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Nonintrusive Appliance Load Monitoring Based on Integer Programming

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Abstract: This paper presents a new nonintrusive appliance load monitoring technique based on the integer programming. Nonintrusive appliance load monitoring is a problem to identify the operating conditions of the electric appliances in a house only by observing the overall load current and voltage. Since the overall load current is expressed as a superposition of each current of the operating appliance, the monitoring problem can be formulated as an integer quadratic programming problem by expressing the operating conditions as integer variables. This problem is solvable with sufficiently small computational burden thanks to the recent development of the commercial software. The proposed method does not require the relearning even when a new appliance is installed in the house. Furthermore, the proposed formulation is applicable to cases that some appliance has multiple modes, and cases that some same-type appliances operate simultaneously. Usefulness of the proposed technique is verified through some experimental results.

Keywords: Nonintrusive load monitoring, Electric appliance, Integer programming

1. INTRODUCTION

Operating conditions of electric appliance in a house or an office is valuable information for electrical power companies to predict electric power demands and to operate electric power facility efficiently. In addition, in modern society, since the operating conditions express user's life style in his/her household, some systems for learning life-style from the daily data of the operating conditions are studied [1][2].

Intrusive appliance load monitoring (IALM) and nonintrusive appliance load monitoring (NIALM) are the main methods for predicting the appliance operating conditions. IALM is based on predicting the operating conditions by using sensors attached to every appliances in a house. Although this method can predict operating conditions precisely, it costs so much to set up many sensors. On the other hand, as shown in Fig. 1, NIALM is a method to identify operating conditions only by observing the overall load current and voltage. This kind of monitoring system is considered to have great advantages in both cost and customers' comfortability when compared with conventional IALM systems.

Hart [3] proposed an NIALM system based on observing step form changes of effective power and reactive power consumed in appliances. However, this method cannot differentiate appliances with same electric power consumption. Yumoto et al. [4] suggested a method based on Neural Network (NN) whose inputs are higher harmonic spectrum in order to identify especially inverter appliances. Also, Murata et al. [5] suggested a method in which Hart's method and support vector machine are combined to NN. Nakamura et al. [6] suggested a method based on Hidden Markov Model (HMM). This method models the current waveforms of overall load current by HMM and estimates the operating conditions based on maximum likelihood estimation. However, these methods, NN and HMM, require massive amounts of training data for constructing the models. This problem is particularly emphasized when the number of appliances is large because the number of required data is in proportion to the number of combination of appliances. In addition, parameters of these models have to be relearned when new appliances are installed in the house.

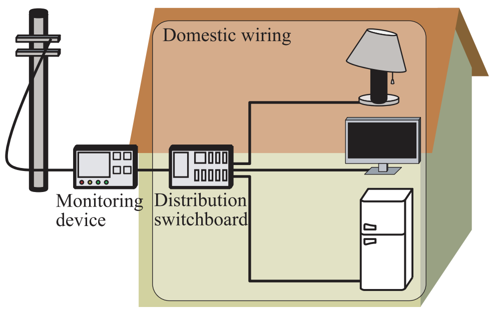

Fig. 1 Conceptual diagram of non-intrusive appliance load monitoring (NIALM) system

This paper presents a new NIALM technique based on integer programming. The estimation problem of operating conditions is represented as an integer programming problem and the operating conditions are estimated by solving it. The proposed technique utilizes the current waveforms of appliance, and so, many kind of appliances can be identified. Since only one period of current waveform of each appliance is needed on ahead, the proposed method does not require relearning even if new appliances are installed in the house. Furthermore, the integer programming problem is solvable sufficiently thanks to the recent development of commercial software.

The construction of this paper is described as follows: In section 2, the identification problem for appliance operating conditions is represented as an integer (quadratic) programming problem. In section 3, experimental conditions are set up. In section 4 and 5, experimental results are shown and usefulness of the proposed technique is verified . Finally, in section 6, we will conclude.

