OPTIMAL ENERGY MANAGEMENT IN SMART HOME IN THE PRESENCE OF PHEV

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ABSTRACT

Although Demand Response (DR) program has potentially several advantages it is currently faced with challenges in its implementation due to the customers' considerations in responding to the time-varying price and signals. The suggested solution to overcome these obstacles is developing an automatic program for management and scheduling of home appliances in order to minimize the resident operation costs. In this paper an automatic and optimized program has been proposed for management of energy consumption in smart homes based on DR implementation. The smart home includes the smart appliances as well as Plug-in Hybrid Electric Vehicle (PHEV). The proposed methodology is based on the time of use tariff and inclining block rates. The proposed DR program is applied to several different scenarios and the results are evaluated.

INTRODUCTION

Demand Response (DR) program in power systems is a concept defined as "changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices when system reliability is jeopardized" [1]

The DR program has several advantages potentially and encourages the consumers to participate in load management programs. However, due to technical and convenience problems the DR implementation has faced with the fundamental challenges. This problems are in forms of the lack of user knowledge's and also response difficulty to DR signals [2].

In order to overcome the mentioned challenges an automatic and optimal DR program should be provided. In the automatic energy management program, all of the controllable loads should be modeled based on their historical data. This program schedules the appliance demands optimally considering the power market price signals and incentives.

Peak to Average Ratio (PAR) is a key economic indicator that reflect the utilization factor of the authorized investments to the generation, transmission, and distribution systems. The utility tariff regulations and DR programs implicitly lead to the PAR decline [3]. Lower peak demands might result in substantial cost reduction for utilities in the long-term as it can postpone the investment in new generation and transmission capacities. Also, utilities take advantages of peak reduction in the short-term due to the operation cost decrement.

Moreover, as Plug-in Hybrid Electric Vehicles (PHEVs) become more popular, the PAR may be reduced due to the average load increment or the peak load growth. The PHEVs are huge uncertain loads that are plugged-in to the home utilities in the most cases [4].

In the previous works, different Direct Load Control (DLC) strategies have proposed that focused on aggregate household devices controlling [3–9]. In [3], a unique model for residential DR analysis was introduced. This model constructs load based on behaviors of different appliances on a multi-agent system. Behavior tropism and uncertainty of large consumer group are achieved by probabilistic modeling of consumers' behavior. A new concept, 'Shifting Boundary', was implemented in this model to measure the largest load shifting potential of several price-based demand response tariffs. Reference [4] proposed an strategy for peak load demand reduction and the costumer cost minimization over certain time periods. The proposed methodology is based on thermostatically controls of appliances that have thermal storage capabilities, e.g. water heater and air conditioner. Moreover, some strategies have been extended to control non-thermostatic devices e.g. Dish Washer (DW), Washing Machine (WM), and PHEV [7–9]. Sánchez-Martín et al. presented in [6] an optimal methodology for scheduling only the charging actions of PHEVs based on dynamic programming without considering another flexible load. Tavakoli Bina and Ahmadi in [8] presented a novel semi-automatic Day Ahead Direct Load Control Strategy (DADLCS). The proposed DADLCS allows calculation of the next day DR to be applied to aggregate controllable domestic appliances i.e. WM, DW and PHEV. The objective of the work is the peak cutting for cost minimization.

The proposed methodologies in the mentioned works is based on the control of a domestic appliance groups in real time scheduling environments [5–7]; these methods require several equipment e.g. smart meter, control and communication infrastructure that can respond in real time. Therefore, these strategies are expensive and complicated in implementation. Hence, this paper propose an uncertain based methodology for energy management in smart homes.

Although the Time of Use (TOU) pricing or Real Time Pricing (RTP) provide the possibility of appliance responses to operate during the low electricity price periods it may be provide a second peak at low price duration. As a result, this paper consider a combination of TOU with Inclining Block Rate (IBR) to overcome to this challenge.

PROBLEM FORMULATION

The objective function is to minimize the energy cost in accordance to implementation of DR under practical constraints from the consumer and aggregator points of view. The energy cost consists of the total energy received from the grid in each hour of a day, which is equal to the sum of consumptions of electric appliances and PHEV. It can therefore be expressed as follows:

$$F_{agg.} = \sum_{t=1}^{24} \left(\sum_{i=1}^{N} \sum_{j=1}^{J} P_{i,j,t} + \sum_{k=1}^{N_{PEV}} P_{PEV,k,t} \right) .T_t \quad (1)$$

where $F_{agg.}$ is the aggregator costs, $P_{i,j,t}$ is the energy consumption of j-th appliance load in i-th home at hour t; $P_{PHEV,k,t}$ is the energy consumption of k-th PHEV at hour t. J is the set of electric appliances; N is the number of homes and T_t and N_{PHEV} respectively denotes the electrical energy tariff at hour t and the number of PHEVs.

