Applied Energy 126 (2014) 142–150

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Economic impacts of small-scale own generating and storage units, and electric vehicles under different demand response strategies for smart households

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HIGHLIGHTS

- A MILP framework based HEM system modeling.
- Evaluation of different demand response strategies.
- Consideration of additional own generating unit, EV and ESS.
- Control of shiftable appliances further to reduce total daily cost.

ARTICLE INFO

Article history:
Received 5 March 2014
Received in revised form 31 March 2014
Accepted 3 April 2014
Available online 8 May 2014

Keywords:
Demand response
Electric vehicle
Energy storage system
Home energy management
Smart household
Vehicle-to-home

ABSTRACT

With the increasing importance given to smart grid solutions in end-user premises, demand response (DR) strategies applied to smart households are important topics from both real time application and academic theoretic analysis perspectives, recently. In this study, a mixed-integer linear programming (MILP) framework based evaluation of such a smart household is provided. Electric vehicles (EVs) with bi-directional power flow capability via charging and V2H operating modes, energy storage systems (ESSs) with peak clipping and valley filling opportunity and a small scale distributed generation (DG) unit enabling energy sell back to grid are all considered in the evaluated smart household structure. Different case studies including also different DR strategies based on dynamic pricing and peak power limiting are conducted to evaluate the technical and economic impacts of ESS and DG units. Besides, shiftable loads such as washing machine and dishwasher are also considered in Home Energy Management (HEM) system structure for the effective operation of the household. Moreover, a further sensitivity analysis is realized in order to discuss the impact of ESS and DG sizing on daily cost of smart household operation considering further pros and cons.

1. Introduction

During the recent years, improving the efficiency and effectiveness of electric energy usage has been a leading concern around the world due to several reasons including the finite sources of conventional fossil fuels, the increasing impacts of global warming, the stochastic nature of main renewable energy systems, political impacts of energy dependence/independence, etc. Thus, new concepts and ideas have been proposed to achieve this target. Among them, smart grid concept has drawn significant attention for the efficient and effective operation of the electric power system during the last decade and notable investments have been declared for this concept by leading country governments [1,2].

During the operation of the existing electric power system structure, a considerable difference occurs between the electricity usage patterns daily and seasonally. High cost peaking power plants are required to be operated during the sharp peaks of daily and seasonally periods and even these peaks are likely to cause the need of constructing new power plants and upgrading the existing asset (lines, transformers, etc.) capacities for transmission and distribution purposes [3]. In order to provide the ability to also control the demand side of the energy balance between generation and utilization to defer the necessity of new investments, smart grid vision enables effectively accommodating all generation and storage options with consumer participation in the demand side

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http://dx.doi.org/10.1016/j.apenergy.2014.04.010
0306-2619/

Nomenclature

Indices

t	period of the day index in time units (h or min)
m	shiftable appliance index

Parameters

CE_{ESS}	charging efficiency of the ESS
CE_{EV}	charging efficiency of the EV
CR_{ESS}	charging rate of the ESS (kW per time interval)
CR_{EV}	charging rate of the EV (kW per time interval)
DE_{ESS}	discharging efficiency of the ESS
DE_{EV}	discharging efficiency of the EV
DR_{ESS}	discharging rate of the ESS (kW per time interval)
DE_{EV}	discharging rate of the EV (kW per time interval)
N_1	maximum power that can be drawn from the grid (kW)
N_2	maximum power that can be sold to the grid (kW)
P_t^{other}	household power demand (kW)
$P_t^{PV,pro}$	power produced by the PV (kW)
$SOE^{ESS,ini}$	initial state-of-energy of the ESS (kW h)
$SOE^{ESS,max}$	maximum allowed state-of-energy of the ESS (kW h)
$SOE^{ESS,min}$	minimum allowed state-of-energy of the ESS (kW h)
$SOE^{EV,ini}$	initial state-of-energy of the EV (kW h)
$SOE^{EV,max}$	maximum allowed state-of-energy of the EV (kW h)
$SOE^{EV,min}$	minimum allowed state-of-energy of the EV (kW h)
ΔT	number of time intervals in one hour
λ_t^{buy}	price of energy bought from the grid (cents/kW h)
λ_t^{sell}	price of energy sold to the grid (cents/kW h)

