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Abstract. Smart grid is a recently growing area of research including optimum and reliable operation of bulk power grid from production to end-user premises. Demand side activities like demand response (DR) for enabling consumer participation are also vital points for a smarter operation of the electric power grid. For DR activities in end-user level regulated by energy management systems, a dynamic price variation determined by optimum operating strategies should be provided aiming to shift peak demand periods to off-peak periods of energy usage. In this regard, an optimum generation scheduling based price making strategy is evaluated in this paper together with the analysis of the impacts of dynamic pricing on demand patterns with case studies. Thus, the importance of considering DR based demand pattern changes on price making strategy is presented for day-ahead energy market structure.

Keywords: Demand response, Home energy management, Optimal scheduling, Real-time pricing

1 Introduction

Smart grid concept refers to operating bulk power system in a more efficient, reliable, secure, environment friendly and economic way together with the utilization of advanced monitoring, protection and control systems by a two-way information and energy flow in all nodes of the power grid. Smartly operated grid structure is envisioned to support high levels of renewable energy penetration, new loads like electric vehicles (EVs), consumer participation with increased level of awareness and to optimize the operation of production, transmission and distribution systems. Especially, the issue of enabling consumer participation in demand side is a pivotal advantage of the smart grid idea providing a smoother power profile to be faced by utilities and all parts of the power grid. In this regard, 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 in a smart grid generally focus on demand response (DR) strategies creating a two-side game between utility and consumers [2].

As one of the most important contribution and interest area for smart grid idea, DR activities for controlling the demand side of the power production/demand balance instead of mature grid structure just dealing with the production side of the equation include a major portion in the latest literature dealing with smart grid applications.

Within the given demand side actions topic, smart home structures together with smart home energy management (HEM) systems capable of controlling home size distributed energy production facilities, electric vehicle (EV) based storage production options, controllable new generation smart appliances have also been the specific topic of some research activities in this area. The dynamic retail price variation for DR activities in end-user premises follows the wholesale price dynamics resulting from the short-term scheduling of the generation side facilities. In this study, a production side scheduling including dispatchable sources of energy will be provided in order to obtain a dynamic price variation to be presented to end-users in a smart grid environment. Then, these price variations will be considered as an input to the HEM of a sample residential end-user in order to provide the relevant demand response activities considering controllable/non-controllable load facilities. Thus, the impact of price variations on end-user load shapes can be easily examined with the provided structure.

The paper is organized as follows: Section 2 gives contribution to Collective Awareness Systems. Section 3 presents the methodology and the obtained results are discussed in Section 4. Finally, concluding remarks and future works are summarized in Section 5.

2 Contribution to Collective Awareness Systems

In the literature, there are several papers dealing with optimum scheduling of production facilities for power systems. Simoglou et al. [3] proposed a detailed model for solving the hydrothermal scheduling problem for a day ahead energy and reserve market. Morales et al. [4] provided a work on evaluating reserves in a power system under high penetration of wind power under the scope of two-stage stochastic programming. They also consider demand side as a bounded or involuntarily shed resource, providing some elasticity but not explicitly referring to DR.

There are also many recent studies dealing with DR strategies for smart households. Chen et al. [5] and Tsui and Chan [6] developed an optimization strategy for the effective operation of a household with a price signal based DR. Pipattanasomporn et al. [7] and Kuzlu et al. [8] presented a HEM considering peak power limiting DR strategy for a smart household, including both smart appliances and EV charging. Shao et al. [9] also investigated EV for DR based load shaping of a distribution transformer serving a neighborhood. Angelis et al. [10] performed the evaluation of a HEM strategy considering the electrical and thermal constraints imposed by the overall power balance and consumer preferences. Chen et al. [11] provided an appliance scheduling in a smart home considering dynamic prices and appliance usage patterns of consumer.

The studies referred above together with many other studies not referred here have provided valuable contributions to the application of smart grid concepts in household areas. However, the papers dealing with scheduling issue generally neglect demand side uncertainties caused by possible DR activities in a smart power grid environment. Besides, from the DR points of view, many of the mentioned papers referred above failed to address either production side of the game for providing the necessary price variations or the demand side in terms of vehicle-to-grid (V2G) option of EVs for lowering the demand peak periods together with different DR strategies.