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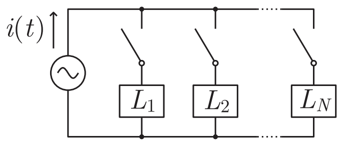

Fig. 2 Circuit model of appliances in house

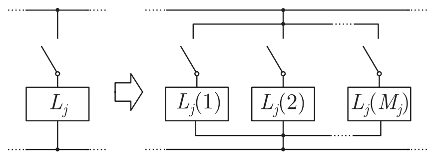

Fig. 3 Appliance with multiple operational modes

2. ESTIMATION OF OPERATING CONDITIONS BY INTEGER PROGRAMMING

2.1 Case 1: Appliance has only two (ON / OFF) modes

First of all, we describe a method to estimate operating conditions of appliance which has only two modes (ON / OFF) based on integer programming. We consider a situation that N kinds of electric appliances $L_1, L_2, \cdots, L_N$ exist in a house. In this case, the electric power line in the house is expressed as Fig. 2. For each L_n, $n \in \{1, \cdots, N\}$, C_n appliances are supposed to be connected to the electric power line of the house, i.e., C_n is the number of appliance L_n. We define one period of current waveform of each electric appliance L_n as $i_n(t)$, $n \in \{1, \cdots, N\}$, $t = \{0, \cdots, T-1\}$ which is measured beforehand independently and stored in a database. Note that t expresses the time index in the one period of waveform and $t = 0$ is the time when the voltage switches from negative to positive. T is the periodic time of the current waveform, generally $T = 1/50$s or $1/60$s. Under these settings, the overall load current $\hat{i}$ is represented by using integer variable $c_n \in \{0, \cdots, C_n\}$ for $n \in \{1, \cdots, N\}$ as:

$$\hat{i}(t) = \sum_{n=1}^{N} c_n(m) i_n(t) + \varepsilon \tag{1}$$

where ε represents the disturbance of overall current brought by noise or unknown electric appliances. Under this setup, we can actualize nonintrusive appliance load monitoring (NIALM) when we can estimate the operating appliance number $c_1, \cdots, c_N$ by observing overall load current waveform $\hat{i}(t)$.

Then, the operating-condition-estimation problem can be described as an integer quadratic programming problem:

$$\text{Find } \mathbf{c}^* = \{c_n | n \in \{1, \cdots, N\}\} \tag{2}$$

which minimize

$$E = \sum_{t=0}^{T-1} \left(\hat{i}(t) - \sum_{n=1}^{N} c_n(m) i_n(t) \right)^2 \tag{3}$$

subject to

$$c_n \in \mathbb{Z},\ 0 \le c_n \le C_n \ \ \forall n \in \{1, \cdots, N\}. \tag{4}$$

In this problem, $c_1, \cdots, c_N$ are nonnegative integer variables since they express the number of operating appliances as shown in (4). NIALM is achieved by finding most plausible operating conditions $\mathbf{c}^*$ which minimize the square error (3) between the observed overall load current and the estimated one. This kind of integer programming problem is solvable in sufficiently small computational burden thanks to the recent development of the commercial software.

2.2 Case2: Appliance has multiple modes

In the second stage, the method proposed the previous section is extended to cases that the appliances have multiple, over two, operating modes. We consider that N kinds of electric appliances $L_1, L_2, \cdots, L_N$ exist in a house. For each L_n, $n \in \{1, \cdots, N\}$, C_n appliances are supposed to be connected in the house, i.e., C_n is the number of appliance L_n. Furthermore, each appliance operates under one of M_n operating modes. And then, one period of current waveform of each electric appliance $i_n(m,t)$, $n \in \{1, \cdots, N\}$, $t \in \{0, \cdots, T-1\}$ is measured beforehand for each operating mode $m \in \{1, \cdots, M_n\}$.

