Impact of Electric Vehicle V2G Operation and Demand Response Strategies for Smart Households

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***Abstract*—The mature bulk power system requires to meet the needs of 21th century in terms of efficient and effective utilization of electric energy, together with the capability of accommodating recently growing renewable energy resources penetration. As a new idea of modernizing the current grid structure, the smart grid issue is a widely growing area of interest with investments from developed/developing country governments. As the smart grid solutions enable active consumer participation, demand response (DR) strategies have drawn much interest as such strategies provide consumers the chance for the real-time control of their consumption to reduce their bills, while utilities can lower the peak power value to be supplied to consumers. As a new type of consumer load in the electric market, electric vehicles (EVs) also provide different opportunities, including the capability of utilizing EVs as a storage unit via vehicle-to-grid (V2G) option instead of peak power procurement from utility. This study aims to discuss the impacts of different DR strategies and EV owner consumer preferences on the reduction of total electricity prices. Different case studies are conducted to better analyze the price reduction potential of different operating strategies.**

***Index Terms*--demand response, electric vehicle, smart grid, smart household, vehicle-to-grid.**

I. Introduction

The deregulation of electric industry is a concern of investors, regulators, and other participants of electric market for more than a decade with the aim of obtaining more efficient use of electric energy with improved profits. As a recently growing new concept for an effective deregulation of mature electric industry, smart grid issue has drawn a significant attention with the huge investments declared from leading developed country governments.

Smart grid is the vision for enhancing the efficiency of electricity utilization from the production to end-user points, together with effectively accommodating all generation and storage options and enabling consumer participation in demand side. Coupled with the growing importance of smart grid vision, smart households that can monitor their use of electricity in real-time and take actions to lower their electricity bills have also been given specific importance for the research of possible demand side actions [1].

Demand side actions for smart households in a smart grid generally focus on demand response (DR) strategies creating a two-side game between utility and consumers. DR is a term 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 or when system reliability is jeopardized*" by the US Department of Energy (DOE) and is composed of *incentive based programs* and *price based programs* (time-of-use, critical peak pricing, dynamic pricing, and day head pricing) [2].

DR strategies generally focus on shifting the electric use of consumers from peak to off-peak periods to reduce the stress on utility-handled assets such as distribution transformers, lines, etc., and may provide a valuable resource for efficient operation of smart grid structure [3].

The utilization of DR strategies can be considered as mature for industrial customers, but this is a relatively new concept for employing in residential households responsible for nearly 40% of energy consumption in the world [4].

There are many supporting devices and technologies for DR activities in residential areas. Especially, home energy management systems (HEMs) and smart meters have the leading role for effectively applying DR strategies.

With the introduction of different kinds of electric loads in market, the load shapes of households have started to change significantly. As a new type of end-user appliance/load, electric vehicles (EVs) have recently gained more importance as electrification of the transport sector, which traditionally is a major fossil fuel consumer.

EVs have a different structure with challenges and opportunities that should be examined in detail. As a load, the energy needs of EVs can reach to the levels of new power plant installation requirements.

The recommended charging level of a Chevy Volt as a small sized EV is 3.3 kW [5], which can even exceed the total installed power of many individual homes in an insular area. Besides, EVs can also be employed as a resource, especially during peak periods with the possibility of vehicle-to-grid (V2G) option.

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There are many recent studies dealing with DR strategies for smart households. Chen et al. [6] and Tsui and Chan [7] developed an optimization strategy for the effective operation of a household with a price signal based DR.

Pipattanasomporn et al. [8] and Kuzlu et al. [9] presented a HEM considering peak power limiting DR strategy for a smart household, including both smart appliances and EV charging.

Shao et al. [10] also investigated EV for DR based load shaping of a distribution transformer serving a neighborhood. These papers together with many other studies not referred here have provided valuable contributions to the application of smart grid concepts in household areas.

However, many of the mentioned papers failed to address either distributed renewable energy contribution for reducing load demand on utility side or V2G option for lowering the demand peak periods together with different DR strategies.

Hence, this study aims to investigate a collaborative evaluation of different DR strategies, distributed small scale renewable energy generation systems and EVs together with V2G options. Different case studies including price based and peak power limiting based DR strategies with different consumer preferences to manage EV charging/discharging are presented.

