Advanced Electrical Load Monitoring: A Wealth of Information at Low Cost

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Introduction

This paper describes a low-cost approach to obtain and analyze electrical power data that are very useful for performance monitoring and fault detection.

Goals:

- Reduce the energy consumption and associated environmental degradation of commercial buildings in California, the U.S. and throughout the world;
- Reduce energy costs.

How to meet these goals?

- Deployment of appropriate methods for monitoring building performance and automatically detecting and diagnosing faults in energy-consuming equipment or in building components that directly affect energy usage.

Measurements are valuable but often expensive:

- Can't control what cannot be measured;
- Component-specific data brings into sharp focus variations in whole-building energy consumption patterns that may hint at operating problems and energy waste;
- Building owner and operators are naturally reluctant to invest in more sensors.

One way to move forward is to make as much use as possible from electricity-consumption data:

- Electricity-consumption data can be directly related to operating costs through electricity rates or bilateral purchase contracts;
- Detailed measurements can help detect and diagnose excessive whole-building energy usage and component-level faults.

How to keep costs down?

Researchers at MIT over the last 15 years have taken significant strides toward developing a very powerful electricity monitoring approach that can pull component-level information out of whole-building electrical service, the electricity supplied to a major building subsystem (HVAC), or other electrical systems (transportation, industry). The product based on this approach is known as a Non-Intrusive Load Monitor or, more simply, NILM. More information about the NILM is found in [1-4].

We consider several field applications to illustrate the utility of the NILM.

1. HVAC Monitoring

Measurement of electrical power at the distribution panel for a large HVAC plant serving three connected buildings:

- One-megawatt plant consists of multiple chillers, ventilation fans and pumps;
- Data averaged over one-second intervals;
- A 20 kW chilled-water pump was cycled on and off four times during the test period.

Looking at electricity data:

- The pump on-off transitions appear as very small variations in the total power (Figure 1). The pump transitions are partially masked by large noise spikes, which are caused by power electronics used in variable-speed drives (Figure 2);
- A median filter rejects the spikes but retain the step transitions [5];
- A signal-processing technique known as the generalized-likelihood ratio (GLR) was used to detect the on-off events [6-10]. This method searches over a sliding window for the maximum value of the ratio of probability distributions of data points about pre- and post-event mean values. If there is no step change, the ratio is small; if a motor or lamp bank or other equipment switches on, the ratio is large as the window slides through the event.
- Four pairs of GLR spikes mark the four on-off events (Figure 3). Note in this case that we were able to tune to detection method to eliminate all false alarms. We are currently working to automate the tuning process in response to measured characteristics of the electrical signal.

The GLR output provides confirmation that equipment has turned on or off when scheduled by the Building Energy Management System (BEMS). The absence of such confirmation indicates a fault. While such confirmation can be provided by current transducers attached to each piece of equipment, the GLR method is able to discern the switching events from a single point, reducing sensor costs. Further, the GLR works with power rather than current. Differences in power before or after an on-off transition provides information about equipment performance, normal or faulty. We will say more in the next example about an ongoing demonstration that uses centralized power measurements for fault detection.

