BUILDING COMMISSIONING AS AN OPPORTUNITY FOR TRAINING NON-INTRUSIVE LOAD MONITORING ALGORITHMS

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ABSTRACT

In this paper we explore the synergetic relationship that could exist between the building commissioning process and the necessary training for Non-Intrusive Load Monitoring (NILM) algorithms. First we describe the application of NILM as a tool to support building commissioning, by obtaining individual electrical load profiles and equipment health indicators from a single measurement point in the building. Then we argue that, since the training process is usually one of the stumbling blocks for the deployment of NILM technology, taking advantage of the commissioning process for this end could facilitate the procedure. We present a number of ideas for achieving this vision inspired primarily by early results obtained from a residential building in Pittsburgh, Pennsylvania where we have installed a prototype NILM system.

Keywords: Building Commissioning, Electricity Management, Load Monitoring

1. INTRODUCTION

Building commissioning is the process through which the different equipment and systems in a building are evaluated to ensure that they are operating according to the building owners' and designers' expectations. It is a quality assurance process that can span the whole life-cycle of the building (Portland Energy Conservation, Inc. 2006).

The California Commissioning Collaborative defines three types of commissioning: (a) new building commissioning, (b) retro-commissioning, which applies the process to existing buildings; and (c) re-commissioning, referring to the process when applied to a building which has already undergone commissioning before. In all three types of commissioning, there is a need to measure the performance of equipment and systems by collecting data and analyzing it, a process that they refer to as "functional testing and monitoring" (Portland Energy Conservation, Inc. 2006). Others refer to this as Monitoring-based Commissioning or MBCx (Brambley et al. 2009). Typically, commercially available sensors, data loggers and building management systems are used to collect this data.

Many of the systems that are evaluated during the commissioning process are electrically powered, thus making their power consumption an important quantity to monitor. Generally, their electricity consumption profiles are obtained from power meters temporarily installed on each major load. Although there are advantages to using individual monitoring devices to assess the performance of each major system, this method does not scale very well, as the associated costs (both hardware and installation) are high and increase linearly with the number of loads being examined.

We believe Non-Intrusive Load Monitoring (NILM), a technique for monitoring individual electrical loads from measurements taken at the main feed of the building by analyzing the equipment's power signatures, can be used to decrease these costs. Additionally, the commissioning process can benefit NILM systems by serving as a proxy for training the algorithms that are used to properly recognize the loads of interest.

The synergetic relationship that could exist between the building commissioning process and the necessary training for NILM algorithms will be the main topic of this paper. Although the idea can be applied to commercial, residential or industrial facilities, we will draw results from experiments performed in residential buildings and will refer the reader to similar examples found in the literature, which deal with commercial facilities.

Background

Energy Information Systems (EIS) is the term generally utilized to refer to the collection of software and hardware systems used to provide energy information of a building to the interested parties (Motegi et al. 2003). These technologies have been used for more than a decade and many studies indicate they can have a positive effect on energy savings (Parker et al. 2006; Darby 2006; Fischer 2008) during the operation phase of the building, as well as during the commissioning process (K. Brown & Anderson 2006).

First investigated more than twenty years ago (Hart 1989; Hart 1992), NILM proposed to facilitate the monitoring process by reducing the number of sensing points by carefully analyzing the overall voltage and current feeding the building. Early research efforts targeted residential buildings, while more recent ones have been applying and improving the techniques in commercial and industrial facilities (Leslie K. Norford & Steven B. Leeb 1996; Dong Luo et al. 2002; Smith et al. 2003; Paris 2006).

Of particular interest to our discussion is the application of NILM techniques to: (1) equipment scheduling, (2) equipment cycling, (3) fault detection and (4) diagnosis. Work in the first two areas has demonstrated promising results (Dong Luo et al. 2002; Smith et al. 2003) for estimating air distribution equipment cycling and schedule based on measurements taken at the main electrical entrance of the building. Research into fault detection and diagnosis is equally relevant, as it can further benefit the commissioning process. Albeit modest, this area of research has also yielded results (Robert Cox 2006; S. R. Shaw et al. 2002). Already, the techniques for fault detection and diagnosis are being considered for developing low-cost monitoring systems to be embedded within packaged air conditioners and heat pumps.

The majority of the work we have cited so far is the result of incremental sophistication of the techniques developed initially in the 1980's, largely by increasing the resolution of the sampled signals, use of advanced computing, applying more advanced signal processing methods and introducing new parameterized models to better estimate the behaviour of loads. Our research, however, aims at enhancing the technology primarily through better user interaction and the integration of additional sources of data, other than the overall power. In particular, we believe that the process of training the NILM system is often overlooked, even though it plays a major role in how the technology is adopted. The training process itself, we argue, can be an opportunity for performing building commissioning.

