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Development and Application of a High-Speed, High-Resolution Data Acquisition System for Monitoring Power at the Service Entrance to Buildings

T. R. Sharp

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Energy Division

DEVELOPMENT AND APPLICATION OF A HIGH-SPEED, HIGH-RESOLUTION DATA ACQUISITION SYSTEM FOR MONITORING POWER AT THE SERVICE ENTRANCE TO BUILDINGS

T. R. Sharp

February 1995

Prepared for the
Existing Buildings Efficiency Research Program
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The author would like to acknowledge the preliminary high-speed monitoring work performed by Bill Levins of Oak Ridge National Laboratory. This work is described in Appendix B of this report and represents the initial experimentation performed as part of this research. The monitoring system used by Levins is the portable version of the non-intrusive load monitoring system referred to in this report.

ABSTRACT

A non-intrusive load monitoring system (NILMS) was developed and tested to determine its capabilities and examine ways that the system can supplement the understanding of how energy is used in a building. The investigation of the system as a method for obtaining short-term building energy use and demand data faster, as less cost, with less complexity, and less intrusively than from conventional submetering is described in this report.

Data acquisition hardware and software, a power transducer, and current transformers were assembled into a system that could be used to sample the instantaneous real and reactive power coming into a building. The system was used to collect power profiles at a commercial and a residential building.

The NILMS can sample power at low speeds (one sample per hour or less) and at speeds exceeding 100 Hz. Large changes in building power such as those due to central heating and cooling systems, water heaters, or banks of lights can easily be discriminated from total building power profiles collected by the system. Smaller loads, less than 1 or 2 kW, can be resolved when there is little "noise" (frequent profile fluctuations close or larger in magnitude than the load being resolved) in the power profile. Very small loads, less than 100 W, can be resolved in a residential application. Resolution becomes more difficult as larger and more frequent fluctuations occur. Resolution of smaller loads can be difficult in an office building where numerous computers and other office equipment cycle on and off frequently.

The ability of the system to easily collect valuable, short-term building power profiles, which permit individual loads to be determined (resolved), makes the system attractive for a number of applications. The system could prove very useful for measuring short-term energy use and demand, assisting building energy auditors in assessing building deficiencies, providing short-term performance data for validating engineering-based savings estimates and calibrating computer-based building performance models, and for validating, developing, and/or improving building and building system operating strategies.

EXECUTIVE SUMMARY

The improved accuracy of energy use predictions and the energy demand monitoring capabilities that submetered data provide over more aggregated data (such as monthly billing data) continue to make submetering a popular method for demand and energy use measurements on buildings and building systems. The installation time requirements, complexity, and intrusiveness of conventional submetering complicate and increase the cost of energy and demand measurements for the U.S. Department of Energy's Existing Buildings Research Program, utilities, and other researchers. These factors restrict the confirmation of energy and demand savings estimates for important retrofit projects and impose limitations on the study of energy use and demand for buildings and building systems.

A non-intrusive load monitoring system (NILMS) was developed and tested to determine its capabilities for overcoming or reducing the restrictions of conventional submetering and supplementing existing measurement capabilities. Four areas of NILMS application were of particular interest:

1. As a rapid, low-cost, and non-intrusive method for:
    a. Measuring energy use and demand for buildings and building systems,
    b. Measuring energy use and demand reductions from building retrofits,

2. As a tool to improve energy audits for buildings,

3. As a tool for improving the accuracy of energy savings and demand reduction estimates from calibrated building models, and

4. As a system that might allow the quantification of building or building system energy use from short-term measurements.

The primary differences between a NILMS and other monitoring techniques are 1) the need to interrupt power for installation is reduced or can be avoided and 2) a much higher resolution and sampling speed allows a NILMS to "see" individual end-use loads from a higher level monitoring point. In many cases, these capabilities may offer opportunities for substantially lower-cost and less-intrusive performance monitoring.

The NILMS consists of a data acquisition board and compatible software, a power transducer, and associated current transformers. Two systems were developed, a desktop-PC-based system using a PC to drive the data acquisition card, and a portable, data-logger-based system with the card built-in. These systems were used to collect real and reactive total (whole-building) power profiles for a 12,000 ft^2 commercial office building and an 1800 ft^2 residential building. Building equipment (including lighting) was cycled to establish changes in (time series) power profiles associated with each piece of cycled equipment. The results were then examined to determine if distinct patterns in the profiles exist that allowed equipment and equipment start/stops to be identified by simple examinations of total building power profiles.

For short-term measurements, experiments confirmed that the system can be installed rapidly, within one hour, and does not, by itself, require the interruption of building power. The installation time was longer in the commercial building where a more permanent type of installation was performed (an instrument cabinet and wiring conduit were installed). In addition, because of the phase relations between currents and voltages, the installation is inherently more complex for the three-phase power system in the commercial building.

Measurements in the commercial building were made at frequencies of 0.033 Hz (2 samples per minute) and 40 Hz. The slower sampling frequency was used to collect longer-term power profiles (profiles over multiple days) that provided valuable insight into building and building systems operations. These profiles confirmed important building operational characteristics such as the effectiveness of the building energy management system, building demand levels, high power factors, and how the building and building systems are operated during the occupied, unoccupied, and transition periods. The measurement of both real and reactive power was necessary to help distinguish the types of equipment that were producing the sizeable changes in building power profiles. Reactive loads (such as motor-driven loads) impact both real and reactive power in contrast to purely resistive-type loads (such as a water heater) which only impact real power. When different equipment has similar power requirements, this additional measurement capability can help tie power profile changes to the operation of specific building equipment. The ability to identify and separate out the impact of individual equipment on the total building power profile is critical to monitoring individual building loads from a centralized point. The faster 40 Hz sampling frequency allowed the high in-rush power (the rapid power surge that takes place at the starting of motors and other reactive equipment) to be observed in the total building power profiles.

The amount of equipment and the frequency that it cycles on, off, or between different power levels impacts how well individual equipment can be identified from total power profiles. The monitored commercial

building contains a large amount of frequently used power consuming equipment, including 46 room-sized, thru-the-wall packaged terminal air conditioners (PTACs), more than 50 each computers and printers, two copy machines, and three central air conditioners. Frequent and sizeable fluctuations of 2 to 3 kW resulting from this equipment made it difficult to easily distinguish small loads from total power profiles. For this building, equipment requiring around 5 kW or larger, such as the three central air conditioners, were easily distinguishable from building power profiles. The startup of PTACs, which required around 0.8 kW, could be easily distinguished from reactive power profiles, but their stops were masked by profile fluctuations.

Measurements in the residential building were made using a portable NILMS sampling at 40 Hz. Except when major equipment is operating (heating/cooling system, refrigerator, dryer, etc.), power levels are usually very small, less than 2 kW. As a result, the operation of major appliances, including the refrigerator, heating and cooling system, dryer, and water heater are very distinguishable in building power profiles. In addition, because there is limited equipment in the residence, fluctuations in the building power profiles are small, leading to excellent discrimination abilities. The switching of an individual 60 W lamp was easily visible during operation of a 6 kW cooling system.

A portable NILMS was also used to verify the demand and energy use reductions from lighting improvements in a 13,000 ft^2 office building. The system's easy and lower-cost installation made it particularly attractive for this application because a single week of monitoring before and after the retrofit very clearly verified its impact.

A simple NILMS can have sufficient resolution to allow discrimination of individual building loads from total building power profiles. Detection and quantification of these individual loads depends on the amount of equipment in the building, the magnitudes of the power required by the individual equipment, and how frequently the equipment is cycled. Both real (kW) and reactive (kVAR) power measurement capabilities are needed. The capabilities of the system to discriminate small loads will be degraded when rapid fluctuations occur in power profiles (such as where a large amount of equipment is used, or equipment is started, stopped, or cycled between power levels frequently, or other cause).

A NILMS has attractive benefits for the four applications of interest. A NILMS offers a monitoring capability that is non-intrusive and easy to install, and often is the low-cost option for monitoring. As a result, a NILMS will be an attractive option for measuring the impact of retrofits, and particularly for those whose

performance can be verified over a short period. The use of a NILMS for building auditing/evaluation purposes will likely be limited to commercial and industrial buildings where deficiencies that can be identified with the system have greater demand and energy use implications. Because it is possible to measure short-term energy use at much lower cost and with much less complexity, a NILMS may be used to collect short-term performance data that can be used to calibrate building simulation models. In the past, researchers were often restricted to higher level weekly or monthly data to calibrate models. Because a NILMS can "see" many individual equipment loads in a total power profile, the system could easily be applied to the quantification of energy use for both a building and individual building systems.

A power profile can be a valuable tool in identifying operational problems of buildings and building equipment, or in validating building operations. Because a NILMS can collect the power profile easily and at low cost in many cases, the system could also be very valuable for validating building system operations and energy performance.

1. INTRODUCTION

The improved accuracy of energy use predictions and the demand monitoring capabilities that submetered data can provide over more aggregated data (such as monthly billing data) continues to make submetering a popular method for demand and energy use measurements of buildings and building systems. The limitations of cost, complexity, and intrusiveness of standard submetering, however, have restricted its use in many applications. These limitations have driven the development of non-intrusive load monitoring systems (NILMS). The primary differences between a modern NILMS and past monitoring systems are 1) the need to interrupt power for installation is reduced or avoided using a NILMS and 2) the much higher resolution and sampling speeds allow the NILMS to "see" individual end-use loads from a higher level monitoring point. Conventional submetering uses time steps of a month, week, day, hour, or sometimes one-quarter hour, and this resolution does not provide the information available when measuring power at time steps less than one second. Using a high-speed NILMS, the startup, steady-state, and shutdown impacts of individual end use loads can be seen on power profiles measured from a single, centralized monitoring point such as a building service entrance. Because of this capability, major advantages over conventional submetering can be obtained. These systems have numerous applications for residential, commercial, and industrial buildings and building systems, and potential applications for utility distribution and load control networks.

The installation time requirements, complexity, and intrusiveness of conventional submetering complicate and increase the cost of energy and demand measurements for the Existing Buildings Research Program, utilities, and other researchers. These factors restrict the confirmation of energy and demand savings estimates for important retrofit projects and impose limitations on the study of energy use and demand of buildings and building systems. A non-intrusive, high-speed data acquisition system was developed and tested for its ability to minimize or eliminate these concerns and lead to a rapid, lower-cost, and non-intrusive method for making these measurements. In addition to simplifying performance measurements, this system was also examined for potential as a tool to improve energy audit methods, to improve energy savings and demand reduction estimates, and in quantifying building energy use from short-term measurements.

1.1. BACKGROUND

One of the early applications of high speed monitoring systems on electrical distribution networks was performed with the Athens Utility Board in Athens, Tennessee (Reed et. al. 1989). Data were measured at the electrical substation level at 50 Hz to monitor automated feeder load transfers and determine the amount of load

shed and restored during load control actions. Fig. 1 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 in less than 1 second, a speed much faster than conventional monitoring systems can sample.

Monitored data from the Athens system were of sufficient resolution to allow detection of the starts of individual residential air conditioners at the feeder level. The start of an individual residential air conditioner (size around 3 tons) is visible in the measured feeder power shown in Fig. 2. Note that this individual system is detectable at a feeder power level approaching 900 kW. These results suggest that it may be possible to identify numerous events on electrical distribution networks at the feeder level.

The Athens work indicates that future high speed monitoring systems could become valuable monitoring systems for utility distribution networks. The ability of the systems to also be non-intrusive would be an important advantage, as installation of the Athens system required a substation-level 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,
d. reducing the need for expensive point monitoring, and
e. minimizing the data transfer required to monitor distribution systems.

High-speed sampling of power at centralized locations to disaggregate end use loads is relatively new to demand-side management 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). The MIT 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 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.

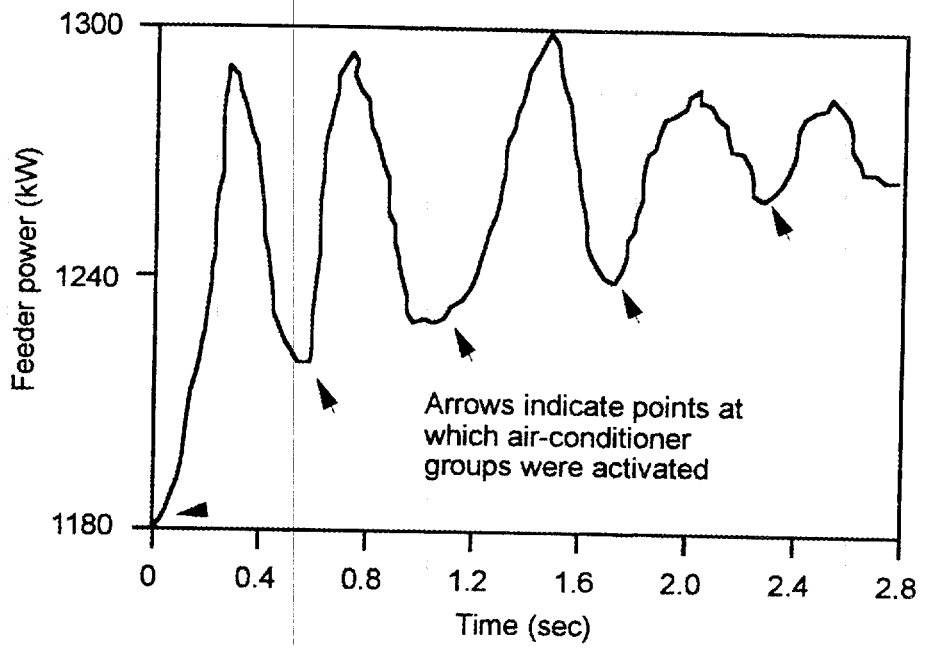

Fig. 1. Feeder power increases when five groups of air conditioners were restored during a load control operation.

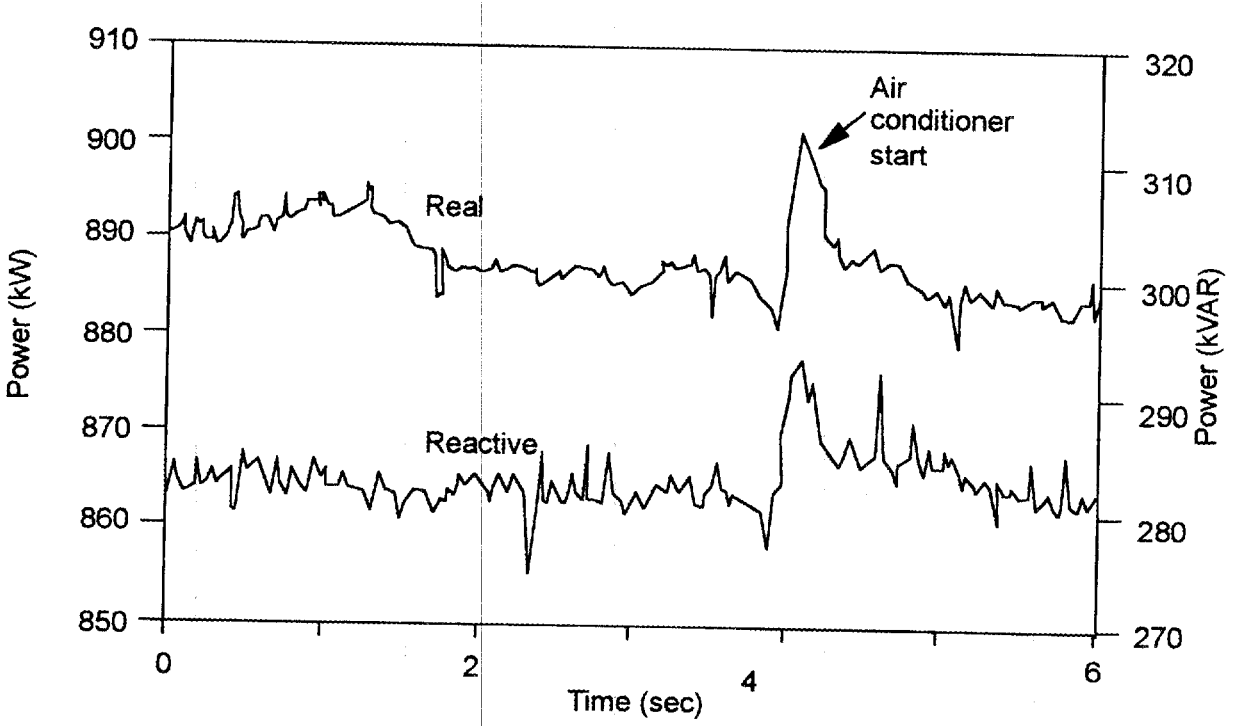

Fig. 2. Residential air conditioner start as observed from high-speed substation monitoring.

1.2. PURPOSE

This report addresses the development of a NILMS, testing to determine its capabilities, and examines ways that the system can be used to supplement the understanding energy use in a building. The work was undertaken to develop a method to obtain short-term building energy use and demand data in a faster, less costly, less complex, and less intrusive manner than conventional submetering. Numerous considerations for using a NILMS, including their capabilities for event detection, and possible current and future applications are also presented.

Complexity and cost are primary factors that limit performance monitoring conducted by Oak Ridge National Laboratory's (ORNL) Existing Buildings Research Program (EBRP), utilities, and other energy researchers to confirm energy and demand savings from retrofit projects. A NILMS can reduce or eliminate these limitations in many cases.

Four areas of NILMS application were of particular interest to the EBRP:

1. As a rapid, low-cost, and non-intrusive method for:
    a. Measuring energy use and demand for buildings and building systems,
    b. Measuring energy use and demand reductions from building retrofits,
2. As a tool to improve energy audits for buildings,
3. As a tool to improve energy saving/demand reduction calculations based on metered data, and
4. As a system that might allow the quantification of building or building system energy use from short-term measurements.

1.3. APPROACH

Data acquisition hardware and compatible data acquistion software were selected and assembled into a system that could be used to sample the instantaneous real and reactive power measured by electronic watt transducers. This system was used to collect power profiles at the service entrance to a small commercial building (approximately 12,000 ft^2) and a residential building with approximately 1800 ft^2 of conditioned space. Short-term (generally less than 90 seconds) and longer term (around 1 to 3 days) continuous power profiles were collected for both buildings. Real and reactive power changes associated with various equipment starts and stops

were examined in these profiles to determine the ability of the system to discriminate these loads through measurements at the building service entrances.

Real and reactive power were recorded while building equipment (including lighting) was cycled to establish changes in (time series) power profiles associated with each piece of cycled equipment. The results were then examined to determine if distinct patterns in the profiles exist that allowed equipment and equipment start/stops to be identified by simple examinations of monitored power profiles.

1.4. REPORT ORGANIZATION

This report is dividend into six main sections. Following the introductory section, Section 2 describes the desktop and portable data acquisition systems assembled to monitor building power. Instrumentation common to both systems are described. Section 3 details installation considerations for both systems in a commercial and residential application. Measurement applications, power trace, and event detections capabilities are discussed in Section 4. These are discussed for both commercial and residential applications. Results are summarized and conclusions presented in Section 5, followed by a reference list in Section 6. An appendix to the report is included to identify hardware used to build the power monitoring systems and detail instrumentation hookup at the building service entrance for single and three-phase applications.

2. SYSTEMS DESCRIPTIONS

Two separate monitoring systems were developed because the distinct advantages of each were needed to make measurements on both buildings. The first was assembled using a desktop computer. The advantages that this system has over the second include: higher level of automation, faster data sampling and storage (in excess of 200 Hz), sampling and storage of large amounts of data simultaneously, and display of collected data in near real time. The second system was designed specifically for portability. This system was assembled using a portable data logger (which already contained a data acquisition board) and a portable computer. The portable computer was used for data storage, because the data logger storage was too limited, and for display of the monitored data.

2.1. DESKTOP-PC-BASED SYSTEM

The desktop system was assembled using a 386-based PC running at 33 MHz. A 16-bit, analog-to-digital (A/D) data acquistion board was installed in the computer. GUI-based (graphical user interface) data acquistion software compatible with the A/D board was used for data collection programming. The low-voltage outputs from an electronic watt/var transducer (precision resistors were installed across the mA transducer outputs) were fed into the A/D board. The watt/var transducer measured total and reactive power through clamp-on current transformers (CTs) and voltage taps. The software allowed many options to be adjusted for data collection including sampling speed, voltage input range, display, amplification, multiplication and offset factors, data storage, sampling triggering, and display scaling. Table A.1 in Appendix A contains specifics about the hardware and software.

2.2. PORTABLE SYSTEM

The portable system was built around an off-the-shelf data logger with multiple input options. The configuration of the watt/var transducer, CTs, and voltage taps were the same as for the desktop system. A portable computer was connected to the data logger so that its 80-Mbyte hard disk could be used for storing data files. The data storage capacity of the data logger was easily filled from a single short-term test. The computer also provided for data display in the field. The main advantages of the portable system were portability (small size and lightweight) and fast hookup

and disconnect (ease of installation). Main disadvantages were limited data storage, no near real-time display, and lower sampling speed. The data logger and its associated software are also described in Table A.1 of Appendix A.

2.3. COMMON HARDWARE

Both systems use the same type of transducers and CTs. Watt/var transducers were three-element type for commercial application and two-element type for residential. CTs were clamp-on to avoid power interruption. Transducers were chosen for compatibility with the PC A/D board and portable data logger. CT's were chosen for compatibility with transducers and line currents being measured. Some CT's were fabricated by a supplier to obtain the lower CT ratios desired in some cases.

3. INSTALLATION

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, unattended 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 which 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 transducer 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.

3.1. COMMERCIAL BUILDINGS

Installation in commercial buildings will normally involve the monitoring of 3-phase, 3-wire or 3-phase, 4-wire service. A single three-element watt transducer can be used to monitor both types if the proper hookup is followed. Wiring diagrams for the Ohio Semitronics, Inc., three-element watt/var transducers, models GWV5-

007B and GWV5-008B, used on commercial systems are shown in the appendix. It is important to note that the wiring hookup may differ for transducers supplied by other manufacturers. Monitoring commercial buildings usually means encountering higher voltage power at the service entrance, normally 480V except perhaps at larger buildings. Because of this and because voltage taps from each phase are required inputs to the watt transducers, special precautions may be needed to install the monitoring system.

