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Load Monitoring

CEC/LMTF Load Research Program

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November 2007

Prepared for
Lawrence Berkeley National Laboratory
for the California Energy Commission
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SUMMARY

This report is intended to serve as a reference for future load monitoring projects. The identification of specific vendor's equipment/software, etc. in this document is for research documentation only and does not constitute an endorsement of these items.

Load monitoring provides an important means to understand load behavior in the actual system. This understanding helps to develop load models to represent the load behavior in simulation studies. Load monitoring provides measured data needed for load model validation, load composition studies, and load uncertainty analysis.

Depending on various needs, load monitoring may be implemented differently with different monitoring hardware, different measured quantities, and different requirements for sampling rates, signal types, record length and availability, with different costs. Potential load monitoring options include traditional supervisory control and data acquisition (SCADA), phasor measurement units (PMUs), portable power system monitors (PPSMs), digital fault recorders (DFRs), protective relays, power quality monitors, and a low-cost monitoring device being developed by Western Electricity Coordinating Council (WECC) Disturbance Monitoring Working Group (DMWG). Characteristics of these options are summarized in this report.

Current load monitoring practices at several utility companies are presented as examples of load monitoring. Each example consists of the following aspects of load monitoring: objective of load monitoring, monitoring location selection, description of monitoring equipment, communication for load monitoring, cost, and use of the data.

The purpose of load monitoring is to provide better load characterization and better load management, i.e., the core element of load monitoring is focused on applications. Five load monitoring applications are proposed in this report, with some preliminary case studies:

- Load monitoring for top-down load composition: The total load profile obtained from load monitoring data can be decomposed to derive fractions of individual load types if load profiles of individual load types are known.

- Load monitoring for load composition validation: Load profiles generated by the load composition model can be validated against load profiles derived from load monitoring data.

- Load monitoring for load model validation: The general approach of model validation is to compare model simulation against measurements, as was applied to WECC generator model validation. Load monitoring provides the basis for load model validation.

- Load monitoring for uncertainty analysis: Statistical analysis can be performed on load monitoring data to quantify load variations over selected time periods.

- Load monitoring for load control performance evaluation: This is the trend that loads will play a more and more active role in managing the power system. Similar to generator performance monitoring, load monitoring can be used to ensure the load behaves as designed for correct credits and control enforcement.

The case studies show promising results of the use of load monitoring for the above purposes. Based on these results, recommendations on future load monitoring work are presented. It is important to point out that load monitoring efforts should be consistent with and driven by load research needs. Given the current ongoing load modeling work in WECC, a roadmap for load monitoring is proposed.

ACKNOWLEDGEMENT

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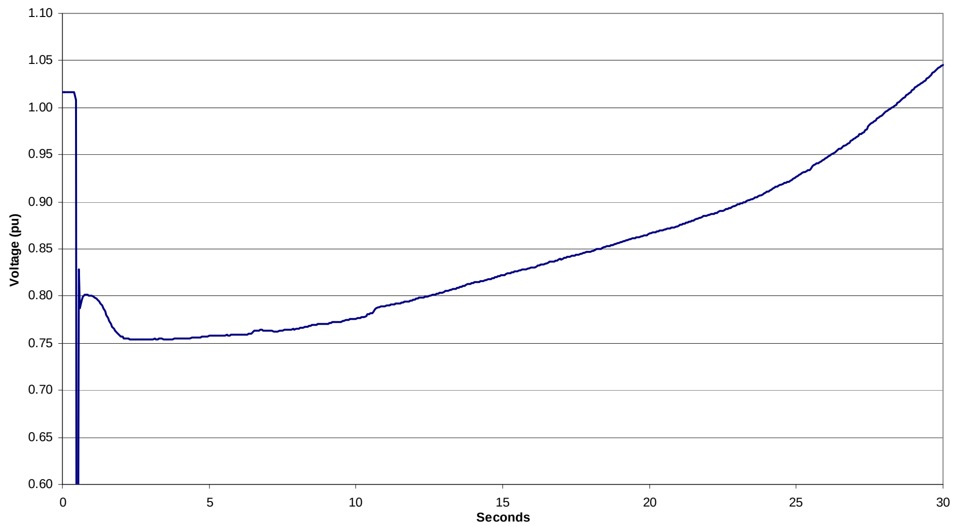
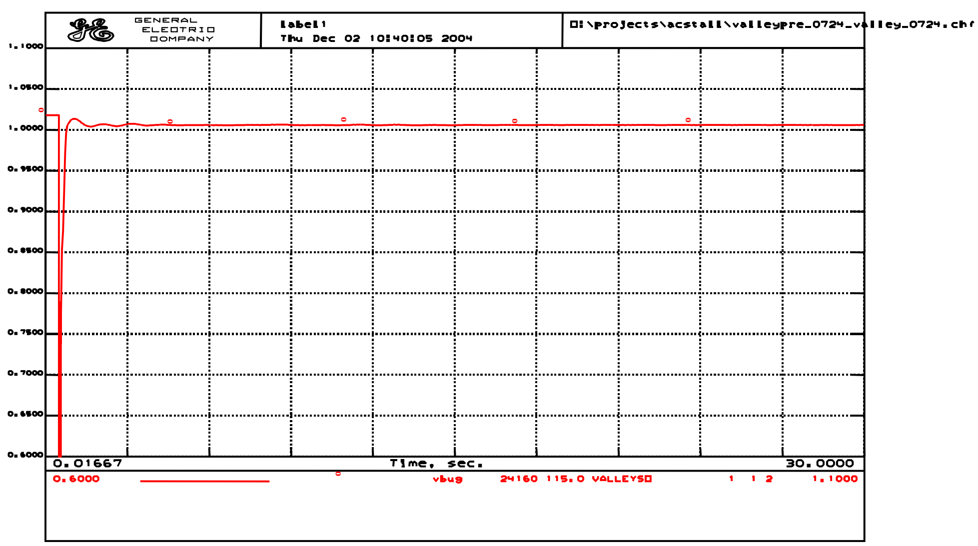
1.0 BACKGROUND

The Load Modeling Task Force (LMTF) is nearing completion of defining a new composite load model to be implemented in both GE PSLF and Siemens PTI PSS/E for use in Western Electricity Coordinating Council (WECC) dynamic simulation studies. Currently the default load model for dynamic simulations is to replace 20% of the bus load with a three-phase induction motor and use a ZIP model (a combination of constant impedance, constant current, and constant power elements) for the other 80% of the load (Pereira et al. 2002). While this model has been successfully used to validate several large system-wide disturbances including the August 1996 outage, it has failed to simulate several other significant outages that resulted in slow voltage recovery and the loss of significant load (Figure 1).



(a) Real Event – voltage recovers in almost 30 seconds after the fault, load tripping, stalled air-conditioners



(b) Simulations – voltage recovers almost instantaneously after the fault, no load tripped

Figure 1 Voltage at Valley Substation during a Fault Event in Southern California

Through studies performed by Southern California Edison (SCE), Pacific Gas & Electric (PG&E), California Independent System Operators (CALISO), and Bonneville Power Administration (BPA), the basic requirements for an improved load model were determined. These requirements included modeling the substation transformer and feeder impedances, as well as more detailed motor modeling that included both large and small motor dynamics. All of these parameters have been included in the new composite model (Figure 2). The composite load model is to be used for transmission-level system dynamic simulation, so it should represent, at a relative high voltage level (e.g., 60 kV), the aggregated behavior of all the load components on a feeder system.

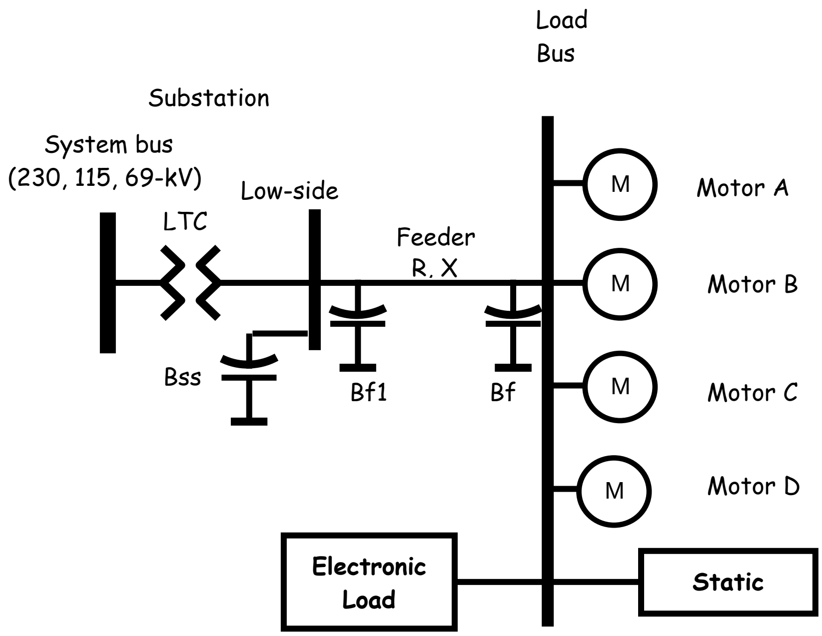


Figure 2 General Composite Load Model Structure

Following development of the composite load model, the next step will be to develop data for the model that will represent the characteristics of each load. The California Energy Commission (CEC) and the WECC Load Modeling Task Force (LMTF) joined forces and set up a load research program. One task in this program is to test air-conditioning (a/c) units in a laboratory environment and use the testing data to develop a/c models. A/c units are of great concern because they slow voltage recovery events. Good progress has been made in the testing and model development. Laboratory tests of a/c units were performed by Bonneville Power Administration (BPA), by Southern California Edison (SCE) and by the Electric Power Research Institute (EPRI). Bonneville Power Administration (BPA) is also conducting laboratory tests of other residential appliances including lighting, refrigerators, dishwashers, clothes washers, dryers, fans, and electronic equipment for developing model databases for individual load components. Besides laboratory tests of individual load components, there is another aspect of data for load model development – load monitoring. Load monitoring generates data of actual load behaviors and reveals insights about load representations in power system simulation studies. Load monitoring is of importance for load model validation, load model composition and load uncertainty studies. This document will address the needs, options and examples of load monitoring, followed by recommendations for further work in this area.

2.0 LOAD MONITORING NEEDS

Load monitoring provides a means to understand load behavior in the actual system. The understanding helps to develop load models to represent the load behavior in simulation studies. Three aspects of load monitoring needs are addressed below: load model validation, load composition, and load uncertainty analysis.

2.1 Load Model Validation

The CEC/LMTF load research program takes a bottom-up approach to develop models for individual load components and then aggregate them at a higher voltage level for transmission system simulation studies. The individual load component models are being developed and validated via laboratory testing. However, the aggregated load model, shown as a composite load model in Figure 2, needs to be validated as well. It is expected that this development effort will generate better quality load models which matches recorded events, especially those delayed voltage recovery disturbances. If the validation process is successful, one can conclude that the model is an improvement over the existing modeling procedure. With the new composite load models populated with data, validation studies will be run on selected major WECC disturbances identified by the LMTF by comparing model simulation against recorded load behavior, as shown in Figure 1. This WECC-wide validation needs to have monitoring devices to record system response. Currently there are about 60 phasor measurement units (PMUs) installed, most at high voltage levels (500 kV and 230 kV) across the WECC power grid for event recording purposes (Figure 3). These PMUs provide good data for model validation in general. To better validate load models, one would need to have monitoring devices at lower voltage levels to better capture load behavior. If monitoring data are available, one can even validate load models at different levels using the "playback" function developed during previous model validation studies (Kosterev 2004; Huang et al. 2006). This multi-level validation would provide a way to identify how the model performance would evolve because the models are gradually aggregated at higher levels, so load aggregation techniques can be validated. Figure 4 provides an example of "playback"-based load model validation.

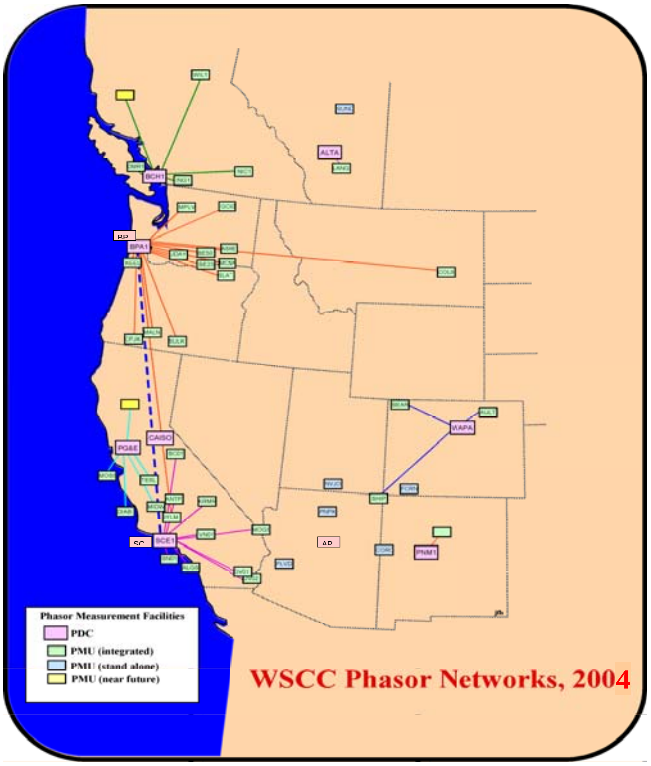


Figure 3 WECC WAMS Network

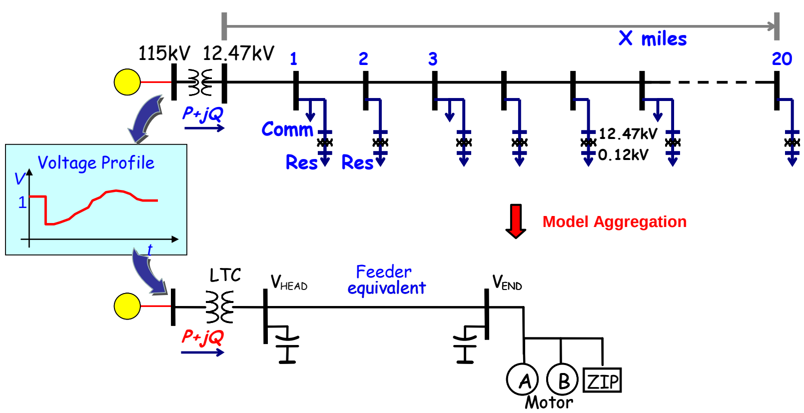


Figure 4 Load Model Validation by Playing Back Voltage at the Feeder Head

The benefits of load modeling may be impacted by the customer type: industrial, commercial, agricultural, and residential. As noted above, if a broad spectrum of load is being modeled only at higher voltage levels (e.g. 230-kV level), then the broader system monitoring devices such as PMUs are likely sufficient for validating the model. However, for smaller discrete modeling, the monitoring needs may vary by customer type:

- Industrial loads: These loads typically are motor dominated and should be relatively straight forward to a model based on the type of industrial processes involved. BPA has already done validation studies on industrial loads in the Pacific Northwest.

