Residential Demand Response Wireless Sensor Network

Coalton Bennett, Steven B. Wicker, Judith Cardell
Department of Electrical and Computer Engineering, Cornell University
E-mail: cb322@cornell.edu

Abstract-- **The purpose of this paper is to show how a network, of wireless current sensors can be used to help consumers, at the residential level, monitor and control appliances, within their home in order to lower both total peak electricity demand and the individual's electricity costs. This project proposes a novel; new, and promising demand response technology, by monitoring these appliances. The principal component of this system is a wireless current sensor which, when coupled with user preferences, will notify customer's when a predefined threshold in power consumption has been surpassed based on the current readings taken. This is accomplished by querying the regional ISOs website for real time pricing information, in five minute intervals. We provide the results of our experiment and then discuss our future work. Which will be a comparison between existing technologies with similar sensing capabilities, such as the Watts Up meter and Faraday couplers with 802.11 wireless networking capabilities.**

II. Introduction

With the widespread use of sensors capable of real time, synchronized measurements and transmission of data, low voltage power distribution systems are being considered as a prominent element in next-generation Supervisory Control and Data Acquisition (NG-SCADA) systems for the power grid. NG-SCADA will be essential in providing a reliable, stable, well monitored, and protected power distribution system while increasing the efficiency of electricity markets. The incorporation of sensor networking along with other key NG-SCADA components will provide a substantial increase in power system monitoring at the low voltage, customer level. This information is not exclusively limited to suppliers however; it will also be made available to the customer. Our sensor design is such that the granularity of monitoring is sufficiently fine enough to improve not only system reliability and power quality, but will also serve as an effective basis for demand response systems. Such a system provides consumers/customers with pricing information that they could use as a basis for consumption/timing decisions. Although this provides an incentive for the customer the removal of such data from within the home could be the source of serious privacy concerns.

III. Motivation

The motivation for the use of our sensor is multidimensional. Our design will not only pave the way for new and novel technologies like NG-SCADA, and demand response systems, but will also aide in the development of a system encompassing both objectives—microgrids.

A microgrid is a semiautonomous power sub-system, located within a single distribution system, and designed to operate as a unified, controllable entity from the perspective of the high voltage system. The initial context for a microgrid has been assumed to be that of a self-contained sub-system, such as a university, hospital campus or industrial complex, that has co-generation facilities and readily coordinated load[1] that can be integrated into the power system in an intelligent manner with the control necessary to island from the grid when required. Future distributed power systems have the potential to operate in such a way that the high voltage transmission grid and central generating facilities would provide the baseload energy exclusively, while allowing microgrids to provide services such as load following, balancing, frequency regulation and voltage support, to the extent possible, and coordinated through price-based control signals. These objectives can be efficiently implemented if accurate demand information is made available at the granularity of individual homes and small businesses.

This information can be generated and tracked through demand/response systems. Such a system will track consumption while providing real-time pricing information to consumers. A motivating factor for the use of this system, by consumers, is the varying price; they pay from hour to hour, to keep certain appliances on. More importantly it also aids in reducing the total demand during peak periods. Four major trends are dramatically

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[1] Three such examples are those in the service territories of Ameren, AEP, and Green Mountain Power, operated by Northern Power Systems.

increasing the level of interest in demand response, several of which are intertwined with microgrid deployment.

A. Incentives for the power industry and customers

The power industry has found the construction of new high voltage transmission and large generating facilities to be very expensive and generally difficult. If customers can be given incentives to decrease their consumption at times of high demand through demand response programs such as real time pricing, the need for power system expansion will be significantly decreased, and system reliability will increase.

B. Contributions to an efficient electricity market structure

Electricity markets traditionally have focused almost exclusively on the supply side, resulting in markets, which are at best, only marginally competitive. In addition to this consumers often times experience rampant market power abuse by their suppliers. The introduction of demand elasticity to electricity markets through real time customer pricing would significantly decrease, and possibly eliminate, the ability of suppliers to exercise market power—and hence create competitive market structure. Ultimately this would lead to a decrease in the prices paid by the customers for electricity.

