Non-Intrusive Load Monitoring Systems: Considerations for Use and Potential Applications

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The value of measured energy performance data and the desire to acquire them without the cost, complexity, and intrusiveness of standard submetering techniques have led to recent research on non-intrusive load monitoring systems. These systems offer installation simplicity and the ability to discriminate important load changes through high-resolution, higher-speed sampling at a central monitoring point such as a building's electrical service entrance. Important hardware and installation considerations learned from Oak Ridge National Laboratory's (ORNL) experience with these systems are reviewed. In addition, the ability to discern important load changes in residential and commercial buildings using these systems is discussed based on recent ORNL experiments in two buildings. Potential applications, with examples, are also discussed. Using a non-intrusive load monitoring system, an experienced user can collect valuable building power profiles that provide insight into building operations, energy use, demand, and building systems problems easily and at low cost. These systems, when available, could be valuable to DSM and energy management professionals, utilities, researchers, building management firms, energy service companies, and others.

Introduction

The cost, complexity, and intrusiveness of standard submetering has limited its use to measure the demand and energy use of buildings and building systems. On the other hand, evaluators have come to appreciate the accuracy that submetered data can provide over higher level data. These considerations have led to research on non-intrusive load monitoring systems (NILMS) for measuring total building and end use loads. The primary differences between a modern NILMS and past monitoring systems is (1) the need to interrupt power for monitoring (not required by a NILMS) and (2) the much higher resolution and sampling speeds which allows the NILMS to "see" small individual end-use loads from a higher level monitoring point. Using a NILMS at higher sampling speeds, the startup, steady-state, and shutdown impacts of small individual end use loads can be seen on power profiles measured from a single, centralized monitoring point such as a building service entrance. The systems have numerous applications for residential, commercial, and industrial buildings and building systems, and potential applications for utility distribution and load control networks.

High-speed sampling of power at centralized locations to disaggregate end use loads is relatively new to DSM and energy-efficiency professionals. Researchers at Massachusetts Institute of Technology (MIT) were the early users of this technology to disaggregate residential and commercial end-use loads (Hart 1991, Norford 1992). This work focused on the development of algorithms that could pick out end use loads from real and reactive power changes occurring on power profiles measured at the service entrance for residences and at the central service point for HVAC systems in commercial buildings. The early MIT residential research utilized 1 second sampling intervals and their more recent commercial research has led them to much higher sampling rates.

This paper discusses important considerations for developing and using a NILMS. The capabilities for capturing power profiles and detecting rapid load changes at sampling speeds up to 40 Hz are presented. Results are based on experiments at the service entrance to both a commercial and residential building. Potential applications are illustrated and discussed.

Hardware Considerations

Although a NILMS can be designed using different types of hardware, different designs will function similarly. Line voltages and currents are sensed and a signal proportional to them (in magnitude and phase) is supplied to a watt meter, usually a watt transducer. The transducer output, which is proportional to the measured power, is supplied to an analog-to-digital (A/D) converter board in a data logger or computer to allow processing and final data storage. A multiplier is often applied to digital values to make them directly representative of the power being consumed. Pulse outputs from pulse-initiating kWh meters are normally not used because these meters have integration times slower than that needed.

Hardware selection should be performed carefully because numerous factors need to be considered to insure a system adequate for the measurements being made. Many of these factors are typical concerns when interfacing outputs from systems or sensors to A/D converter boards. Maintaining measurement resolution is one of the more important factors and is achieved by matching equipment outputs and inputs as best possible. Matching components to maintain measurement resolution is a concern all the way from the sensor to the A/D converter board.

The system that runs the A/D converter board and its data storage capabilities should not be overlooked. Data loggers typically contain the A/D board and sometimes have very limited data storage, while computers normally have to have an A/D board installed and have much more data storage capacity. A data logger or the computer and A/D board will constitute the majority of hardware costs for a NILMS. If a computer with an A/D card is utilized, the need for software and its ease of use is very important to system design. The more advanced commercial software packages for PC-based data acquisition can be challenging to select and setup. In addition, the cost of this software can be significant. Data loggers often have an advantage here since they have programmability built in without the need for additional software. Data loggers and computers also have other important features that may decide the design of the system. Two other primary concerns are sampling speeds and portability.

