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Improving Dynamic Load and Generator Response Performance Tools

Author
Lesieutre, Bernard C.

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Improving Dynamic Load and Generator Response Performance Tools

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Principal Author

Bernard C. Lesieutre

Ernest Orlando Lawrence Berkeley National Laboratory
1 Cyclotron Road, MS 90R4000
Berkeley CA 94720-8136

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Acronyms and Abbreviations

ACE	Area Control Error
AVR	Automatic Voltage Regulator
BPA	Bonneville Power Administration
CAISO	California Independent System Operator
CEC	California Energy Commission
CERTS	Consortium for Electric Reliability Technology Solutions
CIEE	California Institute for Energy Efficiency
DMWG	Disturbance Monitoring Working Group (WECC)
IEEE	Institute for Electrical and Electronic Engineers
HVAC	Heating, Ventilation, and Air Conditioning
LMTF	Load Modeling Task Force (WECC)
LTC	Load Tap Changing transformer
MIT	Massachusetts Institute of Technology
NERC	North American Electric Reliability Council
NILM	Non-Intrusive Load Monitor
PCM	Probabilistic Collocation Method
PIER	Public Interest Energy Research
PNM	Public Service Company of New Mexico
PSS	Power System Stabilizer
SCADA	Supervisory Control and Data Acquisition
SCE	Southern California Edison
WECC	Western Electricity Coordinating Council
WSCC	Western Systems Coordinating Council
ZIP	Constant Impedance (Z), Current (I), and Power (P) load model

Acknowledgements

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Executive Summary

This report is a scoping study to examine research opportunities to improve the accuracy of the system dynamic load and generator models, data and performance assessment tools used by CAISO operations engineers and planning engineers, as well as those used by their counterparts at the California utilities, to establish safe operating margins. Model-based simulations are commonly used to assess the impact of credible contingencies in order to determine system operating limits (path ratings, etc.) to ensure compliance with NERC and WECC reliability requirements. Improved models and a better understanding of the impact of uncertainties in these models will increase the reliability of grid operations by allowing operators to more accurately study system voltage problems and the dynamic stability response of the system to disturbances.

Secure operation of the grid relies on advanced planning for credible contingencies. Anticipatory studies are used to establish operating limits for secure operation as established by NERC and WECC reliability criteria. The criteria have very specific goals, for example, “The interconnected power system shall be operated at all times so that general system instability, uncontrolled separation, cascading outages, or voltage collapse, will not occur as a result of any single contingency or multiple contingencies of sufficiently high likelihood” ([23], III-119). This famous N-1 criterion, by itself, does not provide specific guidance to achieve this goal. Additional criteria are concretely specified in terms of measurable system quantities such as voltage, frequency, active and reactive power flows, and other measures derived from these. For the initial response after an event, reliability criteria specify the allowable ranges for transient deviations in voltage and frequency. Adherence to these criteria should prevent catastrophic failures. To study these transient events, model-based computer simulations are required to predict the system response to possible contingencies. It is the adequacy of these models that is the subject of this report.

Today, CAISO staff report growing concerns their load models have become inaccurate and no longer adequately reflect the actual states of the system that they are witnessing in real time, especially under stressed system conditions. They report that anticipated voltage problems sometimes do not occur, while other, unexpected voltage problems do. They have suggested that their models may no longer be accurately representing the actual behavior of load or performance of generator controls, especially during major disturbances on the system.

These suggestions are not un-founded. The load models in use today were first developed over 20 years ago and due to the difficulty of acquiring and maintaining accurate information, they are rarely updated to capture the changes that have taken place in the underlying composition of load (for example, increased saturation of power electronic devices, induction motors, etc.). Moreover, the forms of the load models that are used throughout the year are unrealistically based on the estimated load composition during the summer peak period; they are not adapted to seasonal conditions. Likewise, until recently the models for governor frequency response control have not kept pace with changes in the industry. CAISO staff have noted decreased frequency response after large outages, and NERC has documented a persistent decline in frequency response in both the Eastern and Western Interconnects. As a result of restructuring, the settings on generator controls are no longer known to the transmission system operators, since different firms now operate the generators and transmission system. Newer generation technologies, especially, have plant controls that are believed to override the automatic governor controls on the generators, which transmission operators depend on to ensure system reliability. The assumption of availability of traditional governor response is optimistic and better information is required. Recent WECC modeling work has resulted in new plant control models that should improve the simulations of plant response.

The development and use of improved models will have a considerable impacts on system reliability, reducing the risk of costly-blackouts, and on long-term and short term (operational) planning, and will increase confidence in operator control of the grid.

The risk to blackouts exacerbated by inaccurate models was clearly illustrated by the August 10, 1996 blackout (and others) in which simulations after the event were unable to replicate the event. A study of that disturbance showed deficiencies in models of generator and plant controls, DC lines and their control, and in load models. Since that time WECC members have improved the DC line and generator and plant control models, and continue to work on improving load models, which remain deficient. “Close call” events in the West show the need for improvement in load models because of the concern that system damping to events is not precisely known, and observed slow voltage recoveries could propagate and lead to voltage collapse. We are reminded that the costs of blackouts are high. The August 14th 2003 blackout was estimated to have cost in the range of $4 billon and $10 billion in the United States (at least $2.3 billion in Canada)[20], and a recent report estimates that power system disturbances cost $80 billion annually in the United States[7].

The most direct manner in which more accurate models can improve security is to increase confidence in operational limits and operator controls. Secure operation of the grid is maintained through planning for credible contingencies, including the specification of path ratings and the deployment of remedial action schemes. Improved models may identify the need to curb optimistic ratings or may allow increases for overly conservative ratings. In either case, confidence in grid security will increase. Confidence for operator actions will also increase with the ability to accurately predict system responses to events and actions. (In the Introduction we present an example in which the observed voltage response in no way resembles the simulation-based prediction.)

In the longer-term improved models will benefit the decision process for capital investments, which must account for how operational limits affect the value of a proposed resource. For example, the motivation for one load modeling study was to gain a better understanding for system responses to contingencies to evaluate investment in components for remedial action schemes[6]. Likewise, since models impact operational path ratings, they will impact decisions for transmission and generation investment.

In this report we:

- Document the need for improved models.
- Review present modeling practices.
- Make recommendations for modeling research and development.

We base our recommendations on interviews with participants at CAISO, members of WECC, and with academic researchers; a review of relevant research in the literature; and our own prior work and expertise in this area.

The scope of this report is broad in the research needs related to load modeling. Some of the recommendations do not require CEC's support to proceed. We feel PIER should be aware of all of these needs and activities. The focus of the research needs is limited to issues faced in the West, since this is the geographic area of primary interest to the PIER. In the West we emphasize the importance of WECC modeling activities. WECC maintains the standard models for the Western Interconnect that are used by all members for their studies. Significant change in models and modeling practices must undergo WECC analysis, scrutiny, and acceptance.

In our review of WECC modeling activities we report that the present load modeling practices are crude. The representations for load characteristics that are important for assessing transient voltage and frequency responses are not detailed; and, as comparison to many observed events show, there are legitimate questions about model adequacy. To examine these questions, WECC launched a Load Modeling Task Force in 2002. We detail many of their activities and results, and we draw on much of their experiences to identify many of the load modeling needs and recommendations in this report.

We find it useful to separate the modeling issues addressed in this report into the following topical categories:

1. Load Model Development and Policies
2. Load Modeling
3. Measurement and Validation
4. Load Monitoring
5. Measurement-Only (Black-Box) Models
6. Uncertainty Analysis
7. Generator Governor Models

We briefly summarize the issues within each category and present recommendations for research to address them.

ES.1 Load Model Development and Policies.

This category addresses higher-level issues with model development that are not covered by the subsequent categories that focus more on detailed deficiencies in the model themselves.

First we note that the characteristics of the load model are not adapted to seasonal changes when it is clear that the characteristics do change seasonally. Air conditioning load dominates the load in the Southwest in the summer, and heating load becomes important in the winter in the Northwest. The present load model characteristics are designed for summer conditions – even those used in the winter reliability assessments.

The second topic in the category involves the use of the models in on-line state estimators to help validate the standard WECC models (and vice-versa). While the models serve different purposes, and do not completely overlap, it is likely that more than 90% of the electric grid representation is common to both and a comparison of the models would likely identify some inconsistencies that would benefit from further study.

The third and most important topic in this category is consideration of how more accurate models may require reevaluation of reliability criteria. Based on the study of slow-voltage recovery events (near voltage collapse), it is believed that stalled induction motors make up portion of the load that may be considered "voltage sensitive." The present reliability criteria that were developed for voltage sensitive loads were based on consideration of voltage-sensitive electronic load. Reevaluation of reliability criteria may be required in light of more accurate models that represent the voltage recovery characteristics of induction motor loads.

Summary of recommendations:

Recommendation: Include seasonal variations in load models.
Recommendation: Incorporate state estimator models into the modeling process.
Recommendation: Anticipate and support activities to review reliability criteria, taking into account better information provided by more detailed characteristics of new load models.

ES.2 Load Modeling

This category addresses specific deficiencies of the model to represent known physical characteristics. All three of the following recommendations involve the characterization of induction motor loads since it is widely believed that discrepancies between model-based simulations and observed behavior are largely due to inadequate induction motor representation.

The first observation is that induction motors perform mechanical work: they turn fans, pumps, and compressors. The mechanical characteristics of the motor-driven loads are crudely represented in load models and preliminary studies show that the results of simulations are sensitive to this representation.

The second observation is that there is large variation in the sizes and types of induction motors in use. All system models that include an induction motor representation assume a "three-phase" induction motor - as might be found in industrial and some commercial loads. On an average day three-phase motors constitute the major part of the total load. On hot days the residential air-conditioning load can become the dominant part of the total load, and residential appliances use "single-phase" induction motors. Since many disruptive events occur on hot summer days, it is reasonable to study the effect of single-phase motors on system studies. There neither has been research on the use of single-phase motor models for this purpose nor the adequacy of three-phase motors to represent single-phase motors in this context.

The third observation is that some induction motors trip off immediately due to contactor operation and other overloaded stalled motors eventually trip off-line through their own protective circuitry. There is some capability in simulation packages to account for this effect by including otherwise redundant motor models, some of which trip off-line during low voltage conditions. Research into a simpler model that performs this function could facilitate analysis and remove duplicity. Furthermore, improvements to low-voltage protection should be discussed with manufacturers. [1]

Summary of recommendations:

Recommendation: **Perform studies to determine mechanical load characteristics for induction motors.**
Recommendation: Compare the responses of singe-phase and three-phase motors under different disturbances.
Recommendation: Model motor load shedding behavior under low voltage conditions.
Recommendation: Discuss improvements to low-voltage protection on residential air conditioners with manufacturers.

ES.3 Measurement and Validation

This category addresses the benefit of certain types of measurements for load modeling, and anticipates the near-term issue of how to efficiently perform model validation with increased availability of quality measurements.

To monitor load characteristics, it makes sense to measure voltage and frequency at points near the load. To this end, WECC Disturbance Monitoring Working Group (DMWG) has specified requirements for a new measuring device that monitors electrical quantities on feeders at substations. To gain benefit from these monitors, we should encourage their use.

It is expected that in the future there will be an increase use in wide area measurement systems and we should anticipate how to incorporate the data in model validation studies. One can envision a mathematical tool akin to a state estimator that would estimate dynamic phenomena on a short timescale (cycles) instead of the quasi-steady state estimators in use today (minutes). [1]

Summary of recommendations:

Recommendation: Encourage the placement of the $10K load monitors.
Recommendation: Support a basic research project to outline the challenges associated with automated model validation and developing a dynamic state monitor.

ES.4 Load Monitoring

This category addresses the goal of estimating physical load composition from measurements. Present load modeling practices are based largely on assumption of typical load composition (motor, lighting, heating …) and not measurement. Consequently there is a large amount of uncertainty in the models that are used. We draw attention to three separate aspects of load monitoring, although we expect that all three would be best addressed in a single project. These are developing and extending techniques for estimating load composition from measurements

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[1] This topic is not directly within the scope of this report, but we feel it is worth recommending.

(we review prior work on this topic in the report), estimating model uncertainty as part of the analysis, and seeking additional information in the harmonics of electrical waveforms that may help identify load composition (harmonics are often filtered out of the data and their information is lost). The uncertainty also includes geographic extent: how well a model translates to different locations. That is, is a residential load model typical enough that the model can be substituted to other locations?

Decisions that depend on load models have tremendous impact. Operating limits (path ratings, nomograms), remedial action schemes, capital improvement projects may all be impacted by dynamic studies and presently the load models used in such studies are crude. Any support for decisions that may be gained though measurement (over assumption) and related uncertainty analysis should be pursued.

Summary of recommendations:

Recommendation: Support activities to estimate load composition from measurements.
Recommendation: Support activities to test load model substitutability assumptions, and to characterize a range of uncertainty in models.
Recommendation: Assess the value of harmonic information for the purposes of estimating load composition.

ES.5 Measurement-Only (Black-Box) Models

A report on load modeling needs would be incomplete without consideration of so-called black-box models. In contrast to physically based load models that seek to represent fundamental physical characteristics of the load, black box models set out to match observed system behavior without constraint on the form of the model. This is a powerful approach that has wide application. But it relies on having a wealth of measured data with which to estimate the model, and this data is not common in power systems. For this reason and details described in this report we do not recommend new research in this area at this time.

Recommendation: Follow efforts to develop measurement-only (black-box) load models.

ES.6 Uncertainty Analysis

The motivation for this scoping study is that there is presently considerable uncertainty in the models we use, and correspondingly reduced confidence in analyses performed using these models. The load is changing continually and a single dynamic representation may not identify adverse conditions under differing loading conditions. The load models are necessarily simplified models and the loss of accuracy may be accommodated with a characterization of model parameter uncertainties. We can improve the models by gathering more data and information, but we must always cope with some level of uncertainty. With load models, this level may be high. There are technical challenges that make traditional approaches to uncertainty analysis prohibitive (Monte Carlo and derivatives), and we need to adapt or develop new methods to this task.

Like the topic of model estimation, this topic is very important as it can be tied to decision-making processes in a natural way. Furthermore, it is uncertainty in load models that is widely believed to be the dominant cause for discrepancies between simulations and observed behavior.

Recommendation: Initiate a program to develop methods to evaluate the effect of load model uncertainties on system studies.

ES.7 Generator Governor Models

This category addresses issues associated with the observed decline in generator governor frequency response in the nation's electric grids. We review the reported reasons for this decline in the main text. Here we note that the WECC has a new plant control model with the capability of representing the reduced availability of "droop governor" response by introducing a higher-level feedback control loop that regulates to a plant output set point. We recommend this model be used. The remaining issue is how to determine the specific parameters for each generator in the model. Ideally this information may be obtained voluntarily through survey, or a policy could make reporting this information mandatory. In the extreme, it is possible that the data may not be obtained voluntarily or that the average response reported in a survey may differ from actual response in important instances, and a new monitoring and analysis tool may need to be developed to estimate the characteristics of each generator.

Recommendation: Use the governor model of [19][18] and support WECC activities to maintain a database of plant governor characteristics.

Recommendation: Develop or adapt tools to monitor supplier governor frequency response.

Summary of Recommendations

In Table ES-1 we summarize the recommendations listed above and provide a qualitative comparison of significance and research requirements for each. Distinctions are made on level of effort, time required, need for PIER direction and support, and significance of the results. The difference between stated levels are presented next.

<u>The level of effort required to complete the research</u>, a relative measure encompassing the staffing, focus, design and installation of special equipment, and in a general sense, total cost.

- High: Multiple investigators and necessary installation of equipment and analysis of measured data.
- Moderate: Single lead investigator and need for development of new techniques for analysis. Or this designation may refer to an otherwise costly activity that is best combined with another recommendation.
- Low: Single investigator using established techniques to perform the study.

<u>The expected time to completion</u>: The distinction here is between an activity that should take one-year or less, and those that will require multiple years. A further note is made on those that will continue as on-going activities after the initial study (such as maintaining and updating data).

The level of PIER direction and support. Some projects require little direct PIER support, as they will be initiated and completed by others. Some projects involve long-term and basic research and might not be initiated without and PIER support.

- Low: will be initiated and completed by others.
- Moderate: may require some direction or support to supplement projects with others.
- High: Long-term or basic research that will require PIER direction and support to conduct the research.

Significance: An estimate of the impact on improving the models and tools.

- Low: the research will not likely have a significant impact.
- Moderate: will provide an incremental improvement in models and analysis tools.
- High: introduces a fundamental improvement in the models and analysis tools.

Table ES-1 appears on the next page.

