Development of Non-Intrusive Appliance Load Monitoring System to Easily Estimate the Power Consumption of Individual Appliances

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1. Introduction

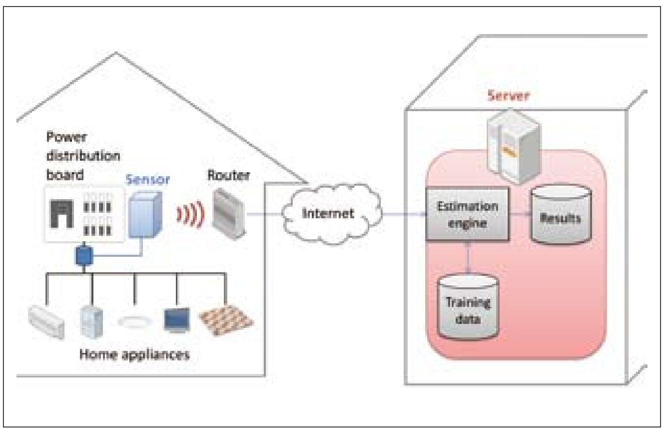
Since the Great East Japan Earthquake in 2011, there has been an increased interest in energy saving, and expectations for energy-saving techniques remain very high.

In order to continue saving energy at the level of the individual, it is important to both reduce waste and save energy without degrading the standard of living. However, wasted electricity varies depending on the household, so individuals typically follow only general advice such as "Turn off the light when you leave the room". Understanding the power consumption tendency of individual homes would enable us to save energy more effectively.

In terms of understanding power consumption tendencies, there are already a few systems in place that visualize total power consumption in a house for commercial use. However, these systems are not very user-friendly, and users need to guess where electricity is wasted. There is a great need to know not only the total power consumption but also a breakdown of this consumption, for example, with respect to individual appliances or rooms. Conventionally, to meet this need, sensors are attached to each appliance or each branch breaker, but this method necessitates the use of many sensors and often the replacement of power distribution boards, and thus its initial cost is very high.

There is currently a move to popularize a communication standard such as ECHONET Lite for home appliances. If most home appliances adopted such a standard, the power consumption of individual appliances could be understood and controlled automatically. However, because home appliances typically have a long life cycle, there may be some appliances that will not adopt the new standard for some time yet.

■ **Figure 1: System overview**



In response to these needs, we have developed a non-intrusive appliance load monitoring system (NIALMS) that estimates the power consumption of individual appliances by analyzing current data measured at a power distribution board.

2. NIALMS overview

In NIALMS, the current waveform is measured by a sensor attached to a power distribution board. The total power consumption is then calculated, and the power consumption of individual home appliances can be estimated. This system consists of a sensor installed in the home and a remote server that analyzes the current data sent from the sensor (Figure 1).

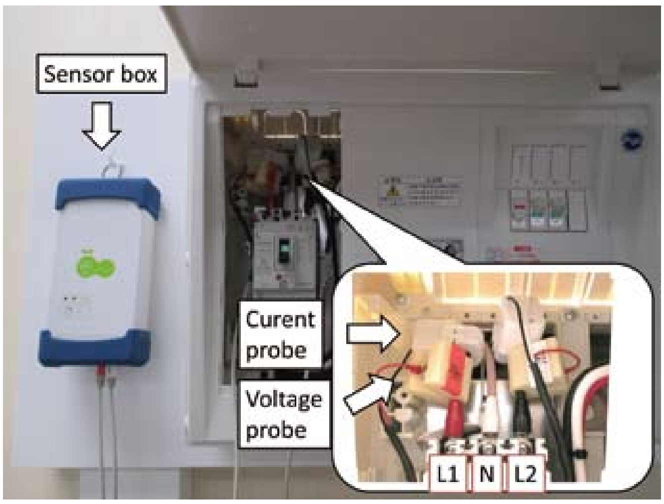
2.1 Sensor

In this system, the sensor is attached to a power distribution board and measures the current. If the system requires electrical work or that the power distribution board be replaced, this becomes a barrier in terms of reaching the masses, so it is desirable that we be able to install the system in an existing power distribution board easily. We therefore developed a sensor that consists of a current and voltage probe and a sensor box, as shown in Figure 2.

