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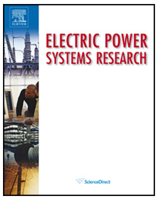

Optimal use of incentive and price based demand response to reduce costs and price volatility☆

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ABSTRACT

There are two general categories of demand response (DR): price-based and incentive-based DR programs. Each one has its own benefits taking advantage of different aspects of flexible demand. In this paper, both categories of DR are modeled based on the demand-price elasticity concept to design an optimum scheme for achieving the maximum benefit of DR. The objective is to not only reduce costs and improve reliability but also to increase customer acceptance of a DR program by limiting price volatility. Time of use (TOU) programs are considered for a price-based scheme designed using a monthly peak and off-peak tariff. For the incentive-based DR, a novel optimization is proposed that in addition to calculation of an adequate and a reasonable amount of load change for the incentive, the best times to realize the DR is found. This optimum threshold maximizes benefit considering the comfort level of customers as a constraint. Results from a reduced model of the WECC show the proposed DR program leads to a significant benefit for both the load serving entities (LSEs) and savings in customer's electricity payment. It also reduces both the average and standard deviation of the monthly locational marginal price (LMP). The proposed DR scheme maintains simplicity for a small customer to follow and for LSEs to implement.

1. Introduction

Ongoing developments in the so-called Smart Grid promise a future power system that is more economically efficient, environmentally friendly, fault resilient and operationally flexible. This future system will depend on new digital communications, computing, monitoring and control down to the customer level. Among the many innovations related to these developments, a key component is effective demand side management [1,2].

The U.S. Department of Energy (DOE) defines demand response (DR) as "a tariff or program established to motivate changes in electric use by end-use customers in response to changes in the price of electricity over time, or to give incentive payments designed to induce lower electricity use at times of high market prices or when grid reliability is jeopardized" [3].

The literature broadly shows two types of DR: price-based (PB) and incentive-based (IB) [4]. PBDR programs pass on the variation of wholesale market electricity price directly to customers so that they pay for the value of electricity at different times of the day. PBDR schemes typically considered include: time-of-use pricing, critical peak pricing, peak load pricing and real-time pricing [5,6], although there are many other possible PB schemes. The main idea behind all PBDR is that a significant difference between prices in different hours leads customers to adjust timing of their flexible loads in order to take advantage of lower price periods. From the load aggregator or utility point of view, peak shaving resulting a powerful approach to avoid capacity upgrades by peak shaving.

IB programs include Direct Load Control, Interruptible service, Demand Bidding/Buy Back, Emergency Demand Response Program, Capacity Market Program and various Ancillary Service Markets. These programs offer customers incentives in addition to their retail electricity rate, which may be fixed or time-varying for their load reduction. Demand reductions are needed either when required for system reliability or when prices become too high. In percentage terms, IBDR programs provide about 93% of the peak load reduction from existing DR resources in the U.S. today [7]. Among all IBDR programs, the interruptible load contract (ILC) is the most common approach for controlled demand reduction. Utilities and regulators have encouraged ILC for larger loads since 1980s [8,9]. Peak time rebate is another type of IBDR program [10]; however, the rebate paid to consumers is typically very high and does not reflect the actual supply-demand market conditions.

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Nomenclature

α	load variation economic weight
β	percentage of affordable load reduction for TOU program
ΔD_{bt_j}	load change of customer type *j* in time period *t* and bus *b* due to IBDR program
Δd_{bt}	load change at bus *b* and time *t* in response to TOU program
Δp_b^{OPT}	retail load tariff in change in off peak time
Δp_b^{PT}	retail load tariff in change in peak time
$\Delta \bar{D}_{bt}$	load change at bus *b* and time *t* in response to IBDR program
ε_j	elasticity of customer type *j*
ε_{tt_1}	elasticity of time *t* respect to time *t*1
ε_{tt_2}	elasticity of time *t* respect to time *t*2
CB_b	customer benefit at bus *b*
d_{bt}	new load at bus *b* and time *t* after TOU program
d_{bt}^0	demand at bus *b* and time *t* in base case with no DR
D_T	type of customer
LMP_{bt}	locational marginal price at time *t* and bus *b*
LSE_b	LSE benefit at bus *b*
N_B	total number of buses
NT	number of time in study period
p_{bt}^{inc}	incentive payment to customer at bus *b* and time *t*
p_b^0	retail load tariff at bus *b* in base case with no DR
p_b^{OPT}	retail load tariff in off peak time
p_b^{PT}	retail load tariff in peak time
T	study time period
T_d	daily period of study
T_h	hourly period of study
T_m	monthly period of study
DR	demand response
IBDR	incentive based demand response
LSEs	load serving entities
M	total number of time that IBDR implement
OPT	off peak time
PBDR	price based demand response
PT	peak time
TOU	time of use DR program
WECC	Western Electricity Coordinating Council