3.2. RESIDENTIAL BUILDINGS

Installation in a residential building, unless multi-family, normally involves the monitoring of single-phase, 220V, Edison-type, 3-wire service. Two-element watt transducers are designed for this application. Wiring diagrams for the Ohio Semitronics, Inc., two-element watt/var transducer, model GWV5-004B, used for residential monitoring are shown in the appendix. If the installation is temporary, a simple location to install CTs is on the conductors at the weatherhead (the head at the top of the service entrance conduit where individual wires from the power pole first enter the conduit). This location provides plenty of room for installation and minimizes the work inside the electrical panel.

3.3. GENERAL CAUTIONS FOR CURRENT TRANSFORMERS

Current transducers always pose a safety hazard if they are installed on energized conductors, which is a primary purpose for the advent of clamp-on current transformers. If not wired to the monitoring system or shunted when installed on live conductors, dangerous potentials (voltages) can be created across the transformer's terminals. Manufacturers normally include warnings of this fact when transformers are purchased.

Finding room to install current transformers is often a challenge. Electrical panels/cabinets often have limited interior space. This can be a problem for CT installations because most off-the-shelf CTs are rather large in size. CTs may be installed in circuit panel boxes, junction boxes adjacent circuit panels, or in transformer cabinets. Local electrical codes should be consulted to insure that installations meet local requirements, especially for longer-term installations.

CTs installed in close proximity to other conductors may experience induced currents when currents flow in the adjacent conductors. Because of this, CTs should be installed away from other conductors as best possible,

especially when the other conductors carry large currents. The induced current is proportional to the magnitude of the current in the adjacent conductor and the distance between the conductor and CT.

4. POWER TRACING, EVENT DETECTION, AND MEASUREMENT APPLICATIONS

4.1. COMMERCIAL BUILDINGS

The desktop-computer-based system was used to monitor a two-story, 12,000 ft^2, all-electric, office building as a test building. Real and reactive power were monitored at the building service entrance (480V, 3Ph, 3-wire). Additional 480V/208V transformers (one on each floor) were between the monitoring sensors and all loads in the building. Short-term (normally under 60 seconds) and longer-term (1 to 3 days) profiles were examined. Short-term profiles allowed the examination of individual equipment starts and stops without collecting large amounts of data.

Overnight (24 hours) traces of real and reactive power for a summer weekday are shown in Fig. 3. The data were collected at a 1/30 Hz sampling rate, one sample every thirty seconds. Several operational features are visible or can be deduced from these profiles. They include:

a) confirmation of energy management control system (EMCS) operation,
b) confirmation that the EMCS control strategy is effective for the most part (thermostat setup occurs and no morning demand spikes due to this are created),
c) that part of the HVAC system is either not controlled by the EMCS or is minimally impacted by it,
d) that no power factor problem is evident at the building,
e) that equipment requiring substantial energy use remains operating during some unoccupied hours,
f) that limited operations are occurring within the building until around midnight,
g) because the profile is taken in more moderate weather (September) and the building heating and cooling are electric, the building will incur a demand charge during most of the year because the local utility demand charge limit is 50 kW, and
h) that the primary building operating schedule is 8am to 5pm.

The EMCS is operating and is effective in controlling energy use. It sets up thermostat control temperatures for approximately 20 kW of HVAC systems around 5 pm. Also, the morning startup to bring the building and its contents back to operating temperature does not create an undesirable demand spike (Mondays,

which follow two consecutive unoccupied days could be somewhat different). While effective, some of the HVAC equipment is not controlled by the EMCS or is minimally impacted by it. This is indicated by the immediate cycling pattern that begins around 5:15 pm and is visible throughout the night. This indicates that approximately 5 kW of HVAC has either no or minimal setback (in this building, this corresponds to minimal setback used for the upstairs central system which has trouble recovering when outdoor temperatures are high). Comparisons of the average real and reactive power indicates that no power factor problem exists with power factors exceeding 0.93 during mid-day and evening hours (power factor is the cosine of the inverse tangent of the ratio of reactive to real power). The real power levels between 5 pm and 12 am indicate that some limited activities and significant lighting use occurred during this period. The minimum power reached during unoccupied hours is 7 kW and occurs between midnight and 5 am. This includes little if any HVAC energy use. Considering weekends also, a 7 kW constant load during unoccupied periods corresponds to almost 20% of the total energy used in the building.

A second set of overnight profiles is shown in Fig. 4. Using the EMCS, HVAC systems were shut down four times during the occupied period for 5 minutes each. These measurements can be used to quantify the combined lighting and baseload energy use for the building during the occupied period. An individual measurement of these is often an approximate indicator of their energy use because lighting and baseload energy use are often relatively constant in many commercial buildings. The occupied lighting and baseload energy use appears to be around 35 kW on average. The last measurement made at 4:20 pm appears to have been made near the time when some occupants began to close down for the evening (lighting, computer, and other energy uses are beginning to be reduced). As a result, this point may not be a good indicator of occupied period consumption. Similar measurements could be made during evening hours to quantify lighting and baseload use during these periods. Differences between total building power and combined lighting and baseload power are greatest during the occupied period, much less between 5 pm and midnight when limited activities are occurring and most HVAC systems are set up, and very small between midnight and 5 am. The minimum power levels between midnight and 5 am are approximate indicators of lighting and baseload use during this period, with the fluctuations above them accounting for HVAC energy use. Because power levels are changing considerably between 5 pm and midnight, multiple measurements with HVAC systems shut down as done during the occupied period may be required to quantify an average lighting and baseload energy use for this period.

A second use of the system in commercial buildings is to determine the starts, stops, and energy use by a particular HVAC system or other end use. Short-term measurements, usually less than 60 seconds, were used

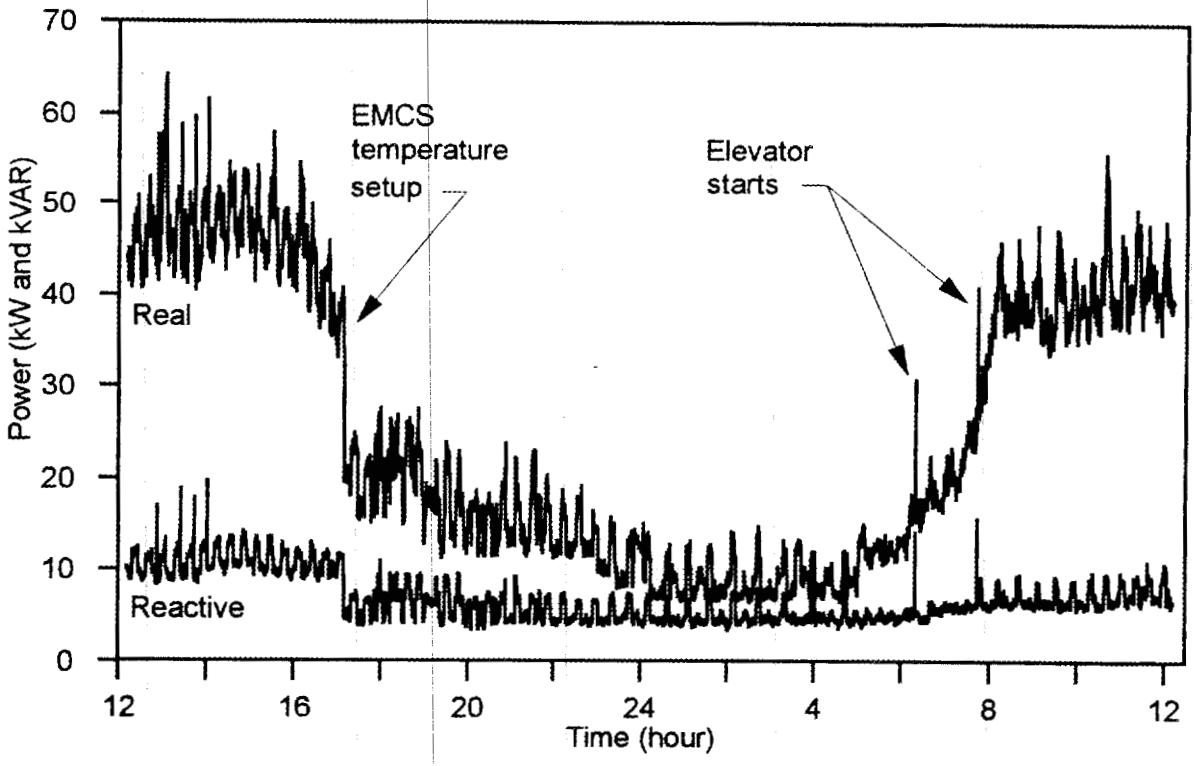

Fig. 3. Small office building power trace.

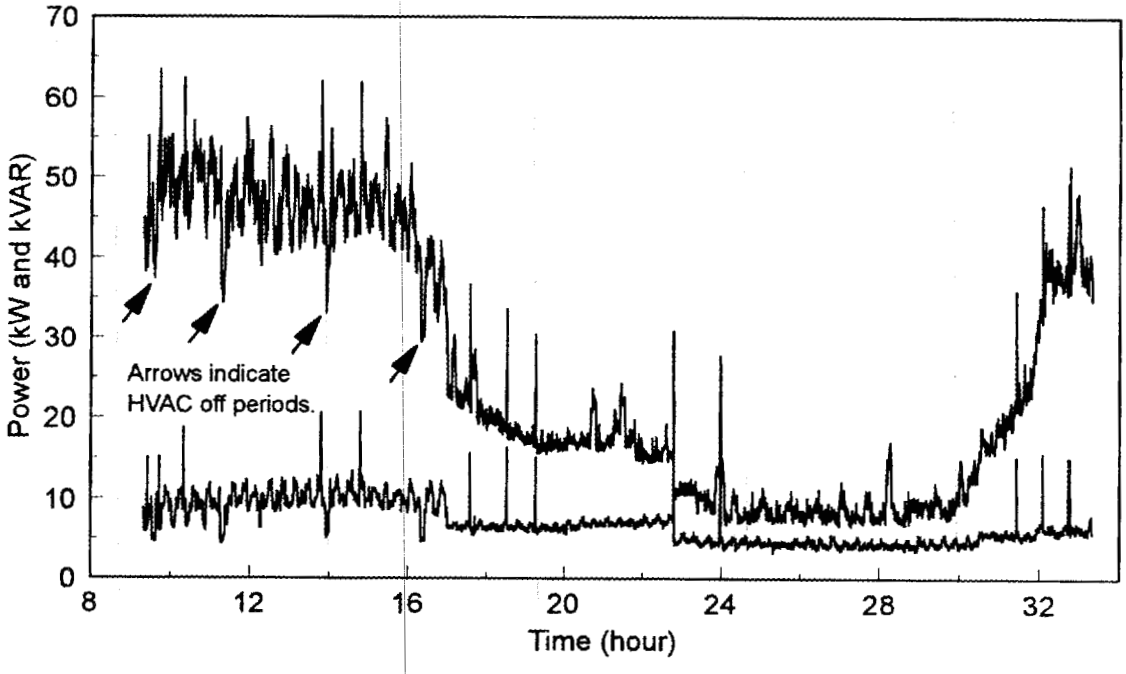

Fig. 4. Power profiles showing HVAC shutdowns during the occupied period.

to examine how well particular end uses could be seen in total building power profiles. Sampling speeds of 10 (Fig. 5), 20 (Figs. 6 and 7), and 40 Hz (Figs. 8 and 9) were used. These speeds were necessary to see the rapid ramp up and fall of the power profiles that occur at the start of motor-driven end uses. The largest individual HVAC system in the test building is only 4 tons of cooling. Most of the building is served by 46 small, through-the-wall units. Total building power profiles taken over the forced operating period of a 4-ton, packaged, rooftop air conditioner are shown in Fig. 5. These profiles show that this system, which represents approximately 1/10 the total installed cooling capacity in the building, requires around 5 kW -- around 1.25 kW per ton of rated cooling capacity. The 5 kW required, around 1/10 of the building demand when measured, is an easily distinguished load at the start and stop in both the real and reactive power profiles. The change in total building power profiles for a smaller, 3-ton system is illustrated in Fig. 6. This system requires around 4 kW, approximately 8% of the building's average demand, and also has easily distinguished starts and stops in both profiles. The smallest air conditioners were the through-the-wall units, rated at only 7000 Btu/h (0.6 ton). Each unit represented less than 2% of the installed capacity in the building. While the start of one of these units is easy to see in the reactive power profile in Fig. 7, the stop which occurred at 15 seconds is not. While a filtering or other averaging technique might help detect the stop, the presence of 46 of these smaller systems in this building would make detection more difficult.

Using the portable, data-logger-based version of the monitoring system, similar results were obtained for the heating modes of the HVAC systems. In the heating mode, the impact of the start and stop of the electric resistance heat in one of the 4-ton rooftop units to the total building power profiles is shown in Fig. 8. Comparing this figure to Fig. 5, the heating mode changes in the two profiles are very distinguishable from those resulting from system operation in the cooling mode. First, the step increase in real power is just over double that in the cooling mode. This is directly related to the COP of the system in the cooling mode. Secondly, there is no significant spike in the real power at system start. This results because the heating mode is primarily resistive compared to the motor-driven cooling mode. Finally, in contrast to the cooling mode, there is only a small ripple in reactive power at the start, due to the use of fan motors only in the heating mode. These characteristics make the different operating modes of HVAC systems very distinguishable.

Distinguishing between heating and cooling modes could be much more difficult if heat pumps were used. Because heating energy use in the building is almost all resistive, little if any starting spike will occur for the thru-the-wall systems. This will make the starts of these systems, around 2.3 kW each for heating, even more difficult to detect than in the cooling mode.

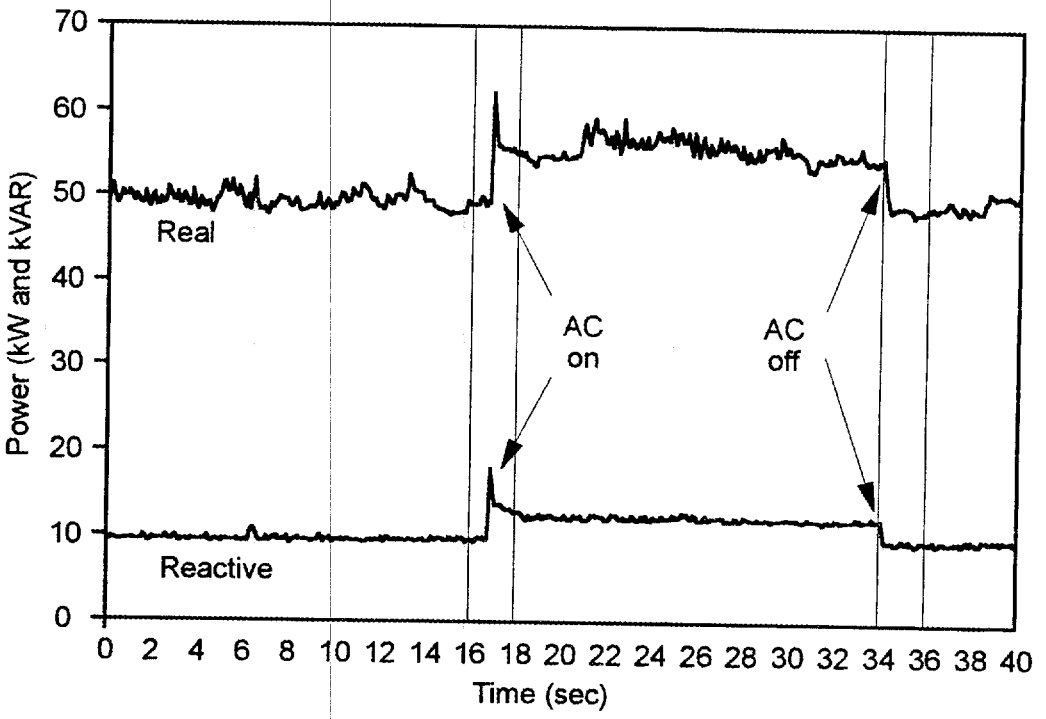

Fig. 5. Building power profiles showing the start/stop of a 4-ton air conditioner.

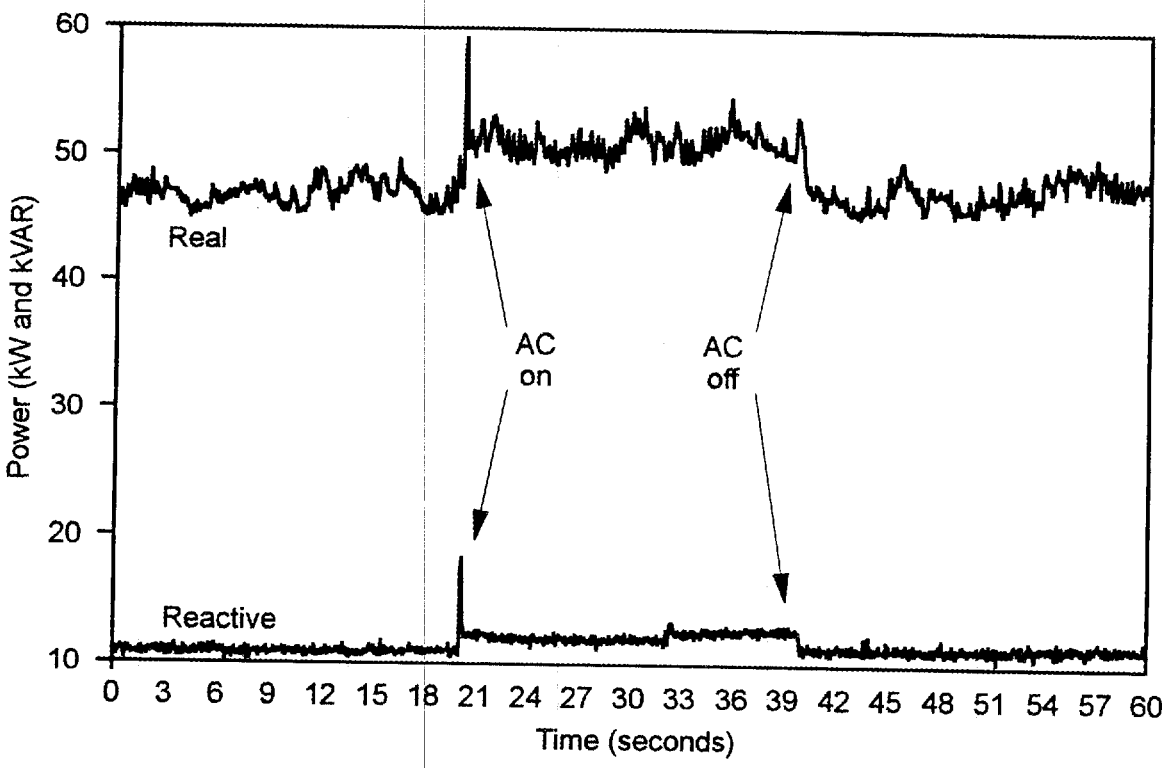

Fig. 6. Building power profiles showing the start/stop of a 3-ton air conditioner.

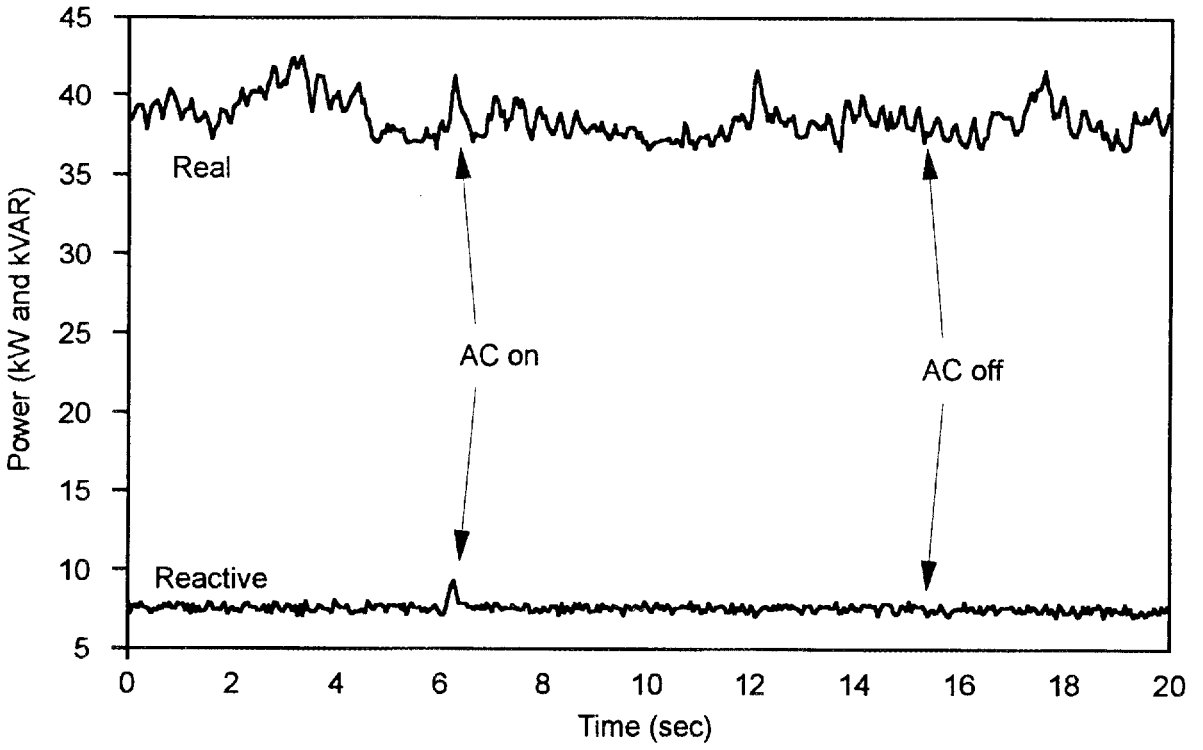

Fig. 7. Building power profiles showing the start/stop of a 0.6-ton air conditioner.