Installation Considerations

A primary concern for the installation of a NILMS will be safety. If data are taken short-term, and the system is attended while installed, long-term safety is not a concern and installation time requirements and expense are very minimal. If the system is to be left unattended overnight or longer, long-term safety is a concern and a more permanent type of installation may have to be done (mounting electrical equipment in temporary boxes, voltage and current lines in conduits, etc.).

A primary intent of this type of monitoring system is to be non-interruptive to building or system power. In some cases, safety practices may require shutdown of power to install the voltage and current sensors. The use of clamp-on current transformers and the installation of voltage taps on the load side of smaller circuit breakers can often be used to keep building or system power interruptions to a minimum. In commercial applications, sensors will almost always have to be mounted in existing panel boxes. For residential short-term measurements, conductors at the service entrance weather-head (the head at the top of service entrance conduit where individual wires from the power pole first enter the conduit) are very convenient for mounting current transformers. This eliminates mounting them in the limited space of service entrance electrical panels.

A careful installer can connect a NILMS to building or system power feeds in less than one hour. Inexperienced installers may require significantly more time due to the ease in connecting a NILMS incorrectly. The NILMS must be hooked up such that secondary voltages and currents (those from the NILMS voltage and current sensors) are in phase with primary voltages and currents (those supplying the building), a situation very confusing to the inexperienced installer. If mixed, the watt meter may output no signal or a signal that appears reasonable but could be significantly less than the true power being consumed. For this reason, it is critical that measurements from the system be correlated with accurate power measurements made using an independent device. Interpreting power from the revolutions of a kWh meter provides an easy way of doing this for total building power.

Event Detection and Identification

Vision Capabilities

The ability of a NILMS to “see” individual end uses is limited by the power measurement range of the NILMS, the resolution of the A/D conversion, the sampling speed the system can achieve, electrical noise, and the magnitude, variability, and quantity of individual loads in a building. Because commercial buildings often have many more pieces of equipment (and sometimes significant electrical noise), discrimination of loads is normally much easier in residential buildings. Figure 1a shows parts of whole-building power profiles recorded using a portable NILMS that include the operation of a residential heat pump in a cooling mode. A single 60 W lamp is turned on at 40 seconds and off at 60 seconds of elapsed time in the profile. Although barely visible on this scale, if the profile is magnified as shown in Figure lb, the on/off switching of the lamp is clearly visible above the signal noise. These measurements were acquired using a data-logger-based system with 14-bit resolution.

The magnitude and shape of profile changes associated with individual equipment plays a major role in the ability to discriminate individual loads. For the residential air conditioner represented in Figure 1a, a large spike is

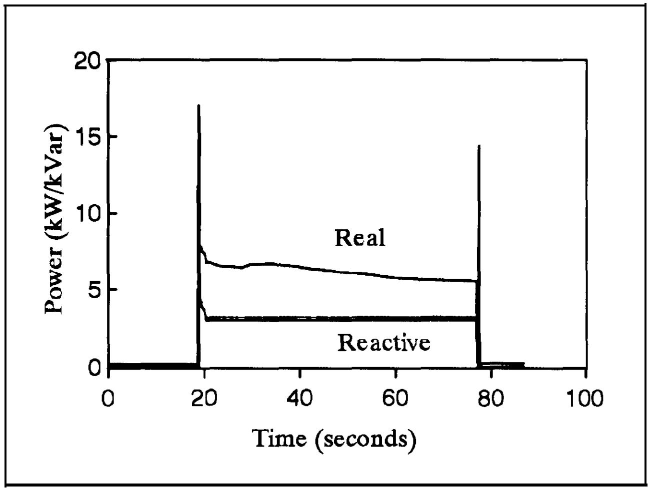

Figure la. Total Power Profiles Showing a Residential Air Conditioner Start and Stop as Recorded by a NILMS

