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A Novel, Low-Cost, Reduced-Sensor Approach for Providing Smart Remote Monitoring and Diagnostics for Packaged Air Conditioners and Heat Pumps

MR Brambley

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Summary

Packaged air conditioners and heat pumps used on commercial buildings are often poorly maintained and operated. Remote monitoring of this equipment would increase the awareness by building owners and maintenance service providers of the condition and quality of performance of these units, enabling conditioned-based maintenance rather than the reactive and schedule-based preventive maintenance approaches commonly used today. Improved maintenance would help achieve persistent peak operating efficiencies, reducing energy consumption by an estimated 10% to 30%. The costs of such remote monitoring systems, however, are currently too high by approximately an order of magnitude.

This report describes conceptually an approach to providing automated remote performance and conditioning monitoring and fault detection for air conditioners and heat pumps that shows great promise to reduce the capital and installation costs of such systems from over $1000 per unit to $200 to $400 per unit. The approach relies on non-intrusive electric load monitoring (NIELM) to enable separation of the power use signals of compressors and fans in the air conditioner or heat pump. Then combining information on the power uses and one or two air temperature measurements, changes in energy efficiency and occurrence of major faults could be detected. By decreasing the number of sensors used from between 10 and 20 in current diagnostic monitoring systems to 3 for the envisaged system, the capital cost of the monitoring system hardware and the cost of labor for installation would be decreased significantly. After describing the problem being addressed and the concept for performance monitoring and fault detection in more detail, the report identifies specific conditions and faults that the proposed method would detect, discusses specific needs for successful use of the NIELM approach, and identifies the major elements in the path from concept to a commercialized monitoring and diagnostic system.

Acknowledgements

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1. Introduction

Operation faults are common in packaged heating, ventilating and air-conditioning (HVAC) equipment. This equipment is commonly used for space conditioning of commercial buildings with less than about 50,000 square feet (sf) and many larger buildings with three floors or less. Maintenance of these units is most often driven by occupant complaints, other unplanned reactive maintenance (e.g., complete loss of cooling), or scheduled preventive maintenance, which is often done seasonally. Remote diagnostic monitoring systems have been developed, but they are expensive and, as a result, have not achieved significant penetration into the market. Both hardware and installation costs are too high.

Smart monitoring and diagnostic systems (SMDSs) built for field testing sponsored by the Washington State Office of the Attorney General in a follow-on to the current project had an estimated cost of approximately $1000 per SMDS unit.[1] Furthermore, installation of each SMDS on a packaged air conditioner or heat pump required anywhere from 4 hours to 10 hours of technician time. For technician costs of $50 to $100 per hour, this corresponds to an installation cost of $200 to $1000 per SMDS unit (not including time and costs for traveling to the customer site). For a small packaged air conditioner rated at 5 tons of cooling, which itself might cost only $5000, a total installed cost for a monitoring and diagnostic system of $1200 to $2000 per HVAC unit is much too high. For large HVAC units of 50 tons or more, such a cost might be more in line with the cost for energy that a unit of this size consumes and the total installed cost of the HVAC unit. For example, for a 50-ton unit that costs $50,000, the $2000 cost of an SMDS unit is only 4% of the cost of the HVAC unit, while for a 5-ton unit costing $5000, the SMDS cost could be 40% of the HVAC unit cost. Because many of the units in the field are smaller units of 15 tons or less, this tends to indicate that a much lower-cost monitoring and diagnostic system is required to serve this market effectively.

As a result, the project team explored alternatives to the approach used in the current project that could potentially lead to a monitoring and diagnostic system with a capital cost of $100 to $400 per unit, roughly an order of magnitude lower in cost than the system originally developed in this project and the SMDS unit developed and built for the Washington State project. Furthermore, to reduce the cost of installation, which could account for as much as 50% of the total installed cost (i.e., $1000 out of a total of $2000), the team sought an approach requiring few sensors and a simple installation procedure.

