Development and Validation of a Transient Event Detector

Steven B. Leeb
James L. Kirtley, Jr.
Massachusetts Institute of Technology

Michael S. LeVan
Joseph P. Sweeney
AMP Incorporated

ABSTRACT

The nonintrusive load monitor (NILM) determines the operating schedule of the major electrical loads in a building from measurements made at the utility service entry. This paper describes techniques used to develop, test, and implement a transient event detector that extends the applicability of NILM to challenging commercial and industrial sites. Software has been developed that can flexibly and quickly simulate the electrical harness and loads in a building. Data from this simulator were used to design a transient event detection algorithm. This algorithm has been implemented on a real-time digital signal processing system that can be used to monitor actual loads in operation. The performance of the algorithm is illustrated with results from the prototype transient event detector.

BACKGROUND

Electric utilities and commercial facilities managers want to develop detailed electric power consumption profiles of their customers. Conventional metering of individual appliances is costly and inconvenient to the consumer. To deal with these concerns, we are exploring methods for determining the operating history of an electrical load from measurements made solely at the utility service entry of a building. The residential nonintrusive load monitoring project of MIT's Laboratory for Electromagnetic and Electronic Systems has demonstrated the feasibility of a low-cost microprocessor-based recorder that competes favorably with conventional load monitoring schemes.[1-4]

The current implementation of the residential NILM tracks the operating schedules of the loads at a target site by looking for changes in steady-state levels of real and reactive power. While informative in the residential setting, changes in steady-state power levels are less revealing in commercial or industrial environments, where substantial efforts (e.g., power factor correction and load balancing) are made to homogenize the steady-state behavior of different loads.

Preliminary experiments conducted at AMP Incorporated manufacturing facilities and at MIT have led to the conclusion that the behavior of many important load classes is sufficiently distinct to serve as a reliable indicator of load type. This paper reviews the performance of a transient event detection algorithm[5] that can be used to identify observed transient waveforms even when multiple transients overlap. This *NZLMscope* algorithm is suitable for incorporation into an advanced NILM, which would be capable of monitoring demanding commercial and industrial sites.

The test procedures used to design and evaluate the performance of the *NZLMscope* algorithm have proven particularly effective. These procedures and testing tools serve as a useful guide for the development of any monitoring system for electrical distribution systems. The algorithm was developed and tested in two steps, first in software on a personal computer, and second with a hardware prototype of a transient event detector based on the *NZLMscope* algorithm. The software tests and their role in the development of the algorithm are described below, followed by a review of the event recognition algorithm itself, and finally by a section illustrating the performance of the algorithm with results from the hardware prototype.

RAPID TESTING

Initial development of the *NZLMscope* algorithm was conducted off-line. This software testing challenged the algorithm with transient data generated by the Radial Panel Installation Designer (RAPID), a computer program for simulating the electrical harness and loads in a building.[6] The RAPID simulator was developed jointly by MIT and the Facilities Services Division of AMP Incorporated to assist with the design, analysis, and simulation of building power distribution networks. While originally developed as a maintenance tool for AMP manufacturing facilities, the RAPID simulator also proved invaluable for testing and tuning the *NILMscope* transient event recognition algorithm. This section describes the RAPID simulator and how data from RAPID was used to develop and test the event detector.

RAPID is a software program that can be run on a PC-AT class computer with an EGA monitor and a mouse. The program enables a user to quickly and easily create, move, or alter the data stored in the program's database, which constitutes a description of a building's electrical harness. Like a spreadsheet, the program can be used to conduct "what if" studies of a network. The program remembers the relationships between the various network elements (e.g., the location and type of transformers, upstream breakers, service entry capacity, etc.) and will automatically compute relevant network parameters. RAPID is capable of checking a network description and also of recommending network components for compliance with the National Electrical Code or with local codes that a user has specified. The program is also able to answer questions about the dynamic operation of parts of a network by simulating mathematical descriptions of individual loads in the network.

The program models the electrical distribution system in a building as a radially distributed network of *panels.* A *panel* may represent an actual circuit breaker panel in a building, or a busbar, or a transformer. The *root-panel* in a building model typically represents an actual circuit breaker panel fed by the main three-phase utility service entry into the building. Each *switch* on a panel represents a circuit breaker or bus connector, which initiates a connection to a load or a subpanel, busbar, or transformer.