- Commercial loads: Purely commercial loads would be found where substations serve commercial buildings or large business/warehouse parks. Commercial loads should be fairly consistent across

- Agricultural loads: Agricultural loads are primarily pumps used for irrigation. They vary depending on region's climate.

- Residential loads: Residential dominated loads will show the greatest regional and seasonal variations. Air conditioning modeling is of prime concern to the summer peaking WECC members, especially in California (as shown in Figure 1).

- Mixed commercial and residential loads: These will be the most common loading type across the system and again will vary by region as a result of air conditioning needs.

To capture load dynamic characteristics, load monitoring devices are necessary to have high sampling rates and data records in the seconds to minutes range, like phasor data.

2.2 Load Composition

Load composition plays a critical role as modeling techniques in the outcomes of power system simulation studies. The type of load modeled at each individual bus varies throughout the system and in addition, the detail of how this load is modeled also varies. In the Pacific Northwest, for instance, each substation is modeled down to 55-kV systems. This allows the distribution of customer types to be determined at a fairly granular level (i.e., approximately <25 MW per bus). This also allows industrial customers with dedicated substations to be modeled separate from commercial and residential loads. In other areas, loads are aggregated up to the 230-kV level, which results in modeling a broader distribution of customer types, including industrial customers in some cases.

It is recognized that load composition will be dependant on the customer class being served, as well as the season and loading level. For load composition, one can use customer billing data if available as monitored load behavior and try to derive typical customer mix by zone or owner or where available, at a bus-by-bus basis. Once the initial load composition for zones/buses is determined, assumptions based on input from current on-going studies by PNNL will be used to determine model parameters based on seasons and loading levels.

Besides the derivation of initial load composition from billing data, load monitoring also provides data necessary for developing load composition methods and validating load composition results.

There are basically two approaches for determining load composition – bottom-up approach and top-down approach. The bottom-up approach is based on individual load profiles and aggregates them into a load mix – motor, lighting, electronics, etc., from which the load composition is determined. Monitoring at individual end use would provide excellent insight about individual load profiles. On the other hand, the top-down approach decomposes recorded load data into different load "elements", similar to spectrum-analysis-like decomposition. The elements would indicate the percentage of a certain load mix, so load composition is determined. Load monitoring plays a crucial role, providing recorded data for this top-down approach.

For the bottom-up approach, load monitoring devices can have slow sampling rates, like metering data, but need to have long records of days or months to capture load behavior over different times and seasons. The monitoring devices should be installed at the end use level.

For the top-down approach, the requirement for load monitoring depends on the specific method. It is possible that very high sampling rates are required to have the fine granularity to derive load composition. The monitoring devices are at the feeder level.

2.3 Load Uncertainty Analysis

Loads are known for their diversity and uncertainties, which adds to the challenging job of load modeling. No model is complete without uncertainty analysis. Uncertainty analysis can reveal how the uncertainties would affect the model performance and identify what is not modeled so the models can be used with confidence. The goal of uncertainty analysis is to minimize the impact of the uncertainty in the load model data on the decisions that engineers make on grid operating limits and capital investments. First hand load uncertainty information comes from actual load behavior, which requires monitoring data of typical loads. One example is to continuously record load data for a selected time period and compare daily load profiles to show the range of load changes over a day. Load models may be adjusted based on the time of the day to reduce the impact of load uncertainty. However, the uncertainty at this specific time is not modeled; but, its impact on load model performance can be quantified based on the range of load changes.

2.4 Load Control Performance Evaluation

Load solutions for delayed voltage recovery caused by stalled air-conditioning units are being identified under the current CEC/LMTF load research program, and various load controls are expected to be implemented by utilities like SCE and BPA to improve load response to adverse system conditions. To validate the load response and evaluate the performance of load controls, load monitoring devices need to be installed in the system (e.g., at the feeder level) to monitor load behavior. For this purpose, a technical approach similar to generator performance monitoring can be developed. Analysis of the load monitoring data shall be conducted to confirm the performance improvement of the load solution implementation.

3.0 LOAD MONITORING DEVICE OPTIONS

Good load monitoring will provide required data (real and reactive power, voltage, frequency, etc.) at necessary sampling rates. Ideally it will also be remotely accessible. To save on data storage, event triggering would be beneficial. For dynamic validation, event recording would be the main focus, although there is an interest in seeing if steady state data would be helpful in determining load composition.

There are different devices available for monitoring loads or for event recording in general. Some are even installed in the system, and data are available for load monitoring purposes with minimal efforts. As mentioned earlier, PMUs are excellent general event recording devices (Figure 3). Digital fault recorders (DFRs) can record dynamic behaviors but record lengths are shorter. General supervisory control and data acquisition (SCADA) measurements are more readily available in the system. They are long records, which are good for load composition studies, but contain less dynamic information. This section will address the features of each monitoring option, (i.e., sampling rate, measured quantities, record length, availability, hardware structure, and cost information, when available). A summary is shown in Table 1.

Table 1 Features of Different Monitoring Options

Monitoring Device Options	Sampling Rate (sps)	Measured Quantities	Measurement Type	Record Length	Availability	Cost to Implement
SCADA	Low, ~1/4	V, I, P, Q	RMS	Long	High	Low
PMU	Medium, ~30	V, I, θ, f	Phasor (GPS-synch)	Long	Low	High
PPSM	High, ~960	V, I	POW (GPS-synch)	Long	Low	Moderate
DFR	High, ~5760	V, I	POW	Medium	Moderate	High
Relay	High, >960	V, I	POW	Short	High	Moderate
Power Quality Monitor	High, >960	V, I	POW	Short	Moderate	Moderate
GFA Controller	Medium, ~30	V, I, f	RMS	Long	Low	Low
DMWG Low-cost Monitor	Medium, ~30 for phasor, High, ~960 for POW	V, I, θ, f	Phasor, POW (GPS-synch)	Long	Low	Low

*Note: sps – samples per second.
RMS – Root mean square.
POW – Point-on-wave.
GPS-synch – Global Positioning System time synchronized.
DMWG – Disturbance Monitoring Working Group.

3.1 SCADA

Traditionally, power system operators primarily rely on SCADA measurements to understand power system status and guide system operations. Redundant SCADA measurements are available for the major portion of power systems. SCADA systems measure RMS values of bus voltage and line current, and in turn, real power and reactive power on a transmission line. These quantities are measured at an interval of seconds (typically 4 seconds), so these measurements will reflect slow changes (quasi steady state) in the system, but typical dynamic behaviors are not captured. For load monitoring purposes, SCADA measurements are good for deriving load composition, and possibly for load uncertainty analysis. One advantage of using SCADA measurements is that the additional cost is minimal because they are already available. In addition, SCADA measurements are continuous recordings, and they are good data sources for identifying load changes over a long period of time.

3.2 Phasor Measurement Units (PMUs)

PMUs are a relatively new type of measurements in power systems. Phasor measurement technologies emerged about 2 decades ago (Phadke et al. 1983), and currently there are a number of companies manufacturing PMUs, the hardware device that measures phasors. Appendix A provides an incomplete list of PMU manufacturers. Output of a PMU includes voltage and current phasors (including phase angles) and frequency. Real and reactive power quantities can then be derived from phasors. Phasor measurements are GPS-time synchronized and have a higher sampling rate (typically 30 samples per second), which makes phasor measurements a data source for constructing a more accurate real-time picture of system dynamic status, compared with traditional SCADA measurements. A phasor measurement network – wide area measurement systems (WAMS) – is being developed in both the Western and Eastern Interconnections, with between 60 and 70 PMUs, respectively. These WAMS systems perform well for collecting data for large system-wide events and local events at high voltage levels (500 kV/230 kV) near the recorders. PMUs can have long data records with continuous recording functions, or at least the event length as defined by triggering functions.

Most PMUs are installed at high voltage level substation or power plant points of connection to the transmission system. From load monitoring perspective, these PMUs provide good data for system-wide load model validation studies. There are also some PMUs in lower voltage systems, which can be good data sources for specific load model validation or load composition development. However, cost to install new PMUs at desired load locations can be significant. The cost includes several aspects like hardware (PMU), software and data communication. The Eastern Interconnection Phasor Project (EIPP) Performance Requirements Task Team (PRTT) conducted a survey on PMU installation in 2006, and 11 responses were received. Figure 5 through Figure 7 are the PMU cost information excerpted from the survey summary (Centeno et al. 2006). More specific PMU hardware cost information can be found in Appendix A. Actual cost varies depending on specific situations.

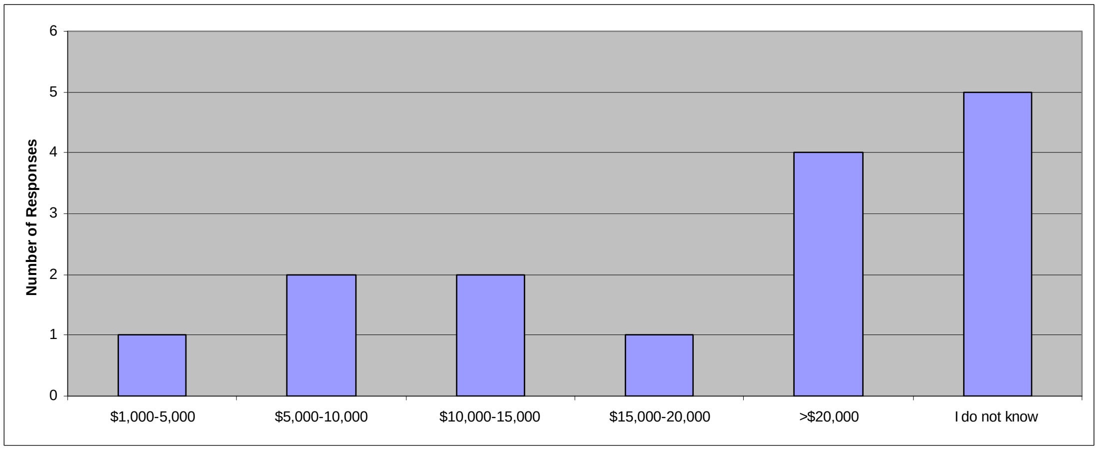


Figure 5 Average Hardware Cost of one PMU Installation (response to the question: What is the average cost of hardware, including PMU, for one installation?)

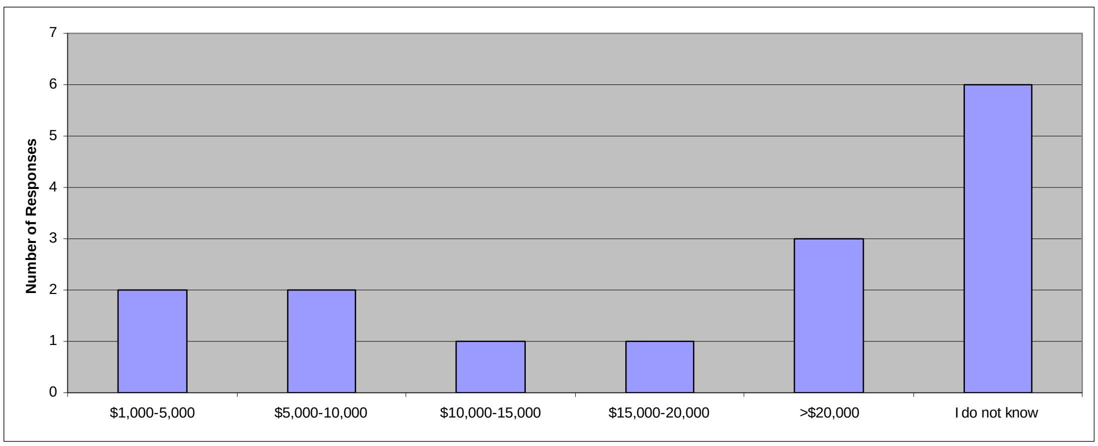


Figure 6 Average Labor Cost of one PMU Installation (response to the question: What is the average cost of labor for one PMU installation?)

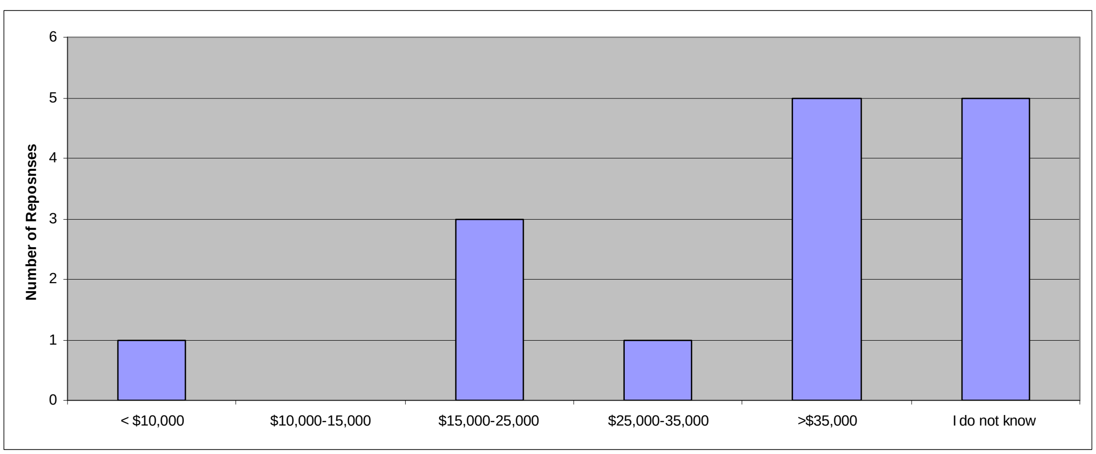


Figure 7 Average Total Cost of one PMU Installation (response to the question: What is the average Total cost for one PMU installation?)

3.3 Portable Power System Monitors (PPSM)

PPSMs have been developed and used for about 15 years at Bonneville Power Administration (BPA). Currently, there are 14 PPSMs within the BPA region, 3 of them in power plants, 6 of them at point-of-connection to power plants, 1 at the commercial building (BPA's Headquarters) and rest of them at different parts of the system. Data from these PPSMs have been used for generator model validation, system model validation, and system studies. PPSMs collect point-on-wave data for voltages, currents and other signals at a very high sampling rate. These PC-based PPSMs consist of off-the-shelf signal conditionings and transducers. This makes PPSM very versatile and easy to modify for different types of signals. It also has the capability to synchronize to GPS-time and can sample data in multiples of 60 using an external clock source, which can be useful for the analysis. PPSMs are most desirable for temporary monitoring or testing. However, it can also be designed for permanent monitoring. PPSMs use a circular buffering for continuous recording, and also have a triggering function. PPSM file formats can be selected from LabView, MATLAB or Excel.

