Load Modeling
Current State and Next Steps

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The Western Interconnection has made significant advancements in dynamic load modeling in the past 10 years. A composite load model was developed, tested and implemented in all major production-level grid simulators used in WECC including General Electric’s PSLF, PowerWorld Simulator, and Siemens PTI PSS®E. Load composition data sets are developed for 24 hours, four seasons, and various types of substations (residential, commercial, mixed and rural) in 12 climate zones across the West, as well as for several types of industrial loads. Tools for load model data management have been developed, and processes for creating load model records are put in place. WECC planning base cases now have populated climate zone and feeder/substation identifiers. Load models are a fundamental part of power system planning and operating studies.

WECC adopted a phased implementation of the composite load model. Stalling phenomenon of single-phase compressor motors needs further validation against event recordings and tests. System performance criteria used to plan and operate the power system also need to be updated to recognize the phenomenon of Fault Induced Delayed Voltage Recovery. Therefore for Phase 1, the air-conditioner stalling feature was disabled in the model pending further validation. WECC approved Phase 1 composite load model for planning studies starting with the 2014 study program.

Phase 2 work is under way including validation and improvement of single-phase air-conditioner models, integration of distributed generation models, improved protection and control representation. The need for more comprehensive tools for load composition assessment and data management has also emerged. WECC Reliability Subcommittee is also developing guidelines for system performance criteria to be used in planning and operating studies.

The objective of this paper is to inform on the current state of load modeling in the West and to articulate the areas where additional research and development efforts are needed. The paper also outlines a vision of an “ideal” set of tools for load modeling from the perspective of a transmission planner.
1. Vision

Our vision is that a system planner will have knowledge, tools and data sets:

- to validate forecasted \textit{load demand} (active and reactive power) by a substation, including:
  - sensitivities of assumptions on economic development, energy efficiency and climate policies, and technology advances
  - load forecast confidence intervals for sensitivity studies
- to provide reasonable estimate of \textit{dynamic load models}, including end-use composition and dynamic characteristics of end-uses, and their protection and controls
  - for a given season, time of day and weather conditions
- to size up demand response opportunities
- to perform system studies to identify system performance impacts of changes in end-use characteristics and distributed generation integration, and then
  - to determine the effectiveness of wide range of solutions at utility and end-use (or distributed generation) level
  - to inform development of regulatory standards
2. History and Current State

2.1 Load Demand

Powerflow studies need forecasted load demand and power factor for each substation. Any load demand forecast carries a degree of uncertainty. For system planning standpoint, it is not the precision of the demand forecast that is important, but establishing a range of plausible load levels corresponding to various economic and weather scenarios.

A) Long-term forecast

Long-term (1 – 10 years) load forecasting methods use mostly statistical approaches that are based on time-series regressions of historic load peaks.

The BPA’s Agency Load Forecasting (ALF) system produces demand forecast for most Federal agency, public and cooperative customers. ALF uses a statistical approach based on time-series regressions that reflect a fundamental assumption that historical electrical retail consumption patterns will continue into the future. Forecasts produced by ALF allow customer demand forecasts to be adjusted to reflect heating and cooling weather conditions, to model explicitly addition/retirement of industrial sties, as well as energy efficiency measures. BPA also reviews load forecasts for the regional IOUs’ retail load within Pacific Northwest. The forecast is usually done by delivery points, which are mapped to substations in planning cases.

System planners question the “accuracy” of the demand forecast, particularly for out years. The reason is the lack of context given with the forecasted peak demand. System planners need to understand the base assumptions and sensitivities around the data. System planners use historic SCADA data to independently validate the demand levels in power flow base cases, and often have to make adjustments to the demand before performing system reliability assessment.

Incorporating load-temperature dependency is essential for testing robustness of system plans. Appendix A illustrates the sensitivity of load profiles for residential and commercial load substation with respect to temperature for three days during summer 2009— a cool day, a ‘normal” summer day, and a heat-wave condition.
B) Short-term forecast

Short term load forecasts are usually well understood, and is utilized by utilities, system operators, power marketers, and energy traders. Statistical methods are used to forecast the short-term demand adjusted for weather dependency.