Companies serving as installers and users of the SMDS technology in the Washington State project indicated that the capabilities of the SMDS technology could be reduced without significantly detracting from the value of the system. They indicated that the most important

[1] The Washington state project used a design based on the results of the U.S. DOE project documented in this report.

information that could be provided by remote monitoring of HVAC unit condition would be information necessary for the service provider and owner to decide whether service was needed or not. Detailed diagnostic information is generally not needed until the service technician is at the site and ready to service the equipment. These HVAC service providers indicated that detailed diagnostic measurements can be made when on site, potentially even using an automated fault detection and diagnostic hand tool for assistance. They emphasized that the most important information from remote monitoring would enable them to inform the building owner of the cost of not performing service, the cost of servicing the unit, and the corresponding payback period of servicing. A measurement of the decrease in unit efficiency or increase in energy use of the unit compared to when the unit is operating properly, and some information that enables the service provider to isolate the fault or condition causing the increase in energy use sufficiently to estimate the type of repair required and its cost, would make the technology valuable to owners and service providers. (Brambley et al. 2009)

2. Methodology

The requirements described in the introduction led the project team to a solution that will use only measurements of electric power use of the air conditioner or heat pump and one or two air temperature measurements (e.g., of outdoor air and return air). The measurements will enable detection and quantification of the degradation in unit efficiency and capacity and isolation of a limited set of other specific faults. By the process of elimination, the service provider (or system if rules providing this capability are developed) could infer the occurrence of other faults from the absence of the detectable faults.

Basic non-intrusive electric load monitoring (NIELM) techniques can be used to extract information about the electricity use and efficiency of individual components of the heating, ventilating and air conditioning unit from measurement of power supplied to an individual HVAC unit. By using very few sensors, the capital cost and time/cost required for installation will be minimized, creating a monitoring and diagnostic system with a cost an order of magnitude lower than previous systems developed by the research team and compared to the one somewhat similar product on the market.

We hypothesize that changes in electric power use, length of run time, and degree of cycling under similar outdoor weather conditions can be used to infer degradation (or improvements) in the actual efficiency and capacity of rooftop air conditioners and heat pumps, when evaluated over appropriate time periods. As a result, these changes can be used for detection of performance degradation of this equipment and, therefore, as input to guiding maintenance decisions. Detection of these changes in electric power consumption of packaged units would be accomplished using measurement of electric power at one point, the entrance to the unit, with methods adapted for non-intrusive electric load monitoring used to distinguish among the energy-use patterns of different packaged unit components (e.g., compressors, condenser fans and supply fans).

NIELM was first conceived by George Hart (Hart 1992) at the Massachusetts Institute of Technology (MIT) in the early 1980s for the purpose of monitoring the electricity use of individual appliances in homes from information detected on the electric power supply to the home. Compared to sub-metering, for which end-use meters are installed on individual appliances or individual circuits at the electrical panel, NILM as originally conceived uses a meter reading unit installed at the electrical service entrance to a home. Known at the time as a non-intrusive appliance load monitor (NALM), a collar-mounted monitor was designed that was installed between the existing utility revenue meter and the existing socket for the meter, with the NALM providing a new socket into which the existing meter was plugged. By monitoring the real power and total reactive power at the electric entrance as functions of time, the times at which individual appliances turned on and off could be identified as well as the electricity use by each while on. This provided the equivalent of sub-metering without disturbing occupants or the need to install end-use monitors on each appliance and string wires throughout the house connecting the sub-meters to a central data acquisition and storage point. Enhancements to the approach and expansion of applications (e.g., to heating, ventilating and air-conditioning system diagnostics) took place through the 1980s and 1990s to today (e.g., Hart 1989, Hart 1992, Norford et al. 1992, Norford and Leeb 1996, Shaw et al. 1998, Drenker and Kader 1999, Luo et al. 2002, Laughman et al. 2003).

