Electrical Power and Energy Systems 65 (2015) 282–290

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Evaluation of nonlinear models for time-based rates demand response programs

H.A. Aalami [a,*], M. Parsa Moghaddam [b], G.R. Yousefi [c]

[a] Department of Electrical Engineering, Imam Hussein University, Tehran, Iran
[b] Faculty of Electrical & Computer Engineering, Tarbiat Modares University, Tehran, Iran
[c] Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran

ARTICLE INFO

Article history:
Received 1 August 2013
Received in revised form 16 September 2014
Accepted 10 October 2014

Keywords:
Demand response
Elasticity
Nonlinear models
TOU

ABSTRACT

Demand Response (DR) programs have been implemented in many competitive electricity markets to prevent price spikes and power systems unreliability. Mathematical modeling of these programs helps regulators to evaluate the impact of price responsive loads on market conditions. In this paper, several nonlinear economic models of price responsive loads are derived based on price elasticity of demand and customer benefit function. The main objectives of the paper include extracting different mathematical models for Time of Use (TOU) programs, and comparing these models to find out which model shows more conservative and which one shows non-conservative results compared with the initial load curve. This could be used by ISOs or DR programs developers as a guideline to use conservative models to have lower error in load profile characteristics estimation, such as variation in peak load or amount of energy consumptions. In order to evaluate the performance of the proposed nonlinear DR models, numerical studies are conducted on the load curve of different markets. Results obtained by using different models are presented and compared considering different scenarios for price, elasticity and potentiality of DR programs implementation. Characteristics of both linear and nonlinear economic models of price responsive loads have been evaluated.

Introduction

Over the last two decades, electricity markets have been involved in restructuring aimed at promoting competition among market participants. One typical market design often requires electricity to be sold in a spot wholesale market where potential buyers (retailers or end consumers) and sellers (producers) submit their bids for each time period. The demand and the supply sides meet in the electricity power exchanges. The resulting auction yields the equilibrium prices, which vary over time and space, considering network constraints and supply/demand balance. However, a common feature of the electricity wholesale markets is lack of price responsiveness measured by the value of demand elasticity [1]. This is due not only to the peculiar characteristics of the commodity, such as non-storability, lack of good substitutes, and the relatively small impact of electricity bill on the typical consumer's budget, but also to the relation between wholesale and retail markets. Since end users simply do not see the "true" spot prices, they cannot use these prices when making decisions regarding power withdrawal; this "inelastic" behavior is transmitted to retailers, who have legal obligations to serve their customers and therefore to the wholesale demand. Furthermore, the overwhelming lack of interest from consumers in seeing the real price of electricity makes it politically difficult to implement demand elasticity improvement measures [2].

In these circumstances, Demand Response (DR) programs are such useful tools for the independent system operator (ISO) that can be implemented at times of critical system conditions to provide the much needed system demand reduction and an operating reserve that can be activated within a relatively short time. The idea is to make it attractive for customers to use less power during periods of peak load [3]. In a DR program, the customer signs a contract with the retailer, local utility or the ISO to reduce its demand as and when requested. The utility benefits from reduction of its peak load and thereby saving costly generation reserves, restoring quality of service and ensuring reliability [4,5]. The customer benefits from reduction in its various energy levels, costs and particularly from incentives provided by the local utility or the ISO. Utilities typically commit their expected energy requirements with a mix of bilateral forward contracts with generators and purchases

* Corresponding author. Tel.: +98 21 77104901; fax: +98 21 77104907.
E-mail addresses: halami@ihu.ac.ir (H.A. Aalami), parsa@modares.ac.ir (M. Parsa Moghaddam), yousefi@cc.iut.ac.ir (G.R. Yousefi).

http://dx.doi.org/10.1016/j.ijepes.2014.10.021
0142-0615/

Nomenclature

i	For i hour	E	Price elasticity of demand
j	For j hour	$E(i,i)$	Self-elasticity
$B_0(i)$	Customer's benefit when the demand is equal to The nominal value $d_0(i)$ ($)	$E(i,j)$	Cross-elasticity
$B(d(i))$	Customer's benefit in i-th hour ($)	ρ_0	Initial electricity price ($/kW)
d_0	Initial demand value (kW)	$\rho_0(i)$	Initial electricity price in i-th hour ($/kW h)
$d_0(i)$	Initial demand value in i-th hour (kW h)	ρ	Spot electricity price ($/kW)
d	Customer demand (kW)	$\rho(i)$	Spot electricity price in i-th hour ($/kW h)
$d(i)$	Customer demand in i-th hour (kW h)	S	Customer's profit ($)

in day-ahead and real-time markets. The extent of customer savings from price reductions thus depends on how much energy is purchased in spot markets [6].