When we think the situation that appliance L_n, $n \in \{1, \cdots, N\}$ has multiple M_j operating modes, we treat the appliance L_n as different M_j kind of appliances $L_n(1), L_n(2), \cdots, L_n(M_n)$ (see Fig.3). However, since the number of the appliance L_n is C_n and we cannot operate multiple modes at the same moment, then, we have to consider a constraint to the operating conditions of these virtual appliances $L_n(1), L_n(2), \cdots, L_n(M_n)$ as follows:

$$c_n(1) + c_n(2) + \cdots + c_n(M_n) \le C_n. \tag{5}$$

Under these settings, the overall load current $\hat{i}$ is represented by using integer variable $c_n(m) \in \{0, \cdots, C_n\}$ as:

$$\hat{i}(t) = \sum_{n=1}^{N} \sum_{m=1}^{M_n} c_n(m) i_n(m,t) + \varepsilon \tag{6}$$

where ε represents the disturbance of overall current brought by noise or an unknown electric appliance. Note that the integer variable $c_n(m)$ has the constraint of (5).

Then, the operating-condition-estimation problem can be described as an integer quadratic programming problem:

$$\text{Find } \mathbf{c}^* = \{c_n(m) | n \in \{1, \cdots, N\}, m \in \{1, \cdots, M_n\}\} \tag{7}$$

which minimize

$$E = \sum_{t=0}^{T-1} \left(\hat{i}(t) - \sum_{n=1}^{N} \sum_{m=1}^{M_n} c_n(m) i_n(m,t) \right)^2 \tag{8}$$

subject to

$$0 \le c_n(m) \in \mathbb{Z} \ \ \forall n \in \{1, \cdots, N\},\ m \in \{1, \cdots, M_n\}, \tag{9}$$

$$0 \le \sum_{m=1}^{M_n} c_n(m) \le C_n \ \ \forall n \in \{1, \cdots, N\}. \tag{10}$$

Table 1 Electric appliances connected to line L1

n	Appliance	m	Operating mode	C_n
1	Fluorescent lamp (Room 1)	1	50W	1
		2	68W	
2	Fluorescent lamp (Room 2)	1	50W	1
		2	68W	
3	Fluorescent lamp (Room 3)	1	50W	1
		2	68W	
4	Fluorescent lamp (Sink)	1	On (50W)	1
5	Incandescent lamp (Entrance)	1	On (60W)	1
6	Incandescent lamp (Lavatory)	1	On(100W)	1
7	Incandescent lamp (Mirror stand)	1	On (120W)	1
8	Incandescent lamp (Bathroom)	1	On(54W)	1
9	Incandescent lamp (Toilet)	1	On (50W)	1
10	Air fan (Lavatory)	1	On	1
11	Air fan (Bathroom)	1	On	1
12	Air fan (Toilet)	1	On	1
13	Air fan (Room 3)	1	On	1
14	Air fan (Kitchen)	1	On	1
15	Washing machine	1	15A	1
		2	13A	
		3	9A	
		4	5A	
		5	4A	
		6	Idling 1	
		7	Idling 2	

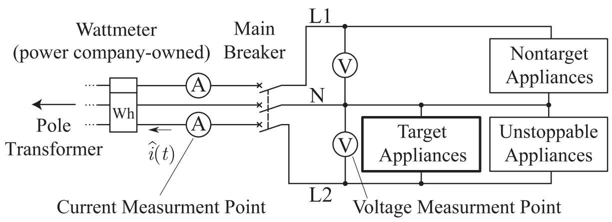

Fig. 4 Measurement of overall load current and voltage

This integer programming problem is also solvable in sufficiently small computational burden thanks to the commercial software.