ES 1 Summary or Research Recommendations

Recommendation	Level of Effort	Time Req'd	PIER Support	Significance
Load Model Development and Policies				
Develop seasonal models.	low	1-year	low	moderate
Validate with state estimator models.	low	1-year	low	moderate
Review reliability criteria.	low	multi-year	low	high
Load Modeling				
Study motor mechanical load characteristics and impact.	moderate	1-year	moderate	high
Study impact of single-phase and three-phase motors.	moderate	1-year	high	high
Model motor load shedding and low-voltage conditions.	moderate	1-year	moderate	low
Improve low-voltage protection.	low	1-year	low	high
Measurement and Validation				
$10K load monitor.	low	1-year	low	high
Scoping study: research needs for automatic validation and dynamic state estimation.	moderate	1-year	moderate	moderate
Load Monitoring				
Estimate load composition from measurements.	high	multi-year	high	high
Characterize model uncertainties using measurements.	moderate	multi-year	high	high
Use harmonic information in measurements to enhance load composition estimates.	moderate	multi-year	high	unknown
Measurement-Only (Black Box) Models				
Follow research activities in this area.	low	multi-year	low	low
Uncertainty Analysis				
Develop methods to assess the impact of load model uncertainties on system studies.	high	multi-year	high	high
Generator Governor Models				
Support WECC activities to implement best model and maintain data for generator characteristics.	low	multi-year	Low	high
Develop tools to monitor individual generator frequency response.	high	multi-year	high	moderate

1. Introduction

This report is a scoping study to examine research opportunities to improve the accuracy of the system dynamic load and generator models, data and performance assessment tools used by CAISO operations engineers and planning engineers, as well as those used by their counterparts at the California utilities, to establish safe operating margins. Improved models and a better understanding of the likely impacts of remaining uncertainties in these models will increase the reliability of grid operations by allowing operators to more accurately study system voltage problems and the dynamic stability response of the system to disturbances.

Accurate models are necessary to help maintain reliability. These models are used by system planners and operators to analyze expected and worst-case operating conditions to determine limits to maintain secure operation of the grid.

Today, CAISO staff report growing concerns their load models have become inaccurate and no longer adequately reflect the actual states of the system that they are witnessing in real time, especially under stressed system conditions. They report that anticipated voltage problems sometimes do not occur, while other, unanticipated voltage problems do. They have suggested that their models may no longer be accurately representing the actual behavior of load or performance of generator controls, especially during major disturbances on the system.

These suggestions are not un-founded. The load models in use today were first developed over 20 years ago and are rarely updated to capture the dramatic changes that have taken place in the underlying composition of load (for example, increased saturation of power electronic devices, induction motors, etc.). Moreover, the forms of the load models that are used throughout the year are unrealistically based on the estimated load composition during the summer peak period; they do not adapt to seasonal conditions. Likewise, until recently, the models for governor frequency response control have not kept pace with changes in the industry. CAISO staff have noted decreased frequency response after large outages, and NERC has documented a persistent decline in frequency response in both the Eastern and Western Interconnects. As a result of restructuring, the settings on generator controls are no longer known to the transmission system operators, since different firms now operate the generators and transmission system. Newer generation technologies, especially, have plant controls that are believed to override the automatic governor controls on the generators, which transmission operators depend on to ensure system reliability. The assumption of traditional governor availability is optimistic and better information is required. Recent WECC modeling work has resulted in new plant control models that should improve the simulations of plant response.

The development and use of improved models will have a considerable impacts on system reliability, reducing the risk of costly-blackouts, and on long-term and short term (operational) planning, and will increase confidence in operator control of the grid.

The risk to blackouts exacerbated by inaccurate models was clearly illustrated by the August 10, 1996 blackout (and others) in which simulations after the event were unable to replicate the event. A study of that disturbance showed deficiencies in models of generator and plant controls, DC lines and their control, and in load models. Since that time WECC members have improved the DC line and generator and plant control models, and continue to work on improving load models, which remain deficient. “Close call” events in the West show the need for improvement in load models because of the concern that system damping to events is not precisely known, and observed slow voltage recoveries could propagate and lead to voltage collapse. We are reminded that the costs of blackouts are high. The August 14th 2003 blackout was estimated to have cost in the range of $4 billon and $10 billion in the United States (at least $2.3 billion in Canada)[20], and a recent report estimates that power system disturbances cost $80 billion annually in the United States [7].

The most immediate direct manner in which more accurate models can improve security is to increase confidence in operational limits and operator controls. Secure operation of the grid is maintained through planning for credible contingencies, including the specification of path ratings and the deployment of remedial action schemes. Improved models may identify the need to curb optimistic ratings or may allow increases for overly conservative ratings. In either case, confidence in grid security will increase. Confidence for operator actions will also increase with the ability to accurately predict system responses to events and actions. (In the Introduction we present an example in which the observed voltage response in no way resembles the simulation-based prediction.)

In the longer-term improved models will benefit the decision process for capital investments, which must account for how operational limits value the benefit of a proposed resource. For example, the motivation for one load modeling study was to gain a better understanding for system responses to contingencies to evaluate investment in components for remedial action schemes [6]. Likewise, since models impact operational path ratings, they will impact decisions for transmission and generation investment.

In this report we:

- Document the need for improved models.
- Review present modeling practices.
- Make recommendations for modeling research and development.

We base our recommendations on interviews with interested participants at CAISO, WECC members, and with academic researchers; a review of relevant research in the literature; and our own prior work and expertise in this area.

A few general observations are in order. The initial focus of this work was on load modeling and generator frequency response characteristics. Our research suggests that there are additional fundamental modeling issues of equal importance. There is concern that there are basic inconsistencies between planning models used to anticipate problems in the grid, and the state-estimator models used to monitor the operating state of the system. Some minor variations are expected, of course, as components in operation change due to maintenance schedules, however more pervasive and significant differences are believed to be present. Procedures for validating models could be improved, in addition to the models themselves. Basic information about transmission line and transformer characteristics should be validated in addition to the load and generator models.

We also need to be realistic about the amount of modeling improvement that can be achieved or that may be needed. The load comprises all end-use electrical equipment in every home, business, and factory connected to the grid. It is impossible and unnecessary to include models for all individual components. As we will present below, dynamics seen in measurements from severe disturbances, while complex, do suggest that aggregate models can sufficiently capture the observed phenomena. Nevertheless, we must acknowledge that perfect knowledge of load dynamic behavior will be impossible to ascertain from present and likely future measurement technologies.

Given that imperfect knowledge of load characteristics is inevitable, we will need to speculate on the level of accuracy that can be achieved and the amount of uncertainty that must be accommodated. By specifically characterizing the uncertainty in load model parameters, we can develop tools to calculate the effect of this uncertainty on studies used to determine operating policies.

In the following Background chapter we review type of models considered, their application, some events that indicate the need for model improvement, and we give an overview of WECC structure and relevant activities. WECC is the primary source for modeling and model validation activities in the West, and WECC models are used by all its members.

This report is focused on the needs and activities in the West because they are most relevant to the CEC's PIER program. The report is not limited solely to issues that may be addressed by PIER, but discusses a wide range of research needs. In our recommendations, we distinguish between those needs that will benefit from PIER involvement and those that will likely be addressed by others.

2. Background

The load and generator models that are the subject of this report are used to assess system response immediately following a disturbance. It is expected that the models have sufficient fidelity to enable engineers and operators to determine whether post-fault voltages and frequency deviations satisfy specific reliability standards.

In the West, the Western Electricity Coordinating Council is responsible for developing and maintaining detailed models of the Western Interconnect. Is important to emphasize the role WECC takes in this modeling effort. As the NERC reliability region in the West, WECC has obvious interest in maintaining accurate models. Moreover, the models that WECC develops are shared among WECC members and form a common basis for analysis of grid. These are the standard models and all the members use these models. There is a committee process for evaluating and recommending improvements to the models as needs arise. We discuss this in more detail later; here we note that all general changes in the recommended form of models will benefit from WECC involvement in the process. We begin this background section by highlighting some of the uses of the dynamic models.

2.1 Application of Dynamic Models

The models discussed here for the evaluation of immediate system response after a network disturbance are used in:

- Anticipatory studies – typically used to establish operating limits such as transmission path ratings, operating nomograms, and designing and tuning of certain controllers such as remedial action schemes.
- Post-disturbance studies – for model validation, and to better understand the underlying cause and spread of a particular event.
- Individual studies of interest – to study specific events and operating conditions that may not be covered in typical anticipatory studies.

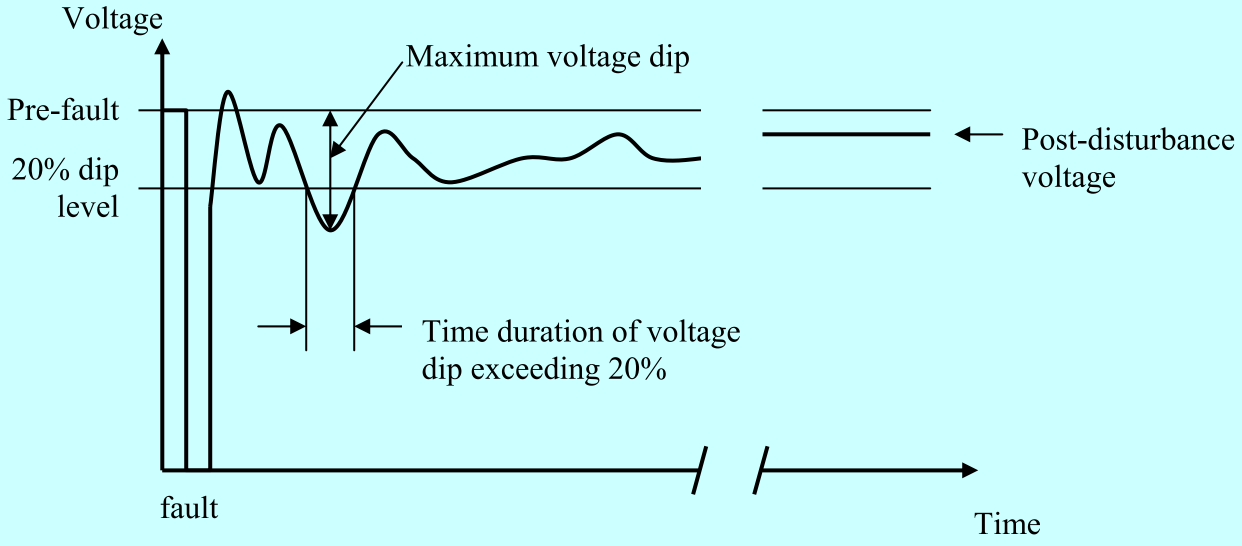
Secure operation of the grid relies on anticipation and advanced planning for credible contingencies. These anticipatory studies are used to establish operating limits for secure operation as established by NERC and WECC reliability criteria. The criteria have very specific goals, for example, "The interconnected power system shall be operated at all times so that general system instability, uncontrolled separation, cascading outages, or voltage collapse, will not occur as a result of any single contingency or multiple contingencies of sufficiently high likelihood" ([23], III-119). This famous N-1 criterion, by itself, does not provide specific guidance to achieve this goal. Additional criteria are concretely specified in terms of measurable system characteristics such as voltage, frequency, active and reactive power flows, and other measures derived from these (ACE for example). Because we are interested in the response of the system after some initiating event (generator trip, faulted line, etc.), we briefly present some of the representative requirements with respect to voltage and frequency.

NERC and WECC designate system performance into four categories: A. no outages, B. loss of a single element, C. loss of two or more elements, and D. severe disturbance arising from loss of two or more elements. The standards emphasize the prevention of uncontrolled loss of load. As a sample of engineering proxies for this goal, we list the frequency and voltage requirements for the effect of an event in one area on other areas ([24], XI-18) in the following table. Note that we don't list category A here - there is no contingency – or category D since this category corresponds to catastrophic failures where frequency and voltage levels are not assumed to be contained. In the sidebar we describe the voltage criteria more visually.

Category	Frequency	Voltage			
	Lower limit	Maximum dip	Dip not to exceed size for duration		Post-disturbance deviation
			size	duration	
B: single element outage	59.6 Hz	25 %	20 %	20 cycles	5 %
C: multiple outages	59.0 Hz.	30 %	20 %	40 cycles	10 %

The system is expected to be designed to be able to meet these criteria (and many more) during operation. In turn, these criteria are intended to ensure that the grid remains stable and robust to outages. To analyze the system's ability to meet these criteria, and to establish appropriate operating limits, it is necessary to use model-based computer simulations. The most severe disturbances are simulated to determine if the system operating limits are stringent enough to ensure the system response satisfies these voltage and frequency criteria.

Transient Voltage Characteristics



This figure shows the measures used to assess transient voltage deviations. After the fault is cleared the three important characteristics are the maximum voltage dip, the duration of time the voltage dip exceeds 20%, and the final post-disturbance voltage level.

These measures are used in reliability criteria and are intended to enforce the goal to maintain the integrity of the interconnected electric grid.

Another important application of these models is their use in evaluating themselves. Model validation is important activity to better models using all the information that is available. Measurements from disturbances are compared to those predicted by computer simulation to assess the accuracy of the models. Because the models are used to establish operating limits, the design of remedial action schemes and related decisions related to adjustment (expansion) of grid capabilities, it is important to use the most accurate models possible. In the next section we discuss evidence that suggests that models are in need of improvement.

2.2 The Need for Improved Models

A fundamental maxim of modeling is to use the simplest model that captures the phenomenon of interest. Given the difficulties in characterizing the dynamic characteristics of loads, the necessary aggregate nature of the model and the inability to perform tests to design and validate models, it is typical to employ very simple models for the loads, perhaps too simple. When can we tell that our models are not adequate? When are fundamental changes required and when can relatively mild adjustments tune the models?

During severe disturbances devices in the network will record frequency, voltage, current, active and reactive power. A comparison of these recordings to computed values using mathematical models can be used to assess the accuracy of the model for a given disturbance. A detailed mathematical study is required to identify and improve model shortcomings, whether fundamental or tuning. Let us consider a few historical disturbances that have led to changes in load modeling and then examine a few more recent and local disturbances that suggest renewed activity in load modeling is warranted.

An example of a disturbance that concluded in a fundamental change in modeling of load characteristics is the Swedish Blackout of 1983. The initiating event for this disturbance was the loss of a transmission line connecting the generation rich northern part of the country to the load centers in the south. There were a number of redundant lines connecting the north and south and it was a surprise that this event resulted in a complete blackout of the entire country. Model-based simulations initially concluded that this event should not have caused such a severe disturbance. Clearly the models were deficient in some way. A detailed study concluded that the disturbance could not be replicated without a fundamental change in the load model, in this case the explicit incorporation of induction motor models [21]. With an induction motor load model in place, the event could be simulated.

We will discuss the form of load models in more detail in the next chapter. Here it is worth mentioning that models for induction motors differ from simpler static models for loads due to their different interaction with the network: because a motor stores energy in its rotational mass, it is possible for a motor to sometimes supply energy to the network, affecting overall system damping. It is also possible for induction motors to stall at low voltages, which will exacerbate low voltages.

Another important example reported in the literature, also involving induction motors, is the August 10, 1996 WSCC[1] disturbance that resulted in a loss of more than 30GW of load [12]. This disturbance occurred on a hot day when the system was operating under stressed conditions. The initiating event involved a transmission line fault to a nearby tree. The loss of that line led to overloaded conditions on other lines, and subsequent trippings of generators and additional lines. The measurements from disturbance recorders indicate that the event was characterized by a dynamic instability leading up to an eventual cascading outage. The power flowing across key interfaces oscillated, initially undamped, and then began to oscillate in a negatively damped fashion (the magnitudes of the oscillations increased). The system became unstable.

The initial simulation of the disturbance using standard WSCC data set, adjusted for operating conditions, failed to capture the observed voltage and frequency deviations and the power flow oscillations. A detailed study showed five basic deficiencies in the standard model:

1. Inadequate DC line model.
2. Automatic Generation Controls were not in the standard model, and were important for some hydro plants during the disturbance.
3. Large thermal generators may take minutes to respond to frequency deviations and the revised model blocked governor controls for these plants throughout the WSSC system.
4. Voltage controls for some hydro generators were not adequately represented in the standard model.
5. Dynamic induction motor load models were introduced to represent the air conditioning and irrigation load that were present on the system. The standard model had employed a constant current representation for the load.

With these updates to the model, the simulation captured the basic voltage, frequency, and power oscillations of the disturbance.

We note here that the first four items involved updates to the model to better represent known characteristics of the components. The fifth item, load model adjustments, involved tuning unknown load characteristics to best match the data. Without the changes to the load model, the simulations did not show growing oscillations and system instability. The load model representation was crucial for replicating the disturbance.

The study of this disturbance was a major motivation for changing the standard load model in the Western Interconnect models to include 20% induction motor loads. Again, we will discuss the explicit forms of models in the next chapter. Here we note that the analysis of this disturbance required an adjustment to a standard load model.

Recent disturbances indicate that there is need for modifications to the standard load model. Recordings from two different representative disturbances in which load dynamic are believed to have considerable impact are shown in Figure 2-1 and Figure 2-2 below. In the June 2002 disturbance, voltage oscillations are observed. While these oscillations are slightly damped, the uncertainty in load characteristics in our models raises legitimate concern that we will not

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[1] Now WECC. WSCC (Western Systems Coordinating Council) joined with the Southwest Regional Transmission Association and the Western Regional Transmission Association to form WECC in 2002.

anticipate undamped, unstable conditions. In the July 2004 disturbance we observe a sustained voltage depression. In this case the depression is believed to be caused by air conditioning motors (induction motors) stalling. This plot shows what appears to be an incidence of near voltage collapse. In both cases the standard models fail to predict the observed response.