Power system operators use state estimator models for near-term operational studies. Most delivery points are metered and included into a state estimator model. Load levels in a state estimator model can be adjusted for weather dependency for the day-ahead day, or even week-ahead, studies.

C) End-Use Load Forecast

End-use based demand forecasting is mentioned in the literature. BPA transmission planning has performed end-use load composition and demand analysis during the development of WECC composite load model. The end-use approach is data intensive and requires significant tuning and validation of building models. It is hard to envision this approach being used in place of regression analysis for demand forecast. The end-use approach, however, is beneficial for evaluating the relative impact of new technologies on load shapes and demand in 10+ year horizon. Such technologies include electric vehicles, rooftop solar, energy efficiency measures. End-use modeling is discussed in greater detail in Dynamic Load Modeling section.
2.2 Dynamic Load Models

Dynamic load models are used in transient stability assessment of the power grid.

A) History of Dynamic Load Modeling

1970’s – 80’s. Load models were represented with static models in the interconnection-wide power system studies, mainly constant current for active power and constant impedance for reactive power. Special studies, usually local area or industrial sites, used motor models.

1990’s. EPRI Loadsyn project led to use of static ZIP models, where components are represented as a combination of constant impedance, constant current and constant power components [5]. IEEE efforts to include motor models for the interconnection-wide studies did not get much traction in the industry. Modeling was a reflection of the computing capabilities of that time as well as the complexity of data management.

2001. BPA and WECC MVWG argued the need for representing motor load in dynamic simulations following model validation of July 2 and August 10 1996 outages, and August 4 2000 oscillation event. WECC adopted 20% of load to be presented as induction motor load at every load bus across the interconnection for all seasons [11]. Induction motors were connected to high-voltage buses (115-kV or 138-kV), which was not realistic, but what could be reasonably accomplished with the computing technology of the time.

Events of Fault-Induced Delayed Voltage Recovery (FIDVR) were first recorded in Southern California, Florida, and Atlanta Metro area in early 1990’s. Southern California Edison, Florida Power and Light, and Southern Company developed detailed dynamic models for their regions to study the system impact of residential air-conditioner stalling. The models included a distribution equivalent and required special models for residential air-conditioners [6-10]. The models were used for special studies, not on interconnection-wide basis.

B) WECC Composite Load Model

In 2002, WECC started a process to develop a Composite Load Model for the interconnection-wide studies. The model structure used by SCE, Southern and FPL for their special studies was used as a starting point. The main features of the model are (a) recognition of electrical distance between a transmission bus and where end-uses are connected, and (b) representation of diversity of electrical end-uses. In 2005, WECC successfully prototyped the composite load model in interconnection-
wide studies. In 2007, General Electric implemented the first version of the model in its PSLF simulator. Figure 2 shows structure of WECC composite load model

![Figure 2: WECC composite load model](image)

WECC also recognized that single-phase compressor motors, used in residential air-conditioners and largely responsible for FIDVR events, cannot be represented with three-phase motor models and require special modeling. SCE, BPA and EPRI conducted extensive testing of residential air-conditioners to determine their dynamic response characteristics to voltage and frequency disturbances [15]. WECC developed single-phase positive sequence motor models, and vendors implemented them in their grid simulators [3,4]. The primary concern is stalling of single-phase air-conditioner motors. Both tests and disturbance recordings show that single-phase compressor motors can stall in as few as two cycles when the terminal voltage drops to about 60%. The stall voltage and duration are affected by motor loading which in turns depends on the ambient temperature. To make the matter more complicated, the stalling also depends on the point-on-wave where the fault is applied. While the existing single-phase compressor motor model [3] represents the system impact of the air-conditioner stalling, more work is needed to be able to predict whether and how many of air-conditioners stall during a fault. Recognizing that the efforts to improve the air-conditioner modeling need to continue, WECC adopted a phased approach for implementing the composite load model. Phase 1 assumes that compressor motors ride thought a fault and do not stall. Phase 2 will be implemented when the single-phase motor model is sufficiently validated against actual system events, and appropriate requirements are developed for transient voltage dip and recovery.

