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Investigating the Impacts of Different Price-Based Demand Response Programs on Home Load Management

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Abstract – Application of residential demand response (DR) programs are currently realized up to a limited extent due to customers' difficulty in manually responding to the time-differentiated prices. As a solution, this paper proposes an automatic home load management (HLM) framework to achieve the household minimum payment as well as meet the operational constraints to provide customer's comfort. The projected HLM method controls on/off statuses of responsive appliances and the charging/discharging periods of plug-in hybrid electric vehicle (PHEV) and battery storage at home. This paper also studies the impacts of different time-varying tariffs, i.e., time of use (TOU), real time pricing (RTP), and inclining block rate (IBR), on the home load management (HLM). The study is effectuated in a smart home with electrical appliances, a PHEV, and a storage system. The simulation results are presented to demonstrate the effectiveness of the proposed HLM program. Peak of household load demand along with the customer payment costs are reported as the consequence of applying different pricings models in HLM.

Keywords: Demand response, Home load management, Time-differentiated pricing, Payment cost.

1. Introduction

Smart Grid refers to the next-generation network that integrates information technology into the existing power grid to optimize energy efficiency through a two-way exchange of electricity/information between suppliers and customers in real time. In the context of energy efficiency, demand side management is one of the most important responsibilities of the future electric grid. To this end, smart grid operators design different programs to manage customers' consumption patterns. Demand response (DR) programs play a major role in persuading customers to change their electric consumption patterns. The concept behind all the DR programs is to induce lower electricity use at times of high wholesale market prices or when system reliability is endangered.

DR offers a variety of financial and operational benefits for electricity customers and grid operators. Maintaining the supply of and demand for electricity in balance and preventing from high cost investment on generation and transmission are the most important benefits of DR application for grid operators [1]. The most important benefit of DR for customers is lower cost of electricity consumption. This would be resulted from adjusting load in response to the declared prices and decreasing market prices resulted from reduced supply costs. In addition, reductions in the probability of forced outages lead to imposing lower financial cost on the customer.

Since various time-differentiated pricing models have yet been proposed, different price-based DR programs can be offered to residential customers. Level of residential customers' participation in the DR programs depends on the extent of comfort and benefits provided by the offered program. Several works verified that household customers would likely benefit from participating in DR programs if they properly respond to received signals.

The main obstacle of implementing price-based DR programs is customers' difficulty in manually responding to declared prices. Home load management (HLM) is the promise solution to alleviate this issue in the smart home. HLM system can automatically manage the electrical appliances consumption in response to the time-varying tariffs. Plug-in hybrid electric vehicles (PHEVs) should be also incorporated in the HLM programs [2]. These vehicles are equipped with large batteries that are charged from the grid [3]. Analogously, the independent storage devices facilitate saving energy in the valley-time and sends energy back to the own consumption or to the grid in the peak-time of the load profile curve [4]. Vehicle to grid (V2G) describes an operation mode in which storage systems and electric vehicles are able to sell back electricity to the grid. This capability can effectively affect the HLM implementation results.

Several papers in the literature focus on controlling household appliances, such as washing machine, dryers, and other responsive plug loads [2, 5-6]. Reference [6] presents a novel appliance commitment algorithm that schedules thermostatically controlled household loads based on the price and consumption forecasts. In this

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algorithm, the time-varying temperature range to reflect consumer choices on the appliances' thermostat settings is specified as the user comfort. In [7], an automatic energy consumption scheduler improvised in smart meters find 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. The authors of [8] develop mathematical models for household appliances and propose the mathematical optimization models of residential energy consumption with the objectives of minimizing energy consumption, total cost of electricity and gas, emissions, peak load, and/or any combination of these objectives. These works study the issues of optimal appliance scheduling to minimize household energy consumption. To better decide on choosing and designing a proper price-based DR program for customer and operator, it seems essential to investigate impacts of different price-based DR programs on the HLM results. Neither of the previous works focuses on this challenge.