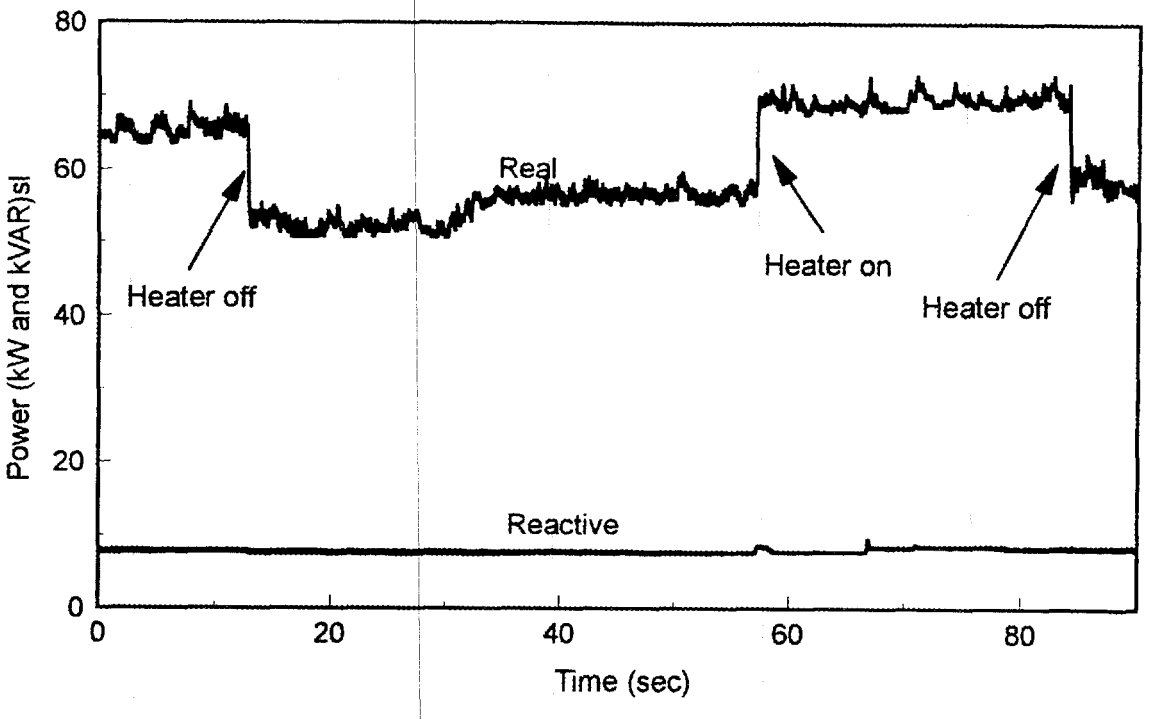

Fig. 8. Building power profiles showing central heating system start/stops.

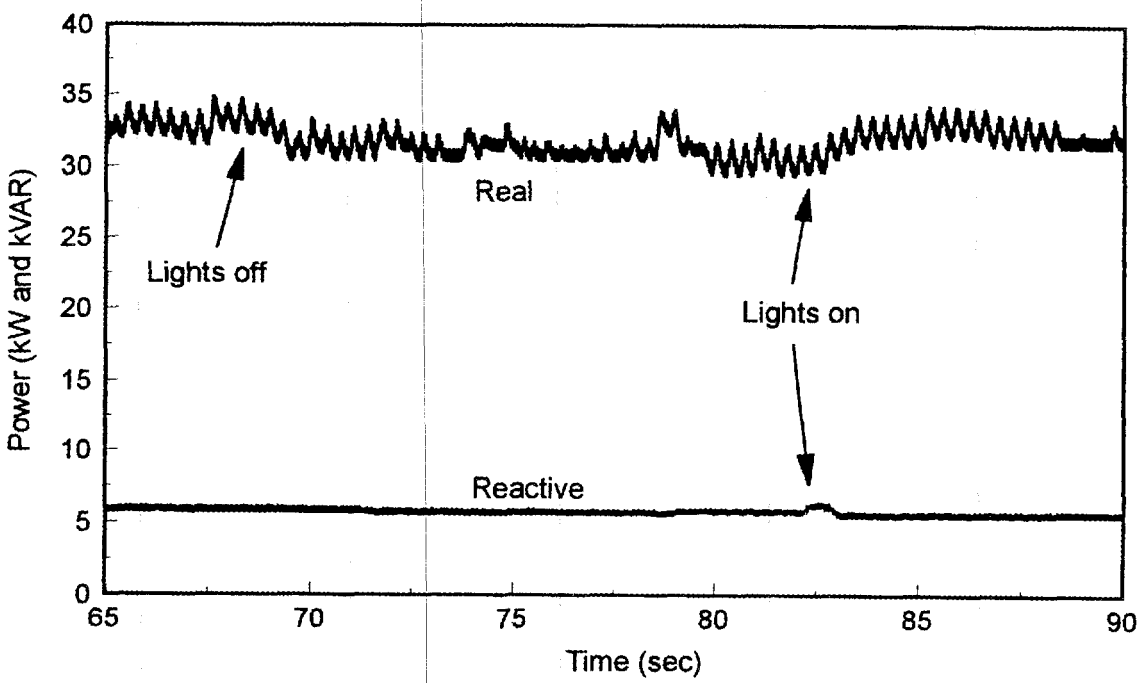

Fig. 9. Building power profiles showing fluorescent lighting on/off.

Power profile changes due to lighting were also examined. Real and reactive power changes due to switching a 2 kW bank of fluorescent lights are shown in Fig. 9. Impacts to the profiles are small, suggesting that the switching of individual fixture sets (two 4-lamp, 2-ballast fluorescent fixtures requiring around 400 W total) would be difficult to detect in this building. Although the impact of switching off the bank of lamps can be seen in the real power, this event is likely unidentifiable without knowing that it occurred. Switching on is more distinguishable. A small increase in the real power corresponds with a unique change in the reactive power that could be used to identify this event. The reactive power increases as the lamps come on and then settles to slightly lower than at the start due to ballast capacitance. These measurements were made around 7 am before the building was fully occupied. As a result, detection of this event may be slightly easier at the lower 33 kW real and 6 kVAR reactive power levels that existed.

4.2. RESIDENTIAL BUILDINGS

The portable system was used to monitor energy use in an 1800 ft_2 residential building. Real and reactive power were monitored at the service entrance (220V, 1Ph, 3-wire). Only short-term profiles (under 120 seconds) were collected to examine individual equipment starts and stops (event identification). Sampling was performed at 40 Hz.

Except when major equipment is operating in the residence, power levels are very small, less than 2 kW. In addition, power levels appear very steady. These characteristics and the high resolution of the data acquisition system allow small load changes to be detected.

The impacts to real and reactive power from the central air conditioner start and stop can be seen in Fig. 10. This plot confirms the small magnitude and steadiness of power levels in the building. The start and stop of the air conditioner are easily detected due to the large changes in both real and reactive power. A power spike that settles out within 3 seconds occurs, which is typical of motor-driven systems.

The resolution of the data acquisition system in a residential setting is demonstrated in this figure. With close examination, a very small rise and fall can be seen in the real power profile at 40 and 60 seconds into the profile. This is the switching on and off of a single 60 watt lamp. If this area of the profile is enlarged as in Fig.11, the clarity of the lamp switching is much more visible. The lamp represents less than 100 watts of

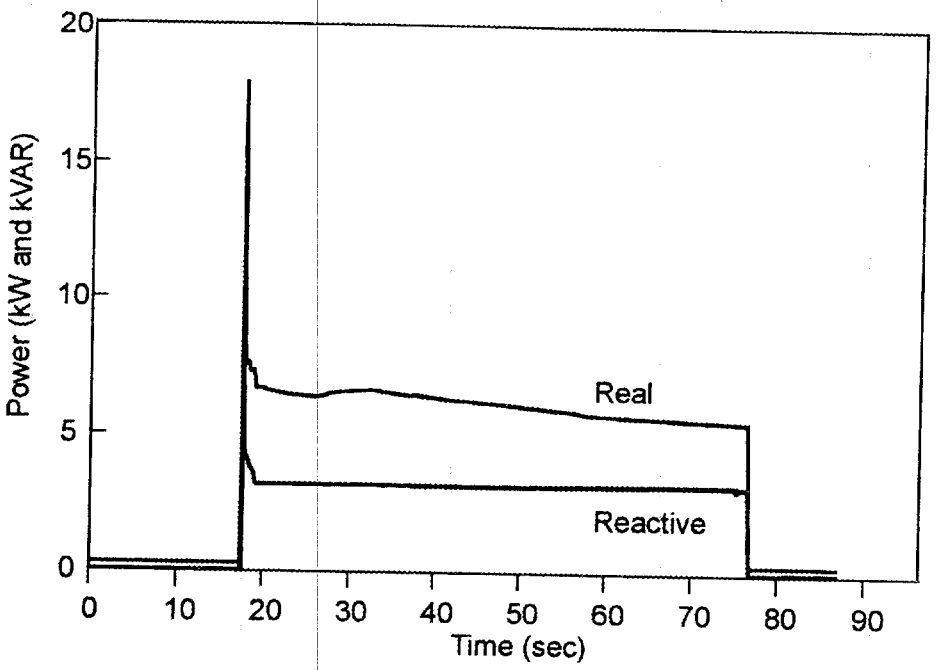

Fig. 10. Air conditioner start/stop with 60W lamp switching.

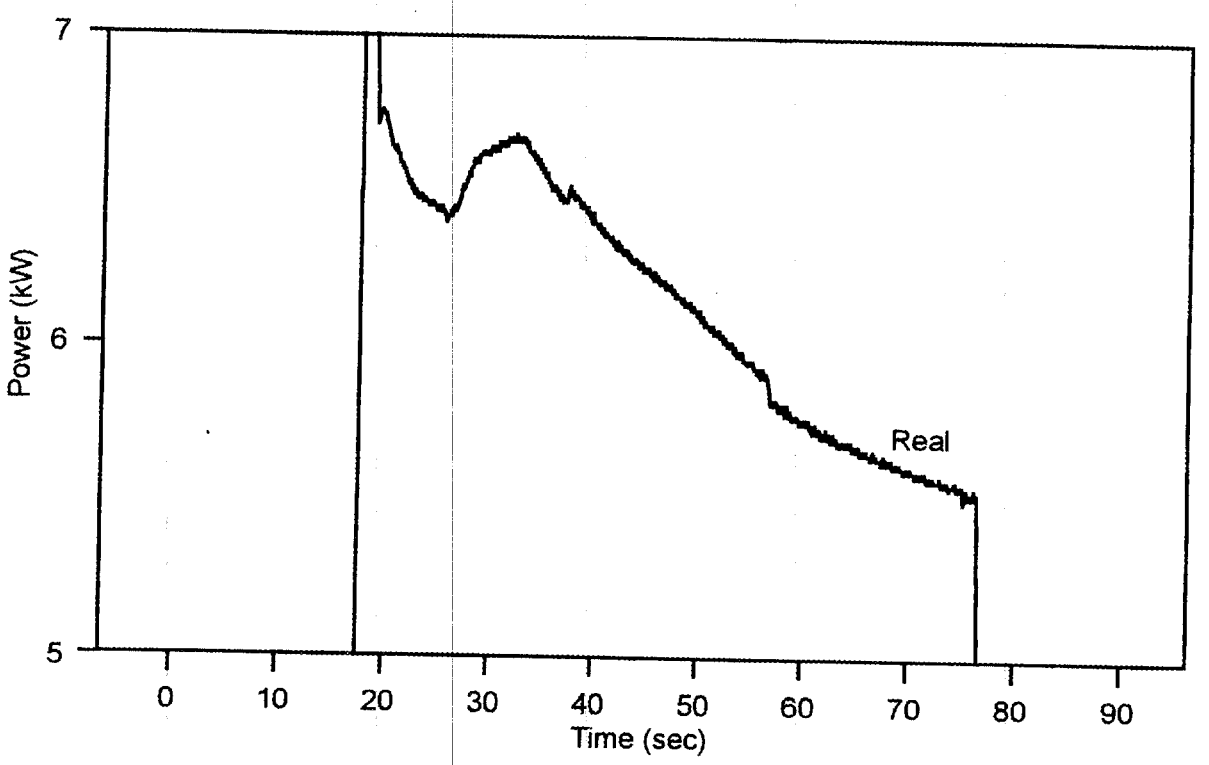

Fig. 11. Zoomed view of air conditioner start/stop with 60W lamp switching.

resolution. With this resolution, this system should be very effective in identifying most residential loads and in quantifying their respective energy use.

Other loads within the residence were also examined using short-term profiles. The start/stop of a 21 ft^3 refrigerator is shown in Fig. 12. Because the refrigerator is also motor/compressor driven, the profile is very similar to that for an air conditioner. Magnitudes of the profiles are smaller, however, reflecting the smaller size of the motor/compressor system as compared to that for a central air conditioner. Ramping of the power and settling out occur much faster for the smaller system.

Impacts due to the starts and stops of the water heater are shown in Fig. 13. This water heater is the electric-resistance type and therefore its start has no impact on reactive power. The water heater start has a small spike that settles out in about 6 seconds. This spike is much different in appearance from that of motor-driven systems. The settling out of real power reflects the time required for the element to reach a near steady-state rate of heat transfer to the water.

The power profiles for the start and stop of an electric clothes dryer are shown in Fig. 14. These data were collected at a 10 Hz sampling rate, much slower than that used for the other residential systems. At this sampling speed, the profile is very similar in appearance to that for the electric water heater. The dryer is motor-driven and also has a sizable resistive load due to the electric heating element. A larger spike at the start similar to that noted for other motor-driven systems would likely have been recorded had sampling been performed at the faster 40 Hz rate used on other systems. Note a sharp spike is visible in the reactive profile.

4.3. VALIDATION OF ENERGY/DEMAND IMPACTS FROM BUILDING AND SYSTEM IMPROVEMENTS

The non-intrusiveness and fast hookup of a NILMS make it a very attractive option for short-term validation of reductions in energy use and/or demand from building improvements. A portable version was used to obtain the two-week power profile shown in Fig. 15 for a 13,000 ft^2 office building (Building 2518 at ORNL). Power levels reflect periods just before, during, and after a major lighting retrofit. These results confirm the approximately 15 to 20 kW drop in total building power during occupied periods and the 6 kW drop during unoccupied periods. These short-term measurements confirm that the retrofit will save approximately 84,000 kWh of lighting energy annually and reduce building peak demand by around 30%. Short-term, non-intrusive

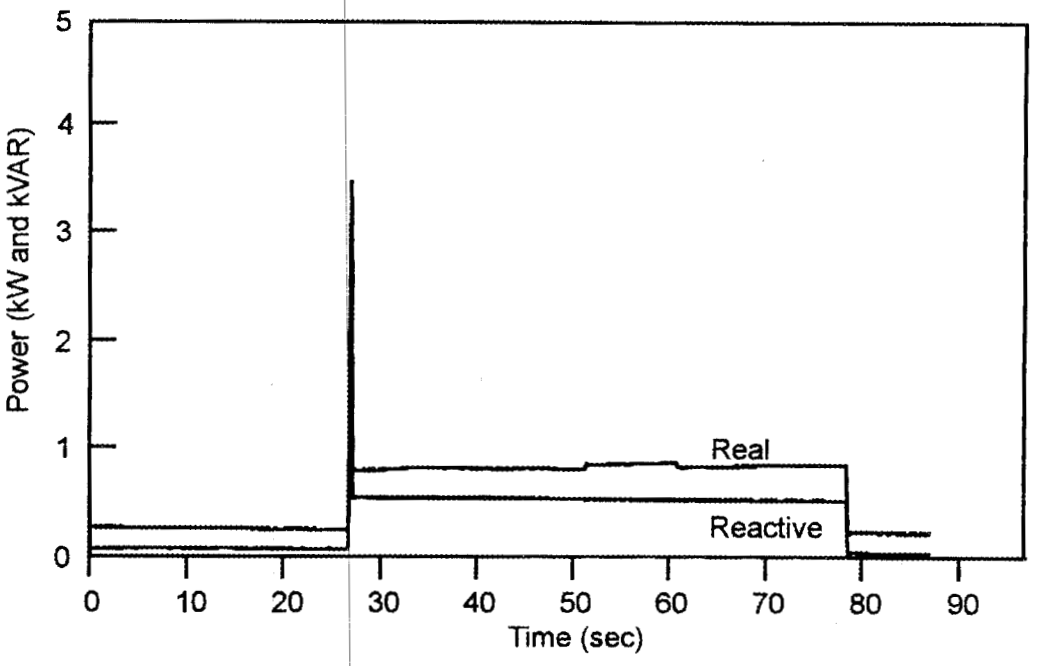

Fig. 12. Power profile impacts of a residential refrigerator.

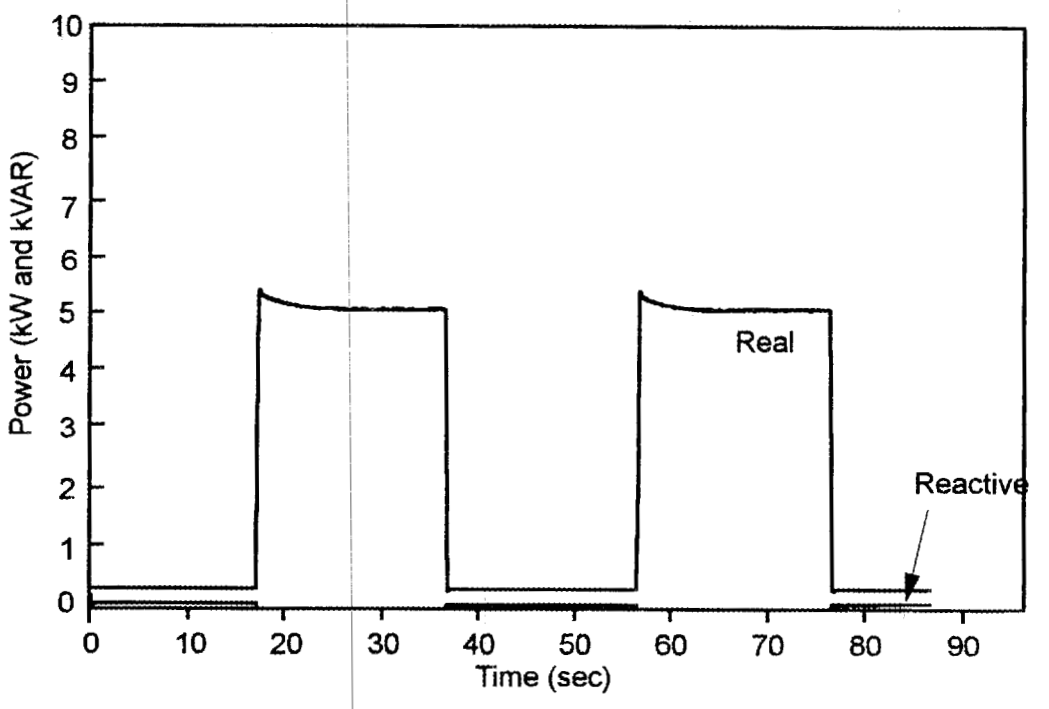

Fig. 13. Water heater impacts to power profiles.

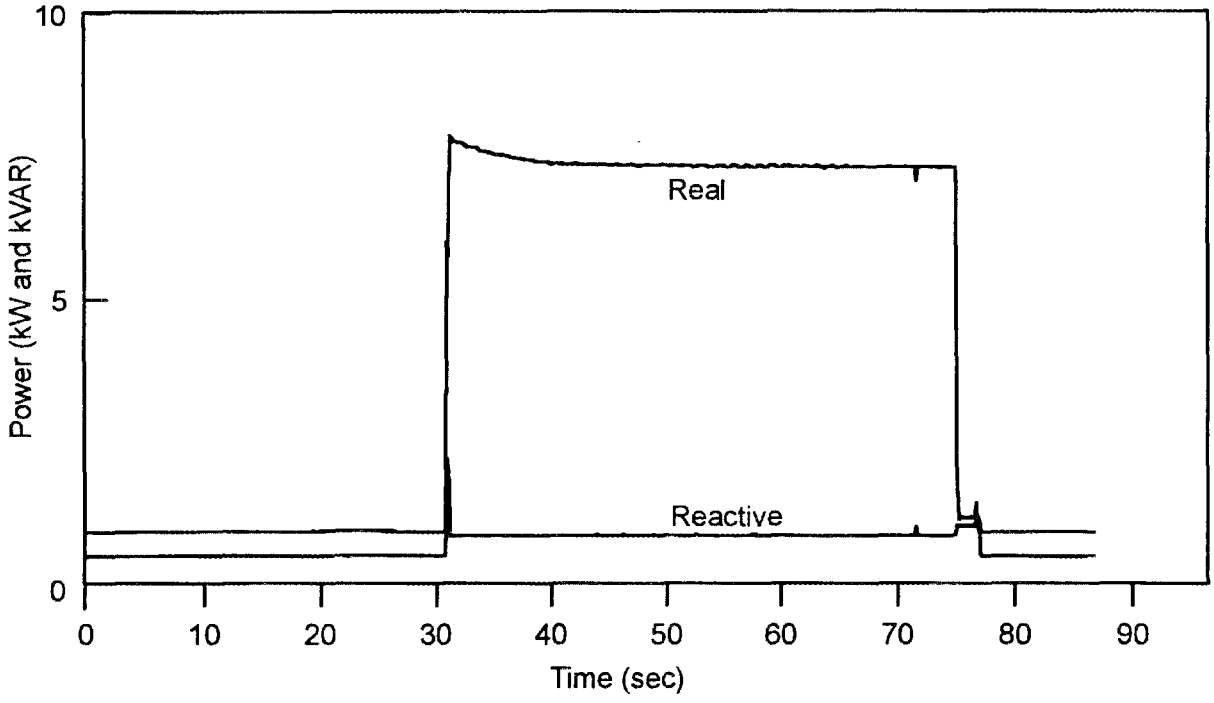

Fig. 14. Building power profiles showing a residential clothes dryer on/off.

monitoring like this is accomplished easily with this portable system. As a result, the system offers the ability to confirm savings from major retrofits at very low cost.

4.4. FILTERING

The 60 Hz waveform present in building power can bleed through and show up on the DC output of a watt transducer. As a result, this electrical "noise" can show up as rapid fluctuations on recorded power profiles for both commercial and residential applications. This type of noise is partly responsible for the rapid fluctuations visible in many of the building power profiles presented. Filtering techniques can be used to remove or average out these fluctuations. A digital, low-pass filter was used to remove the 60-Hz noise from the commercial unfiltered power profile in Fig. 16. As can be seen in the filtered signal, significant profile variation can still exist after application of a digital low-pass filter. The multitude of small, cyclic loads common in the commercial building tested 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.

