPS performance create an equivalent representation of the distribution system which is a simplification and in its very nature introduces some uncertainty.

Once an appropriate and reasonable load model has been developed, some level of sensitivity analysis around uncertain aspects of the model is prudent in planning studies. Determining the sensitivity scenarios to run and investigate is a function of many factors including load composition, system topology, and the study being performed. Sensitivities worth considering are parameters that lead to the greatest impact in system performance as well as those with the greatest level of uncertainty. For example, key parameters for voltage stability analysis are those that lead to the greatest impact on system voltage recovery. In general, the following load parameters tend to be the ones that cause the greatest sensitivity in study results:

- Load composition (i.e., percentage of Motor A, B, C, D, power electronic load, and ZIP load); greater percentage of motor loads, particularly motor D, tends to have significant impact on voltage recovery.
- Voltage trip and reconnection settings for large three-phase motors (Motor A, B, and C)
- Stalling voltage threshold for the residential A/C motor (Motor D)
- Percentage of Motor D that stalls and can recover
- Feeder impedance

Any sensitivity analysis should use parameters that are physically meaningful and based on engineering judgment. For example, laboratory tests[39] have revealed that residential air conditioner compressor motors stall for voltages ranging from around 0.45 pu to 0.65 pu for a duration as short as three cycles. This is affected by the point-on-wave where the fault is initiated as well as the ambient temperature. In a planning study, this information can be used for summer peak contingency analysis to study the impacts higher ambient temperature days can have on voltage stability and transient voltage response. The most difficult sensitivities to study are those aspects of the load behavior which are not well known, and in most cases impractical to explicitly model in large-scale studies. Regardless, sensitivity studies play a key role in more comprehensively understanding how the load will impact BPS reliability and stability.

[39] A. M. Gaikwad, R. J. Bravo, D. Kosterev, S. Yang, A. Maitra, P. Pourbeik, B. Agrawal, R. Yinger, and D. Brooks, "Results of Residential Air Conditioner Testing in WECC", Proceedings of the IEEE PES General Meeting, Pittsburg, July 2008.

Chapter 10: Measurement-Based Approaches

One of the evolving methods for gaining greater confidence in the modeling of load dynamic behavior is using a measurement-based approach for model verification and estimation. The concept of measurement-based approaches is to use a measured response of load (e.g., monitoring at the head of a distribution feeder). A set of load model parameters is then derived that best fits the actual response (i.e., tuning the model) through parametric analysis or optimization techniques. The advantage of such an approach is that if a good fit can be achieved with reasonable and physically meaningful parameters, then the established model has been verified against actual system behavior. Disadvantages are: (i) the verified model is only good for the one snapshot in time for which the measured event occurred[40]; and (ii) the process of iteratively optimizing model parameters can become complex and yield multiple credible (and non-credible) solutions[41]. For these, and other reasons, a measurement approach used in isolation is unlikely to yield useful results.

A more suitable approach is to use the RoA to develop reasonable model parameters and use measurement-based verification to confirm a reasonable fit and fine tune parameters against actual system events. This helps achieve a baseline model for use in the optimization process of the measurement based approach.

One example of a measurement based approach is the EPRI Load Model Parameter Derivation tool,[42] illustrated in Figure 10.1. A digital monitoring device is placed at the source end of a distribution feeder,[43] which records the response[44] of the feeder to a disturbance on the transmission system or adjacent feeders. The recorded events are pre-screened to identify those suitable for the model verification process and selected events are processed to convert the data into an appropriate format[45] required for the parameter optimization tool. In the tool, an appropriate load model structure is chosen. Then, an optimization algorithm runs that compares the simulated response at the head of the feeder to the actual measured response, and tries to optimize selected parameters to achieve a least-squares best fit between the measured active and reactive power response of the load and the simulated response. Figure 10.2 illustrates the process and tool for an actual event.

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[40] For example, the if event was during light load conditions, the verified model may not be a good representation of load dynamics for peak conditions, and vice versa. This issue may not exactly relate for purely industrial load where composition does not change significantly.

[41] This may make it hard to decide what the most reasonable load model is.

[42] A. Maitra, A. Gaikwad, P. Pourbeik and D. Brooks, "Load Model Parameter Derivation Using an Automated Algorithm and Measured Data", Proceedings of the IEEE PES General Meeting, Pittsburg, July 2008.

[43] This might be a digital fault recorder (DFR), a power quality (PQ) meter, or other device that can preferably record several seconds worth of data following a significant voltage depression

[44] Three phase voltages and currents.