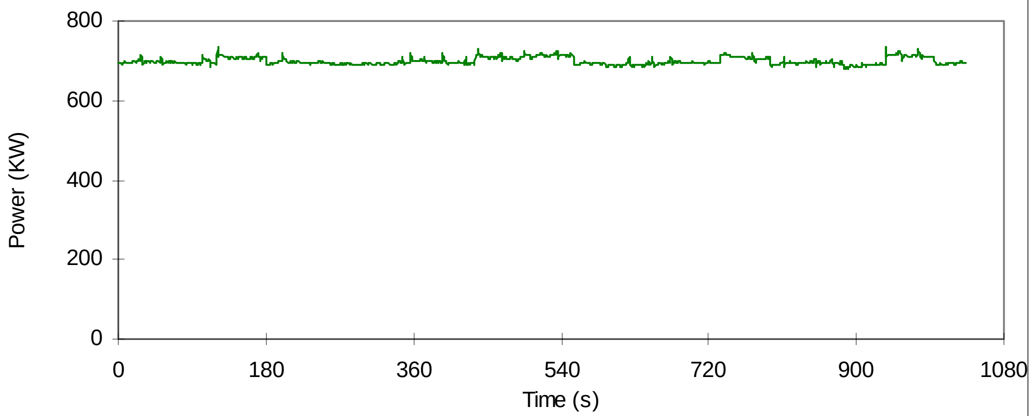

Figure 1 1-Hz power data with 4 on/off events of a pump in MIT building E17

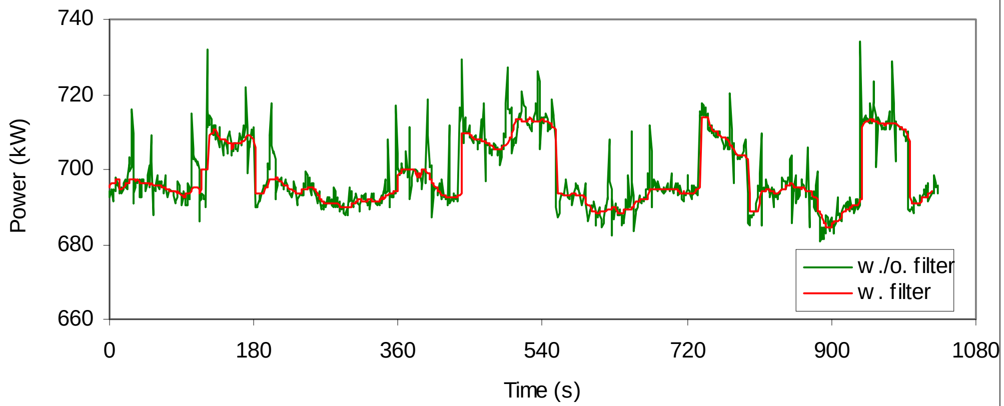

Figure 2 1-Hz power data with 4 on/off events of a pump in MIT building E17
-- with & without the median filter

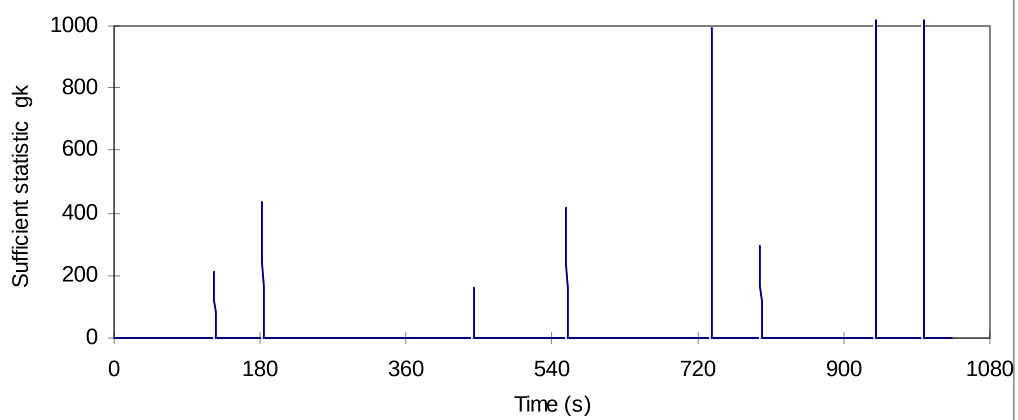

Figure 3. Output of the GLR detector with a median filter for E17

2. Fault Detection

Detection and diagnosis of HVAC faults:

- The test site is a research building run by the Iowa Energy Center and known as the Energy Resource Station. It consists of two sets of test rooms, each with a separate variable-air-volume (VAV) ventilation system, and a set of rooms occupied by research staff, served by a third VAV system.
- MIT and Loughborough University, UK, are currently demonstrating FDD methods, under ASHRAE sponsorship. A detailed description of this work will be publicly available when MIT and Loughborough have completed their work and ASHRAE has approved a final report.
- We are comparing results from analysis of two different data streams, one from traditional (and more expensive) submetered power measurements and the other from MIT's latest NILM hardware platform. The hardware platform consists of a Pentium-based personal computer with an installed digital signal processor (DSP) board.
- The DSP board analyzes real and reactive power, at the fundamental and higher harmonics.
- The PC can deliver information remotely, over the web (http://nilm.mit.edu).
- The host and the DSP board together cost about $500.