This paper aims to study HLM results, i.e., payment cost and peak of household load demand, incorporating various time-differentiated tariffs. In doing so, at first, HLM is mathematically formulated as an optimization-based problem to minimize the household payment cost of electric energy consumption during a day. Then, the result of HLM is studied under the implementation of different price-based DR programs, i.e. real time pricing (RTP), time of use (TOU) pricing, peak time rebate (PTR) pricing, and the possible combinations of them. The on / off operation statuses of responsive loads including operation periods of household responsive appliances and charging/discharging periods of PHEVs and storage systems are outcomes of the proposed HLM problem. Vehicle to grid (V2G) capability is also considered in the problem. In order to provide customer comfort, the problem is subjected to practical constraints such as allowable interval for operation of appliances and charging PHEVs. Peak of household load demand along with the payment costs are broadly studied as the consequence of applying different time-varying tariffs. The results would explore the pros and cons of familiar priced-based DR programs from the customer and operator points of view.

2. Time-Varying Tariffs

Economists have long advocated for electricity pricings that accurately reflect time-varying production costs. Electricity pricing usually peaks at certain predictable times of the day. In particular, if generation is constrained, prices can rise if power from other authorities or more costly generation is brought online. Billing customers by time-varying tariffs will encourage customers to adjust their consumption habits to be more responsive to market prices. Furthermore, regulatory and market design agency hope these price signals to delay the construction of additional generation or at least the purchase of energy from higher priced sources, thereby control the steady and rapid increase of electricity prices. In conclusion, time-differentiated pricing models can potentially lead to economical and environmental advantages compared to the flat rates [9]. In this section, familiar time-differentiated tariffs, i.e. real time pricing (RTP), time of use (TOU), and inclining block rate (IBR), are briefly described. Also, possible combinations of these tariffs are probed and their advantages are reported.

2.1 TOU Tariff

In recent years, the TOU energy price is researched by many scholars and also implemented by lots of utilities [10]. It is recognized that carrying out TOU energy price has significant effects on the load shifting [11]. In the TOU tariff, electricity price changes in definite levels during hours of the day. In this paper, a three-level (on-peak, mid-peak, off-peak) TOU tariff is utilized. Three-level TOU pricing can be formulated as below:

$$R(t) = \begin{cases} \lambda_1 & if\ t \in T_1 \\ \lambda_2 & if\ t \in T_2 \\ \lambda_3 & if\ t \in T_3 \end{cases} \tag{1}$$

where, t is the hourly time index, $R(t)$ is the TOU electricity tariff at hour t, λ_1, λ_2, and λ_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, $T_1 \cup T_2 \cup T_3 = 24\ hrs$ and $\lambda_1 \le \lambda_2 \le \lambda_3$. Transferring energy consumption from on-peak tariff periods to lower tariff ones leads to peak load shaving and valley filling which are also desirable from distribution system operator point of view.

2.2 RTP

In RTP, electricity prices may change as often as hourly. This type of pricing better presents the market price variation. This pricing mechanism is based on the fact that the energy system's operation cost in the peak load time is much higher than that in the valley time [12]. The above principle insures that the energy price is higher when the consumption is higher. With RTP prices, the price of electricity is time dependent. When demand is low, less expensive sources of electricity are used. When demand rises, more expensive forms of electricity generator are called upon, making prices higher.

2.3 IBR

Many utilities such as Pacific Gas & Electric (PGE), San Diego Gas & Electric, and the Southern California Edison companies have used IBR pricing for years [13]. An IBR tariff, $R(E_t)$, is mathematically presented as:

$$R(E_t) = \begin{cases} \alpha & 0 \le E_t \le \gamma \\ \beta & E_t > \gamma \end{cases}, \quad (2)$$

where, E_t is the total amount of consumed energy at period *t*, and γ is the predetermined threshold of IBR pricing which is time independent. Tariffs of the energy consumption lower and higher than γ are respectively α and β where β is obviously greater than α.

Applying IBR can lead to load balancing and reducing peak load [14]. In the IBR pricing, energy consumption more than a predetermined threshold would impose a penalty cost to the customer [15]. This penalty is such that the amount of consumed energy more than the threshold should be paid by a higher tariff than that of below the threshold.

2.4 Combination of tariffs

In this subsection, possible combinations of introduced tariffs are proposed. It seems that combining these non-flat rate pricings can collect their advantages together.