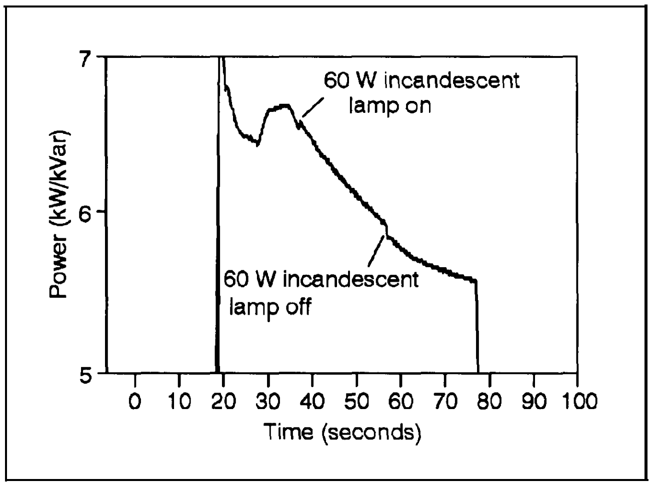

Figure lb. Magnification of the Real Power Profile of Figure la Showing the Operation of a Single 60 W Lamp

visible at startup in both real and reactive power which settles out as the motor begins to reach normal operating speed and the starting winding cuts out. These real and reactive power profiles are very similar in appearance, but normally differ in magnitude to one another and to those from other residential motor-driven systems such as fans and refrigerators. Figure 2 shows the power profile changes recorded for an electric water heater, a pure-resistive load which causes a significant jump in real power with no increase in reactive power. There is a peak when the system is started that fades as the electric heating elements approach their normal operating temperature. Except in magnitude, the profile for other resistive-type appliances is very similar to that of the electric water heater. A number of residential systems are also multi-state (they can operate at different power levels at different times such as refrigerators, ranges, and dryers) and many contain both resistive and reactive components which further complicate their identification from total power profiles.

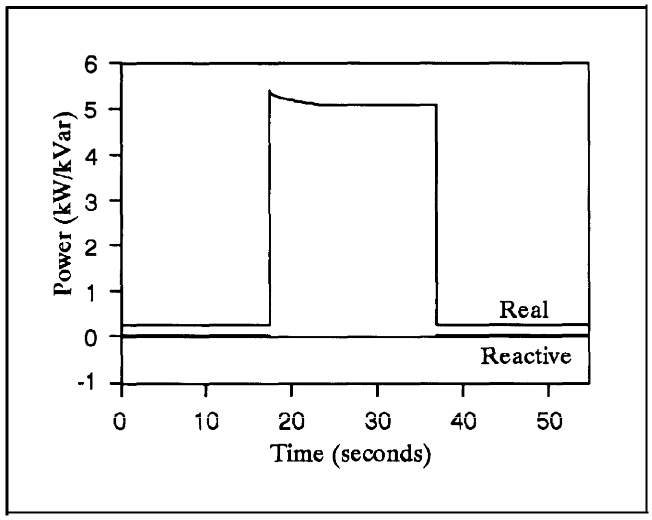

Figure 2. Total Power Profiles Showing a Residential Water Heater Start and Stop

A desktop computer-based NILMS was used to examine air conditioner starts and stops in a small commercial office building of 12,000 sq. ft. The building has 38 tons of air conditioning, approximately 25 kW of lighting, and numerous computer systems. All tests were done during fully occupied periods. The starts and stops of 4-ton (Figure 3) and 3-ton central air conditioners were easily distinguishable. This indicates that air conditioners representing less than 1/10 the total installed cooling capacity within the building are easily distinguished at the service entrance. While the start of a room air conditioner (less that 1 ton) was noticeable in the reactive power profile (Figure 3), the stop was masked by signal variability and noise. Water heaters in the building required around 4 kW and were easily visible in the total building power profile. Individually-switched office lights accounted for less than 1 kW each. As a result, only groups of lights switched at one time could be easily detected at the service entrance.