C. Inclusion of customers as market players via demand response

Microgrids present an opportunity to integrate individual residences and small commercial establishments into the dynamics of power system operation and markets. Demand response can be used in this context to decrease overall demand and facilitate demand reduction at times of air quality alerts, avoiding the use of high polluting generators. Microgrids also encourage the increased use of small-scale, clean technologies, such as residential solar photovoltaic systems that could provide electricity to a home as well as sell power to neighbors within the microgrid and back to the high voltage system.

The current policy environment is encouraging the development of advanced metering and demand response infrastructure. The federal Energy Policy Act of 2005, not only suggested the development of advanced metering and demand response programs, but also directed the attention of the Department of Energy to identify target levels of demand response benefits that could be achieved by January of 2007. The Department of Energy is charged with beginning to educate consumers on the benefits of advanced metering and demand response. State and federal agencies are also charged with investigating the potential of, and making plans for, demand response adoption. In the midst of the California energy crisis of 2000-2001, the California Energy Commission (CEC) and California Public Utilities Commission (CPUC) were, and still are, aggressively pursuing different "demand response" energy programs aimed at reducing peak energy demand. There is an exigent effort being made by state officials to seek out and implement the developing technologies that will enable demand response benefits, which include: advanced metering, the development of [OpenAMI], as well as the development of sensor and control technologies [DRETD].

IV. Wireless Current Sensor Application and Architecture

There are several sensor designs that could be used to monitor the consumption of power by different appliances within the home. Currently there are companies, providing sensors that are capable of measuring the real power being consumed by an appliance "real time". Take for instance the "watts up" meter [7], which measures the real time power consumption of the device plugged into the meter. Although the meter provides a real time power reading for any number of devices it is not only costly, but it does not provide the key functionality, that our sensor does, which is wireless accessibility. In addition to this the devices are rather large measuring a little over half a foot in length. This coupled with the lack of the wireless communication link makes alternate designs, which do incorporate the wireless component more desirable.

Other sensors with similar capabilities have been considered, notably the coupling of Faraday-couplers with 802.11 transmitters to monitor current, which when combined with voltage data provide the necessary consumption data for the demand response system.

In our design, however, we consider a self-powering sensor [2], which has been shown to be an ideal candidate for a demand response system. This design not only provides convenience for the customer, but it also provides a significant portion of the demand response infrastructure—the communication link between utilities and customers. Additionally our proposed current sensor has the potential to be scaled down to the "MEMS" level. Installing these sensors in appliance cords as they are being manufactured implicitly provides customers with the means to be participants in the demand response system. Although at this point, our sensor

design does not provide power measurements, it does provide current measurements which when coupled with voltage measurements makes computing real power possible.

The design of the sensor is well documented in [2]. The sensors are composed of two main components, a thin strip of piezoelectric material, the bimorph, and a wireless transceiver, the Micaz mote. As is shown in [2], the current sensor consists of a pair of magnets attached to the free end of the bimorph, which interact with the magnetic field produced by the current in the appliance cord. Thus causing the bimorph to oscillate and produce an AC voltage at the opposite end. Using this as the input to the ADC onboard our 802.15 ready Zigbee wireless radio, provided by Crossbow Technologies[2], the waveform is digitized, and transmitted to the PC/server for further processing. The current passing through the appliance cord can then be reconstructed via a series of electromechanical equations. In what follows next we provide a synopsis of this computation.

V. Sensor & Network Design

Our experimental setup is almost an exact replica of the one explored in [2], however we have attached the wire leads from the piezo bimorph to the analog-to-digital converter (ADC) on board the Micaz mote. The focus of this section is to outline how we will use the output of the bimorph, voltage waveform, to reproduce the current waveform of the appliance. This is accomplished through the use of a series of equations used in solid mechanics/mechanics of materials [1], which describe the relationships between the mechanical and electrical properties of piezoelectric materials. In addition to this, the report also presents a relationship, vis-à-vis a set of mechanics and electromagnetic equations, between the stresses experienced by the material and the magnetic field responsible for producing this stress. Which consequently gives rise to the relationship between the voltage produced by the piezoelectric material and the current in the appliance cord. This is made possible via the relationship between the magnetic field and the current in the appliance cord.

Without going into grave detail about the mechanics of materials a basic explanation of the electromechanical relationship(s) that exist in piezoelectric material as they relate to our work are explained below. A good reference for a comprehensive study of such material and the constituent equation is offered in [1] and [3]-[5].