3 Methodology

In this section, the methodology for the optimum operation strategy combined with DR activities is presented. First, a short-term generation scheduling algorithm that covers next day's load profile with the least cost is presented. Then, utilizing the mentioned scheduling based price variation, a DR strategy with considering different case studies of utilizing the EV in different modes of operation is performed. The relevant details of the employed methodology are as follows:

3.1 Scheduling Model for Obtaining Price Variation

For the sake of simplicity, in the presented scheduling model we neglect the need of considering reserves. The overall objective of the day-ahead energy market clearing procedure is to minimize the total costs associated with electricity production. The objective function given in Eq. (1) could be easily extended to comprise other costs such as generator´s no load cost or the cost of energy not served.

$$Minimize \sum_{t\in T}\sum_{i\in I}(SUC_i \cdot y_{i,t} + SDC_i \cdot z_{i,t}) + \sum_{t\in T}\sum_{i\in I}\sum_{f\in F} c_{i,f} \cdot b_{i,f,t} \quad (1)$$

The objective of the system should be achieved subject to several constraints presented in (2)-(12):

$$\sum_{i\in I} p_{i,t} = D_t \,, \forall t \in T \quad (2)$$

$$p_{i,t} \geq P_i^{min} \cdot u_{i,t} \,, \forall t \in T, \forall i \in I \quad (3)$$

$$p_{i,t} \leq P_i^{max} \cdot u_{i,t} \,, \forall t \in T, \forall i \in I \quad (4)$$

$$\sum_{f\in F} b_{i,f,t} = p_{i,t} \,, \forall i \in I, \forall t \in T \quad (5)$$

$$0 \leq b_{i,f,t} \leq B_{i,f,t} \,, \forall i \in I, \forall f \in F, t \in T \quad (6)$$

$$p_{i,t} + p_{i,(t-1)} \leq RU_i \cdot 60 \,, \forall i \in I, \forall t \in T \quad (7)$$

$$p_{i,(t-1)} - p_{i,t} \leq RD_i \cdot 60, \forall i \in I, \forall t \in T \quad (8)$$

$$\sum_{\tau=t-UT_i+1}^{t} y_{i,t} \leq u_{i,t} \,, \forall i \in I, \forall t \in T \quad (9)$$

$$\sum_{\tau=t-DT_i+1}^{t} z_{i,t} \leq 1 - u_{i,t} \,, \forall i \in I, \forall t \in T \quad (10)$$

$$y_{i,t} - z_{i,t} = u_{i,t} - u_{i,(t-1)} \,, \forall i \in I, \forall t \in T \quad (11)$$

$$y_{i,t} + z_{i,t} \leq 1 \,, \forall i \in I, \forall t \in T \quad (12)$$

Constraints (2)-(4) enforce system power balance and generating unit technical limits. The cost for generating power for each unit is described with a step-wise non-decreasing marginal cost function like the one presented in Ref. [3] and is expressed by the second term of (1) and the constraints (5) and (6). Constraints (7) and (8) enforce the unit ramp rate limits. The unit minimum up and down time constraints are considered by (9) and (10), respectively. Constraint (11) considers the start-up and shut-down status change logic while (12) states that a unit cannot be simultaneously started-up and shut-down.

3.2 Demand Response Activities

A HEM system for DR strategies regulates the operation of such a 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. In this paper, the smart EV operation considering smart charging and possible V2G mode is evaluated with an optimization based HEM strategy. 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 [12]. The Chevy Volt is employed with a charging station limited to a charging power of 3.3 kW. 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:

$$State - of - Energy = E_{bat,in} + \frac{\int_0^t P_{bat} dt}{E_{bat,cap}} \quad (13)$$

There are many DR strategies for load demand management for households. In this study, a dynamic price based DR strategy is considered for the interaction with smart grid operator utility. The time-varying price signal available for the consumer via smart meter is obtained by the scheduling mentioned above in Section 3.1, adding a flat rate that reflects the fact that the retail prices are the wholesale market prices plus surcharges for transmission and distribution networks usage plus taxes. The DR action is provided as leading to the optimized operation of household appliances with lowest daily price under limitations of power supply guarantee.

4 Test and Results

The load demand considered in this study is created using real demographic data from Crete Island, Greece and is separated in two components [13]. The first component, comprising the industrial and commercial loads is shown in Fig. 1 and reflects the fact that Crete´s economy is primarily based on agricultural and light commercial sector, rather than heavy industry.

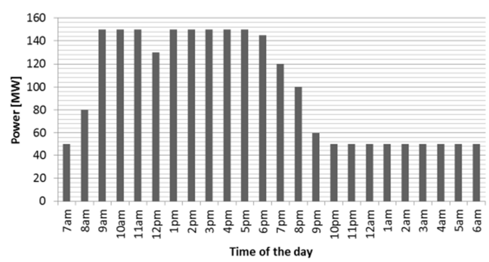

Fig. 1. Industrial load demand.