The distinction between our proposed used of NIELM and the advancements by various investigators at MIT for fault detection and diagnostics of HVAC units is the level of sophistication. While we suggest that the basic approach of Hart (1989, 1992) can be adapted to meet the needs for packaged HVAC unit monitoring and fault detection, other investigators have focused on increasing the sophistication of the NIELM method to enable isolation of very specific faults, such as refrigerant undercharge and flooded compressor starts (Armstrong et al. 2004, 2006). Many of these faults require very high sampling rates (e.g., 120 Hz) to provide data with which to characterize start-up transients.

We hypothesize that much smaller sampling periods of tens of seconds to a couple minutes might be used to distinguish the on-off events of packaged unit compressors and fans and to quantify their individual electric energy consumption. This together with measurements of outdoor-air temperature (and possibly return-air or supply-air temperature) should be sufficient to detect the following faults:

1. Efficiency degradation by increases in the total power use given the outdoor-air temperature
2. Degradation in capacity from
    a) Increase in on time per cycle for each specific outdoor-air temperature
    b) Continuous operation without cycling at a lower outdoor-air temperature or lower outdoor-air enthalpy than previously observed
3. Operation during unoccupied times (or incorrect schedule specification) via power level indicating supply fan, condenser fan, and compressor are operating during times when the building or specific building zones are not occupied.
4. Operation of individual components (e.g., compressor or condenser fan) during unoccupied times via the corresponding power level being detected during unoccupied times.
5. Excessive cycling indicated by compressor power cycling at a frequency higher than acceptable.
6. Unit not operational - zero power during conditions (e.g., time of week and outdoor-air temperature) when the unit has historically operated.

In some cases (e.g., a unit not operating), detection of the fault occurrence alone will be sufficient to instigate servicing of the unit. If the unit is monitored closely and alarms provided for catastrophic faults, owners might be contacted about the problem or servicing started even before occupants complain about uncomfortable conditions. For other faults (e.g., degradation in unit efficiency), quantification of the magnitude of the fault and impacts on operation costs will be necessary to determine or reach agreement with the building owner regarding when servicing should be undertaken. In all cases, however, the information provided by such a remote monitoring and diagnostic system will provide the information necessary to base servicing on the condition of the equipment, helping maintain HVAC equipment and systems at peak operating efficiency.