Analysis of data measured at the electrical service entry for the entire building:

- Fifteen-minute average data, similar to the output of a conventional data logger, show little component-specific detail (Figure 4);
- Higher-speed data (10-second sampling period) shows more information and more noise (Figure 5);
- Data filtered with a median filter show regular, block-like oscillations that are due to the cycling of the reciprocating chiller that serves one of the air-handling units (Figure 6).

Detection or air-handler faults:

- Change in the cycling period, under known conditions, indicates a leaky recirculation damper or a leaky cooling-coil valve;
- Fan and pump power measurements are made with a second NILM attached to the motor-control center that powers all the fans and pumps in the building;
- Changes in supply fan power at shutdown reveal faults due to pressure sensor offsets and stuck recirculation dampers.
- Changes in pump power, if detectable with sufficient accuracy, can be used to detect blockages in cooling coils.
- Power oscillations indicate poorly tuned local-loop controllers.

Figure 4. 15-minute averaged total power data from the NILM of the Iowa building -- without the median filter
99/02/28/ 23:42:00 ~ 99/03/01 23:41:59

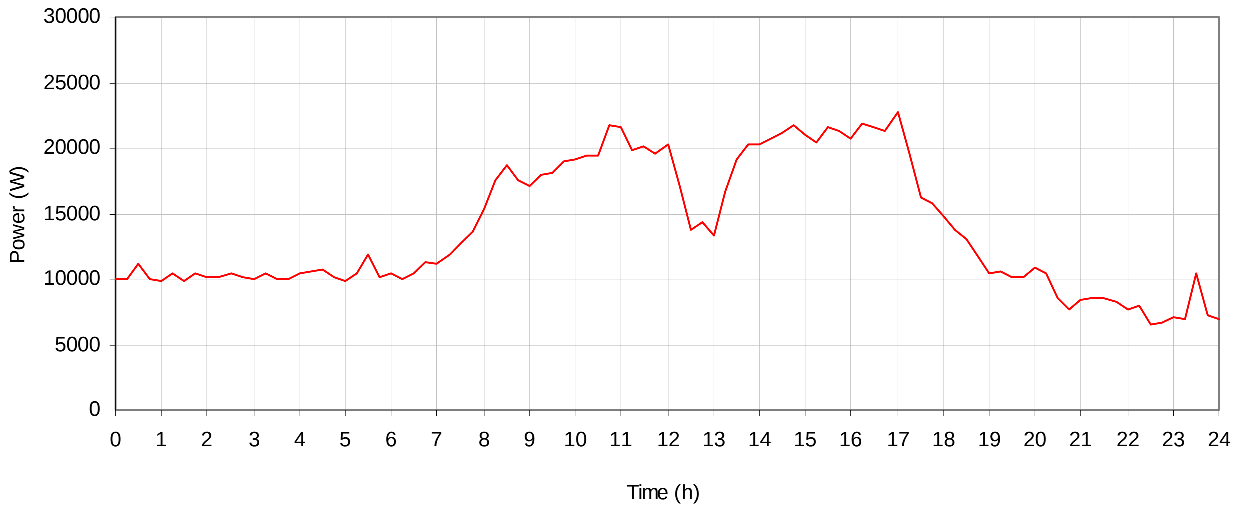

Figure 5. 0.1-Hz total power data from the NILM of the Iowa building -- without the median filter
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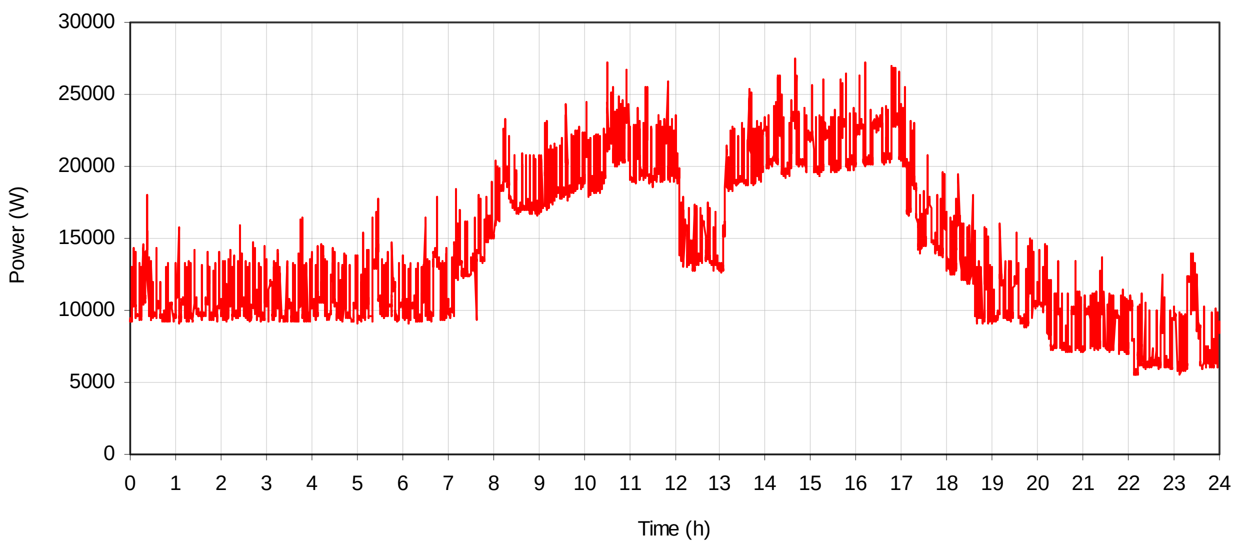