Our objective, however, was to find a relationship between the voltage output of the piezoelectric bimorph which is cantilevered at one end and the force applied to the tip of the free end. This relationship is discussed in [3][4]. Interestingly enough a linear relationship exists between the applied force and the voltage produced by the piezoelectric cantilevered beam; and is given here:

$$V_{out} = F_{in}\left[\frac{a_3 c_p d_{31} t_p}{a_2 k_2 m\varepsilon\left[(j\omega)^2 + 2\zeta_m\omega_n(j\omega) + \omega_n^2\left(1 - \frac{c_p d_{31}^2}{\varepsilon}\right)\right]}\right] \quad (1).$$

F_{in} is the applied force at the free end of the cantilevered bimorph and V_o is the electric potential produced as a result. An in depth development of this expression can be found in [4]. The other terms are constants whose values are determined by the material. It is worth noting that the absolute value of the expression gives the magnitude of the output voltage. The angle is the phase shift between the input force and the output voltage. The value d_{31} is the piezoelectric strain coefficient or piezoelectric modulus, which is a constant and represents the amount of polarization resulting from a unit of stress. The polarization being defined as the net dipole moment per unit volume, averaged over the volume of the unit cell. This entire expression reduces to the following.

$$V_{out} = F_{in}K(d_{31}) \quad (2)$$

The voltage and force relationships are related to the magnetic field and thus the current in the appliance cord as follows.

$$F_{in} = I\alpha \quad (3)$$

Given equation (3) a relationship between the output voltage of the sensor and the current in the appliance cord can be formed.

$$V_{out} = I\alpha K(d_{31}) \quad (4).$$

The linear relationship between the current and voltage makes the computations much easier, and as a result requires less battery power to perform calculations. This increases the sensor's lifetime.

These values are then reported back to the computer via the Micaz's radio. In our experiment we used the MDA300CA data acquisition board to sample the voltage values produced by the piezo bimorph [6]. Given that the sampling rate is greater than the frequency of the signal, we can reconstruct the signal with a certain amount of accuracy. Thereby providing not only the Root Mean Square values of the current, but the actual current waveform in the appliance cord. This of course presents certain privacy issues for customers. Their data would be available to eavesdroppers, due to the innate security issues surrounding wireless

technology. Although this problem can easily be fixed by encrypting the data as it is sent over the wireless link between the sensor(s) and base station (computer) [6].

The voltage values are currently being computed with a multimeter for the sake of the experiment. We are considering, in future works, the inclusion of proximity voltage sensors [8] in hopes of creating a fully autonomous network. The voltage values as reported by these sensors would also be digitized and sent via the wireless link to the computer to compute real time real power values. Based on the root mean square values for both the current and voltage, the real power can be computed.

Once the power has been computed for an appliance, the computer queries the Independent System Operators website for pricing information. In another related project students from Smith College created a program, which queries the New England ISO at regular five-minute intervals for pricing information. Using this information the program executes an algorithm, based on the customer's preferences, that determines whether or not the appliance should be left on. In short, the program decides whether or not to notify a customer based on their willingness to pay a certain amount of money to keep the appliance on. [9] The customers are then notified via SMS when the cost to run a certain appliance has exceeded their personal predefined threshold.

VI. Experiment & Future Work

In our experiment we used a simple resistive load, a space heater with a variable setting, and attached the senor to the appliance cord as shown in Figure 1 below. We varied the current between 0 and 13 Amperes. The circuit, as seen in Figure 2, was used to bias the voltage waveform to within the Vcc value for the data acquisition board used—the MDA300CA.

Our next objective is to actually sample the waveform and report the values to the computer (base station). We are currently testing different source codes to complete this task. Right now we have our ADC set to sample the current waveform at a variety of rates. Once the waveform has been sampled the raw data values will be converted into actual voltage values corresponding with the current in the appliance cord via the following relationship. [MDA300CA users manual]

$$V_{out} = \frac{2.5 * ADC\_READING}{4096} \ (5)$$

Using the linear relationship between the current and voltage given in equation (4) we can compute the current in the appliance cord.

$$I = \alpha V_{out} \ (6)$$
$$\alpha = \frac{1}{74 \times 10^{-3} \frac{V}{A}}$$

The computed current values coupled with the voltage readings, which were taken with the multimeter will give us corresponding real power values. These results suggest that there is possibly a very bright and promising future for such proximity based sensors. Although we have only conducted the experiment with a simple resistive load, we have also considered using this technology with other appliances, which are not purely resistive in nature (e.g. washers/dryers, HVAC units, televisions, refrigerators, and other appliances with non-linear behaviors).