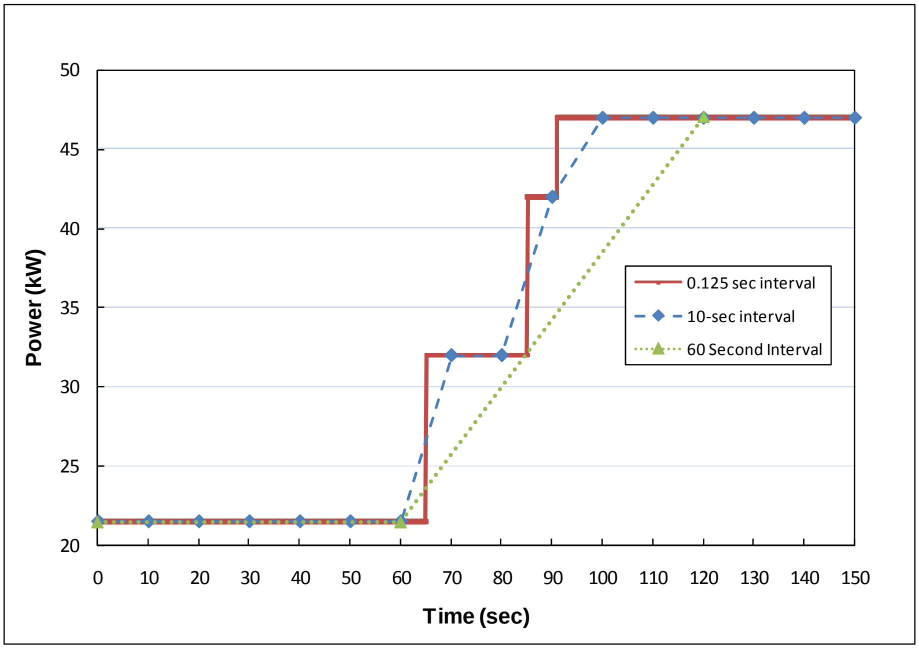
3. Requirements for Realization

Because we suggest a focus on fault detection rather than fault isolation (or fault diagnosis), much lower sampling rates (i.e., longer sampling intervals) can be used. Luo et al. (2002) show that shorter sampling intervals enable detection of sequential start-up events separated by short times. For example, they show that for three devices turned on sequentially over a 30-second interval, a power measurement sampling period of 0.125 seconds is required to distinguish among the three events. Figure 1 illustrates this graphically, where two examples constructed from data from Figure 4 of Luo et al. (2002) are shown. In both examples, measured values of power are assumed to hold from the time of a measurement until the next measurement for three sampling time intervals: 0.125 sec, 10 sec and 60 sec. In plot (a), measurement sampling starts at time = 0. The measurements are able to capture all three start-up events for both the 0.125-sec. and 10-sec. sampling intervals, but for the 60-sec. sampling interval, the three events appear as one large event in which the power changes from 21.5 kW to about 47 kW. When the sampling starts at time = 5 sec., as in plot (b), only the performance of the measurements made at the 10-sec. sampling interval changes with respect to the ability to detect start-up events. In this case, data for only two of the events is obtained with samples at 10-sec intervals, creating the appearance that two start events occurred, one increasing the power use from 21.5 kW to 32 kW and the other (which is really two events) increasing the power use from 32 kW to 47 kW. Comparison of Figure 1(a) and Figure 1(b) demonstrates that not only the length of time interval between samples affects the ability to detect events, but also for events that exist for a time approximately equal to the sampling interval or less, the timing of occurrence of the event relative to when measurements are made also affects the ability or probability of detecting an event.

Furthermore, as Luo et al. (2002) demonstrate, the ability to collect one or a small number of data points corresponding to a start-up event and to discern them visually on a graph is not a guarantee that the event-detection algorithm will detect the event. For example, in Figure 4 of that paper, the authors explain that that when the sampling interval was set to 1 sec., the algorithm detected the first two start-up events, but was not able to detect the third event (the increase in power from 42 kW to 47 kW in Figure 1 in this report), even though the last event was visually discernable.

The problem of detecting start-up events based on the ability to recognize separate increases in power use associated with individual physical devices starting up is particularly troublesome for using NIELM to detect the on and off times for a large set of devices that are present in a home. Several devices in a home might have power consumptions of similar magnitude, and frequent cycling can occur, making short sampling times particularly important. However, when applying NIELM techniques to a packaged HVAC unit, the on-off events for very few components are of interest, the compressors, the condenser fans, and the evaporator or supply fan. Each of these can be discerned by the magnitude of its power consumption. Furthermore, combinations of

(a)



(b)