The second component of the load demand, residential load profiles are created by considering general daily habits of inhabitants and possibility of owning EV and smart DR opportunities. There are approximately 200,000 households in Crete. The general load profile of a household is obtained using the home appliance data in Table 1. In this table, the cycle of utilization presents how many cycles the appliance face in separate hours.

Table 1. Considered household appliances.

Appliance	Power [kW]	Cycle of utilization	Appliance	Power [kW]	Cycle of utilization
Refrigerator	0.3	24	Toaster	0.85	3
TV	0.125	17	Oven	2	3
Coffee Maker	0.85	4	Washing-machine	2.3	1
Computer	0.15	15	Dishwasher	1.3	3
Water heater	2	1	Lighting	0.15	7

The load demand of a sample household without and with EV using the data given in Table 1 is shown in Fig. 2. It should be noted that the household owners arrive home at 5 pm and directly plug their EVs. Besides, it should be stated that the percentage of households for cases (1) without EV, (2) with EV, (3) with DR, EV and without V2G, and (4) with EV, DR and V2G are assumed as 70%, 10%, 10% and 10%, respectively.

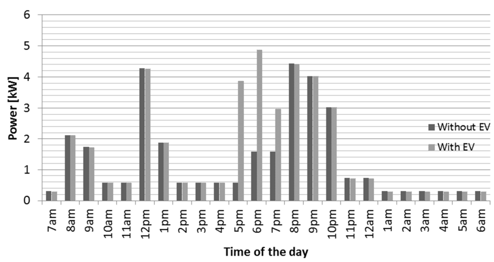

Fig. 2. Household load demand with and without EV.

In the first stage, for the scheduling of production facilities, the DR and V2G opportunities are neglected and the load demand without EV is assumed to contain 70% of the total households and the rest is taken into account to cover the load profile given in Fig. 2 for the case of EV. Besides, the load demand given in Fig. 1 is added to the obtained total residential load demand. Thus, the total load for scheduling is given in Fig. 3.

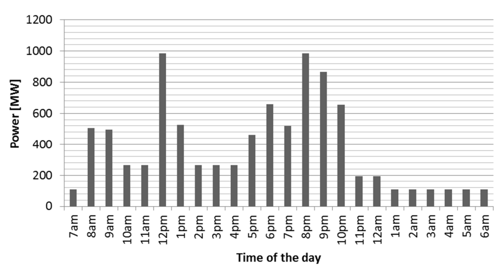

Fig. 3. Considered total load demand for scheduling.

The test power system consists of five units of different technologies, a fact that explicitly affects the associated costs and technical features. Detailed technical and economic data are given in Table 2 and Table 3. After the scheduling procedure, the obtained price variation for analyzing the DR activities is shown in Fig. 4, corresponding to the wholesale market prices plus the extra charges described above, considered a flat 5cents/kWh surcharge. As seen, for the peak power periods of total demand given in Fig. 3, the scheduling algorithm provides higher prices compared to off/peak periods as expected.

Table 2. Technical Data of Generating Units

	Pmax [MW]	Pmin [MW]	SUC [€]	SDC [€]	RU [MW/min]	RD [MW/min]	UT [h]	DT [h]	Tech.
Unit1	180	40	45500	10000	1.8	1.8	8	4	Lignite-fired
Unit2	200	50	60000	10000	3	3	8	4	Lignite-fired
Unit3	250	100	16000	5000	20	20	4	3	CCGT
Unit4	300	90	19800	5000	24	24	4	3	CCGT
Unit5	120	30	2600	500	8	8	1	1	OCGT

Table 3. Economic Data of Generating Units

	b1 [MW]	c(b1) [€]	b2 [MW]	c(b2) [€]	b3 [MW]	c(b3) [€]	b4 [MW]	c(b4) [€]	b5 [MW]	c(b5) [€]
Unit1	80	32	40	32.2	30	32.4	20	32.6	10	32.8
Unit2	100	32.7	60	32.9	40	33.1	-	-	-	-
Unit3	120	40	50	40.5	40	40.7	30	40.8	10	41.3
Unit4	130	42	60	42.5	50	42.9	40	43.2	20	43.5
Unit5	70	60	35	61	15	62	-	-	-	-

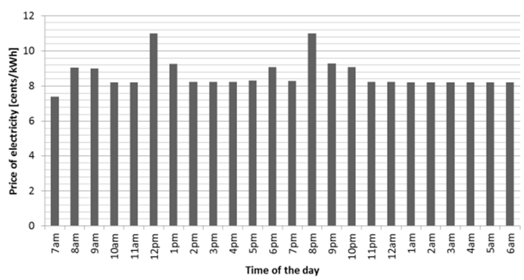

Fig. 4. Obtained price variation.