The impacts of all case studies in terms of consumer electricity bill reduction performance are evaluated with relevant comparisons. Besides, a real-time measured load demand and normalized photovoltaic (PV) based distributed energy resource production data are utilized in the simulation based evaluation process in Matlab/Simulink environment.

The paper is organized as follows: Section II gives the methodology employed in the study. Afterwards, Section III includes the case studies for evaluating daily DR based operation strategies for the smart household. Finally, concluding remarks are presented in Section IV.

II. Methodology

The block diagram of a fundamental DR strategy is presented in Fig. 1.

The HEM system regulates the operation of the smart household considering price based and other signals from the utility, production of small scale own facilities, load consumption of smart appliances, etc. together with different consumer preferences as seen from Fig. 1. The rest of this section briefly presents the details of the considered smart household.

A. Load Demand

The real-time measured load demand of an average house in Portugal is employed in this study. The mentioned nearly 140 meter-square household includes 4 habitants with different electric appliances, including fridge, TVs, microwave, washing and dish machine, computer, oven, etc.

It is to be noted that the household includes a water heater producing gas instead of electricity. The production of each day in a monthly period was recorded and the obtained average power consumption profile of the mentioned monthly period is shown in Fig. 2.

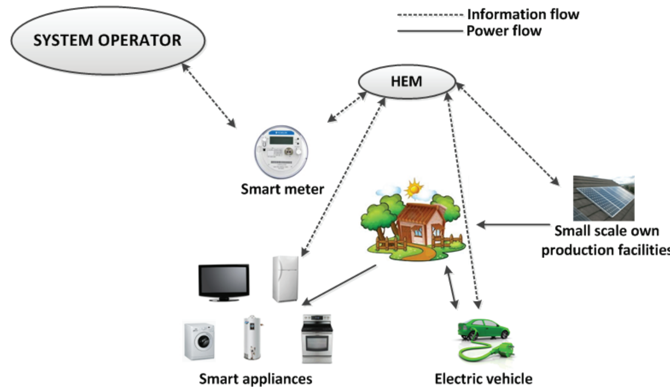

Fig. 1. Block diagram of a fundamental DR strategy for smart households.

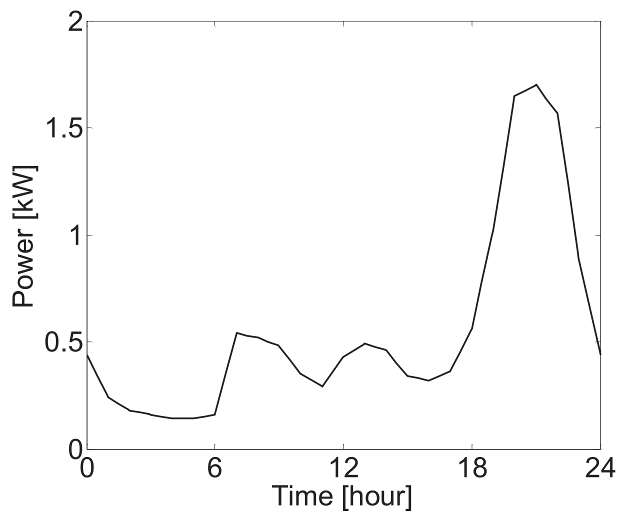

Fig. 2. The real-time measured average power consumption profile of the household.

B. Own Production Facilities

As smart grid encourages the utilization of distributed generation resources in all parts of the grid structure, smart households will become more familiar to obtain their own production facilities in the near future.

It is considered in this study that the household includes a small-scale PV system of 1 kW. The production data of the mentioned PV system is the normalized version of a measured daily solar farm production profile. The considered PV system power production curve is given in Fig. 3.

C. EVs with V2G option and DR strategy

As the penetration of EVs in the market rapidly grows with many recent EV models of leading automobile manufacturers, there are many studies in the literature considering EVs from different points of view [11]-[13]. Among the realized studies, the management of EV charging power requirement is given a special importance. Besides, the utilization of EV in V2G mode for distribution grid balance, household peak demand reduction, etc., is also evaluated within different research papers [13]-[15].