3.4 Digital Fault Recorders (DFRs)

Digital fault recorders are installed throughout most major utility systems, and newer ones may have the capability to provide good validation data for local faults, with triggering and sampling rate capabilities separate from those used for protection. DFRs record point-on-wave voltage and current signals at very high sampling rate (e.g., 5760 samples per second) and at a typical length of several seconds. They usually have communication back to the main office. Concerns have been expressed that the CTs may not be suitable, and that protection engineering may not be willing to open their system for planning purposes.

Where newer units are installed with suitable sampling rates and event durations, DFRs can provide data for system-wide load model validation studies. They are also more likely to be found in lower voltage systems, and can be good data sources for specific load model validation or load composition development.

3.5 Protective Relays

Protective relays are widely installed in power systems for various protection purposes, e.g., under/over voltage protection, reverse time line overloading protection, generator under/over frequency protection, and grounding protection. Protective relays can record point-on-wave voltage and current at very high sampling rates (>960 samples per second). Their record length is usually short as tens of cycles because of their designed purposes. Similar to DFRs, a concern is that protection engineers may not be willing to open their protective relay system for planning purposes.

3.6 Power Quality Monitors

Most utilities have power quality monitors used by substation field personnel for testing and monitoring. Most power quality monitors can store only tens of cycles of data at sampling rates higher than 960 samples/second. They are typically mobile units that are used on an as-needed basis. While they may not work well for event recording, they could be used for short term steady state recording, if it is determined that there is modeling value in the steady state data.

3.7 Low-cost Monitoring Device being Developed by WECC DMWG

WECC Disturbance Monitoring Working Group (DMWG) intends to obtain standardized low-cost performance monitors for WECC members to use. The design of the basic unit shall be such that it can be installed and used without specialized technical expertise for the following test practices:

- Connection within a member system's substation to monitor generator output quantities (V, I, P, Q and frequency)

- Connection within a member system's substation to monitor load feeder quantities (same as above)

- Connection within a member's substation to measure SVC, STATCOM, FACTS device quantities (same as above)

Specific technical requirements of the low-cost monitoring device are listed in Table 2. This device is expected to provide high-sampling-rate long-length records of voltage and current signals. Time synchronization is included as part of the functionality.

3.8 Grid Friendly™ Controller

Grid Friendly™ Controllers are an emerging technology developed at the Pacific Northwest National Laboratory (PNNL) in Richland, Washington (Grid Friendly™ Appliances 2007). The Grid Friendly concept focuses on demand side management (DSM), but it goes beyond traditional DSM technologies like under frequency and under voltage load shedding. Unlike load shedding, which would interrupt power supply to entire feeders, the Grid Friendly controller focuses on interruptible load. The Grid Friendly technology enables active load control so electrical loads can be used as an active resource, participating in stabilizing power grids, rather than just be passive components in the power grids.

Central to the Grid Friendly technology is a small digital controller that can continually monitor frequency or voltage of the power grid at the local point and process this information to control electrical loads based on pre-defined control strategies (see Figure 8). The Grid Friendly controller can be integrated into appliances like water heaters and refrigerators, and it is very cost-effective (batch production is estimated to be $2-5 per controller). When the grid experiences an emergency condition, the Grid Friendly controller would identify this situation within milliseconds and adjust the load for a short period of time.

Table 2 Technical Requirements of DMWG Low-Cost Monitoring Devices

Element		Minimum
Frequency response (calculated data)	FR	40 Hz
Maximum rolloff at frequency response (FR)	Rfr	-3dB
Maximum deviation from 0 to 1/2 FR		-0.5dB (-0.1dB preferred)
Rejection above Nyquist frequency	Rnq	40dB (60 dB preferred)
Rejection at 60 Hz harmonics	R60	60dB
Step response ringing		not excessive (see details in text)
Sampling rate	Sm	3600 Hz
A/D sampling resolution		16 bits
Full scale range adjustment	AC voltage AC current DC coupled	50 - 600 V peak 1 - 20 A peak 100 mV – 600V
Active bits (as determined by full scale adjustment)		12-14
Measurement noise		see text
Documentation		Required
Continuous storage capability	overwriting	10 days
Continuous storage capability	non-overwriting	60 days
Triggered event retention		60 days
Measurement synchronization to UTC		100x10-E6
Data access alternatives	A	Network
	B	leased line
	C	dial up
Data format		see text
Minimum record length		300 seconds
Pre-disturbance time for triggered events		60 seconds
Availability		99.99%
Power supply		125 VAC or VDC

* Note: UTC – Universal Time Coordinates

Figure 8 Grid Friendly Controller

Recent development of the Grid Friendly controller hardware features a more compact design and expands recording capabilities to store RMS voltage, current and frequency signals at a sampling rate of between 10 and 30 samples per second. As a result of research on the Grid Friendly concept, PNNL and major appliance manufacturers have begun to define a simple appliance interface based on successful implementation of such an interface during the Pacific Northwest GridWise™ Demonstration [Hammerstrom et al. 2007]. This interface will guide not only appliance manufacturers but designers of any residential product in developing a standard way to receive communications and respond to a load reduction request from an advanced load management system. And including the Grid Friendly controller in appliances at the manufacture stage would make the monitoring capability ubiquitously available at the appliance level. This type of data can be used for developing and verifying models of individual appliances.

3.9 Custom Recorders

Several utilities have developed individual recording units based around either PC or laptops and installed them in individual substations. The units have typically monitored feeder loading on a continuous basis with some form of communication back to the main office. These monitors have typically cost approximately $5K per installation for hardware plus the cost to establish the communication link. These monitors provide good data but do require upfront costs and effort to install and maintain.

4.0 EXISTING LOAD MONITORING EXAMPLES

This section summarizes several representative examples in load monitoring. The purpose is to provide reference information for future load monitoring projects. Each example addresses the following aspects of load monitoring:

- Objective of load monitoring
- Monitoring location selection
- Description of monitoring equipment (make and model, quantities measured, record length, sampling rate, etc.)
- Communication for load monitoring
- Cost (if available)
- Use of the data.

4.1 Building Monitoring at BPA

4.1.1 Objective

Recently, BPA installed monitoring devices for one of its headquarters building. It is intended for characterizing load consumption for energy efficiency applications, as well as for developing and validating load models at the building level.

4.1.2 Location

For the load monitoring purposes, BPA has a PPSM installed at their headquarters. It is monitoring main distribution of the building (see Figure 9).

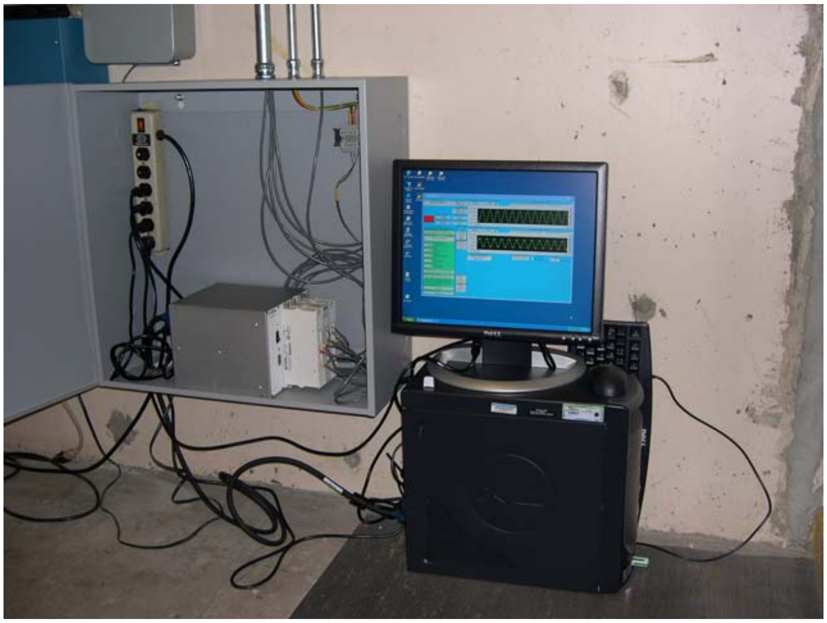


Figure 9 PPSM Monitoring Unit at BPA's Portland Headquarters

4.1.3 Description of Monitoring Equipment

The PPSM has 18 channels and is sampling at 2500 sps. With 150-GB memory, its record length is about 16 days.

4.1.4 Communication

This PPSM unit uses a dial-up link to transfer data.

4.1.5 Cost

The cost of the PPSM monitoring system was about $ 14,000, which includes PC, A/D board, SCXI signal conditioning, current transformers (CTs), cables, etc. Detailed cost information for PPSMs can be found in Appendix B – PPSM Cost Breakdown.

4.1.6 Use of the Data

The recorded data have been used for analyzing building consumption, which leads to a better understanding of load composition at the building level. Further use of the data is planned for the development of the top-down load composition approach. Load model validation at the building level will be explored as well with the recorded data.

4.2 Distribution Substation Monitoring at PNM

4.2.1 Objective

Starting in 1997, PNM deployed a load monitoring system consisting of six custom-built data loggers at different distribution stations. The primary purpose of this project was to verify load composition assumptions for the design of PNM's Import Contingency Load Shedding Scheme (ICLSS). Specifically, the primary purpose was to estimate the portion of the demand that corresponds to large industrial motors. Sensitivity studies demonstrated that the performance of ICLSS would depend on the portion of the motor load that would disconnect from the system (via under-voltage relays) following the loss of the two principal 345-kV circuits that supply the Albuquerque area. A secondary, but very important objective was to demonstrate the feasibility of identifying parameters for physically-based load models.

4.2.2 Location

Monitors were deployed at the following distribution unit stations: Reeves, Iron, Prager, North#2, Juan Tabo, and Rodeo. The former five are in the Albuqueque area, and Rodeo is in the Santa Fe area. Each monitor was setup to monitor all distribution feeders at 12.5 kV (four in each station). In total, 24 feeders were monitored. The feeders were selected to provide a sample of industrial, commercial and residential customer classes. The class mix of each feeder was known a priori. Physically, the monitors were installed at the relay panels of the unit station, where access to all secondary potential transformers (PT) and CT signals was relatively easy. In addition, PNM developed a portable monitor with the same specifications, which was used to capture voltage sensitivity data at several other stations, primarily using manual tap changes.

4.2.3 Description of Monitoring Equipment

Each monitor consists of a National Instruments® signal conditioning stage and a ruggedized Windows PC. For the first three installations, a calibrated shunt was inserted in each phase of the CT secondary. The last three monitors had clamp-on CTs for ease of installation. DataTake was used to handle high-speed point-on-wave data sampling (1200 samples per second) of per-phase, per-feeder voltage and current. A separate custom application was developed to perform additional data processing (calculation of RMS voltage, current and power at 10 samples per second; RMS triggering; data compression; local data storage); and communications. Each monitor produced 15 point-on-wave signals: 12-phase currents (three per feeder) and 3- phase voltages. For each feeder and for each phase, RMS current, voltage, real power and reactive power were calculated. Frequency was also calculated and included in the RMS data table.

The monitors were setup to collect data continuously, hoping to capture naturally-occurring disturbances. Actually many natural events were captured over the years. In addition, PNM also performed several tap tests on these stations during specific times and seasons (e.g., summer peak, winter peak, and off peak). The test data proved to be more useful than naturally-occurring disturbances. But the one thing learned from naturally-occurring disturbances is that modeling the voltage sensitivity of the load is far more important than the frequency sensitivity.

4.2.4 Communication

Communications from the monitors was via telephone/modem link. Each monitor was programmed to initiate an FTP session once a day to transfer triggered data (both RMS and corresponding point-on-wave data) to an FTP server. Users could access the data from the FTP server as needed. Data stored in the local rolling buffer could also be accessed manually using PC Anywhere[1].

4.2.5 Cost

The PNM load monitors were custom-built for approximately $8,000 each. This does not include installation and the cost of DataTake and other custom software development. The cost of commercial alternatives would be much higher, considering the number of signals collected and the sampling rate.

4.2.6 Use of the Data

Custom software was developed for data post-processing. The primary purpose of the software is to perform model identification; however, various extensions such as automated data mining were later added. The project was discontinued in 2002, after the primary research objectives were achieved.

4.2.7 Other Aspects

Reliability has been a major issue. Because unit stations are not climate-controlled, several equipment failures occurred as a result of high temperatures (140°F during the summer). Telephone communication was difficult because of the slow data rates and service quality (high noise). The custom software and operating system performance was inconsistent, often resulting in outages and requiring manual equipment restart. As stated before, alternative off-the-shelf equipment and software to accomplish the same job would cost much higher. These factors played a role in PNM’s decision not to continue the load-monitoring program after the primary research objectives were accomplished.

[1] Manufactured by Symantec, Cupertino, CA.

4.3 Load Monitoring at IPC

4.3.1 Objective

A load monitor was installed at Idaho Power's Grove station to obtain response data from feeder loads to system disturbances and to gain experience with the monitoring device.

4.3.2 Location

The first (and the only one so far) load monitor was installed in IPC's Grove station. The location was chosen because it had a fast communication link, it was relatively close to the office, and its feeders represented a different mix of commercial and residential customers.

4.3.3 Description of Monitoring Equipment

The "load monitor" was assembled by IPC staff with components purchased separately from a company by the name "Chassis Plans", outside of San Diego, CA. The load monitor is basically a PC mounted inside a special chassis with an alternate power supply for the station 48Vdc source, an A/D card and a timing card (by Summetricom) used for providing synchronized timing with the rest of the WAMS system. This particular unit is set for ½ msec sampling cycle and a record length of ~ 5 minutes. All three-phase currents and voltages for three different feeders are continuously monitored and recorded by this equipment.

4.3.4 Communication

Communication is via a broadband internet connection. File management, archiving and retrieval are done through PC Anywhere, while the triggering and PC to A/D control are implemented with LabView (original routines provided by BPA).

4.3.5 Cost

The load monitor is basically a refurbished PC, with the following additional parts (most of the components listed below were obtained from www.chassis-plans.com):

- Chassis ~ $300 (by Chassis Plan)
- Alternate power supply for substation 48VDC Source ~ $200
- A/D card ~ $750
- Timing card (for GPS) by Symmetricom ~ $1500 (presently not used for synchronizing monitor with other similar devices, but to obtain a more stable sampling rate).
- Clamp type CTs ~$60 each
- Signal conditioning module (used to reduce PT and CT signal levels to fit the A/D card)
- Terminal Block (for conditioning module)
- Cable (from terminal block to PC) ~ $200
- Total: ~$3,000.