The user specifies the details of each switch or breaker on every panel, including the load connected to the breaker, one switch at a time. Figure 1 shows a computer screen image showing the main panel for a building named "TEST." Several of the switches on this panel have already been specified.

The window labeled *Switch* in Figure 1 lists the loads connected to the panel under examination as specified by the user. The *Circuit* window provides data about the details of individual switches and their associated loads. The user may examine different parts of the network by selecting new panels in the *Network* window. Program functions, such as transient simulation, maybe controlled through the *Menu* window.

For example, Figure 2 shows one of the three-phase currents computed by a RAPID simulation of a panel with two loads, a three-phase induction motor, and a single-phase resistive heater. The induction motor starts at time 0. The resistive heater starts at time 1, after the induction motor has entered steady-state operation. The induction motor draws a large current while accelerating the rotor from zero speed, but then settles to a smaller current level once the rotor has accelerated to nominal operating speed. RAPID is capable of computing detailed, cycle-by-cycle representations of load dynamics. Data from the simulations may be stored in an ASCII file for analysis by other programs. We have used stored transients computed by RAPID to test the ability of the *NILMscope* transient identification algorithm to associate transients with particular loads.

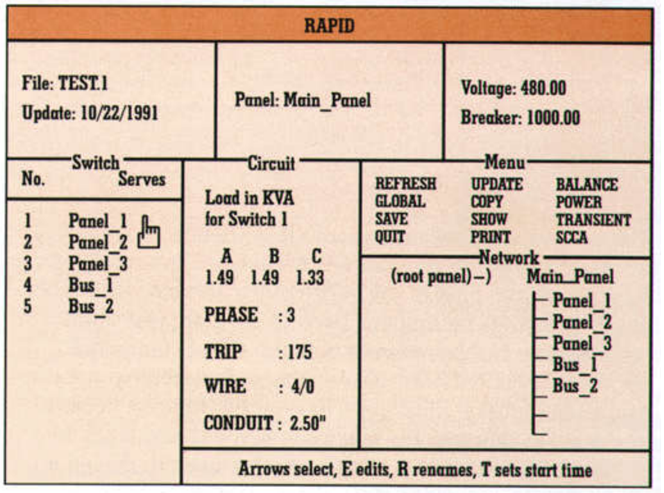

Figure 1. The RAPID main interface window.

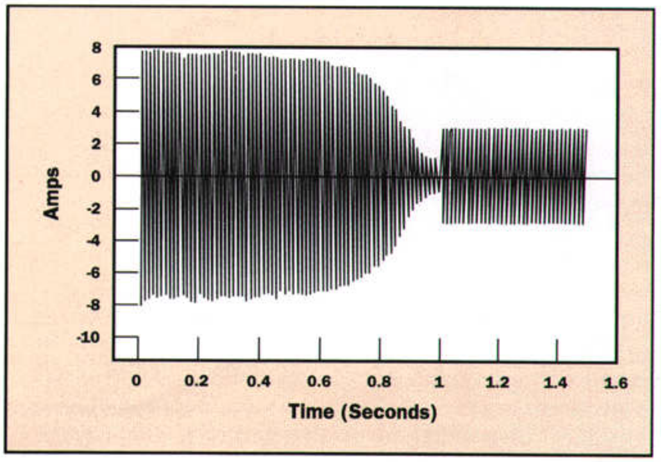

Figure 2. A RAPID simulation.

TRANSIENT RECOGNITION ALGORITHM

Experiments with RAPID and measurements of several commercial and industrial electrical loads, summarized in the load survey conducted in Reference 5, indicate that the transient behavior of a typical load is intimately related to the physical task that the load performs. The turn-on transients or *events* associated with a fluorescent lamp and an induction motor, for example, are distinct because the physical processes of igniting an illuminating arc and accelerating a rotor are fundamentally different. Transient profiles tend not to be eliminated, even in loads that employ active waveshaping or power factor correction. Therefore, it is reasonable to be able to identify many common loads by matching observed transient profiles with known transient shapes or templates. These templates can be collected on-site during a learning or installation phase, or they can be generated by a simulator like RAPID.

