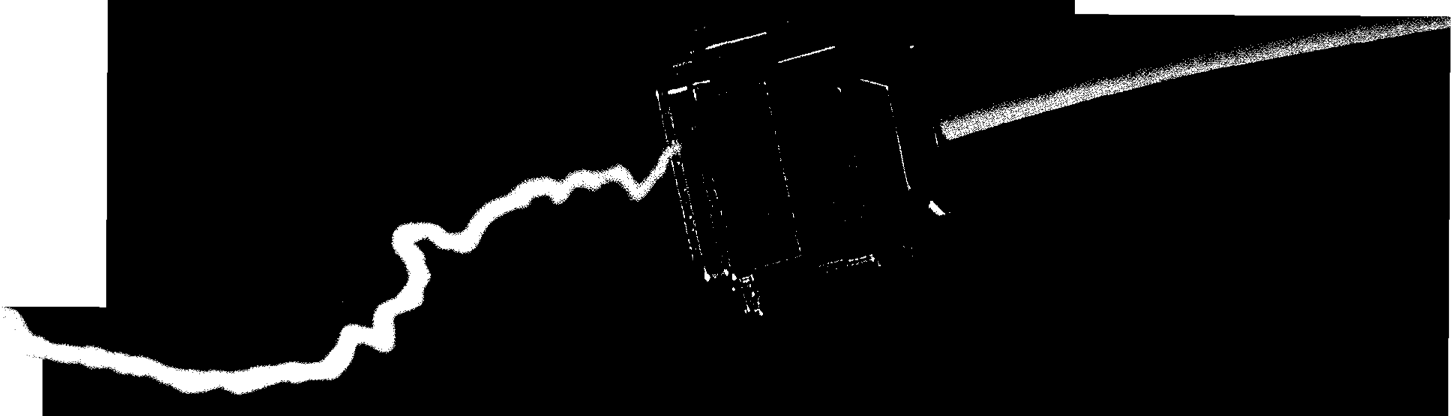
Nonintrusive Monitoring of Electric Loads



*Steven Drenker,**
*Ab Kader**

The Electric Power Research Institute (EPRI) commissioned an implementation and commercialization of a nonintrusive appliance load monitoring system (NIALMS) based on EPRI-developed intellectual property. The system determines the energy consumption of individual appliances being turned on and off within a whole building electric load. Working under EPRI direction since 1993, Enetics, Inc. today offers hardware and software products that perform nonintrusive appliance load monitoring.

NIALMS monitors the total load of a building and recognizes the signatures that indicate energy consumption of appliances as they turn on and off

The system is based on the discovery that, as electric appliances are turned on and off, the waveform of the total site load changes in predictable ways. Appliances have characteristic signatures that make it possible to disaggregate the total load. By sophisticated analysis of the total load waveforms, the system estimates the number and nature of individual loads, their individual energy consumption, and other relevant properties, such as time-of-day variations.

* Electric Power Research Institute

NIALMS electronics connect to the total load at a single point, usually the electric service entrance, using an extender adapter plugged into the standard revenue meter socket. Thus, no access to the individual appliances is necessary for installing sensors or making measurements. This permits easy installation, removal, and maintenance, compared with conventional intrusive load monitoring techniques that require submetering and interior wiring. Customers can disable conventional load monitors on individual loads.

Algorithm and Appliance Signatures

NIALMS monitors the total load and recognizes the signatures that indicate the energy consumption of the appliances as they turn on and off. For example, if the premise contains a refrigerator, which consumes 250 W and 200 var, then, a step increase of that characteristic size indicates that the refrigerator turned on, and a decrease of that size indicates that it turned off.

