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Home energy management incorporating operational priority of appliances

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ABSTRACT

Home energy management (HEM) schemes persuade residential customers to actively participate in price-based demand response (DR) programs. In these price-based HEM methods, a controller schedules the energy consumption of household's controllable appliances in response to electricity price signals, considering various customer preferences. Although numerous methods have been recently proposed for HEM application, prioritizing the operation of controllable appliances from the customer's viewpoint in price-based HEM has not been addressed, which is the focus of the present paper. To do this, the value of lost load (VOLL) of each appliance is defined to indicate the operational priority of that appliance from the customer perspective. Considering appliances' VOLL, electricity tariffs, and operational constraints of appliances, an optimization problem is proposed to minimize customer energy and reliability costs. The output of the proposed HEM would be the optimum scheduling of household electrical demand. Numerical studies illustrate the effectiveness of the proposed HEM method in a smart home, considering different time-varying electricity pricings.

Introduction

In smart grids, demand response (DR) programs play major roles in activation of end-users participation in the distribution system operation. In DR programs, the distribution system operator designs an electricity tariff or an incentive to convince customers to voluntarily change their daily electrical consumption pattern [1,2]. Since the residential demand is a significant portion of the total system load, residential DR programs are important from the system operator's perspective.

One of the obstacles in widespread application of residential DR programs is the lack of customers' knowledge in responding to the received pricing or incentive signals [3]. One of the proposed solutions is a control system that automatically responds to the received signals by solving a simple optimization problem, which is generally referred to as home energy management (HEM) systems [3,4]. A HEM program typically minimizes the customer's costs, which could be a factor in stimulating customers to participate in DR programs [4,5]. The output of solving an optimization-based HEM problem is the energy consumption schedule of controllable appliances. In addition to controllable appliances, in coming years, plug-in hybrid electric vehicle (PHEV) technologies will expectedly penetrate into smart homes because of their environmental advantages [6]. Since these vehicles have batteries that can be charged in different levels by the grid and can be discharged to return the energy back to the grid (e.g. vehicle to grid capability), it is necessary to incorporate PHEV in the load management procedure. Hence, solving the HEM problem results in energy consumption schedules of households' controllable appliances and charge/discharge scheduling of PHEVs.

Several papers [7–12], have focused on HEM modeling and formulations. The proposed methods in those papers reduce the energy cost for the customer as well as the household's peak load. In addition, to convince customers to actively participate in the DR programs, the customers' comfort is modeled in these works. Some works, such as [13–22], mathematically model the customer inconvenience in addition to energy costs. Models of inconvenience in these works can be classified into two categories: inconvenience as a result of timing, and inconvenience as a result of undesirable energy states. In the former class, a penalty is attributed to delays in the use of devices due to load shifting, such as washing machines and dryers [13–18]. In the latter one, a penalty is attributed to deviations from an ideal energy state, such as the temperature of a house [19–22].

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Some works introduce the priority of an appliance for the customer to add another level of satisfaction to implement DR programs [23,24]. In [23,24], the designed DR scheme is to cap the customer's consumption to a predetermined limit. Accordingly, the priority for controllable appliances along with the associated thermal and operational constraints is set in [23,24] to determine which appliances can be turned off in the case of DR implementation. Although the concept of appliances' priority is incorporated in these works, their proposed DR plans do not include price-based DR programs.

In summary, although the concept of proposing an optimization problem for HEM [2–5,8–10] and also incorporating priorities of running household's appliances in DR implementation [23,24] have been presented in the literature, modeling the priorities of appliances in the implementation of HEM, based on price-based DR programs, has not been addressed in the previous works.