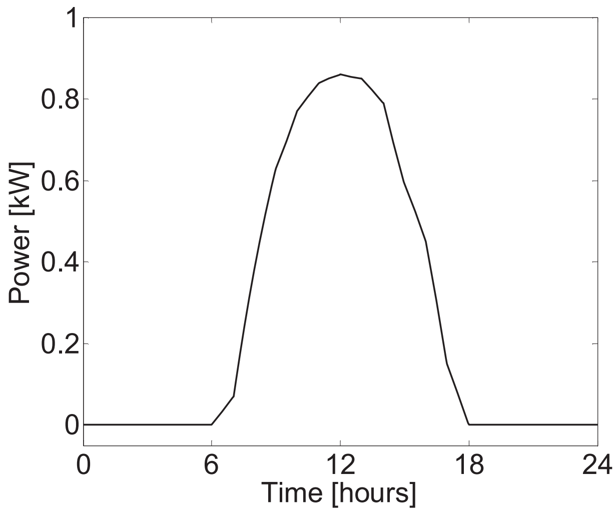

Fig. 3. PV system power production curve.

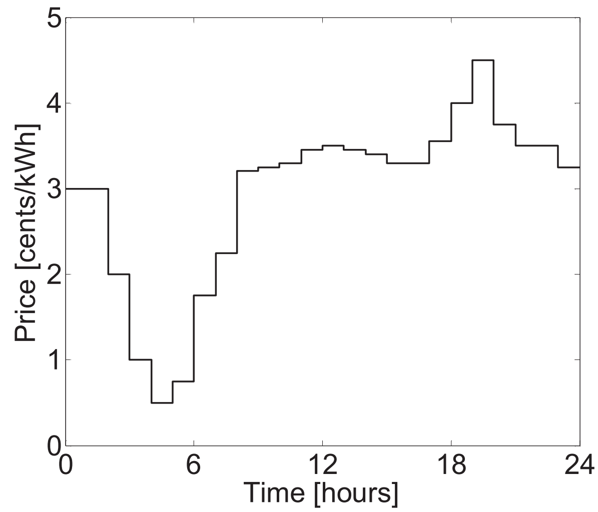

Fig. 4. Time-varying dynamic price signal for DR.

In this study, a bi-directional EV grid connection is considered for the analyzed household structure.

The specifications of a Chevy Volt with a battery rating of 16 kWh is taken into account. The Chevy Volt is employed with a charging station limited to a charging power of 3.3 kW [5].

The same power limit is also assumed to be valid for discharging operation in V2G mode. The charging and discharging efficiencies are considered as 0.95.

The EV is modeled with a state-of-energy equation, as follows:

$$State-of-Energy = E_{bat,in} + \frac{\int_0^t P_{bat}dt}{E_{bat,cap}} \quad (1)$$

where $E_{bat,in}$ is the initial battery energy while the EV arrives home (kWh), P_{bat} is the battery charging/discharging power (kW) and $E_{bat,cap}$ is the battery energy storage capacity (kWh).

There are many DR strategies for load demand management for households. In this study, a dynamic price based DR and a peak demand power limiting based DR are considered for the interaction with smart grid operator utility. The time-varying price signal available for the consumer via smart meter is shown in Fig. 4 [7].

III. Test and Results

To evaluate the impact of DR strategies and V2G operation together with own production facilities on consumer electricity bills, the overall household simulation model is tested and the relevant obtained results are discussed in this section.

DR strategies, especially price-based DR activities are mainly considering the preferences of the consumer, and the preferences of the consumers may vary from consumer to consumer.

In this study, three types of consumer preferences, namely consumers willing to charge their EV immediately, consumers willing to charge their EV with lower prices and consumers willing to charge their EV with lower prices together with utilization of V2G option for peak household power demand periods, are considered under dynamic price and peak power limiting based DR strategies.

Here, the test of the general system is realized considering the price variations data and utility signals as inputs and total daily load curve faced by the utility and the related daily total electricity cost as the output.

Fig. 5 presents the total household demand for consumers willing to charge their EV immediately after arriving home at 6:00 pm. It is to be noted that to better observe the DR activities after midnight, the simulation scale that starts from 7 am ends at the same time of the next morning and the 7 hours shifted time axis of the figure should be considered as 12 means 7 pm (19:00) in real time.

