EVALUATION OF DEMAND-SIDE MANAGEMENT PROGRAMS: WHAT TECHNOLOGIES?

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1. SYNOPSIS

This paper provides an assessment of the state-of-art of the technologies that can be used for monitoring demand-side management programs.

2. ABSTRACT

The aim of this paper is to provide an assessment of the state- of-art of the technologies that can be used for monitoring demand-side management programs. This paper examines the following techniques that can be used for end-use monitoring: field test equipment, general purpose data loggers, run-time data loggers, utility-oriented data loggers, energy management systems, smart meters, direct and distributed load control, power line carrier techniques, non-intrusive load monitoring and building automation. Additionally, the paper suggests research and development activities, the implementation of which can contribute to more accurate and cost-effective evaluation of the performance of end-use technologies.

3. INTRODUCTION

3.1 Monitoring technologies and methodologies for DSM evaluation

Demand-side management (DSM) electric utility programs are carried out in three main steps: design, implementation, and evaluation. Evaluation provides the necessary feedback to measure the energy and demand savings, as well as costs associated with DSM programs. The evaluation procedure must correctly assess the energy and demand performance of specific end-use equipment before and after the implementation of the DSM program. The feedback provided by program evaluation is essential to correct the implementation of ongoing programs and to improve the design and implementation of future programs, and as an input to load forecasting and planning.

In some states in the US, the utilities are allowed not only to recover the costs of DSM programs, but also to receive as a profit a percentage of the net savings due to the implementation of those programs. Thus, there is a need for an accurate and independent assessment of DSM program savings, and regulatory agencies are pressing for an increased effort in DSM program evaluation. DSM programs can be evaluated using four methods:
Engineering models
- Statistical models
- Hybrid engineering/statistical models
- Metering

These methods provide different precision and costs, with metering providing the highest precision and the highest costs. Normally, the most cost-effective evaluation procedure uses a combination of the above methods. Metering, and in particular end-use metering measurements made on a sample of customers, is used to validate, calibrate and improve the estimates obtained through the use of less expensive methods.

The cost of end-use metering has been the major barrier to its greater use. In addition, end-use metering also has other other limitations, namely:

-In order to conduct before and after metering, the DSM program may need to be delayed, in order that the "before" metering is carried out. This may take too long, in which case a control group of participants can be used instead. In some programs, such as the ones with a high market saturation, the identification of a suitable control group is difficult. Certain types of load control (for example, distributed load control) can be used to avoid the need for pre-metering or the need of a control group. -The length of time required to collect the data may be long, ranging from a few months to a year, depending on the application. -When some factors (e.g., weather) interfere with the loads, post-measuring analysis is required to normalize the results. -End-use metering at short intervals for a large number of customers generates a huge amount of data for later analysis. However, local pre-processing of this data can mitigate this problem. -The results of metering may be subject to bias associated with the non-average behavior of volunteer participants in DSM programs and with the change in behavior of consumers.

3.2 Utility Requirements for End-use Monitoring

According to some utilities, the ideal monitoring system would have the following capabilities [3]:
-Capability to monitor at least six end-uses, in addition to the whole building data.
-Possibility of increasing in a modular fashion the number of channels up to 16. -Programmable time intervals for collecting data, below and above 15 minutes.
-Capability to collect other data such as temperature, water or gas flow.
-An accuracy of +/- 8% for kWh, +/- 3 degrees F for temperature, and +/- 4 minutes for the recorded time.
-Flexible data retrieval means (serial interface, optical port, power line carrier, telephone).
-Communication and data formats similar to ones used now by the utilities.
-Minimum of 36 days of recording capacity and a minimum of 10 days of data protection in the event of a power failure.
-Minimum installation inconvenience for the consumer. Ideally the system should be non-intrusive and mounted on the outside of the building.
-Moderate cost (equipment and installation), $2000 being a reasonable upper bound.