In this paper, a price-based HEM framework is designed to incorporate the priority of operating different appliances in the optimization model of an energy management system. As an example, a home may have two controllable appliances, and the operation of one of them for the customer is more important than the other one. This customer should be able to distinguish between these appliances in the HEM scheme. To do this, the value of lost load (VOLL) is determined for each appliance, according to common time-varying tariffs for residential customers, i.e., time of use (TOU) and inclining block rate (IBR). In other words, considering the different tariff rates, the customer determines a value for operation of an appliance. Actually, VOLL value of an appliance shows the importance of running that appliance for the customer in comparison with the electricity cost. Subsequently, VOLL values are used to calculate the customer reliability cost for the next day. Thus, the objective function is to minimize the customer's energy and reliability costs for the next day. The output of the proposed HEM is the scheduled household demand for the next day. In conclusion, the main contribution of this paper is to consider the operational priority of appliances in a HEM model designed for implementation of price-based DR programs. The significance of the proposed method is to add another level of customer satisfaction and flexibility to the existing price-based HEM models.

The rest of this paper is organized as follows. Section 'Methodo logy and Problem Formulation' is dedicated to description and formulation of the proposed method. The method is examined in two designed case studies in section 'Numerical Studies'. The paper is concluded in section 'Conclusion'.

Methodology and problem formulation

Background

In the context of HEM, many works propose a method to minimize the customer costs, satisfying the operational constraints of the household devices. For example, in [7] the optimal scheduling of smart homes' energy consumption is determined using a mixed integer linear programming (MILP) approach. The optimization-based model is proposed to minimize the total day-ahead expense of a smart building's energy consumption. Ref. [8] presents a controller that curtails the peak load as well as saves the electricity cost while maintaining the reasonable thermal comfort associated with heating, ventilation and air conditioning (HVAC) systems at homes. In [9], an automatic energy consumption scheduler improvised in smart meters finds the optimum scheduling based on the received price from the utility. The optimum scheduling is achieved with interactions among the users/customers and the utility company in the energy consumption game. In [10], mathematical models are developed for household appliances, and mathematical optimization models of the residential energy consumption are proposed with the objectives of minimizing energy consumption, total cost of electricity and gas, emissions, peak load, and/or any combination of these objectives. In addition, Ref. [11] mathematically formulates an optimization-based HEM consists of a set of solar photovoltaic modules, a small wind turbine, an energy storage system, an electric vehicle, and a set of controllable appliances. The objective is to minimize the energy costs in the format of mixed integer linear programming from the consumer's perspective.

In summary, the abovementioned works support the idea of proposing optimization-based HEM to facilitate the implementation of price-based DR programs. Neither these works nor other related works in the context of price-based DR programs, present a model to consider the priority of running household's appliances in the optimization procedures. In these works, the importance of all appliances is assumed to be the same from the customer's viewpoint, which may not always be the case in reality. In this section, a HEM model considering the priority of appliances from the customer's viewpoint is proposed to further facilitate the implementation of price-based DR programs. At first, different categories of controllable appliances are introduced. Then, TOU and IBR tariffs as the most popular price-based residential DR programs are mathematically presented. Since VOLL values of controllable appliances have the main role in the proposed method, the manner of determining these values by the controller according to customer's preferences is explained in this section. Finally, the optimization problem, i.e., the objective function and the constraints, in MILP format, is described.

Different categories of controllable appliances

For the proposed HEM scheme, household appliances are divided in two groups, i.e., controllable and uncontrollable appliances. The operation of controllable appliances can be scheduled in the HEM, based on the received prices; while uncontrollable appliances have non-programmable operation time and consumption level. In the following, the controllable appliances, similar to [3,4,13], are partitioned into two categories for modeling in the HEM program.

ON/OFF controlled appliances

Some controllable appliances such as dishwasher, washing machine, and clothes dryer can be controlled in ON/OFF manner. In other words, the energy consumption of these appliances at each operating time step is definite and independent of time, and the operating time steps of these appliances can be determined by solving the HEM problem. This assumption is in line with the proposed model in the literature [3,4,13]. The required time for proper operation of these appliances is assumed as a known parameter in the problem.