Other appliances have their own unique signatures, as illustrated in Figure 1, which shows total (real) power

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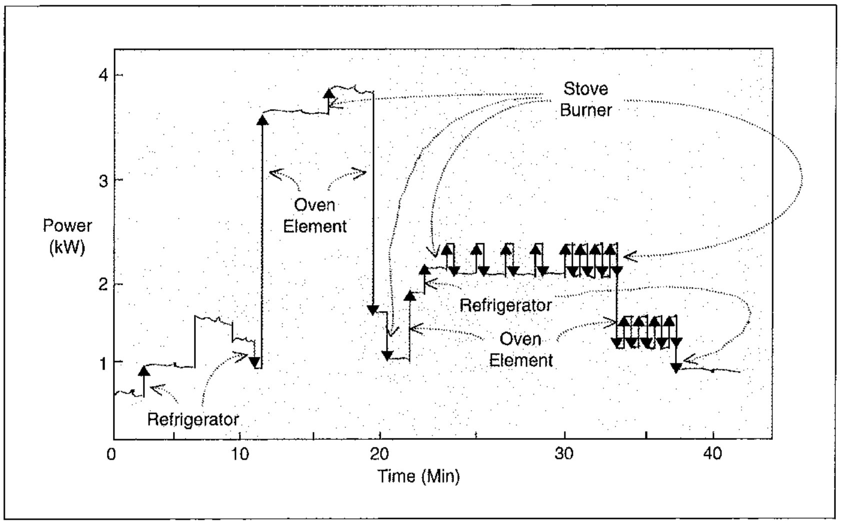

Figure 1. Appliance signatures on total load waveform

power signify an appliance turning off. A *matched* cluster pair consists of a positive cluster and a negative one that have the same magnitude change (in the complex power signature space). Figure 3 illustrates the matching of clusters shown in Figure 2.

Anomaly Resolution deals with *left-over* clusters or spurious points in the complex power plane that do not match up. For example, if two appliances change states simultaneously, the result is a change in power that will not match an identified load cluster. The program collects these unmatched changes and tries, by taking the sum or difference of each, as well as the time based attributes of the premise loads, to determine if there is a possible match with unpaired edges.

consumption for a single family home during a 40-minute period. During this interval, the waveform of the total load shows a series of edge transitions (signature events) caused by different appliances. Four different-sized step changes are clearly present, providing signatures of a refrigerator, two oven elements, and a stovetop element. By assessing measurements of the total reactive power along with the real power shown, changes in the resulting vectors over time reveal even more information about the particular appliances. Once the exact on and off times are determined from the signature events, energy consumption can be calculated.

The algorithm used to analyze the load data is complex, but can be summarized by presenting the functionality of each of its five main phases: edge detection, cluster analysis, cluster matching, anomaly resolution, and appliance identification.

Edge Detection compares load changes to a user set threshold. If a change in the load exceeds the threshold for longer than a set time, the system records this edge as an event.

Cluster Analysis sorts the on/off events (identified during edge detection) by the magnitude of real and reactive power changes associated with them. The observed changes define a scatter plot in the complex power signature space. These are grouped into clusters, i.e., sets of events that are all approximately the same in all change components, as shown in Figure 2. Ideally, each cluster represents one change of state (e.g., from off to on or from on to off) in one appliance.

Cluster Matching tries to pair up the clusters created during cluster analysis. *Positive* clusters consisting of step increases in real and reactive power signify an appliance turning on, while *negative* clusters consisting of step decreases in real and reactive

Appliance Identification associates matched clusters with specific appliances. This process exploits the fact that most specific appliances are remarkably similar, both in their power requirements and their usage patterns. The program uses these similarities, encoded in load libraries, to attach the clusters to their associated appliances.

System Architecture

The algorithm is implemented by a combination of hardware and software (illustrated in Figure 4). The hardware handles edge detection and data communications, and the software uses pattern-recognition algorithms to determine specific appliance usage.

The recorder is the hardware component that resides in the customer's premise. Originally, it was encased in an under-meter collar extender that mounts in the meter socket between the panel and the meter. While this configuration is still used for residential applications, a new version for application in commercial buildings with