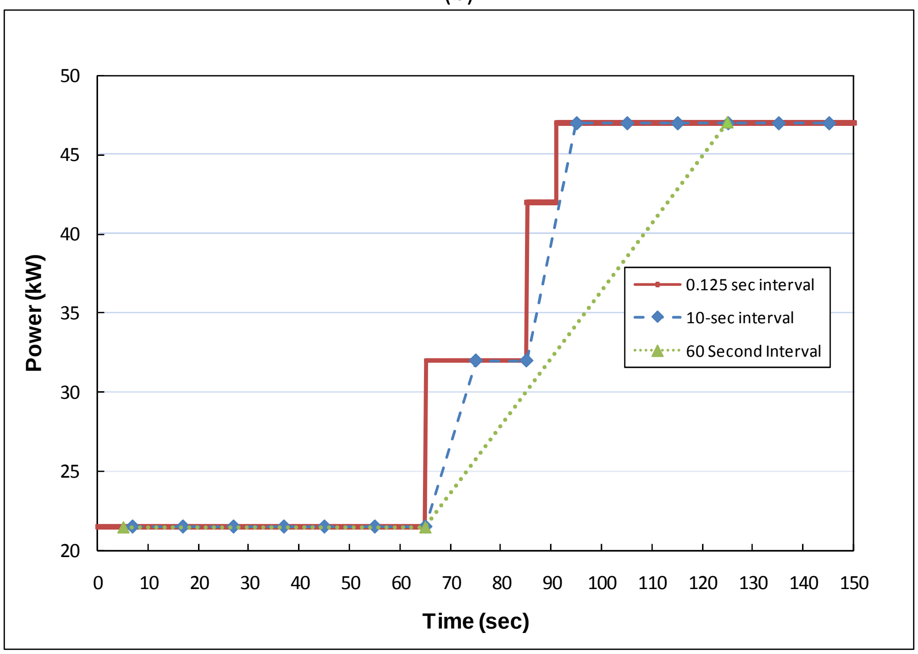


Figure 1. Hypothetical examples of measured power plotted against time for three sampling intervals (0.125, 10 and 60 seconds) for three start-up events all occurring within a 30-second interval with measurements starting at a) time = 0 seconds and b) time = 5 seconds. After Figure 4 in Luo et. al (2002).

devices starting within a sampling period (i.e., simultaneously from a sampling perspective) and measured as a large increase in power can be detected by the knowing the sum of the power draws of the individual components. Because the number of components is so small, the number of combinations (i.e., sums) that need to be considered is relatively small and manageable. Therefore, we hypothesize that sampling times that are on the order of 1 minute are probably acceptable for the proposed application of NIELM, considerably reducing the amount of data that requires management, processing and communication.

Methods for detecting changes in power use and associating them with individual appliances were developed in early work at MIT and shown to be particularly effective for residential single-point metering of time of use and energy consumption of individual appliances of many types. Later work focused on developing the NIELM techniques for use on commercial buildings for which there are generally many times the number of appliances found in a home. The problem of monitoring a few components in a packaged HVAC unit shares much in common with simpler residential applications of NIELM and, in fact, are likely much simpler than monitoring appliance use in a home because the number of devices is much smaller (two to four major components for a packaged air conditioner or heat pump), the population of devices does not change with time, and except for degradation in efficiency and capacity over time, the power consumption can be known in advance for each component and is relatively stable over time. This makes packaged unit monitoring particularly well matched to the capabilities of NIELM.

4. Next Steps

Development and practical application of the NIELM technology for remote monitoring and the detection of performance degradation of packaged air conditioners and heat pumps will require the following major steps to bring the concept to reality:

1. Development of the details of air conditioner and heat pump monitoring based on the small number of measurements proposed and documenting of the corresponding algorithms.

2. Adaptation of algorithms from previous work and development of some new algorithms for using NIELM to extract on-off times, power draw, energy use, cycling frequency of packaged unit compressors and fans from the power connection to the unit and implementation of them in software.

3. Development of a very low-cost hardware package with the necessary processing, data storage and communication capabilities for implementing the NIELM and fault detection algorithms.

4. Testing of the algorithms, software, hardware and end-to-end system in a laboratory setting.

5. Field testing of the resulting system.

6. Commercialization.

5. Conclusions

Non-intrusive electric load monitoring shows considerable promise for substantially reducing the cost of smart monitoring and diagnostic systems for packaged air conditioners and heat pumps, while providing the capabilities that HVAC service provides see as most important. Systems for this purpose available or prototyped previously have been far too expensive for widespread practical use. This approach based on NIELM should reduce the number of sensors from the order of 15 to a few and decrease the time for installation to 1 to 2 hours rather than the 4 to 10 hours that the authors have observed for more complex prototype systems. The technology, although proposed initially for retrofit on existing packaged units would be readily adaptable for installation at even lower cost during manufacture of HVAC units. The changes possible from successfully developing and implementing the NIELM-based technology described conceptually in this document will help transform how packaged HVAC equipment is operated and maintained, increasing its operating efficiency and decreasing the energy used for space conditioning the 90% of commercial buildings and the 55% of commercial floor area that these units serve.

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