Regulating appliances

Controllable appliances such as cooling/heating systems, whose energy consumption level at each time step can be controlled, are named regulating appliances. These appliances can have maximum and minimum limits for their consumption at each time step. In addition, the total daily energy consumption of these appliances is defined as the problem input. It should be noted that PHEV can be accommodated in this category.

Residential electricity tariffs

TOU is the most common residential electricity tariff [25]. In TOU tariff, the electricity price changes in definite levels during hours of the day. TOU can be described in different levels. A three level TOU tariff is mathematically presented as follows:

$$\gamma(t) = \begin{cases} \gamma_1 & if\ t \in T_1 \\ \gamma_2 & if\ t \in T_2 \\ \gamma_3 & if\ t \in T_3 \end{cases} \quad (1)$$

where t is the time step index, $\gamma(t)$ is the TOU electricity tariff at time step t; γ_1, γ_2, and γ_3 are, respectively, tariffs at off-peak periods (T_1), mid-peak periods (T_2), and on-peak periods (T_3) during a day. Obviously, $T_1 \cup T_2 \cup T_3 = 24$ h and $\gamma_1 \leqslant \gamma_2 \leqslant \gamma_3$. Transferring household demand from on-peak tariff periods to lower tariff ones not only decreases the customer energy cost but also leads to peak load shaving and valley filling, which are desirable for the distribution system operator.

Many utilities such as Pacific Gas & Electric, San Diego Gas & Electric, and the Southern California Edison companies have used IBR pricing for years [26]. Applying IBR can lead to load balancing and reducing peak to average ratio [27]. In the IBR pricing, energy consumption more than a predetermined threshold in a day would impose a penalty cost to the customer [28]. This penalty is such that the amount of energy consumed above the threshold value should be paid by a higher tariff than the case of less than the threshold. An IBR tariff, $R(E)$, is mathematically presented as:

$$R(E) = \begin{cases} \alpha & 0 \leqslant E \leqslant \partial \\ \beta & E > \partial \end{cases} \quad (2)$$

where E is the total amount of received energy from the grid at a day, and ∂ is the predetermined threshold of IBR pricing. The cost of energy consumption less and higher than the threshold ∂ is respectively calculated by tariffs α and β, where β is greater than α.

VOLL of controllable appliances

VOLL of controllable appliances are determined by the energy management system based on the operational priority of appliances for the customer. The priority of an appliance in the next day from the customer's point of view is supposed to be *high*, *medium*, or *low*. In this paper, it is assumed that the energy management system translates these qualitative concepts of operation priorities to quantitative values of VOLL. This procedure is presented here according to the declared tariff.

In the previous HEM works, no priority order has been considered for household appliances in the case of price-based DR implementation. However, sometimes, operation of some appliances is not as critical for the customer as the electricity cost, and postponing or canceling the operation of such an appliance does not impose much inconvenience to the customer. Thus, we can interpret this concept in the form of assigning a VOLL to each appliance; the VOLL for such an appliance with lower priority can be set to be lower than the highest level of electricity tariff. One can say that a comparison between the assigned VOLL value for an appliance and the tariff determines the importance of operating the appliance for the customer. For example, if the operation of washing machine in a day is not as important as its electricity cost for the customer, VOLL of washing machine is set to a lower value than the tariff rate. Thus, the energy management system prefers to turn off washing machine, which imposes the reliability cost instead of the energy cost. Assigning VOLL values to appliances according to common time-varying tariffs are briefly described in the following.

Assume that the tariff is a three-level TOU tariff defined in (1). When the priority of running an appliance is *low*, the appliance's VOLL should be set to a lower value than the lowest tariff level ($VOLL \leqslant \gamma_1$); If the priority of an appliance is *medium*, it is reasonable to set a value between the lowest and highest tariffs for the appliance's VOLL ($\gamma_1 \leqslant VOLL \leqslant \gamma_3$); the high operational priority of an appliance should be indicated by a VOLL more than the highest tariff ($\gamma_3 \leqslant VOLL$). In other words, VOLL for an appliance with *low*, *medium*, or *high* priority should be set, respectively, lower than γ_1, between γ_1 and γ_3, or higher than γ_3. Considering IBR tariff defined in (2), *low*, *medium*, and *high* priorities of an appliance are equivalent to VOLL values, respectively, lower than α, between α and β, and higher than $\beta$for that appliance. For example, if the declared tariff is considered to be a IBR tariff with $\alpha = ¢10$/kW h and $\beta = ¢$ 15/kW h and the priority of running an appliance for the customer is low, VOLL of that appliance will be set a quantity lower than ¢ 10/kW h, e.g., ¢ 9/kW h.