Although noise can occur on residential power profiles, it was found to be much less significant. In the residential profile in Fig. 11, power fluctuations can be seen, but they are small even when compared to the power required by a single 60W lamp. As a result, filtering is not needed to successfully identify and quantify the loads measured in the residential test building.

While filtering can be used to remove electrical noise and perhaps to smooth signals such that significant events are easier to identify and quantify, it does impose some requirements on the user. One of the more important requirements is that the use of signal filtering may require higher sampling frequencies. Otherwise, the rapid spikes that characterize the start of numerous types of commercial and residential equipment can be skewed or perhaps missed.

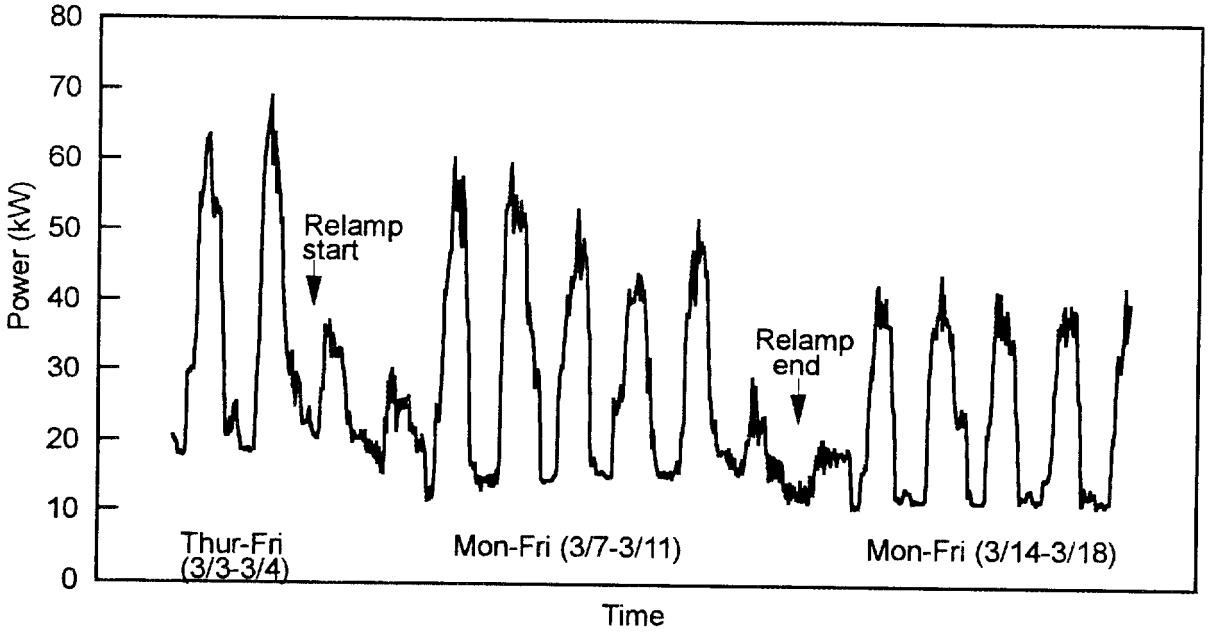

Fig. 15. Power trace showing impact of lighting retrofit in a small commercial building.

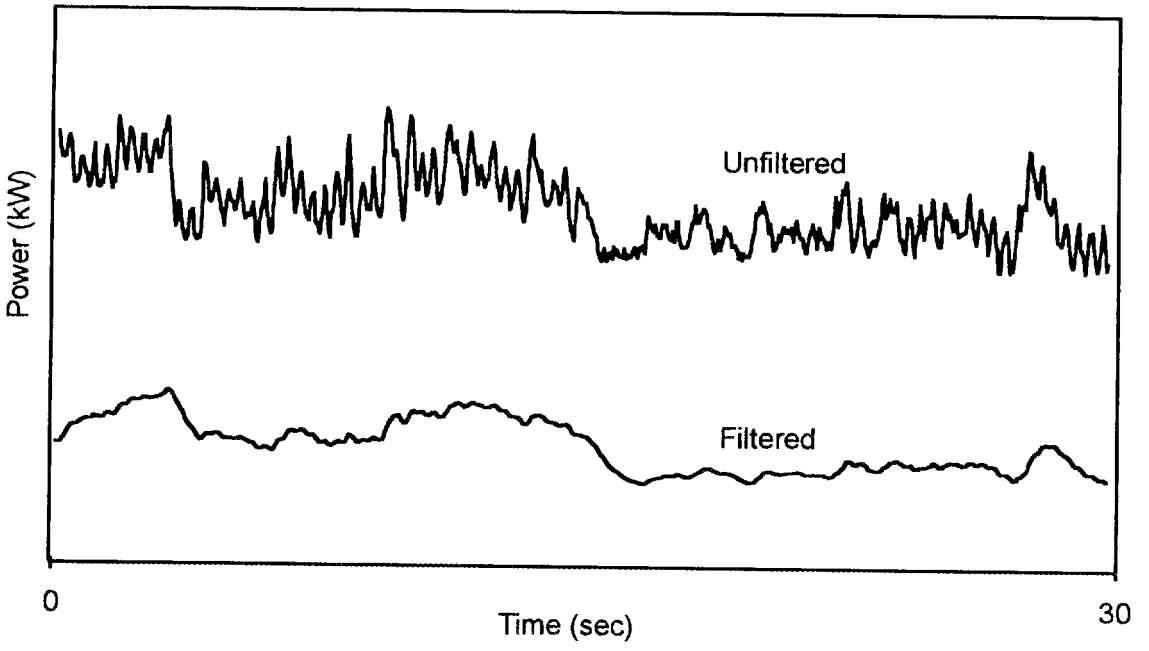

Fig. 16. Unfiltered and filtered real power profiles from an office building.

4.5. ADVANTAGES/LIMITATIONS FOR THE EXISTING BUILDINGS RESEARCH PROGRAM

4.5.1. Measuring Energy Use and Demand

A NILMS offers capabilities that will supplement the energy/power monitoring techniques currently used in the EBRP. The system can provide an efficient method for measuring energy use and demand. The system can be hooked up rapidly, resulting in low installation cost, and non-intrusively in many cases. Non-intrusiveness is accomplished by installing the system at a central electric service panel outside or inside a building, and by avoiding power interruption for the installation (safety practices may require power interruption in some cases).

The system can be installed and ready to collect power data in about one hour. Using a NILMS for measuring building energy use and/or demand is straight-forward, so a NILMS should be an efficient method for measuring energy use and demand reductions for building retrofits. The system should be most attractive for retrofits whose performance can be verified in a short period (less than one day and up to one month).

The next level of NILMS application would be for monitoring a building end use (such as HVAC or lighting). If monitoring at an electrical panel serving only the end use, short-term monitoring could be started rapidly and accomplished at low cost. If an end use is assessed based on whole-building power monitoring, cost becomes mostly dependent on data handling and analysis and not on the monitoring system. Short-term monitoring in this case could still be accomplished at low cost. Short-term monitoring for measurement of building system retrofits is where a NILMS would most benefit the EBRP.

4.5.2. Improving Energy Audits

The ability of a NILMS to enhance energy audits will depend on the extent of the audit and the types of building and building systems being assessed. A NILMS will likely find use in more detailed energy audits where identifying equipment inefficiencies, evaluating existing motor performance, sizing new motors, measuring demand profiles, measuring power factor, and validating building or building systems operations are audit objectives. These objectives are most typical for audits in commercial and industrial buildings. With the high-speed monitoring capability of a NILMS, it is possible that many of these measurement objectives could be accomplished at a central monitoring point such as the building power entrance.

4.5.3. Improving Estimates of Energy Savings and Demand Reductions

The EBRP often uses hourly building models to estimate the energy savings and demand reductions that occur from specific retrofits. To improve accuracy, models are often "tuned" to measured weather and performance data collected at the site. Hourly weather data is often used for tuning because it is readily available in many cases. Tuning normally relies on longer-term performance data (weekly and monthly), however, because shorter-interval data are often unavailable and too expensive to obtain. Because a NILMS can easily measure performance data at shorter intervals and at low cost, its use could enhance our building modeling capabilities and lead to improved savings estimates.

A NILMS could also provide a low-cost way of validating engineering estimates which often are the sole basis for evaluating retrofit cost-effectiveness and making retrofit decisions. It is not uncommon for actual retrofit performance to be dramatically different from engineering estimates. The reliance of savings estimates made solely on engineering calculations is due in part to the complexity and cost associated with measuring performance. A NILMS could often dramatically reduce this complexity and cost such that better informed decisions can be made regarding retrofit options.

4.5.4. Quantifying Energy Use From Short-Term Measurements

A NILMS can be used to quantify energy use for buildings and building systems. A NILMS can be used for either short-term or long-term measurements. If the building load being studied is approximately constant, such as lighting and water heating, short-term measurements using a NILMS could provide a low-cost way of estimating annual energy use. Longer-term measurements or a series of short-term measurements might be adequate where the building or end use consumption varies over time. Because of power interruption, a non-intrusive system might still be desirable for long-term monitoring.

4.5.5. Validating, Developing, and Improving Operating Strategies

A NILMS can be used to obtain valuable building and building system power profiles that provide knowledge of existing building and building systems operations. As a result, the system could be valuable in validating an operating strategy (perhaps for commissioning), assessing the impact of and developing new operating strategies (load control, load shifting, HVAC system setup/setback, etc.), and in identifying problems

with existing operating strategies (are they practiced and/or working). Specific issues that power profiles can resolve include:

Determination of operating strategies for controlling/reducing energy use and demand,

Determination if buildings and building equipment operate as designed, and

Identification of building and equipment operation problems such as:

a) excessive occupied and/or unoccupied energy use,
b) simultaneous heating and cooling,
c) inefficient control strategies that increase energy use and/or demand,
d) demand peaks,
e) power factor problems,

and perhaps many other operating problems that occur for both buildings and building systems.

5. SUMMARY AND CONCLUSIONS

A NILMS provides an easy and low-cost method for obtaining measured performance data on a building or building system. With sufficient resolution and sampling speed, many individual building loads can be identified and quantified from whole-building power profiles. The resolution or ability to discern load changes can be excellent in residential buildings and in commercial buildings that do not have an excessive amount of cyclic equipment. The existence of numerous pieces of cyclic equipment in a commercial building can degrade the available resolution to detect smaller loads. Lower-speed sampling, 1 or 2 samples per minute, can provide substantial information about building and building system operations. Somewhat higher-speed sampling, perhaps as high as 1 Hz, allows disaggregation of many loads from a whole-building power profile. To consistently capture the distinguishing power profile impacts that help characterize specific loads within a building, however, such as equipment starting spikes, it is necessary to sample at a much higher speed, 20 Hz at least and preferably 40 Hz or higher. If filtering is used, sampling speeds exceeding 40 Hz may be required to insure that unique power profile impacts are not filtered out of the resulting signal.

While applications for a NILMS seem numerous, additional work is needed to verify their usability and perhaps improve upon their capabilities. Suggestions include:

- Apply the system to more buildings to better determine how effective it can be utilized to identify building and building system operating deficiencies.
- Investigate approaches to making the system even less intrusive, such as making power profile approximations solely from current monitoring. This would eliminate the intrusiveness sometimes associated with installing voltage taps.
- Further investigate the combination of higher-speed data collection and filtering techniques to produce improved profiles while capturing the unique profile impacts that specifically identify equipment.
- Make longer-term measurements (perhaps one month to a year) on residential and commercial buildings to see how well long-term loads can be characterized using short-term measurements.

Because a NILMS can be used to obtain power profiles easily and at low cost, it could be valuable for a number of applications. Applications can span all building sectors-- commercial, residential, and industrial. With the ability to "see" and quantify both energy use and demand through short-term monitoring, a NILMS should prove valuable for the performance assessment of existing buildings, building systems, power-related

processes and process equipment, the evaluation of retrofits, as a supplemental tool for the energy auditor, as a validation tool for building commissioning, for identifying demand problems and the development of demand solutions, and for a number of other applications. These systems could prove very valuable to private companies, utilities, universities, government agencies and others that have a need for the characterization and/or performance assessment of buildings, building systems, and other energy-using equipment or processes. Its most beneficial applications will likely be those that are best served by its advantages (fast and simple hookup, low-cost, and limited intrusiveness).

6. REFERENCES

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APPENDIX A. SYSTEMS DESIGN, INSTRUMENTATION SCHEMATICS, AND HOOKUP DETAILS

A.1. Systems Design

Desktop-PC-based system:

Laboratory Technologies LabTech Notebook data acquisition software

Data Translation DT2837, 16-bit A/D board

Data Translation DT717-T, external terminal panel

Data-logger-based system:

Campbell Scientific 21X data logger

Campbell Scientific GraphTerm software
(for data transmission from logger to portable computer)

Power measurement equipment:

Ohio Semitronic watt transducers

Models GWV5-004B, GWV5-007B, GWV5-008B

Current transformers

Close-pin type:

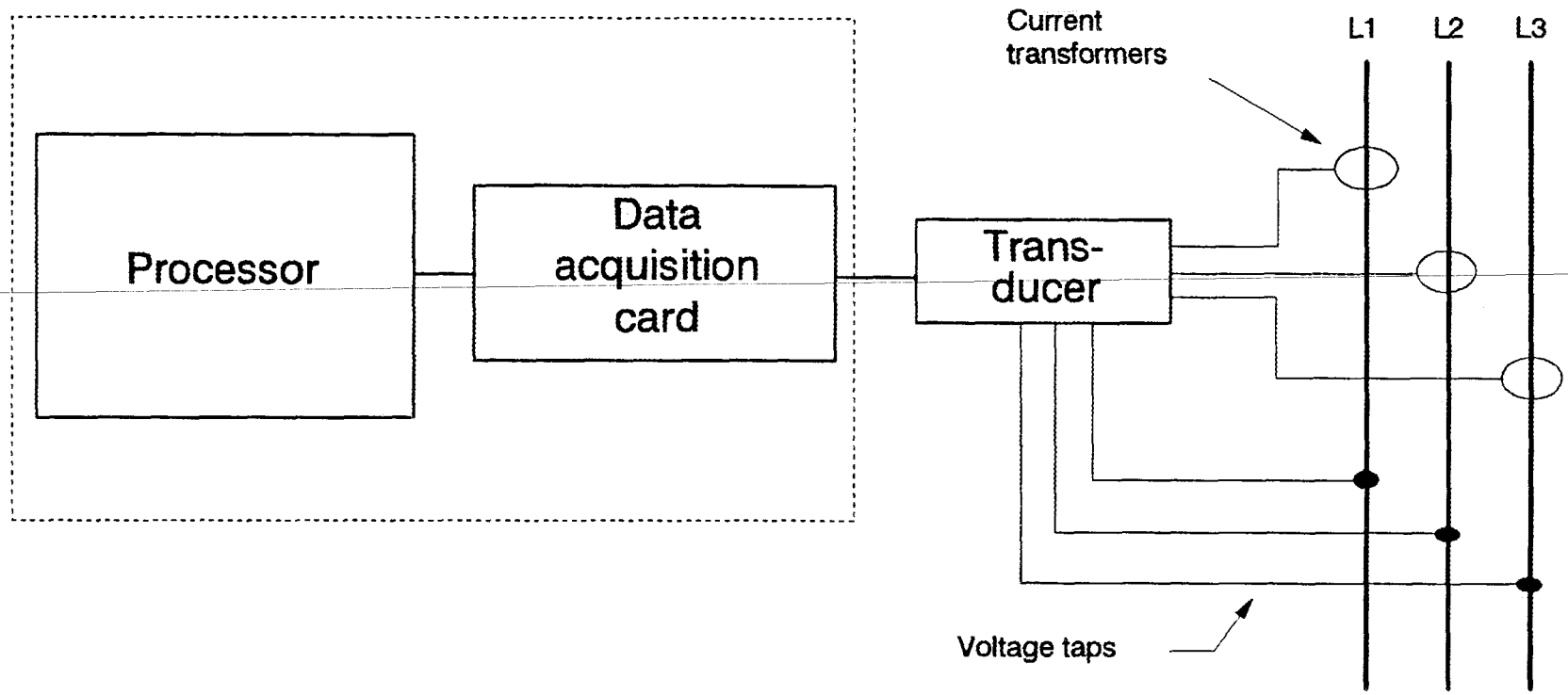
Davis Instrumentation Model 1201.37 (100:1 ratio)

Davis Instrumentation Model 100.270 (100:1 ratio)

Clamp-on ring type:

Magnetic Specialties custom made with ratios of 500:5 and 100:5.

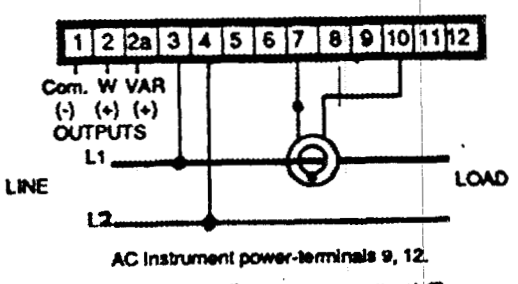
A2. System Components



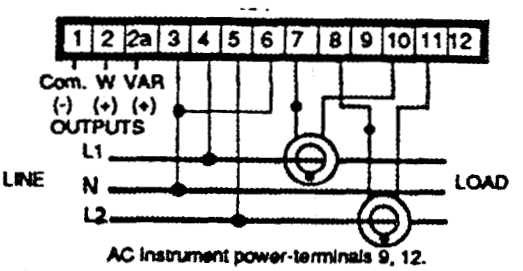
Voltages and currents are input to the watt transducer. A 0-1mA current proportional to the power draw is output from the transducer to the data acquisition card. The current from the watt transducer is passed through a resistor at the input to the data acquisition card to provide a voltage input matching the input range of the data acquisition card. Data acquisition card setup and data acquisition are controlled by programming instructions contained in the processor (LabTech Notebook software on the computer and internal programming for the data logger). In the desktop-PC-based system, a data acquisition card is installed in the PC. In the data-logger-based system, the processor and data acquisition card are both part of the data logger when purchased.

A.3. Watt Transducer Connections

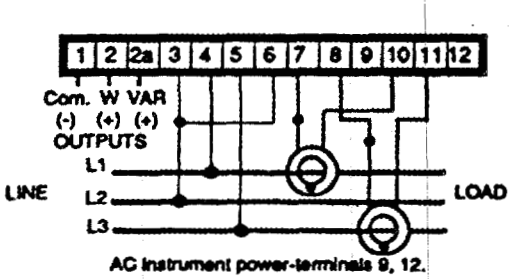
Connection diagrams for Ohio Semitronic, Inc., watt transducers - models GWV5-004B, GWV5-007B, and GWV5-008B.



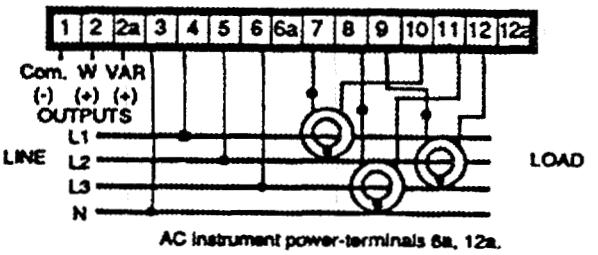
1φ, 2 WIRE, 2 ELE.: GWV5-004B



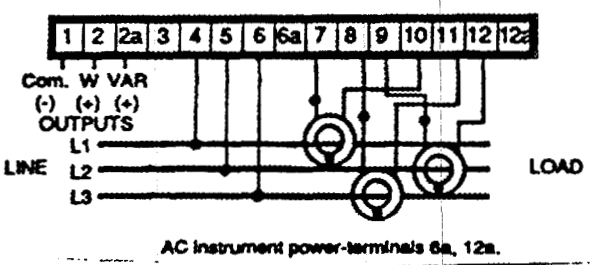
1φ, 3 WIRE (EDISON), USING 2 ELEMENT: 004B



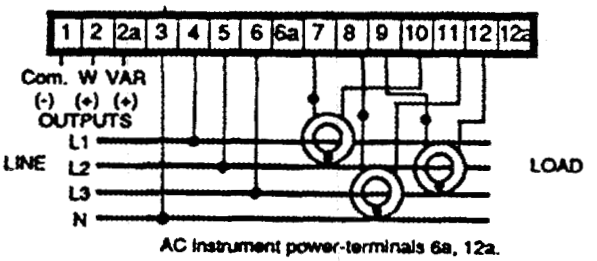
3φ, 3 WIRE, Δ USING 2 ELEMENT: 004B



3φ, 4 WIRE, 3 ELEMENT, $V_{L-N} \leq 150$, 007B



3φ, 3 WIRE, $150 < V_{L-N} \leq 300$, 3 ELE., 008 B



3φ, 4 WIRE, $150 < V_{L-N} \leq 300$, 3 ELE., 008 B

APPENDIX B. SUMMARY REPORT OF PRELIMINARY WORK ON BUILDING 3147 AT ORNL

HIGH SPEED DATA MONITORING TESTING

W. P. Levins

June 12, 1992

HIGH-SPEED DATA MONITORING TESTING

PURPOSE

The purpose of this exploratory high-speed monitoring testing was to collect, identify, and quantify building equipment and system loads by nonintrusive monitoring of building entrance service power lines. This type of monitoring has the potential to replace the much more expensive submetering monitoring which is prevalent in present-day building monitoring programs.

DESCRIPTION OF BUILDING AND METHODOLOGY

The testing took place at Building 3147 at Oak Ridge National Laboratory. The building, built in 1988, houses the staff of the Energy Efficiency and Renewables Section of the Energy Division. It is a 12,000 Ft^2, two-story, flat-roofed brick office building. It contains 60 room-type offices, mostly along the periphery of the building, a conference room, a vending machine room, rest rooms on each story, and an elevator.

All but 11 of the offices contain individual HVAC systems consisting of combination electric A/C and resistance heat units. The A/C is rated at 7000 Btu/h output at 740 Watts input, the resistance heaters at 6500 Btu/h (1900 Watts), and the fan at 1/10 HP @ 0.8 Amps. The conference room has its own similar HVAC system, and each story has its own combination HVAC system, but with a larger capacity than the office units.