In general the smart home appliances are divided into two categories. The first group is uncontrollable appliances and consequently unresponsive to time-varying prices (e.g. TV or personal computers). The second group is controllable appliances and sensitive to the prices (e.g. dish washer and washing machine). The $P_{i,j,t}$ can therefore be defined as follows:

$$P_{i,j,t} = \sum_{m=1}^{J_{uncont.}} P_{m,i,t} + \sum_{n=1}^{J_{con.}} P_{n,i,t} \tag{2}$$

where $J_{uncont.}$ and $J_{cont.}$ are the set of unresponsive and responsive appliances respectively; $P_{m,i,t}$ is the power consumption of m-th unresponsive load in i-th home at hour t and $P_{n,i,t}$ is the power consumption of n-th responsive load in i-th home at hour t.

In this paper, in order to have a better evaluation of the impact of PHEVs on the cost and load profile, three different scenarios are considered for electric vehicle charging profile:

- Scenario 1-uncontrolled charging: It is assumed that the PHEVs are charged after the last trip upon arrival at home.
- Scenario 2- controlled charging: It is assumed that PHEVs charge with a maximum time shift of three hours after arriving to home.
- Scenario 3- smart charging: PHEVs are assumed capable of valley filling of load profile in off-peak hours. This scenario is the most favorable in the utilities perspective because of providing full control over time and amount of charging power of vehicles. Development of advanced measurement infrastructure enables distribution companies to minimize the adverse effects of electrical vehicles on the grid by shifting vehicle charging loads to off-peak hours, i.e. before the next day trip.

The optimization problem is subjected to the following constraints.

Load balance: Hourly power consumption must be equal to the total power generated and received from the grid. Therefore

$$\sum_{i=1}^{N}\sum_{j=1}^{J} P_{i,j,t} + \sum_{k=1}^{N_{PEV}} P_{PEV,k,t} = P_{grid,t} \qquad t = 1,..,24 \tag{3}$$

Maximum shift: A maximum three hours of shift to later or previous hours is considered. Therefore

$$d_j \le d_{\max}, \qquad d_{\max} = 3 \tag{4}$$

IBR: If the energy consumption at an hour exceeds a threshold, the cost of energy in excess of the threshold is considered higher than its normal value for the hour. Implementation of IBR on TOU tariffs is expressed as follows:

$$\lambda_{IBR}(t) = \begin{cases} \alpha = 1 & 0 \le E(t) \le \gamma \\ \beta & E(t) \ge \gamma \end{cases} \tag{5}$$

$$\lambda_{TOU\,\&\,IBR} = \begin{cases} \begin{cases} \lambda_1 & \text{If } t \in T_1 \\ \lambda_2 & \text{If } t \in T_2 \quad 0 \le E(t) \le \gamma \\ \lambda_3 & \text{If } t \in T_3 \end{cases} \\ \begin{cases} \beta \times \lambda_1 & \text{If } t \in T_1 \\ \beta \times \lambda_2 & \text{If } t \in T_2 \quad E(t) > \gamma \\ \beta \times \lambda_3 & \text{If } t \in T_3 \end{cases} \end{cases} \tag{6}$$

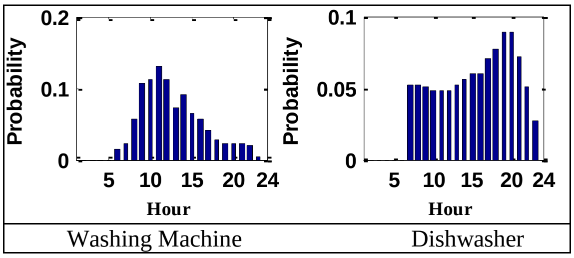
Equation (5) is the mathematical representation of IBR. γ is the consumption threshold for an hour, while α and β is respectively the coefficient for lower and higher threshold values. A combination of TOU and IBR tariffs is shown by the formulation (6). λ_1, λ_2 and λ_3 are respectively, tariffs at off-peak, normal load and on-peak periods during a day, So, $\lambda_1 \le \lambda_2 \le \lambda_3$.

SIMULATION RESULTS

In this section, we present the simulation results to show the superior performance of our proposed approach for home energy management. The optimal energy management considered as an optimization problem that solved using Genetic Algorithm (GA). More details about GA can be found in [10].