Searching for complete transients is an undesirable approach, however, because it limits the tolerable rate of event generation. No two transient events could overlap significantly if each transient were to be identified correctly. Instead, the *NILMscope* transient event detector searches for a time pattern of segments with significant variation, or *v-sections,* rather than searching for a transient shape in its entirety. Figure 3, for example, shows the measured envelope of real power on one phase during the turn-on transient of a three-phase induction motor. The locations of the v-sections are indicated by the rectangles in Figure 3. In practice, a complete transient identification would be made by searching for a precise time pattern of v-sections. The v-sections are relatively narrow, so even if one or more transients overlap, it is likely that the v-sections will not be fatally corrupted.

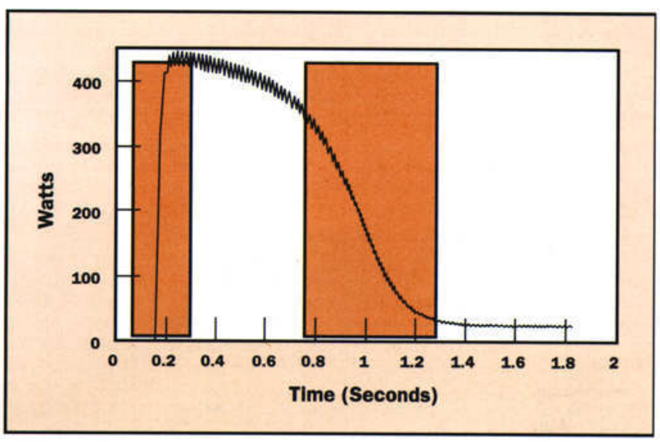

Figure 3. Measured induction motor real power transient.

The prototype event detector employs a transversal or matched filter as a pattern discriminator, although other possibilities could be used and are discussed in Reference 5. The impulse response of a transversal filter is proportional to the time-reversed signal for which the filter is designed to search. In operation, the transversal filter computes the inner product of a vector of sampled input data with a template vector derived from a known transient prototype. The transversal filter is an attractive signal-processing construct for performing pattern discrimination because of its conceptual simplicity and because there are many highly efficient hardware solutions available for implementing a transversal filter. The precise details of the recognition algorithm are contained in Reference 5.

PROTOTYPE TESTING AND PERFORMANCE

In the second phase of testing, the *NILMscope* software was ported to a high-performance digital signal-processing system with sufficient computational power to identify load transient signatures in real-time. This system constitutes the prototype event detector. This detector has been used to monitor and identify the transient signatures of a collection of four actual loads in operation. These loads include an instant-start fluorescent lamp bank, a rapid-start fluorescent lamp bank, and two induction motors differing in horsepower rating.

Figures 4 through 9 show screen prints from the computer running the *NILMscope* software during six of the experiments conducted with the prototype. The top graph window in each figure shows the envelope of real power in watts observed by the prototype on one phase of a three-phase electrical service. The bottom graph shows reactive power on the same phase. Any transient events that the prototype has been able to identify appear under the heading "Contacts" in the lower left-hand corner of the screen. The load type responsible for the transient event is denoted by a shorthand notation: "Motor" for induction. motors, "Rapid" for rapid-start fluorescent lamp banks, and "Instant" for instant-start fluorescent lamp banks. Following the load type responsible for each event listed in the contact window is the time of occurrence of the event. The origins of the graph windows are arbitrarily assigned to be time zero. Finally, each event and time of occurrence is listed under the time scale on which it occurred.

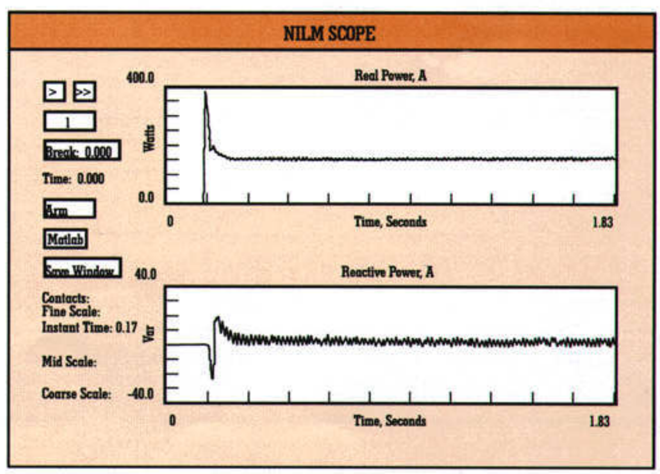

Figure 4. Instant-start fluorescent lamp bank transient as shown on *NILMscope* contact report.