The July 2004 disturbance was initiated by fault on a 115 kV line in the Southern California Edison (SCE) system. The fault was cleared within four cycles (67 milliseconds). The 30-second voltage sag that followed the fault clearing was unexpected. In Figure 2-3 the simulated response (using the standard model) is shown. The simulated response shows no delay in voltage recovery; the voltage immediately returns to normal levels after the fault clearing. The observed behavior is quite different and is believed to be due to air conditioning motor stalls. A 1992 laboratory study of voltage recovery after motor stalls demonstrated this type of slow recovery[25]. That report also noted that this class of motors would stall for any voltage dip below 65%, regardless of duration, with additional probability of stall at higher voltages for sustained dips. An analysis of the July 2004 event in which a stalled motor current model was imposed for the low voltage condition was able to adequately represent the event [4]. In the simulation, the motors began to trip-off line after some delay, allowing the system voltage to recover.

These and other disturbances are under study by WECC committees to help validate and improve models. (The LMTF is working on validation of eight events.) The problem of concern to us is that these disturbances are not well predicted using the standard WECC models, and load model deficiencies are considered to be important. The questions that need addressing are whether the existing form of models can represent the observed behavior or is some phenomenon not being modeled, how uncertain are our models and can we assess the effect of uncertainties in the models.

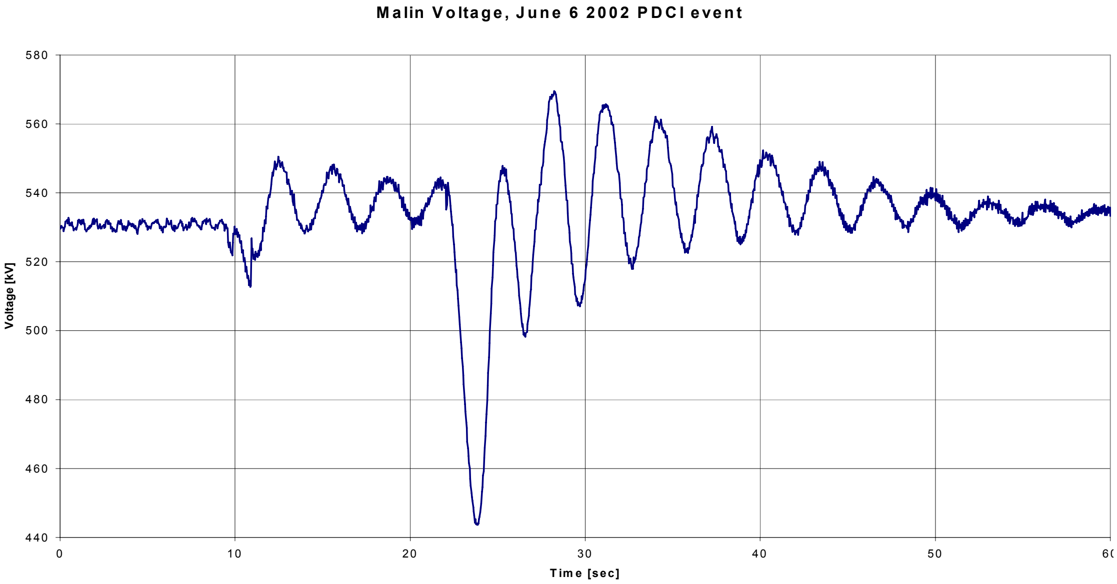

Figure 2-1. June 6, 2002 event. (courtesy of D. Kosterev)

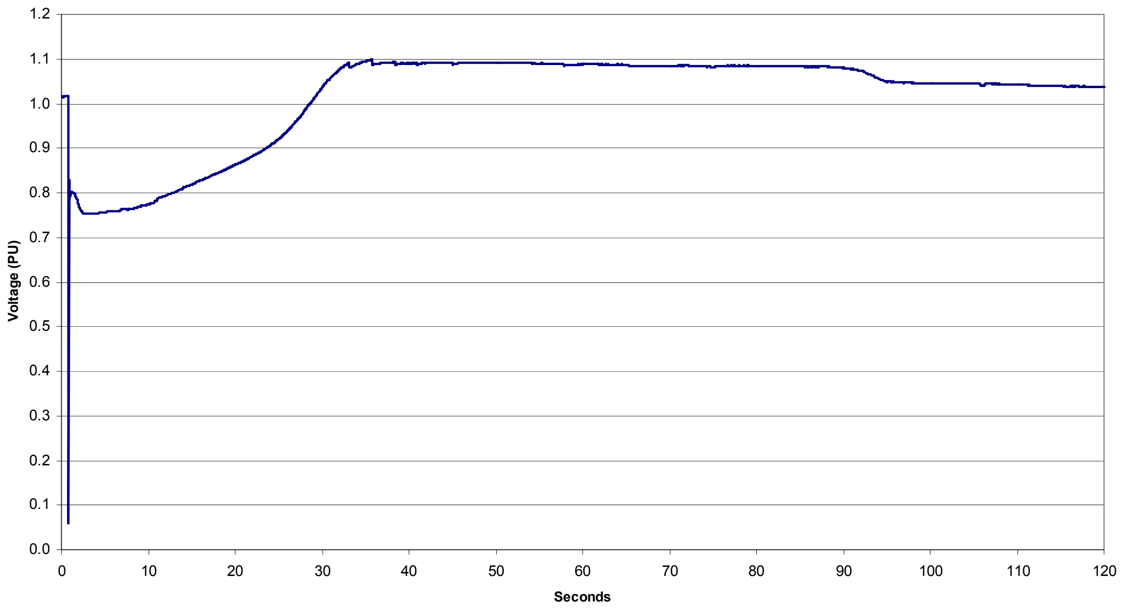

Figure 2-2. July 2004 Valley event . (courtesy of G. Chinn)

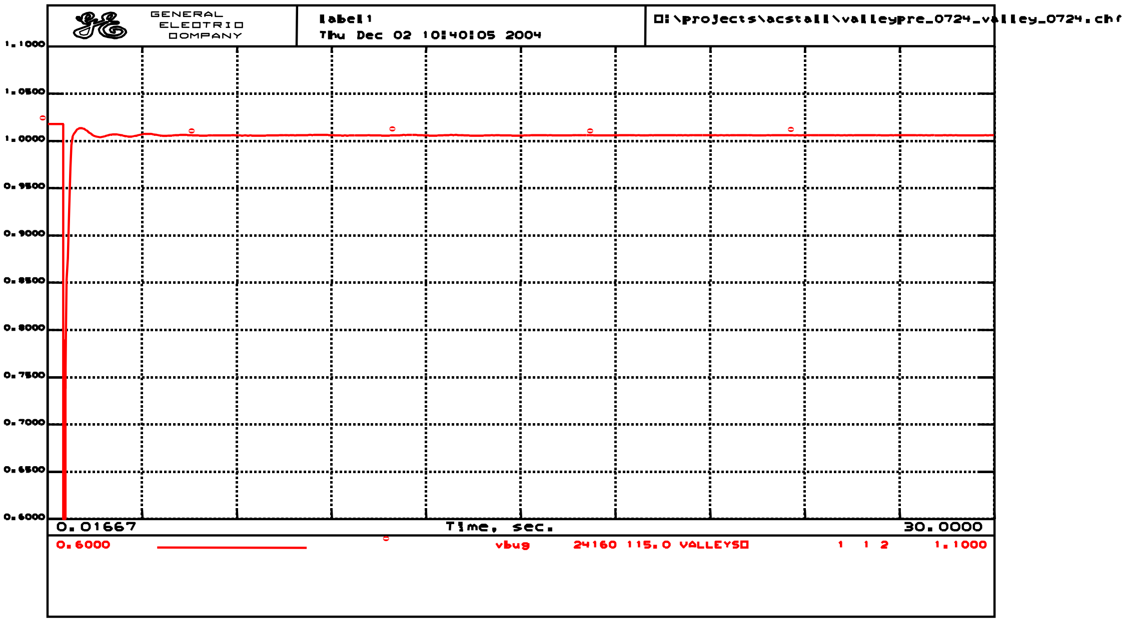

Figure 2-3 Simulation of the July 2004 Valley event using the standard model. Note that the voltage recovery is immediate after the fault is cleared. (courtesy of G. Chinn)

As partial answers to these questions we note that the 20% induction motor load that worked well in the analysis of the 1996 outage has not proven to be accurate in all subsequent analyses. Surveys indicate that induction motors constitute around 60% of the load. It appears that the process of aggregation of loads and distribution system seems to reduce the impact of induction motor loads somewhat, but a complete understanding is lacking. Another phenomenon not well represented in aggregate induction motor loads, for large disturbances, is the discrete tripping of some motors while others remain connected. The creation of a simple model to represent these features may be important to explain the sustained dip, and eventual rise in the voltage profile shown in Figure 2-2. Finally, the models are uncertain and methods to assess uncertain models need to be explored.

The need for research on load modeling is clear. Studies of major past events indicate that simulations are sensitive to load models. Studies of more recent close-call events, demonstrate that the models require refinement. Research is being done on these issues. As mentioned above, WECC committees are actively conducting research on the both the analysis of disturbances and on general model techniques. They are an important source of information and expertise and in the next section we discuss their structure and activities in the modeling area.

2.3 System Modeling in WECC

System reliability in the West fall under the purview of the Western Electricity Coordinating Council (WECC), the NERC region comprising all or parts of 14 western states in the U.S., the provinces of Alberta and British Columbia, and part of Baja California, Mexico. Because WECC collects data and develops models for reliability studies, and has a responsibility to do so, it is useful to review the organization’s goals, basic structure, and activities. In particular, in this report we will review the activities of the WECC Load Modeling Task Force and it is appropriate to provide the context for their work within WECC.

Membership in WECC includes participants and organizations with a common interest in maintaining the integrity of the grid. WECC’s 167 members are classified by transmission providers, transmission customers, and state and provincial representatives. WECC conducts the business of applying NERC reliability criteria, developing its own system specific and sometime more stringent reliability criteria, performing various analyses to assess near- and long-term reliability, and developing common operating procedures to maintain system security.

As a NERC region, WECC is responsible for coordinating reliability in the West. The WECC organization has a number of administrative and policy committees, and two primary system specific committees, the Operating Committee and the Planning Coordination Committee. Generally, the Operating Committee is responsible for policies and procedures for secure operation of the grid, including (and not limited to) establishing reliability criteria, emergency procedures, interchange scheduling, overseeing compliance monitoring and operator training and certification, analyzing severe disturbances, and more. The Planning Coordination Committee is generally responsible for maintaining models and data to perform studies on the system, and to perform these studies. These include regional planning studies and specific evaluations of changes in system facilities. There is overlap between the two committees, and they coordinate on planning activities and system simulations. For details on the specific activities of these two committees the reader may refer to the WECC Operating Committee Handbook[23], and the WECC Planning Coordination Committee Handbook [24].

For our purposes we are interested in the models that are developed and used by WECC. NERC and WECC standards require that the electric system must be planned to withstand probable outages (Specific definitions and conditions related to system adequacy and security may be found in Chapter 3 of [23].) The process of evaluating system security in the planning process uses simulated testing of the system (page III-15, [23].) As a NERC region, WECC is required to perform winter and summer reliability assessments, and near-term (1-5 yrs) and long-term (6-10yr) assessments. Consequently, WECC is required to maintain a working model and database with which to perform these studies.

The Planning Coordination Committee maintains the models and data to perform the required studies, and a committee structure to evaluate and make changes to recommended models as becomes necessary. The committee also reviews and suggests changes, as appropriate, to the NERC/WECC planning standards. There are two subcommittees and six working groups under the Planning Coordination Committee (see Figure 2-4) The Reliability Subcommittee and the Reliability Performance Evaluation Working Group are responsible for evaluating and recommending changes to the planning standards. The Technical Studies Subcommittee is responsible for developing and maintaining simulation models and data to be used in reliability studies and to perform these studies. The System Review working group is largely responsible for preparing case studies and performing the required reliability assessments. They maintain the system model database and coordinate data submissions from WECC members. The two computer programs used by the subcommittee have users groups to ensure that the programs meet WECC and members needs. Most important for the purposes of this report is the Modeling and Validation Working Group. This group compares data recorded from system disturbances to predictions from simulations to determine if modeling improvements are warranted. They will recommend new models and modeling techniques as appropriate. Under this working group is a task force dedicated to improving load modeling.

We will discuss the specific activities of the WECC Load Modeling Task Force in the next chapter of this report. Here we try to place their activities in the context of WECC goals and administrative organization. In summary, WECC uses model-based simulation to assess reliability. The models are constantly under review for opportunities for improvement, and load model improvement would be beneficial to more accurate evaluation of system security. Furthermore, these models are in common use among WECC members.

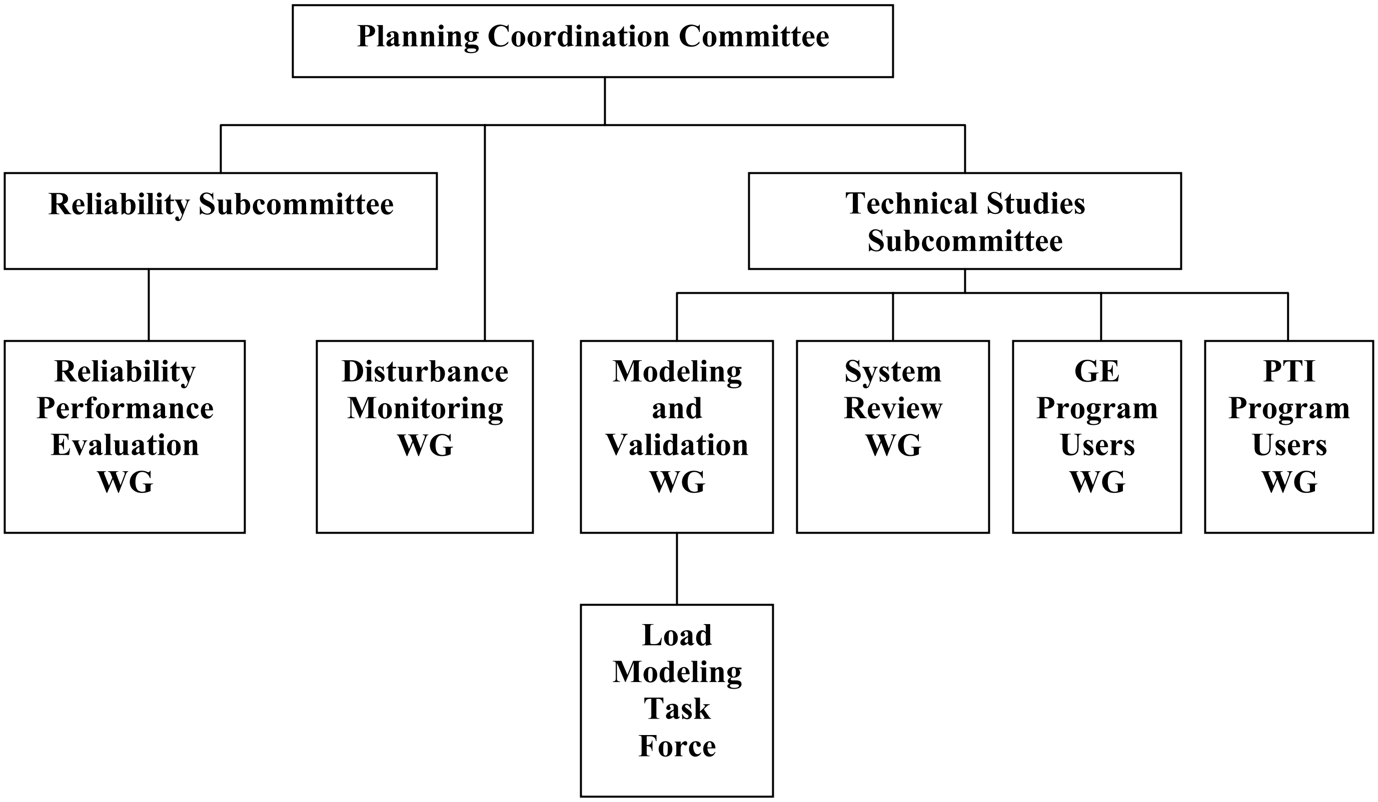

Figure 2-4. Organization chart for the Planning Coordination Committee

3. System and Load Modeling

In this chapter we discuss details of system and load modeling and the relevant issues that may benefit from modeling research. We will review a typical modeling exercise to identify areas for improvement. In this case we discuss the WECC procedure for developing planning models. We will mention the benefit of consistency checking with state estimator models. The majority of this chapter is dedicated to the need for load modeling research. We provide a background in general approaches, what is done in practice, present research activities, and the areas of need for basic research in the load modeling.

The discussion in this chapter will be directed towards the specific forms models may take. We dedicate the next chapter to how measurements and monitoring may be used to improve models and the need to proactively consider how to handle data as appropriate metering equipment becomes available.