4.3.6 Use of the Data

Presently the data is not being collected. Remote access has been lost and no information on the status of the device is available. IPC plans to bring it in for inspection as soon as time becomes available. It is expected that in the near future it would be used for load model validation work.

4.4 Load Monitoring at PSE

4.4.1 Objective

The objective of load monitoring at PSE is to collect load data for validating dynamic and steady state load modeling in the Puget Sound area.

4.4.2 Location

Monitoring devices have been installed at several locations across the Puget Sound region, monitoring primarily 115-kV lines and several 230-kV lines covering a variety of customer classes.

4.4.3 Description of Monitoring Equipment

The monitoring device is AMETEK's DFR model TR2000 with disturbance monitoring capability of two samples/cycle for up to 5 minutes.

4.4.4 Communication

Two units currently can be poled from a central office with the remaining units to be connected by the end of 2007.

4.4.5 Cost

Units have been installed in association with substation control house upgrades at the request of the protection group. The estimated installed cost is approximately $100K.

4.4.6 Use of the Data

Event recording (phasor data) is used by protection engineers. Disturbance recording (RMS data) will be used for initial and on going load modeling and validation purposes.

4.5 Feeder Load Monitoring at PG&E

Feeder load monitoring at PG&E is undergoing fundamental changes. An Automated Meter Initiative (AMI) at PG&E resulted in the selection of a vendor (DSI) and PG&E has begun installing automated meters that are read by power line carriers from a modem installed at the feeder substation. Domestic customer meters will be read hourly; meters for large energy users will be read every 15 minutes. The data collected by AMI will fundamentally alter many engineering programs now in place at PG&E, resulting in improved load flow studies (for planning and for distribution management system (DMS) – PG&E's distribution management system for distribution operations), and for transformer load monitoring.

4.5.1 Objective

In the future, customers will be able to monitor their daily energy usage (collected via AMI) over the Web.

In the near term, hourly usage data, combined with meter-transformer connectivity, means transformer-load-profiles can be generated in near real-time for transformer load monitoring. This will fundamentally change the transformer loading program at PG&E, which currently relies on average daily usage collected from monthly reads to estimate peak demand on the transformer. (While individual customer's power factor and harmonics will still be unknowns, these parameters are less variable than hourly usage.)

Transformer load profiles at the transformer level will also provide the P,Q (watt and Var) inputs to the DMS and other planning programs. DMS applications include calculation of line and equipment loading, and analysis of normal and emergency switching analysis. Other planning programs at PG&E that require load data are ASPEN DistriView – used by PG&E planners for setting distributed generation relays, for fault analysis, and for phasing studies.

4.5.2 Locations

While AMI addresses energy usage at the customer's panel, other load parameters still require load monitoring. The power quality group at PG&E is addressing current and voltage harmonics, power factor, displacement power factor, surge amps, etc. at individual customers with power monitors (from PMI) placed at the customer's panel.

Many PG&E customers are considering installing solar panels or have installed solar panels. Consumer products for measuring instantaneous watts, current and voltage are now available (i.e., the "kill-a-watt" monitor available in some consumer catalogues for less than $35) -- to help acquaint customers with the load demands of individual appliances. For off-grid applications, solar installers size the number of panels and batteries based on daily demand (appliances and usage rate) and will provide customers with suggested alternatives – e.g., energy efficient, and highly insulated refrigerators – to reduce size and cost of the solar installation. The "kill-a-watt" monitor can tell the customer how much energy the appliance uses, and whether that appliance might be an inappropriate load for an off-grid solar system.

Increased awareness of energy costs by consumers, together with more stringent energy standards for appliances -- has affected feeder demand and feeder power factor. PG&E has found that the power factor on feeders has risen (improved) over the last 15 years.

In 2004, PG&E redid its power factor study for domestic customers. To get an initial sense of what the power factor range might be on a domestic residence, a PG&E engineer took a power quality meter home, and attached it to his house panel. To his utter surprise, the meter indicated a "leading" power factor. Stunned by this observation, the meter was placed on individual home appliances, until the source of the leading power factor was found. The source of the leading power factor turned out to be the compact fluorescent bulbs (CFBs) that the engineer had installed throughout the house when he first moved in.

Another "load" surprise was when the engineer placed a "kill-a-watt" meter on the home's energy efficient refrigerator. Measured running amps were around 1 amp, instantaneous watts were around 115, and power factor was a remarkable .95. (During the defrost cycle, usage spiked to around 400 Watts. Two-day kWh usage at an average room temperature of approximately 64°F was 1.62 kWh. This included one defrost cycle. Nevertheless, the refrigerator's power factor was higher than the engineer anticipated, and the refrigerator's daily usage was far less than the engineer expected.)

The efficiency of home lighting continues to improve. Consumer awareness of the benefits of replacing incandescent bulbs with compact fluorescent bulbs (CFBs) continues to grow. (Improved LED bulbs may make home lighting a once a decade or more purchase in the future.)

The rising efficiency and power factor of major appliances such as refrigerators is believed to be one of the factors behind the improvement in power factor PG&E has seen on its distribution system.

Considering the recent success governmental efforts have had on energy use and energy efficiency, national laboratories should continue to focus on the nature (harmonics, power factor), demand (kW) and daily usage (kWh/day) of lighting and appliances with the aim of improving all of these factors in the future.

In particular, the replacement of compression a/c with evaporative coolers (swamp coolers) in areas with dry climates – such as Arizona, Nevada and California should be researched by the government together with appliance manufacturers, with the aim of providing home owners with a less energy intensive means of space cooling.

4.5.3 Description of Monitoring Equipment

PG&E has an extensive SCADA system, with data accessed by radio, microwave, and telephone. Consolidation of multiple frequencies and standardization of equipment is on-going.

AMI is the power line for electric meters; gas meters are wireless.

For power quality, PG&E has purchased two Eagle 120 meters from PMI (Power Monitors, Inc.) for single-phase monitoring. These monitors plug directly into 120-V wall receptacles and have the option of connecting a single-phase load to it. A typical use would be at a residential customer facility. For detail information, please see http://www.powermonitors.com/products/eagle120.htm

All of PG&E's power quality monitors are portable as opposed to permanent installations. This is because they are used for three-phase commercial/industrial customer site investigations. The majority of the monitors are reliable power meters (RPM), now part of Fluke Corporation. The RPMs have a sampling rate of 128 samples per cycle per channel and are capable of recording voltage, current, harmonics, transients, waveform capture, and power consumption. The intended use is primarily to investigate voltage problems, i.e., sags, spikes, and power outages (momentary and sustained). For detail information, please see http://us.fluke.com/usen/products/PMPwrRcdr.htm?catalog_name=FlukeUnitedStates&Category=PQTTOP(FlukeProducts)

Commercial and industrial customers have the option of installing their own revenue-grade meter at the main service panel. This allows them to monitor their own distribution system and collect loading information. However, special facility charges apply. An example of a few vendors includes Power Monitor Limited (PML), Dranetz-BMI, Square-D, and GE.

4.5.4 Communication

Communication with the RPMs is accomplished through the use on an Ethernet cable between the monitor and laptop. Remote forms of communication include high-speed DSL, lease line, and wireless connections.

There is one communication system that PG&E has had some experience with in a past collaborative power quality project involving EPRI-PEAC and that is the PASS Signature System from Dranetz-BMI. For detail information, please see http://www.dranetz-bmi.com//products/prod2.cfm?prodcat=5.

4.5.5 Cost

The base cost of the RPM monitor is approximately $10,000 and up to $15,000 with accessories, i.e., 100A, 1000A, or 5000A current transformers. Repair costs are a flat rate of about $1,200.

The cost of an Eagle 120 monitor from PMI, as mentioned above, is approximately $2,000.

4.5.6 Use of the Data

The monitoring data provide insightful information to understand consumer load behavior and characteristics. The insight has helped to develop the composite load model structure, and some of the findings have been applied in the development of load composition.

4.5.7 Other Issues affecting Consumer Loads

The California Solar Initiative provides incentives for residential customers to install solar panels. Besides increasing photovoltaic (PV) (“green”) generation, the California Solar Initiative may have other significant and beneficial consequences:

1. Grid connected solar systems in general, and off-grid solar systems in particular, require a “high-efficiency approach” to energy consumption. This approach often will mean that inefficient appliances must be replaced. As the demand for more efficient lights and appliances grows, the cost for improved energy efficient devices should diminish, benefiting all consumers.

2. Education: PV systems are very visible. As more and more consumers install PV, education about PV generation and home energy consumption should increase, improving consumer’s knowledge about the benefits of PV and home energy efficiency.

3. Energy independence: PV systems provide consumers with a measure of energy independence, and may displace the combustion of fossil fuels.

4.6 Load Modeling Based on Monitored System Disturbance Data

4.6.1 Motivation

The motivation for improved modeling of load is clear, based on the discussion in the previous sections . However, to truly assess the efficacy of new and more sophisticated load models being developed through the WECC efforts, one needs to be able to compare the simulated performance of these models to actual recorded system response. Even more beneficial is the ability to use recorded system behavior to directly derive parameters for the various load model structures being developed through the WECC efforts. This has multiple benefits:

- It assesses the adequacy of the composite load model structure.
- It helps to identify potential limitation in load models and helps to fine tune and improve load models.
- It provides a direct means of estimating load model parameters for “aggregated” load models without the need for guess work.

For these reasons, the ability to systematically deploy monitoring equipment (or utilize existing monitoring equipment such as DFRs and power quality meters) to record the behavior of system loads during system disturbance is an extremely beneficial exercise. It is also important to establish a range of realistic parameters for “aggregated” load behavior on the power system for various seasons, regions, types of load, etc.

4.6.2 Locations

To assess the "aggregated" behavior of system loads, the most effective place to deploy monitoring equipment is at the distribution substations that are considered representative of commercial, industrial, and residential loads. A typical monitoring installation would involve installing data acquisitions systems on the low-voltage side of a distribution transformer. The need is to monitor the three-phase voltage and three-phase current on the low-voltage side of the distribution transformer at a sampling rate of at least several hundred samples to a few thousand samples per second. Typical sampling rates of commercially available devices are 7680, 5760, 2880, 1920, and 1440 samples/second. These sampling rates can be considered adequate to capture time-domain data. Also, to capture slow voltage recovery events, the recorded length of the data during and following a system event should be large enough for the time scale of interest – typically around 30 seconds.

The need for high sampling frequency is to fully capture the system dynamic response (down to sub-cycle phenomena) and to be able to perform various signal processing and parameter fitting exercises with the collected data (e.g., high sampling rates help numerical stability while solving machine differential equations for parameter optimization). Typical power quality meters, as deployed by utilities, can be effectively used for this purpose. Presently EPRI is engaged in this type of work with many Eastern Interconnection utilities.

Ideally, one would want to monitor several locations throughout the system, which represent the diversity of loads in the utility. For example, a few residential feeders, a few commercial feeders, one or two typical industrial feeders of different load types (heavy industry, agricultural industry, light manufacturing, etc.). In this way data can be collected on a variety of load types. In addition, patience is needed because the load monitoring effort may have to continue for several months to capture sufficiently good measurement data for deriving load model parameters, as well as sufficient variety in load composition for capturing parameter sensitivity. That is, to account for regional, seasonal and daily variations in load composition. In the work that EPRI has been doing over the past couple of years, it has been found that the most fruitful data is that recorded during severe and relatively balanced voltage dips – e.g., as caused by a three-phase fault in the transmission system. This is clearly a rare event and at times data have been collected for months before such an event could be captured.

Often the tendency could be to use existing monitors in the system without having to purchase and install a new device for collecting data. In these cases, existing data acquisitions systems (power quality meters, digital fault recorders and other recording equipment) may exist already and may be used to serve the required purpose. A detailed study to assess the applicability of commercially available monitoring systems for load modeling purposes was performed as a part of EPRI's Power System Load Modeling (PSLM) Phase #1 collaborative R&D effort. Some of the key findings of that study are summarized in the next section. For detailed information, please refer to the EPRI report "Measurement Based Load Modeling" (EPRI 2006).

4.6.3 Description of Monitoring Equipment

Common types of monitoring equipment that can be used for acquiring load modeling data include: power quality monitors, digital fault recorders (portable as well as permanently installed), and digital relays. These devices are commonly referred as intelligent electronics devices (IEDs). There are a large number of commercially available IEDs that are already deployed by numerous utilities for monitoring power system data. However, significant differences exist in the way individual IEDs are configured to capture natural system disturbance data. To capture natural system disturbances using commercially available IEDs and make sure the available data is suitable for load modeling, the requirements and guidelines of load monitoring functions should be defined. As part of a study, EPRI developed a performance matrix such that measurement data from these devices can be used in load modeling development and validation. Main performance indicators to look for in an IED are shown in Table 3.

Table 3 Performance Matrix for Commercially Available IEDs

Performance Criteria	**Description**
Type of data acquired	Should be capable of acquiring time domain data
Number of input analog channels	**6/9/12/15** At least six channels (three for phase voltages and three for phase currents to monitor one feeder). The more the better ,especially if one desires to record individual feeder currents as well as the total substation current
Number of input digital channels	Optional, not needed most of the time
Sampling rate	Should have at least 960 samples/second/channel, Many IEDs especially DFRs have adjustable sampling rates
Trigger	Programmable triggers (voltage and current), user should be able to set trigger and reset thresholds
Pre-fault and post-fault recording time	It is necessary to capture a few cycles of pre-fault data to obtain steady state conditions before the fault. Post-fault recording duration is a function of reset threshold and maximum storage capability
Memory storage (RAM)	Ideally, the device should be able to store up to tens of seconds worth of data to capture slow voltage recovery events
Hardware requirements	Should have peripheral ports for networking, data transfer, user interface, etc.
Data format	Data could be stored in various data formats such as COMTRADE, comma separated, etc.

A list of commercially available IEDs that meet most of the performance criteria are shown in Figure 10.