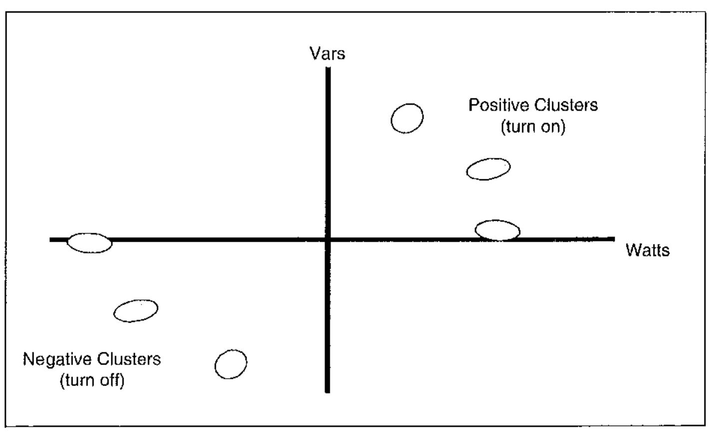

Figure 2. Appliance signature events clustering

three-phase service has been integrated into a solid-state GE kV meter. The recorder periodically measures the current and voltage of the two service legs, then computes rms voltage and current, as well as watts and vars. The recorded data consists of interval data for the whole premise, as well as event data consisting of the time and magnitude of load changes. The recorder downloads the data to a master station computer on either a user-defined schedule, on demand by the master station, or when its memory is full (the unit stores, on average, edge data for 30 days). It communicates with the master station via telephone lines, but it is readily adaptable to other communication media (cellular phones, packet radios, and cable TV systems). Its recording and reporting configurations, as well as all of its internal operating software, may be modified remotely.

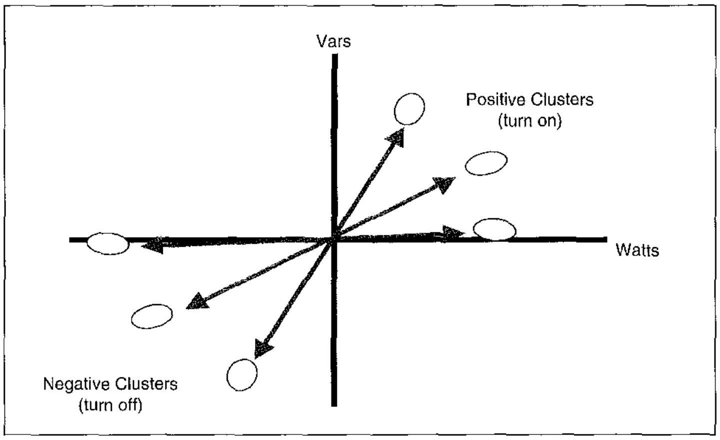

Figure 3. Appliance event cluster matching

The master station manages the recorders, and processes the edge data collected at the unit. Recorder management includes information about each recorder's configuration and location, as well as demographic information pertaining to the premises where each recorder is located. The master station normalizes and processes the collected time-based load data with the algorithm to generate appliance specific load data. Detailed load profiles are computed in the master station.

The database includes a library of load models that are used for appliance identification. The user selects the appliances in the premise from the library, and, as the algorithm processes the edge data, appliances with characteristics matching those in the library are automatically identified. The database also contains the detailed load profiles computed in the master station. Thus, it can serve as a platform for various appliance load applications. One such application is the last component of the system, namely the analysis station.

The analysis station retrieves user specified load data to create reports and graphs. Load profiles in 1-, 5-, 10-, or 15-minute increments are computed, as well as daily, weekly, and monthly appliance energy usage. Data can be presented in a variety of tables and charts, or presented to the utility customer over the Internet. The data can also be exported in ASCII, Microsoft Excel, and MV-90 formats.

Residential Beta Test

Before commercializing the residential product, EPRI sponsored a utility beta test program that was completed in 1996. Each participating utility selected several homes on which were installed both NIALMS and conventional multichannel metering equipment. The latter provided parallel load data that served as a basis for performance evaluation of the NIALMS unit. Each utility chose the type of parallel metering equipment to be used and which appliances, at each participating