The current probe outputs the voltage proportional to the current that passes through itself and the voltage probe detects the electrical potential with capacitive coupling between the electrode and conductor in the cable and measures the voltage between two wires. These probes can easily be attached by the general user.

We use two current probes and two voltage probes so that the

■ **Figure 2: Sensor attached to distribution board**



system can accept the single-phase, three-wire system, which is the most prevalent in Japan.

The sensor box measures the current waveform, extracts the features, and transmits them to the server periodically, e.g., every three minutes. Using voltage as a trigger, we obtain the current waveform that has a fixed phase relation to commercial power and then split them into low ($f < 10$ kHz) and high (10 kHz $< f < 150$ kHz) frequency domains via frequency filter. The low frequency domain is measured to extract the component that contributes to power consumption and the high frequency domain is to extract the noise component coming from the power supply circuit.

In order to prevent any extra load on the network, the sensor extracts the peak frequency and level for the high frequency domain and reduces the communication traffic to 1 KB at a time.

Extracted features are encrypted and transmitted to the server with additional data (the sensor's serial number, etc.).

This sensor works on battery and AC power. If we set the measurement interval to three minutes, the sensor can function for a maximum of six months.

2.2 Server

The server estimates the breakdown of power consumption by analyzing the current data using previously obtained training data. The current that flows along the main breaker is the summation of the currents of all appliances. We synthesize the assumed current waveform using training data and then analyze using a support vector machine for the low frequency component. For the high frequency domain, we use the level as a threshold for whether or not to use the estimation and then perform the estimation on the basis of the existence of the frequency component.

Two independent results are obtained by the estimates using the low and high frequency components. We use the logical sum of both to suppress any oversight and then save the results to a database sequentially.

2.3 Installation

When users install this system in their homes, they must perform two operations: attaching the sensor and acquiring the training data.

First, they attach the current and voltage probes to the cables at the power distribution board and connect them to the sensor box.

Second, they acquire the training data for each appliance. They do not have to attach the sensor for each appliance; rather, they can use the sensor previously attached to the power distribution board and calculate the difference between the on-state and off-state of the current data.

Training data can also be shared among users. If training data are acquired by some other user, a new user can save time when installing the system.

Figure 3: User interface

2.4 User interface

Users can check the change and breakdown of the power consumption for individual appliances, as shown in Figure 3. By checking the power consumption of individual appliances, users can easily identify the source of wasted electricity.

3. Accuracy evaluation

We evaluated the estimation accuracy of the proposed system in a laboratory. Specifically, we tested five appliances with large power consumptions: an air conditioner, a ceiling light, a television, a refrigerator, and an electric carpet. We compared the actual state with the estimated state when these five appliances were connected to the distribution board. Results showed an accuracy of 90.6 % for all combinations of appliance state.

4. Field trial

We performed a field trial of the proposed system in 32 ordinary homes from February to August 2013. We evaluated the energy reduction effect and conducted survey research by questionnaire.

We found that, on average, there was a power consumption reduction of about 5% compared to the same term in the previous year. In addition, the questionnaire results indicated that many of the users check the power meter more frequently: over 80% of the users contributed to saving energy by using this system. This demonstrates the effectiveness of visualizing the power consumption of individual appliances.

Questionnaire data related to recouping initial costs indicated that both "less than 1 year" and "2 or 3 years" were about 40%. We therefore estimate that the allowable initial cost of a sensor for an average four-person household if they accomplished an energy reduction of 5% should be less than 18,000 yen.

At the beginning of the field trial, over 40% of the users accessed the server more frequently than once a week. However, this number decreased as time passed. To encourage users to perform more continuous monitoring, we need to add some extra motivation or push notification.

5. Conclusion

In this article, we introduced a non-intrusive appliance load monitoring system. The results of a field trial demonstrated its effectiveness in visualizing detailed power consumption. However, consumers require more functions to make it easier to use, so we are now developing such functions. Business customers, on the other hand, have a growing need for visualizing power consumption in detail, so we are expanding our target market to include business customers.