[45] Positive sequence rms

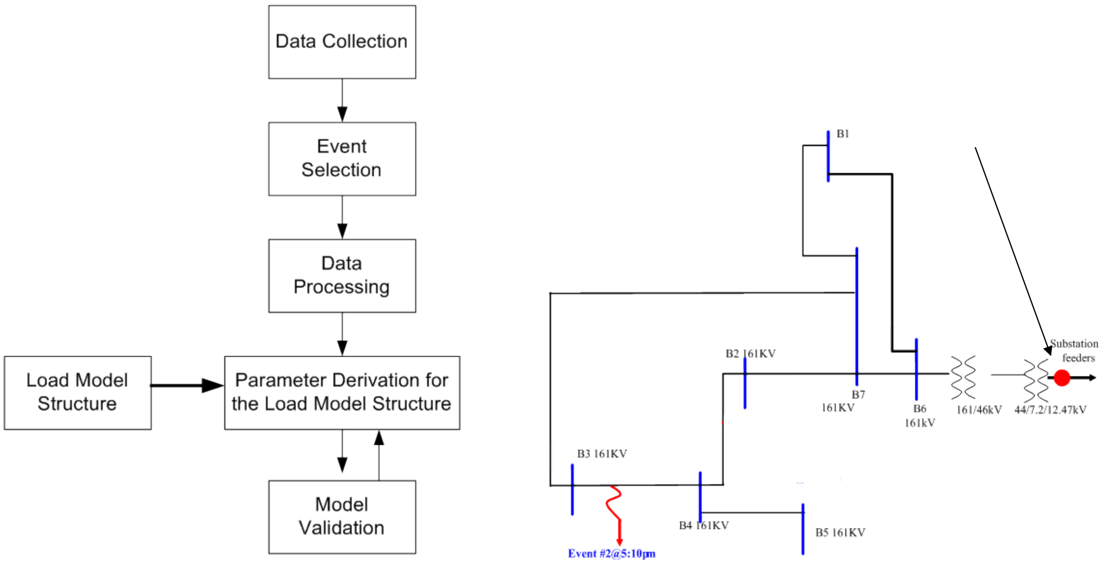

Figure 10.1: Measurement-Based Load Model Parameter Derivation Process [Source: EPRI[46]]

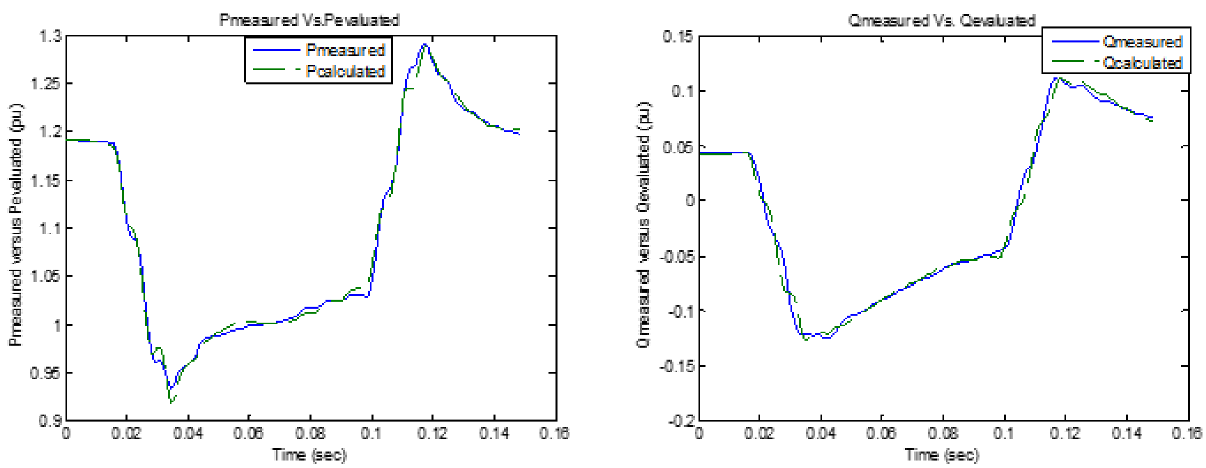

Figure 10.2: Comparison of Active and Reactive Power after Optimization [Source: EPRI]

[46] EPRI Product ID 3002005744, Technical Update on Load Modeling, December 2015. Available: HERE.

Appendix A: Default Industrial Load Compositions

Table A.1 provides default composition data for common industrial loads to be used as a starting point when additional information is not available.

Table A.1: Industrial Load Compositions

Load Types		Load Composition Fractions						Static Load Equation Coefficients & Exponents									
Load Classification	**ID**	**Motor A**	**Motor B**	**Motor C**	**Motor D**	**Power Elec**	**Dist. Gen**	**Static PF**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**	**Pf**	**Qf**	
Petro-Chemical Plant	IND_PCH	0.15	0.25	0.40	0	0.15	0	1	0	0.05	0	1	0	0	0	-1	
Paper Mill – Kraft Process	IND_PMK	0.10	0.25	0.40	0	0.20	0	1	0	0.05	0	1	0	0	0	-1	
Paper Mill – Thermal-Mech	IND_PMT	0.05	0.55	0.25	0	0.12	0	1	0	0.03	0	1	0	0	0	-1	
Aluminum Smelter	IND_ASM	0.10	0	0	0	0	0	1	0.9	0	0	1	0	0	0	-1	
Steel Mill	IND_SML	0.20	0.25	0.30	0	0.20	0	1	0	0.05	0	1	0	0	0	-1	
Mining	IND_MIN	0.20	0.35	0.35	0	0.05	0	1	0	0.05	0	1	0	0	0	-1	
Semiconductor Plant	IND_SCD	0.10	0.35	0.10	0	0.40	0	1	0	0.05	0	1	0	0	0	-1	
Server Farm	IND_SRF	0.25	0.10	0.05	0	0.60	0	1	0	0.05	0	1	0	0	0	-1	
Industrial – Other[47]	IND_OTH	0.20	0.25	0.30	0	0.20	0	1	0	0.05	0	1	0	0	0	-1	
Agricultural Irrigation	AGR_IRR	0.20	0.25	0.45	0	0.10	0	1	0	0	0	1	0	0	0	-1	
Agricultural Pumps	AGR_PMP	0	0	1	0	0	0	1	0	0	0	1	0	0	0	-1	
Nat Gas/Oil Pipeline Pumps	IND_PIP	0	0	1	0	0	0	1	0	0.05	0	1	0	0	0	-1	
Power Plant Auxiliary	PPA_AUX	0.10	0.50	0.25	0	0.15	0	1	0	0.05	0	1	0	0	0	-1	

[47] This may be used in cases where the classification of the industrial load is not known. This is meant to be a conservative value as a starting point if additional classification information is not known. It may be useful to perform sensitivity studies for cases where the type of industrial facility is not known, particularly for larger industrial loads.