3.3 Technological Evolution of End-Use Monitoring

This paper assesses advanced (state-of-the-art) monitoring technologies for demand-side evaluation, emphasizing technologies that have the potential to achieve a wider application of end- use metering at a moderate cost. The performance/price relation has improved significantly during recent years. End-use energy monitoring has evolved through several generations of equipment:
-Dedicated data recorder (chart recorder, magnetic mass storage, semiconductor memory) for each single load. --- - - Multi-channel data loggers hardwired to individual transducers connected to each load. -Multi-channel data loggers in which the central unit communicates with the individual transducers connected to each load via power line carrier through the existing building wiring.
-Non-intrusive load monitoring techniques, where monitoring of the whole load is done at single point adjacent to the meter. The end-use consumption of individual loads is estimated using sophisticated pattern recognition algorithms.
-A likely scenario in the near future is the penetration of home/building automation ("smart buildings") and two-way communication systems. These technologies allow the utility to continuously monitor end-use energy consumption of loads with smart controllers without any specific additional investment. This means the possibility of monitoring the energy and demand savings of all customers. Because the hardware infrastructure (communication network, controls and metering) required for end- use metering will be used to provide many other services, the scenario described can be not only cost-effective, but also bring substantial performance improvements in the functions carried out.

4. OVERVIEW OF ESTABLISHED MONITORING TECHNOLOGIES

This section presents a short overview of established technologies that can be used for monitoring end-use energy consumption. A more detailed description (manufacturers, models and main characteristics) of these types of equipment can be found in [2] and [4].

4.1 Field Test Equipment for Power Monitoring

Constant or fixed duty cycle loads may only need short-term measurement, and short-term field testing can provide the cheapest solution for that purpose. Portable equipment is used for electric energy auditing and for short-term end-use monitoring. These units normally feature clamp-on current transformers for easy connection.

The low-end field equipment for power monitoring includes single- phase power meters, without data recording capabilities, costing in the range of $200-$1,000, depending on the accuracy, true RMS voltage and current measurement.

The high-end field equipment includes 3-phase power analyzers, that measure the electrical variables associated with the energy conversion process (true RMS currents and voltages in the 3 phases, power, reactive power, power factor, energy, reactive energy). The more advanced units can also perform harmonic analysis. These units normally have data recording capabilities that can be programmed in the front panel. Some of the units feature a built-in graphics recorder or a display to visualize the waveforms as well as the values selected in the keypad. The power analyzers are normally available with a serial interface for dumping the data into a computer or portable terminal. Power analyzers cost in the range of $4,000-$10,000 depending on accuracy and power measurement capabilities.

A special type of field test power measurement equipment is able to measure power, currents and voltages in the three phases, and the field-efficiency of motors [2]. This is done by processing the measurements with special purpose software which calculates the efficiency indirectly by estimating the total motor losses from the measurements taken. However, there is a need to develop equipment able to measure the field efficiency of other types of important loads, such as HVAC loads.

4.2 General Purpose Data Loggers

Portable data loggers have experienced a substantial evolution during the last decade, benefiting from improvements in the field of micro-electronics. Powerful microprocessors, very high density memory, and integrated analog front-ends, contributed to the introduction of compact, reliable and fairly inexpensive data loggers. The main reasons for the increase in reliability in modern data loggers are due to the lack of moving parts and the use of low power electronic components. Typically the units used for energy monitoring have the following capabilities:

-Multi-channel analog front-end, including signal conditioning, multiplexers and analog-to-digital converter. The data inputs (normally in the range of 8 to 256 inputs), are digitized with a 12-bit resolution: Although most measurements do not require 12- bit accuracy, the 12-bit resolution allows the discrimination of small changes and accommodates variables having a wide range of values. The data loggers are normally able to cope with programmable sampling rates (from a few Hz to several tens of kHz). Some variables may require low sampling rates (e.g., temperature), while other variables may require fast sampling rates (e.g., harmonic current measurement). Analog inputs are used to measure continuously varying variables such as temperatures, fluid flows, solar radiation, electric power, currents and voltages, receiving the signals from suitable signal transducers. Some transducers may be placed inside the case, whereas other transducers are connected to a block of terminals or to special sockets in the outside of the data logger case.
-Multi-channel digital inputs, normally opto-isolated, receive information from pulse-emitting transducers or from operating status transducers. In the last case, each channel only gives a simple information "on-off" or "open-closed", such as status of a load or the position of a damper.
-Powerful microprocessors, that can control the data acquisition process and perform pre-processing of the data. Normally, data acquisition routines are supplied, but signal processing is not part of the system.
-The program is stored in non-volatile semiconductor memory.
-Capability of local set-up, either with a keypad/display combination or with a portable terminal connected to a serial interface.
-Data semiconductor memory which is used to store the data. Typically modern data loggers have between 32 kBytes and 1 MByte of memory.
-Built-in modem for remote metering of the data through the telephone line. The units can either be interrogated, or they can be programmed to transmit data at certain times. Some manufacturers offer the possibility of remote programming of the units. Some units can also be daisy-chained and connected to the same phone line.
-Some manufacturers offer, normally as an option, opto-isolated digital outputs that can be used for setting-up alarms or for controls.