3. EXPERIMENTAL CONDITION

In order to verify the usefulness of the proposed monitoring technology, some experiments were performed in a house wherein one married couple live. This house received electricity through three single-layer type lines L1, L2 and N (Fig. 4). Tables 1 and 2 show the appliances connected to the lines L1 and L2, respectively. From these tables, the constraint condition of each line is expressed in (11) and (12), respectively.

$$
\begin{aligned}
0\le\ & c_1(1),c_1(2),c_2(1),c_2(2),c_3(1),c_3(2),c_4(1),\\
& c_5(1),c_6(1),c_7(1),c_8(1),c_9(1),c_{10}(1),\\
& c_{11}(1),c_{12}(1),c_{13}(1),c_{14}(1),c_{15}(1),c_{15}(2),\\
& c_{15}(3),c_{15}(4),c_{15}(5),c_{15}(6),c_{15}(7)\in\mathbb{Z},\\
& c_1(1)+c_1(2)\le 1,\\
& c_2(1)+c_2(2)\le 1,\\
& c_3(1)+c_3(2)\le 1,\\
& c_k(1)\le 1 \text{ for } k=\{4,\cdots,14\},\\
& c_{15}(1)+c_{15}(2)+c_{15}(3)+c_{15}(4)\\
& +c_{15}(5)+c_{15}(6)+c_{15}(7)\le 1.
\end{aligned}
\tag{11}
$$

Table 2 Electric appliances connected to line L2

n	Appliance	m	Operating mode	C_n
1	Microwave oven	1	Warming mode	1
		2	Rice mode	
		3	Milk mode	
		4	500W	
2	Toaster oven	1	1000W	1
		2	500W A*	
		3	500W B*	
3	Air conditioner	1	On	1
4	Vacuum cleaner	1	Strong	1
		2	Middle	
		3	Weak	
5	Television	1	Bright	1
		2	Regular	
		3	Dark	
6	Hair dryer	1	Hot (High)	1
		2	Hot (Low) A*	
		3	Hot (Low) B*	
		4	Cool A*	
		5	Cool B*	
7	Refrigerator	1	Mode 1	1
		2	Mode 2	
		3	Mode 3	
		4	Mode 4	
		5	Mode 5	
		6	Mode 6	
		7	Mode 7	

* The modes A and B are originally same but the waveforms differ because the directions of the plug connection are inverted.

Table 3 Time at which daily life was measured

Day	Time
1	8:55∼12:59
2	6:17∼23:00
3	16:51∼22:59
4	6:53∼22:15
5	12:04∼21:55
6	10:16∼21:33

$$
\begin{aligned}
0\le\ & c_1(1),c_1(2),c_1(3),c_1(4),c_2(1),c_2(2),\\
& c_2(3),c_3(1),c_4(1),c_4(2),c_4(3),c_5(1),\\
& c_5(2),c_5(3),c_6(1),c_6(2),c_6(3),c_6(4),\\
& c_6(5),c_7(1),c_7(2),c_7(3),c_7(4),c_7(5),\\
& c_7(6),c_7(7)\in\mathbb{Z},\\
& c_1(1)+c_1(2)+c_1(3)+c_1(4)\le 1,\\
& c_2(1)+c_2(2)+c_2(3)\le 1,\\
& c_3(1)\le 1,\\
& c_4(1)+c_4(2)+c_4(3)\le 1,\\
& c_5(1)+c_5(2)+c_5(3)\le 1,\\
& c_6(1)+c_6(2)+c_6(3)+c_6(4)+c_6(5)\le 1,\\
& c_7(1)+c_7(2)+c_7(3)+c_7(4)\\
& +c_7(5)+c_7(6)+c_7(7)\le 1.
\end{aligned}
\tag{12}
$$

First, the current waveform of each electric appliance $i_n(m,t)$ was measured for all appliances $n\in\{1,\cdots,N\}$ and modes $m\in\{1,\cdots,M_n\}$ by operating the appliance independently. The current waveform of each appliance is depicted in Fig. 5 and Fig. 6. In addition, the voltage was measured simultaneously in order to extract one period waveform of current. The frequency of the voltage was 60 Hz, and the sampling interval was 25 μsec.