Objective function

The first criterion that each customer considers is the energy cost minimization. The energy cost is the function of declared time-differentiated tariff and electrical energy consumption at each time step. The linearized energy cost function (EC) according to TOU and IBR tariffs are, respectively, illustrated in Eqs. (3) and (4).

$$EC = \sum_{t \in T} \gamma(t) E(t) \quad (3)$$

$$EC = \alpha \times El + \beta \times (E - \partial) \quad (4.a)$$

$$E = \sum_{t \in T} E(t) \quad (4.b)$$

where t is the time step index, T is the horizon time of scheduling, which is assumed to be one day in this paper, EC is the energy cost function, $E(t)$ is the household electrical energy consumption at time step t, $\gamma(t)$ is the TOU tariff at time step t as defined in (1), E is the total electrical energy consumption in a day, El is the daily electrical energy consumption lower than threshold ∂, and $(E - \partial)$ is the daily electrical energy consumption more than the threshold. It is obvious that El should be lower than or equal to the threshold ∂.

In addition to the energy cost, we propose to incorporate VOLL as the indicator of operational priority of household appliances for the customer in the HEM procedure. The controller should determine operation scheduling of appliances based on the predetermined VOLL of appliances and electricity tariff. Since reliability cost (RC) is the function of VOLL of appliances, this function is added to objective function to take the priority of appliances into account. The reliability cost function is mathematically presented as follows:

$$RC = \sum_{a \in A} VOLL_a LE_a \quad (5)$$

where a is the index of appliances, and A is the set of appliances. In addition, $VOLL_a$ is VOLL of appliance a, determined by the customer based on the value of running the appliance. LE_a is the lost energy of appliance a. Each controllable appliance, either ON/OFF or regulating appliance, has definite total energy consumption in a day. Accordingly, if the total energy consumption of appliance a in the day is less than the predetermined total energy consumption for that appliance, the difference between the resulted energy consumption and the predetermined energy consumption will be the lost energy of appliance a, i.e., LE_a.

Thus, the objective function is:

$$\min COST = EC + RC \quad (6)$$

where $COST$ is the total customer costs in a day, EC is the energy cost of the customer and RC is the reliability cost. It means that the HEM results are driven from a compromise between the energy cost and reliability cost of the customer.

Constraints

At each time step of the studies, the household electrical energy consumption is the summation of consumption of controllable and uncontrollable appliances, that is,

$$E(t) = E^{c}(t) + E^{uc}(t), \tag{7}$$

where $E^{c}(t)$ and $E^{uc}(t)$ are, respectively, controllable and uncontrollable household demand at time step t. A good estimate of $E^{uc}(t)$ is usually assumed to be known. As mentioned before, at each home, controllable appliances such as washing machine, clothes dryer, and dishwasher operate in ON/OFF manner. The energy consumption level of some others such as heating/cooling systems and PHEV at each time step can be controlled in their allowable range of energy consumption. Considering J and K as sets of, respectively, ON/OFF controlled appliances and regulating appliances, following equations are operational constraints of controllable appliances at each home, similar to mentioned models in [4,13,14].