The building contains 2 copy machines, a refrigerator, an electric water heater for each story, soft-drink and condiment vending machines, and ceiling-mounted fluorescent lighting in the corridors. Each office contains eight 40-Watt ceiling-mounted fluorescent lamps and a personal computer system.

Building 3147, like many other buildings at ORNL, is supplied with 480 VAC three ϕ 4-wire power. This power is split into 208 and 120 VAC three ϕ and single ϕ power through the use of step-down transformers and distributed through the building.

Calibration tests were run in an attempt to isolate known events, such as turning on an individual HVAC system, in order to obtain a "signature" of the event for use in later identification of power line profiles.

A data logger was used to collect and store total and reactive power data before, during, and after each planned event so that subsequent analysis of the data could be carried out on a personal computer. Although no real-time data analysis was done, most future uses of high-speed building monitoring would include real-time analysis.

EXPERIMENTAL SETUP

The main item of instrumentation used to monitor power coming into Bldg. 3147 was a FLEX-CORE Model GWV5-008B Watt-VAR transducer with a linear 0 to 1 ma DC output (1 ma output equals 3 KW input). It was manufactured by Morlan & Associates of Worthington, Ohio. Specification sheets for GWV5 series transducers are included in the Appendix. The transducer is powered by 115 VAC single ϕ.

Since the feeder lines into Bldg 3147 are 480 VAC three ϕ with a neutral wire (a "WYE" type connection), the outputs from three clamp-on current transformers (CTs) are fed into the watt-var transducer. The CTs have a turn ratio of 500:5 (maximum 500 amps primary rating gives 5 amps output) or a linear 100/1 ratio, and were wound by Magnet Specialties, Inc., of Trenton, NJ and designated as their Part No MS4069.

The feeder lines into Bldg 3147 are split into two wires per phase in order to make the wires more flexible mechanically, a technique that is not uncommon. This allows large feeder lines to be handled more easily by electrical workers. A CT was clamped around one line of each of the three phases for this installation. Assuming that the same current is carried by each line of the same phase, a multiplication factor of 2 must be applied to the transducer output to obtain the correct total power and reactive power loads.

An output of 1 ma (full scale rated output) from the transducer corresponds to 3 KW if wired directly, but the 2 lines per phase situation and a 100/1 CT ratio makes the actual power input equal to:

$$2 \times 100 \times 3 \text{ KW} = 600 \text{ KW}.$$

The data logger used to sample the outputs from the Watt-VAR transducer was a Model 21X Micrologger made by Campbell Scientific, Inc. of Logan Utah. This logger is able to scan and convert at least 80 samples per second when reading voltages in the range of 0 - 500 mv DC.

A 2.49 KΩ $\pm$ 1% resistor was installed between the total power output terminal and ground, and another between the reactive power output terminal and ground. This means that a 1 ma output from (600 KW input to) the Watt-VAR transducer would correspond to a voltage drop across the resistor of:

$$1 \text{ ma} \times 2.49 \text{ K}\Omega = 2490 \text{ mv}.$$

Each KW would therefore correspond to:

$$2490 \text{ mv} / 600 \text{ KW} = 4.15 \text{ mv}$$

or

each mv would correspond to:

$$600 \text{ KW} / 2490 \text{ mv} = 0.24 \text{ KW}.$$

A short computer program was developed using Campbell PC208 Support Software that can be downloaded into the 21X Micrologger through serial ports coupled by a Campbell SC32A Optically Isolated RS232 Interface. A listing of the data collection program is included in the Appendix.

The program allowed the user to initiate data collection by pressing a key on the Micrologger keyboard. The logger had sufficient internal memory so that 40 readings per second of total and reactive power could be collected and stored for a 90-second period. This time period appears to be sufficient in order to obtain the necessary information for both before, during, and after conditions for a scheduled "calibration" event. Usually 10 to 15 seconds of data were collected before an event, such as manually turning on an A/C or heater, took place. Data were collected for 15 to 60 seconds while the appliance was operating. The appliance was shut down while there was still 10 to 15 seconds of data collection remaining.

The data stored in the Micrologger were then downloaded into a personal computer through optically-isolated serial ports using the Campbell PC208 Support Software. The data files downloaded into the personal computer were in ASCII (American Standard Code for Information Interchange) format, and able to be imported into a spreadsheet. Boreland's Quattro Pro2 was the spreadsheet used to analyze and plot the downloaded data.

DISCUSSION OF RESULTS

Figure 1 shows a plot of an initial run made on February 7, 1992, to determine if the experimental setup was working properly. Note that this is the only figure presented with data taken at 10 samples/channel/second - all other sampling rates are at 40 samples/channel/second. The higher value line on the plot is the reactive power, while the lower value line represents the reactive power. Two things are readily apparent from the plot - the total power looks noisy and several events had occurred during the time period.

Figure 2 is a plot of testing done to determine the effect on the power line of cycling a 1900 Watt resistance heater in one of the offices. The on, off and on again events are marked as such on the plot. The upper line on all plots is the total power, while the lower line is the reactive power. Once again it appears that the total power line is noisy and that some other events have taken place during the test period.

In order to get a closer view of what was happening, Figures 3a and 3b show the total power in more detail for the on and off periods, while figures 4a and 4b show the corresponding reactive power for each event. Figure 3a shows that the total power increased by about 2½ to 3 KW for a second or so and then settled down to about a 2 KW increase over the pre-on level. Figure 4a shows the reactive power increasing slightly by about 0.2 KVAR and essentially staying there.

Figure 4b shows a drop of about 2KW when the heater was turned off while the corresponding reactive power in Fig 5b shows a drop of about 0.1 KVAR.

Figure 3a and 3b are extremely interesting in that both show the total power to have a major frequency (ripple) of about 3 Hz and an amplitude of about ±1.5 KW.

The specifications for the Watt-VAR transducer (see sheets in the Appendix) state that maximum output ripple is < ±0.5% of full scale (300 KW) or ±1.5 KW. This means that any variations less than 3 KW are within the tolerances of the transducer. It is possible to lower the

ripple by adding a capacitor between the output and ground, but that would increase the time constant of the transducer. The specifications also state that the response time to arrive at 99% of a step change is 400 milliseconds.

Based on the transducer specifications, it appears that the Watt-VAR transducer may be the source of the apparent "noise" which appears on the power line. However, two other potential sources of error could be the sampling rate and also the high-speed stability of the A/D conversion process in the datalogger.

It is possible to alias, or misrepresent, the true frequency, waveshape, and value of a periodic signal if it is not sampled at a proper rate. In general the sampling rate should be as high as is practical, and the sampling rate should not be at the same frequency as the input signal or at one of its lower harmonics.

It appears that the 3 Hertz ripple in the total power in Figures 3a and 4a is real, because about 13 samples were taken for each cycle. Therefore, the sampling rate is probably OK for the total power.

However, the frequency of the reactive power appears to be higher, at about 10 Hertz or perhaps 20 Hertz, while the amplitude is lower, at about 0.3 KVAR. Again, a 40 Hertz sampling rate is probably OK in this case also, but a higher rate might be safer.

One should keep the above comments in mind, while the remaining plots are discussed.

Figures 5a and 5b deal with the 1st floor central heating and A/C systems respectively. The I^2R heating system turn off is easily recognized in figure 5a by the approximate 13 KW drop in total power, and a very, very slight drop in reactive power. An interesting 5 KW slow rise in total power occurred during the 30 to 35 second interval. The cause of this rise is unknown, but the building was full of people and in normal operation, so almost anything could have happened. No change in the reactive power took place, so this unknown load does not appear to be motor operated. When the heating system was turned on again the total power rose 13 KW and the reactive power surged about 1 KVAR and then dropped down about 0.75 KVAR after a few seconds. This surge is caused by the distribution fan going on with the heaters. Another reactive power surge shows up about 10 seconds after the heaters went on, but the cause of this is unknown. Further testing revealed that the increase does not appear to be connected to the heating system operation. This event caused the reactive power load to increase by about 0.5 KVAR. The heating system was turned off at about 85 seconds on the time scale with results similar to the initial shut off.

Figures 6a and 6b show the reactive components of the load when the heater was turned off and on respectively, in more detail.

Figure 5b shows the changes in total and reactive power when the A/C was turned on and off. The total power increased by about 6 KW, while the reactive power surged about 5 KVAR and then decreased 3 KVAR from this peak over the next 2 seconds. The A/C was turned off at about 52 seconds on the time scale accompanied by corresponding drops in total and reactive power. Figures 6a and 6b respectively show the reactive power A/C on and off histories in more detail.

Figure 7a shows the drop in reactive power when the heater was turned off. This 0.2 KVAR drop was caused by the distribution fan motor shutting off, as the heaters themselves have no reactive component. Likewise, Figure 7b shows a reactive load increase of 0.2 KVAR after an initial surge when the heaters were turned on. The heater fan motor caused this increase, also. Figure 7b also shows the reactive load increase of about 0.6 KVAR caused by the before-mentioned unknown event.

Figure 8a shows the total and reactive components of the building elevator going up and down. Both profiles are easy to recognize because of the magnitude and initial surges when the elevator starts. Note that the duration of the power usage is 20 seconds when the elevator goes up one floor, but only 2 seconds when the elevator goes down a floor.

Figure 8a also shows the effects of cycling a bank of corridor fluorescent lights on and off. The total power changes about 2 KW each time, but does so over about 2 to 2.5 seconds. Figure 8b shows both components of fluorescent lighting operation in more detail. The reactive load does not appear to change as the lights are turned off, but appears to increase slightly as the lights are turned on, only to decrease to a slightly lower value than the original after a second or so. The capacitive ballasts in the lighting cause the decrease in the reactive power.

Figures 9a and 9b show the detailed effects on total and reactive power of making 10 copies on one of the copy machines.
The operational cycle of a copy machine is rather complex as it contains controlled motor, resistance heater and high-voltage components. Indeed, figure 9a shows what appears to be 3 different events taking place over a five-second interval. Copy machines may also have a warm-up period if they have not been used for a period of time, but such a period is not present during this data period. The reactive power component does not appear to be as complex, showing a 0.15 KVAR increase. However, both the frequency and relative magnitude of the noise level on the reactive power is high (about +7%, -2.5%), suggesting that perhaps a smoothing filter could be used to advantage.

Figures 10a and 10b are repeats of the corridor fluorescent light turn-on cycle. These plots are similar to figure 8b which shows both total and reactive power on the same plot. Figure 10a, the total power plot, is rather unspectacular, showing a slight increase of about 1.3 KW on a noisy line as the lights were turned on. The reactive power in figure 10b is more definitive, clearly showing the initial surge in reactive power followed by a steady-state value about 0.2 KVAR lower than the pre turn-on period.

Figures 11a shows the total and reactive power plots for a period with the copy machines operating and include a fluorescent light off-on cycle. Figure 11b shows two fluorescent light off-on cycles, this time with both copy machines turned off. The purpose of this testing was to determine if the copy machines were the source of any line noise. The data were taken on a Saturday to minimize occupancy effects, but there were two other people working in the building.

The total power line noise appeared to drop from about 2 KW to 0.4 KW after the copy machines were turned off, but the total power in the building dropped from about 18 to 9 KW also. Since each machine uses about 2 KW, about half of the drop in total power can be attributed to them - the source of the other 5 KW load is unknown. The fluorescent light cycles are visible in figure 10b and match those from previous tests.

CONCLUSIONS

One fact which became apparent during the course of this exploratory testing was that it is difficult to recognize what is happening in an occupied office building. Total power monitoring by itself cannot be used to identify most of the events occurring in a building. The reactive component of the entrance power, when used in conjunction with the total power, offers a trained analyst a means of identifying singular events as they occur. However, modern office buildings contain many complex devices, and the identification process is not a simple one, especially in larger office buildings during regular business hours. Many of the events which occur amount to a small (< 2%) percentage of the building load. When coupled with a noisy power line or noisy output from a transducer, the task becomes more difficult.

More sophistication in both the monitoring equipment (i.e. line filters, transducers, data acquisition system) and the analysis tools (i.e. waveform analysis software) are definitely necessary in order to identify random events occurring in an office building. If real-time analysis is desired, the task becomes yet more difficult, and will require specialized custom software and high-quality hardware to do the job. However, a knowledge of the equipment in a building as well as calibration signatures are necessary in order to carry out an analysis. I do believe that inlet power-line monitoring is feasible and practical- but it is still in its developmental stages.