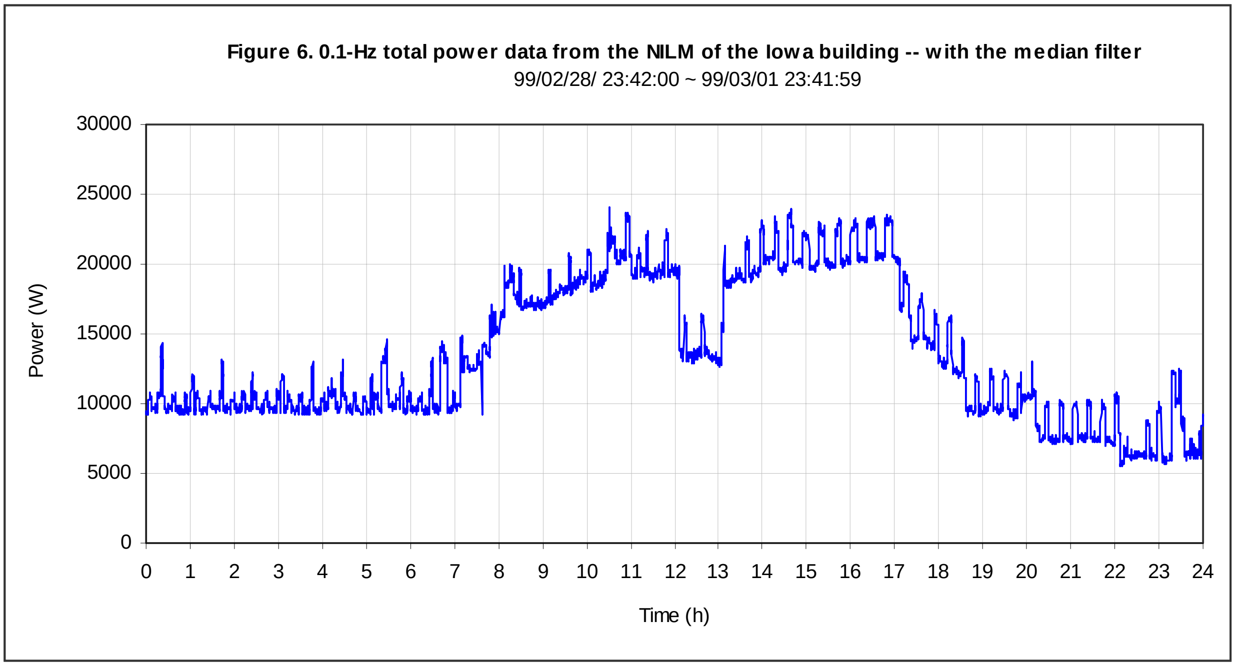

3. Parameter Identification

Our third and last example focuses on wringing the most information out of the high-frequency data collected and analyzed within the DSP board:

- Focus on the start-up period of electrically powered equipment. This start-up period can vary in duration from about 0.1 second for instant-start fluorescent lamps to several minutes for variable-speed motor drives. In all cases, the transient behavior of a typical electrical load is strongly influenced by the physical task that the load performs.
- Measurement of real power demanded by a variable-speed fan drive in an HVAC system (Figure 7). The drive begins with an "open loop" spin-up to operating speed during the first 40 seconds of operation. From 100 seconds on, the drive is operating under closed loop control as it attempts to regulate the pressure in a distant duct by varying fan speed.
- Distinctive transient profiles like those shown in Figure 7 tend to appear even in loads which employ steady-state active waveshaping or power-factor correction, which tends to make reactive loads appear as purely resistive loads in steady state.

Value of start-up transient analysis:

- Identify types of equipment when a BEMS control signal is not available. If we know, from the BEMS, that a pump has been turned on, we can look in steady state with the GLR and check for changes in power. If, on the other hand, a building lacks a BEMS or we want to analyze equipment that is manually controlled, we would like to be able to identify equipment characteristics from the start-up data.
- Even with a fully automated building for which there is little or no need to identify equipment type from the start-up transient, we would like to be able to deal with devices turning on at nearly the same moment, where steady-state analysis would combine them, and to assess changes in the start-up pattern as indicators of equipment faults.

Figure 7 illustrates not only a characteristic start-up pattern for a VSD but a fault as well. The steady-state oscillations in nominal operation (after 100 seconds) result from a poorly-tuned control loop. These oscillations are relatively slow and easily missed by a casual inspection of the VSD control panel, but are easily detected by the NILM with transient event detection. In a NILM installed in an automobile and also in the Iowa test site, we have been able to use the start-up transient for a fixed-speed motor as a reliable indicator of a change in flow resistance in a duct or pipe, which could be caused by a number of types of blockages.

Development of a high-performance transient event detection algorithm for the NILM [3, 4]:

- Detection algorithm extends the applicability of the NILM to demanding residential, commercial, and industrial sites, where substantial efforts are made to homogenize or mask the steady-state behavior of different loads, and where loads may turn on and off very frequently at a range of different power levels.
- A NILM operating with a transient event detector can serve as a platform for power quality monitoring as well.
- Output from a prototype, real-time, load monitor (Figure 8). Four loads, including two induction motors and two different types of fluorescent lamp banks, are activated at nearly the same time. The prototype event detector is able to identify the turn-on transients of all four loads strictly by examining the aggregate traces of real power, reactive power, and harmonic content at the service entry.
- Web-based remote interaction with a NILM platform installed on the MIT campus in a dormitory laundry room (Figure 9). The four graphs show traces of real and reactive power, as well as harmonic content, during the turn on of an induction motor spinning a drum in a clothes dryer.