$$\sum_{t \in AI_j} I_j(t) = U_j, \quad \forall j \in J, \tag{8}$$

$$E_j(t) = E_j I_j(t), \quad \forall j \in J, \tag{9}$$

$$E_k^{\min}(t) \leqslant E_k(t) \leqslant E_k^{\max}(t), \quad \forall k \in K, \; \forall t \in AI_k, \tag{10}$$

$$\sum_{t \in AI_k} E_k(t) = E_k, \quad \forall k \in K, \tag{11}$$

$$\sum_{k \in K} E_k(t) + \sum_{j \in J} E_j(t) = E^{C}(t), \quad \forall t \tag{12}$$

where j and k are indices of, respectively, the ON/OFF controlled appliances and regulating appliances can be controlled. $I_j(t)$ is a binary variable, which 1 means the jth electrical appliance is ON at time step t. U_j is the required uptime of appliance j to properly do its task. E_j is the energy consumption of appliance j at each operating hour, which is determined according to the appliance's characteristics. AI_j and AI_k are respectively the allowable interval for operation of appliances j and k, which are determined by the customer. $E_j(t)$ and $E_k(t)$ are, respectively, the electrical energy consumption of appliance j and appliance k at time step t. $E_k^{\min}(t)$ and $E_k^{\max}(t)$ are, respectively, the minimum and maximum allowable energy consumption level of appliance k (e.g., minimum and maximum charging rate for PHEV) at time step t.

Eq. (8) shows that ON/OFF controlled appliances need a definite operation time to complete their task and this operation time should lie in the allowable time interval (AI_j). The energy consumption of this type of controllable appliances at each time step is shown in (9). The energy consumption of appliance k at each time step is more than a minimum and capped to a maximum value according to (10). The total energy consumption of appliance k in its allowable operation interval should be a definite value (E_k). For example, the energy fed into the battery of PHEV should provide a fully charged battery at the departure time. This constraint is mathematically expressed in (11). As presented in (12), the household controllable energy consumption is summation of the energy consumption of all controllable appliances in sets J and K. As a conclusion, $E_j(t)$ and $E_k(t)$ are the results of solving the optimization problem addressed in (6)–(12).

Numerical studies

In this section, the proposed HEM method is studied in a smart home with different controllable and uncontrollable appliances, and a PHEV. At first, three-level TOU tariff is incorporated in the HEM. Then, the optimization problem is solved considering IBR tariff. Energy and reliability costs are reported as outcomes of solving the propounded optimization problem. In addition, the household load is presented after solving the HEM problem with the two time-differentiated tariffs.

In these cases, optimization time step is assumed to be 10 min. Thus, the scheduling horizon time (next 24 h) is 144 time steps. Uncontrollable household demand is assumed to be known as shown in Fig. 1.

A PHEV with the associated characteristics tabulated in Table 1 is considered at home [4].

In this table, $E_{PHEV}^{\max}$ is the maximum in-home charge/discharge rate of the PHEV's battery. In other words, the maximum allowable rate for charging and discharging of PHEV battery through the household charger's structure is assumed to be 0.233 kW. *cap* is PHEV battery energy capacity, *PHE0* is the initial charge state of PHEV battery, *PHEf* is the final charge state of PHEV battery in the day, and η_{ch}/η_{dch} are charge/discharge efficiencies of PHEV battery. Note that, the PHEV is out of home in the time interval [49, 102] and consumes 5 kWh electrical energy in this interval. The PHEV battery should be fully charged before the trip. Washing machine, dishwasher, and clothes dryer are assumed as ON/OFF controlled appliances. Table 2 concludes the operational characteristics of these appliances [29]. In addition, consumption level of heating system is controlled at different hours of the next day in the declared ranges in Table 3 [4]. Note that, the total energy consumption of heating system is assumed to be 2 kW h in the day ($E_{heating}$ = 2 kW h).

The most determinant factor in the proposed method is the VOLL of controlled appliances. Here, it is assumed that the operation priorities of washing machine and clothes dryer are not as high as other appliances for the customer. Hence, priorities for them are assumed to be *medium*. For other appliances, the priority is considered to be *high*.

Case 1: Incorporating TOU tariff

In this case, reliability and energy costs are minimized considering that the declared tariff to the customer is three-level TOU as presented in Table 4 [4].