Sampling Rates

The amount of building equipment, the extent of monitoring (both real and reactive power), how detailed the start and stop of equipment is to be captured, and the use of filtering all influence the sampling rate needed. In a residential setting, with knowledge of the building systems, slow sampling rates, between 1 second and 1 minute, could allow identification of most loads. These sampling rates will likely miss the ramping up and settling of the power profile associated with motor-driven systems. If reactive power is monitored, however, reactive power changes can be used to distinguish motor-driven systems

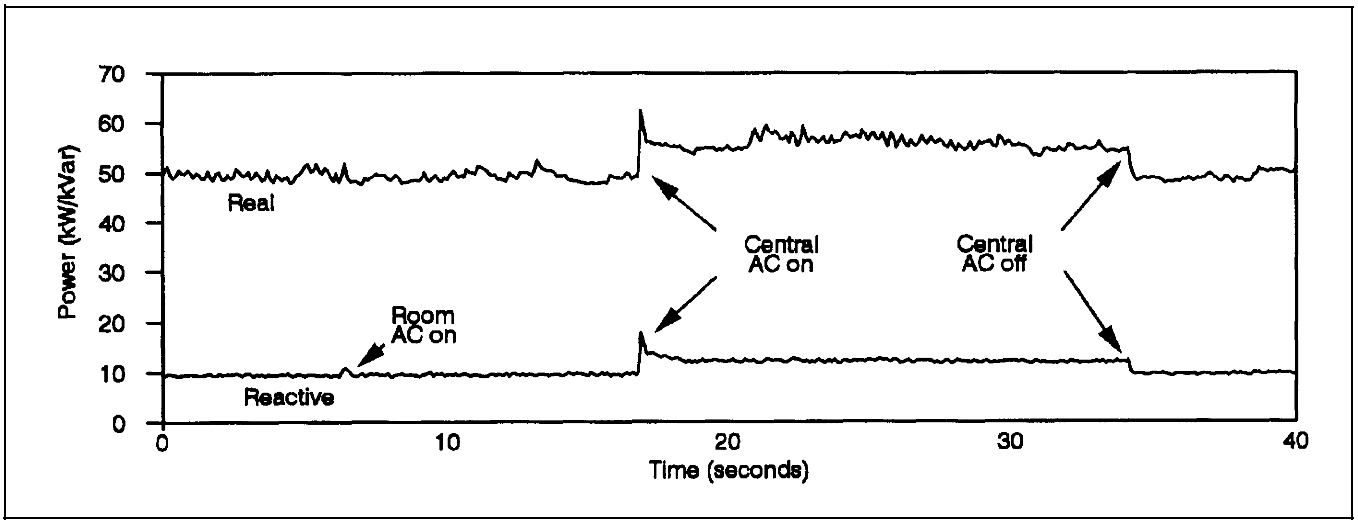

Figure 3. Short-term, Service Entrance Power Profiles to a 12,000 sq. ft. Office Building Showing the Start/Stop of a 4-on Central Air Conditioner

from purely resistive loads such as electric ovens and water heaters. The ramping up and settling of the power profile associated with motor-driven systems occurs in around 200 msec. If capturing this is desired, sampling frequencies of 20 Hz or faster will be needed to yield multiple data points on the ramping portion of the power profile for both residential and commercial applications.

A very important consideration in the selection of sampling rate is the amount of data that can be handled. Twenty hertz sampling generates 1200 data points per minute, and 72,000 points per hour. Without processing capabilities for this amount of data, the user will likely be able to utilize higher frequency sampling only for short-term testing. A NILMS with processing capabilities like that being developed for commercial applications at MIT will make higher speed sampling possible over longer periods by storing only the transition portions of power profiles.

Filtering

Filters can be used to remove much of the noise from the power signal coming from the watt transducer. In addition, filtering can also be used to smooth the signal such that significant events are easier to identify. Use of multiple point averaging or other filtering techniques are often used for signal smoothing. Filters can consist of hardware filters, software digital filters, or the filtering routines available on some packaged data acquisition software.