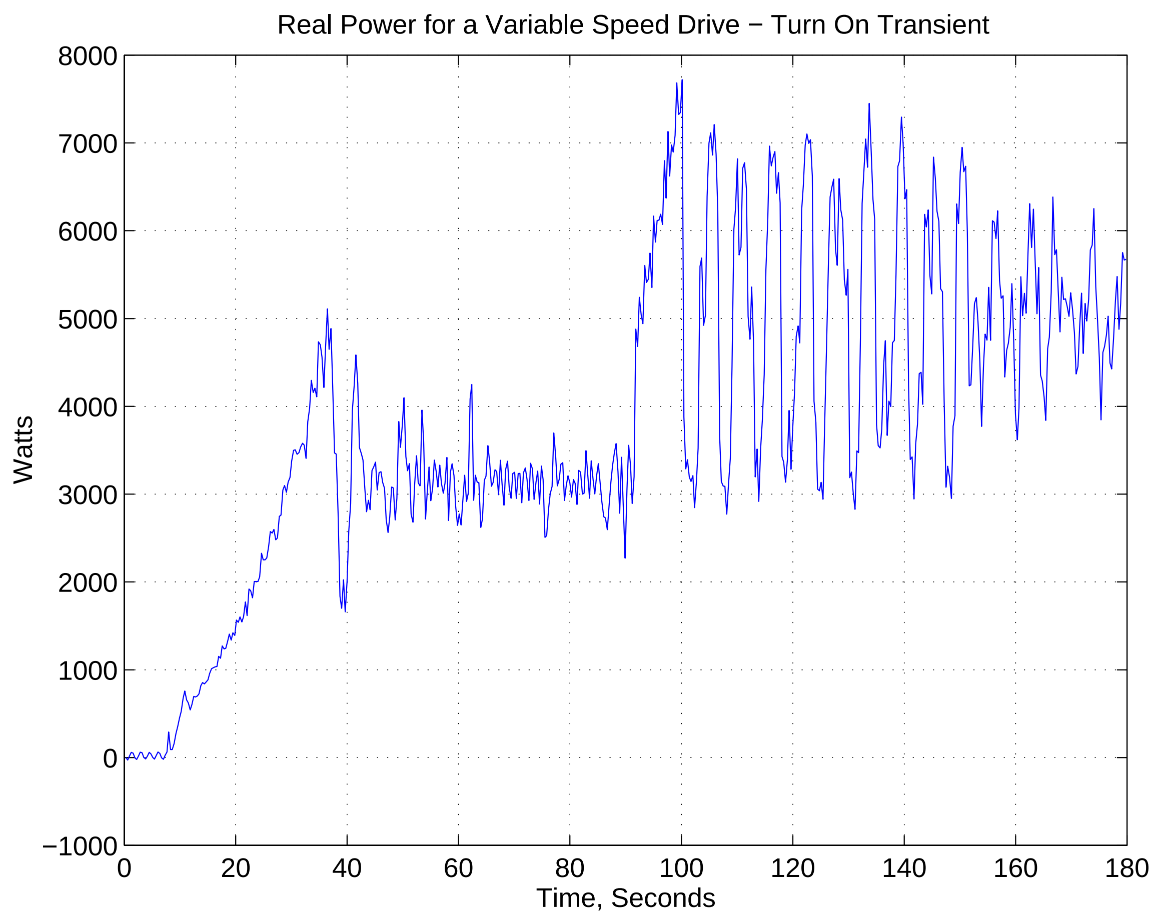

Figure 7. Start-up electrical power transient for a fan motor equipped with a variable-speed drive.