C) WECC Load Composition Model
Assumptions on load composition are paramount for dynamic load modeling. WECC approach divides the interconnection into twelve climate zones, as shown in Figure 3. Within each climate zones, substations can be designated as:

- Residential, representative of a sub-urban area
- Commercial, representative of down-town areas and office parks
- Mixed, a mix of residences and commercial areas
- Rural

In addition, industrial and irrigation loads have their own identifiers.

![Figure 3: “default” climate zones in Western Interconnection](image)

David Chassin at PNNL developed the original full-scale Load Composition Model. The model was very detailed and included comprehensive models of various types of residential (e.g. single-family detached and multi-family) and commercial (e.g. large office, grocery, retail, assembly, hotel, etc) buildings. The model was very instructive in understanding load profiles and load composition of various types of buildings and feeders.
The commercial end-use survey performed by California Energy Commission provides the most complete data sets for commercial building [13]. The data was “extrapolated” to other regions within WECC.

Ultimately, BPA developed a light version of the Load Composition Model. 24-hour load composition profiles were generated for normal summer, summer heat-wave, shoulder and winter seasons for all 12 climate zones. A user can visualize load profile and composition for a chosen make-up of residential, commercial and industrial loads in a given climate zone, Figure 4.

![Figure 4: load shape and load composition form BPA/WECC Load Composition Model](image)

Given hour and season, the LCM generates a spreadsheet with load composition data for all 12 climate zones times 4 feeder types in the Western Interconnection.

**D) End-Use Model Data**

*One test is worth a thousand of expert opinions.*

SCE and BPA tested a number of electrical end-uses, including various sizes and types of air-conditioners, refrigerators, fans, pumps, consumer electronics, lighting, and power electronic drives. The tests provided basis for the load model parameters. Survey of manufacturers’ data sheets was also done particularly for large commercial and industrial loads.

Assumptions on end-use control and protection are essential for load modeling. WECC and DOE funded initial work by John Kueck on how various
end-uses are impacted by voltage sags and their duration. The report is available at the WECC website [14]. Follow up activities are planned.

E) Tools for Data Management

BPA developed the Load Model Data Tool for managing the load model data. The original Load Model Data Tool is a sequence of EPCL programs in GE PSLF software. LMDT links (i) climate zone identifiers in GE PSLF base case with (ii) LCM-produced load composition data and (iii) end-use dynamic model data to generate *dynamic load model* records for GE PSLF grid simulator.

WECC MVWG and PNNL also developed a stand-alone Load Mode Data Tool to accommodate Siemens PTI PSS®E users.

F) WECC Composite Load Model Implementation Plan

WECC checklist for composite model implementation includes:

- Robust and stable model structure is implemented in production grid simulators – GE PSLF, Power World, and Siemens PTI PSS®E
  - The model is implemented in GE PSLF, Power World, and Siemens PTI PSS®E. The model was extensively tested during the evaluation period and system impact studies.
- Default model data sets are developed WECC-wide (recognize climate diversity, seasonal and time of day load variations)
  - Default data sets are developed for 12 climate zones, 4 types of feeders/substations, for 24-hours, 4 seasons
- Tools for managing load model data are available
  - Load Model Data Tool and Load Composition Model are available for data management, WECC powerflow base cases are populated with load identifiers
- Validation and system impact studies are completed
  - Initial set of validation studies is completed. Additional studies of air-conditioner stalling phenomenon are planned.
- Appropriate reliability metrics are developed
  - WECC Reliability Subcommittee is addressing the system performance issues

G) System Impact Studies
Phase 1 composite load model went through a comprehensive evaluation and testing by WECC transmission planners for almost two years, and WECC TSS approved the model at their August 2013 meeting.

Several Transmission Planners, including BPA, SCE and PSE, are also in process of conducting sensitivity studies with Phase 2 composite load model. Such studies are very instructive in identifying further model improvements, better understanding of system impacts, and development of system performance requirements.

WECC Reliability Subcommittee (RS) is in the process of developing guidelines for transient voltage dip and recovery. The expectation is that TPs and Planning Coordinators (PC) will use the guideline to establish their performance criteria per requirement R5 in NERC TPL-001-4 Standard.

3. Acknowledgement

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Substantial time contributions have been made by study engineers in many WECC utilities and WECC technical staff.