Before applying the proposed method, it is worthwhile to solve the optimization problem without reliability cost, i.e., without considering different priorities for appliances from the customer's viewpoint. To do this, the VOLL values of appliances are set the same and a high value (e.g. ¢ 100/kW h). The resulted cost, i.e., the energy cost of customer, would be ¢ 224.2, in this mode.

Considering the operational priorities of appliances, according to the TOU tariff, the VOLL values of washing machine and clothes

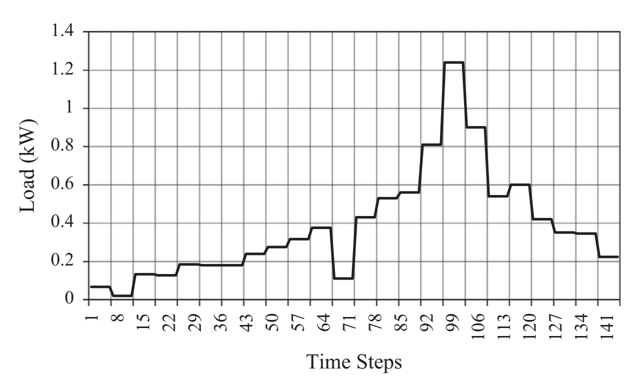

Fig. 1. Typical uncontrollable demand.

Table 1
PHEV characteristics [4].

E^{max}_{PHEV} (kW)	Cap (kW h)	PHE0 (kW h)	PHEf (kW h)	η_{ch}	η_{dch}
0.233	7.8	3.9	3.9	0.88	0.88

Table 2
ON/OFF controlled appliances data [29].

Appliance	U_a	E_a (kW h)	AI_a
Washing machine	3	0.200	[42, 60]
Clothes dryer	5	0.205	[61, 126]
Dishwasher	3	0.0625	[67, 138]

Table 3
Energy consumption (kW h) limits of heating system at each time step [4].

t	$E^{max}_{heating}$	$E^{min}_{heating}$
[1, 6] and [109, 144]	0.030	0.025
[37, 42] and [103, 108]	0.020	0.015
[43, 48] and [91, 102]	0.010	0.005
[7, 36] and [49, 90]	0.005	0

Table 4
TOU tariff [4].

γ_1	γ_2	γ_3	T_1	T_2	T_3
9.9	11.4	14.9	Time steps [1, 42] and [139, 144]	Time steps [43, 60] and [121, 138]	Time steps [61, 120]

dryer are set to be ¢ 10 kW h, which is between γ_1 and γ_3. The resulted energy cost and reliability cost are, respectively, ¢ 207.9 and ¢ 14.25 in this case. Accordingly, the total cost of customer, which is resulted from solving the optimization problem is ¢ 222.2. This shows that total cost of customer may be also decreased by considering reliability cost in the HEM process. This result illustrates that the proposed HEM method satisfies the customers more, not only by considering their preferences in the scheduling, but also by decreasing their electricity costs by 7.5%, from ¢ 224.2 to ¢ 207.9. The operation time steps of ON/OFF controlled appliances are reported in Table 5, with and without considering reliability cost (*RC*). For example, resulted operation time steps for washing machine in the case of study without reliability cost (without RC) are steps 42–44, i.e., [42, 44].

As presented in Table 5, since VOLL values of washing machine and clothes dryer are lower than the mid- and high-peak tariffs, it is profitable to switch off these appliances in the associated time steps. Thus, washing machine is ON, just in one off-peak tariff time step (time step 42), and clothes dryer is OFF at all time steps. This leads to higher reliability cost, but causes lower total cost.

Total electrical demand of heating system and the PHEV is presented in Fig. 2. The negative load in this figure illustrates the capability of returning the discharged energy to the grid. This is designated as vehicle to grid (V2G) capability. Since the PHEV battery is charged at low tariff time steps, and discharged at high tariff ones, V2G capability effectively reduces the energy cost of customer.