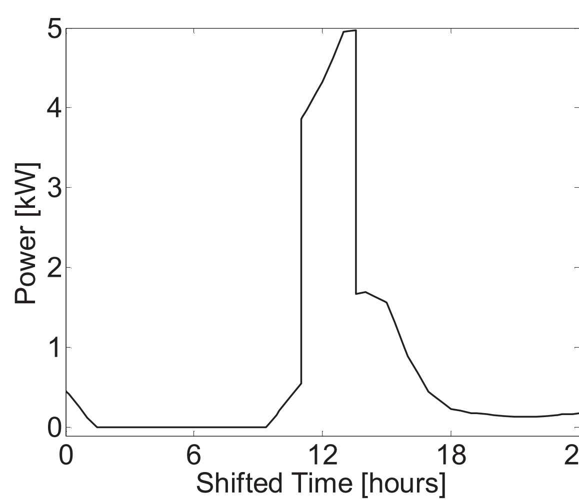

Fig. 5. The total household demand for consumers willing to charge their EV immediately.

Besides, it is also to be mentioned that the excess PV production after supplying the household demand is fed back to the grid via net-metering and the profit obtained from selling excess energy is not considered in this study. Moreover, it is considered that the initial EV battery energy is 8 kWh (50%state-of-energy) while arriving at home and the restricted lower limit of EV energy is 4.8 kWh (30% state-of-energy) to avoid deep-discharging.

It can clearly be seen that the EV load significantly contributes to the available peak period in the load demand given in Fig. 2 and this peak reaches to nearly 4.9 kW instead of the available peak power value of 1.7 kW in regular household demand.

This type of operation leads to a daily consumption price of 67.49 cents for the consumer. If a peak power limiting of 4 kW via a second DR strategy is employed from 6:00 pm to 10:00 pm by the utility, the total price is obtained as 66.92 cents. This situation causes the fact that the EV full charge is obtained in a later time; but the daily total price slightly decreases as some of the required EV charging power is shifted to lower price periods.

The second consumer preference of charging EV with lower prices after 10 pm provides a total household demand profile shown in Fig. 6.

This type of operation provides a result of 60.35 cents as daily electricity consumption price.

The peak power limiting strategy is not employed in this case study as utility based peak power limiting actions are generally taken during well-known peak demand periods in the evening and the EV is already considered to be in idle mode before 10 pm in this case study.

Shifting the EV charge to further lower price periods after midnight starting from 2 pm is also considered as a different case. This issue provides a significantly lower total price of 43.42 cents. However, this issue has a serious disadvantage of providing new peaks in general off-peak periods of utility load and should again require a further power limiting action.

As the last case study, the consumers willing to charge their EV with lower prices together with an V2G option to decrease their energy procurement from the utility during peak power and price periods are examined.

The total household demand profile is shown in Fig. 7. It is considered in this case study that as soon as the EV owner arrives home at 6 pm, the EV is plugged-in and the household load demand is supplied by the EV until the battery energy reaches to the restricted lower battery energy limit.

After reaching this limit, procurement of energy from utility starts again. Besides, the EV is again considered to be charged during off-peak and lower price periods in this case study.

The total price of daily consumption is obtained as 57.37 cents if the EV is charged after 10 pm.

Also, if further lower price periods after midnight starting from 2 pm are considered for EV charging, the price decreases to 32.86 cents.

The comparison of the different case studies in this paper is summarized in Table 1.

It is clear that the V2G option of EVs provides a significant opportunity for household owners in terms of price reduction in electricity bills, reaching more than 50% compared to the worst condition.

However, the impact of such an extra charge-discharge cycle on battery life is another point to take into account and this issue can be further evaluated with pros/cons of utilizing V2G option.

It should be noted that price variations are not just related with the generation side, but are also related with the changing load side due to DR like activities. This issue will be studied in the future by the authors, considering the impacts of DR based changing load patterns on the day-ahead market prices.

Nevertheless, similar to many literature studies dealing with just smart home operating strategies, a sample price curve assumed to be pre-defined was also employed in [7].