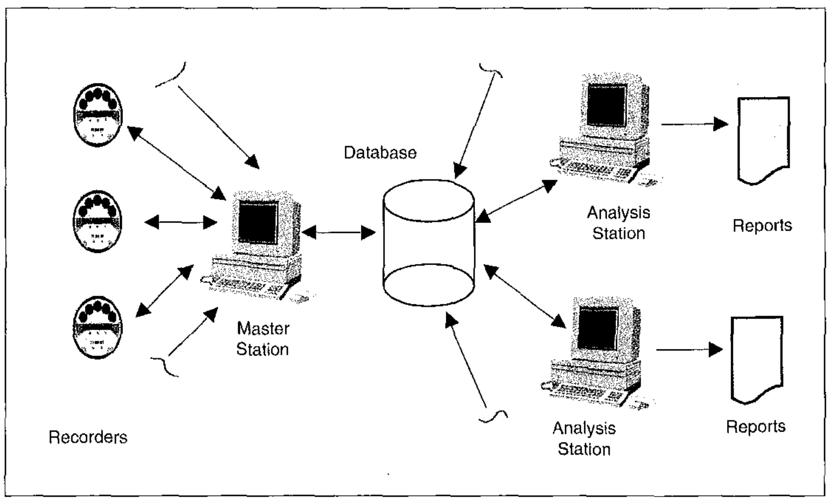

Figure 4. Nonintrusive appliance load monitoring system

[illegible]

Appliance	Number
Refrigerator/freezer	15
Central air conditioner	6
Water heater	6
Pump (well or sewage)	6
Furnace blower	2
Water bed heater	3
Total	38

site, would be included in the parallel metering, which operated in tandem with NIALMS for the duration of the test. (Although the program only took two-state (on/off) appliances into consideration, multistate appliances such as heat pumps and dishwashers were included in the test. In this article, we focus on the two-state appliances.) Table 1 lists the type and number of appliances included in the test.

Table 2. NIALMS residential beta test results

Appliance	NIALMS Identification Success Rate (%)	Average Performance Ratio	Average Difference From Parallel Data (%)
Clothes dryer	88	0.96	10.4
Refrigerator/ freezer	100	0.96	13.9
Central air conditioner	100	0.88	13.2
Water heater	100	0.96	3.5
Pump (well or sewage)	83	0.99	3.3
Furnace blower	0	—	—
Water bed heater	100	0.96	3.7

Evaluation of the hardware was based on utility reports that covered installation or operational difficulties experienced in the field. It was also evaluated on its ability to store and transmit recorded data to the master station. The hardware was found to be extremely easy to install and proved to be highly reliable in operation. Data collection problems were solely due to failures or interruptions in telephone lines and service.

The software was evaluated on its ability to accurately identify appliances and to determine the load and energy use characteristics of each identified appliance.

All parallel data received was subjected to multiple validation tests. In cases where the parallel data was highly suspect or missing, both the questionable parallel data and the corresponding interval NIALMS data were discarded from the analyses. Thus, some months include data for only a portion of the month. Once all monthly energy totals were finalized, a performance ratio was computed for each appliance at each site. This was defined as the ratio of NIALMS derived monthly energy to parallel metered monthly energy. A weighted average performance ratio was also computed for each appliance at each site covering the entire beta test period.

The hardware handles edge detection and data communications, and software uses pattern-recognition algorithms to determine specific appliance usage

The software evaluation is summarized in Table 2. With one exception, the identification success rate was 100 percent for two-state appliance types. (The exception, a furnace blower, was unexpected. The two blowers in the sample could have been of the variable speed type, but no specific information was available to test this hypothesis. It is also possible that the slow startup characteristics preclude creation of a NIALMS-usable "on" edge.) On average, NIALMS calculated appliance energy to within 4 percent of that derived from parallel data metering for three appliances. The range was wider for air conditioners, but was still within 13 percent of the parallel data.

The encouraging results of the beta test led to offering the tested products for commercial sale. The residential system has been available as a commercial product since mid-1996. Over that time, continued refinement of the software algorithms has resulted in further improvements in the accuracy and ease-of-use of the products. Today, accuracy has improved substantially over the figures reported in Table 2, and the technology is being extended to multistate loads and three-phase commercial applications.

Applications and Innovative Services

The program was originally developed to simplify the collection of energy consumption data by utilities, for the purpose of residential load research and DSM program verification. However, the architecture of is flexible enough to allow a variety of applications and to allow the product to be extended to energy analysis of commercial buildings.