Combining IBR and three level TOU tariffs can be mathematically represented by:

$$R_t(E_t) = \begin{cases} \begin{cases} \alpha_1 & t \in T_1 \\ \alpha_2 & t \in T_2 \\ \alpha_3 & t \in T_3 \end{cases} & 0 \le E_t \le \gamma \\ \begin{cases} \beta_1 & t \in T_1 \\ \beta_2 & t \in T_2 \\ \beta_3 & t \in T_3 \end{cases} & E_t \ge \gamma \end{cases} \quad (3)$$

where, $\{\alpha_1, \beta_1\}$, $\{\alpha_2, \beta_2\}$, and $\{\alpha_3, \beta_3\}$ are, respectively, blocked rates of off-peak, mid-peak, and on-peak periods. It is clear that $\alpha_3 \ge \alpha_2 \ge \alpha_1$ and $\beta_3 \ge \beta_2 \ge \beta_1$. In (2), α and β were constant. Nevertheless, in (3), calculating the electrical energy price by α_i and β_i depend on not only the total energy consumption at periods, but also the time of day. According to (1) and (3), It would be rational to have α_i less than λ_i and β_i higher than λ_i.

IBR and RTP can be similarly combined. At each period, two rates for lower and higher energy consumption than predetermined threshold would be likely defined. This can be mathematically represented as bellow:

$$R_t(E_t) = \begin{cases} \alpha_t & 0 \le E_t \le \gamma \\ \beta_t & E_t > \gamma \end{cases} \quad (4)$$

The cost of energy consumption at period *t* less than and beyond threshold γ are respectively calculated by tariffs α_t and β_t.

3. Proposed HLM Method

Home appliances are divided into two categories, responsive and non-responsive. The consumption of responsive appliances unlike the non-responsive ones can be reduced and shift to off-peak tariff periods. Here, HLM is defined to schedule the operation periods of responsive appliances while satisfying operation constraints as well as constraints determined by the customers. Also, other developing technologies, i.e. PHEVs and storage systems, are incorporated and V2G capability is taken into account. Needless to emphasize, the HLM is solved from customer viewpoint. The HLM determines the optimal operation time vector for responsive appliances. Also, HLM determines the PHEV and storage system charging/ discharging periods.

The tariff is determined by the operator and the user's total electricity payment within the upcoming scheduling horizon is minimized as

$$\min PC = \sum_{h \in H} Tr_h (E_h + E_h^{Bat} + E_h^{PHEV}), \quad (5)$$

where, PC is the payment cost function, Tr_h is the tariff at period h, E_h is energy consumption of appliances at period *h*, E_h^{Bat} is the charged / discharged energy of the battery at period *h*, E_h^{PHEV} is the charged/discharged energy of PHEV at period *h*, and **H** is the set of periods in which the responsive appliances are scheduled. Here, **H** is one day ahead. Since each scheduling period is assumed to be equal to ten minutes in this paper, the total number of periods would be $24 \times 6 = 144$ periods. So, $H = \{1, 2, 3, ..., 144\}$. E_h is the summation of responsive and non-responsive appliances' consumption which is formulated as:

$$E_h = FE_h + \sum_{j \in J} E_j I_{jh}, \quad \forall h, \quad (6)$$

where, FE_h is the energy consumption of non-responsive appliances at period *h*, E_j is the energy consumption of appliance *j* at each period [kWh/period], and I_{jh} is status binary indicator of appliance *j* at period *h*, where 1 means appliance *j* is on at period *h*. E_j is the known parameter and I_{jh} is determined by solving the problem.

HLM should provide customer's comfort. So, possible customer constraints should be included in the optimization process. The customer is allowed to determine an allowable time interval for each responsive appliance operation, i.e. both the beginning and the end periods of allowable interval for operation. For example, the customer wants to wash the dishes after 10 a.m. and before 4 p.m.. So, he sets the beginning of time interval (b_j) to 10 a.m. and the end of time interval (e_j) to 4 p.m.. The operation time of responsive appliance *j* should lie within determined allowable time interval of that appliance. This is certified in (7):

$$\sum_{h=b_j}^{e_j} I_{jh} = U_j, \quad \forall j, \quad (7)$$

where, U_j is the up time needed for proper operation of the appliance *j*. Obviously, b_j is lower than e_j and e_j-b_j is equal to or greater than U_j. For more clarification, assume that allowable operation time for washing machine is 9 a.m. and 11a.m. and required operation time to wash the clothes properly is 30 minutes. Having the scheduling period equal to 10 minutes, U_j=3, b_j=9× 6+1=55, and e_j=11× 6=66.