3.1 WECC Modeling Process

The System Review Working Group under the Technical Studies Subcommittee is responsible for developing and maintaining models in WECC, and for conducting reliability studies. They perform 11 studies per year including 5 operating studies for upcoming seasons, 2 scenario cases, 2 typical cases, and generic 5 and 10 year studies. The data required to perform these studies are collected from WECC members, roughly on a monthly basis as these studies are designed, scheduled, and completed.

Members of the System Review Working Group serve as “Area Coordinators” and develop models for designated regions in WECC (e.g. Northern California, Southern California, etc.). They collect study-specific information, such as expected load profiles and generator availability, that are important for power flow studies, and they maintain a database of system dynamic information used in stability studies. The database includes information on generator characteristics and controls, and dynamic load models. (We will comment more on this dynamic information shortly.) The Area Coordinators check their models for internal consistency and quality and pass along the models to WECC staff. WECC staff piece together the area model to form a complete model of the Western Interconnect. They also perform checks for consistency and quality. For example, they ensure that scheduled flows between regions are reported consistently. This model is then used to study the specific case it was designed for. Such cases are distinguished by season and loading characteristics, such as a heavy winter base case or light spring base case.

A Master Dynamics File, as used by the simulation software, is generally maintained and updated as members submit more accurate data, but this information is not required to be reviewed and updated with each case. Consequently it is updated less frequently. For example, NERC standards require that generators be tested at least once every five years. Between tests the dynamic data for a specific generator is not likely to be updated. Typical, generic representations are applied for generators that are in the planning stages and for which testing has never been done. Dynamic load models, which are important for stability studies, are also infrequently updated. Furthermore, the models submitted by WECC members typically use a single static load model for an entire region. While there are exceptions, this simplified load modeling assumption is generally the rule. Based on validation studies, WECC has adopted an interim model in which 20% of the load is represented by a generic induction motor model throughout the entire system. WECC staff introduce this in the final model.

These models are then used to simulate credible contingencies to ensure the responses satisfy WECC reliability criteria. These criteria include restrictions on allowable transient voltage and frequency deviations from nominal after a fault has been cleared. The transient voltage conditions are defined in terms of an absolute minimum allowable voltage and a (higher) minimum voltage that the system may only go below for a defined duration. The frequency criteria are based on absolute deviations from nominal frequency. Four different event classifications are defined which dictate the appropriate load and generator shedding and network interruptions that may be needed to maintain operation of the grid. It is intended that such load loss should be handled in a controlled manner. For single failures (N-1), no load, generator, or network interruptions should be required (other than to remove the source of the disturbance).

Important to us here is the consideration given to load modeling when developing these reliability criteria. A discussion is provided in [11]. The voltage sensitive loads used to develop the transient voltage reliability criteria are assumed to be related to computer and electronic equipment. There is reasonable evidence in the recent events to suggest that induction motor loads also constitute a voltage sensitive load that needs consideration. The July 2004 event described in the introduction is believed to have an uncontrolled loss of load (air conditioners) and a suppressed voltage *after* the fault was cleared. As we will detail in this chapter, much of the research on load modeling is centered on the appropriate representation of motor loads. With this focus we need to recognize that consideration of induction motor voltage sensitive loads may require a review of transient voltage reliability criteria.

Based on our interviews we echo the following three recommendations concerning this type of modeling procedure.

Recommendation: Include seasonal variations in load models.
It is clear that the load changes substantially with season. Most dramatically is the air-conditioning load in the Southwest that is present in the summer, but absent in the winter, and the heating-related load that is present in Northwest in the winter and largely absent in the summer. Some form of regional and seasonal variations in the models can be made as they presently exist, and will benefit from the improved models that we discuss in the next section.

Recommendation: Incorporate state estimator models into the modeling process.
State estimators are used in several regions in the West and the models that they use should be the most accurate available. It would be particularly valuable to compare the planning models with state estimator models as one check for consistency. The WECC Technical Studies Subcommittee is presently considering ways to use state estimator models in the modeling process. As WECC moves forward along this sensible path, it is possible that data confidentiality issues will arise that will need consideration. The CEC may be positioned to aid in making useful state estimator data available to improve system models.

Recommendation: Anticipate and support activities to review reliability criteria, taking into account detailed characteristics of new load models.
Recognition that induction motor loads constitute a portion of the load that may be considered voltage-sensitive, reliability criteria associated with voltage transients should be reviewed to account for this portion of the load.

3.2 Load Modeling

Here is it useful to begin with a review of load modeling issues and provide an abbreviated historical perspective before delving into the details of present models and in-depth discussion of future needs.

First we clarify what a “load” model is in order to contrast it from generator and network models. The greatest distinction is that a load model usually represents an aggregate of many components, often including low-voltage distribution networks. Generator models are specific mathematical models that represent physical operating characteristics of that component and its associated controls. Equations are used to model magnetic fluxes, rotor speed, field winding voltage and controls (AVR and PSS), turbines, governors, and more. Likewise, network models include mathematical representations for transmission lines, transformers, reactive power controls, and the like. These focus on the operation and characteristics of individual components. Load models are also mathematical models, but they do not represent individual components. Rather, they are used to represent entire portions of the power system that are not explicitly modeled. These tend to be low voltage networks to which the tens of thousands of end-use electrical appliances are ultimately connected. To be accurate, a load model must adequately represent not only the end-use characteristics of the energy supply, but also the effect of intervening lower-voltage grid with its transformers, capacitors, lines, and regulators.

Historically, very simple models have been used and they continue to be used. In many instances simple models are entirely adequate. In a power flow study with the purpose of evaluating whether projected generation and transmission is capable of serving projected loads, the power flow equations can be used with the load quantity specified as constant constraints in terms of active and reactive power. No sophisticated model is needed, simply accurate information about the projected demand is required (including effects of the lower-voltage network). For power flow studies with the purpose to assess the steady-state operating condition after a contingency (assuming a steady-state is reached!), it may sensible to include voltage-dependent models for certain loads to represent the change in demand with a change in voltage profile. There are often voltage regulating components in the lower-voltage network that will readjust voltages after a contingency, effectively restoring voltages and power levels. So even in this contingency scenario, the need for a sophisticated load model is not clear. The need for a detailed load model is for the analysis of the network after a contingency and before a steady state is achieved, especially to determine if the system will remain stable enough to return to a steady state.

The simplest model for the load (other than constant demand) is to assume that the load appears to react to voltage variations as a constant impedance would. This form of model was common in the more distant past when network analyzers were used to simulate the network for stability studies. The analyzer could then simulate the entire system, or with an impedance representation for the network and loads, the engineer could reduce the entire network down to generator buses and then perform a simulation of generator responses. A discussion of this usage is found in Kimbark's book [10]. While one might argue that the constant impedance load could represent the lower-voltage subtransmission and distribution networks and characteristics of resistive heating and lighting loads, undoubtedly the form was chosen for ease of implementation. It made the analysis practical. For reference to the more detailed models that followed, we write the constant impedance load model below in (1). P, Q, and V represent the active power, reactive power, and voltage, and P_L, Q_L, and V_0 represent the pre-disturbance values for active power, reactive power, and voltage.

$$P = P_L\left(\frac{V}{V_0}\right)^2 \qquad Q = Q_L\left(\frac{V}{V_0}\right)^2 \tag{1}$$

As tools for analysis progressed to the use of digital computers, the reliance on simple load models to facilitate analysis remained a practical issue. In their 1993 paper on "Load Representation for Dynamic Performance Analysis" [1], the IEEE task force of the same name, presented information on a survey of industry representatives that reported that the dominant load model for stability analysis was a "constant current" model for active power and a constant impedance model for reactive power[2]. Other respondents reported using impedance models for both active and reactive power, polynomial models of the powers in terms of voltages, and two respondents used induction motor models for some studies. In (2) we display a second-order polynomial model for active power in terms of voltage. A similar equation is used for the reactive power. This is commonly referred to as a ZIP model because the first term corresponds to constant impedance, the second term to constant current and the last term to constant power, and the common electrical engineering symbols for impedance, current, and power are Z, I, and P respectively.

$$P = P_2\left(\frac{V}{V_0}\right)^2 + P_1\left(\frac{V}{V_0}\right) + P_0 \tag{2}$$

The static models, such as the ZIP model, have the practical benefit of not increasing the computational complexity of simulations, whereas dynamic models such as induction motors, do tend to make simulation run slower.[3] This was a concern up and through the 1980s but has become less a concern now with faster computers. The static models suffer from detail and cannot represent dynamics that many loads exhibit. Half of the respondents to the survey

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[2] "Constant current" is a slight misnomer since the load current will not remain constant with voltage changes in this case with the reactive power described as a constant impedance. Constant current refers to a model in which the power is directly proportional to voltage. When both the active and reactive powers are described this way, the model will enforce constant current magnitude at constant power factor.

[3] The adjectives "static" and "dynamic" refer both to types of studies and to the form of load models used in studies. Static studies, such as power flow, refer to steady-state analysis. Dynamic studies refer to stability studies involving the response of the system to disturbances. Static loads models have no "memory;" they respond instantaneously to changes in voltage frequency. Dynamic load models have memory and can store and exchange energy with the network.

mentioned above stated dissatisfaction with the models they were using. Improved accuracy in models was warranted.

The IEEE Task Force on Load Representation for Dynamic Performance followed their 1993 paper with a paper in 1995 with recommended models for standard load models [2]. This task force comprising industry experts with common interest in the load modeling put significant effort into this study. Many of their observations are recommendations are valid today, ten years later. Their observations and recommendations include:

1. Load models should be physical and flexible.
2. Multiple load models should be placed at each bus to represent the phenomena to be captured.
3. They emphasize the need for induction motor models, including details of saturation and mechanical load characteristics.
4. Include models of synchronous machines as applicable.
5. Include representation for distribution transformer saturation.
6. Include control actions in LTCs.
7. Model load shedding.

In Item 1 it is clear without discussion that the models should be flexible enough to support accurate models as needed, and this is reiterated in Item 2 by stating that multiple important loads should be explicitly represented. The notion that models should be physically based is not a fundamental axiom. There are two-basic approaches to load modeling, measurement-based, and composition-based. The former approach is entirely based on fitting a model to data without restriction on the form of the model. Neural Net-modeling is common for developing such models. The risk with such models is that they are only guaranteed to be accurate for the data from which they were developed, and there is understandable concern that without a physical basis, the models will not be accurate under different conditions that may arise. Since data are relatively rare, there is little opportunity to construct and then validate such models. We will discuss this more in the next chapter, which we devote to measurement issues. Composition-based models derive from assumed knowledge of the dominant types of loads present in network and direct incorporation of their characteristics or aggregation of similar characteristics. One has increased confidence in results using physically based models for disturbances since they can be accepted as physically possible based on the assumed load composition. And, of course, data from disturbances can be used to refine the model and assumptions.

The third item persists as a dominant modeling issues. Induction motors comprise at least 50% of the load used, and under heavy summer loading conditions, air-conditioning load alone can reach this level. As we discussed in the Introduction of this report, inadequate representation for induction motor load contributes to discrepancies between simulations and observed disturbances. The 1995 IEEE recommended modeling practices suggest that consideration be given to distinguishing between large and small induction motors because they have different characteristics. (Large induction motors have magnetic flux dynamics that can often be neglected in small motors.) The mechanical load torque on the motor can have an impact on the dynamics and they recommend a particular form for modeling this, which we will discuss shortly as part of the WECC load modeling work. Other details of load models can include the different types of motors, a representation for magnetic flux saturation, and low-voltage protection that may be present.

The fifth item in the list emphasizes the importance of magnetic saturation in distribution transformers, especially for studies that involve potential overvoltages. Note, however, that distribution transformers are typically not included in large-scale studies. A more detailed model of the load with some representation of the distribution network may be warranted. We visit this issue shortly in the WECC load modeling work.

As they note in their paper, Item 6 concerning LTC control actions is usually a network modeling issues where models for these transformers may already be present. The voltage regulating action of these transformers has been shown to be critical for representing certain voltage instabilities.

The last item we listed above represents the actions of undervoltage and underfrequency relays to shed load. These may apply to certain loads represented at a bus, some portion of each load, or to the entire load.

This 1995 paper suggests the following static load model to be used as part of the load at a bus, along with more detailed models for induction motors:

$$\begin{aligned}\frac{P}{P_{frac}P_0} &= K_{pz}\left(\frac{V}{V_0}\right)^2 + K_{pi}\left(\frac{V}{V_0}\right) + K_{pc} \\ &\quad + K_{p1}\left(\frac{V}{V_0}\right)^{n_{pv1}}(1+n_{pf1}\Delta f) + K_{p2}\left(\frac{V}{V_0}\right)^{n_{pv2}}(1+n_{pf2}\Delta f)\end{aligned} \tag{3}$$

$$K_{pz} = 1-(K_{pi}+K_{pc}+K_{p1}+K_{p2}) \tag{4}$$

where P, Q, V, and Δf are variables representing active power, reactive power, voltage, frequency difference from nominal. The remaining symbols denote various constants in the model to distribute the relative proportion of load to the ZIP model in the first three terms of (3) and the two frequency-dependent, voltage-exponential terms, their exponents, etc. There is an equivalent form for reactive power. While it may not be obvious from the form, the terms in the model are motivated by and related to physical characteristics of various tested load components, but remain general enough to allow for the aggregate modeling of different components within the same framework.

A dominant dynamic portion of the load model is the induction motor motel. One mathematical representation for a basic induction motor (three-phase, single cage, no saturation) is given by the equations:

$$V_D = E_D^{'} + R_s I_{Ds} - X^{'} I_{Qs}$$
$$V_Q = E_Q^{'} + R_s I_{Qs} + X^{'} I_{Ds}$$
$$T_0^{'} \frac{dE_Q^{'}}{dt} = -E_Q^{'} + \frac{X_m^2}{X_r} I_{Ds} - s \frac{X_r}{R_r} E_D^{'}$$
$$T_0^{'} \frac{dE_D^{'}}{dt} = -E_D^{'} - \frac{X_m^2}{X_r} I_{Qs} + s \frac{X_r}{R_r} E_Q^{'}$$
$$2H \frac{ds}{dt} = T_L(1-s) - E_Q^{'} I_{Qs} - E_D^{'} I_{Ds}$$

where V_D, V_Q, I_{Ds} and I_{Qs} are related to the terminal voltage and current, $E^{'}_D$ and $E^{'}_Q$ are related to rotor magnetic flux, and s is the slip (difference from synchronous speed). The remaining symbols are constants. The first equation is algebraic representation of the stator circuit, the first two differential equations represent rotor magnetic flux dynamics, and the last differential equation is the rotor torque equation. The differential equations indicate that the model has memory; the motor characteristics are not instantaneous functions of the terminal voltage. The inclusion of an induction motor in the load model does increase the complexity, but it adds important physical characteristics that are not well represented by the static models.

The recommendations of the IEEE task force are excellent, but there remains the issue of how to gather the data and information with which to populate the model. The model is not simple. The static model described by (3) and (4) and the reactive power counterpart requires the definition of 20 parameter values. Each induction motor model will require the definition of approximately 10 parameter values. Inclusion of other detailed model for discharge lighting, transformer saturation, LTC controls, and synchronous motors, will require even more parameters.

The traditional approach, at least philosophically, is to develop representative models by load class and then appropriately aggregate these models to form a composite model. A procedure for developing a detailed load model begins with an estimate of different customer classes that are part of the load, with distinctions made between residential, commercial, and industrial loads. For each class a typical model is imposed. Industrial customers, for example, will have a high proportion of their energy consumed in large induction motors, some with power electronic drives. A composite model will then include a detailed model of an induction motor, a model for the power electronic drive load (constant power over typical voltages), and a representation for the rest of the load. Similar, but different models are assumed for residential and commercial load classes. Based on the residential, commercial, and industrial loads present at a location, an aggregate model is built. Software aids are available to help. The EPRI LOADSYN program is used, and the WECC Load Modeling Task Force is developing a complementary tool for this purpose.

As we noted in the beginning of this chapter, WECC models are initially derived from data submitted by members. The detail of the model then depends on the members' submission. Here we note that the computer software used by the WECC members is capable of representing the models suggested in the IEEE Task Force recommendations. The WECC recommended standard static model is based on the IEEE recommendations, although mildly simpler. It takes the following form [17]:

$$P = P_0\left(P_1V^2 + P_2V + P_3 + P_4(1 + K_{pd}f)\right) \tag{5}$$

$$Q = Q_0\left(Q_1V^2 + Q_2V + Q_3 + Q_4(1 + K_{qd}f)\right) \tag{6}$$

This model is similar to (3) in that incorporates a ZIP model, but it differs in that in only includes a single frequency-dependent term (for each active and reactive power) and that this term is assumed to be insensitive to voltage.