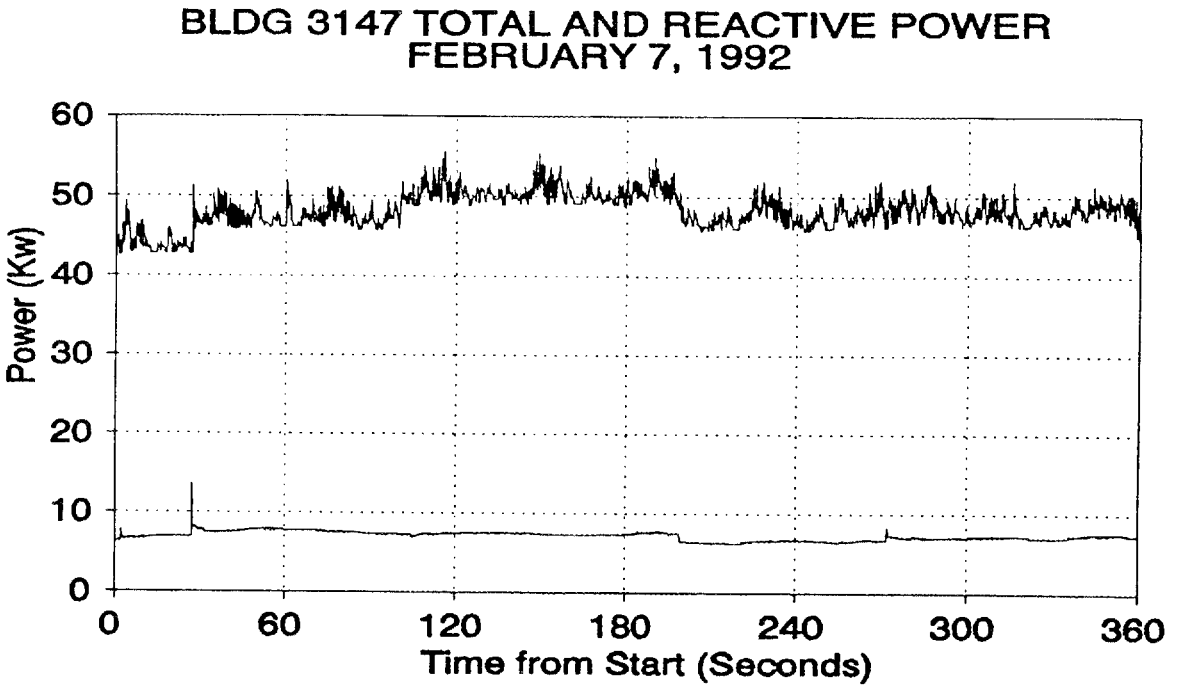


Figure 1 Building 3147 Total and Reactive Power
February 7, 1992

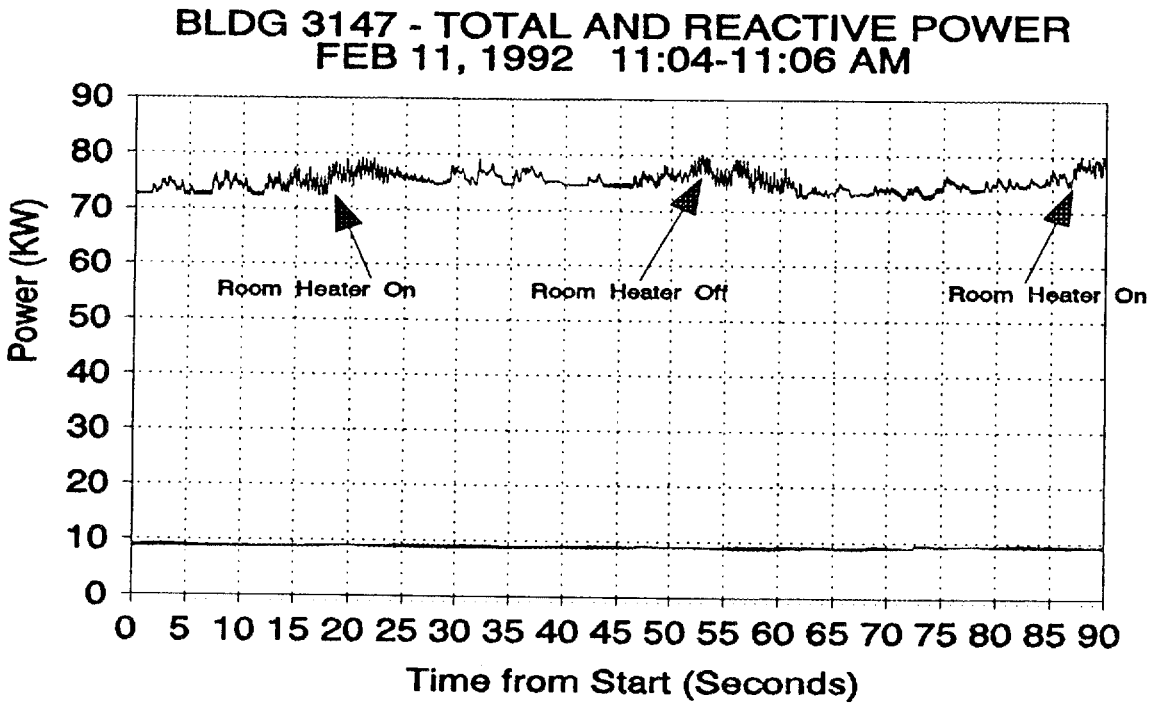


Figure 2 Building 3147 Total and Reactive Power
February 11, 1992

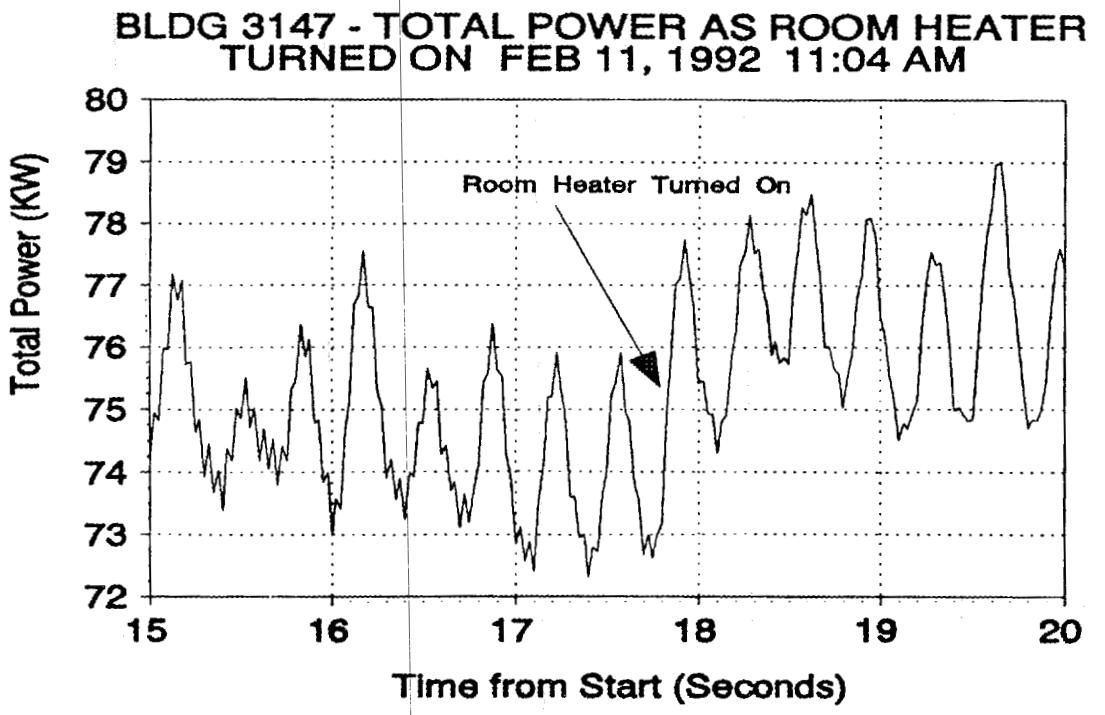


Figure 3a Building 3147 Total Power, Room Heater On
February 11, 1992

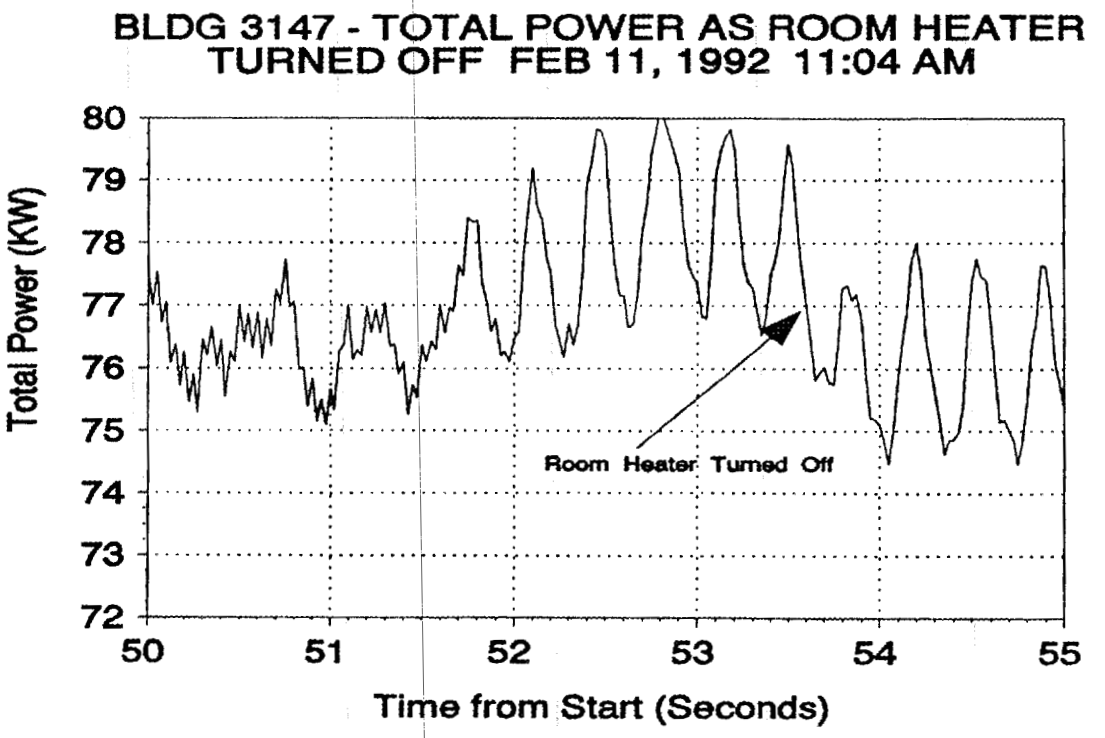


Figure 3b Building 3147 Total Power, Room Heater Off
February 11, 1992

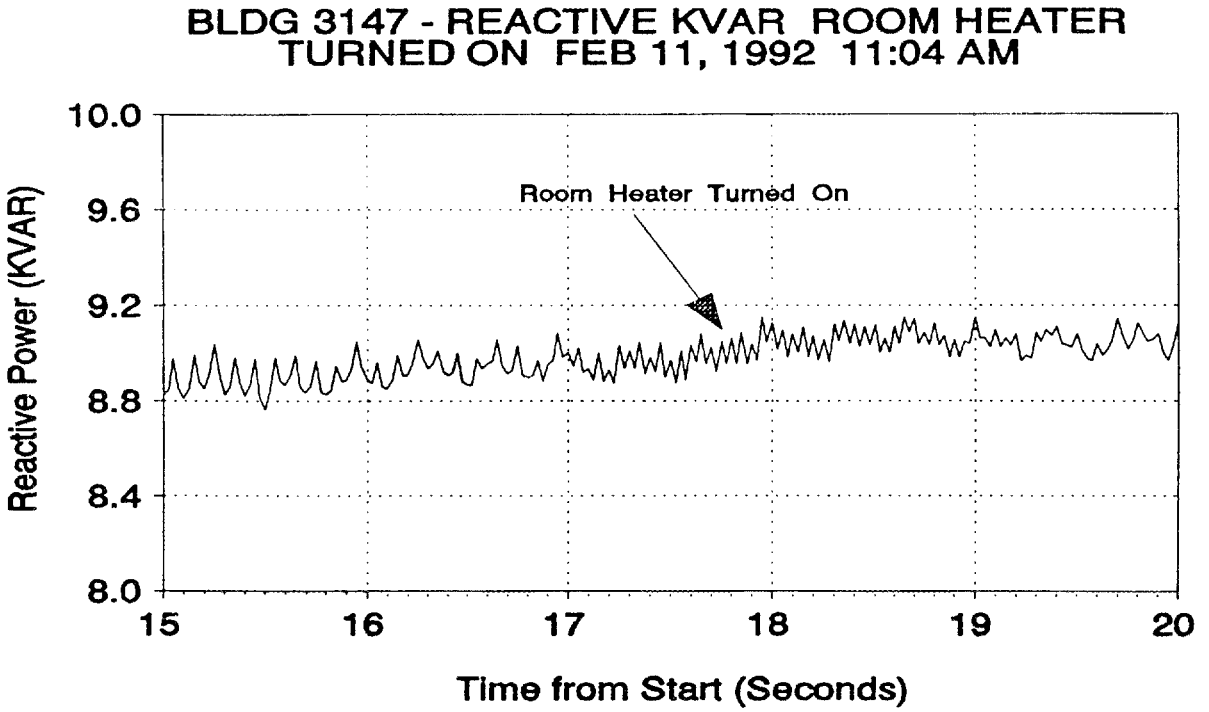


Figure 4a Building 3147 Reactive KVAR, Room Heater On
February 11, 1992

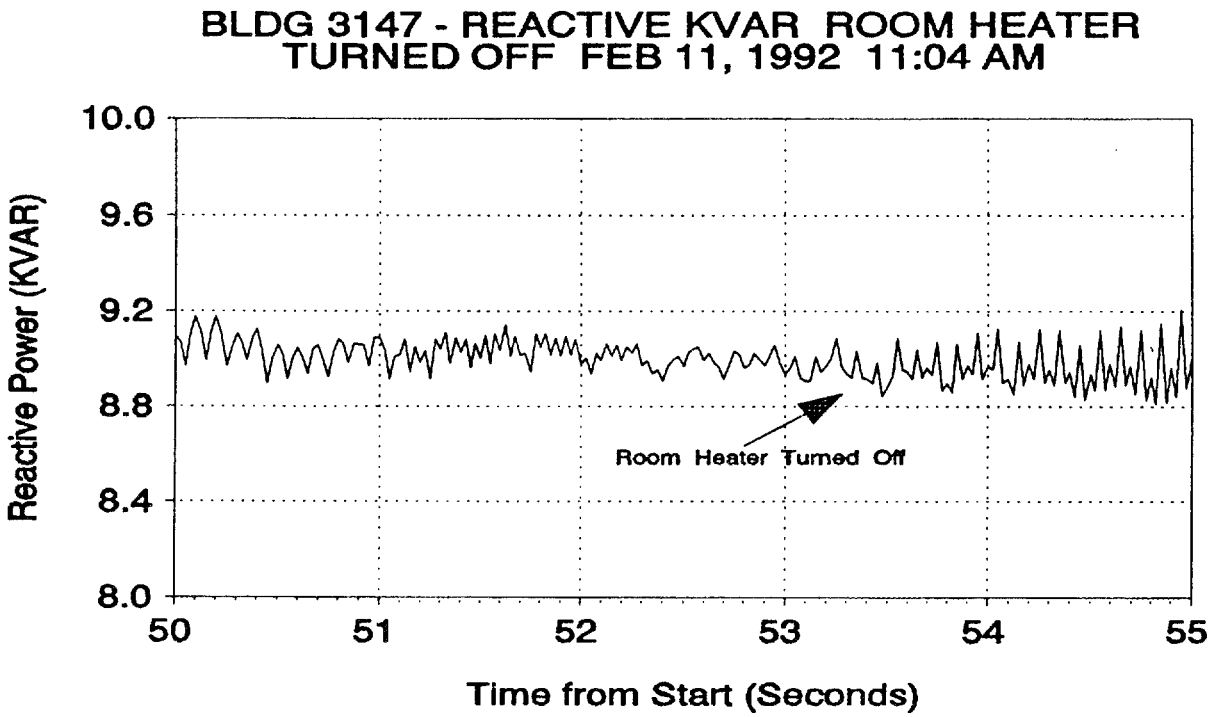


Figure 4b Building 3147 Reactive KVAR, Room Heater Off
February 11, 1992

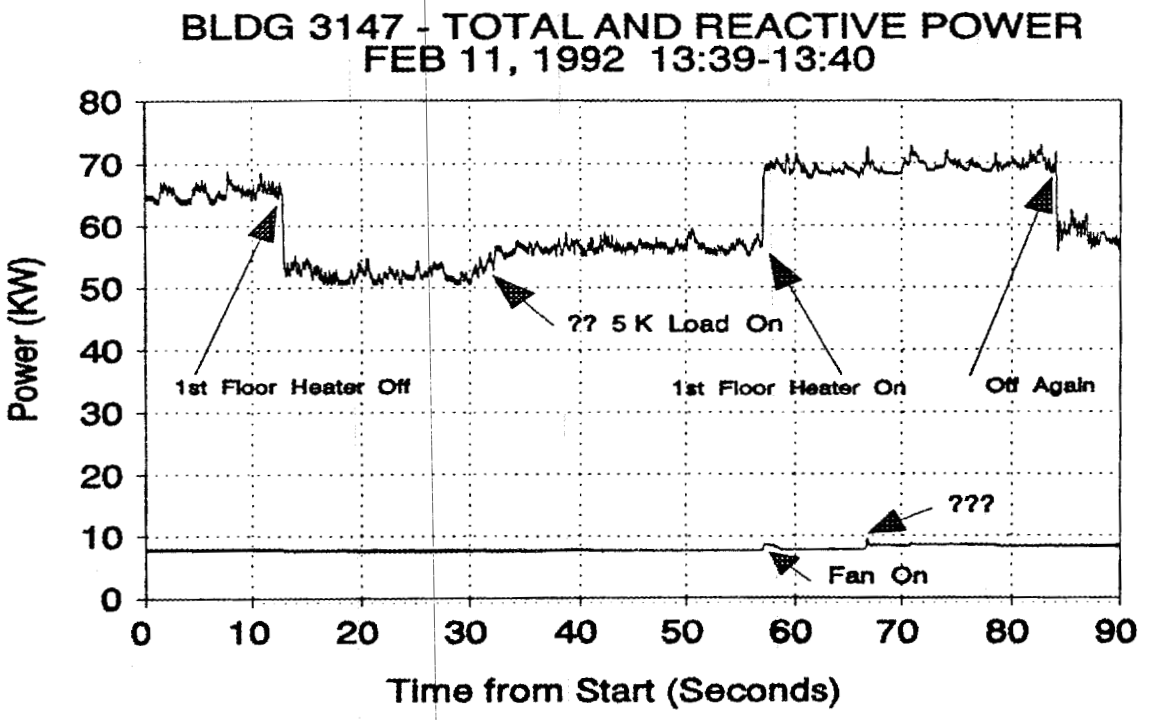


Figure 5a Building 3147 Total and Reactive Power
February 11, 1992

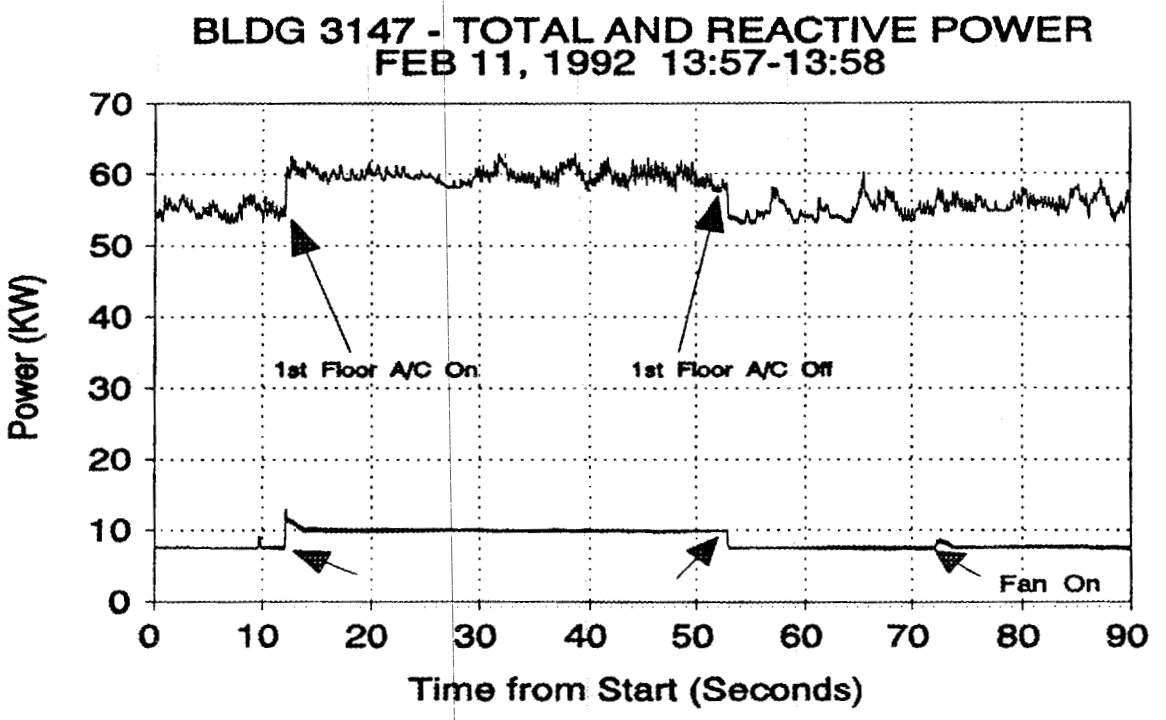


Figure 5b Building 3147 Total and Reactive Power
February 11, 1992

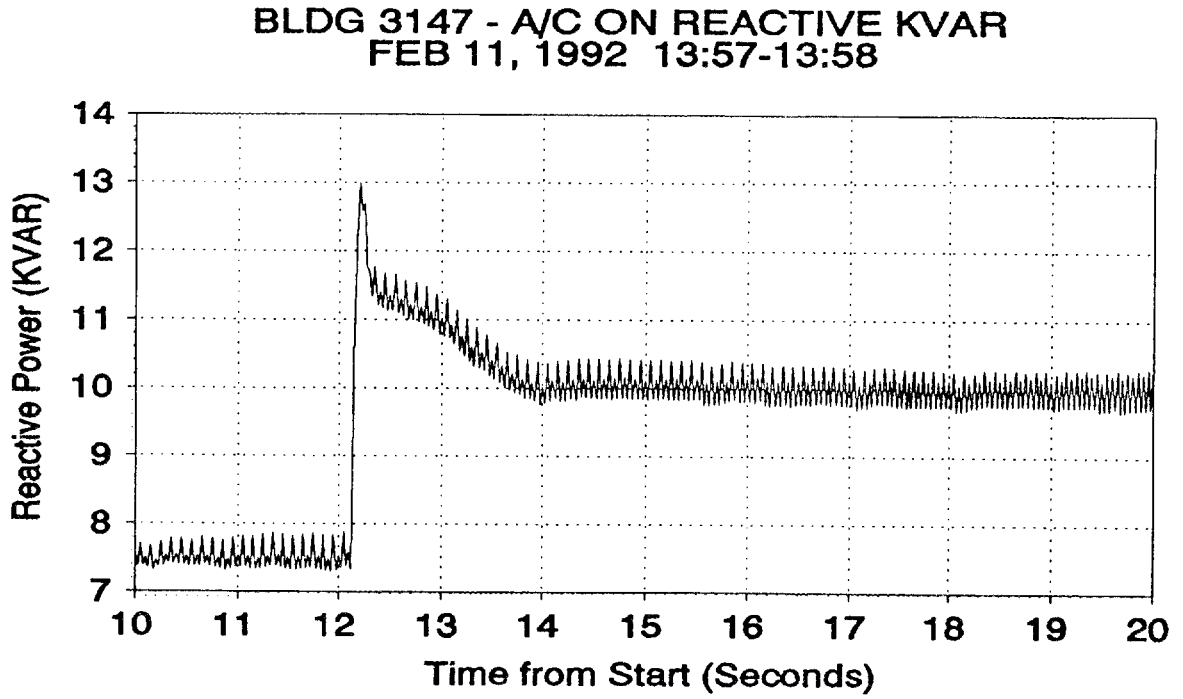


Figure 6a Building 3147 A/C On Reactive KVAR
February 11, 1992

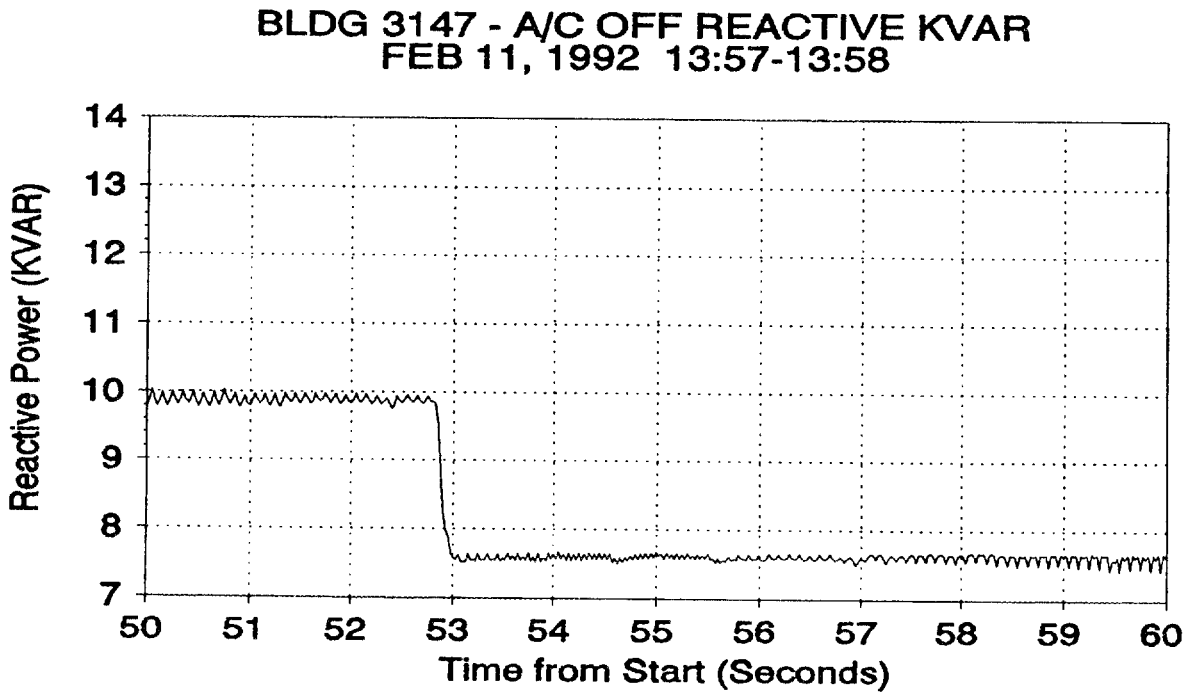


Figure 6b Building 3147 A/C Off Reactive KVAR
February 11, 1992

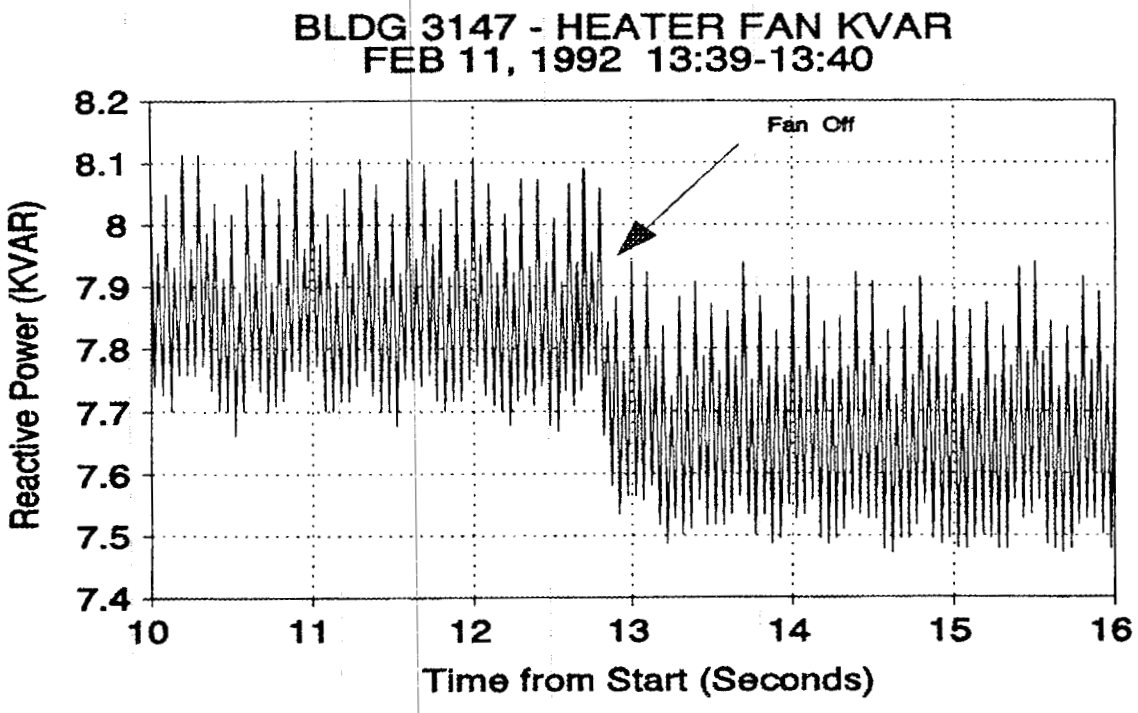


Figure 7a Building 3147 Heater Fan On KVAR
February 11, 1992

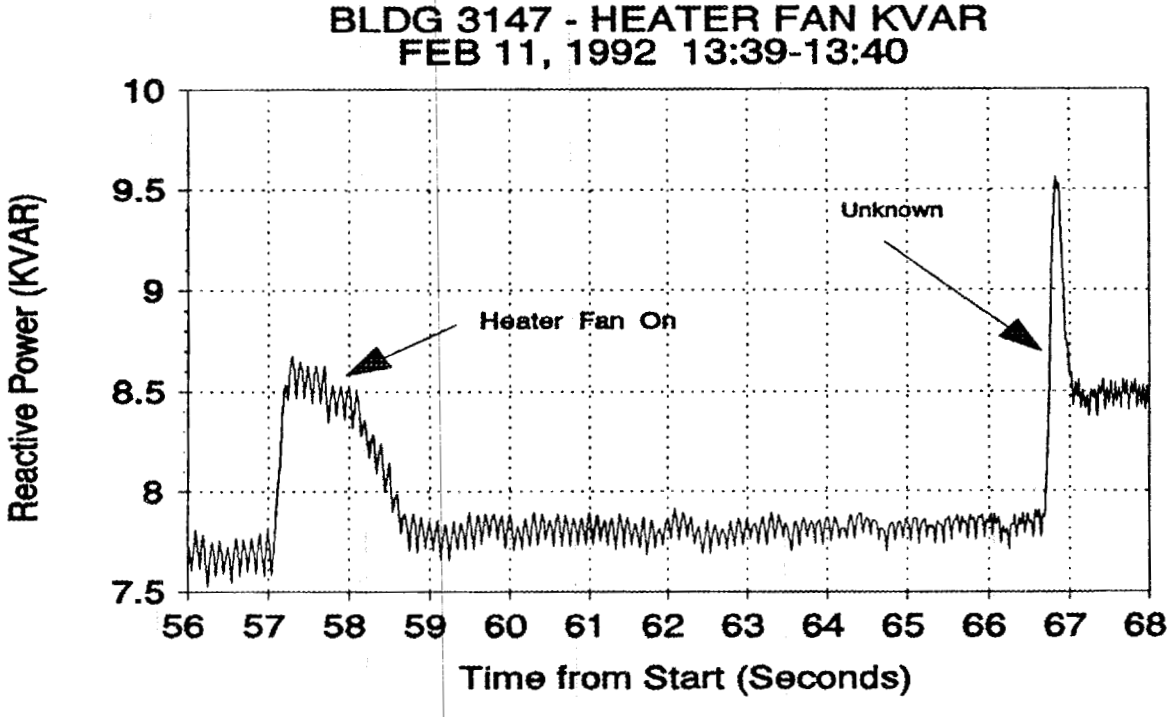


Figure 7b Building 3147 Heater Fan Off KVAR