Also, appliances should operate uninterruptedly and the operation periods should be consecutive. This is mathematically represented by

$$\sum_{T=h}^{h+U_j-1} I_{jT} \geq U_j y_{jh}, \quad \forall h \leq 144 - U_j + 1, \forall j, \tag{8}$$

where, y_{jh} is the start up indicator. Equation (9) is to relate the appliance status (I_{jh}), startup (y_{jh}), and shutdown (z_{jh}) indicators at period *h* for appliance *j*.

$$y_{jh} - z_{jh} = I_{jh} - I_{jh-1}, \ \forall h, \forall j. \tag{9}$$

Since an appliance at a given period cannot be simultaneously started up and shut down, we have (10).

$$y_{jh} + z_{jh} \leq 1, \quad \forall h, \forall j. \tag{10}$$

Other constraints related to PHEV and storage system, and their operation conditions are described in the following.

Two modes are defined for the battery: B_p indicates the charging mode and B_n signifies the discharging mode. E_{Bp} and E_{Bn} represent the chemical energy consumed or produced in the battery. Actual electrical energy is concluded with multiplying or dividing the chemical energy by AC/DC and DC/AC efficiency. Same as battery storage, two modes are defined for PHEV: P_p and P_n. I_h^{Bn} and I_h^{Bp} are respectively discharging and charging binary indicators of battery during period *h*. I_h^{Pn} and I_h^{Pp} are respectively discharging and charging binary indicators of PHEV during period *h*.

Therefore, the charged/discharged energy of battery and PHEV at each period incorporated in (6) are calculated by:

$$E_h^{Bat} = \frac{1}{\eta^B}(E^{Bp} I_h^{Bp}) - \eta'^B (E^{Bn} I_h^{Bn}) \tag{11}$$

$$E_h^{PHEV} = \frac{1}{\eta^P}(E^{Pp} I_h^{Pp}) - \eta'^P (E^{Pn} I_h^{Pn}) \tag{12}$$

where, η^B , η^P , η'^B and η'^P are respectively charging efficiency of the battery, charging efficiency of PHEV, discharging efficiency of the battery, and discharging efficiency of the PHEV.

In addition, the batteries cannot be simultaneously in charging and discharging modes. Hence,

$$I_h^{Bn} + I_h^{Bp} \leq 1, \qquad \forall h. \tag{13}$$

and,

$$I_h^{Pn} + I_h^{Pp} \leq 1, \qquad \forall h. \tag{14}$$

For a PHEV, the out-of-home interval, [g_p,c_p], is determined by the customer. So, I_h^{Pp} and I_h^{Pn} are zero in this interval.

The discharging value at each period should be less than the available battery charge. This is verified for battery storage in (15):

$$E^{Bn} I_h^{Bn} \leq E_0^B + \sum_{m=1}^{h-1} (E^{Bp} I_m^{Bp} - E^{Bn} I_m^{Bn}), \ \forall h \in H. \tag{15}$$

where, E_0^B is the initial charge of the battery storage. At the right hand side of (15), E_{Bn} appears with a minus sign to show the opposite direction of the discharging energy flow.

This constraint is slightly different for PHEV before and after the out-of-home interval:

$$\begin{cases} E^{Pn} I_h^{Pn} \leq E_0^P + \sum_{m=1}^{h-1} E^{Pp} I_m^{Pp} - E^{Pn} I_m^{Pn}, \forall h \leq g^P \\ E^{Pn} I_h^{Pn} \leq E_0^P + \sum_{m=1}^{h-1} E^{Pp} I_m^{Pp} - E^{Pn} I_m^{Pn} - E^P, \forall h \geq c^P \end{cases} \tag{16}$$

Where E_0^P is the initial charge of the PHEV battery. From (16), it is deduced that before the out-of-home interval, the charge level of the PHEV battery is calculated similar to the storage system. But after arrival period of PHEV, its energy consumption during *[g_p,c_p]*, E_p, is also considered for calculating the PHEV charge level.

Also, the capacity limit of the battery, $E^{\max B}$, is satisfied in (17).

$$E_0^B + \sum_{m=1}^{h} E^{Bp} I_m^{Bp} - E^{Bn} I_m^{Bn} \leq E^{\max B}, \quad \forall h. \tag{17}$$

The capacity limit of the PHEV battery, $E^{\max P}$, before and after out-of-home interval is met in (18).

$$\begin{cases} E_0^P + \sum_{h=1}^{m} E^{Pp} I_h^{Pp} - E^{Pn} I_h^{Pn} \leq E^{\max P}, & \forall m \leq g^P \\ E_0^P + \sum_{h=1}^{m} E^{Pp} I_h^{Pp} - E^{Pn} I_h^{Pn} - E^P \leq E^{\max P}, & \forall m \geq c^P \end{cases} \tag{18}$$

When the discharged energy is more than the home own consumption, the energy could be sold to the utility with the same tariff of that time, if profitable.