The studied system comprises a set of 100 houses. Responsive appliances are considered to include washing machines and dishwashers, while nonresponsive loads consist of TVs, computers, lighting and heating. Fig.1 and table.1 give the model and data used for responsive loads, while the model and data for nonresponsive loads are taken from [6].

Fig.2 shows the model used for the charging of PHEVs, whose penetration level is considered 30%. PHEV has a battery with storage capacity of 13.5 kWh. Only 80% of battery capacity can be used to optimize the life expectancy. This gives an available capacity of 10.81 kWh; and efficiency of PHEV equal 88% [11].



Washing Machine | Dishwasher

Fig. 1: Responsive appliance model

In this paper a three-level TOU tariff are used. The three-level tariffs taken from [2] and has been utilized in the Baltimore Gas and Electric (BGE) company's summer program. On-peak tariff, between 11 a.m. and 8 p.m. is 14.958 ¢/kWh. Mid-peak tariff between 8 a.m. and 10 a.m.

or between 9 p.m. and 11 p.m. is equal to 11.453 ¢/kWh. In the remaining hours, the off-peak tariff is set 9.866 ¢/kWh [2].

Table 1: Details of responsive appliances

Appliance	Power(W)	Owning Rate (%)
Washing machine	2500	78
Dishwasher	1800	50

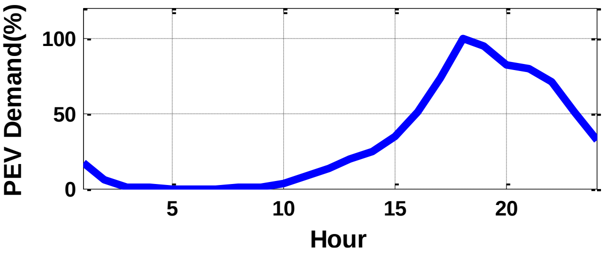


Fig. 2: The charging consumption profile of electrical vehicles

This section analyzes the management formulation through five case studies. The following case studies are conducted:

Case1: Without management of appliance and uncontrolled charging PHEVs.
Case2: Management of Appliance (MOA) and uncontrolled charging PHEVs.
Case3: MOA and controlled charging PHEVs.
Case4: MOA and smart charging PHEVs.
Case5: MOA and smart charging PHEVs and IBR.

Case1:

In this case, uncontrolled charging scenario is considered for PHEVs and the load curve and cost are calculated irrespective of responsive load optimization, which is equivalent to unwillingness of consumers to participate in demand response programs. Table 2 summarizes the results of the program for all cases. Owing to the simultaneous peak load of electrical appliances at homes and peak charge of vehicles, Fig. 5 contains a very high grid obtained peak with a PAR of 2.0612. The energy consumption cost is also equal to 183.683.

Case2:

This case considers the effect of responsive appliances optimization in the uncontrolled charging scenario of vehicles without IBR. As shown in Fig. 3 and Fig. 4, consumption of washing machine and dish washer, regarding the limitation of maximum time shift of 3 hours, transferred from 10:00-13:00 and 17:00-20:00 (on-peak) to 7:00-10:00 and 20:00-23:00 (mid-peak) respectively, and also from 7-10 and 20-21 (mid-peak) to 4:00-7:00 and 23:00-24:00(off-peak). As seen in Fig. 5, the planning of responsive loads without the control and management of electrical vehicles charging brings about a small reduction in the peak load; the management and control of vehicles charging is therefore necessary to control the peak consumption. Table 2 gives the cost of energy consumption as well as PAR.

Case3:

This Case considers the controlled charging for electrical vehicles with a maximum forward shift of three hours for the vehicles. Fig. 5 shows the profile of the load absorbed from the grid. The controlled charging scenario relocates the charging time of electrical vehicles from peak load hours (17-20) to medium load hours (20-23) and low load hours (23 to 2). According to figure 3, using this scenario, which only causes a 3 hour shift of charging, may cause an increase or decrease in the peak consumption compared to the unlimited charging mode. It has led to an increase in the peak consumption on this sample day. Furthermore, due to a shift in the charging time, the cost of energy consumption has been reduced. The cost as well as PAR is given in table 2. Consumption of responsive appliances are the same as case2 (Fig.3 & Fig.4).