In the first full year of deregulation in California, 90 percent of the switched load has been commercial and industrial load. To better serve these critical large energy-consuming customers, energy service providers and energy service companies are looking for innovative new services. A version of NIALMS for commercial markets could create the platform for a variety of services, such as:

- **Bill Disaggregation**: Individual load information can be based on direct measurements rather than estimates.
- **Time-of-Use, Real-Time Pricing and other Incentive Rates**: More creative price structures may

apply to individual loads within a building rather than to an entire building.

- **High Bill Resolution**: The origin of customer high bill complaints can be pinpointed.
- **Load Diagnostics**: Energy service companies can help customers make sure equipment is operating at peak performance. For example, is a bank of chillers cycling in the proper sequence?

By sophisticated analysis of the total load waveforms, NIALMS estimates the number and nature of individual loads, their individual energy consumption, and other relevant properties

Commercial Beta Test

The successful development, testing, and commercialization of the residential product, combined with utility deregulation in many states, led to the development of a product version for commercial buildings. If utilities could have this technology work in commercial buildings such as restaurants, motels, hotels, convenience stores, and office buildings, they could offer itemized bills, differential tariffs diagnostic services, and utility-specific value-added services. Towards this end, EPRI launched a beta test program of a prototype commercial instrument in late 1998. The objective is to complete development and bring to market a commercial nonintrusive load monitoring system (C-NILMS). Three utilities are participating in the beta test, and C-NILMS is operating at four commercial sites.

The goals of the C-NILMS beta test are to:

- Validate two versions of recorder hardware
- Enhance algorithms and software
- Develop commercial appliance-load libraries.

The evaluation of the commercial product's performance is proceeding along the same lines as the residential beta test. Parallel metering is providing intrusive measurements at the same time as the nonintrusive measurements, so that meaningful data analysis can be made. Data from the C-NILMS unit and parallel metering system are being collected and sent via phone line to the master station at each participating utility. Analyses are being performed there and at the analysis station in a central facility responsible for collecting data from all sites. At the end of the data collection period (late summer 1999) the data will be verified, compared to the parallel data, and a final report on the results will be provided. The C-NILMS hardware is contained within a GE kV meter as depicted in Figure 5.

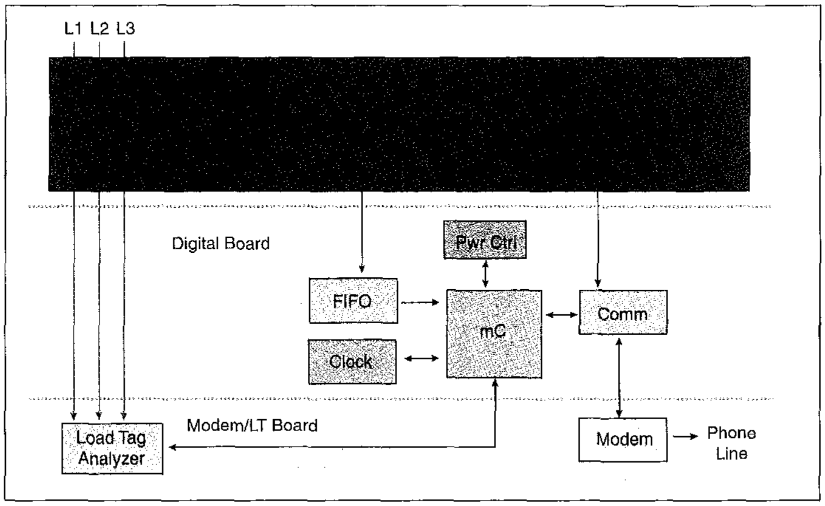

Figure 5. Hardware components within the meter

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Biographies

Steve Drenker manages the Information Systems & Telecommunications area at EPRI in Palo Alto, California. He is responsible for the development of Internet-based systems that deliver new value-added services to the customers of energy companies. He has a BSME, MBA, and a telecommunications engineering program certificate.

Ab Kader recently joined ABB Systems Control. At the time of this writing, he was a manager in the Information Systems & Telecommunications (IS&T) business area of EPRI, where he was responsible for the evaluation and deployment of best of breed information technology solutions that serve the strategic business interests of electric utilities in a quickly changing market. He has a BSEE, BS in mathematics, MS in engineering-economic systems, and PhD in engineering-economic systems and computer science.