The other point is that PHEV charge level before g^P should be equal or greater than out-of-home energy consumption. This is certified in (19).

$$E^P \leq E_0^P + \sum_{m=1}^{g^P-1} E^{Pp} I_m^{Pp} - E^{Pn} I_m^{Pn} \tag{19}$$

Solving HLM determined the statuses of all appliances and other facilities for a day-ahead period. Obviously, the results directly depend on the hourly tariffs. It seems that different pricings lead to not only different payment for the customer but also different home load curve, which is more important from operator viewpoint.

4. Numerical Study

This section analyzes the HLM formulation through different case studies to probe the impacts of different defined price-based DR programs on the HLM results. The payment cost and load demand are reported in each case. The problem is solved by using a MIP solver, i.e. CPLEX 11.0.0 under GAMS environment. Computation times are not reported in detail as they all were less than 10 seconds on a PC equipped with a 3.2 GHz Pentium 4 processor and 2 GB of RAM.

We derive a variety of cases comprising

Case I: HLM considering TOU tariff;
Case II: HLM considering IBR tariff;
Case III: HLM considering combination of TOU and IBR tariffs;

As the concept behind the RTP and TOU pricing are the same, the results of applying RTP and combination of RTP and IBR are similar to applying TOU pricing and combination of TOU and IBR. Therefore, to prevent superfluous, RTP implementation is omitted from the case studies.

Non-responsive appliances load demand is assumed as Fig. 1.

Table 1 outlines the energy consumption (E_j), the number of operation periods (U_j), the beginning (b_j), and the end time (e_j) of allowable operation interval for each responsive appliance.

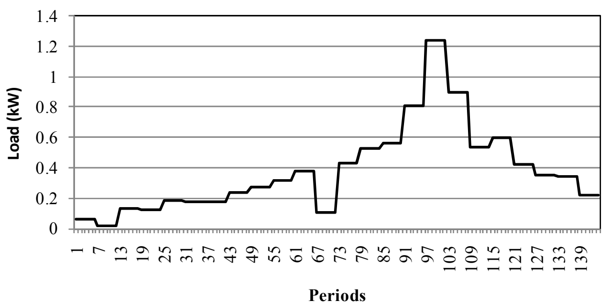

Fig. 1. The non-responsive load curve

Table 1. Responsive appliances data

Appliance	Watt Hours/Day	U_j	E_j	b_j	e_j
Clothes dryer	3,885	5	777	1	144
Dishwasher	600	3	200	60	84
Washing machine	188	3	62.67	72	132

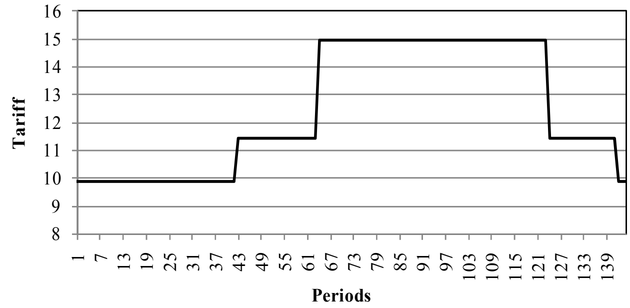

Fig. 2. Three-level tariffs for a day

Battery storage and PHEV battery capacity is assumed 10 kWh and the efficiencies are equal to 0.88. Returning the energy back to the grid (V2G) capability is possible with the tariff of that period.

Three-level TOU tariff, presented in Fig. 2, is obtained from [16] as the input of the HLM in Case I.

In Case II, IBR pricing is applied to HLM algorithm. Generally, the distribution system company (DisCo) determines the tariff so that the DisCo's cost plus a reasonable profit are covered. Consider a daily IBR pricing; if the energy consumption of the consumer during a definite period is less than a defined threshold, the customer will pay based on α [\$/kWh] and if the energy consumption goes beyond the threshold, the amount of consumed energy below and beyond the threshold are calculated based on α and β, respectively. Due to proven positive impacts of IBR on the distribution system operation, the DisCo should specify α and β so that it convinces customers to participate in the IBR pricing. Based on the respected reviewer's comment, α can be equal to the flat rate tariff to cover DisCo's cost as well as its profit. However, in this way, no customer is willing to participate in IBR pricing; since, the payment cost in the case of applying IBR would be definitely more than the case of flat rate tariff application. Therefore, α should be less than flat rate tariff to encourage customers to participate in this program. Meanwhile, β should be higher than flat rate tariff. This creates incentives for end users to distribute their load at different times of the day in order to avoid paying for electricity at higher rates. Accordingly, the cost and a reasonable level of profit are guaranteed for the DisCo as well.

