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Exponential Modeling Evaluation of Time-of-use Demand Response Programs in Restructured Power Markets

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Abstract: In this study an exponential modeling of Time-of-use programs (TOU) as most Prevalent Priced-based Demand Response Programs (DRPs) is presented. In this way, nonlinear behavioral characteristic of elastic loads is considered which causes to more realistic modeling of demand response to TOU rates. In order to evaluation of proposed model, the impact of running TOU programs using proposed exponential model on load profile of the peak day of the Iranian power system in 2007 is investigated.

Key words: Demand response programs, elasticity, time-of-use programs

INTRODUCTION

According to the U.S. Department of Energy (DOE) report, the definition of Demand Response (DR) is: "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" (US Department of Energy, 2006).

According to DOE classification, demand response programs (DRPs) are divided into two categories as shown in Fig. 1.

Time-of-use programs (TOU) are the most prevalent priced-based programs. Most customers are exposed to some form of TOU rates, if only with rates that vary by six-month seasons. For instance, a summer-peaking utility may charge a higher rate for the energy use part of a bill than for the same amount of electricity consumed during the off-peak six months. This is a seasonal (time-varying) rate. More sensitive time-of-use rates establish two or more daily periods that reflects hours when the system load is higher (peak) or lower (off-peak), and charge a higher rate during peak hours. The definition of TOU periods differs widely among utilities, based on the timing of their peak system demands over the day, week, or year. TOU rates sometimes have only two prices, for peak and off-peak periods, while other tariffs include a shoulder period or partial-peak rate (FERC report, 2006; FERC report, 2008).

In (Goel *et al*., 2008; Faruqui and George, 2005; Aalami *et al*., 2006; Aalami *et al*., 2010; Schweppe *et al*., 1988; Schweppe *et al*., 1985) a linear economic model for DRPs have been developed. This simple and widely used model is based on an assumption in which demand will change linearly in respect to the elasticity. The outstanding researches considering the use of linear model of responsive demand have been presented and analyzed in (Schweppe *et al*., 1988; Schweppe *et al*., 1985). However, those models do not consider nonlinear behavior of the demand which is of great importance in analyzing and yielding the results.

In this study, an exponential model to describe price dependent loads is developed such that the characteristics of TOU programs can be imitated.

Elasticity definition: Generally, electricity consumption like most other commodities, to some extent, is price sensitive. This means when the total rate of electricity decreases, the consumers will have more incentives to increase the demand. This concept is shown in Fig. 2, as the demand curve.

Hachured area in fact shows the customer marginal benefit from the use of MWh of electrical energy. This is represented mathematically by:

$$B(d) = \int_0^d \rho(d).\partial d \tag{1}$$

Based on economics theory, the demand-price elasticity can be defined as follows:

$$e = \frac{\Delta d / d}{\Delta \rho / \rho^0} \tag{2}$$

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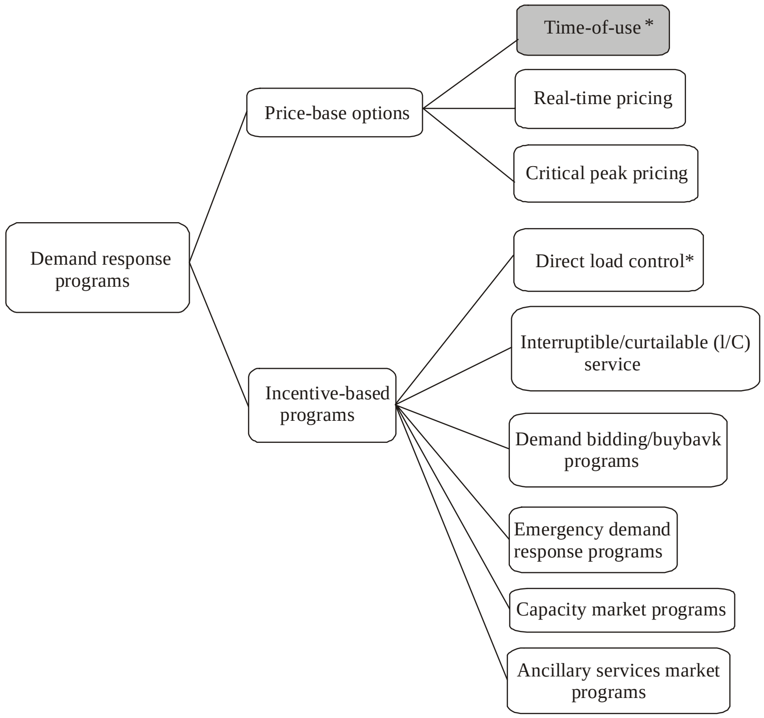