Paper Organization

Section 2 will provide a more detailed description of how NILM works. A prototype system that we implemented and deployed in an occupied building is also presented and used to analyze the potential benefits for the commissioning process as well as the barriers that need to be overcome. In section 3 we discuss the process of training NILM algorithms and explore the viability of incorporating it into the building commissioning cycle so that the functional tests of the equipment in the building provide the necessary data for future recognition. We conclude by reviewing the challenges that remain and describing possible directions for future work.

2. NILM SUPPORTED BUILDING COMMISSIONING

The main idea behind Non-Intrusive Load Monitoring is that by analyzing high speed samples of current and voltage at the main feed of the building, it is possible to detect changes in these signals that correspond to the operation of equipment in the building. Then, by carefully analyzing a short time-window of samples around the detected event, it is possible to classify it as being the result of a specific task performed by specific equipment. The greatest value of this approach lies in the reduced costs due to requiring only measurements at a central location (i.e., the main feed).

Because there are many ways of implementing the technology, and each one has its advantages and disadvantages, we try to remain impartial in our discussion and refer to general observations rather than specific implementation details when discussing the benefits it could bring to building commissioning. However, to avoid being too abstract, we will draw many of our conclusions from a particular implementation; namely, a prototype system we developed and installed in an apartment unit in Pittsburgh, PA.

The prototype system measured voltage and current on the two voltage sources (A and B phases) coming into the apartment from the utility's transformer. A desktop computer with a data acquisition card sampled these signals at a rate of approximately 10kHz, and computed estimates of the spectral envelope coefficients, which are equivalent to real- and reactive-power measurements, as described in (S.R. Shaw et al. 2008). Using an event detection algorithm inspired by (Dong Luo et al. 2002), the system could identify the precise time when an appliance in the house had changed its state. Following this, we applied kernel regression on a fixed window of samples of the power signals around the event, and used the coefficients of this regression as a "signature" for the given state-transition. These signatures were stored during the training phase, and used during regular operation to compare new, unknown state-transitions against them using a nearest-neighbor method in Euclidean space, resulting in a label assignment. Figure 1 shows a diagram of the data acquisition system. More details on the system can be found in (Berges et al. 2009).

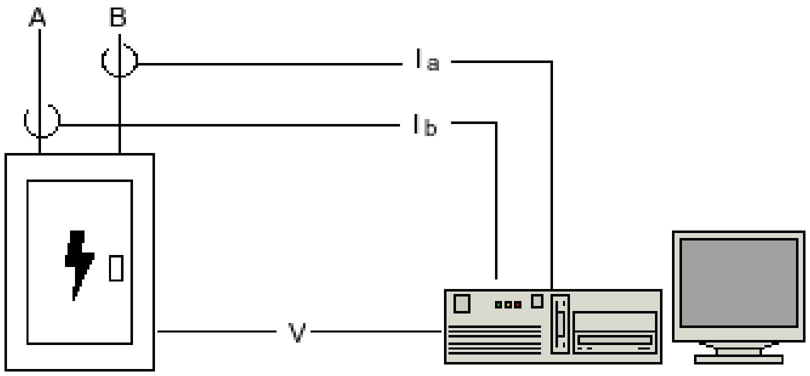

Figure 1 Diagram of the data acquisition configuration for the NILM prototype developed by the authors. I_a and I_b are measurements of the current on phase A and B, respectively, as measured by two split-core current transformers. V represents measurements of the voltage in one of the phases. The system assumes the other phase is shifted half a period from the other one, assuming a split-phase configuration.

To test the performance of the system we collected ground-truth data, which consisted of a time-series of whole-house power measurements with labels assigned to every sample that falls close (in time) to when an equipment state-transition occurred. Because of the difficulty of obtaining these labels (i.e., knowing exactly when each appliance in the house changed from one state to another), we relied on manually created datasets to obtain our results, each consisting of two or three hours of voltage and current measurements and one or two hundred marked events. In other words, for each dataset the authors spent two or three hours in the building manually recording the timestamps for each and every appliance state transition that occurred during that period of time. In this paper it is not our intention to delve into the details of the performance of our implementation, but rather to give the reader a general idea of how the technology performs.

When trained, the system is able to correctly recognize most of the loads in the apartment, being more accurate with larger loads. For example, presenting the algorithms with 44 randomly chosen appliance state transitions resulted, on average, on a 79% classification accuracy, where most of the misclassifications were for lights with similar characteristics. Two functional components of the system should be discussed separately to understand the performance: the event detector and the classification algorithm. The former achieved mixed results during our tests, mainly because we did not implement the multi-resolution techniques described in (Dong Luo et al. 2002), thus resulting in a large number of false positives triggered by slow start-up transients. As an example, when not accounting for events generated by the heat pump (slow start-up) the event detector could achieve sensitivity values of 95%, but when the heat pump was present in the experiment, the numbers dropped to 72%. In contrast, and as described earlier, the classification algorithm fared much better, achieving above 90% average 10-fold cross validation accuracy on most loads (Berges et al. 2009).