Each category of DR has its own benefits and takes advantage of different aspects of the potential for flexible demand. In this paper, both categories of DR measures are modeled based on the demand-price elasticity concept to design an optimum scheme for realizing the maximum potential of DR benefit. The main objective is to reduce costs and improve reliability. In addition, we suggest high price volatility negatively impacts both residential customer satisfaction and may be indicative of overall system stress. Thus, DR can be used both to mitigate price volatility and reduce overall costs.

It has been shown that customers' attitudes toward PB and IBDR programs are not similar. From the perspective of human behavior, there are two main reinforcement conditions: reward and punishment, which lead to some significant changes in the subject's behavior [11,12]. Psychologists mainly believe, in most societies, the reward may cause more considerable improvement for habit development relative to punishment [13,14]. In this paper, a different elasticity value is considered for each DR program to emphasize this variable response from customers. IBDR as a reward-based system should lead to higher elasticity. Note that the DR discussed in this paper is more related to small customers who cannot participate in a wholesale market directly. As will be detailed in Section 3.2, customers in this study are divided into three groups: small commercial, small industrial and residential.

Price volatility over a period of time reflects the uncertainty of prices. Power markets, especially in terms of hourly prices and peak loads, are often volatile. Several elements lead to price volatility or price spikes [15]. Price spikes may occur when the demand side has no response to electricity prices so generators completely determine price, e.g., when the market lacks sufficient competition to constrain GenCo bids. In addition, price spikes might occur when generation reserves are lower during peak demand hours. To compensate for generation shortages at peak hours, generators with high marginal costs must supply peak demands, which results in a significant under-utilization of such generators at off-peak periods [16]. In some cases, electricity prices can vary by several multiples, e.g., from less than $20 per MWh to several hundred dollars per MWh [17].

In a competitive electricity market where all generators are paid the market clearing price (MCP) under a uniform price auction structure, even a small reduction in demand can result in considerable reduction in the system marginal costs of production [18]. Although these peak price events may be short in duration, they still add significantly to the average cost per kWh for a consumer. Allowing DR in a constrained electricity grid can significantly lower these peak energy costs and potentially act as a check against the exercise of market power by GenCos [19,20].

2. Literature review

There is extensive literature on PBDR. Jia et al. [21] propose an application of on-line learning theory tailored to the problem of pricing for retail load customers who participate in a demand response program. This work considers thermal dynamic loads for which electricity is consumed to maintain the temperature near preferred comfort settings. In [22], an optimum time-of-use pricing scheme for use in monopoly utility markets is developed. The optimal pricing strategy maximizes the societal benefit. Vivekananthan et al. [23] propose an improved real time pricing scheme for residential customers using smart meters and in-home display units to broadcast the price and appropriate load adjustment signals. Application of this program manages overloading problems and voltage issues and ensures both customers and utility benefit from this scheme. In [24], a novel demand response program for optimizing power systems electric vehicle charging load is introduced. A demand response program which includes multiple tariffs for different groups of customers is proposed. Three scenarios are considered, i.e., standard tariff, single-tariff and multi-tariff programs. The results show that a multi-tariff program could help utilities reduce daily cost by 1.5% and help customers reduce electricity bills by 7% compared to the standard tariff. Kamyab et al. [25] used the idea of transferring market price via smart meter in smart grid to design PBDR program for residential customers. They address the interaction among multiple utility companies and multiple customers in smart grid by modeling the DR problem as two non cooperative games: the supplier and customer side games.

The literature on IBDR is also extensive. Research by Yu et al. focused on the price elasticity of electricity demand where the loads are managed using energy management controller units (EMC). The purpose of the study is to maximize benefit of users by considering both load and the corresponding real time electricity prices in the wholesale market [26]. The main goal of research conducted by Pagliuca et al. is to present a new approach to modeling flexible loads to understand the potential of residential demand response. The selected demand response option is based on interruptions of appliances for short periods [27]. Mallette and Venkataramanan