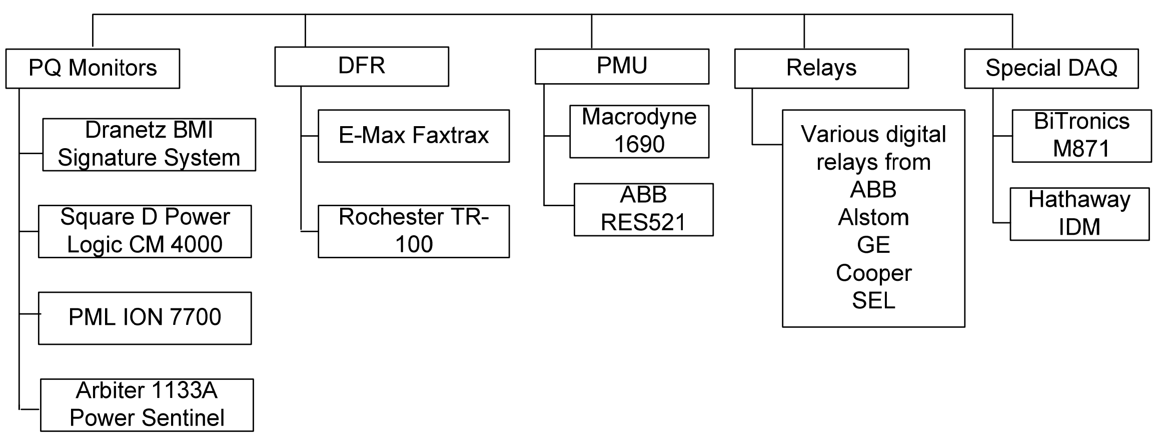


Figure 10 Commercially Available IEDs

Note that many power quality monitors can store only tens of cycles of data at sampling rates higher than 960 samples/second. If a power-quality (PQ) monitor does not have an adequate number of channels, more devices can be installed (which will increase the overall cost) for monitoring multiple feeders coming out of a substation. The PQ monitors mentioned in the table typically cost between $5,000 to $8,000. All of them have dial up and/or Ethernet ports, which enable remote data access.

All the digital fault recorders (DFRs) mentioned in Figure 10 are portable DFRs that do not need elaborate mounting cabinets. DFRs are more flexible than PQ monitors because they have adjustable sampling rates, more analog input channels, and bigger RAM to store longer disturbances. They also have dial up and Ethernet ports for remote data access. Portable DFRs typically cost between $9,000 to $11,000. One issue with DFRs is that protection engineers typically configure them for recording fault current and not load response. This specifically affects current measurements. Therefore, even though there might be an existing DFR installed at a distribution substation, it may not record “suitable” data for load modeling purposes.

The EPRI load modeling team has not worked with either PMU or digital relay data. All the data being used for the various load-modeling projects is either from PQ monitors or DFRs. The primary reason for this is that PMUs are typically installed at major transmission substations, whereas for load-modeling purposes, data is required at the distribution level, where PQ monitors and DFRs are more prevalent. .

4.6.4 Cost

PQ devices capable of waveform data capture required for load modeling applications:

- PQ instrument costs: $5,000 - $12,000

- Other costs associated with installing permanent monitoring devices: Additional costs of 2 to 10 times the cost of the monitoring equipment can be incurred for the installation and maintenance of a permanent substation instrument. These costs vary depending on whether the substation has available PT/CT measurement points, whether the station has communications capability, etc. Potential installation cost components could include
    - Engineering and line crew labor
    - Instrument costs
    - Calibration and other maintenance costs
    - Purchase of ancillary equipments (CTs and PTs)
    - Provision of necessary communications in the substation

  Example Costs:
  Instrument Costs – $10,000
  Installation costs (available metering points and communications) - $25,000
  TOTAL = $10,000+$25,000 = $35,000

- Installing portable monitoring devices: Additional costs of 1 to 1.5 times the cost of the monitoring equipment is typically incurred for new installation and maintenance of any portable instruments.

  Example Costs:
  TOTAL = $10,000 + $10,000 = $20,000

4.6.5 Use of the Data

The main use of the load monitoring data is to

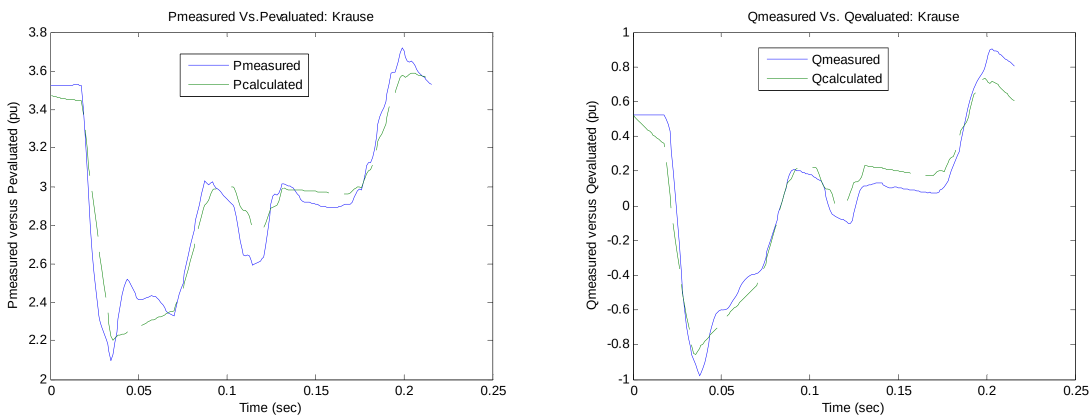
- Estimate load composition (percentages for motor load versus other load types) and load model parameters (parameters for each type of load)

- Identify which parameters can be estimated reliably from available measurements

- Evaluate different parameter estimation techniques and load model structures
- Identify variations in load model parameters and composition over time (seasonally etc.) and for different types of loads in the system

In this way one can develop a pool of information on the behavior of various "aggregated" loads (residential, commercial and industrial) for different times of the year and day.

Presently, EPRI is engaged in a research project funded by several utilities in the Eastern Interconnection related to this type of work. The outcomes of that project can be leveraged to the Western System. EPRI's load model structure is based on positive sequence representation of loads and uses balanced three-phase disturbance data. The positive sequence representation incorporates both static and dynamic characteristics of the loads. The parameters obtained can be easily incorporated in various load models in Siemens PSS/E™ and GE PSLF™ programs. As an example, Figure 11 shows a sample result from the work being done by EPRI to illustrate the use of load monitoring data for model validation. Figure 12 shows the model structure used in this case to derive estimated parameters for the model. The load model parameter estimation is done using an optimization algorithm developed in MATLAB®. EPRI is currently testing the algorithm using field events collected by various member utilities.



(The solid blue lines are positive sequence real and reactive powers of the feeder calculated using monitored three-phase feeder voltage and current. The dashed green lines are simulated results based on optimally estimated parameters.)

Figure 11 Example Parameter Estimation using an Optimization Algorithm to fit Load Model Parameters to a Specified "Aggregated" Load Model Structure.

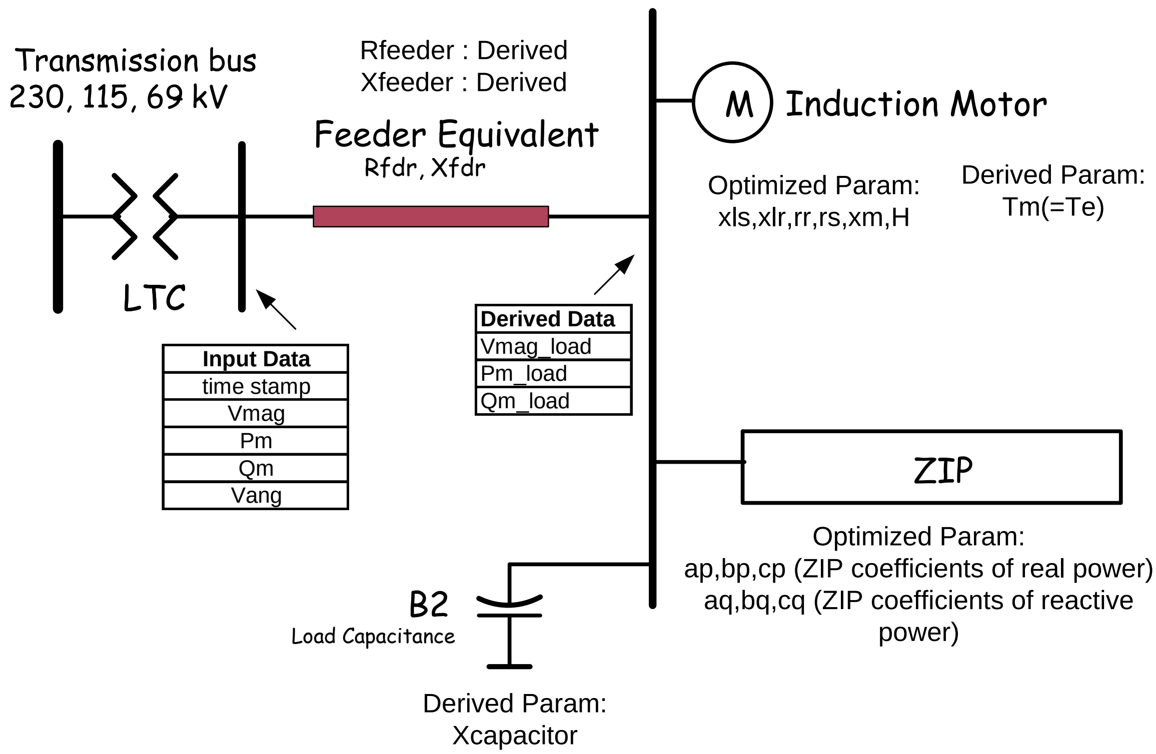


Figure 12 Load Model Structure used for Parameter Estimation.

4.6.6 Summary

Ideally, one would like to obtain a load model that would be accurate across a wide spectrum of system conditions. In reality this level of generality may be insurmountable as a result of the wide variation in load composition both geographically and hourly/daily/seasonally. In general, the results of any study should be evaluated to determine how much they can change if assumptions regarding load model structures or parameters change. Thus, a key requirement of load modeling for system studies is the ability to reasonably capture the variations in load model parameters for sensitivity analysis. Load monitoring (over wide geographical areas and various seasons of the year) and subsequent estimation of "aggregated" load model parameters is a key exercise in facilitating this approach.

4.7 Load Monitoring via Commercial or Residential Load Control Systems

4.7.1 Objective

Commercial and residential load monitors for demand response studies have been used by BPA and PNNL for data gathering for several years (see Figure 13). These load monitors use commercially available equipment to sense, record and control home devices. The monitoring data can be provided online in real time for utility and public use in stability studies, energy efficiency studies and demand response studies. The data are already available and only needs to be put online and additional sites could be added to cover various building types and climate zones.

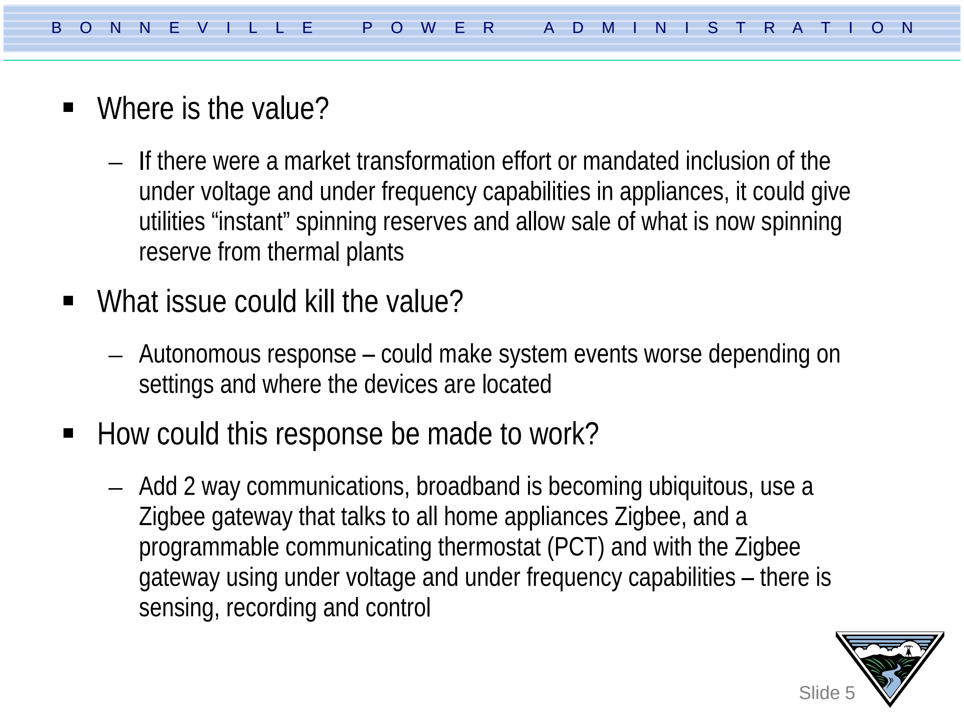


Figure 13 Value Proposition of Load Monitoring via Load Control Systems

4.7.2 Location

Demonstration locations have been Ashland (100 homes), Oregon and the Olympic Peninsula (150 homes) in Washington. Project descriptions are available at:
http://energypriorities.com/entries/2006/04/bpa_ashland_goodwatts.php
http://electricdistribution.ctc.com/pdfs/ED06/Hammerstrom.pdf

4.7.3 Description of Monitoring Equipment

Both commercial and residential monitoring systems used wireless communications to a gateway connected to broadband via Ethernet. Systems could gather down to 1 second data but used 1 minute increments for data gathering of voltage and current signals. Both systems could add frequency data for minimal cost and software tweaks. A potential architecture for use is shown in Figure 14.

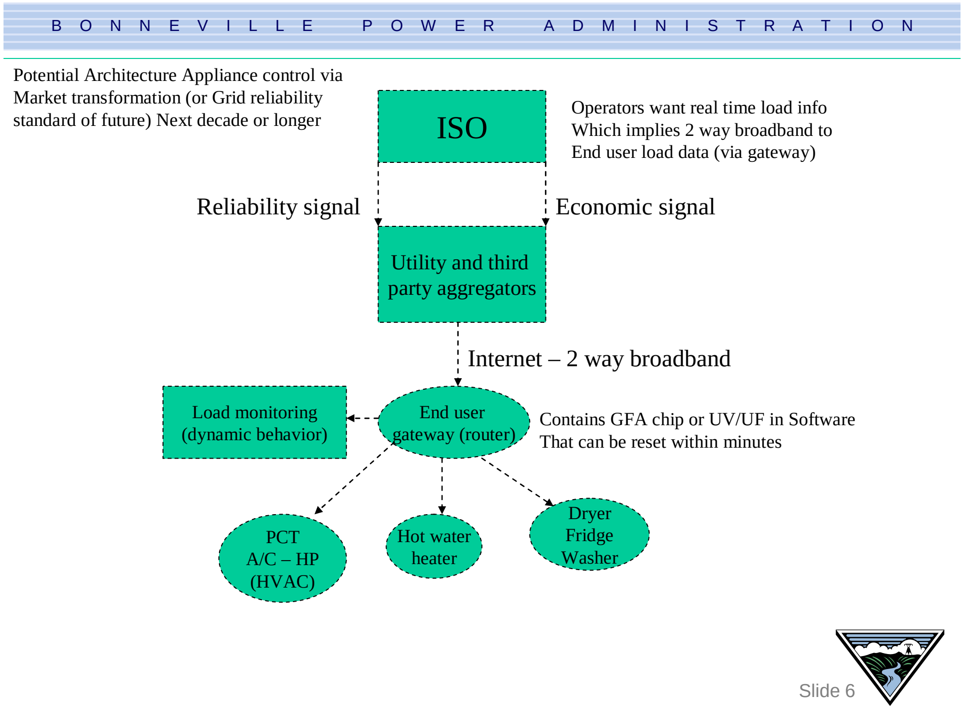


Figure 14 A potential data architecture for load monitoring

4.7.4 Communication

Communication is via a broadband internet connection. Data are collected in real time using an online data base (Oracle and SQL). No special data collection systems are needed over a broadband connection.