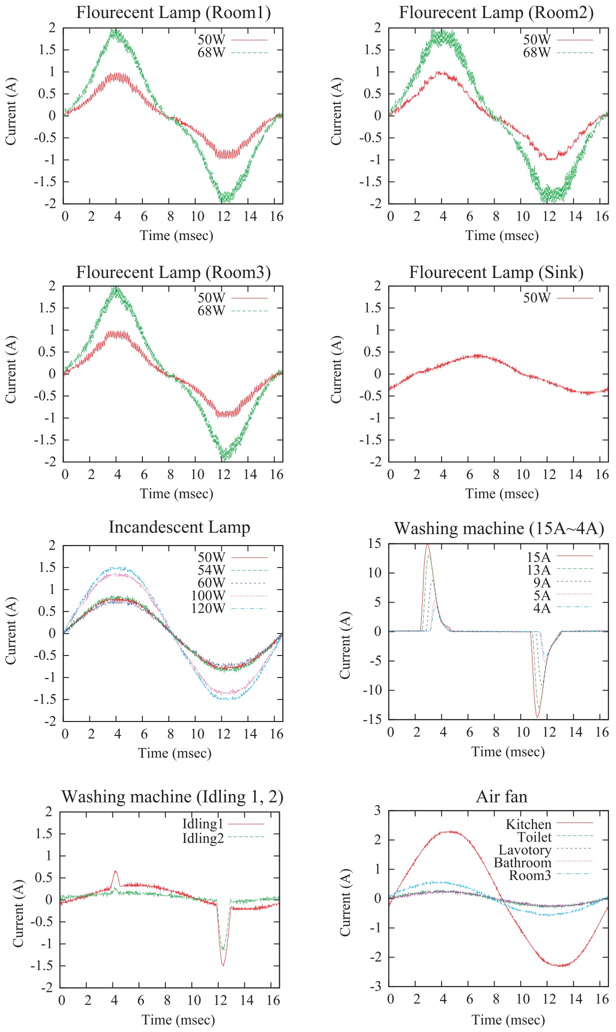

Fig. 5 Current waveforms of appliance on L1

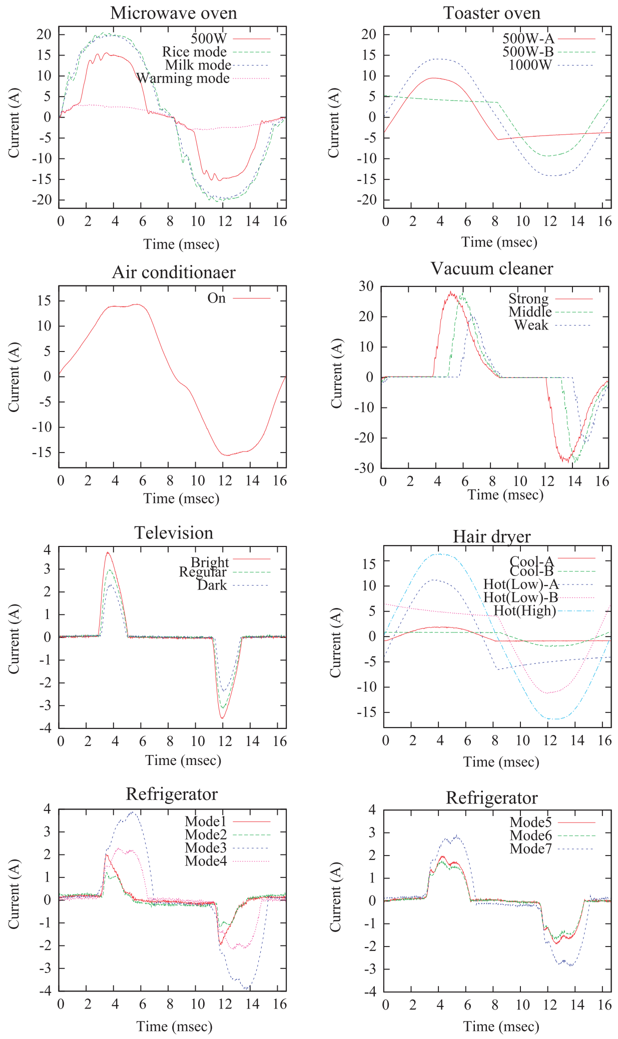

Fig. 6 Current waveforms of appliance on L2

This implies that we got 666 sampled data, i.e., $T = 666$, for each current waveform. Then, we asked the examinees to spend in their time as usual and record the time when they used an appliance. And the data during 6 days under their daily life was measured as shown in Table 3. For example, Fig. 7 shows the overall current waveforms observed on Day 2. In this figure, REF denotes a refrigerator, TV denotes a television, and HD denotes a hair dryer. The estimation of operating conditions of appliances was executed by solving the problems for L1 and L2 once per minute.We used ILOG CPLEX10.2 as an optimization software and PC/AT compatible machine (CPU: Intel Core2 Quad 2.67GHz).

4. EXPERIMENTAL RESULT

Table 4 shows the success rate of estimation wherein the success means that the estimated operating condition agrees with the actual one. The success rate of 96.8% in L2 and 62.7% in L1 were achieved. The wrong estimations seem to be caused by confusing the waveforms which have similar shape. In L1, the wrong estimations were especially caused among the fluorescent lamps and among the incandescent lamps, whose waveforms have almost same shape except small difference in the amplitude as shown in Fig. 5. In L2, the wrong estimations were