Table 5
Operation time steps of ON/OFF controlled appliances in Case 1.

	Washing machine	Clothes dryer	Dishwasher
Without *RC*	[42, 44]	121 and [123, 126]	[106, 108]
With *RC*	42	–	122, 124, 125

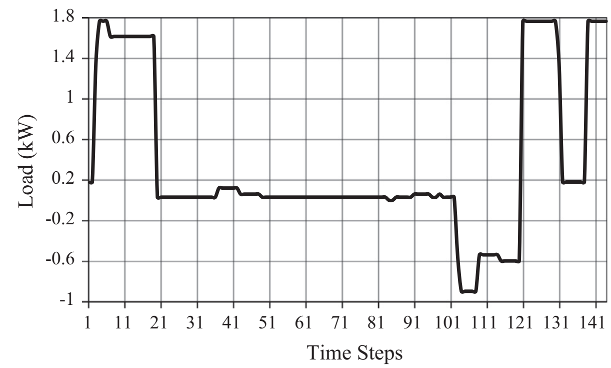

Fig. 2. Demand of electrical heating system and PHEV in Case 1.

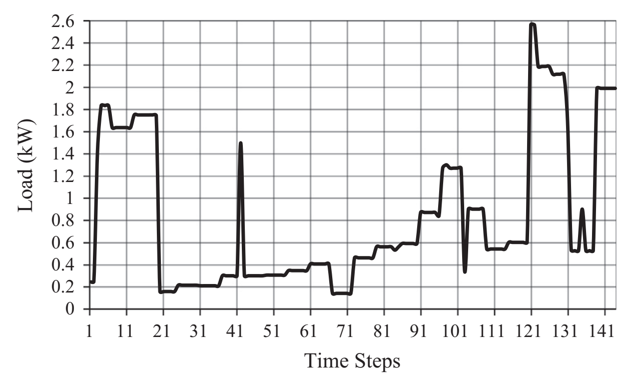

Fig. 3. Household load demand in Case 1.

The optimum scheduling of the controllable appliances' consumption considering the reliability cost leads to the household load demand as presented in Fig. 3. This figure shows the peak load of 2.55 kW, incorporating TOU tariff in the proposed HEM procedure. It is worthwhile to note that the peak of electrical demand in the home without HEM system can be higher than the resulted peak load in Case 1. For example, assume that in the case without the HEM system, at time step 100, the PHEV is charged, clothes dryer is working, and heating system consumes maximum allowable energy. The summation of these appliances' consumption and the uncontrolled demand, leads to 3.05 kW peak load at time step 100, which is 20% more than that of Case 1.

Case 2: Incorporating IBR tariff

Similar to the previous case, this case is also studied in two modes with and without considering reliability cost in the objective function. It is assumed that IBR tariff is incorporated in the optimization problem with $\alpha =$ ¢ 9.9/kW h, $\beta =$ ¢ 14.9/kW h, and $\partial = 15$ kW h. In other words, tariffs of daily electricity consumption less and more than 15 kW h are, respectively, ¢ 9.9/kW h and ¢ 14.9/kW h. Hence, in the mode of considering the reliability cost, VOLL values of washing machine and clothes dryer are assumed to be ¢ 10/kW h, which is between α and β. VOLL of other appliances is assumed to be a higher value than ¢ 14.9/kW h.

Solving the optimization problem shows that the energy cost of customer without and with considering the reliability cost are, respectively, ¢ 202.3 and ¢ 178. This result verifies that incorporating priority of appliances can cause about 12% lower cost for the customer. In addition, ¢ 16.3 as the reliability cost is imposed to the customer in this case. However, the total cost is ¢ 194.3, which

Table 6
Operation time steps of ON/OFF controlled appliances in Case 2.