The programs are usually structured into one of two categories: Incentive-Based Programs (IBP) and Time-Based rate Programs (TBR). Each of these categories is composed of several programs as indicated in Fig. 1. In time-based rate programs (Time of Use (TOU), Real Time Pricing (RTP), Critical Peak Pricing (CPP)) the electricity price changes for different periods. Incentive-based programs include Direct Load Control (DLC), Emergency Demand Response Program (EDRP), Interruptible/Curtailable service (I/C), Capacity market Program (CAP), Demand Bidding (DB) and Ancillary Service (A/S) programs. More detailed explanations of DR programs can be found in [7–10]. In this paper, we have focused on TOU program which is briefly introduced in the following.

In TOU program, the electricity price changes over different periods according to the electricity supply cost. For example, high price for peak period, medium price for off-peak and low-price for low load period, and there isn't any incentive or penalty for this program. Definition of TOU periods differs widely among utilities based on the timing of their peak system demands over the day, week, or year [3]. In order to evaluate the impact of DR programs on the network and market characteristics such as load profile, transmission congestion and reserve margin , developing price responsive demand models is necessary. Obviously, there are many possible structural forms for customer response. Linear economic models of price responsive loads for DR programs have been developed in [1,11–16]. Since the optimization problem of the customer profit is nonlinear, it is necessary to develop nonlinear economic models of price responsive loads for more realistic characterization of the demand. Maximization of the utility benefit function problem by using different nonlinear benefit-demand functions has

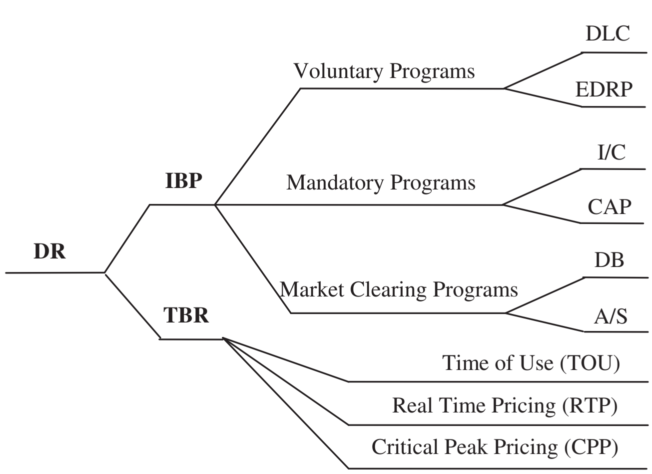

Fig. 1. Categories of demand response programs.

been discussed in [17,18]. In [19], a retailer profit is maximized through using a nonlinear load model with power structure.

In this paper, three nonlinear structures namely; power, exponential and logarithmic economic models of price responsive loads for DR programs are extracted by using the concept of "price elasticity of demand", and "customer benefit function". These models are compared with linear ones to determine the accuracy and consistency with operational strategies. The proposed models can be used to analyze the impact of DR programs on load profile characteristics.

The main contribution of this paper includes extracting different mathematical models for TOU programs, and comparing these models to find out which model shows more conservative and which one shows non-conservative results compared with the initial load curve. This could be used by ISOs or DR programs developers as a guideline to use conservative models to have lower error in load profile characteristics estimation, such as variation in peak load or the amount of energy consumptions. Therefore, they would have a better and more realistic insight in power systems and market operation and in performing related tasks, such as reserve procurement. Furthermore, as another contribution, a procedure is introduced for the selection of the more reliable load economic model for analyzing the impact of implementation of DR programs on power system characteristics. It should be noted that linear model of demand response programs have been discussed in previous works of the authors Refs. [11–13] but, in this study various nonlinear models are developed. Furthermore, in this manuscript the results of the developed nonlinear models have been compared with linear model of previous works.

The remainder of the paper is organized as follows: In Section 'Nonlinear modeling of DR programs', nonlinear models of DR programs are derived. Section 'Numerical studies' is devoted for numerical studies considering different scenarios for price, elasticity and program potentiality for evaluation of proposed nonlinear models of DR programs. Furthermore, sensitivity analysis of models to change price, elasticity and program potentiality has been done by standard deviation. Finally, Section 'Conclusions' concludes the paper.

Nonlinear modeling of DR programs

In order to model the customer response, we consider customer demand for electricity $d(i)$ and assume that it depends on price or tariff that consumer must pay for electricity, $\rho(i)$. Obviously, there are many possible structural forms for customer response. In this paper three such structures namely; power, exponential and logarithmic nonlinear models for customer response are derived. It is important to note that a second-order Taylor Series expansion of the power, exponential and logarithmic benefit functions $B(d(i))$ about $d(i) = d_0(i)$ yields the quadratic income function, and a first-order Taylor Series expansion of the response function $d(i)$ resulting from the power, exponential and logarithmic functions