Sixty-hertz power can bleed through and show up on the DC output of a watt transducer. Low-pass filtering can be used to remove this. A digital, low-pass filter was used to remove the 60 hz noise present on the unfiltered power profile in Figure 4. As can be seen in the filtered signal, significant profile variation can still exist after application of a low-pass digital filter. The multitude of small, cyclic loads in the monitored office building are largely responsible for these variations. A single laser printer, for example, can draw short bursts of power around 1 kW as much as 3 times per minute. Multiply this by the number of printers in the modern office building, add the intermittent loads from computers and other business equipment, and rapid fluctuations of total building power of 2, 3, or more kW are commonplace.

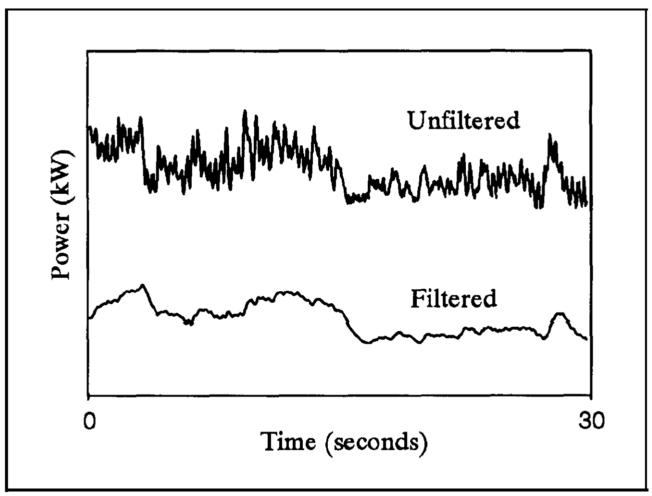

Figure 4. Unfiltered and Filtered Real Power Profiles from an Office Building

Potential Applications

Power profiles acquired using a NILMS can provide a wealth of information about a building, building systems, and how they are operated. Power profiles can be used to determine how energy is used, the effectiveness of energy-efficiency strategies (are they installed or implemented and are they working or practiced), how operations might be optimized for demand control, and the magnitude of specific end use loads.

Demand Measurement

A NILMS was used to obtain the daily total power profiles shown in Figure 5. This office building was constructed in 1987 and received a modern energy management control system (EMCS) to control HVAC systems in the building. The total power profiles indicate that this building requires an average 45 kW and 11 kVar during occupied periods and that both drop significantly during daily unoccupied periods. The ratio of kVar to kW indicates a very desirable, high average power factor of around 0.97 during daytime hours. Power needs during the occupied period fluctuate around 10 kW or less most of the time. Based on 15-minute averages, demand changes very little for this building during occupied periods. This suggests that a load shedding or shifting strategy would have to impact the entire occupied period to be effective in reducing overall demand costs.

The real power profile recorded in Figure 5 confirms that a power peak associated with morning HVAC starts for the building is avoided by starting the systems substantially before the building approaches full occupancy. Without a "warm-up" period, a peak similar to that shown in Figure 6 can occur. This type of peak likely occurred when the office building was commissioned, since all systems were originally started at 8 a.m. Unless severe, an undesirable demand peak in a building is rarely discovered if a power profile is not available. A NILMS could make building power profiles easily accessible. Herzig and Wajcs (1993) found a startup profile similar to that in Figure 6 in a recently constructed, 21,000 sq. ft. office building. Approximately 20 kW was added to a building that normally peaked at around 100 kW during the winter. The building was designed and constructed by competent professionals. The building design engineers occupied the building when brought on line and never suspected this type of problem, and without measured data, would likely never have discovered it. A NILMS could have confirmed this problem more rapidly and at lower cost than conventional metering.

Assessing the Energy Use of Fixed Loads

For near-constant loads, such as lighting during occupied or unoccupied periods, a NILMS can be used to measure the magnitude of the load. The magnitude of constant motor loads such as for pumps or constant-volume air handlers can also be quantified. Combined with occupancy or operational schedules, annual energy use of each could be projected. Again, these measurements are made at the service entrance to a building.