Table 2: Summarizes the results for case1-5

Case No.	Price($)	Load Peak(kW)	PAR
Case1	183.683	117.38	2.0612
Case2	175.512	107.837	1.8936
Case3	172.2153	117.8	2.0685
Case4	161.6	99.2037	1.8009
Case5	169.55	69.5428	1.22

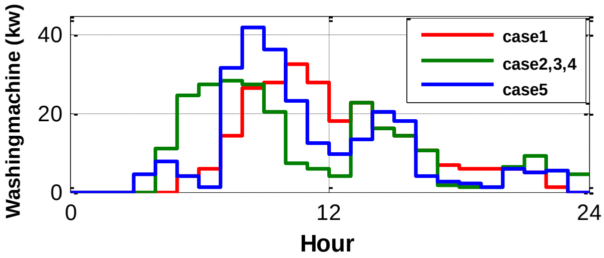


Fig. 3: Washing machine load in cases 1-5

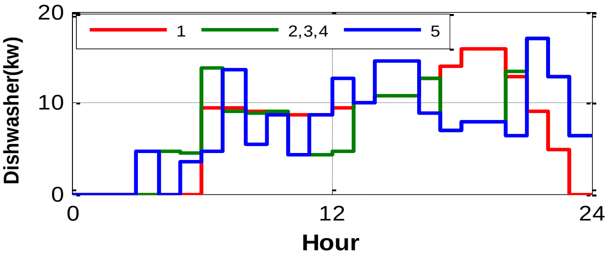


Fig. 4: Dishwasher load in cases 1-5

Case4:

An smart charging scenario is considered for the vehicles without applying IBR. According to Fig.5, it has led to a temporal relocation of charging time to the load curve valley, which prevents from the coincidence of electrical vehicle charging and homes loads (total responsive and nonresponsive loads). Based on table 2, the peak consumption in this case is lower than in other scenarios of vehicle charging. Moreover, the cost of energy consumption is equal to $ 161.6, which is lower than that of the unlimited and controlled charging scenarios. As a result of having the lowest cost of energy consumption, the intelligent charging is considered the best electrical vehicle charging scenario from the perspective of residential consumers. Applying this scenario alone without the use of IBR is however undesirable yet from the grid view because of a small reduction in the peak load (a 10% reduction). Consumption of responsive appliances are the same as case 2 (Fig.3 & Fig.4).

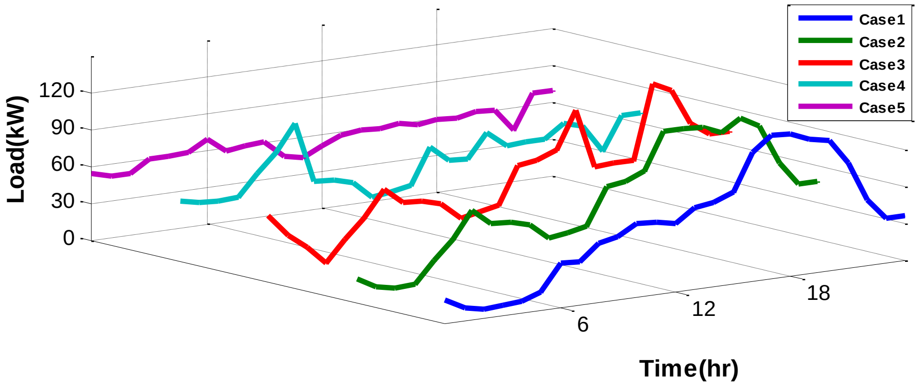


Fig. 5: Load curve in cases 1-5

Case5:

In addition to assumptions in case 4, IBR is included in case 5. The value of β and γ is respectively considered 1.5 and 60 kW. As shown in Fig.3 and Fig.4, responsive loads, i.e. washing machines and dishwashers, are not relocated from medium load hours to 4.00-7.00 and 23.00-24.00 in order to avoid the IBR constraint violation and the increase in the cost of energy consumption. Furthermore, in order to reduce the peak load and the cost, washing machine loads are transferred from low load hours (5.00-7.00) to 2.00-4.00 and dishwasher loads are relocated from 6.00-7.00 to 4.00-5.00. Taking advantage of the intelligent charging scenario and IBR, the peak load is reduced considerably to 69 kW and PAR reaches 1.22. This mode is therefore the best compromise between benefits of residents (cost reduction) and network operators (peak load reduction).

CONCLUSION

In this paper an automatic program is presented to resolve the challenges faced by manual DR. The issue brought by simultaneous EV charging is addressed with utilization of smart charging scheme. In order to avoid a peak demand in low price periods, IBR strategy is employed. It is demonstrated that the proposed policies bring financial benefits for both utility and consumers.

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