There are three scales listed in the contact window: fine, mid, and coarse. Transients with relatively short duration are listed directly under the heading "Fine Scale" in the contact window. By design, events associated with the small motor and both lamp banks should be listed as fine scale events when they appear. The headings “Mid Scale” and “Coarse Scale” indicate events of progressively longer relative duration. The transient associated with the operation of the larger motor will appear under the “Coarse Scale” heading when the prototype functions correctly.

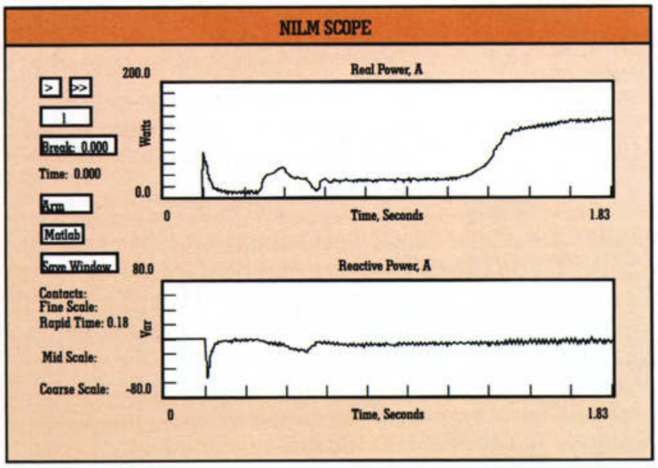

Figure 5. Rapid-start fluorescent lamp bank transient as shown on *NILMscope* contact report.

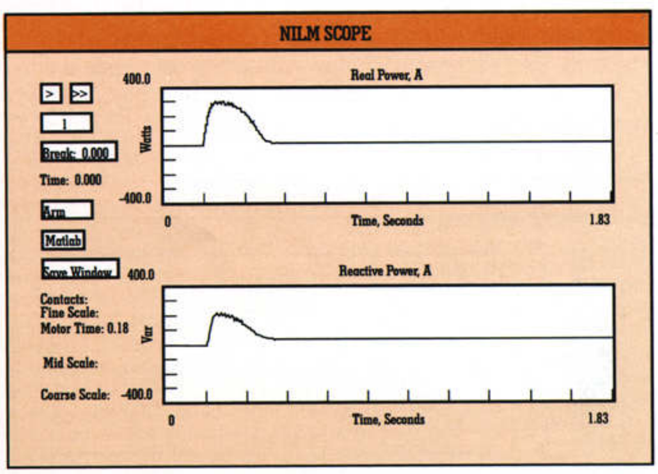

Figure 6. Small induction motor turn-on transient displayed on *NILMscope* contact report.

Figures 4 through 7 record the performance of the prototype when challenged individually with the turn-on events of each of the four loads in the test stand. In Figures 4 through 6, the turn-on transients of the instant-start lamp bank, rapid-start lamp bank, and small induction motor are correctly identified under the fine scale heading, respectively. Figure 7 shows the turn-on event for the large motor, correctly identified on the coarse scale as anticipated.

Figure 8 shows an example where three loads turn on so that three transient events overlap. No key v-sections overlap with each other. First, the rapid-start bank turns on, closely followed by the turn-on transient of the instant-start bank, and then the small induction motor. All three events are correctly recorded at the finest time scale in the contact window.