Recognizing the importance of induction motor models, WECC imposes a 20% induction motor representation in the composite load model. The study forming the basis for this “interim” model is reported in [17]. In this study, the authors report on their efforts to replicate the observed behavior during the summer 1996 blackouts. In particular, they introduce an induction motor model, without which the simulations fail to capture the observed instabilities. From this lesson, they developed a default induction motor model that is intended to be a compromise between large and small motor models, and they considered some important sensitivity studies to test assumptions. The default motor model implemented at high voltage buses (for approximately 20% of the load) across the WECC system succeeds in replicating the basic features of the 1996 blackouts. Then, in this thoughtful piece, they consider sensitivity studies:

1. Connection of motor loads to new low-voltage buses. The results of this sensitivity study shows that motors thus connected increase system damping. They speculate that to achieve the same level of damping (or lack of damping) at a high-voltage bus, the percent of motor load would have to increase to 50%. (Note that this is a reasonable percentage and is consistent with estimates of total motor load.)
2. Different motor load percentages. These sensitivity studies show that increasing motor load percentage results in a decrease in damping.
3. Different motor inertias. These studies suggest that the sensitivity of system damping is relatively modest compared to the sensitivity of motor load percentages. As might be expected, increased inertia resulted in decreased damping.
4. Large and small motor models. Keeping the percentage of motor loads constant, it appears that the small motor parameters resulted in less damping than large motor parameters.
5. Location. In this interesting scenario, the authors find that motors located in the electrical “middle” of the system have the greatest negative impact on system damping.

The authors conclude their analyses with the study of a fictitious event in which the two largest generating stations trip out during heavily loaded summer conditions. These types of hypothetical studies are what the models are designed for, and the inclusion of the induction motors models has a noticeable impact on the results. While the system remains stable, the results show that certain path loadings need to be adjusted to meet WECC reliability criteria. This is an important consequence of improved models; improved models will impact the results of reliability studies.

They recommend this model for interim period while the WECC Load Modeling Task Force is conducting research on how to improve load models. They are accounting for some practical limits of available information and at the same time determining the most sensitive characteristics of the model that need attention. We discuss their activities next, which will lead to some of our recommendations for continued and future research.

3.3 WECC Load Modeling Task Force

The WECC Load Modeling Task Force (LMTF) is engaged in activities to improve load models in WECC planning models. Formed in 2002, the LMTF is tasked with developing a load model form that can be implemented in the two programs used by WECC members, (GE PSLF, and PTI PSE/E), developing a tool to aid in the determining model parameters given information about the load, and to recommended generic models when little information is available.

This is an ongoing research and development activity and some of the advancements summarized here are courtesy of the LMTF and its members. By reviewing some of their current work and the gaps it identifies, we see where future work may be best directed. A recent paper summarizes some of their activities [5].

The model under design and development must meet some sensible criteria. It must be accurate enough to capture the load's effect on system damping during disturbances, and it must be able to reflect the loads impact on voltage dynamics initiated by faults and system voltage dips. Also, from a practical point of view given the paucity of detailed information about loads, it should be robust to parameter variations (uncertainty). The latter objective suggests that key sensitivities should be identified and included in the model. As a recurring theme in this report (and in the load modeling literature in general), motor loads have a significant impact on system response and need particular attention. A final concern is that the model, when implemented, should not tax the capabilities of the computer software. That is, the computational requirements should not dramatically increase, and the algorithms should remain numerically stable.

In their present activities, the LTMF has performed background work on distribution systems, characteristics of end-use loads, load composition by class and location, special models for industrial loads, and load monitoring. With this information they are developing a structure for a recommended load model and a means to determine parameters from information.

3.3.1 Direction of recommended load model.

Two improvements on the structure of the model are:

- The introduction of a basic form of distribution network. This is not a detailed representation of a particular distribution network associated with a specific location. Rather it is a model to capture the effect of the existence of a distribution network including transformers and electrical distance between substation and end use.
- A more detailed and careful use of motor models.

The distribution networks (and typically not-modeled lower voltage networks) can be complicated with many lateral lines and loads. In this effort we emphasize that the distribution network representation is only a stylized version that introduce some key features of the network. This is considered part of a load model, not a directed effort to incorporate details of the distribution network. The features that are included in this manner are transformers and the effect of lines and reactive compensation. The change this introduces in a typical load model is depicted below in Figure 3-1. A transformer and line are introduced to connect the substation bus to a new lower voltage bus to which the end-use load is connected.

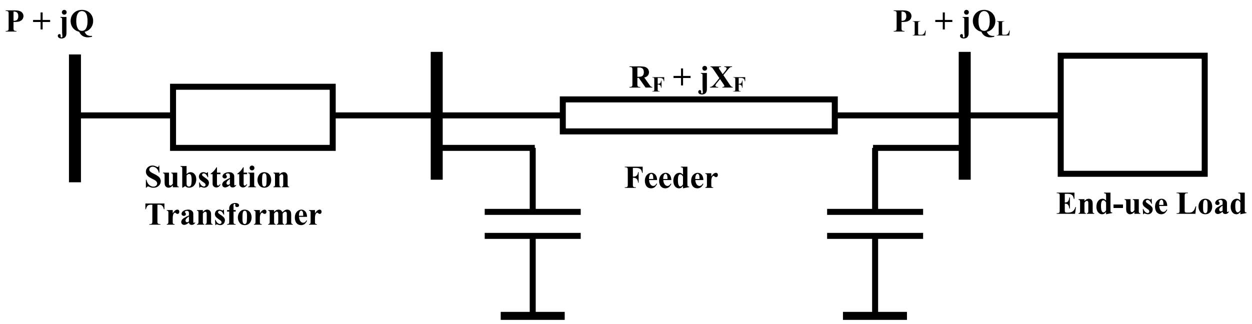


Figure 3-1. The introduction of a stylized distribution network.

The end-use load that is connected at the end of the line in Figure 3-1 will not have the same form as the rough and formerly used (and currently-used) models of loads at the substation bus. The end-use loads in the new model should be closer to those reported in surveys (which we discuss shortly). For example, in [17] the authors introduced a 20% induction motor model (at substation bus) to replicated observed disturbances, while surveys indicate that actual induction motor loads exceed 50% of the load. With the new structure of the model, it is expected that known estimates for load composition can be used directly, which should ease the work of engineers and increase confidence in the models.

The addition of the new lines and transformers requires some assumptions about the specific characteristics these should take. Engineering judgment based on typical distribution feeder voltage drops can be used, recognizing that in some cases other distinctions may be applicable. For example, short urban distribution feeders differ from long rural feeders. LMTF studies show that in the case of a short feeder representation, the simulation results are insensitive to transformer and feeder impedances. However, the results are sensitive to these parameters for long feeder representations [9], and more care may be necessary for constructing those cases.

The second item listed above, motor modeling, remains a significant issue for load modeling. The first issue is that end-use motor loads constitute the dominant part of the energy demand. While under normal operation this is concentrated in the industrial sector, under the heavily-load conditions when most system problems occur, residential and commercial HVAC energy use becomes a primary factor. Neglecting motor loads is believed to be the main reason for discrepancies between observed disturbances and simulations of power system dynamics.

The second issue and challenge in modeling the motor load is that there is such a wide variety in types of motors performing different tasks with different controls that it is difficult to construct a simple model that captures all the necessary features. Some motors are large, others are small, and they have different characteristics. (Magnetic flux dynamics in large motors impact dynamic studies, but do not for small motors.) Some motors are designed to be operated from three-phase supplies, others use single-phase supplies. (The effect of this difference remains unstudied in dynamic simulations. It is a gap that needs investigation.) Some motors have sophisticated power electronic controls that make them appear as constant power demands to the system. Some motor have protective relays that automatically turn them off after sustained low voltages; others do not. Different motors serve different mechanical purposes, driving pumps, compressor, fans, etc. The different mechanical loads also impact the dynamic simulations. (The impact of different mechanical load types remains a gap that needs to be studied.) This large range of different types of motors and usage makes it challenging to design an accurate and simple model, especially when one considers that the aggregate model actually represents thousands of individual components.

Standard methods for aggregating motors appear to work well for combining the effect of motors with basically similar characteristics, but do not work well for combining the effects of fundamentally different motors. Thus an aggregation of a large class of large motors with similar mechanical loading conditions into a single motor model works well for system studies. But significant differences are noticed between a model with both large and small motors when they are combined into a single equivalent motor. Furthermore, the controls of motors, even similar motors, differs at low voltages, suggesting the need for more than one model for, say, small motor loads, to capture the effects at low voltages.

Such a fine distinction among the end use of energy is too detailed for practice given the information that is available. A simpler, but detailed, model will be developed and recommended, such as that shown below in Figure 3-2 in which three aggregate motor models are used.

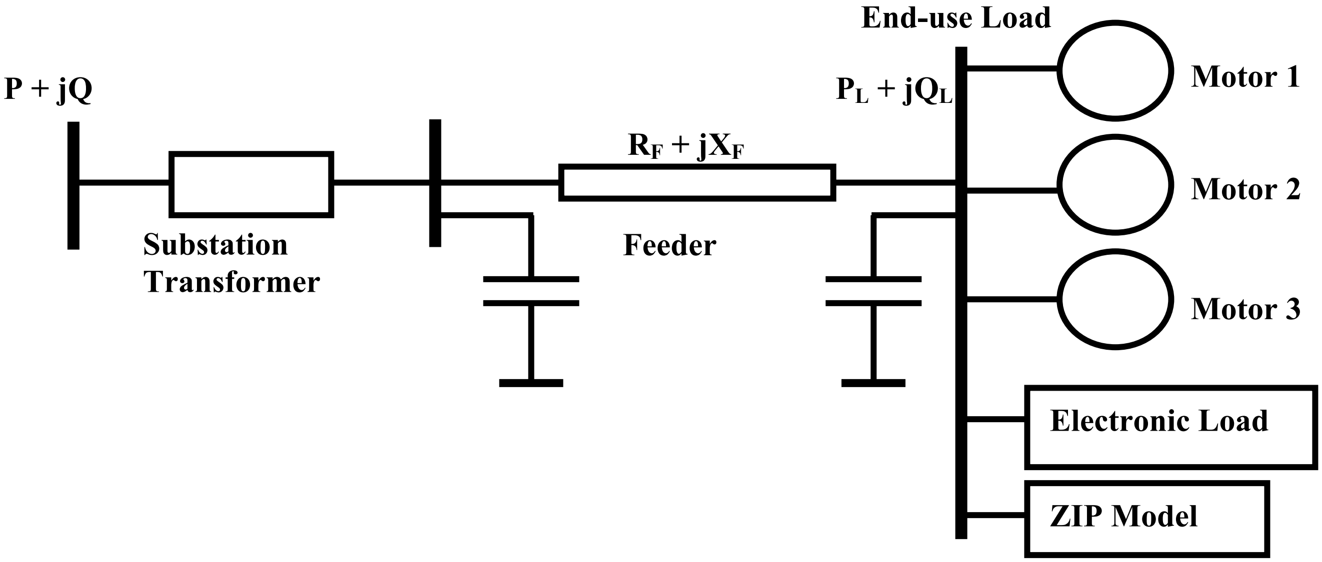


Figure 3-2. An aggregate load model in which three representative motors are employed.

The first two motors will represent three-phase motor load, differing by load shedding capability, and the third motor will represent single-phase motors. The remaining load includes representations for the electronic load and the remaining components using a ZIP model.

3.3.2 The load modeling process: Survey and Aggregation.

The process for updating load models follows the steps of obtaining new estimates for load composition by class (industrial, commercial, etc.) and then performing an aggregation step to combine the effects of representative models for each class. In their efforts, the LMTF has conducted a survey of members to identify load composition by class and is developing a tool to construct and aggregate model in this fashion.

The basic procedure for load composition estimation is shown below in Figure 3-4. Data from substation load class is converted to more detailed descriptions of load components, which are then aggregated to fit the specified load model. In addition, a representation for substation transformer and feeder are added to complete the load models. Details of the present state of the Load Modeling Tool (LMT) that performs these tasks, taking data from substation load class and developing load models, are described in [15].

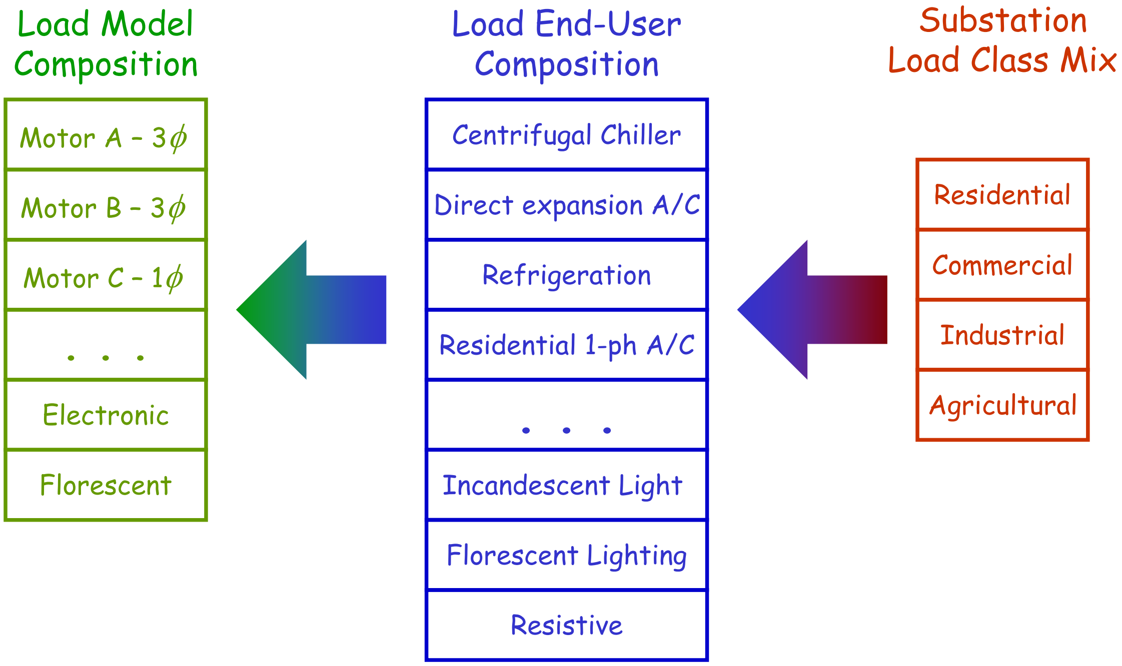


Figure 3-3 A method for load model composition estimation from substation data.

The final step in load model for dynamic performance is in validation. This is accomplished through comparisons of model-based simulations with recorded measurements in the field. The WECC performs model validation based on disturbances, and their experiences in these efforts are part of the motivation for the formation of the LMTF. Some validation studies are reported in the public literature such as [12] [17], while other reports are available only to WECC members.

Validation studies based on disturbances raises the issue of what information is and can be gathered from monitoring devices. This is the topic of the next chapter. Before embarking on that discussion and its own research needs, we summarize the research needs related to load modeling development.

3.4 Load Modeling Needs

In this section we summarize the load modeling needs with respect to the structure of the model and the information that may be gathered to enhance the models. Issues related to measurement, and validation from measurement we leave to the next chapter. We also recognize that significant work has been done by WECC committees already and that on-going research will continue within that structure. We emphasize here the issues that may not be done without some additional support, even for research that is best done by WECC committees and members.

The basic structure of the recommended load model that will come from the LMTF activities is likely to be adequate and serve simulations needs. No additional research is recommended for amending the structure as depicted by Figure 3-2. The models for the components require significant work yet, as well as information gathering for different operating seasons.

By far, the load component requiring the most attentions is the representation of induction motors. While this is long-recognized problem, there remain challenges for accurate modeling. We list items individually in our recommendations.

Recommendation: **Perform studies to determine mechanical load characteristics for induction motors. These studies would best be performed in a testing laboratory.**
Preliminary LMTF studies show that simulation results depend on the representation of the mechanical load's characteristic. At the simplest level, the relation between torque and speed differs between pumps, fans, and compressors, and the models will be improved by quantifying these differences by laboratory measurements (instead of by assumption). It may be the case that more sophisticated dynamic models for the loads may be necessary, especially for compressors.

Recommendation: Compare the responses of singe-phase and three-phase motors under different disturbances. This work should couple laboratory-setting experiments with detailed models and simulations.
The issue here is that under the heavily loaded conditions of great interest, the percentage of single-phase motor load increases (in residential air conditions, for example). The models used in simulation studies all correspond to three-phase motors. There is an unstudied, basic question about how accurately a three-phase motor model can represent the response of a single-phase motor under disturbance conditions. This is a reasonable question in that three-phase and single-phase motors model differ, most notable in the energy conversion to torque. This concern

complements the issue with motor mechanical load characteristics, which is also related to torque, and this recommendation could be studied at the same time as the previous recommendation

Recommendation: More work is required to model motor load shedding behavior under low voltage conditions. The aggregate model of induction motor loads requires a mechanism for allowing a portion of the load to trip off line during a disturbance.
The problem here is the difficulty in representing all the different characteristics of motor loads in a simple aggregate model. Presently the overall model could be augmented with different motors, ones that trip off line during a disturbance, and others that do not. In the traditional spirit and practice of modeling, an aggregate model that represent this low voltage trip, would be beneficial.

