Electric Power Systems Research 143 (2017) 533–543

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Rational consumer decisions in a peak time rebate program

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ARTICLE INFO

Article history:
Received 26 July 2016
Received in revised form 28 October 2016
Accepted 2 November 2016
Available online 18 November 2016

Keywords:
Demand response
Peak time rebate
Stochastic programming
Baseline

ABSTRACT

A rational behavior of a consumer is analyzed when the user participates in a peak time rebate (PTR) mechanism, which is a demand response (DR) incentive program based on a baseline. A multi-stage stochastic programming is proposed from the demand side in order to understand the rational decisions. The consumer preferences are modeled as a risk-averse function under additive uncertainty. The user chooses the optimal consumption profile to maximize his economic benefits for each period. The stochastic optimization problem is solved backward in time. A particular situation is developed when the system operator (SO) uses consumption of the previous interval as the household-specific baseline for the DR program. It is found that a rational consumer alters the baseline in order to increase the well-being when there is an economic incentive. As results, whether the incentive is lower than the retail price, the user shifts his load requirement to the baseline setting period. On the other hand, if the incentive is greater than the regular energy price, the optimal decision is that the user spends the maximum possible energy in the baseline setting period and reduces the consumption at the PTR time. This consumer behavior produces more energy consumption in total considering all periods. In addition, the user with high uncertainty level in his energy pattern should spend less energy than a predictable consumer when the incentive is lower than the retail price.

1. Introduction

In the smart grid concept, DR is a mechanism implemented by SO to equilibrate the load with power generation by modifying consumption. The main purpose of this kind of program is to curtail load at the peak demand times for maintaining the security of the transmission assets, avoiding to exceed the limit capacity of generators and preventing power outages. Therefore, DR is one of the most crucial parts of the future smart grid [28] due to the main objectives of the DR is peak clipping, valley filling and load shifting on the power profile. An important question in DR program design is how to improve the demand profile, namely, to control the noncritical loads at the residential, commercial and industrial levels for matching supply and demand. For instance, DR program might motivate changes in electricity usage by changing the price of electricity or giving an incentive payment.

There are several DR programs implemented as part of strategies to reduce peak power (because the demand trend is growing). In [21,4] are shown a complete summary regarding mathematical models, pricing methods, optimization formulation and future extensions. The common approach is time-varying pricing (TVP), which charge more money for energy use during peak periods. In TVP program, the consumer does not have a significant incentive to curtail the consumption, just the energy is more expensive at certain hours. Others mechanisms have been implemented where the user behavior is modified through economic incentives, therefore, many utilities have employed a change in the residential electricity rate structure [15]. For instance, time-of-use (TOU) [3] program, where the day is divided into adjoining blocks of hours. The price of energy varies between blocks, but not within blocks; critical peak pricing (CPP) [9], is related to TOU, unlike that it is only applied to a small number of event days; in real-time pricing (RTP) [2], the price varies hourly according to the real-time market cost of delivering electricity; direct load control [6], remote control of flexible loads; emergency demand reduction [20], users receive incentive by diminishing energy consumption during emergency events; PTR [24], where customers receive electricity bill rebates by not consuming (relative to a previously established, household-specific baseline) during peak periods, which it is the mechanism studied in this paper; and many other mechanisms.

The baseline is an important concept of the PTR program. A counterfactual model is developed to estimate the baseline. In [17] shows the critical facts on the selection of customer baseline, they design a suitable baseline focusing on administrative and contractual approaches in order to get an efficient DR. Furthermore, in

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http://dx.doi.org/10.1016/j.epsr.2016.11.001
0378-7796/

[8,25,1] the performance of DR baselines are studied and new methods are regarded as establishing the reasonable compensation of the consumer.

Moreover, in literature, there are some of more theoretical DR programs such as in [27] by using a smart grid technology, the authors shows a DR program where a load device could offer retail users coupon incentives to induce DR for a future period in anticipation of intermittent generation. In [10] a cooperative dynamic DR under different market architecture is proposed to evaluate the welfare impacts and the efficiency-risk. In addition, [5] devise schemes for scheduling DR in a deregulated environment. The authors create a new market concept trough a pool-based market-clearing strategy. In [11] a real-time DR algorithm is developed. Furthermore, it is possible to find DR program based on the game theory such as [14] to ensure that users tell the truth in relation to their reduced power consumption employing a Vicrey–Clarke–Grove mechanism.

In this paper, a rational consumer behavior is studied when he is enrolled in a particular DR incentive program based on baseline or counterfactual model called peak time rebate (PTR). In the economic sense, rational behavior means that the users maximize their profits given the mechanism of demand energy reduction. This rebate is calculated using a baseline for each user which is estimated from past energy consumption. In real life, the PTR program has shown to be an inefficient DR mechanism to improve the demand profile because it allows that some users deliberately increase consumption during baseline-setting times [26,19,12]. Such consumer behavior of altering the baseline is formulated as a stochastic optimization problem to understand how the users take their decisions of consumption when they are participating in PTR program. While the user intuitively makes decisions according to the operation of the mechanism, in this work, a mathematical model of consumer choice is proposed in order to find solutions to the aforementioned inefficiency of the PTR mechanism.