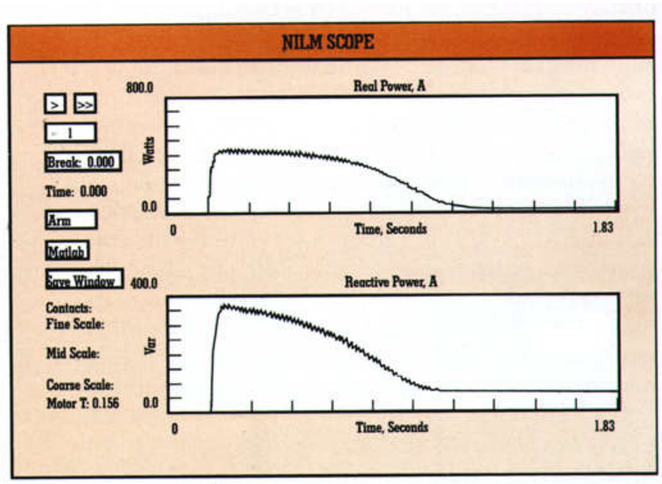

Figure 7. Large induction motor start-up transient displayed on *NILMscope* contact report.

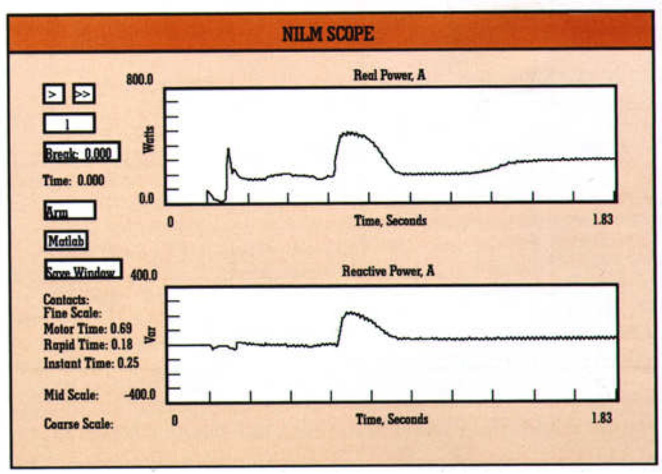

Figure 8. Overlapping transients from the rapid-start and instant-start fluorescent lamp banks and the small induction motor.

In the final experiment with the *NILMscope* reports shown in Figure 9, the small induction motor turns on and completes its transient, followed by the turn-on transient of the large induction motor and the instant-start lamp bank. No key v-sections overlap with each other. All of the events are correctly identified at the appropriate time scales.

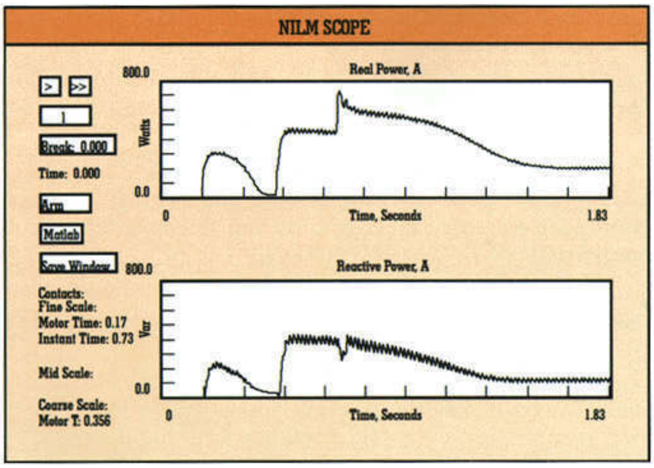

Figure 9. Transients from the small induction motor, the large induction motor and the instant-start fluorescent lamp bank.

CONCLUSIONS

The examples reviewed in the previous section are representative of several hundred experiments conducted with the test stand. Provided the assumptions made in the development of the event detection algorithm are satisfied, the prototype detector performs remarkably well. This performance is perhaps more impressive in light of the fact that fairly little effort was made to "tune" the detector for the loads in the test stand. The RAPID simulator proved invaluable for testing the experimental event detection algorithm, and led to the speedy development and implementation of a successful prototype.

The availability of a transient event detector opens the door to many other related monitoring applications. Currently, for example, a power quality investigation of a load or class of loads at a target site usually involves hooking each suspect load to an expensive, dedicated spectrum analyzer. A NILM with a transient event detector is uniquely capable of reducing the expense of examining power quality at a site. By associating changes in harmonic content at the service entry with the activation of different loads, the NILM is well situated for identifying power quality "offenders" relatively effortlessly and inexpensively.