caused by confusing “Toaster oven (500W) + Hair dryer (Cool)” and “Hair dryer (Hot[low])”. The reason of this confusion is that the waveform of “Toaster oven (500W) + Hair dryer (Cool)” is almost same with one of “Hair dryer (Hot[low])” as shown in Fig. 8.

Table 4 Estimation performance

Day	Success rate	
	L1	L2
1	90.0%	93.1%
2	67.6%	99.6%
3	25.5%	100%
4	77.4%	97.2%
5	52.3%	100%
6	63.4%	91.0%
Average	62.7%	96.8%

The average computational time for estimating one waveform data was 165.1 msec in L1 and 200.0 msec in L2. These computational times show the high possibility of the development of real time load monitoring system.

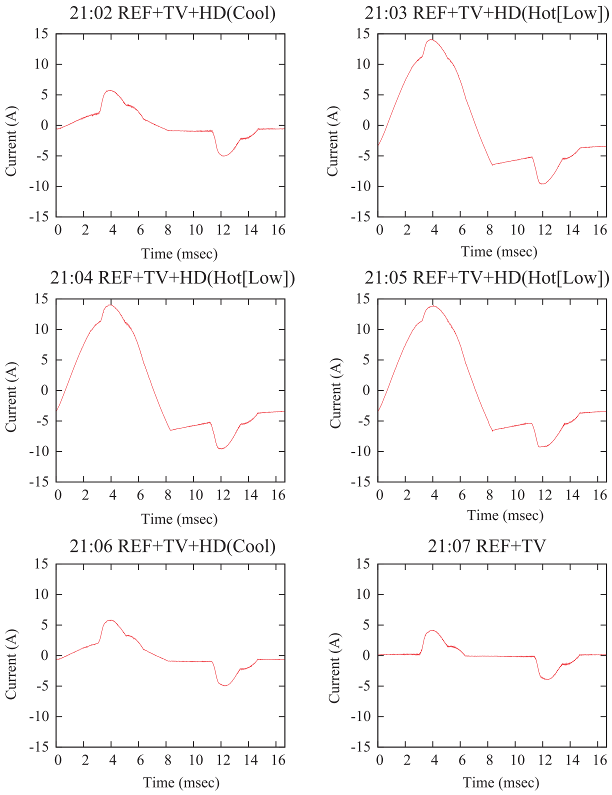

Fig. 7 Current waveforms observed on Day 2

5. UNIFICATION OF SIMILAR WAVES

The success rate of L1 is lower than that of L2 because of confusion among the fluorescent lamps and among the incandescent lamps. The reason of this confusion is that the waveform of these appliances are almost same. In order to avoid this confusion, we regarded the fluorescent lamps in Rooms 1, 2, 3 as same kind of appliance. Also, we regarded the incandescent lamps in bathroom ($n = 8$) and in toilet ($n = 9$), ones in lavatory ($n = 6$) and in mirror stand ($n = 7$) as same kind of appliances. The compensated list of appliances by these unifications is described as Table 5. As the result of this compensation, the constraint condition of L1 (11) is changed to (13).