The HEM system in the sample household considers the daily electricity prices in Fig. 4 together with regular load demand patterns of the household to decide for the best operating strategy for EVs. The smart EV charging by optimization based HEM strategy with and without V2G option is evaluated and the results are given in Fig. 5. The HEM strategy shifts the EV charging to off-peak hours with lower prices. This type of operation leads to a lower total daily electricity cost than the case where consumers manually decide the charging time of their EVs without V2G option.

It can also be seen from Fig. 5 that V2G option decreases the energy procurement from the utility during peak power and price periods. It is considered in this case that 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 for the periods determined by the optimum DR strategy. After reaching this limit, procurement of energy from utility starts again to fully supply the load demand in all conditions.

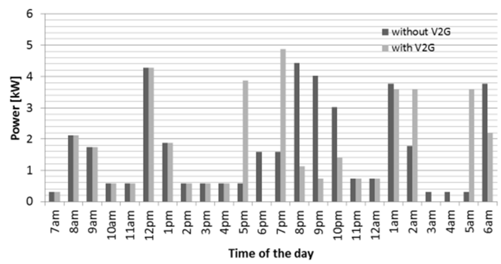

Fig. 5. Household load demand with DR while neglecting and considering V2G.

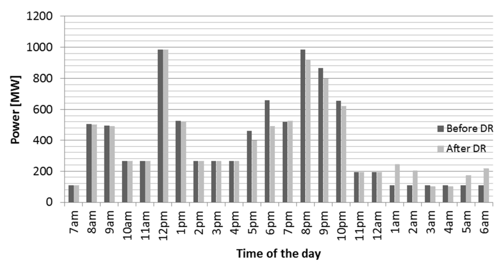

Fig. 6. Compared total load demand profiles with and without DR activities.

Total load demand obtained after considering also DR strategies is comparatively presented in Fig. 6. The load pattern changes considerably with shifting some portion of peak load demand after 5 pm to off-peak periods especially after midnight hours. Also, the load demand before 5 pm is totally the same as only EVs are considered as controllable load in HEM and EV charging/discharging activities are assumed to start after 5 pm when the EV owners arrive home. It is sure that if more high power loads (washing machines, dishwashers, water heaters, etc.) were also considered as controllable in DR strategy, the other hours before 5 pm would be affected by this issue. Besides, it should be stated that the total consumed energy in the evaluated 24-h period is the same for the cases of including and neglecting DR activities as expected.

5 Conclusion

In this paper, a sample generation scheduling with neglecting reserve requirements for the day-ahead market operation was provided. The obtained prices with the scheduling strategy were employed for a smart household structure to better observe the impacts of dynamic pricing on DR activities, according to the total load profile. It is clear that the change in load demand with DR activities would have a significant impact on the price making structure, not only for the reason of load pattern change but also for the reason of reserve requirements and other market based actions in the real time market. This study is an innovative first step towards a thorough market based evaluation of DR as a system resource. Future studies will examine the interaction between DR activities and generating side in several market structures such as day-ahead, intra-day and real-time market. The basic outlook will be the investigation of DR resources to participate actively in the wholesale market providing, apart from peak reductions or peak shifts, different types of critical ancillary services. The research is expected to be particularly focused on insular grids with high penetration of renewables. Conventional storage units and upcoming storage technologies (e.g. hydrogen based storage) will be also be taken into account in order to form smart and flexible portfolios for production and demand facilities.

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Nomenclature. $B_{i,f}$ is size of step f of unit i marginal cost function; D_t is demand in hour t; DT_i is minimum down time of unit i; $E_{bat,cap}$ is battery energy storage capacity; $E_{bat,in}$ is initial battery energy while EV arrives home; P_{bat} is battery charging/discharging power; RU_i is ramp- up rate of unit i; RD_i is ramp-down rate of unit i; SUC_i is start-up cost of unit i; SDC_i is shut-down cost of unit i; UT_i is minimum up time of unit i; $c_{i,f}$ is marginal cost of step f of unit I marginal cost function; $b_{i,f,t}$ is portion of step f of the i-th unit's marginal cost function loaded in hour t; $f(F)$ is index (set) of steps of the marginal cost function of unit i, $i\ (I)$ is index (set) of generating units; $p_{i,t}$ is power output of unit i in hour t limited between P_i^{min} and P_i^{max}; $t(T)$ is index (set) of hours of the planning period; $u_{i,t}$ is binary variable which is 1 if unit i is committed during hour t; $y_{i,t}$ is binary variable which is 1 if unit i is started-up during hour t; $z_{i,t}$ is binary variable which is 1 if unit i is shut-down during hour t.

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