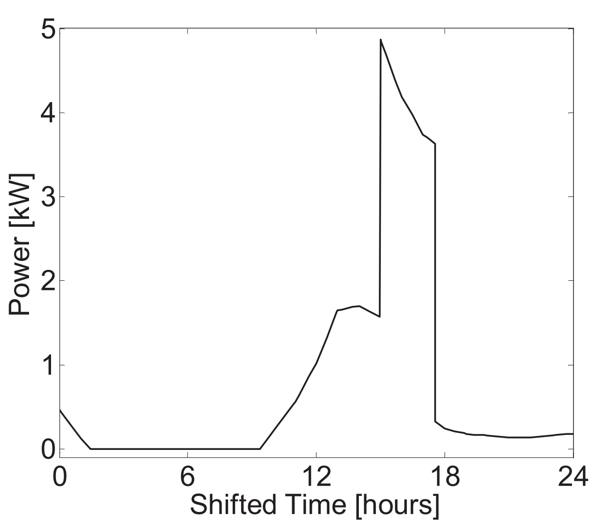

Fig. 6. The total household demand for consumers willing to charge their EV with lower prices.

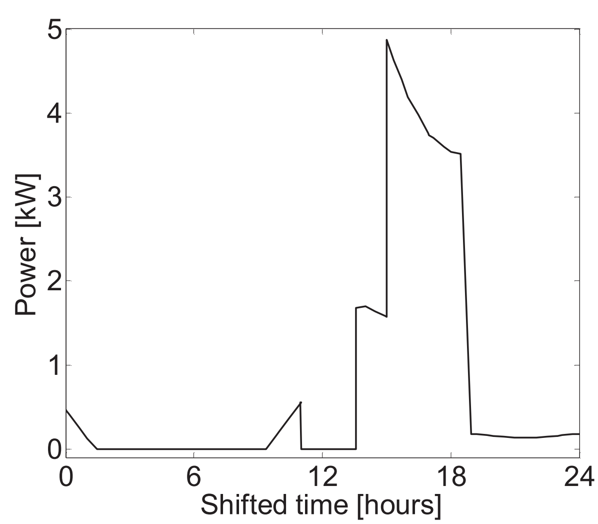

Fig. 7. The total household demand for consumers willing to charge their EV with lower prices together with V2G option.

TABLE I
COMPARISON OF DIFFERENT CASE STUDIES

Case Study	Total Price (cents)
Consumers willing to charge their EV immediately (without peak power limit)	67.49
Consumers willing to charge their EV immediately (with peak power limit)	66.92
Consumers willing to charge their EV with lower prices (after 10 pm)	60.35
Consumers willing to charge their EV with lower prices (after 2 am)	43.42
Consumers willing to charge their EV with lower prices together with V2G option in peak periods (after 10 pm)	57.37
Consumers willing to charge their EV with lower prices together with V2G option in peak periods (after 2 am)	32.86

In addition, shifting the load to off-peak periods will surely have a lowering impact on daily costs as expected before conducting any tests.

In a future study, manual user preferences based load shifting and HEM based optimum operation will be compared and the cost promotion of HEM strategy will be presented.

IV. CONCLUSIONS

The contribution of this study was based on addressing either distributed renewable energy contribution for reducing load demand on utility side or V2G option for lowering the demand peak periods together with different DR strategies. Enabling active participation of consumers on total load demand profile faced by utilities using DR strategies is a leading area of research in the smart grid concept. Different DR strategies focusing on management of the utilization of different load types have been analyzed both in academic and industrial area, and the research on this topic continues increasing. As a new type of consumer load with additional promising features, EVs are considered in this study together with different consumer preferences and DR strategies for managing the power consumption to reduce the consumer bills. Several case studies on different consumer preference conditions and possible DR actions that can be taken by the utility have been conducted with relevant comparisons. It is clear that utilizing EV VG2 option to supply a portion of household load demand during peak power and price conditions provides a considerable decrease in total price, especially when the EV charging is realized after midnight with the lowest costs. However, the utility side of the game should also be careful about the possible new power peaks in former off-peak periods. As future study, it is planned to design an optimization based HEM that automatically directs the power flow within the household for providing the lowest total operating price, again considering the consumer preferences and utility DR strategies.

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