4.7.5 Cost

A residential data system costs about $2,000 per home originally, but will soon be available for $299. The installation cost of the thermostat is estimated at about $150.

A unique source for commercial building data has already been used by the Load Composition Study group. The cost for using the data from existing sites would be a monthly service charge for data hosting, with no incremental hardware cost, except to add new sites where utilities want data.

4.7.6 Use of the Data

Data has been used for demand response and market analysis studies. Some examples of the studies are presented in Figure 15 and Figure 16. In Figure 15, the composition of various end uses is shown during a 24-hour period, as individual end uses are separately metered. Figure 16 gives the HVAC load in percentage of the total residential load, clearly showing the thermostat setback period at night and the high activity period in the late afternoon and early evening.

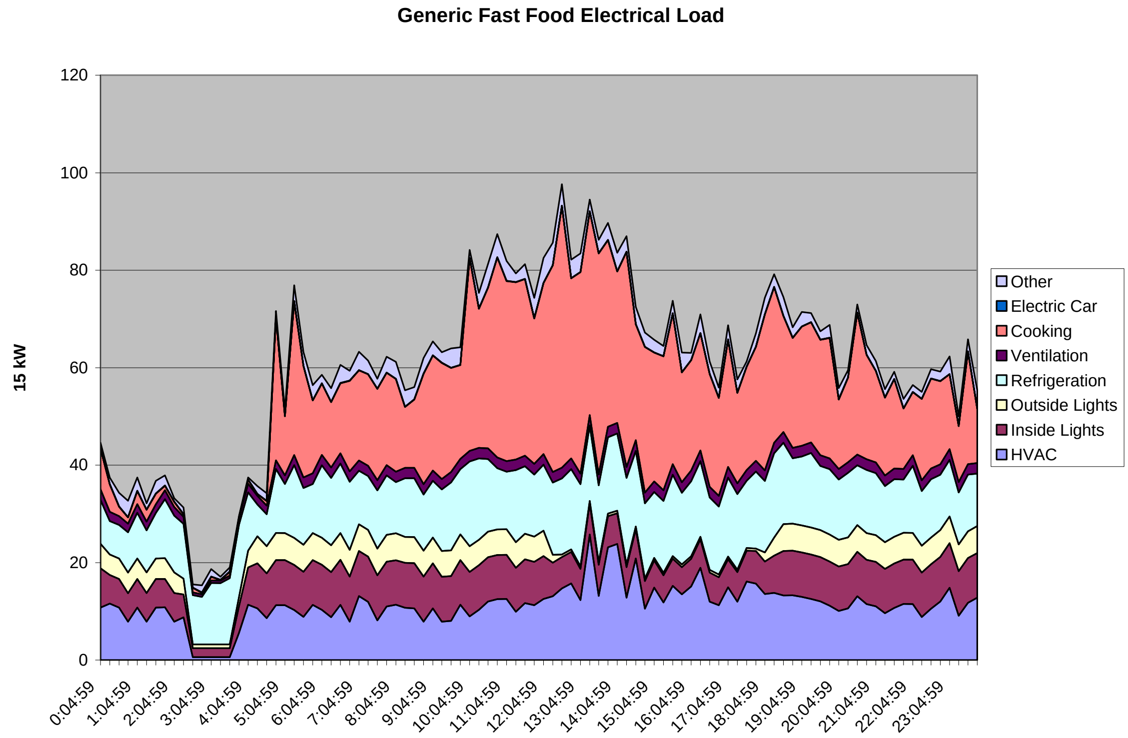


Figure 15 Demand Response and Market Analysis Studies of Commercial Load

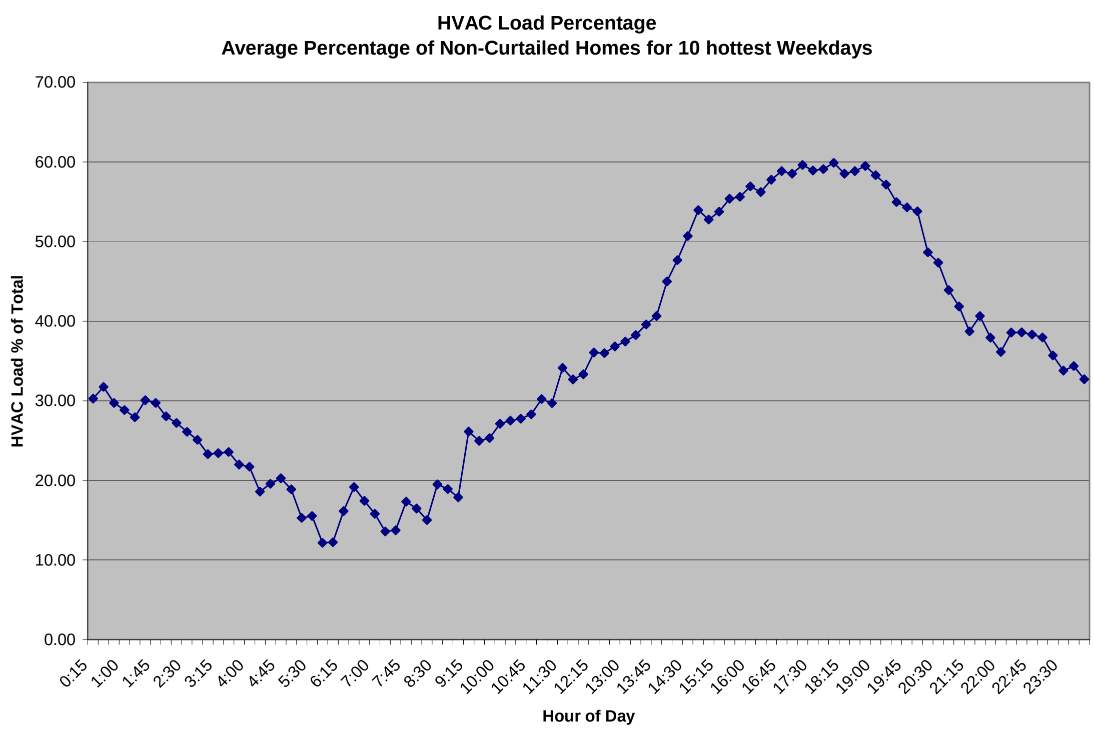


Figure 16 Demand Response and Market Analysis Studies of Residential Load

5.0 LOAD MONITORING APPLICATIONS

The purpose of load monitoring is to serve the needs for better load characterization and better load management, as stated in Section 2.0 Load Monitoring Needs. Load monitoring can find applications in many aspects, including:

- Load monitoring for top-down load composition
- Load monitoring for load composition validation
- Load monitoring for load model validation
- Load monitoring for uncertainty analysis
- Load monitoring for load control performance evaluation

5.1 Load Monitoring for Top-Down Load Composition

The term "top-down" is used in contrast to the "bottom-up" approach, which describes the previous building-simulation-based load composition model. The top-down load composition serves the purpose of estimating load mix and weighting factors that are needed in the bottom-up load composition model. As shown in Figure 17, assuming typical load profiles for individual building types are known, the top-down approach solves for the weighting factors from the total feeder load profile obtained from SCADA data.

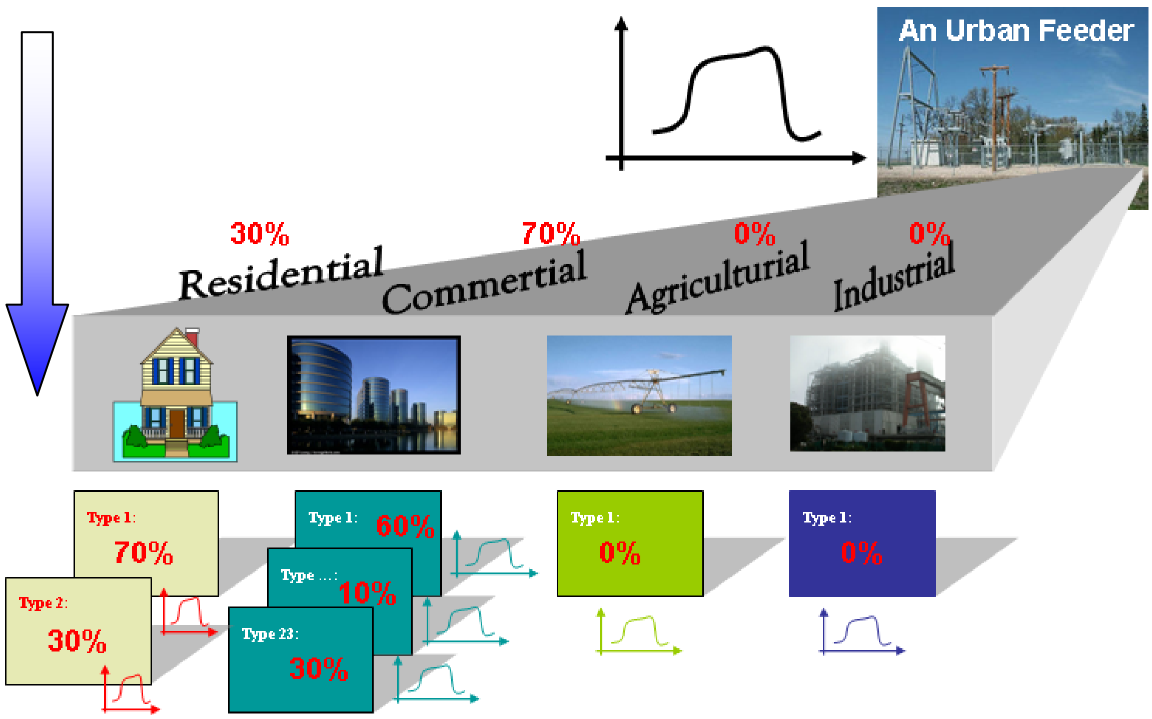


Figure 17 Illustration of the Top-Down Approach for Load Composition Analysis

Technically, the top-down approach employs curve decomposition techniques to separate the measured total load profile (LP_{total}) to the summation of weighted individual load profiles, as illustrated in Figure 18.

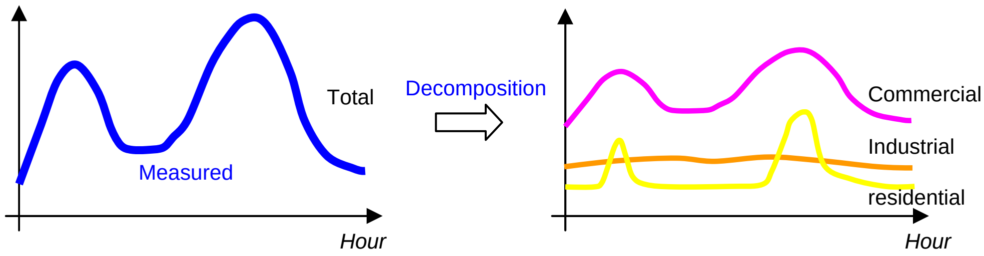


Figure 18 Curve Decomposition for Top-Down Load Composition Analysis

This decomposition can be performed at different levels, and the resulting weight factors represent different levels of load composition information.

$$\text{At the load mix level: } LP_{total} = W_{comm}LP_{comm} + W_{res}LP_{res} + W_{ind}LP_{res}$$

where LP_{comm}, LP_{res}, LP_{ind} are load profiles of commercial loads, residential loads, and industrial loads, and W_{comm}, W_{res}, W_{ind} are the percentages (load mix) of commercial loads, residential loads, and industrial loads.

$$\text{At the building level: } LP_{total} = W_{School}LP_{School} + W_{Mall}LP_{Mall} + W_{Warehouse}LP_{Warehouse} + \cdots$$

where LP_{Shool}, LP_{Mall}, $LP_{Warehouse}$ are load profiles of schools, shopping malls, and warehouses, and W_{School}, W_{Mall}, $W_{Warehouse}$ are the percentages of schools, shopping malls, and warehouses.

Load monitoring data for this purpose need to capture the basic load shapes for a time period of interest. For 24-hour load profile decomposition, hourly data from SCADA systems would be sufficient.

Preliminary research has been carried out at Pacific Northwest National Laboratory to demonstrate the effectiveness of the approach. Two algorithms have been tested: constrained least square and constrained optimization. Stochastic simulation technique is also employed to provide an estimation of the weighting factors on a statistical basis. To evaluate the top-down approach, virtual feeders are built upon simulation data, as shown in Figure 19. In a virtual feeder, loads are synthesized with known individual load profiles. Given a set of weighting factors, the total feeder load profile can be calculated. Then the top-down decomposition approach is applied to the total load profile with the known individual load profiles to derive the weighting factors. The effectiveness of the top-down is determined by comparing the derived weighting factors and the given weighting factors. Example results on the decomposition of the virtual feeder load profile are given in Figure 20. The constrained least square algorithm can estimate load composition pretty well for cooling load (“cool”), equipment load (“equip”), auxiliary load (“aux”), and lighting load (‘light”), as can the constrained optimization. The constrained optimization algorithm can also reasonably estimate the load composition of other load types.

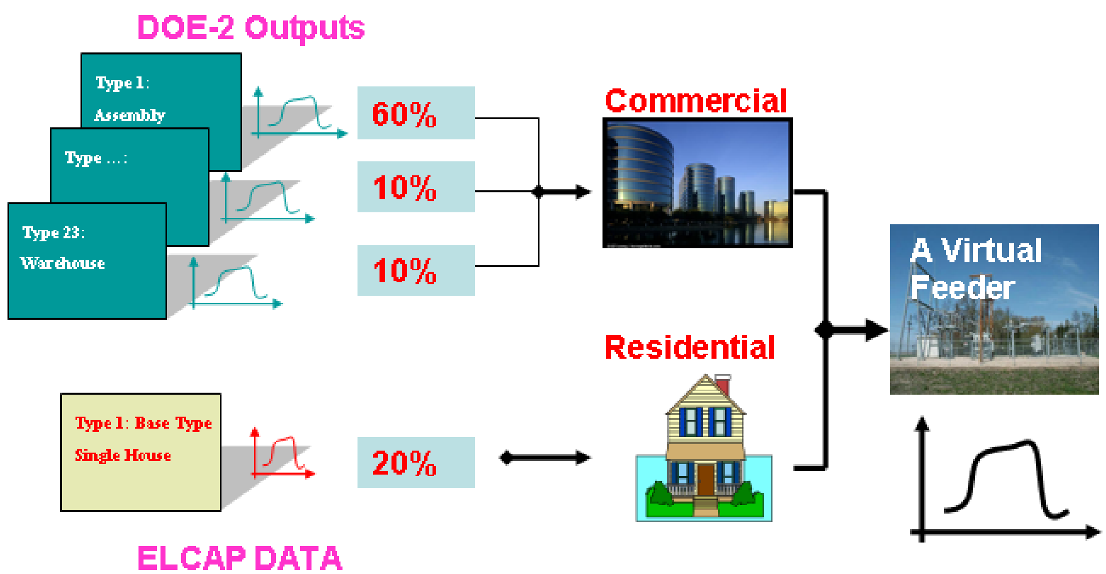


Figure 19 The Setup of a Virtual Feeder

5.2 Load Monitoring for Load Composition Validation

Load profiles generated by the load composition model can be compared with load profiles derived from load monitoring data, e.g., historical SCADA data or building monitoring data. If the load composition model captures the right load characteristics, the load profiles should match SCADA data. Otherwise any mismatch can be used to calibrate the load composition model, e.g., tune load mix and adjust weights. The calibration methodology has yet to be developed.