Based on the above discussion, α and β cannot be determined independently. They are directly related to each other as well as the threshold γ, and the flat rate tariff offered by DisCo.

The lower level of the IBR tariff at each period, α, is assumed to be the ¢ 9.866. The price of the higher level of IBR, β, is considered to be ¢ 14.898. The threshold γ for each 10-minute period is assumed to be 1 kWh.

4.1 Case I

In this case, TOU tariff is the input of the problem and

Table 2. Operating Periods of Responsive Appliances in Case I

Case	Clothes Dryer	Dishwasher	Washing Machine
I	1-5	60-62	130-132
II	66-70	60-62	74-76
III	140-144	60-62	130-132

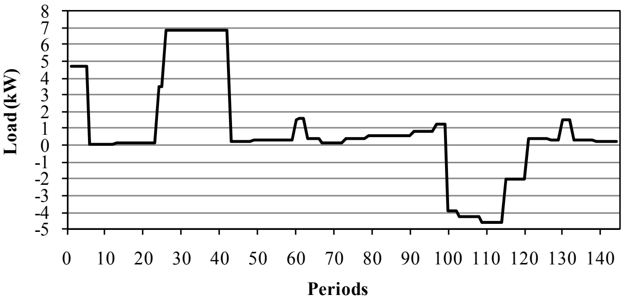

Fig. 3. Net load in Case I

the HLM is solved by the proposed formulation. The results of three cases are summarized in Table 2.

Referring to Table 2, the responsive appliances are on in the lowest tariff periods in their allowable interval of operation.

The net load resulted from the HLM scheduling is depicted in Fig. 3. The net load is the summation of the appliance consumption and the PHEV and battery storage charging/discharging. Positive and negative loads represent the energy flow from and toward the grid, respectively. It can be concluded from this figure that the peak and average loads are 6.851 kW and 1.315 kW, respectively. The payment in this case is ¢ 144.481. This cost is expectedly less than the imposed cost in cases without battery storage and PHEV, because of more potential of returning energy back to appliances or the main grid.

4.2 Case II

Considering IBR tariff, operation periods of responsive appliances resulted from HLM application is presented in Table 2.

The results show that to prevent more payment cost due to exceeding the threshold γ, operation periods of appliances shift to the valley periods of load demand. The resulted load demand shows that the load is limited to the determined threshold such that the peak load is 5.05 kW. In comparison with the previous case, this is more desirable from operator viewpoint. Also, the results certify that applying IBR prevents simultaneous charging of PHEV and battery storage. The payment in this case is ¢ 147.396 which is more than the payment cost in the previous case.

4.3 Case III

This case combines IBR and TOU pricing as mentioned in Section 2. The lower level of the IBR tariff at period *t*, α_t, is assumed to be 0.9 of TOU tariff at that period. The price of the higher level of IBR, β_t, is considered to be 1.4 of α_t [5]. The threshold γ is also assumed to be 1 kWh.

HLM leads to the presented results in Table 2. Although the resulted payment cost, ¢ 150.627, is more than the previous cases, the resulted peak load is 4.902 kW which is less than the previous cases. So, it seems that applying IBR is more desirable from operator facet. However, payment cost directly depends on the tariff rates which can be properly designed to reduce payment cost of customer in addition to the peak load in the case of applying IBR.

5. Conclusion

In this paper, an in-home optimization-based algorithm is proposed to schedule demand side facilities and determine on / off status of responsive appliances and other household facilities. Different time-varying tariffs are employed in HLM to probe the payment cost resulted from solving the problem. The results show that in the case of applying TOU, high-consumption responsive appliances, storage system, and PHEVs might simultaneously operate/ charge at off-peak time and the solution probably creates a new peak during these periods. Application of IBR to TOU pricing prevents the negative impacts of the proposed method on the household load curve; since, IBR application causes appliances operation to be distributed during the allowable interval of their operation. Designing a proper tariff rate as an open research area is currently under our study.

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