The wireless current sensor that we have proposed in this project has reportedly been able to respond to currents as high as nearly 50 Amperes in industrial size cables. [2] The ability of this sensor to detect high values of current creates the opportunity for its use not only with appliances, but also with large current carrying cables within houses and possibly small office buildings. Coupling the wireless current sensor with a corresponding voltage sensing device, capable of measuring higher levels of voltage, offers a new perspective for measuring real power within the entire home and small office buildings. Given the signal processing techniques available, the total load can be disaggregated; subsequently the different appliances, which happen to be on at the time, can be identified. NALM (Non-intrusive Appliance Load Monitoring) algorithms can be employed to accomplish such tasks. [10]

V. Conclusion and Remarks

We have demonstrated that the sensor design proposed in this work provides accurate root mean square values similar to those measured by digital multimeters. In addition to this we have also been able to show that the current waveform in the appliance cord could accurately be reproduced with this particular design. This of course leads to certain privacy issues. If the voltage values are sampled at even a higher rate, then a more accurate picture of the customer's power consumption can be created. This is a concern because of the inherent security issues encompassing wireless sensor networks. However there are several encryption schemes, which remedy this concern for system

administrators, and or customers, who opt to use such a system. [12]

It must be noted that one of the major advantages of this particular design is the possibility of downsizing the actual sensor itself. Currently members of the BSAC (Berkeley Sensor & Actuator Center) are developing prototype sensors that are made of Aluminum Nitride and are 500 by 100 micrometers in size. [11] Crossbow Technologies provides wireless modules that are approximately the size of a quarter, about 25 millimeters in diameter. [13] The coupling of the micrometer proximity based current sensor with the wireless module makes this design much more appealing and feasible as a solution to demand response issues. The sensors could essentially be placed within the appliance cords requiring no physical interaction with the appliance. The manufacturer would provide, a simple plug and use system setup, via the software and the wireless current sensor within the appliance cord. Lastly, another attractive feature of this particular sensor design is its ability to scavenge energy from the oscillation of the bimorph. [2] Given a set of rechargeable batteries, and the proper sleep/awake cycles, the sensor could be attached to an appliance without ever having to replace the batteries. Carrying this idea one step further, it is not implausible to consider a circuit as presented in [11] that could provide enough power to take measurements and send the results back to the computer without the use of batteries at all. With this being a possibility, the lifetime of the sensor can be considered to be indefinite; granted that the mote is not reporting the current readings continuously at sub second intervals. Proper sleep cycles must be considered also in order to optimize the lifetime of the sensor.

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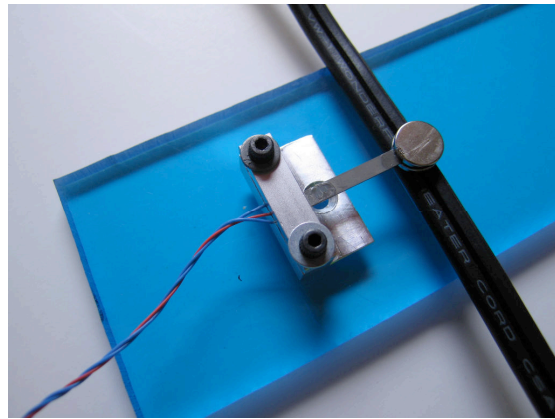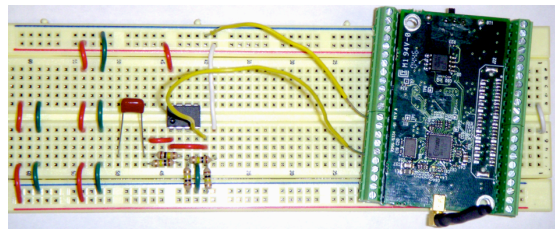
Figure 1.

Figure 2.