Recommendation: Discuss improvements to low-voltage protection on residential air conditioners with manufacturers.
It is observed that the slow voltage recovery observed after a disturbance could be avoided by temporarily removing voltage-sensitive loads, such as air-conditioners, and the restarting them after a few minutes delay. This approach to mitigating the problem on the component level should be discussed with manufacturers.

4. Measurements, Monitoring, and Validation

There is value in system measurements for load modeling. Measurements are crucial for validation work to confirm the accuracy of models, and furthermore, since load models affect operations and policy, justification for the models based on measurements in addition to reasonable assumptions should be required. In this chapter we review these issues, describe some of the uses of measurements, and project on what the uses will be, or can be in the future. Our recommendations will serve to improve load modeling capabilities.

Load models have an impact on reliability studies, planning studies, and even policies for reliability. A change in the load models used could result in a change in path ratings, transmission planning, and reliability criteria, and thus there is an economic value (and economic consequence) to using more accurate load models. Our stand in this report is that more accurate models are justified regardless of the positive or negative economic impact it may impart on planning. The issue that requires very serious consideration is whether the load modeling procedure as alluded to in the previous chapters is justifiable in light of possible consequences. The basic procedure presently being pursued is largely based on some knowledge and some assumptions. For example, the load model is built up from knowledge of load class (which is arguably known or can be known from utility billing records) and assumptions about typical behavior of loads within a class (residential, commercial, industrial). And then there is an imperfect aggregation step to simplify the model enough to allow practical numerical simulation. While the best information available may be used to justify the models, in light of the important impact they have, the results would benefit from use of measurement.

Measurements can be used to:

- validate models,
- form the basis of measurement-based models,
- test assumptions in the modeling procedure with staged testing or continual monitoring, and
- characterize uncertainty in the models.

We review these uses and consider what improvements can be made with existing, expected future measurement capabilities, and more sophisticated measuring equipment that does not presently exist.

4.1 Measurements and System Dynamic Monitoring

Existing data come from a variety of sources including state-estimator outputs, SCADA data, fault recorders, and phasor measurement units. For purposes of monitoring these all have benefits and drawbacks. State estimator data is useful for validation studies because it provides information on the state of they system prior and after a disturbance. Because it only runs every few minutes, a state estimator does not (and is not intended to) follow the fast dynamic responses of loads. Likewise, SCADA is somewhat limited in this regard, sampling every few seconds, but does provide information on relatively slow events that may persist for tens of seconds. Fault data recorders provide much of the information that is used in validation studies. These devices save information on voltages, frequency, and current, once a disturbance in noticed. They are limited for purposes of load modeling and validation in that their placement may not be optimal for any particular disturbance, are not typically placed near loads with the purpose of determining load characteristics. Phasor measurement units provide another source of information that is sampled at a rate consistent with fast response studies (30 samples reported per second). Their use is still not perfect (or designed) for load modeling, since they will also not be placed for this purpose, and they report positive sequence information (i.e., not information along individual phases to which loads are ultimately connected).

The IEEE Disturbance Monitoring Working Group (DMWG) has consider these issues and are seeking a vendor to develop a low cost (under $10K) monitor that is specifically intended to help identify load characteristics. It will be placed on distribution feeders and will measure phase currents and voltages. This provides direct information about what is happening at the interface where the (better-known) system model stops and the load model starts.

Recommendation: Support the development and placement of $10K load monitors.
Encourage the use of monitors, and staff time, to gather information beneficial to improved load modeling.

In the future, it is likely that there will be a proliferation of phasor measurement units and similar high-sampling rate real-time recorders. These offer the promise of improved disturbance validation. Presently, given the paucity of data and rarity of events, each disturbance validation exercise is handled uniquely. One can expect that better models and greater data will allow the creation of a nearly automated process of model validation from measured data. Conceptually this will mimic the activities of a state estimator, except with more sophisticated, dynamic models. Initially, during a development stage, it might be run off-line with historical data, but should be developed with the intent of possible on-line implementation. While this task is not exclusively limited to the topic of load modeling, and might be considered outside the purview of this report, we make the recommendation here to begin the background research to plan for this future. Two basic questions could be addressed in an initial study. One, what are the basic mathematical tools that would be used and their data requirements. Two, what institutional issues related to data gathering will need consideration.

Recommendation: Support a basic research project to outline the challenges associated with automated model validation and developing a dynamic state monitor.
The issues to be addressed are the mathematical tools and data requirements, and institutional challenges with gathering and sharing data.

4.2 Load Monitoring

In the near term, load models need improvement and may benefit from measurements. There are examples in the WECC where this is the focus of research. We discuss a few of the efforts in the West and the lessons learned that can be applied to future research.

In a study of a specific industrial plant, the Bonneville Power Administration (BPA) developed a load model for a paper mill and validated the model using disturbance data. The model was developed with information on the electrical layout about the plant and its end-use components. In Figure 4-1 the simulated and recorded responses are provided for comparison. It is clear that the model represents the actual response very well. The encouraging lesson one may infer from this study is that it is possible to accurately characterize the behavior of the load when information and measurements are available. With an industrial plant the load is concentrated and information may be gathered (assuming cooperation with the load) to form a relatively simple model that captures the basic physical features of the load. If the operation of the plant is fairly consistent over time, it should be a useful representative model for the site. It is understood that a model formed in this manner is specific to the individual plant and care should be taken before replicating the form of the model to other industrial plants, especially of very different types (i.e. not paper mills).

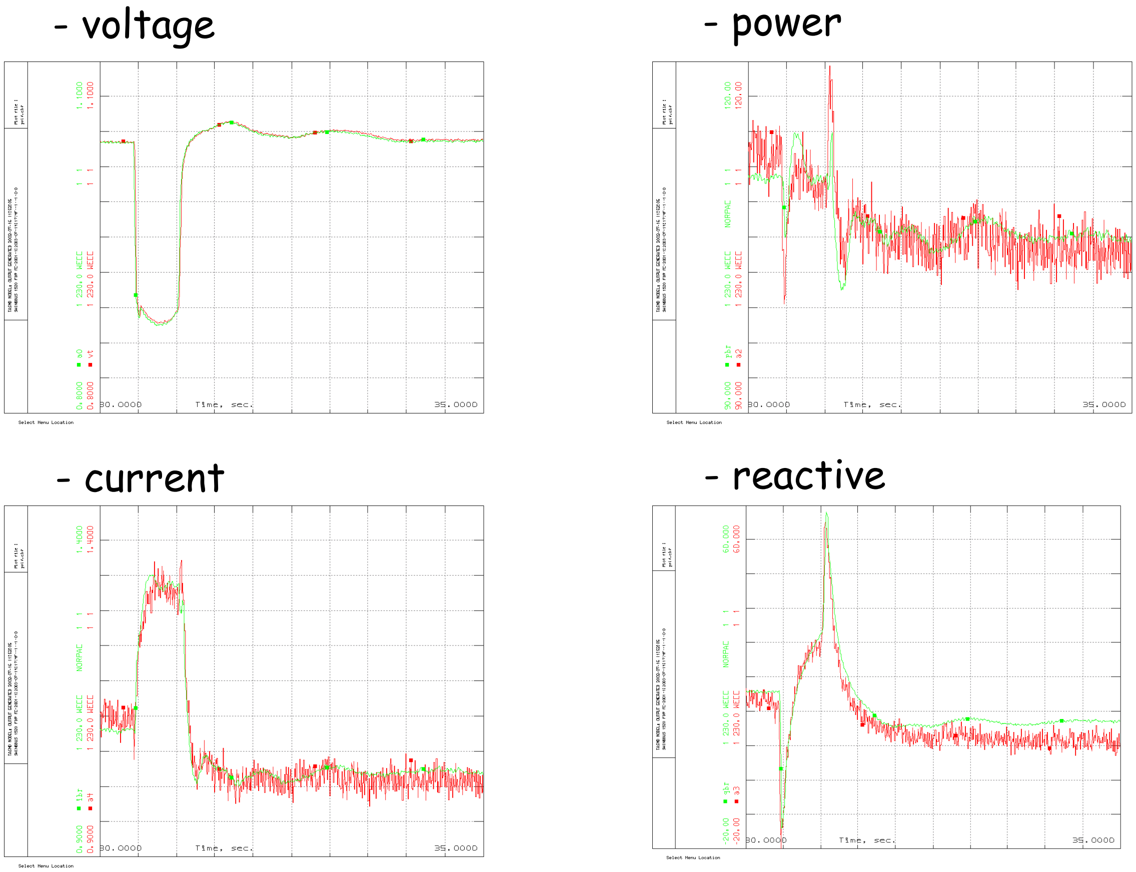


Figure 4-1 Recorded and simulated response to a disturbance at a paper mill (courtesy D. Kosterev).

Public Service Company of New Mexico (PNM) has also conducted research on characterization of loads in their system, from measurements. Some of their results are presented in [6]. Their approach is consistent with the physically based load modeling philosophy discussed in this report. They assume representative models for dominant electrical components and then use measurements to estimate the percentage of each component in load. The components include small, medium, and large motors, incandescent lighting, fluorescent lighting, thermostatic loads, electronics loads, and capacitors. They also designed custom measurement systems to record voltages and currents on individual feeders from a distribution substation. They collected data from natural disturbances, and from staged tests.

While the models are physically based, we emphasize the difference between this approach and the typical physically based modeling approach: the information comes from measurements. Presently model parameters are populated based on knowledge of load class, that is, the percentage of residential, commercial, and industrial load. In the PNM study, model is populated by assumptions of typical load components (not class) and measurement-based estimations of percentages of each component. The report shows that this approach is feasible and provides reasonable results.

The report and discussion with the author also highlight some important observations and lessons. These include the following:

- Any estimation technique will fit the data. It is important to use an estimation technique that respects the physical nature of the load. They noticed that simple least-squares estimation often resulted in coefficients that were not physical (unrealistically large numbers, and negative weights). They effectively employed a fuzzy regression scheme that resulted in physically meaningful coefficients.
- The measurements at the distribution level are noisy. Voltage disturbances of a minimum deviation of 2.5% are necessary to extract useful information from measurements.
- It is important to measure responses of individual phases to estimate single-phase load components.
- There are significant challenges to isolating load characteristic in measurements. These include the time frame of the measurement to exclude effects of load variation and the effect of automatic voltage controls that may be present in the network.
- Load composition changes with time, and data coming from natural disturbances may not yield the most appropriate model for general use.

This is very promising and reasonable work on load modeling. We recommend that it continue with a focus on gaining experience with this approach to load monitoring and how to apply it to system-wide studies, given that relatively few representative substations can be metered in this way. Of particular importance is the question of how to populate load models in general based on a few measurements.

Recommendation: Support activities to estimate load composition from measurements. This includes investigating refinement in metering equipment, assumed load models (such as adding stylized distribution feeder model as WECC moves in this direction), staged testing, and techniques for estimation that may expand conditions under which estimation is possible.

Recommendation: Support activities to test load model substitutability assumptions, and to characterize a range of uncertainty in models.
This addresses the issue of whether or not representative models are truly representative by comparing results from substations that would be assumed to have similar loading characteristics by load class. The matches will not be perfect, so there would be additional value to characterizing the range of values obtained for different load classes that may be evaluating

using uncertainty analyses. Also, a calculation of uncertainty in estimates at each measured location will facilitate uncertainty simulations.

We also believe this measurement approach may benefit from ideas and techniques used in the Non-Intrusive Load Monitor (NILM) that was developed at MIT [13]. The NILM is a device placed at the service entry to a building and through sophisticated signal processing is able to detect when individual components in the building turn on and off. Furthermore, with information of how the equipment should operate, or has operated in the past, it is able to diagnose degradation of equipment and they systems they run. It has been employed and tested in several buildings in California under support from the CEC [3].

The core of the NILM technology is a detection algorithm that correlates observed transients in the spectral components (harmonics) of voltage and currents to the signatures of equipment. The start-up waveforms for motors appear different from those of incandescent lighting, discharge lighting, etc., and at the level of a building many components can be distinguished. At the level of the power grid there is little hope that individual components could be identified in this manner (except, perhaps at industrial facilities). Nevertheless, it may be possible to distinguish in a course sense the operation of classes of particular components based on the analysis of steady-state harmonic characteristics of the load voltages and currents. An initial study of this approach was promising [14]. One could envision a load composition monitor that would attempt to estimate the percent of load in certain categories.

Such research would need to be considered high risk. It is yet unknown whether information in the harmonics will be useful. At the minimum, is very likely that information in the harmonics can improve the component estimates from disturbance data. Presently the best work relies on only the 60Hz waveforms, and the harmonics can only add information. But in the case of steady-state analysis, it is not clear that harmonic information can be correlated to load composition.

The benefit of such research, if successful, could be large. The load changes continually and the best models now in use assume that load composition does not change; the models are prepared for a high summer load scenario. We have made a recommendation for the development of seasonal models, but these do not track hourly and daily changes in composition. An estimate of load composition, from measurement, may save the operators from surprises.

We think it would be prudent to design and install monitoring equipment at some substations with the capability of recording harmonics. This is for the expressed purpose of assessing the value of this extra information. If there appears to be information in steady state, a subsequent project may look into the development of a load composition monitor.

Recommendation: Assess the value of harmonic information for the purposes of estimating load composition.

The additional information in harmonics will augment the primary frequency data now used, and there may be useful information in steady-state waveforms.

4.3 Measurement-Only Load Models

There is an alternative to the physically based load models that we have discussed in this report. One can make an argument for the use of measurement-based load models, the form of which do not necessarily have a physical basis. Neural net models are a common form of measurement-based models. The advantage of this type of model is that the form of the model is not restricted and can adapt to fit measured data. Furthermore, one must admit that physically based models are one only an approximation of the real network; they are designed to capture basic physical features, but only in a coarse sense. The aggregation and uncertainty in composition, etc., make the form inexact. It is entirely reasonable and appropriate to consider generic "black-box" modeling techniques that can accurately reproduce the observed behavior of loads.

The fatal flaw with this approach is the extreme lack of data with which to develop a model that can be expected to perform well (or better than physically-based models) over a wide range of operating conditions. Without any physical basis to the models, one cannot be certain the models will represent load characteristics for conditions outside those used to fit parameters of the model. Severe outages, which are the conditions of interest, are relatively rare and recorded data is scarce – at least from the perspective of having enough data to develop a comprehensive model. Of course it is possible to fit and/or validate black-box models using simulated data with loads modeled in a traditional manner. In doing so there is little doubt that measurement-only models can fit the characteristics of a physically based model. (But a model fit in this manner offers no advantage over a physically based model.) Most practitioners that we interviewed feel that there is not enough data to support such a modeling approach at this time (or in the foreseeable future - hopefully severe disturbances will continue to be relatively rare!).

Measurement efforts are likely to be the most successful and useful for estimates of load composition, and not for the development of black-box load models. However, we should be cognizant of such efforts and employ any breakthroughs if they occur.

Recommendation: Follow efforts to develop measurement-only (black-box) load models. In general, black-box modeling techniques are most valuable when the available data is rich enough to show all the operating characteristics of the modeled component. Presently, we believe that the data set does not support this approach.

5. Uncertainty Analysis

The load models we have discussed are necessarily imperfect. It is not possible to model every end-use component in the system, and it is not reasonable to represent details of every distribution network in a model spanning a continent. And it isn't necessary. An engineer with a background in dynamic phenomena can look at the disturbance plots, such as those shown in Figure 2-1 and Figure 2-2, and recognize that an incredibly detailed model with thousands of components modeled is not required to capture the basic features of the disturbance. The challenge is to develop a parametric model that is flexible enough to be able to represent the observed disturbances, and then to consider parameters suitable for further analysis. Efforts are under way to improve the form of load models to capture some of the salient features of loads and distribution networks, and we have recommended continued research to examine important features that are not adequately featured in the models.

Completion of efforts to improve the form of the load models should yield a representation that is capable of capturing the important features of the load that affect dynamic studies. However, there will remain a significant amount of uncertainty. Even if there exists a particular set of parameters values for the model that will accurately represent the system loads, it is not possible to know the values of these parameters. For example, the form of the load model may allow for accurate analysis of the effect of induction motors on system damping and prediction of low voltage responses of compressor-loaded motors, but we will still not know, with certainty, the amount of motor load that should be present in the model. In a practical sense, we may have adequate models for components and low-voltage systems, but we cannot exactly know what percentage of the loads correspond to each component. Moreover, any aggregation step introduces uncertainty in the representation of the model.

There may be value in considering the effect of model uncertainties may have on the outcome of studies. This is a common practice in many areas of engineering, including power engineering. (For example, scenario analysis is used in transmission planning to evaluate future needs under different assumptions for resource availability, and the N-1 reliability criterion effectively removes uncertainty in location of events by considering them all.) There are a few common methods for uncertainty analysis and their use depends on the information available and computation limits that may be encountered. These methods include

1. Worst Case Study. In this case, one posits a worst-case scenario (a task in itself) under which a system is required to operate, and then designs the system to do so. Presumably this is sufficient to cover all other operating conditions.
2. Scenario Analysis. One posits a set of different scenarios under which the system is expected to operate, and then ensures the system can operate under these various conditions.
3. Weighted Scenario Analysis. This is identical to scenario analysis except weights are assigned to the different scenarios. These may represent the relative importance, or the probability of occurrence of the different conditions. In this case it may not be deemed necessary to operate under all conditions (otherwise there is no need for the weights), rather one may require that operation be expected with some (high) probability. Or, in the transmission planning context, we may expect that today's decisions will suffice to meet future needs with an acceptable (high) probability.