In this work, the optimal strategy of a user that participates in a PTR program is studied in order to earn the highest economic profit under uncertain decisions. The contribution is described as follows:

- The optimal decision problem is posed in general form taking into account several previous periods of setting-time in a PTR program. The purposed solution is solved backward in time to find the optimal choice for consumers where consumer uncertainty is modeled as a random variable. In addition, the choice of the SO is modeled as a binary random variable, namely, for indicating whether the user is called for participating in PTR mechanism.
- A closed form solution of a PTR program is derived for two periods. The previous consumption is assumed as the baseline and the user is always called to participate in the PTR program. The results show that the consumer alters the baseline when the incentive exists in the DR program. Some numerical examples are presented.

The article is organized as follows. Section 2 describes the preliminary setting. In Section 3, the general problem formulation of the PTR program is developed. Section 4, the mathematical solution for two periods given the optimization problem is explained. Section 5, the simulation results are shown. Conclusions are presented in Section 6.

2. Setting

This section presents the notation and assumptions for developing the model. An individual consumer or aggregated demand (a group of users with the same or similar preferences) is considered for this DR model. the decision maker's preferences are specified by giving utility function $G(q_t;\theta_t)$, where q_t is the consumption at time t and θ_t is a particular realization of random variable Θ. The randomness Θ are external factors that influence the energy requirements of the consumer. The randomness in the utility function is modeled as an additive load requirement, that is, $G(q_t;\theta_t) = G(q_t - \theta_t)$. Θ is assumed to have a probability density function $f_\Theta(\theta_t)$ with limited support $[\underline{\theta}, \bar{\theta}]$ and mean zero. The motivation to choose such additive randomness is that an external event, such an as a cold wave, will drive the user to increase his energy consumption until he obtains the same comfort than without the event. Then, given a price, the effect of the random event is to shift the equilibrium point to the left in this situation.

The consumer is assumed with risk-averse behavior. Individuals will usually choose with lower risk, therefore, $G(\cdot)$ is concave [22]. This behavior reflects the assumption that marginal utility diminishes as wealth increases. Also, $G(\cdot)$ is considered smooth, positive and nondecreasing.

A competitive electricity market (consumers are price-takers) is assumed. Thus, the energy price p is given and constant since the utility company set an invariable price to the users during the certain period. Then, the following definitions are stated.

Definition 2.1. The energy total cost is $\pi(q_t) = pq_t$.

Definition 2.2. The payoff function is defined as $U_t\left(q_t, \theta_t\right) = G(q_t - \theta_t) - \pi(q_t)$, which indicates the user benefit of consuming q energy during the interval t.

Definition 2.3. Given $G(\cdot)$, θ_t and p, the rational behavior of the consumer that maximizes the payoff function $U_t(q_t, \theta_t)$ is

$$q_t^*(\theta_t) = \bar{q} + \theta_t \tag{1}$$

this result is found by solving the optimization problem

$$q_t^* = \max_{q_t \in [0, q_{\max}]} U_t\left(q_t, \theta_t\right) = G\left(q_t - \theta_t\right) - \pi\left(q_t\right)$$

where q_{max} is the maximum allowable consumption value, $\bar{q}$ is the optimal solution to the previous condition when $\theta_t = 0$.

2.1. Utility function and rebate description

Under assumption that $G(\cdot)$ is a smooth and concave function, the utility function can be approximated by a second order polynomial around $\bar{q}$. Therefore, a quadratic function is considered, where the user utility is zero whether his consumption is zero and saturates after achieving the maximum of the quadratic form, i.e.,

$$G(q_t) = \begin{cases} -\dfrac{\gamma}{2}(q_t - \bar{q})^2 + p(q_t - \bar{q}) + k & 0 \le q_t \le \bar{q} + \dfrac{p}{\gamma} \\ -\dfrac{p^2}{2\gamma} + \dfrac{p^2}{\gamma} + k & q_t > \bar{q} + \dfrac{p}{\gamma} \end{cases}$$

The saturated part is motivated due to the fact that the agent has a limited well-being with respect to his energy consumption.

Definition 2.4. Under additive uncertainty and using the previous consideration (1), The utility function can be rewritten as follow:

$$G\left(q_t - \theta_t\right) = \begin{cases} -\dfrac{\gamma}{2}\left(q_t - q_t^*\right)^2 + p\left(q_t - q_t^*\right) + k & 0 \le q_t \le q_t^* + \dfrac{p}{\gamma} \\ -\dfrac{p^2}{2\gamma} + \dfrac{p^2}{\gamma} + k & q_t > q_t^* + \dfrac{p}{\gamma} \end{cases} \tag{2}$$

where γ and k are constant. In particular, γ depicts consumer private preferences and k is settled when $G\left(q_t - \theta_t\right) = 0$ if $q_t - \theta_t = 0$. A similar approach to model a utility function is found in [18]. A further discussion about γ can be reviewed in [7].

Note that γ is in dollar or any other currency divided by energy units squared, therefore, this parameter could be interpreted as the