Load monitoring data for load composition can be of low resolution (e.g., hourly) but of long record, e.g., SCADA.

As an example, Portland feeder data have been used to validate the implementation of the top-down approach. Because the measurement data for typical commercial buildings are not available at this stage, DOE-2 simulation data are used to generate the typical load profiles for 23 building types. Assumptions include:

- The building weighting factors are time invariant.
- Typical load profiles are TYPICAL.
- No agricultural load in the feeder.
- No industrial load in the feeder.

DOE-2 is an industry standard tool for commercial building energy use and cost analysis. With input of building layout, construction types, space usage, conditioning systems (lighting; heating, ventilation and air conditioning (HVAC), etc.), and weather data, DOE-2 performs hourly simulation of building energy use and produces yearly building load profiles. From the yearly profile, daily load profiles were derived for three seasons: summer, winter, and spring, which are considered typical. Figure 21 gives the three-season typical load profiles for sit-down restaurants.

(The red curves are the true load profiles. The blue ones are results obtained using constrained least square. The green ones are results obtained using constrained optimization. The X-axis is time by hour; the Y axis is power consumption by kWh.)

Figure 20 Example Results of the Top-Down Approach for Load Composition Analysis

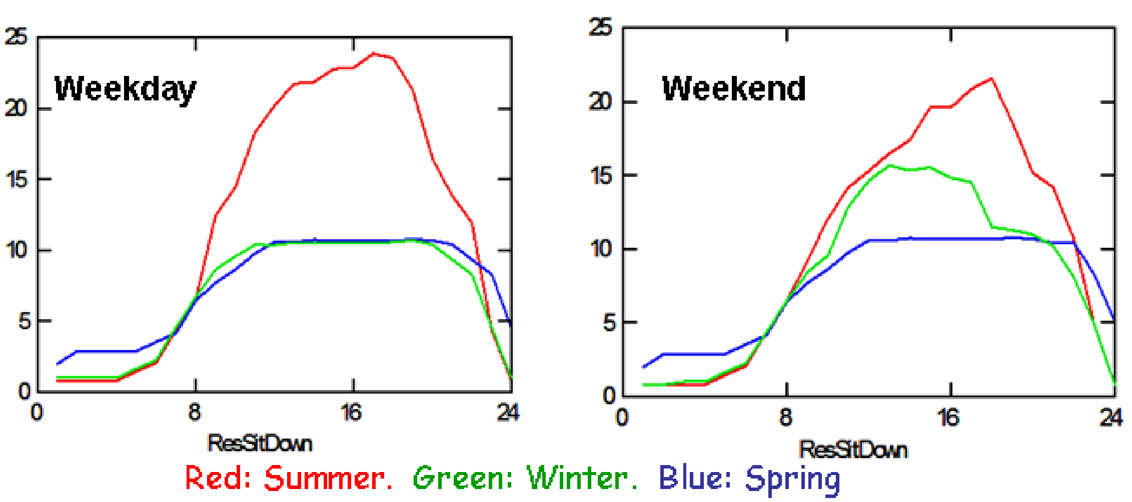


Figure 21 Example Typical Load Profiles for Sit-Down Restaurants.

For residential load, data collected by Bonneville Power Administration (BPA) and PNNL in End-use Load and Customer Assessment Program (ELCAP) are used to generate typical daily residential load profiles for two seasons: summer and winter, as shown in Figure 22.

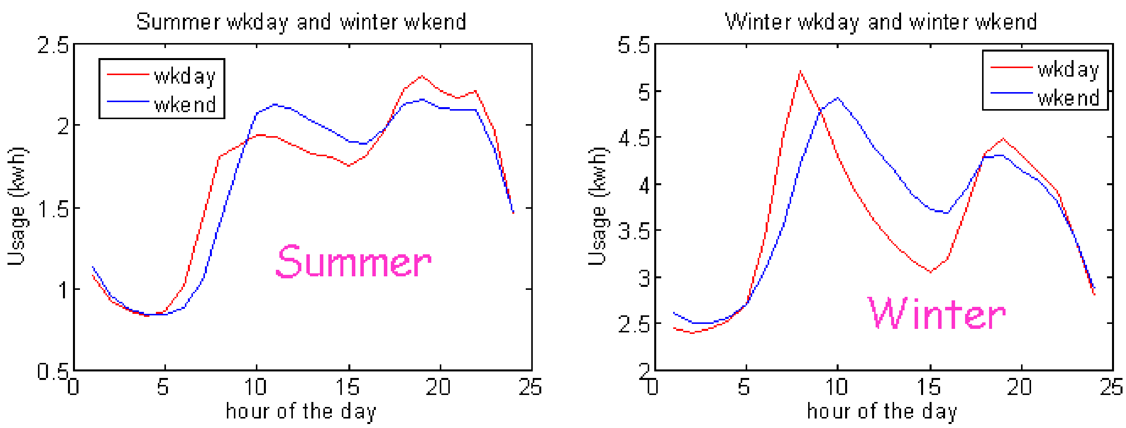
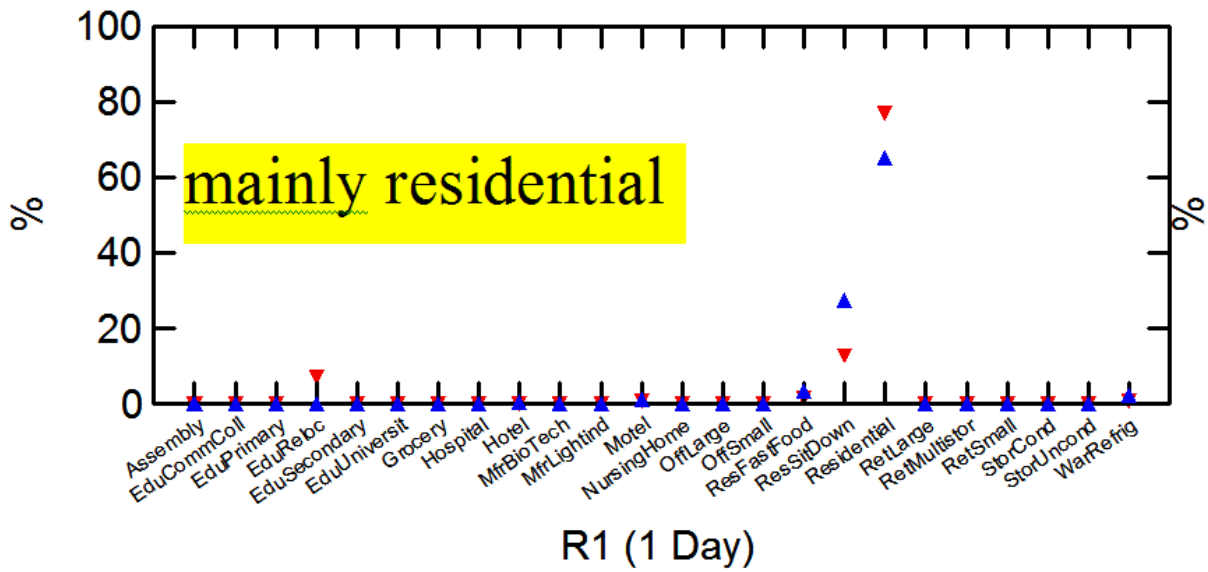


Figure 22 Summer and Winter Typical Load Profiles for Residential Loads.

The developed decomposition algorithm was applied to SCADA data collected for several feeders in Portland area provided by BPA. These feeders are known to supply mixed commercial and residential loads, however the exact mix percentages are unknown. Therefore, the results are not rigorously comparable. It is hoped that by carrying out this preliminary research on the top-down method, a technique that combines the bottom-up and top-down approaches will eventually provide a convenient way to estimate the load composition of distribution feeders. For that purpose, the results are satisfactory. As shown in Figure 23, estimated load composition results are close to that obtained based on the billing information. This example also indicates the validity of the use of load monitoring data for load composition validation purposes.



(Blue and red symbols show load composition percentage obtained by two different decomposition methods as aforementioned. The yellow symbols show the known load composition.)

Figure 23 Example Result of Load Composition Validation for a Portland Feeder Supplying Mainly Residential Loads and Some Small Commercial Loads.

Because measurement data are not available to remove the bias of the DOE-2 modeling results, there exists mismatch between simulation and actual energy consumption. The results are expected to be more accurate once some survey data or field measurement data is obtained to tune the simulation results.

5.3 Load Monitoring for Load Model Validation

General approach of model validation is to compare model simulation against measurements, as having been applied to WECC generator model validation. Load monitoring provides the basis for load model validation.

However, load model validation is far more challenging than generator model validation because of extensive uncertainties and variations of loads. Load models shown in Figure 2 are the aggregated behavior of hundreds of thousands individual load components. It does not make much sense to perfectly match the aggregate model behavior to a specific recording. It is almost certain that the variations and uncertainties would make the load model not match the next recording.

Therefore, load model validation should not focus on how close the curves would match, but should focus on principal load behaviors to match the impact of loads on system studies. If the load model would produce the right high-level system behaviors, it could be concluded that the load model matches the actual load characteristics in principle.

This “in principle” load model validation can be done in two ways: time-domain load model validation and frequency-domain load model validation. Time-domain load model validation compares the time series curves of simulated system level behavior and recorded monitoring data, while frequency-domain validation compares the frequency/damping contents of the simulation results and actual measurements.

Load monitoring data for this model validation purpose should have enough resolution and time length for capturing system dynamic behaviors. Examples of data sources include phasor measurements (WAMS), PPSM data, and potentially, measurements from the low-cost monitor device DMWG is developing.

5.4 Load Monitoring for Uncertainty Analysis

Statistical analysis can be performed on load monitoring data to quantify load variations over selected time periods. Load monitoring data needed for uncertainty analysis can be low resolution data like SCADA measurements or high resolution data like phasor measurements. Load uncertainty analysis is an ongoing effort under the CEC/LMTF Load Research Program. Further results will be reported once the work is done.

5.5 Load Monitoring for Load Control Performance Evaluation

It is the trend that loads will play a more and more active role in managing the power system. At the individual end-use level, SCE is developing solutions for prolonged voltage recovery as a result of a/c stalling. At a larger scale, active load control has been studied for the purposes of spinning reserves, damping improvement, frequency and power flow regulation, etc. Similar to generator performance monitoring, there is a need to ensure the load behaves as designed for correct credits and control enforcement.

Load monitoring data for load control performance evaluation range in a wide spectrum, depending on the control objective. High resolution data like phasor measurements are needed for evaluating load performance for damping improvement. Lower resolution data of long records are needed for evaluating load performance for spinning reserves, frequency and power flow regulation.

To demonstrate load monitoring applications for load control, the following examples are extracted from the results of the Grid Friendly™ Appliance Project (Hammerstrom *et al*. 2007).

The Grid Friendly Appliance Project was undertaken to demonstrate the performance of the Grid Friendly appliance controller developed at PNNL. The controller was applied to 150 Sears Kenmore residential clothes dryers manufactured by Whirlpool Corporation and 50 water heaters. It was configured to perform autonomous under-frequency load shedding. The under-frequency threshold was set quite high to observe many such events during the project. Consistent with PNNL's Grid-Friendly approach for load control, the permitted load curtailments were performed in ways that did not appreciably inconvenience the appliance owners. Indeed, 358 such events were recorded during the project year, and few appliance owners reported observing or being inconvenienced by the reactions of their appliances.

In this case, the appliance controllers and appliances were observed by communication modules placed at each appliance. There remains lively debate concerning how much, if any, communication is needed to and from such autonomous grid-responsive controllers. There will be inherent costs associated with such communications. Regardless, the communications were useful for the experimental observation of these controllers after they had been positioned in residences in three regions in Washington and Oregon. Examples of a single dryer response and the aggregate appliance response to an under-frequency event are presented below. The sample size was not large enough, of course, to observe its effect on correcting grid frequency or deferring the actuation of spinning reserve.

Figure 24 shows the response of a single project dryer during an under-frequency event. The dryer was shown to cycle its heating element on and off with a regular pattern as it maintained its constant drum temperature prior to the event. At the onset of the under-frequency event, the dryer heating element load was shed and remained off throughout the event's 3-minute duration. Thereafter, the heating element turned on until the drum returned to its prescribed temperature and resumed its normal operations and duty cycle.

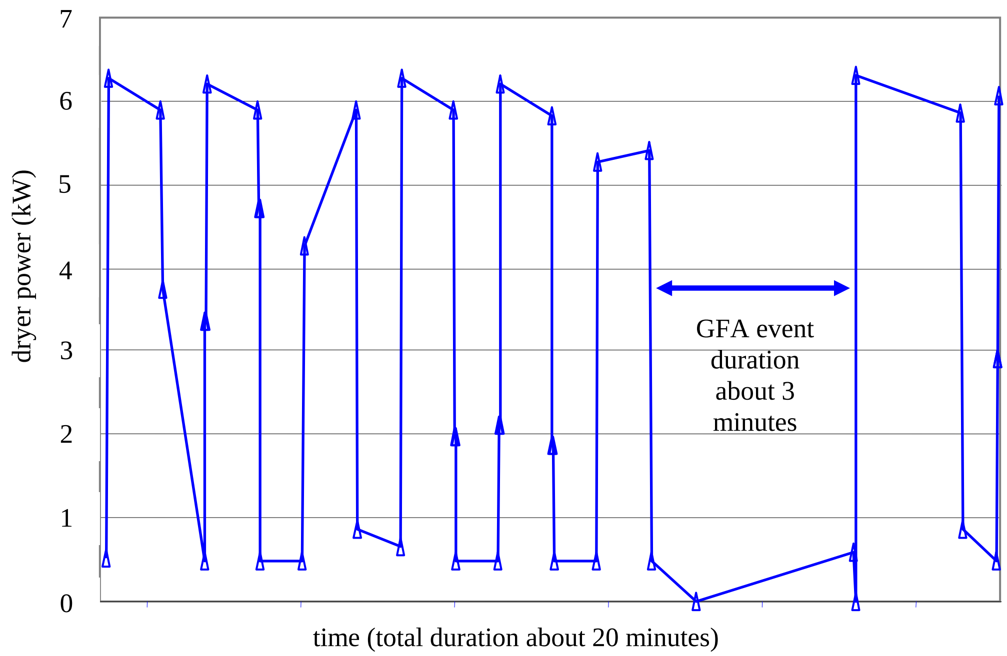


Figure 24 Example Data Logged from Active Project Dryer during an Under-Frequency Event

Figure 25 demonstrates the aggregate response of the controllers at almost 200 appliances. Each appliance replied with an acknowledgement for any under-frequency event that it observed. Each shown point represents one of the 358 events, minimum frequency observed during the event, and the percent fraction of available appliances that recognized the event. Virtually all controllers responded to any under-frequency event that was more than 0.003 Hz below the frequency threshold as measured at PNNL.