Variables

$P_t^{ESS,ch}$	ESS charging power (kW)
$P_t^{ESS,dis}$	ESS discharging power (kW)
$P_t^{ESS,used}$	power used to satisfy household load from the ESS (kW)
$P_t^{EV,ch}$	EV charging power (kW)
$P_t^{EV,dis}$	EV discharging power (kW)
$P_t^{EV,used}$	power used to satisfy household load from the EV (kW)
P_t^{grid}	power supplied by the grid (kW)
$P_t^{PV,sold}$	power injected to grid from the PV (kW)
$P_t^{PV,used}$	power used to satisfy household load from the PV (kW)
$P_{t,m}^{shift}$	power required by shiftable appliance m (kW)
P_t^{sold}	total power injected to the grid (kW)
SOE_t^{ESS}	state-of-energy of the ESS (kW h)
SOE_t^{EV}	state-of-energy of the EV (kW h)
u_t^{ESS}	binary variable. 1 if ESS is charging during period t, 0 else
u_t^{EV}	binary variable. 1 if EV is charging during period t, 0 else
u_t^{grid}	binary variable. 1 if grid is supplying power during period t, 0 else

[4,5]. Related to the recent attention given to smart grid vision, smart households that can monitor their use of electricity in real-time and act in order to lower their electricity bills have also gained specific importance by the research regarding possible demand side actions.

Demand side actions for smart households in a smart grid environment generally focus on demand response (DR) strategies enabling interaction 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 comprises incentive based programs and price based programs (time-of-use, critical peak pricing, dynamic pricing, etc.) [6,7].

DR can be considered mature for industry, but is a relatively new concept for residential users corresponding to 41% of electricity usage [5,8]. Home Energy Management (HEM) systems and smart metering infrastructure play a vital role in effectively applying DR strategies to residential areas. Generally, HEM systems electronically receives the pricing data from the relevant load serving entity (LSE) using the smart metering infrastructure and aims to provide the most economic operation of home appliances together with considering user preferences as seen in Fig. 1. Shifting demand from peak to off-peak hours is desired and this demand shifting depends on the appliance classification. Thus, home appliances can be divided into three categories from the perspective of HEM [3]:

- Non-shiftable appliances (television – TV, refrigerator, etc.)
- Controllable appliances (Heating Ventilation and Air Conditioning – HVAC, lightening, etc.)
- Shiftable appliances (dishwashers, washing machines, etc.)

The demand for non-shiftable appliances should be continuously supplied especially to sustain the comfort level of the end-users. It is to be noted that energy efficiency concepts such as preventing the stand-by mode operation of TV units, etc. are out of scope of this discussion on non-shiftable appliances. On the other hand, the energy demand of controllable appliances can be modified. Besides, the energy demand of shiftable appliances can be totally shifted from peak to off-peak hours. The rated power is fixed for non-shiftable and shiftable appliances. However, the power consumption of controllable appliances changes between a maximum and minimum band considering the operating condition of the relevant appliances due to existing conditions [3].

As a recently considered type of end-user appliance, electric vehicles (EVs) has the potential of offering different pros and cons related to the operating mode [9]. For the charging operation of EVs, considerable levels of power requirements exist as can obviously be derived from the example that the charging station power level of Chevy Volt – which is even a small-sized EV – is 3.3 kW [10]. As a different operating mode possible for EVs, the vehicle-to-home (V2H) and even vehicle-to-grid (V2G) modes can also contribute to the efficient operation of HEM system significantly. Using the existing energy in EV battery after returning home for the clipping of peak hour power demand via V2H mode can be a potential application for DR strategies. In this regard, different types of energy storage systems (ESSs) can also provide peak clipping and valley filling by storing energy during off-peak periods and consuming this energy during peak times of general use [3,6].

There are many recent studies dealing with DR strategies for the optimum appliance operation of smart households. Li and Hong [3] proposed an "user-expected price" based DR strategy for a smart household also including a battery based ESS for the aim of lowering the total electricity cost by charging and discharging the ESS at off-peak and peak price periods, respectively. However, the impact of including an additional EV load that can also be helpful for peak