February 11, 1992

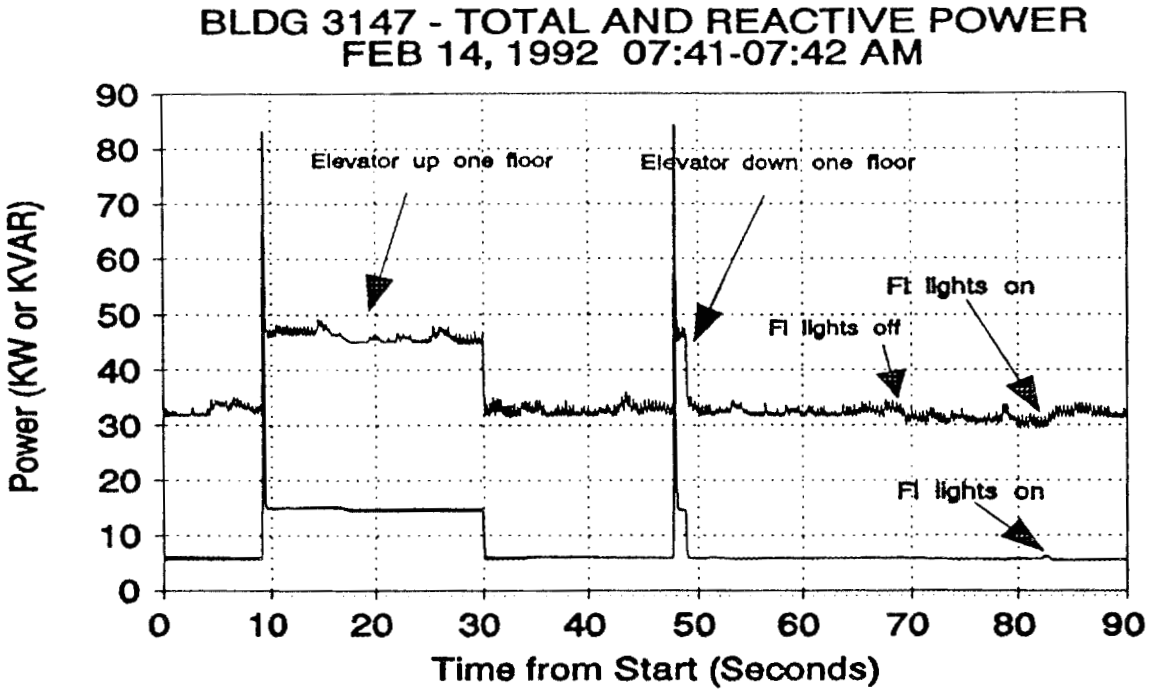


Figure 8a Building 3147 Total and Reactive Power
February 14, 1992

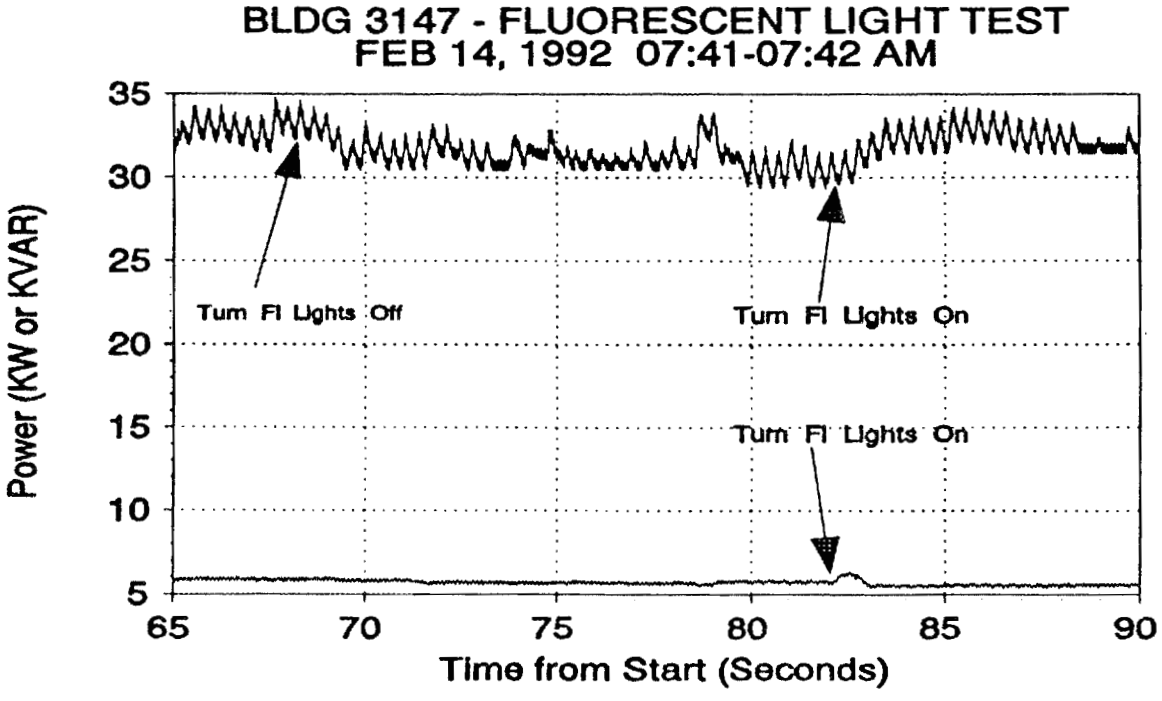


Figure 8b Building 3147 Fluorescent Light Test
February 14, 1992

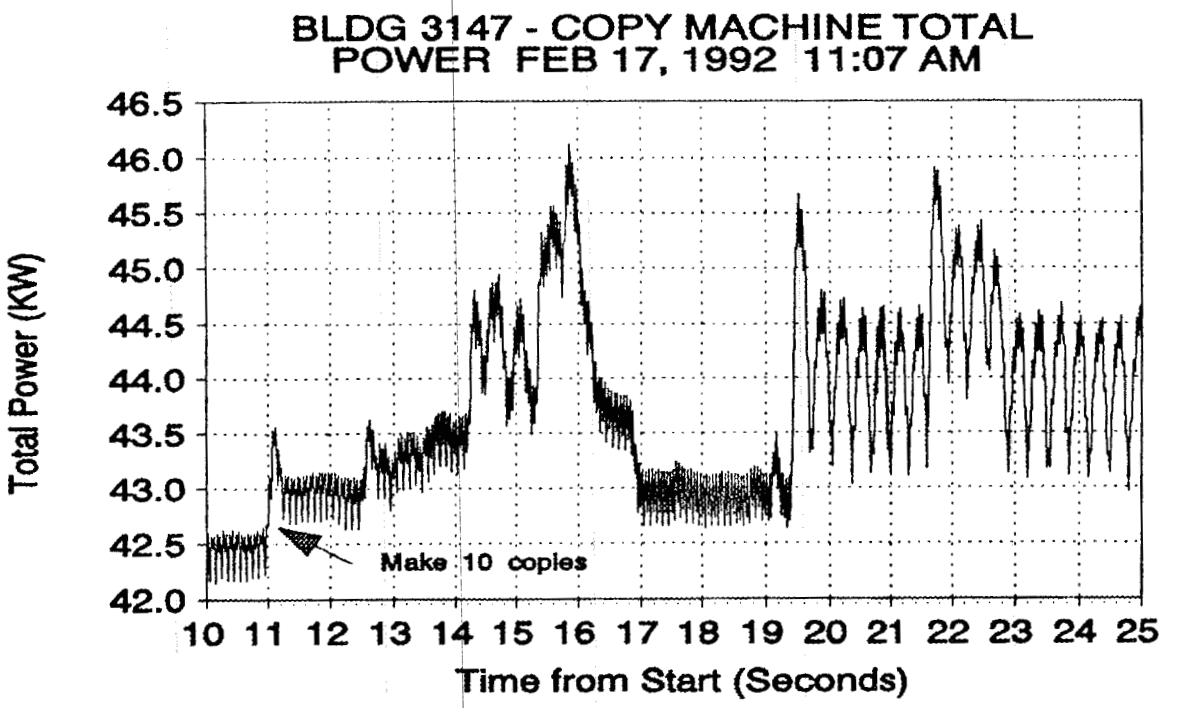


Figure 9a Building 3147 Copy Machine Total Power
February 17, 1992

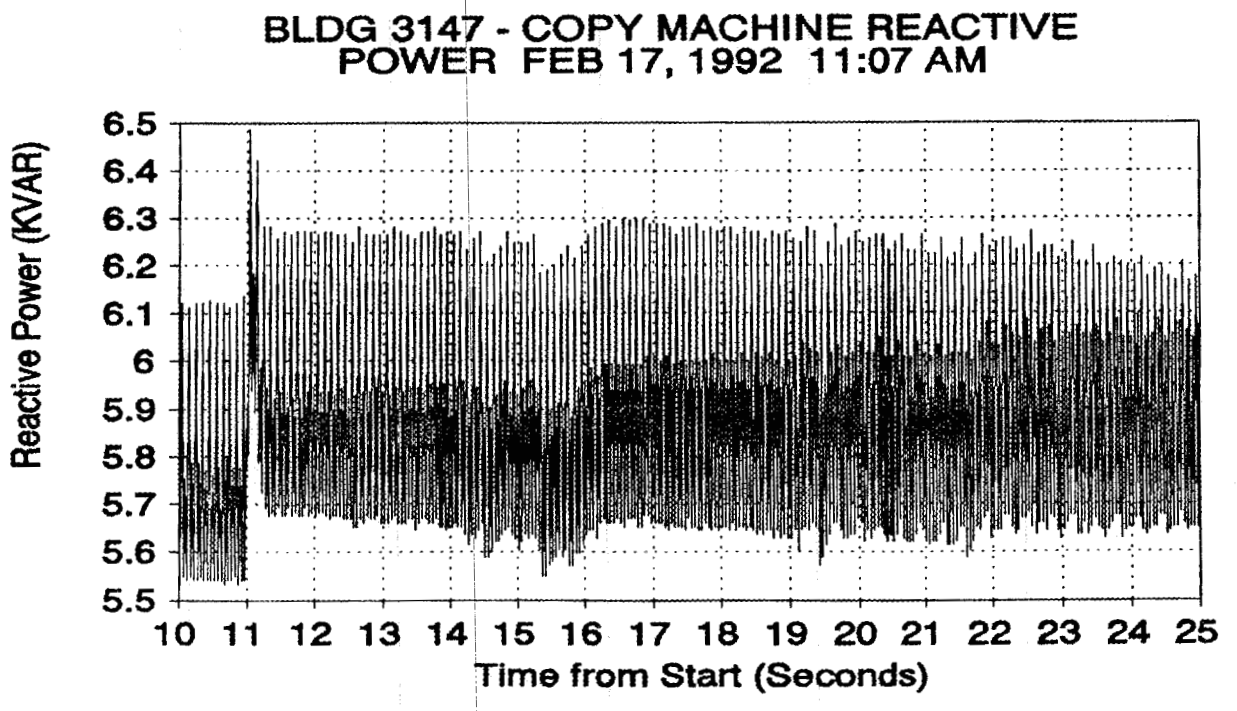


Figure 9b Building 3147 Copy Machine Reactive Power
February 17, 1992

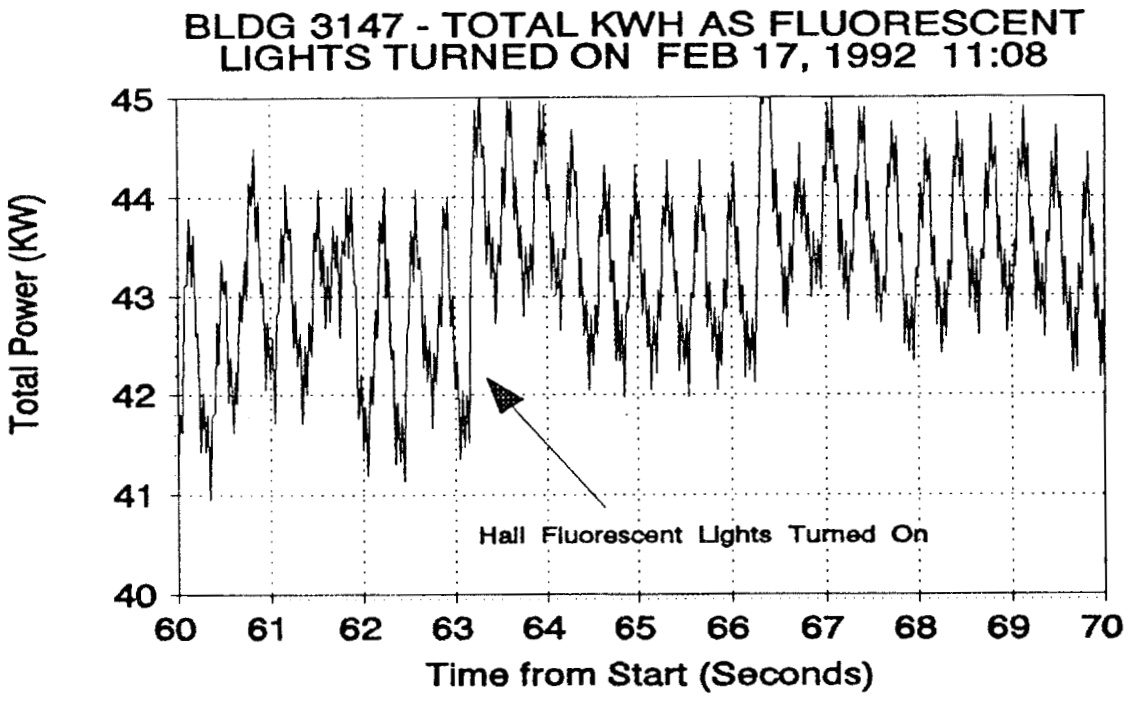


Figure 10a Building 3147 Fluorescent Lights on Total Power, February 17, 1992

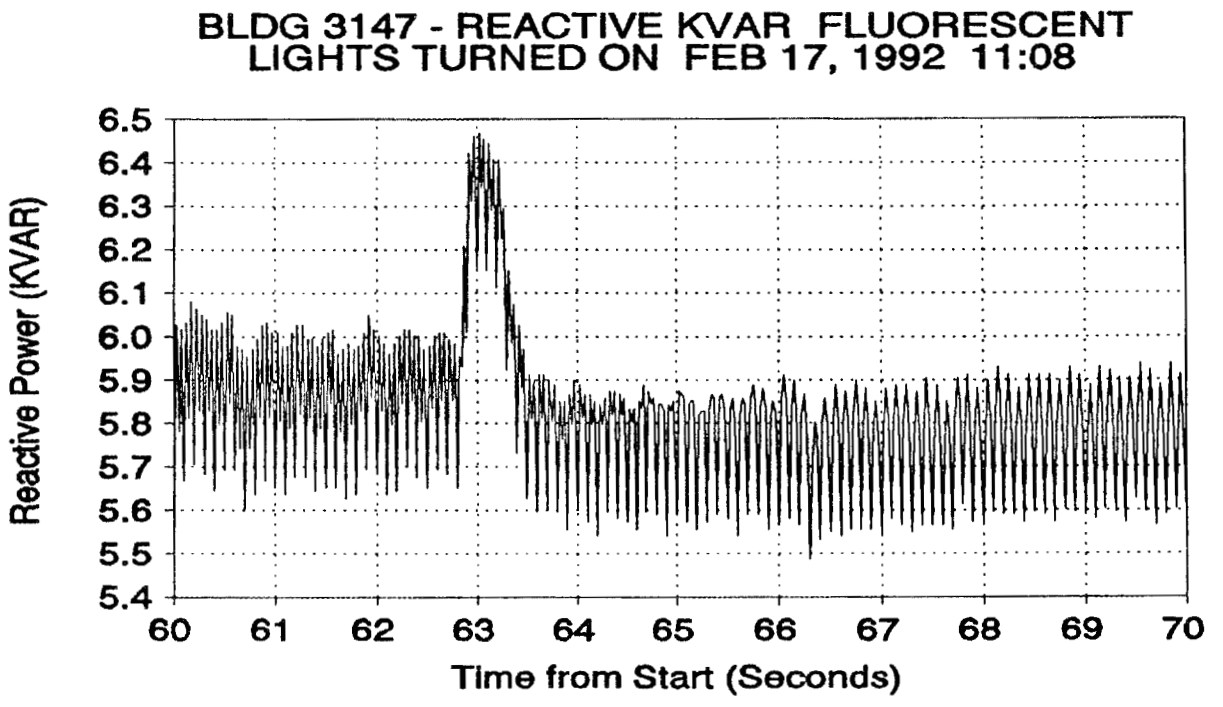


Figure 10b Building 3147 Fluorescent Lights on Reactive KVAR, February 17, 1992

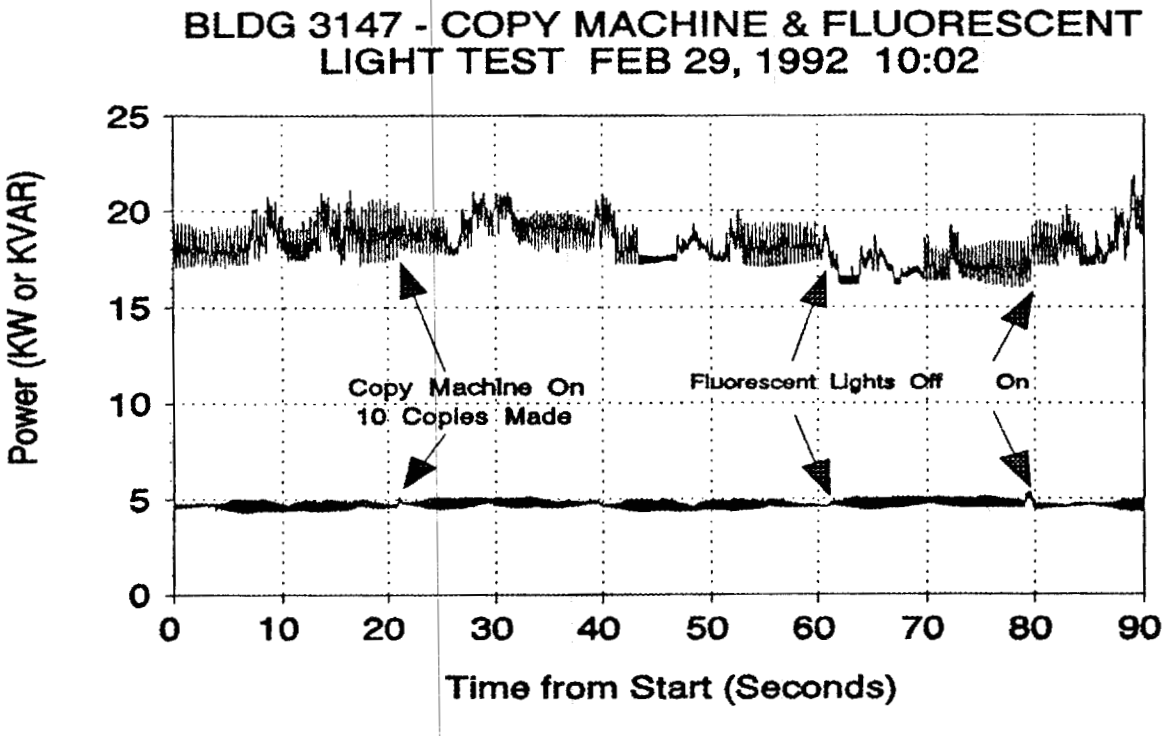


Figure 11a Building 3147 Fluorescent Lights Test with Copy Machine, February 29, 1992

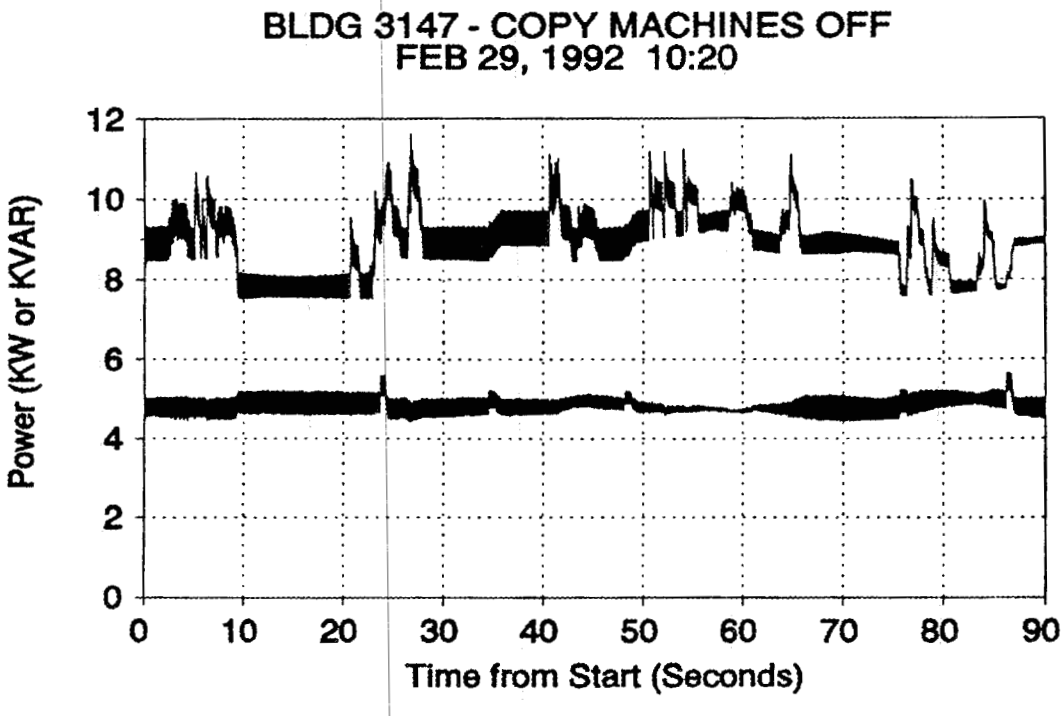


Figure 11b Building 3147 Fluorescent Lights Test with Copy Machine, February 29, 1992

WATT TRANSDUCERS

PRECISION AC WATT TRANSDUCER MODEL GW5

ACCURATE TO 0.2% OF READING

FEATURES

- Accurate regardless of variations in voltage,current, power factor, or load.
- Available with 1, 2, 2½, or 3 element configurations. Provides bi-directional operation.
- Accuracy maintained over wide temperature range.