We believe there are many fronts on which NILM can support building commissioning. The ones we find most important are:

1. Equipment-Specific Energy Consumption Measurements: Originally developed for this task, NILM can utilize the information from the events it has recognized to keep track of the energy consumption of the different loads, in near real-time. Although the techniques for doing this with non-steady-state loads, common in commercial facilities, are still being investigated (S.R. Shaw et al. 2008; Wichakool et al. 2007), current research shows promise.

2. Duty Cycle Estimations: Regardless of whether or not the techniques for keeping track of variable loads become robust enough for real-world deployment, duty cycles can still be estimated by correct identification of off-on and on-off transitions. In other words, even if the power consumption between these on and off states is unknown, the timing between them can still be estimated. Such information would also be valuable to manufacturers.

3. Fault Detection and Diagnostics: Perhaps the most compelling argument in favor of using NILM to support the commissioning process comes from the possibility of being able to detect equipment faults and diagnose the problems. As discussed earlier in this paper, there has been a growing amount of work in the area, which indicates that for some particular cases (e.g., certain air distribution systems) solutions are already available to achieve this, while for others it may be more reasonable to embed the technology into the equipment itself and perform NILM on the current and voltage feeding it.

4. Continuous Commissioning: Due to its low cost, the ability to be fine-tuned to specific building scenarios, and the ability to improve with time, the technology can be used continuously throughout the lifetime of the facility, supporting a continuous commissioning process.

In order to achieve this vision, a number of challenges need to be overcome. Particularly, the issue of having to train the system in one way or another for each new installation remains a barrier impeding wider adoption of the technology (Smith et al. 2003). For that reason, we devote the following section to exploring the other side of the synergetic relationship between NILM and building commissioning: how the commissioning process can provide training examples for the system.

3. TRAINING NILM ALGORITHMS

As previously explained, NILM relies on a pattern matching algorithm that makes use of a library of equipment signatures to assign labels to newly detected events. In our implementation, for example, the equipment signature library is a collection of signature vectors for each training example of an equipment state transition. Figure 2 shows the real and reactive power trace for one state transition: the start-up transient of a fluorescent lamp with a ballast. Instead of storing the raw transients as shown in the figure, the signatures are generally encoded as lower-dimensional representations of these signals. Hart (Hart 1992), for example, used the difference between steady-states in both real and reactive power, resulting in 2-dimensional signatures; whereas we used the coefficients of a kernel regression, and obtained signatures in *n*-dimensional space, where *n* is the number of coefficients.

Depending on the particular implementation of the algorithms, the signatures can be specific to a given equipment, a type of equipment (fluorescent lights, heat pump, etc.) or even a type of component (motor, electric ballast, heating coil, etc.). For this reason, the training process can vary greatly. For instance, if the signatures represent equipment components, then they will likely be chosen to behave as shift- and scale-invariant representations of the way motors, in general, affect the voltage and current of the building. This makes it possible for the NILM system to recognize new and different motor-loads based on signatures that were provided before the installation of the system. On the other hand, if the signatures are equipment-specific, then two heat pumps of different size, for example, would each have separate entries in the library.

The prototype we implemented followed the latter approach and for this reason required training examples for every equipment in the building where it was installed. The advantage of this approach, however, is that it results in a system that is fine-tuned to the specific environment where it was deployed. Furthermore, it relies on a model-free approach that makes very few assumptions about what the signatures for the appliances should be like. However, the main drawback is the necessity to provide the system with one or more examples of every equipment state transition present in the building. Fortunately, this process of making every building equipment go through all its operating modes is typically what is done during the functional testing and monitoring phase of building commissioning.