General Electric Company did the initial implementation of the composite load model in its PSLF simulator.
4. Next Steps in Research and Development

4.1 AC Stall Models

Single-phase compressor motors in residential air-conditioners and heat-pumps tend to stall quickly during voltage sags. SCE, BPA and EPRI tested 27 residential air-conditioners. General air-conditioner characteristics are understood [1-4]. However, the effects of point-on-wave and of part of the compression cycle when a fault is applied need further investigation, as currently planned by SCE and BPA.

Point-on-wave single phase motor models have been available for decades. Our challenge is to model single-phase compressor motors in positive sequence simulators. Two models are currently developed (i) performance motor model [2,3] and phasor model [4]. Both models are implemented in GE PSLF grid simulator. While the models are available, our experience is that the model represents reasonably well system response after air-conditioners stall, but somewhat less accurate in predicting whether air-conditioners stall and how wide spread is the stall area. It is possible that the point-on-wave of a fault plays a significant role.

BPA is seeking proposals from universities and practitioners on advancing the development of single-phase motor models for positive sequence grid simulators. Specifically, we are asking the following questions:

- How is the air-conditioner stalling affected by point-on-wave when a fault is applied? How air-conditioner stalling is affected by a part of compression cycle when a fault is applied (reciprocating and scroll compressors)?
- What are the key sensitivity parameters and how to quantify them in a positive sequence model, including the following: point on wave when a fault is applied, position of compressor crankshaft, compressor type, and ambient temperature?
- How accurate can we expect a positive sequence model to represent responses of a single-phase compressors to a fault?
- How to equivalence the behavior of multiple single phase motors along distribution feeders in a positive sequence equivalent models?
What is the expected level of modeling accuracy that can be achieved with model equivalencing with respect to voltage sags?

**BPA** expects MATLAB code to be delivered for point-on-wave and positive sequence models developed under this project.

### 4.2 Load Monitoring and Model Validation

Load model validation is essential for ensuring that the load models are reasonably accurate. Model validation is done by comparing model simulations with the actual event recordings, and by understanding how the sensitivities in modeling assumptions affect the model response. While our primary concern is a large-scale FIDVR event initiated in the high-voltage transmission system, such events are very rare, and therefore the data sets of model validation cases are very limited. FIDVR events are much more common in sub-transmission and distribution systems, and since they rarely propagate upward, they are not easily observable by PMUs in high voltage transmission system. PMUs usually record only positive sequence quantities. Loads are single-phase and their behavior is sensitive to the point-on-wave where a fault is initiated, therefore individual phase point-on-wave quantities are needed to get the insight into load behavior. In addition, PMU quantities are usually filtered over at least one cycle, and in many cases over 4 to 5 cycles, and do not capture the full magnitude of a system fault. Therefore, transmission level monitoring with PMUs is not sufficient and needs to be supplemented with distribution-level monitoring.

Southern California Edison with support from the DOE CERTS program installed a number of power quality recorders in its distribution systems [12]. The program has been a huge success. A large number of events were recorded since the start of the program, many being FIDVR. The data is available for analysis through CERTS. The data is essential for validating and tuning single-phase air-conditioner models, for both positive sequence and transient.

BPA is developing a plan to install a number of similar power quality recorders devices in the Pacific Northwest. The installation will include distribution substations and customer locations. The power quality recorders will record:

- Point-on-wave data during a fault – 5 cycles before, 30 cycles after
- RMS quantities at 1 sample per second for 30 seconds past fault
- Continuous 5-minute recordings of load voltage, frequency, active, and reactive power

The data will be available for analysis and model validation similarly to SCE data.

**BPA is seeking proposals from universities on developing methods, techniques and tools for analysis of distribution level disturbances for the purpose of validating and calibrating components of the composite load model.**

**Specific requirements:**
- the available recordings are taken on the customer side (240 or 480 voltage) of a
distribution transformer, and include point-on-wave voltage and current waveforms before
and after a fault
- the validation models must include EMTP-level models of corresponding residential and
commercial customers, and their positive sequence equivalent models

Project 4.2 may be pared with project 4.1.