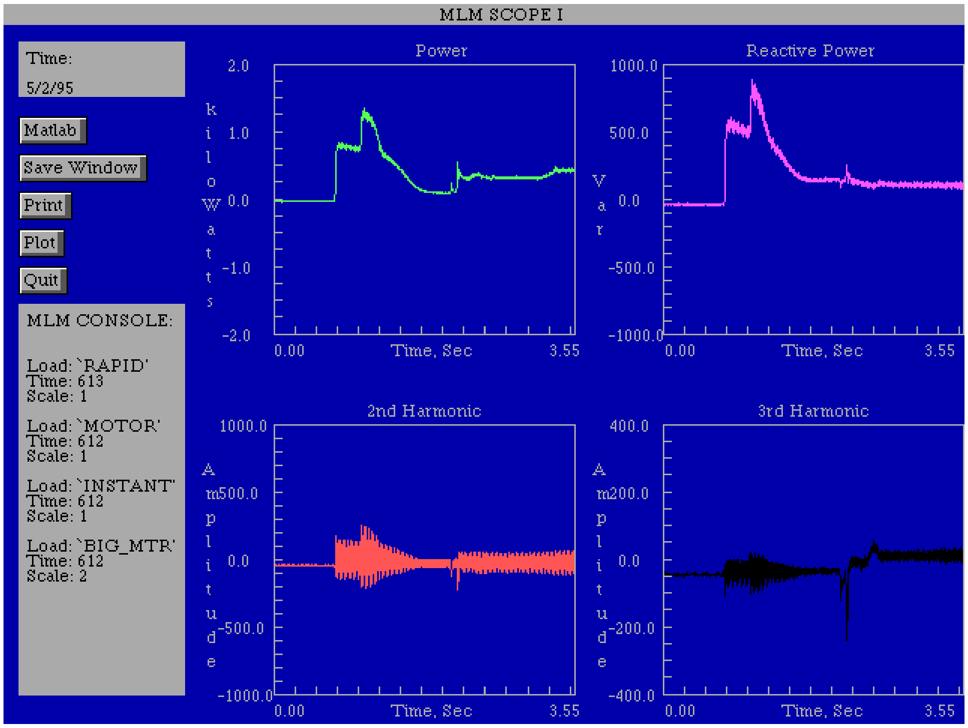

Figure 8. Output of the transient-event detector, incorporated into a prototype NILM.