General purpose data loggers can also be based on a personal computer. There is a wide variety of data acquisition boards on the market able to meet most requirements. PC-based units can also receive communication and control cards, as well as perform advanced data analysis and display. PC-based units are more powerful than stand-alone data loggers, but do not have the same robustness. PC-based units are more appropriate for sites where there is frequent interaction with users.

The price of a general purpose data logger with the characteristics mentioned above typically falls in the range of $1,500-$3,000, depending on the amount of memory, number of channels, and signal conditioning requirements. The installation costs can be significant due to the labor required to install the transducers and the dedicated wiring. The installation process is an intrusive procedure and may not be accepted by some consumers.

General purpose data loggers can measure electric power by receiving the pulses of a kWh meter with pulse initiating capabilities, or by using external power transducers. These transducers, which provide an analog output proportional to the power, cost typically in the range of $200-$500, depending on the number of phases and the level of accuracy.

4.3 Run-Time Data Loggers

4.4 Utility-Oriented Data Loggers

The expanding requirements for utility end-use monitoring has created a market for data loggers especially designed for monitoring specific end uses. These units have the characteristics of general purpose data loggers and have several built-in power transducers. Besides power, other quantities which can be metered include apparent power, energy, reactive energy, RMS current, RMS voltage and power factor. To monitor the consumption of appliances, the user only needs to install the current transformers (normally of the split core or clamp on types), which leads to lower installation costs. These units also feature digital inputs that can be used for pulse counting and for status monitoring. The information provided by status monitoring can be used to measure equipment run-time and the number of on-off cycles. Other variables such as temperature, humidity, and process flows can be measured using the analog inputs connected to suitable transducers. Similar to general purpose data loggers, utility-oriented data loggers are expensive to install and are intrusive. The equipment cost is typically in the range of $2,000-$4,000, depending on the number of channels and power transducers.

4.5 Energy Management Systems (EMS)

The use of Energy Management Systems (EMS) with whole-building data has a very large potential for estimating end-use load profiles, as many large and medium-sized commercial buildings already have installed metering equipment that collects energy consumption at periodic intervals (typically, every 15 minutes to one hour). Engineering algorithms and/or statistical methods can be used to disaggregate the whole-building data into the main end uses [5], taking into account the weather dependency of the loads, on-site equipment and operating surveys. A small sample of end-use metering can be used to calibrate the estimates provided by the disaggregation procedure.

Since the EMS can not only control some of the loads, but also collect information on their status, it is possible to measure the power of constant loads by measuring the step change in the total load value. These tests could be done at a non-critical time (outside working hours), and values taken should be normalized as a function of the voltage level. These values could reduce the required amount of end-use metering in a certain project.

In order to optimize building energy use, an EMS can be connected to distributed sensors in the building. The combination of sensors with power line carrier communication can substantially reduce the installation costs of the monitoring system. The distributed sensors allow the detection and analysis of potential savings opportunities as well as the implementation of sophisticated strategies. For example, the optimal implementation of a real-time pricing system with an EMS requires detailed sensing of controllable loads [1]. The same sensors can be used for end-use monitoring.

5. ADVANCED METERING AND COMMUNICATIONS

5.1Technological Developments in Communications

For many years, existing one-way communication systems have provided reliable service for tariffing purposes and load management. The most widely used technologies for this purpose are ripple control (low frequency line carrier) and radio broadcast. Simple on-off control of loads is possible. Implementation of dynamic tariffs is cumbersome, and remote reading of the meters is impossible with one-way communication.

Two-way communication networks, in which the electricity meter is a low level intelligent device (smart meter), offer much improved capabilities and should be able to perform the following tasks:

-Collection of load data for demand-side evaluation,
tariffing, load forecasting, and planning.
-Tariff management (dynamic tariffs, remote meter reading,
automatic printing of bills).
-Load control.
-Information to customers
-Distribution automation and monitoring the quality of
supply.