4.3 End-use protection and control response to low voltages

Assumptions on end-use control and protection are essential for load modeling. WECC and DOE
funded initial work on understanding how various end-uses are impacted by voltage sags and their
duration [14]. We would like to build on the initial work.

*BPA is seeking small proposals from experienced practitioners on how control and protection*
*systems in various commercial buildings are affected by voltage sags. The list of buildings to*
*include groceries (e.g. Safeway, Whole Foods), box retailers (e.g. Target, Ross), shopping malls*
*(Westfield), restaurants (e.g. Applebee’s, Olive Garden), office building in an office park, office*
*building in downtown area, etc. The project needs to include field visits to various types of*
*buildings and interviews of building operators.*

4.4 End Use Dynamic Characteristics

*One [properly done] test is worth a thousand expert opinions – Mike Johnson, BPA engineer*

Southern California Edison has premier facilities for testing a wide
variety of electrical end-uses and distributed generation. BPA has
previously done the end-use testing in other BPA labs. BPA is now
constructing its dedicated end-use testing facility, including a large
chamber with controlled temperature. BPA and SCE plan to continue
testing a wide range of electrical end-uses, including additional tests
on air-conditioners (3-phase commercial units, high efficiency
electronically connected units), heat-pumps (including variable
refrigerant flow units), various types of fans, consumer electronics,
lighting, power electronic drives, and solar PV inverters.

*BPA is seeking an on-going collaboration with local universities in*
*conducting test analysis, developing and validating models of*
electrical end-uses.*
4.5 Distributed generation modeling

Southern California Edison experiences unprecedented addition of distributed generation, mainly roof-top PV panels. State of California mandates that the new residential construction starting 2020 be zero-net energy. There is a need to understand the impact of large-scale integration of distributed generation on stability of the interconnected power systems. The system impact studies need to assess the benefits of advanced features in solar PV inverters including volt/VAR controls, voltage ride through, frequency ride through, generation ramp rates, power factor needs, communications, and voltage oscillation damping. Tripping distributed generation during a grid disturbance is a concern. The studies will inform regulatory developments, such as present efforts to revise current standards to allow advance features in both the IEEE 1547 and CPUC Rule 21 but there is need of meaningful system wide system impact studies to support his effort.

Additionally there is the need to monitor and capture load profile and composition of net-zero energy homes to properly study their impact on regulation and balancing requirements. Net-zero energy homes will have excess generation and excess load at different times, while yielding a yearly average of zero energy consumption and generation. As penetration of these homes increases, the typical load profiles will change. Therefore, their needs to be properly studied and assessed.

SCE has installed several power quality monitor in solar PV plants to assess the performance of these plants during voltage and frequency disturbances. The data will be used to develop and validate computer models needed to perform system impact studies.

There is a need to model the distributed generation in both powerflow and transient stability studies. There are efforts to expand WECC Load Model Data Tool and WECC composite load model to include distributed generation.

*SCE and BPA plan to do this work with internal resources at this time.*

4.6 Load composition analysis and data management applications

There is a need to improve load composition analysis and data management. While the existing WECC Load Composition Model (LCM) and WECC Load Model Data Tool (LMDT) are adequate for an interim period, further advancement and integration of LCM and LMDT is important and has been requested by many users in WECC. BPA in consultations with David Chassin at PNNL developed a paper on load model data management.

*We recommend continuing this work as an internal BPA project to develop specifications for the next generation Load Model Data Tool application, prepare a statement of work and and then have a consultant to develop, demonstrate, populate with data, and validate the application.*
5. References

Modeling


**Regulatory References**


17. NERC White Paper on Delayed Voltage Recovery, posted at www.nerc.com

18. DOE-NERC FIDVR Workshop on April 22, 2008, presentations posted at www.nerc.com

19. DOE-NERC FIDVR Conference on September 29, 2009, presentations posted at www.nerc.com
6. Contacts

Bonneville Power Administration
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CERTS
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WECC
- Donald Davies, WECC Staff
- Stephanie Lu, Seattle City Light, Chair of WECC Modeling and Validation Work Group
Appendix A: Load sensitivity to temperature

Residential loads (cool summer, “normal” summer, heat-wave)
Commercial loads (cool summer, “normal” summer, heat-wave)