	Washing machine	Clothes dryer	Dishwasher
Without *RC*	53, 54, 60	102, 104, 105, 106, 126	114, 115, 138
With *RC*	–	–	114, 115, 138

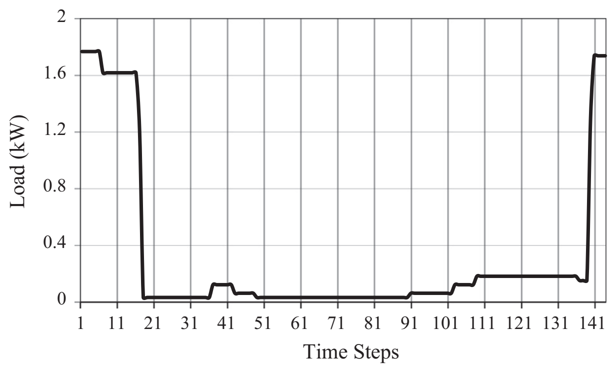

Fig. 4. Demand of electrical heating system and PHEV in Case 2.

is also lower than the cost before considering the appliances' priorities. Accordingly, in Case 2, the total cost decrement with reliability cost is 4%, which is more than that of Case 1, which was 1%. This shows the effectiveness of the IBR pricing in comparison with TOU tariff from customer's viewpoints. It is worthwhile to note that the daily household energy consumptions without and with reliability cost in this case are, respectively, 18.63 kW h and 17.01 kW h.

Operation time steps of ON/OFF controlled appliances and total demand of heating system and PHEV in Case 2, are, respectively, presented in Table 6 and Fig. 4.

As presented in Table 6, since VOLL values of washing machine and clothes dryer is less than the higher rate of IBR (β) and the daily energy consumption is more than the threshold, it is profitable to turn off these appliances during the day. Fig. 4 shows that PHEV is charged at early and last hours of the day to provide predetermined charge state for PHEV at the departure time step (time step 49) and at the end of the day. Unlike the previous case, according to the essence of IBR pricing and because of the conversion efficiencies of PHEV battery, it is not profitable to discharge the PHEV battery at some periods and charge it again at other ones. Thus, PHEV battery is not discharged at any time steps in this case as presented in Fig. 4.

The household load demand in Case 2 with the reliability cost is presented in Fig. 5.

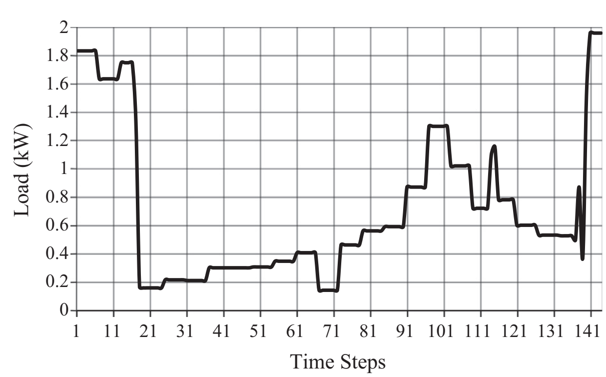

Fig. 5. Household load demand in Case 2.

This figure shows the household peak load of 1.95 kW. Comparing Figs. 3 and 5 shows that, in the case of considering RC, incorporating the IBR tariff more distributes electrical demand during the day in comparison with TOU tariff. This leads to lower peak load in Case II. This result, which may not be attractive for customers, is appealing for distribution system operators.

Conclusion

This paper employs operational priorities of appliances from customers' viewpoints in the HEM model to better satisfy the customers to respond to time-differentiated prices of electricity. To do this, the priority of operation of an appliance is, at first, interpreted as the VOLL of that appliance. Then, reliability cost, which is the function of VOLL of controllable appliances, is added to the objective function of the HEM problem. This paper also studies the impact of incorporating TOU and IBR tariffs in the proposed HEM program on the customers' costs.

Results of studies in this paper show that incorporating priorities of appliances in the HEM procedure can lead to the lower cost for the customer. The study also illustrates that incorporating the daily IBR tariff in the HEM program compared to the TOU tariff leads to the lower cost and flatter household load, which are more appealing for customers and distribution system operators.

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