5.2 Smart Meters

The existing rotating disc meters (both single phase and three phase) can be converted to hybrid meters by retrofitting the electronic modules inside the meters. These microprocessor-based modules perform energy monitoring by counting the rotations of the disc in a programmed time period, typically between 5 and 15 minutes. The data energy and demand data can be read with a portable data logger that is coupled to the meter through an optical port. Some hybrid meters have a serial interface that can be coupled to a telephone modem for remote communication. The price of the modules lies in the range of $120-$250, depending upon the memory available and the communication capabilities.

6. LOAD CONTROL TECHNIQUES FOR DEMAND-SIDE MANAGEMENT AND MONITORING

DSM programs that use load control techniques can also use them for monitoring purposes. Control techniques can be classified as direct load control techniques, local control technologies, and distributed control technologies. Direct control techniques use a communication system to transmit real-time control commands from the utility to the customer. The utility alone decides the timing and extent of the control actions. The most widely used direct control technologies are power line carrier (or ripple control system) and radio. Local load control techniques allow the customer to control loads, to limit demand or to save electricity; e.g., demand- actuated breakers, load interlocks, timers, thermostats, photo- cells, and occupancy sensors. Distributed load control techniques allow control over loads by customers in communication with utilities. The utility may send information such as prices and requests to reduce demand. The control actions are taken by the smart controller in the customer premises, based on the utility signals, local conditions and customer strategies. This type of control is being used mainly by large industrial customers, with whom the utilities have special contracts (such as interruptible loads). Distributed control often makes use of telephone lines, which limits the number of customers that can be contacted by the utility.

Advanced two-way communication systems can considerably increase the scope of application of distributed control technologies. Two-way communication will enable automatic and faster interruption of non-essential loads for a larger number of customers (potentially all customers), including small consumers. A good example of a distributed load control system occurs when a user programs the HVAC thermostat to respond to changes in the utility rate.

Direct and distributed load control can be used with existing whole building electronic metering equipment to measure the power demand of the controllable load, by measuring the step change in the meter. With distributed load control systems, an override agreement must be made with the consumer to ensure that loads are turned off during special test periods to measure the demand of a particular load.

7. ADVANCED TECHNOLOGIES FOR END-USE MONITORING

Since the late 1970s, the US based Electric Power Research Institute (EPRI) has sponsored the development of technologies for monitoring end-use loads. Three EPRI projects have resulted in advances in the technologies for end-use monitoring:

- The Electric ARM (Appliance Research Monitoring)
- The LCES (Load Control Emulator System)
- The NIALMS (Non-Intrusive Load Monitoring System)

In Europe the utilities have not conducted as much demand-side management (DSM) and therefore the development of monitoring technologies has not received as much attention as in the USA. However interest in DSM in Europe has been growing and advanced technologies are now being developed. In France and Switzerland the DIACE [7] has been developed with similar capabilities to the Electric ARM.

7.1The Electric ARM

The Electric ARM (Appliance Research Metering) is suitable for monitoring the consumption of individual loads, either in residences or small commercial buildings. The ARM includes a central receiver/recorder and load-sensing units. The receiver/recorder, placed next to the consumer meter, receives information using power-line carrier (PLC) communication from the loads' transponders (up to 8 transponders can be used with a single receiver). These units are watt transducers that measure instantaneous power and send load profiles to the receiver/recorder. For wired appliances, such as a water heater or a central air conditioner, current transformers have to be inserted in the distribution panel to enable the current measurement of the transponders. The transponders, which monitor appliances with a plug (such as a refrigerator or the washing machine), have a much easier setting as they are placed between the appliance's plug and the wall socket. The data can be read with a portable terminal through an optical port, or the recorder can be read remotely via the telephone.

The Electric ARM has been commercially available since the mid- eighties, and its typical cost is around $3,000-$3,500 for monitoring six independent loads. The incremental cost for each additional load is $400.

7.2 The LCES

Data acquisition in the LCES (Load Control Emulator System) uses a system similar to the Electric ARM: appliance modules communicate with a central unit via power line carrier. The LCES is also able to monitor the consumption of individual loads in residences and small commercial buildings.

Additionally, the LCES allows the implementation and fine tuning of energy management programs, namely the implementation of direct, local and distributed control programs [2]. A central control unit installed at the utility can send through the telephone line load managements controls (on-off switching of loads, change of thermostats settings, and remote programming of the controls), and can read end-use load profiles, temperatures, and customer interactions.