4. Monte Carlo Simulation. This is a common technique for uncertainty analysis when uncertainty in models can be parameterized by distribution functions. It may be considered an automated weighted scenario analysis where the scenarios considered are randomly chosen based on the distribution functions. In this manner many thousands of scenarios may be considered. Like the weighted scenario analysis, it allows one to place decisions in a likelihood context.

In the context of uncertainty in load modeling, these approaches are not routinely applied. For the dynamic simulations that are of most interest in this report, WECC uses static model supplied by participants, augmented with a 20% induction motor load. This is largely due to results of model tuning from the 1996 disturbances. Presently the WECC LMTF is developing a new model with data that will be applicable to a heavy loaded summer condition. This might be considered akin to a worst-case analysis. The LMTF will likely conduct load modeling sensitivity studies as part of their research investigations. There is no plan to evaluate uncertainty in load models for standard planning and reliability studies.

It should be clear that many studies are (and should be) driven by worst-case analyses. It is a challenging task to pose the conditions and load models suitable for realistic worst-case analysis. Sensitivity studies are helpful for isolating the key characteristics that are represented in the worst case models, and can provide information about the sensitivity of to worst-case model assumptions. These same parametric models and sensitivity information can be used to evaluate model uncertainties in formal way, at least in theory.

Part of the problem is that there are several impediments to evaluating load model uncertainties, including:

- There are no quantitative data on load model uncertainties. One has to characterize uncertainty in order to evaluate it.
- There are few efficient tools to perform the uncertainty analysis. In the context of dynamic simulations this is computationally challenging. The analysis relies on evaluation of repeated simulations using different load modeling assumptions. A Monte Carlo study, for example, would require thousands of simulations and is computationally prohibitive.
- There has not been a study to quantify the value of such an uncertainty analysis.

The last point does not suggest that there is not value in improved models. It was noted in [17] that the inclusion of 20% induction motor load in the model would warrant changes in path ratings, and in [6] the purpose of the estimation of load model composition was for studies to design remedial action schemes. The last point differs slightly in that it suggests not only improved models, but also that there is value to an evaluation of the uncertainties in the models. While this has not been proven, it appears sensible. Since we cannot represent every component in the system, some uncertainty in the model is unavoidable. Moreover, it is generally felt that deficiencies in load modeling are dominant weakness in the model. We proceed with a discussion of this research topic assuming that there will be value in uncertainty analyses, and we expect that researchers will consider this question as work is done in this area.

The first issue of availability of data on uncertainty is addressed by recommendations in the monitoring section of the last chapter. The load monitoring activities can be augmented to quantify uncertainty in two ways. One, uncertainty in the load composition estimates may be calculated from the data and calculation, and two, typical ranges for different substation locations may be compiled for use in models for which there is little data and no monitors.

A visual description of uncertainty analysis

Figure 5-1 shows the ideal: a complete uncertainty description of the input is available; an exact, trusted model is used to compute a complete uncertainty description of the output. This is typically done with a Monte Carlo simulation. If a tool analyzing the exact model is time consuming, the repeated sampling approach of the Monte Carlo will be computationally prohibitive. If a simulation set requires 100 simulations, each requiring 1 minute of processing and computation time and the Monte Carlo simulation requires 1000 repetitions, then (without parallel processors) the computations time will approach 100,000 minutes. While potentially computationally costly to compute, the output description is very useful. The output distribution obtained through this approach can be analyzed easily to answer most questions about the range of possible outcomes and their likelihood of occurrence.

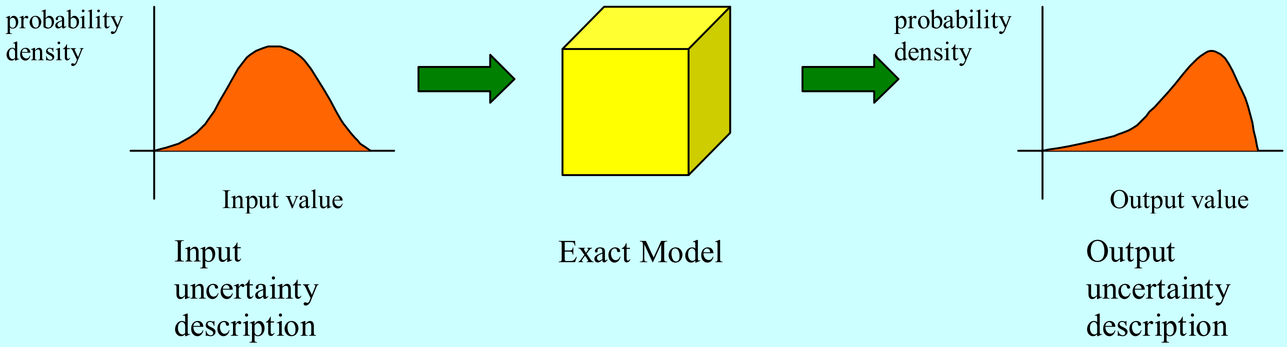


Figure 5-1 A complete uncertainty analysis. The uncertainty is contained in a parameterized description of inputs into an exact model. Analysis of the uncertainty and exact model yield a description of the uncertainty of the outcome, shown on the right. Typically a Monte Carlo method is used for the analysis.

Scenario Analysis is commonly used. Instead of a detailed uncertainty description, selected scenarios are chosen to evaluate using the exact model. This does not inherently apply likelihood weights to the scenarios (Figure 5-2), but probabilities can be applied to scenarios if desired (Figure 5-3). The output descriptions aren't as valuable as that shown in Figure 1, but computationally, scenario analysis is practical.

An alternative approach is to maintain the exact uncertainty description and perform a Monte Carlo (or even better, analytic) analysis using an approximate model that runs very quickly, possibly several orders of magnitude more quickly than the original. If this can be done without losing too much accuracy, it is an attractive approach. It supplies the desired form of output uncertainty description. This is depicted in Figure 5-4.

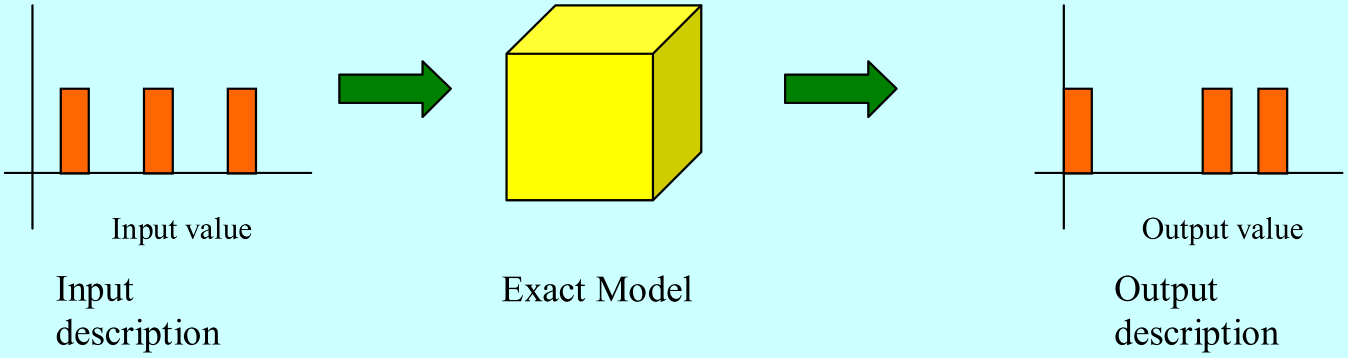


Figure 5-2Scenario Analysis: select input scenarios are analyzed with an exact model yielding the output results. No likelihood is explicitly indicated.

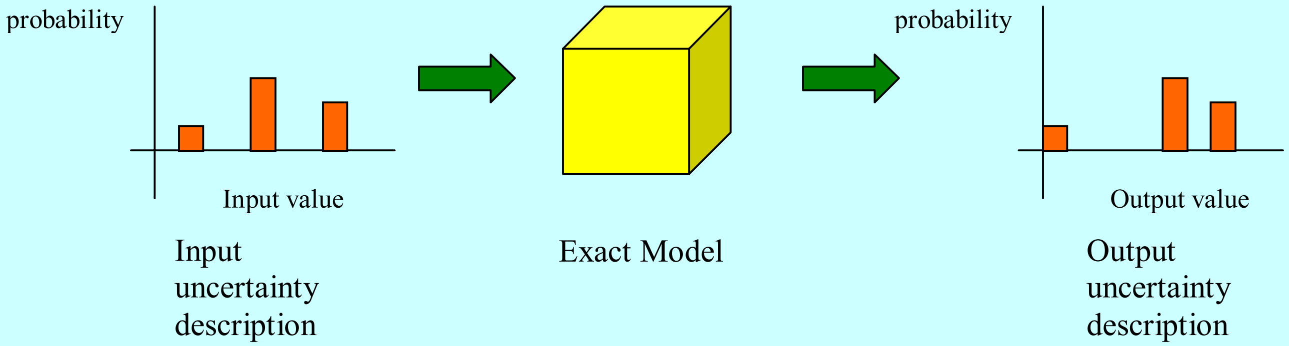


Figure 5-3 Weighted scenario analysis: Likelihoods (probabilities) are assigned to each scenario.

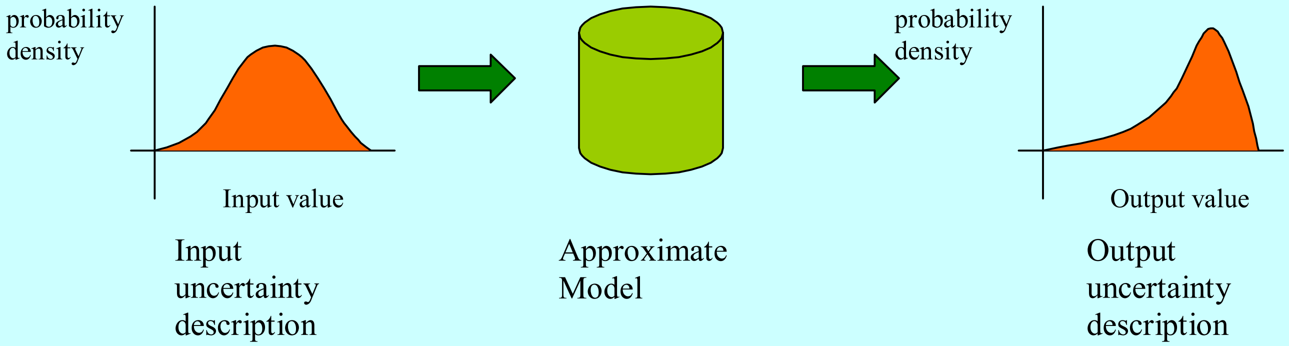


Figure 5-2 Full uncertainty description with approximate model yields an approximation of the full uncertainty description of the output.

Parallel research can be initiated to determine how to evaluate uncertain information if it were available. This research will need consider the type of analysis to use (worst case, scenarios, Monte Carlo) based on the information that is available and the purpose of the study. If it can be shown with confidence that there is a particular worst-case load model and that it can occur in the actual grid, then a worst case scenario study is the easiest to perform. On the other hand if no such worst-case model is known, or is deemed extremely unlikely, or there are several (or numerous) model combinations that may be consider worst-case, then scenario analysis or Monte Carlo simulation will be appropriate.

In the sidebar on uncertainty analysis, we give a visual presentation of the differences in these approaches. An "exact" evaluation of uncertainty typically requires significant computation, and presumes an accurate description of the uncertainty is available. Scenario analysis and weighted scenario analysis are computationally more efficient, but do not consider all possible uncertainties, or all possible outcomes. Care must be chosen when using scenario analysis to ensure that all uncertainties of interest and outcomes are considered.

The last portion of the sidebar depicts a relatively recent development in uncertainty analysis in which the detailed model is replaced by an approximate, reduced-order model. The premise is that the detailed model is difficult (or time consuming) to evaluate and that a well-designed approximate model is simpler. Furthermore, the approximate model can be designed specifically to support the uncertainty analysis. An example of this is the Probabilistic Collocation Method (PCM) (also known as the Deterministic Equivalent Modeling Method (DEMM)) that was introduced to evaluate global climate change models [22]. The global climate models can be very sophisticated and require up to a days worth of computation to evaluate a single scenario. A Monte Carlo simulation is out of the question. By gathering information for a few well-chosen simulation runs, an approximate model that maps the uncertain inputs to the outputs of interest is developed, and this simpler model is easily evaluated using Monte Carlo techniques. This approach has been applied to a power system model in an academic setting with promising results [8]. The authors evaluated uncertainties in load models and fault characteristics in dynamic simulations of power systems. Using the PCM method they were able to reduce the computation requirements by a factor of 300 (2 days reduced to 10 minutes). This and similar approaches are worth pursuing in this context.

Recommendation: Initiate a program to develop methods to evaluate the effect of load model uncertainties on system studies.

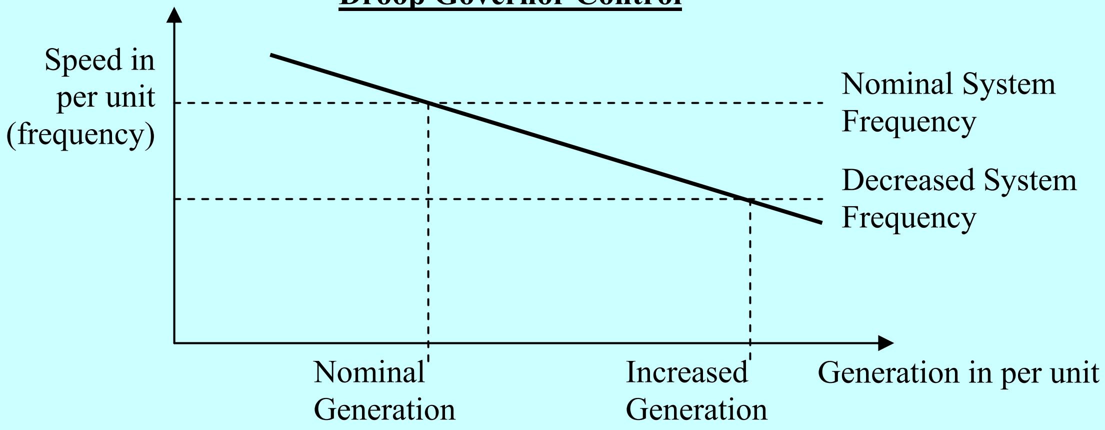
Load models and their parameters will never be known with certainty. Since they are believed to be a main source of discrepancy between simulations and observations, it is sensible to begin a program into studying the effect of uncertainties on outcomes of interest.

6. Generator Governor Models

In the dynamic simulation tasks of interest, generators are modeled in great detail and the models are largely believed to be accurate. Unlike load models that are aggregate by necessity, detailed physical representations of individual generators are feasible. Mathematical models are developed for the physical generator itself and for all the supporting subsystems and controls.

In theory, all generators should be equipped with a droop governor control (see sidebar) that helps maintain the system energy balance after sudden, unanticipated changes. These often occur if a generating plant trips off-line and the remaining generators must increase output to compensate. As the frequency changes, the generators should respond by increasing (or decreasing) output to reestablish an energy balance. By setting all generators to the same droop setting (5% in the West), they all should compensate in proportion to their relative sizes.

Droop Governor Control



A disturbance in the system that results in a change in frequency signals a net power imbalance. If the load exceeds generation, the frequency will decrease (generators will slow down), and if left unchecked the frequency will continue to fall. Governor controls on generators will act to counter changes in frequency by increasing or decreasing output as needed. The characteristic of this control is shown in the figure above. The slope of the control line is called the droop and is commonly set to 5%. (Note that the independent action – frequency change – is shown on the vertical axis, and the dependent action, generation output, is shown on the horizontal axis.)

To coordinate the response of the many generators, the droop of the governors are set to the same value. This automatically distributes the needed change in generation among the generators by the relative amount of nominal output. Thus a 100 MW generator will contribute 10 times as much in generation change than a 10 MW generator.

In practice it has been noticed by CAISO that after moderate and large disturbances the amount frequency response is smaller than expected and there is concern that this, in part, because some plant operational controls may override the needed governor response. NERC has documented a persistent decline in frequency response over recent years and suggest a number of reasons for it [16]. These include a fundamental change in load characteristics – induction motors that typically decrease energy use with a decrease in frequency supply may no longer do so if controlled by power electronics – and issues related to operating generators near capacity. A generator operating near its maximum supply limit will not be able supply additional energy if called upon to do so. Worse, the NERC document reports, certain combined-cycle generators may actually be operating on a temperature control loop when near the maximum output, and can exacerbate frequency problems by decreasing output with lower frequency. It may also be the case that plant operators simply disable droop governor controls, although they should not. One may also make the observation that in a centralized electricity market there is an economic motivation for suppliers to be fully dispatched, limiting their ability to increase output, and an economic incentive to not decrease output for loss of sales.