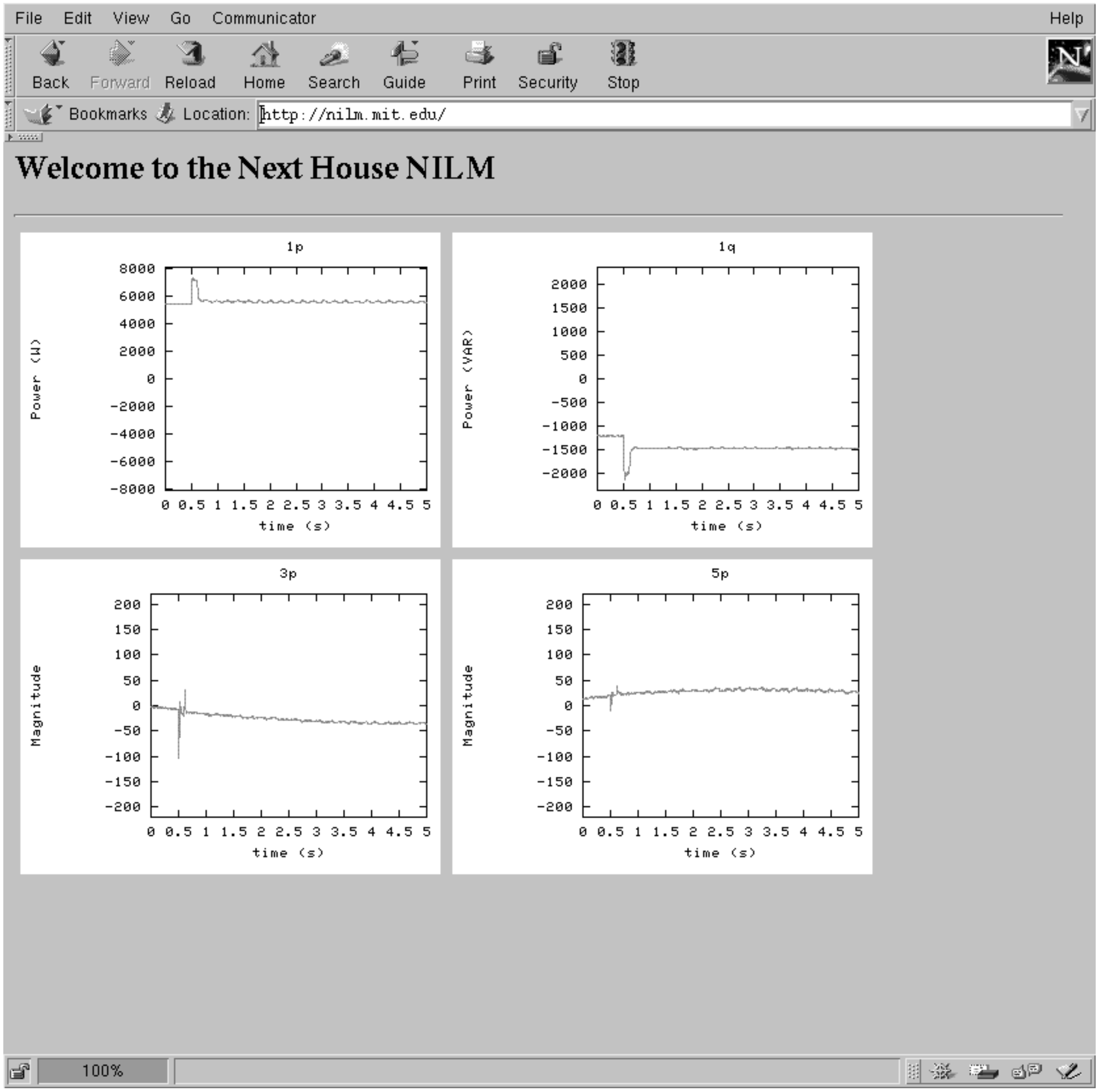

Figure 9. Internet-accessible NILM data from a meter installed in an MIT laundry room.

Conclusion

To conclude, the MIT NILM is, today, a low-cost platform capable of wringing valuable information from electrical measurements about equipment performance and building energy use. Continued research and development, combined with deployment of the NILM in field-test sites, will enhance application-specific capabilities (packaged HVAC units for example), strengthen its ability to detect faults from start-up transients, and improve its interaction with other FDD and performance-monitoring methods.

References

1. Norford, L. K. and S. B. Leeb. 1996. "Nonintrusive Electrical Load Monitoring." *Energy and Buildings*, Vol. 24, pp. 51-64.

2. Abler, C., R. Lepard, S. Shaw, D. Luo, S. Leeb, and L. Norford. 1998. "Instrumentation for High-Performance Nonintrusive Electrical Load Monitoring." ASME *J. Solar Energy Engineering*.

3. Leeb, S. B. 1993. "A Conjoint Pattern Recognition Approach to Nonintrusive Load Monitoring," Ph.D. Dissertation, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA.

4. Leeb, S. B., S. R. Shaw, and J. L. Kirtley, Jr. 1995. "Transient Event Detection in Spectral Envelope Estimates for Noninstrusive Load Monitoring." *IEEE Transactions on Power Delivery* Vol. 10 No. 3, pp. 1200-1210.