7.3 The NIALMS

The NIALMS (Non-Intrusive Load Monitor) [6] was developed to provide information about the load profiles of individual appliances without submetering. The NIALMS can be placed unobtrusively between the meter and the meter socket. There is no need to place wiring and transducers inside customer premises.

The individual load profiles are estimated by analyzing the global load diagram of the consumer. Let us consider first loads with two operating state conditions (ON and OFF). Each appliance is characterized by consuming a certain amount of active and reactive power and, thus, it is possible to identify which load is turned off or on, by looking at the step transitions of the global load. The NIALMS samples the load at 1-second intervals, and step changes that exceed a certain threshold are analyzed with pattern recognition algorithms. In order to achieve a higher level of accuracy, the step changes are adjusted as a function of the voltage level.

The overall performance of the NIALMS can be summarized as follows:

-Multi-state appliances generally presented higher errors than single-state appliances: 16% for frost-free refrigerators and 47% for cooking ranges. However, other multi-state appliances, such as dishwashers, clothes dryers and washing machines, were identified with errors below 10%. -NIALMS cannot identify continuously varying loads, such as variable speed heat pumps and air conditioners, as they do not produce steep load changes. -Due to the noise being present in the line and the voltage fluctuations, only appliances above 100 Watts can be identified. Although the NIALMS was able to identify lighting with an error of 15%, it was not able to monitor individual lights. -Appliances that run continuously cannot be identified. Present work is directed at monitoring multi-state appliances [6]. Frost-free refrigerators, which have a compressor, a heater, and a fan for a short defrosting cycle, have already been successfully monitored.

8. BUILDING AND HOME AUTOMATION FOR ENERGY MONITORING

Home automation technology is an excellent base to interact with two-way utility communication networks to perform distributed load control with all candidate appliances. Load control can be performed in a customer-friendly way, due to the participation of the consumer in load control. Additionally, since smart appliances already have control devices, the utility saves in the cost of the load control units. Additionally if the appliances have built-in power transducers, end-use metering can be performed inexpensively and in a non-intrusive way.

Therefore, there is a need to encourage the development of smart appliances that feature built-in power measurement and control. Distributed load control implies the need of power switching devices in the input stage of the appliance or of its controller. Current sensing can be performed in the power switching devices at little extra cost. Power measurement, calculated by multiplying the current samples by the voltage samples, can be performed by the smart controller provided that it has an analog front-end.

Mass production of appliances with built-in power measurement should not carry a large price premium over a smart appliance. A price premium of a few tens of dollars seems likely for the self- metering appliance. Additionally, the built-in power transducer can be used by appliance manufacturers to offer increased features to the consumer (e.g., enhanced self-diagnostics). Utility incentives, similar to the ones used to encourage the purchase of energy-efficient appliances, can also be used to offset the larger cost of self-metering appliances.

9. CONCLUSIONS

There are a wide variety of techniques that can be used for end- use monitoring. The appropriate techniques will vary, according to data requirements and available budget. The following activities are needed for advancing the state-of-the-art of monitoring technologies:

-Development of equipment to measure field efficiency of important loads, namely for HVAC systems, due to their high potential for savings. The main difficulty is in measuring HVAC process flows with portable transducers with acceptable accuracy. The development of smart, self-calibrating portable sensors to measure water, gas, and air flows with good accuracy is required. The field kits should include software for data analysis.
-Development of a low-cost, smart power transducer, having negligible power consumption and with built-in remote communication capabilities (power line carrier and other).
-Development of self-monitoring appliances to be used with building/home automation. The use of self-sensing power transistors and the use of enhanced micro-controllers in smart appliances, has the potential to achieve that goal with a small incremental cost.
-Development of improved versions of NIALMS, to cope with multi- state loads and with continuously varying loads, and to be used not only in residences but also in commercial and industrial buildings. The use of harmonic signatures seems to be particularly promising to complement existing pattern recognition algorithms.
-Development of monitoring equipment with comprehensive self- checking and data validation capabilities. Some recent monitoring systems already offer self-checking and diagnostics of the hardware. It is desirable to have systems that can validate the acquired data in real time. The automation of the quality control procedure will save expensive resources to analyze the data, as well as allow earlier detection of existing faults in the measurement system. The error detection, and if possible correction, can not only be based on redundancy (e.g., check-sum procedure), but also based on the physics of the process being monitored (e.g., relations between variables, rates of change, values outside plausible range).

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