$$
\begin{aligned}
0 \leq c_1(1), c_1(2), c_2(1), c_3(1), c_4(1), c_5(1), c_6(1),\\
c_7(1), c_8(1), c_9(1), c_{10}(1), c_{11}(1), c_{11}(2), c_{11}(3),\\
c_{11}(4), c_{11}(5), c_{11}(6), c_{11}(7) \in \mathbb{Z},\\
c_1(1) + c_1(2) \leq 3,\\
c_3(1) \leq 2,\\
c_5(1) \leq 2, \quad (13)\\
c_k(1) \leq 1 \text{ for } k = \{2,\ 4,\ 6, \cdots, 10\},\\
c_{11}(1) + c_{11}(2) + c_{11}(3) + c_{11}(4)\\
+ c_{11}(5) + c_{11}(6) + c_{11}(7) \leq 1.
\end{aligned}
$$

By this procedure, the success rate of estimation increased up to 79.0% as shown in L1' of Table 6. As stated above, unification of some appliances increase the estimation performance when the waveforms are similar. Finding effective method to unify different appliances is our future work.

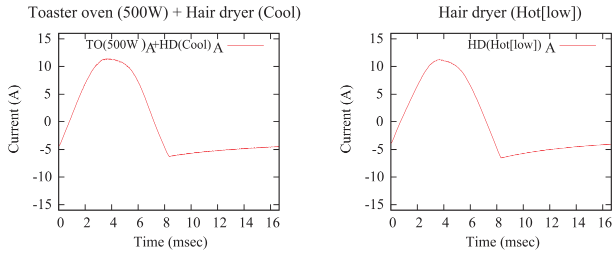

Fig. 8 Confusion of waveforms in L2

Table 5 Compensated list of L1

n	Appliance	m	Operating mode	C_n
1	Fluorescent lamp (Room 1,2,3)	1 2	50W 68W	3
2	Fluorescent lamp (Sink)	1	On (50W)	1
3	Incandescent lamp (Bathroom, Toilet)	1	ON(50/54W)	2
4	Incandescent lamp (Entrance)	1	On (60W)	1
5	Incandescent lamp (Lavatory, Mirror stand)	1	ON(100/120W)	2
6	Air fan (Lavatory)	1	On	1
7	Air fan (Bathroom)	1	On	1
8	Air fan (Toilet)	1	On	1
9	Air fan (Room 3)	1	On	1
10	Air fan (Kitchen)	1	On	1
11	Washing machine	1 2 3 4 5 6 7	15A 13A 9A 5A 4A Idling 1 Idling 2	1

Table 6 Compensated estimation performance of L1

Day	Success rate	
	L1 (before)	L1' (after)
1	90.0%	96.7%
2	67.6%	85.5%
3	25.5%	64.1%
4	77.4%	90.4%
5	52.3%	64.4%
6	63.4%	73.2%
Average	62.7%	79.0%

6. CONCLUSION

This paper presented a new nonintrusive appliance load monitoring technique based on the integer programming and showed the usefulness by some experiments. In addition, we present a countermeasure to the problem that appliances which have similar current waveform are misunderstood each other. However, in this paper, the way to unify the appliances depends on heuristic maneuver. Therefore, finding effective method to automatically unify similar appliances is our future work.

In this paper, we have shown the performance of estimation in one household, a married couple, but we need more experiments in various households to verify the proposed system. Especially, we have performed no experiment about appliances whose current waveform changes in continuity. The proposed system can be applied only to such appliances that have the operating modes discretely. Finding a countermeasure to such appliances is also our future work. Additionally, reduction of computational burden and proposal about applications using the result of estimation of the operation condition of electric appliances are also our future work.

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