Droop governor response is intended to provide quick a quick response to maintain the integrity of the system. It is not intended to dictate long term dispatch and in a centralized control system frequency will be restored to its nominal value by an economic redispatch of generation. When there is not a centralized control system to dictate the output of all generators, then there may be plants with their own controls to maintain a generation set point. While they may be equipped with functioning droop governors that do react to a disturbance, their own controls to regulate output will work against the initial droop governor response.

This is a serious problem. It is not clear that it is a modeling problem as much as an information problem. Present models for generators and generator controls are probably adequate or can be adapted to account for actual generator operation. A recent addition to generator models controls includes a power setting that represents controls that adjust to maintain a specified power output [19] [18]. This effect tends to reduce the governor response. This model has been shown to increase the accuracy of simulations. In anticipating the response to a disturbance, CAISO needs to know how a generator's output will respond, and operate monitoring tools to verify that the response is what it should be. The issues involve mechanisms to get this information, and to maintain an up-to-date database of this information.

Recommendation: Use the governor model of [19][18] and support WECC activities to maintain a database of plant governor characteristics.

Recommendation: Develop or adapt tools to monitor supplier governor frequency response.

WECC has adopted a governor model that captures the effect of reduced frequency response. They populate the model based on information from survey of generator owners, and have validated the model using historical data. In order to gain accurate model parameters based on measurements, one can develop a tool to identify the responses of individual units.

7. Summary and Recommendations

Load models have an impact on dynamic studies and deficiencies in the models are believed to be a dominant source of discrepancy between observations and model-based simulations. Improved load models should increase confidence in operational limits for reliability. Changes in load models can result in operating limits, and may require reconsideration of reliability criteria. In a general sense, improvements to load models include:

1. The development and use of different models for different operating conditions. Most notable is the lack of different models for different seasons.
2. Improving the understanding and form of load models.
3. Improving confidence in models and usage through measurement and uncertainty analysis.

There is considerable work being done on load modeling already. In the West, WECC is actively engaged in research activity in this area. WECC models are widely used by all WECC members, and as a NERC region they have an interest and responsibility in ensuring reliability. Where there is overlap and existing expertise, it is sensible to support these activities and researchers as their results have a direct impact on operation in the West.

Throughout this report we have suggested recommendations by research topic. These are general recommendations to the field and all do not require direct backing and sponsorship by the PIER. Here we restate the recommendations still organized by research topic. Some recommendations require little PIER input and will likely be completed under existing work, while others suggest initiating completely new programs that may not be accomplished without PIER support. In addition to a summary of each recommendation, we provide an assessment of the necessary research in four categories: 1) the level of effort required to complete the research, 2) the expected time required, 3) the level of needed PIER direction and support, and 4) the significance of the research. We conclude with a summary table of recommendations.

Before proceeding with a summary of the recommendations, we further describe the distinctions used in the four categories of research requirements.

<u>The level of effort required to complete the research</u>, a relative measure encompassing the staffing, focus, design and installation of special equipment, and in a general sense, total cost.

- High: Multiple investigators and necessary installation of equipment and analysis of measured data.
- Moderate: Single lead investigator and need for development of new techniques for analysis. Or this designation may refer to an otherwise costly activity that is best combined with another recommendation.
- Low: Single investigator using established techniques to perform the study.

<u>The expected time to completion</u>: The distinction here is between an activity that should take one-year or less, and those that will require multiple years. A further note is made on those that

will continue as on-going activities after the initial study (such as maintaining and updating data).

The level of PIER direction and support. Some projects require little direct PIER support, as they will be initiated and completed by others. Some projects involve long-term and basic research and might not be initiated without PIER support.

- Low: Will be initiated and completed by others.
- Moderate: May require some direction and support to supplement projects with others.
- High: Long-term and basic research that will require PIER direction and support to initiate the research.

Significance: An estimate of the impact on improving the models and tools.

- Low: the research will not likely have a significant impact
- Moderate: will provide an incremental improvement in models and analysis tools.
- High: introduces a fundamental improvement in the models and analysis tools.

7.1 Review of Recommendations

Here we list the report recommendations. For reference we include the page number in the report where these recommendations originate, and we include a brief comment about the recommendation.

7.1.1 Load Model Development and Policies

Recommendation: Include seasonal variations in load models (pg 16).
It is clear that the load changes substantially with season. Most dramatically is the air-conditioning load in the Southwest that is present in the summer, but absent in the winter, and the heating-related load that is present in Northwest in the winter and largely absent in the summer. Some form of regional and seasonal variations in the models can be made as they presently exist, and will benefit from the improved models that we discuss in the next section. This work is best done by WECC (LMTF initially), but they currently do not have plans to do so.

Level of Effort: *Low.* Requires new survey for seasonal load composition and application of tools and techniques already under development by the LMTF.
Time Required: *1-year.* Ongoing maintenance of data will be required.
PIER support: *Low.* A small amount of support may be required to initiate the activity.
Significance: *Moderate.* Most of the significant events are observed during the summer conditions, which corresponds to the one seasonal model in use.

Recommendation: Incorporate state estimator models into the modeling process (pg 16).
State estimators are used in several regions in the West and the models that they use should be the most accurate available. It would be particularly valuable to compare the planning models with state estimator models as one check for consistency. The WECC Technical Studies Subcommittee is presently considering ways to use state estimator models in the modeling

process. As WECC moves forward along this sensible path, it is possible that data confidentiality issues will arise that will need consideration. The PIER may be positioned to aid in making useful state estimator data available to improve system models.
Level of Effort: *Low.* Likely to be initiated by WECC.
Time Required: *1-year* initiate research followed by continual use.
PIER support: *Low.*
Significance: *Moderate.* A comparison of planning models and state estimator models will likely turn up a few inconsistencies. Fixing these will provide and incremental improvement to the models.

Recommendation: Anticipate and support activities to review reliability criteria, taking into account information provided by detailed characteristics of new load models (pg 17).
Recognition that induction motor loads constitute a portion of the load that may be considered voltage-sensitive, reliability criteria associated with voltage transients should be reviewed to account for this portion of the load.

Level of Effort: *Low.* Will need to be conducted by WECC.
Time Required: *multi-year.* Reviewing and changing standards can be a long process.
PIER support: *Low.*
Significance: *High*. A change in reliability standards by definition requires a fundamental change in analysis of the grid.

7.1.2 Load Modeling

Recommendation: **Perform studies to determine mechanical load characteristics for induction motors (pg 27).**
Preliminary LMTF studies show that simulation results depend on the representation of the mechanical load's characteristic. At the simplest level, the relation between torque and speed differs between pumps, fans, and compressors, and the models will be improved by quantifying these differences by laboratory measurements (instead of by assumption). It may be the case that more sophisticated dynamic models for the loads may be necessary, especially for compressors. This is unknown at this point, and this research is presently beyond the WECC LMTF supported activities. These studies would best be performed in a testing laboratory.

Level of Effort: *Moderate.* Can by carried out by single lead investigator, but it will require laboratory facilities, and equipment to test.
Time Required: *single-year.*
PIER support: *Moderate.* This is important project that the LMTF would like to see done. Limited testing and modeling is likely to be initiated by some WECC members, but supplemental PIER support will allow more comprehensive testing.
Significance: *High*. This involves a fundamental changing in accurate load model representation.

Recommendation: Compare the responses of singe-phase and three-phase motors under different disturbances (pg 27).
The issue here is that under the heavily loaded conditions of great interest, the percentage of single-phase motor load increases (in residential air conditions, for example). The models used in simulation studies all correspond to three-phase motors. There is an unstudied, basic question

about how accurately a three-phase motor model can represent the response of a single-phase motor under disturbance conditions. This is a reasonable question in that three-phase and single-phase motors model differ, most notable in the energy conversion to torque. This concern complements the issue with motor mechanical load characteristics, which is also related to torque, and this recommendation could be studied at the same time as the previous recommendation. This work is not likely to be undertaken without additional support. This work should couple laboratory-setting experiments with detailed models and simulations.

Level of Effort: *Moderate.* Can by carried out by single lead investigator, but it will require laboratory facilities, and equipment to test.
Time Required: *single-year.*
PIER support: High. This is important project that the LMTF would like to see done. This is fundamental research and PIER support is likely to be needed to initiate this work.
Significance: *High*. This involves a fundamental changing in structure of the load model and may have a fundamental impact on results.

Recommendation: More work is required to model motor load shedding behavior under low voltage conditions. The aggregate model of induction motor loads requires a mechanism for allowing a portion of the load to trip off line during a disturbance (pg 28).
The problem here is the difficulty in representing all the different characteristics of motor loads in a simple aggregate model. Presently the overall model could be augmented with different motors, ones that trip off line during a disturbance, and others that do not. In the traditional spirit and practice of modeling, an aggregate model that represent this low voltage trip, would be beneficial. Such research is not currently being done.

Level of Effort: *Moderate.* Can by carried out by single lead investigator, but involves development of fundamentally new models, or novel mechanisms to switch between established models.
Time Required: *single-year.*
PIER support: *Moderate.* It is not likely to be initiated without PIER funds.
Significance: *Low.* While this research does result in a fundamental change in the structure of the load model, the same impact can be achieved with existing models if one is willing to accept more motors being represented at the end use load.

Recommendation: Discuss improvements to low-voltage protection on residential air conditioners with manufacturers (pg 28).
It is observed that the slow voltage recovery observed after a disturbance could be avoided by temporarily removing voltage-sensitive loads, such as air-conditioners, and the restarting them after a few minutes delay. This approach to mitigating the problem on the component level should be discussed with manufacturers.

Level of Effort: *Low.* Appropriate industry staff need to contact relevant industry representatives.
Time Required: *single-year.*
PIER support: *Low.* It does not require significant support.

Significance: *High.* This change to protection could significantly reduce the chance of the propagation of a voltage disturbance.

7.1.3 Measurement and Validation

Recommendation: Support the development and placement of $10K load monitors (pg 30.)
Encourage the use of monitors, and staff time, to gather data beneficial to improved load modeling.

Level of Effort: *Low.* The specification work has already been completed by WECC.
Time Required: *single-year,* and on going. Encourage use of the monitors.
PIER support: *Low.*
Significance: *High.* Data is valuable. A special monitor for the purpose of monitoring loads will aid in all modeling and analysis activities.

Recommendation: Support a basic research project to outline the challenges associated with developing a dynamic state monitor (pg 30).
The issues to be addressed are the mathematical tools and data requirements, and institutional challenges with gathering and sharing data. This could evolve into a major research program and a scoping study or white paper on the issues would need to be prepared.

Level of Effort: *Low.* Single investigator and scoping study report
Time Required: *single-year.*
PIER support: *Moderate*: This will require PIER support to initiate, but it is a low-cost effort.
Significance: *Moderate*: It will identify issues associated with the development of a new technology. Ultimate success and value will be in the subsequent research.

7.1.4 Load Monitoring

Recommendation: Support activities to estimate load composition from measurements (pg 32).
This includes investigating refinement in metering equipment, assumed load models (such as adding stylized distribution feeder model as WECC moves in this direction), staged testing, and techniques for estimation that may expand conditions under which estimation is possible. This requires significant effort and testing in the field. This work will need to be done with the cooperation of a utility in the West.

Level of Effort: *High.* This will require cooperation with a utility to install equipment to gather data. This is basic research that will require novel analysis techniques to complete the task.
Time Required: *multi-year,* and on-going to maintain database.
PIER support: *High.* This is a significant project to be conducted with utility partnership.
Significance: *High.* These measurements will provide a fundamental improvement in the accuracy of load models.

Recommendation: Support activities to test load model substitutability assumptions, and to characterize a range of uncertainty in models (pg 32).
This addresses the issue of whether or not representative models are truly representative by comparing results from substations that would be assumed to have similar loading characteristics

by load class. The matches will not be perfect, so there would be additional value to characterizing the range of values obtained for different load classes that may be evaluating using uncertainty analyses. Also, a calculation of uncertainty in estimates at each measured locations will facilitate uncertainty simulations. This work can and should be done jointly with the research in the previous recommendation and may be grouped as a larger project. Again, it will require fieldwork and cooperation with a utility.

Level of Effort: *Moderate.* This will require cooperation with a utility to install equipment to gather data, however this should be combined with the previous recommendation to reduce redundancy in monitoring efforts.
Time Required: *multi-year,* and on-going to maintain database.
PIER support: *High.* This is basic research that should be performed with utility partnership.
Significance: *High.* Assessment of the uncertainty in load models will allow the analysis of uncertainty in dynamic studies. This is not done now.

Recommendation: Assess the value of harmonic information for the purposes of estimating load composition (pg 33).
The additional information in harmonics will augment the primary frequency data now used, and there may be useful information in steady-state waveforms. This will require field testing and possible refinement of metering equipment. This work could be done in conjunction with the previous recommendations.

Level of Effort: *Moderate.* This will require cooperation with a utility to install equipment to gather data; however, this should be combined with the previous two recommendations to reduce redundancy in monitoring efforts.
Time Required: *multi-year,* and on-going to maintain database.
PIER support: *High.* This is basic research that should be performed with utility partnership.
Significance: *Unknown.* It is not known how much information there is in the harmonics. CEC-sponsored research was successful in finding useful information in harmonics at the level of a building or plant.

7.1.5 Measurement-Only (Black-Box) Models

Recommendation: Follow efforts to develop measurement-only (black-box) load models (pg 34).
In general, black-box modeling techniques are most valuable when the available data is rich enough to show all the operating characteristics of the modeled component. Presently, we believe that the data set does not support this approach.

Level of Effort: *Low.* Monitor on-going work or by others.
Time Required: *multi-year,* and on-going monitoring of research in this area.
PIER support: *Low.*
Significance: *Low.*

7.1.6 Uncertainty Analysis

Recommendation: Initiate a program to develop methods to evaluate the effect of load model uncertainties on system studies (pg 39).
Load models and their parameters will never be known with certainty. Since they are believed to be a main source of discrepancy between simulations and observations, it is sensible to begin a program into studying the effect of uncertainties on outcomes of interest.

Level of Effort: *High*. Requires the development of new techniques to analyze the impact of uncertainties in dynamic simulations.
Time Required: *multi-year.*
PIER support: *High.* This is basic research that may require PIER support to initiate.
Significance: *High.* The models will never be know with certainty, and evaluation of uncertainty will lead to greater confidence and better decision in the operations and planning.

7.1.7 Generator Governor Models

Recommendation: Use the new governor model [19] [18] and support WECC activities to maintain a database of plant governor characteristics (pg 41).
This activity will be handled by WECC.

Level of Effort: *Low.* Will be completed by WECC.
Time Required: *multi-year,* and on-going to maintain database
PIER support: *Low.*
Significance: *High.* Prior models overestimated governor response.

Recommendation: Develop or adapt tools to monitor supplier governor frequency response (pg 45).
WECC has adopted a governor model that captures the effect of reduced frequency response. They populate the model based on information from survey of generator owners, and have validated the model using historical data. In order to gain accurate model parameters based on measurements, one can develop a tool to identify the responses of individual units.

Level of Effort: *High.* Need to develop new tools to complete this task
Time Required: *multi-year,* and on-going to monitor generator characteristics
PIER support: *High.* This involves basic research that may require PIER support to initiate.
Significance: *Moderate.* This would be a valuable tool. The alternative is to seek ways to populate the model through surveys or mandatory reporting.

7.2 Summary table of recommendations

Here we present a summary table of recommendations.

Recommendation	Level of Effort	Time Req'd	PIER Support	Significance
Load Model Development and Policies				
Develop seasonal models.	low	1-year	low	moderate
Validate with state estimator models	low	1-year	low	moderate
Review reliability criteria.	low	multi-year	low	high
Load Modeling				
Study motor mechanical load characteristics and impact.	moderate	1-year	moderate	high
Study impact of single-phase and three-phase motors.	moderate	1-year	high	high
Model motor load shedding and low-voltage conditions.	moderate	1-year	moderate	low
Improve low-voltage protection.	Low	1-year	Low	high
Measurement and Validation				
$10K load monitor.	low	1-year	low	high
Scoping study: research needs for automatic validation and dynamic state estimation.	moderate	1-year	moderate	moderate
Load Monitoring				
Estimate load composition from measurements.	high	multi-year	high	high
Characterize model uncertainties using measurements.	moderate	multi-year	high	high
Use harmonic information in measurements to enhance load composition estimates.	moderate	multi-year	high	unknown
Measurement-Only (Black Box) Models				
Follow research activities in this area.	low	multi-year	low	low
Uncertainty Analysis				
Develop methods to assess the impact of load model uncertainties on system studies.	high	multi-year	high	high
Generator Governor Models				
Support WECC activities to implement best model and maintain data for generator characteristics.	low	multi-year	Low	high
Develop tools to monitor individual generator. frequency response.	high	multi-year	high	moderate

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