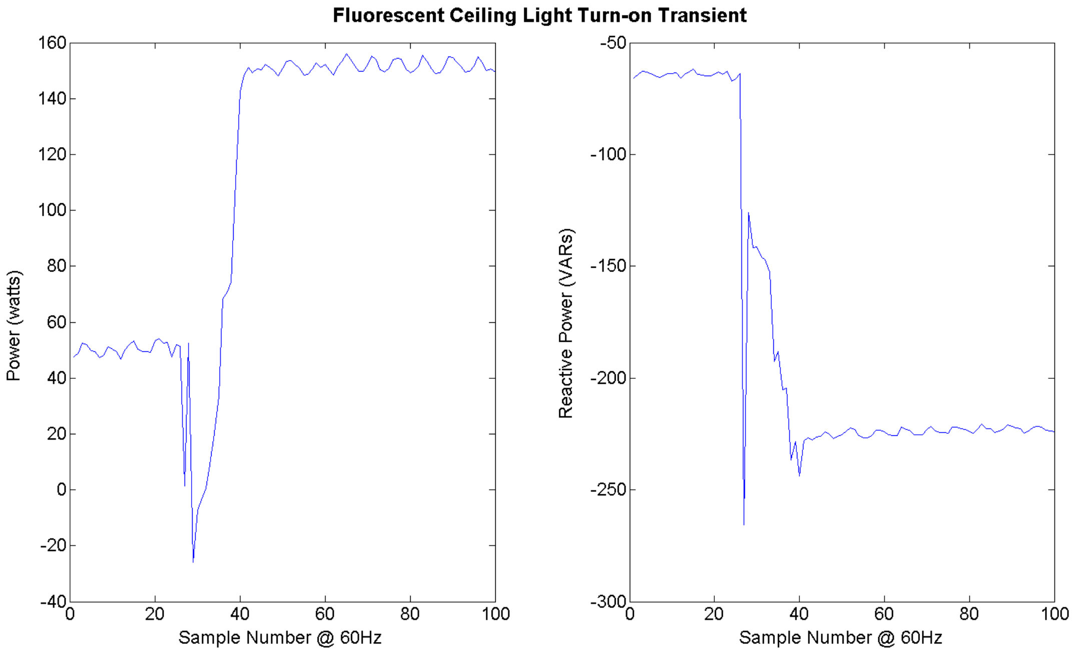

Figure 2 Power and reactive power trace for the start-up transient of a fluorescent lamp with ballast.

Training site-specific libraries

The commissioning team performing the functional tests and monitoring performance diagnostics is primarily interested in knowing whether or not the equipments and systems are performing the way they were designed to. From the four scenarios presented in section 2 detailing how NILM can aid commissioning, the third one in particular, fault detection and diagnosis, is well suited to be applied during training.

By leveraging the ability of NILM techniques to detect faults, even if no diagnosis can be reached, a relationship can be built between building commissioners and the NILM system in which the commissioners provide new examples of equipment state transitions in exchange for metrics indicating possible faults and perhaps accompanying diagnostics.

For the case of faults that can be evidenced in start-up or change-of-state transients, one way this can be achieved is if equipment manufacturers, or some other party, could provide signatures or raw signals obtained from measurements of a fully functional, fault-free device. In this model-free setting, faults can still be detected by comparing the signals from the equipment under study with the ones supplied by the manufacturer. The comparison can be made via a correlation metric (e.g., inner product of the two signature vectors) provided normalization and thresholding issues are taken into consideration. For example, the Euclidean distance between two signature vectors can provide a measure of similarity between them, although setting the right threshold that divides similar from non-similar is an issue that should be investigated.

While not all faults can be detected by analyzing change-of-state transients, once the NILM system is trained, it can begin to provide information that can help the users detect and diagnose other types of faults. In other words, in can start providing the other types of support described earlier in section 2: energy consumption measurements, duty cycle and scheduling estimations and continuous commissioning.

4. CONCLUSIONS AND DISCUSSION

We have presented our ideas for how NILM can benefit from the building commissioning process, and at the same time provide useful information to the team performing the commissioning. In particular, we focused on the process of training a site-specific signature library for NILM, in which every transition from one operational state to another in all equipment in the building is recorded. The functional testing and performance monitoring processes that are part of the typical building commissioning, provide the necessary training examples for the algorithms. The NILM system, in turn, can support the commissioning team by providing relevant performance metrics about the equipment being tested.

In the present paper we have described merely a collection of simple ideas that can help reduce the costs associated with performance monitoring and testing in the context of building commissioning, by leveraging results from research in the field of NILM. Despite more than two decades of work in this area, the technology has yet to reach wide market adoption. Most of the proposed approaches until now try to avoid a continuous interaction between the user and the system. What we propose here, is a training process during which the users (in this case the building commissioners) constantly interact with the system when performing equipment tests, relaxing the need of the system to recognize the different loads upon installation. More research is still needed, however, to test and improve the ideas presented here.

5. FUTURE WORK

Testing and validating the ideas herein described, are the first two tasks that would logically follow. Laboratory as well as real-life settings should be used for these tasks. It would be advisable to start with the elaboration of a list of the most commonly commissioned building equipment, as well as a list of the tests that are usually performed on these. Following that, healthy and un-healthy signatures should be captured for these building systems and analyzed to determine what correlation metrics and what threshold values work best for discerning between them.

Beyond these considerations there is another one of particular importance: the design of simple and effective user interfaces that can facilitate the interaction between the commissioning team and the system. Careful attention should be given to this issue, as it will determine the success of the system being adopted by the commissioning industry.

6. ACKNOWLEDGEMENT

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