APPLICATIONS

- Equipment monitoring for process control.
- Integration into energy management systems, or a variety of sub-metering applications.
- Measurement using direct-connection, current transformers, and/or potential transformers.

SINGLE PHASE MODELS-INTEGRAL SENSOR (ONE ELEMENT)

INPUTS		F.S. IN (WATTS)	STANDARD OUTPUTS MODEL NUMBER GW5-							
VOLTAGE	CURRENT		0-1mA*	0-1mA	0-10Vdc*	0-10Vdc	4-20mA	4-20mA*	0-5Vdc*	0-5Vdc
0 to 150	0 to 5	500	001A	001B	001C	001D	001E	001EG	001CX5	001X5
	0 to 10	1000	010A	010B	010C	010D	010E	010EG	010CX5	010X5
	0 to 20	2000	019A	019B	019C	019D	019E	019EG	019CX5	019X5
0 to 300	0 to 5	1000	002A	002B	002C	002D	002E	002EG	002CX5	002X5
	0 to 10	2000	011A	011B	011C	011D	011E	011EG	011CX5	011X5
	0 to 20	4000	020A	020B	020C	020D	020E	020EG	020CX5	020X5
0 to 600	0 to 5	2000	003A	003B	003C	003D	003E	003EG	003CX5	003X5
	0 to 10	4000	012A	012B	012C	012D	012E	012EG	012CX5	012X5
	0 to 20	8000	021A	021B	021C	021D	021E	021EG	021CX5	021X5

Highlighted models, (5A), can be used with current transformers.

Current transformers shown on page 2 Thru 6.

*Denotes self-powered unit, limiting input voltage ranges to:

85-135 for 150V models

200-280 for 300V models

380-550 for 600V models

All others require 85-135VAC instrument power, (60 Hz.).

LOOP-POWERED 4-20mA UNITS AVAILABLE

CONSULT FACTORY

ORDERING INFORMATION

Example: Self-powered, single-phase, 120V, 5A input with 0-5Vdc output, proportional to 0-500 Watts.

GW5-001CX5

50 HERTZ MODELS

Self-powered units-Add suffix "-50" to part number.

Units requiring external instrument power:

120V, 50Hz.-Add suffix "-51" to part number.

220V, 50Hz.-Add suffix "-52" to part number.

THREE PHASE THREE WIRE MODELS-INTEGRAL SENSOR (TWO ELEMENT)

INPUTS		F.S. IN (WATTS)	STANDARD OUTPUTS MODEL NUMBER GW5-							
VOLTAGE	CURRENT		0-1mA*	0-1mA	0-10Vdc*	0-10Vdc	4-20mA	4-20mA*	0-5Vdc*	0-5Vdc
0 to 150	0 to 5.0	1000	004A	004B	004C	004D	004E	004EG	004CX5	004X5
	0 to 10.00	2000	013A	013B	013C	013D	013E	013EG	013CX5	013X5
	0 to 20.00	4000	022A	022B	022C	022D	022E	022EG	022CX5	022X5
0 to 300	0 to 5.0	2000	005A	005B	005C	005D	005E	005EG	005CX5	005X5
	0 to 10.00	4000	014A	014B	014C	014D	014E	014EG	014CX5	014X5
	0 to 20.00	8000	023A	023B	023C	023D	023E	023EG	023CX5	023X5
0 to 600	0 to 5.0	4000	006A	006B	006C	006D	006E	006EG	006CX5	006X5
	0 to 10.00	8000	015A	015B	015C	015D	015E	015EG	015CX5	015X5
	0 to 20.00	16000	024A	024B	024C	024D	024E	024EG	024CX5	024X5

CONNECTION DIAGRAMS AND DIMENSIONS SHOWN ON PAGES 32-33

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6625 McVEY BLVD. - WORTHINGTON, OHIO 43235

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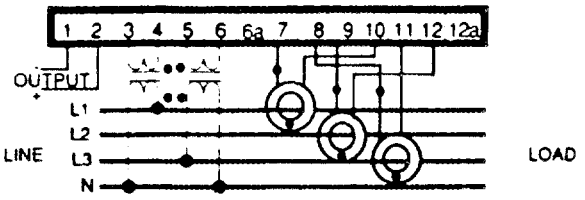
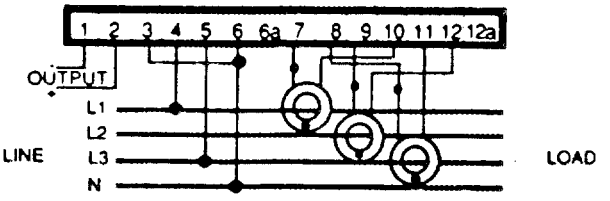
THREE PHASE FOUR WIRE CONNECTIONS
2 1/2 ELEMENT



AC instrument power-terminals 6a, 12a, if not self-powered

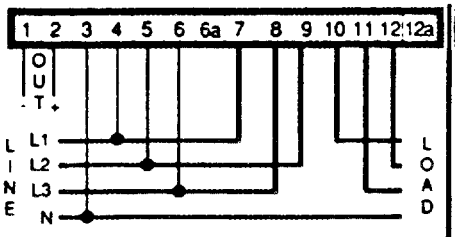
USING POTENTIAL AND CURRENT TRANSFORMERS



AC instrument power-terminals 6a, 12a, if not self-powered

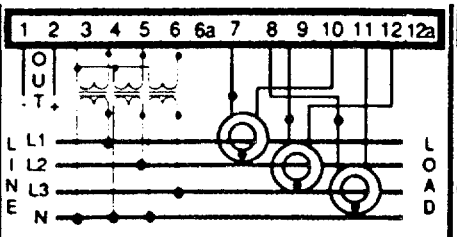
USING ONLY CURRENT TRANSFORMERS

THREE PHASE FOUR WIRE CONNECTIONS
THREE ELEMENT



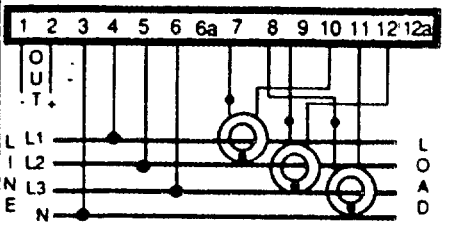
AC instrument pwr.-term. 6a, 12a, if not self powered

DIRECT CONNECTION



AC instrument pwr.-term. 6a, 12a, if not self powered

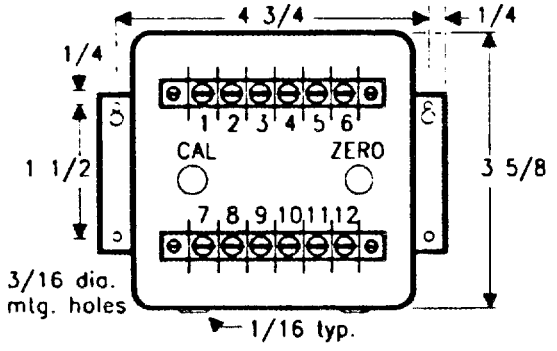
USING POTENTIAL AND CURRENT TRANSFORMERS



AC instrument pwr.-term. 6a, 12a, if not self powered

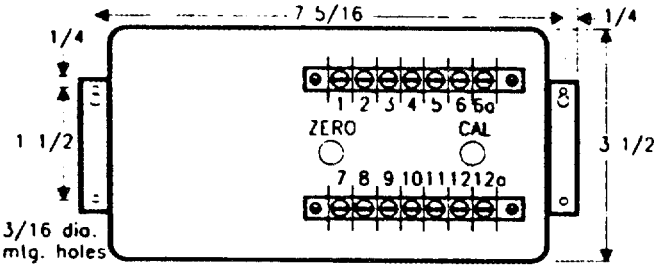
USING ONLY CURRENT TRANSFORMERS

CASE DIMENSIONS



Case height 5 3/4

MODELS WITH 1mA AND VOLTAGE OUTPUTS



Case height 6

MODELS WITH 4-20mA OUTPUT

ALL DIMENSIONS IN INCHES

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PRECISION AC WATT TRANSDUCER MODEL GW5

ACCURATE TO 0.2% OF READING

THREE PHASE FOUR WIRE MODELS-INTEGRAL SENSOR (THREE ELEMENT)

INPUTS		F.S. IN (WATTS)	STANDARD OUTPUTS MODEL NUMBER GW5-							
VOLTAGE	CURRENT		0-1mA*	0-1mA	0-10Vdc*	0-10Vdc	4-20mA	4-20mA*	0-5Vdc*	0-5Vdc
0 to 150	0 to 5	1500	007A	007B	007C	007D	007E	007EG	007CX5	007X5
	0 to 5	1500	7.5A	7.5B	7.5C	7.5D	7.5E	7.5EG	7.5CX5	7.5X5
	0 to 10	3000	016A	016B	016C	016D	016E	016EG	016CX5	016X5
	0 to 20	6000	025A	025B	025C	025D	025E	025EG	025CX5	025X5
0 to 300	0 to 5	3000	008A	008B	008C	008D	008E	008EG	008CX5	008X5
	0 to 10	6000	017A	017B	017C	017D	017E	017EG	017CX5	017X5
	0 to 20	12000	026A	026B	026C	026D	026E	026EG	026CX5	026X5

NOTE: PART NUMBER 7 5 DENOTES 2 1/2 ELEMENT UNIT.

Highlighted models. (5A), can be used with current transformers.

Current transformers shown on page 2 thru 6.

Voltage specifications are **line-to-neutral voltage**.

*Denotes self-powered unit, limiting input voltage ranges to:

85-135 for 150V models
200-280 for 300V models
380-550 for 600V models

All others require 85-135 VAC instrument power, (60 Hz.).

LOOP POWERED 4-20mA UNITS AVAILABLE
CONSULT FACTORY

ORDERING INFORMATION

Example: Self-powered, three-phase four wire,120V, 5A input with 0-5Vdc output, proportional to 0-1500 Watts.
GW5-007CX5

50 HERTZ MODELS
Self-powered units-Add suffix "-50" to part number.
Units requiring external instrument power:
120V, 50Hz.-Add suffix "-51" to part number.
220V, 50Hz.-Add suffix "-52" to part number.

MODEL GW5 SPECIFICATIONS

INPUT

VOLTAGE: See tables
CURRENT: See tables
FREQUENCY RANGE: 58 to 62 Hz.
Optional 50 Hz.: 48 to 52 Hz.
POWER FACTOR: Any
BURDEN:
Voltage: Less than 0.1VA
Current: Less than 0.28VA per element
Output amplifier: 2 Watts
OVERLOAD:
Voltage (cont.): 150V range: 175V
300V range: 350V
600V range: 600V
Current (cont.): 5A range: 2 times full scale
10A range: 2 times full scale
20A range: Full scale
(transient): All ranges
50A (10 sec./hr.)
250A (1 sec./hr.)
DIELECTRIC TEST (Input/Output/Case): 1800VAC (RMS)
SURGE: Withstands IEEE SWC test

OUTPUT

OUTPUT RIPPLE: Less than 0.5% F.S.
OUTPUT LOADING (OHMS):
0-1mA: 0-10K
0-10Vdc: 2K min.
4-20mA: 0-500
0-5Vdc: 2K min.
RESPONSE TIME (99%): Less than 400 milliSeconds
FIELD ADJUSTABLE CAL.: +/- 2% min.
COMPLIANCE VOLTAGE: 12Vdc min.
OPEN CIRCUIT VOLTAGE:
0-1mA, 0-10Vdc, 0-5Vdc outputs: +/- 15Vdc
4-20mA output: + 30Vdc
ACCURACY +/- 0.2% RDG.; +/- 0.04% F.S.
Includes combined effects of voltage, current, load and power factor.
TEMPERATURE EFFECT (-20° to 65°C):
+/- 0.005% per degree C
OPERATING HUMIDITY: 0-95% non-condensing
INSTRUMENT POWER (STD.): 85-135VAC, 60 Hz.

CONNECTION DIAGRAMS AND DIMENSIONS SHOWN ON PAGES 32-33

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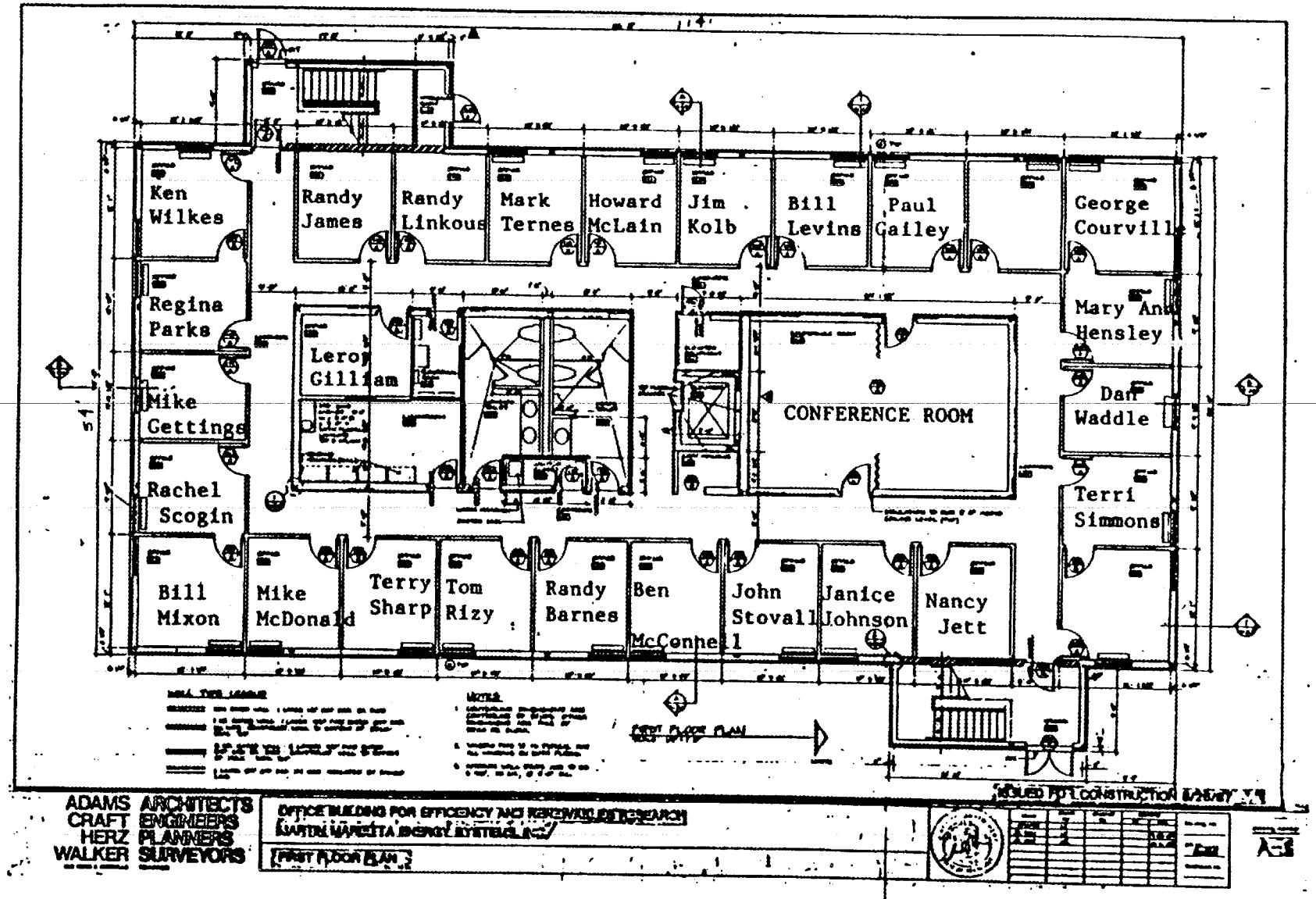
CAMPBELL SCIENTIFIC 21X DATALOGGER PROGRAM FOR HI-SPEED POWER MEASUREMENT

```
Program: TERMTEST - measure high-speed line power
Flag Usage: 1 - start recording with "* 6 A D 1"
Input Channel Usage: 1,2 - both differential voltages
Excitation Channel Usage:None - set flag 1 manually
                                by pressing "* 6 A D 1"
Output Array Definitions: .24Kw/mv good for 2.5KΩ Resistors

*      1        Table 1 Programs
  01: .025      Sec. Execution Interval - gives 40 scans/sec

01:  P2         Volt (DIFF)
  01: 2         Reps
  02: 14        500 mV fast Range
  03: 1         IN Chan
  04: 1         Loc :
  05: 1         Mult - gives mv, make .24 to get KW or KVAR directly
  06: 0.0000    Offset

02:  P91        If Flag
  01: 11        1 is set
  02: 30        Then Do

03:  P32        Z=Z+1
  01: 5         Z Loc :

04:  P89        If X<=>F
  01: 5         X Loc
  02: 4         <
  03: 3601      F
  04: 30        Then Do

05:  P86        Do
  01: 10        Set flag 0 (output)

06:  P77        Real Time
  01: 111       Day,Hour-Minute,Second

07:  P70        Sample
  01: 2         Reps
  02: 1         Loc

08:  P95        End

09:  P89        If X<=>F
  01: 5         X Loc
  02: 1         =
  03: 3600      F - There are about 3600 memory storage locations
  04: 30        Then Do

10:  P30        Z=F
  01: 0         F
  02: 5         Z Loc :

11:  P86        Do
  01: 21        Reset flag 1

12:  P95        End

13:  P95        End

14:  P          End Table 1
```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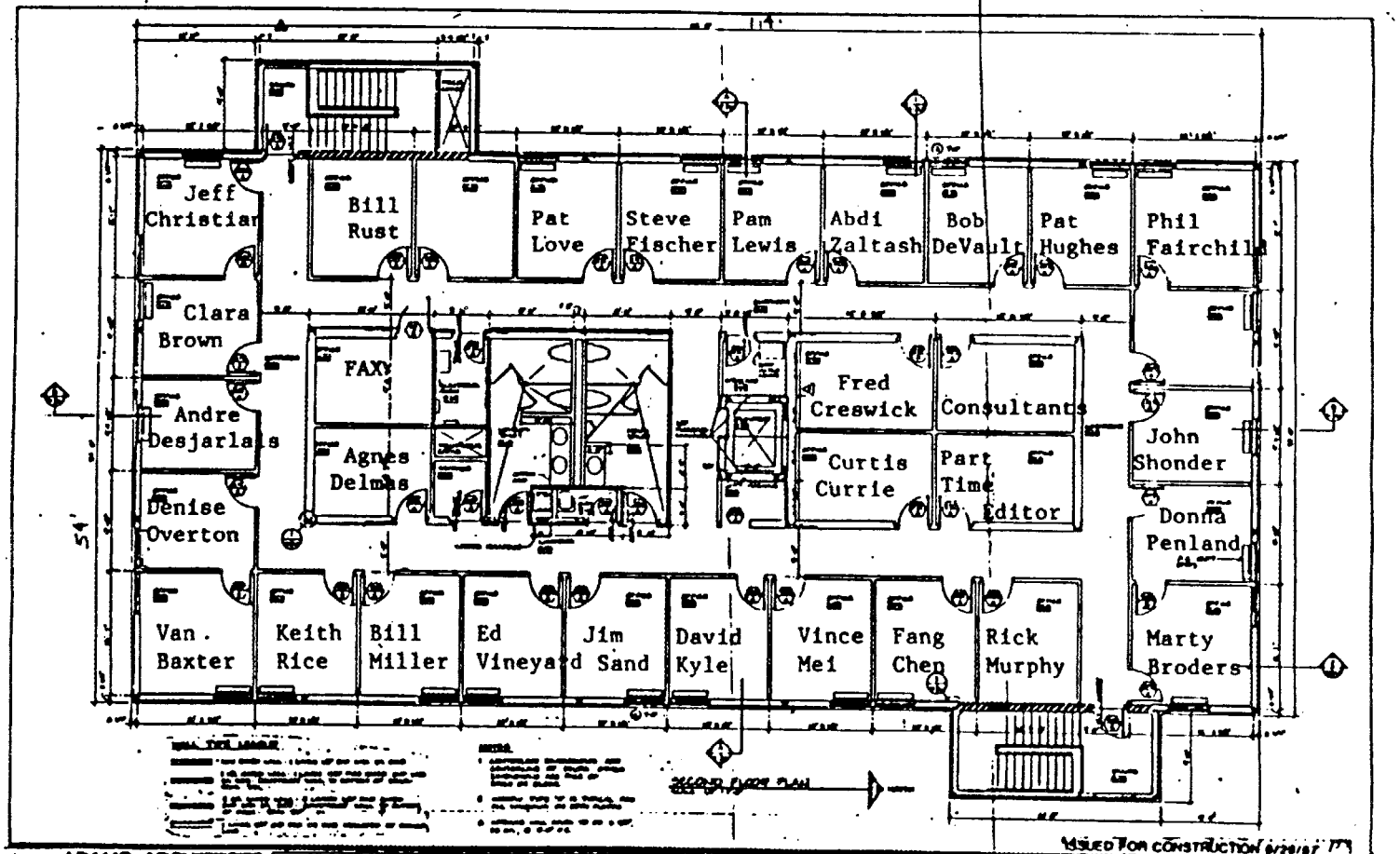

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SECOND FLOOR PLAN

A-2

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