Although varying loads such a motor loads on VAV systems or temperature dependent loads such as heating and cooling can be quantified using a NILMS, the short term nature of most NILMS measurements limit its ability to predict long-term energy use. A NILMS could prove useful in the future for the prediction of long-term energy use by combining its short-term measurement capabilities with computer-based building performance models. This type of evaluation methodology can avoid the time and costs involved in long-term performance monitoring.

Identifying Building/System Operational Characteristics and Problems

One of the most valuable applications of a NILMS is in "seeing" how a building and/or building system is

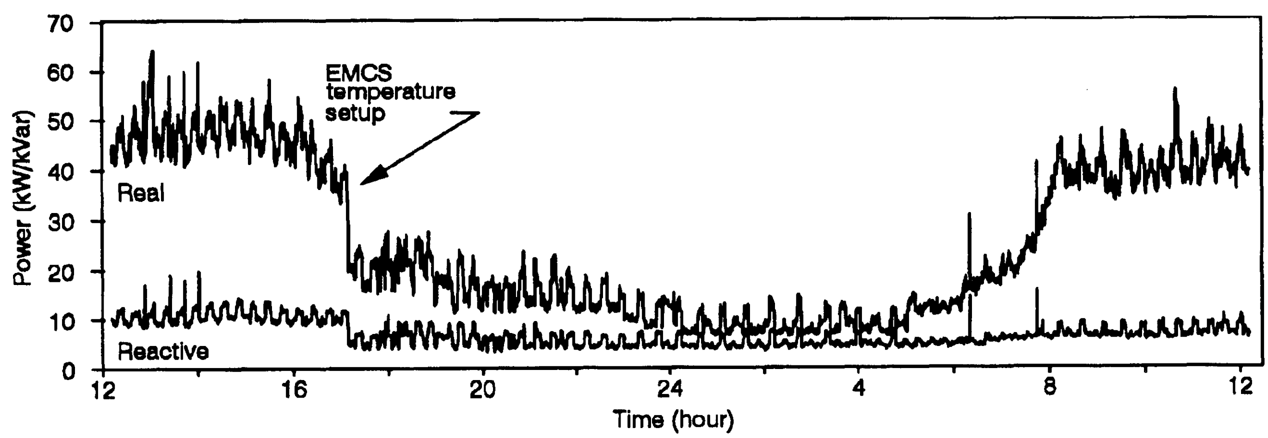

Figure 5. Daily Power Profiles from a 12,000 sq. ft. Office Building

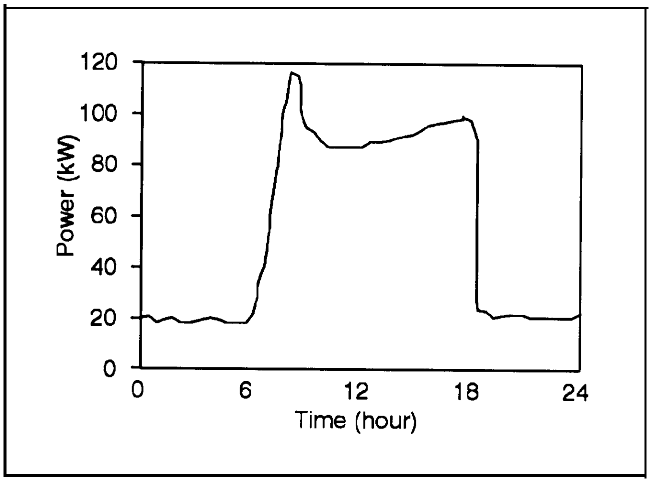

Figure 6. Daily Power Profile Showing Undesirable Demand Spike Due to Building Temperature Recovery

operating. This capability can be used for building commissioning, determining building operational schedules, spotting operational problems, and identifying demand and energy use reduction opportunities.