5. Leeb, S. B., A. Ortiz, R. F. Lepard, S. R. Shaw and J. L. Kirtley, Jr. 1997. "Applications of Real-Time Median Filtering with Fast Digital and Analog Sorters." *IEEE Transactions on Mechatronics*, Vol. 2 No. 2, pp. 136-143.

6. Hill, R. O. 1995. "Applied Change of Mean Detection Techniques for HVAC Fault Detection and Diagnosis and Power Monitoring." Master of Science in Building Technology thesis, Massachusetts Institute of Technology, Cambridge, MA.

7. Benveniste, A., (1986) "Advanced Methods of Change Detection: An Overview," *Detection of Abrupt Changes in Signals and Dynamical Systems*, M. Basseville and A. Benveniste, ed., Berlin, Springer-Verlag.

8. Basseville, M. and I. Nikiforov, (1993). *Detection of Abrupt Changes Theory and Application*. Thomas Kailath, Prentice Hall Information and System Sciences Series, Englewood Cliffs, NJ, P T R Prentice Hall.

9. Willsky, Alan, (1986) "Detection of Abrupt Changes in Dynamic Systems," *Detection of Abrupt Changes in Signals and Dynamical Systems*, M. Basseville and A. Benveniste, ed., Berlin, Springer-Verlag.

10. Basseville, M., (1986) "On-Line Detection of Jumps in Mean," *Detection of Abrupt Changes in Signals and Dynamical Systems*, M. Basseville and A. Benveniste, ed., Berlin, Springer-Verlag.