For facilities managers, the advanced NILM offers a potentially inexpensive source of information for exercising control over the electrical loading in a building. The NILM could make available detailed, almost instantaneous knowledge of the power demand and impact on power quality of individual loads. This information could, for example, be used to reschedule the operating time of different loads or alter the location of different loads to balance a local network or respond quickly to constraints imposed by utility spot pricing schemes. Also, an advanced NILM with a transient event detector may be a remarkably valuable platform for conducting nonintrusive diagnostic evaluation of critical loads in a building. By tracking trends in parameters over time, it maybe possible to make some statements concerning the health of critical loads. The ability to presage the need for maintenance could make the NILM invaluable in many commercial and industrial settings.

ACKNOWLEDGMENTS

This research was funded by the Electric Power Research Institute under EPRI project number RP2568-15. Additional support for the development of RAPID was provided by AMP Incorporated. The authors gratefully acknowledge the valuable advice, support, and encouragement of Laurence Carmichael, Dr. Richard Tabors, and Professors George Verghese, Jacob White, and Les Norford. The authors also acknowledge the assistance of Kurt Levens in constructing the hardware test stand used to test the prototype event detector.

REFERENCES

1. G. W. Hart, "Nonintrusive appliance load monitoring," Proc. IEEE **80** 1870-1891 (1992).

2. G.W. Hart, "Minimum Information Estimation of Structure," dissertation, M.I.T., June 1987.

3. G.W. Hart, "Prototype Nonintrusive Appliance Load Monitor," MIT LEES progress report, EPRI contract RP2568-2, 1985.

4. R. Tabors *et al.*, "Residential Nonintrusive Appliance Load Monitor," EPRI final report, to appear.

5. S.B. Leeb, "A Conjoint Pattern Recognition Approach to Nonintrusive Load Monitoring," Ph.D. dissertation, 1993.

6. S.B. Leeb, J.L. Kirtley, Jr., D.S. Woodruff, and M.S. LeVan, "Building-level power network analysis," IEEE Computer Applic. in Power, **5**, 30-34 (1992).

Steven B. Leeb is the Carl Richard Soderberg Professor of Power Engineering with the Laboratory for Electromagnetic and Electronic Systems at the Massachusetts Institute of Technology.

He received the S. B., S.M. and Ph.D. degrees from the Massachusetts Institute of Technology, Cambridge in 1987, 1989 and 1993, respectively, and joined the faculty in 1993, His research work concerns the design, monitoring and control of servomechanical systems and power electronic drives. He is a member of the IEEE Power Engineering, Power Electronics and Control Systems Societies.

James L. Kirtley, Jr. is Associate Professor of Electrical Engineering at MIT.

Dr. Kirtley received the B.S. and Ph.D. degrees from the Massachusetts Institute of Technology, Cambridge, in 1968 and 1971, respectively, and joined the faculty in 1971. During 1974 and 1975, he worked as a Generator Engineer for General Electric, Large Steam Turbine Generator Department, Schenectady, NY. Dr. Kirtley is a member of the Electric Machinery Committee, the Synchronous Machinery Subcommittee and is Vice-Chairman of the Machinery Theory Subcommittee. He was chairman of the 1990 International Conference on Electric Machines. He is a member of CIGRE, and a member of the editorial board of Electric Machines and Power Systems and a Registered Professional Engineer in Massachusetts.

Michael S. LeVan is the former manager of Design Engineering Services of the Facilities Services Division of AMP Incorporated in Harrisburg, Pennsylvania.

Joseph P. Sweeney retired in 1989 from his position as Vice President, Technology at AMP Incorporated. He continues as a consultant and is a Research Affiliate at the Massachusetts Institute of Technology.

Mr. Sweeney holds B.S. and M.S. degrees from Eastern New Mexico University, and prior to joining AMP he worked in geophysical exploration and aerospace electrical system design. He joined AMP in 1955 as a research engineer and after transferring to operations in 1957 held various development engineering positions, becoming Director of Applied Technology in 1980 and Corporate Vice President of Technology in 1984. Mr. Sweeney has served as an industrial advisor to several universities and to the National Science Foundation. He is a fellow of the Institute of Electrical and Electronic Engineers, and an active member of a number of professional groups. He holds 16 patents and is listed in Who's Who in Engineering.