The profile in Figure 5 shows events and characteristics important to both energy and demand management. Nine hours at full operation is indicated by the daily profile. Normal operations at full load resume at around 8 a.m. The energy management control system (EMCS) appropriately implements thermostat setup as indicated by the approximately 15 kW drop at 5 p.m. The higher average energy use between 5 p.m. and midnight in comparison to the lower average between midnight and 5 a.m. suggests that some operations, although limited, occur during evenings. Within about 15 minutes of the thermostat setup, an air conditioner start is indicated by the corresponding steps in real and reactive power profiles. This suggests that a system is either not controlled by the EMCS, is not setback, or has very minimal setback. A check of the building EMCS programming confirmed that minimal setback (to 80F) was used on this system. This limited setup was used to avoid temperature recovery problems during peak summer temperatures in around 20% of the building's space. When commissioned in 1988, however, all 38 tons of cooling in the building were controlled to this minimal setup temperature. At the time the power profile was recorded, around 30% of the buildings cooling capacity was controlled to this minimal setback. If the building was left as commissioned, the limited effectiveness of the cooling setup would be evident in the power profile recorded by the NILMS.

A NILMS has the potential to assist in the detection of numerous other building or building system operational problems. Norford (1992) found that a NILMS could be used to identify problems with control systems for electric chillers. He also concluded that the system could potentially detect conditions indicating incipient motor failure from a centralized power monitoring location.

Applications to Electrical Distribution Networks

Although not a non-intrusive system, one of the early applications of high speed monitoring systems on electrical distribution networks was that performed on the Athens Utility Board in Athens, Tennessee (Reed et. al. 1989). Data measured at 50 hz was used to monitor automated load transfers and determine the amount of load shed and restored during load control actions. Adapted from this previous work, Figure 7 shows the feeder power levels resulting from the staggered start of five groups of residential air conditioners. The high speed monitoring system was able to confirm that the staggered start allowed all systems to be activated without feeder power levels exceeding 1300 kW. Inrush currents caused the feeder power level to reach a maximum at a speed faster than a 1 sample/second or slower speed monitoring system could sense. A low-cost NILMS such as that being studied could be used for this application,

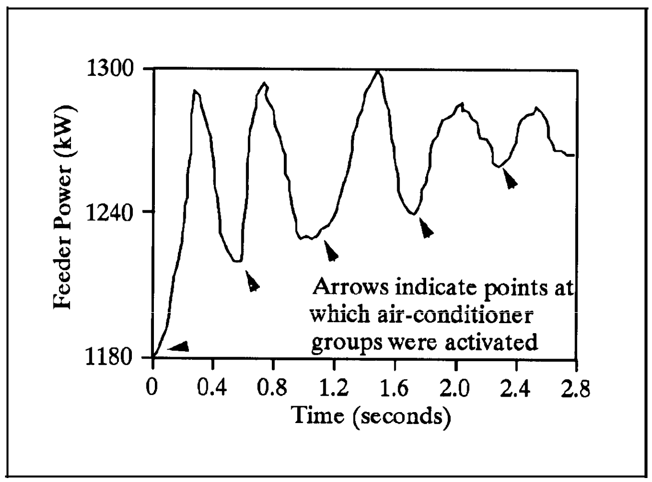

Figure 7. Feeder Power Increases when Five Groups of Air Conditioners Were Restored During a Load Control Operation

High-speed monitoring systems, when available, could become valuable monitoring systems for utility distribution networks. The ability of the systems to be non-intrusive would be an important advantage, avoiding the need for power interruption. Potential areas where these types of systems may play important roles in utility applications include:

a. providing real-time feedback on load shed and restored,

b. determining load types on utility feeders,

c. fault detection and location, and

d. reducing the need for expensive point monitoring.

Conclusions

A simple NILMS (without calculational capabilities) can be developed with minimal equipment and at low cost. With it, an experienced user can collect valuable building power profiles that provide insight into building operations, energy use, demand, and building system problems easily and at low cost. In addition, other valuable applications for this technology likely remain to be identified.

Acknowledgements

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