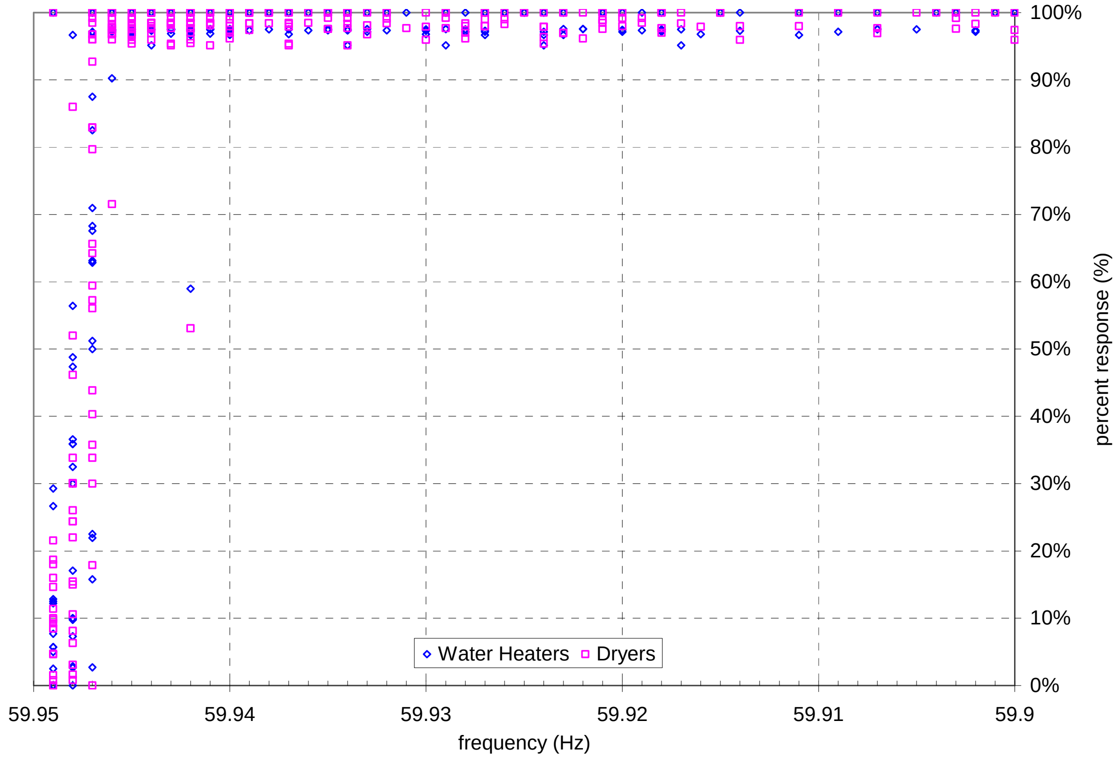


Figure 25 Percentages of Grid Friendly Controllers responding at Various Frequency Depths

6.0 LOAD MONITORING RECOMMENDATIONS

Load monitoring site selection and equipment selection are highly dependent on application purposes. Section 5.0 Load Monitoring Applications summarized five applications of load monitoring:

- Load monitoring for top-down load composition
- Load monitoring for load composition validation
- Load monitoring for load model validation
- Load monitoring for uncertainty analysis
- Load monitoring for load control performance evaluation

The first four of them are focused on load characterization and model development, which is well aligned with current WECC/CEC efforts in the load research area. The last one on load control is case-specific, i.e., load monitoring will reside where the load control is implemented. Its site selection and monitoring requirements are relatively straightforward to determine. Therefore, the following recommendations will mainly focus on the first four applications. Future WECC load monitoring plans should leverage existing load monitoring facilities as much as possible.

6.1 Site Selection

Given the diversity and variety of loads in the WECC, load monitoring needs to cover major load centers and also consider different climate zones and load types. 11 WECC load monitoring locations are identified as:

- Boise, ID
- Boulder, CO
- Calgary, AB
- Cheyenne, WY
- Los Angeles, CA
- Phoenix, AZ
- Portland, OR
- Sacramento, CA
- Salt Lake, UT
- San Francisco, CA
- Vancouver, BC

Large industrial loads have been well studied, and they usually have separate models from the rest of the load. When selecting the sites, primarily consider commercial and residential loads.

6.2 Load Monitoring Levels

For load composition analysis and validation, SCADA measurements at substation levels, where load models are aggregated, would be adequate. The load monitoring efforts would be on working out data collection and sharing issues.

For load model validation, dynamic measurements are needed. Areas that aggregate loads to the 230-kV level may be able to meet their validation needs using WAMS and DFR data. Likewise, even if an area models the lower voltage system, sufficient validation for WECC-wide stability analysis may be obtained from higher voltage monitoring. Monitoring commercially dominated circuits should provide validation for most WECC commercial load. Validation of residential load models, if desired, will require regional low voltage (<35-kV) monitoring. To sufficiently validate and calibrate load component models, load monitoring at feeder level or even building level is necessary. The challenge with low-voltage level is that one has to wait for events that would have enough impact at the monitoring level so meaningful data could be captured. It is also important to point out that the objective of load model validation is to validate load modeling principles and not to validate each load model in the WECC database. Although it may include lower voltage levels, load monitoring for load model validation doesn't have to cover all the 11 load locations for load composition analysis, and many of the existing load monitoring facilities presented in Section 4.0 Existing Load Monitoring Examples can be leveraged.

For load uncertainty analysis, the studies can be performed for different load levels as well. Substation SCADA measurements, WAMS data, or monitoring data at lower voltage levels can all be useful for characterizing load uncertainties. The load monitoring specified above would be adequate for uncertainty analysis.

6.3 Load Monitoring Equipment

Load monitoring equipment selection depends on what characteristics need to be captured. For load composition analysis and validation, steady-state measurements are needed. Existing SCADA facility can be used. For load model validation, PMUs, PPSMs, DFRs, or the low-cost DMWG monitor should be used to record load dynamics. Existing facilities at BPA, PNM, IPC, PSE, and PG&E are examples and should be further explored in terms of their benefits to load research. For load uncertainty analysis, both types of measurements can be used.

Figure 26 summarizes the overall roadmap for load monitoring. It is important to point out that load monitoring efforts should be consistent with and driven by the load research needs. A three-stage load monitoring effort is suggested in Figure 26.

The first stage is to explore the use of SCADA measurements from the identified 11 WECC locations for load composition studies and load uncertainty analysis. This is relatively easy to implement because existing SCADA infrastructure can be leveraged.

With load monitoring experience gained in the first stage, stage 2 on load monitoring for load model validation as well as load uncertainty analysis can be implemented. Again, to be cost-effective, it starts with existing measurement facilities at several power companies as identified in Section 4.0 Existing Load Monitoring Examples. Feedback on the use of load monitoring data can be used to improve existing monitoring facilities or to identify needs for new monitoring capabilities.

The last stage is to implement load control monitoring along with load control. Load control monitoring may well overlap with the facilities put in place for the first two stages. But any new load monitoring capabilities can be built on experience from the first two stages.

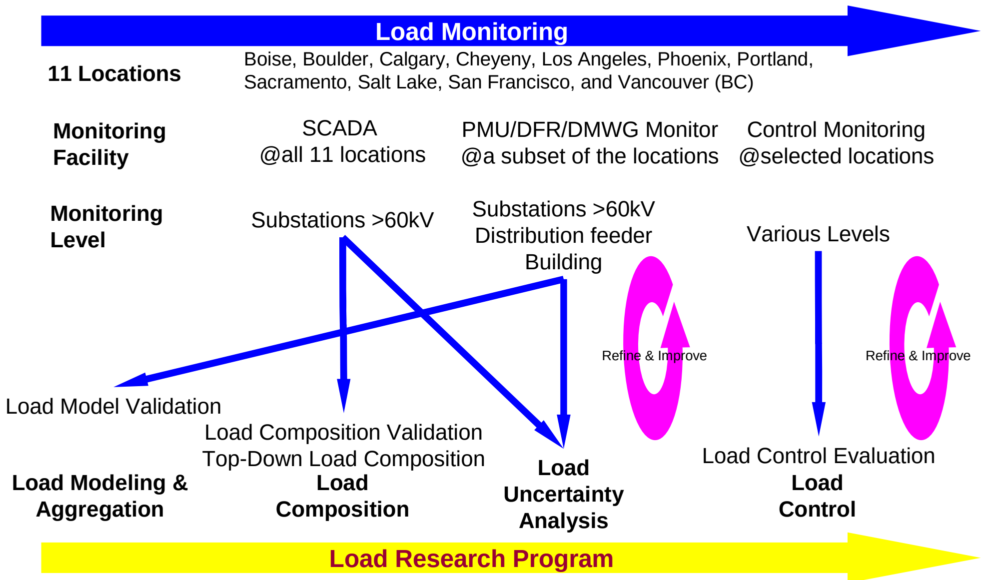


Figure 26. Load Monitoring Roadmap

7.0 REFERENCES

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APPENDIX A – PMU Specifications and Technical Data

Table A- 1 PMU Specifications and Technical Data

PMU Model	**Number of Voltage Inputs**	**Number of Current Inputs**	**Number of Digital (on/off) Inputs**	**Output Data Rate** (sps*)	**Output Data Format** (e.g. IEEE 1344)	**Integrate Relay Function?**	**Time Synchronization Mechanism** (e.g. GPS or IRIG-B**)**	**A/D Conversion Numerical Resolution** (e.g. 16 bits)	**Continuous Data Storage Capability** (e.g. stores data for 10 days)	**Data Link Protocol** (e.g. TCP/IP)	**Event Trigger Level** (e.g. 2 levels for undervoltage)	**Physical Dimension and Weight** (WxHxD inch, lbs)	**List Price** (US$)
ABB RES 521***	6	12	8	60/30/15	IEEE 1344, PC37.118	No	Built-in GPS clock module	16 bits	No local storage, streaming PMU	TCP/IP UDP selectable from HMI	2 f; 2df/dt; 2 uv; 4 oc plus output contacts	19x10.6x10	$10,000 ~ $13,000
Arbiter 1133A***	3	3	4	20	IEEE-1344	Some	Built-in GPS module or IRIG-B		Configurable	Serial Ethernet	32 channels, configurable	1RU 17x1.72x10 5 lbs	$4,500
Macrodyne 1690***	15 V+I 15 V+I (optional)		16 16 (optional)			No	Built-in GPS receiver. Time signal output (IRIG-B, 1 pps).	16 bits	4 MB 1GB (optional)	RS-232	Flexible software triggers	10.5x14.75x 19 45 lbs	
Metha Tech Transcan 2000 IED	8 V+I		16	60	TranScan; Comtrade (optional)		IRIG-B	16 bits	30 min	Ethernet; RS-232; V .34 modem	oc; ov; uv; of; uf; digital triggers		
SEL-734***	3	3	6	20	NA	No	IRIG-B	12 bits	NA	TCP/IP EIA-232	Programmable Logic	7.56x 5.67x6.64 5 lbs	$1,500
SEL-421***	3	3	7	20	NA	Yes	IRIG-B and 1 kpps	16 bits	NA	EIA-232	Programmable Logic	19x5.22x9.52 17.5 lbs	$11,000

(data as of 2003)

*sps: Sample per Second
**pps: Pulse per Second
***Confirmed with vendors
IRIG-B: InterRange Instrumentation Group Time Code Format B.

APPENDIX B – PPSM Cost Breakdown

Table B-1. Cost Estimate for PXI-based Centralia PPSM.

Item #	Description	Source	Model #	Part #	Price (each)	Quant.	Special Comments
1	PC w/15" flat panel monitor	Dell	Dimension 2400		$ 1,500.00	1	
10	Analog I/O Board	NI	PCI-6052E		$ 1,995.00	1	
11	Time & Frequency Board	Datum	bc635CPCI		$ 1,295.00		not used
12	Cable Assembly - T&F Board	Datum	D to BNC Adapt.	Config. 9899047	$ 75.00		not used
13	SCXI Chassis	NI	SCXI-1000	776570-0P	$ 695.00	1	
14	Rack Mount Kit for SXCI-1000	NI	SCXI-1370	776577-70	$ 50.00		not used
15	Shielded Cable Assembly (2 meter)	NI	SCXI-1349	776574-492	$ 175.00	1	
16	8-Channel Input Module	NI	SCXI-1125	776572-25	$ 1,395.00	3	
17	8-Channel Filter Module	NI	SCXI-1143	776572-43	$ 1,795.00		not used
18	Cable - SCXI-1125 to SCXI-1143	NI	SCXI-1352	776575-52	$ 35.00		not used
19	8-Ch. Terminal Block	NI	SCXI-1327		$ 295.00	3	
20	SCXI 3-Way Adapter	NI	SCXI-1349		w/Item #15		
21	SCXI to Time & Freq. Board TB	NI	CB-50LP	777101-01	$ 70.00		not used
22	Cable - TB to SCXI (1m)	NI	NB1 50pin 1m	180524-10	$ 30.00		not used
23	Ethernet Board				w/Item #4		
24	Cable - Ethernet 10baseT	Generic			$ 50.00	1	
25	Clamp-on CTs	AYA	M1V-10-5		$ 208.00	18	
26	Misc				$ 500.00	1	
	Windows XP				w/Item #1	1	
	Windows XP				w/Item #4	1	
	DataTake 4.0	BPA	DataTake 4.0		free	1	
	PCAnywhere	Symentec	PCAnywhere 11.0		$ 129.95	1	
				Total Cost =	$13,858.95		