Fig. 1: Demand response programs (*Highlighted program has been considered in this study)

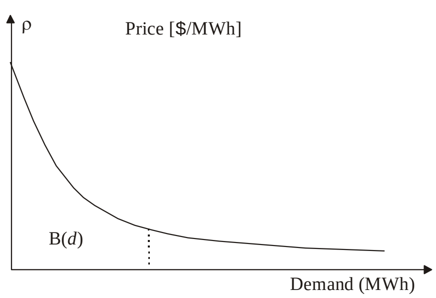

Fig. 2: Demand curve

For time varying loads, for which the electricity consumption vary during different periods, cross-time elasticity should also be considered. Cross-time elasticity, which is represented by cross-time coefficients, relates the effect of price change at one point in time to consumption at other time periods. The self-elasticity coefficient, e_{tt} , (with negative value), which shows the effect of price change in time period *t* on load of the same time period and the cross-elasticity coefficient, e_{tt} ,(with positive value) which relates relative changes in consumption during time period *t* to the price relative changes during time period t are defined by following relations:

$$e_{tt} = \frac{\partial d_t / d_t}{\partial \rho_t / \rho_t^0} \tag{3}$$

$$ett = \frac{\partial d_t / d_t}{\partial \rho_t / \rho_t^0} \tag{4}$$

Exponential modeling of elastic loads: The proper offered rates can motivate the participated customers to revise their consumption pattern from the initial value d^0_t to a modified level d_t in period t.

$$\Delta d_t = d_t - d_t^0 \tag{5}$$

It is reasonable to assume that customers will always choose a level of demand d_t to maximize their total benefits which are difference between incomes from consuming electricity and incurred costs; i.e., to maximize the cost function given below:

$$B\,[d_t] - d_t \cdot \rho_t \tag{6}$$

The necessary condition to realize the mentioned objective is to have:

$$\frac{\partial B[d_t]}{\partial d_t} - \rho_t = 0 \tag{7}$$

Thus moving the last term to the right side of the equality,

$$\frac{\partial B[d_t]}{\partial d_t} = \rho_t \tag{8}$$

Substituting (8) to (3) and (4), a general relation based on self and cross elasticity coefficients is obtained for each time period t as follows:

$$\frac{\partial d_t}{d_t} = e_{tt'} \frac{\partial \rho t'}{\rho_{t'}^0} \tag{9}$$

By assuming constant elasticity for NT-hours period, ett=constant for t,t E NT integration of each term, we obtain the following relationship.

$$\int_{d_t^0}^{dt} \frac{\partial d_t}{d_t} = \sum_{t=1}^{NT} \left\{ e_{tt'} \left[\int_{\rho_{t'}^0}^{\rho_t} \frac{\partial \rho_{t'}}{\rho_{t'}^0} \right] \right\} \tag{10}$$

Combining the costumer optimum behavior that leads to (8), (9) with (10) yields the exponential model of elastic loads, as follows:

$$d_t = d_t^0 \prod_{t=1}^{NT} \exp\left[e_{tt'} \cdot \frac{(\rho_{t'} - \rho_{t'}^0)}{\rho_{t'}^0} \right] \tag{11}$$

Parameter is demand response potential which can be entered to model as follows:

$$d_t = d_t^0 \eta d_t^0 \left\{ \prod_{t=1}^{NT} \exp\left[e_{tt'} \cdot \frac{(\rho_{t'} - \rho_{t'}^0)}{\rho_{t'}^0} \right] - 1 \right\} \tag{12}$$

The larger value of η means the more customers' tendency to reduce or shift consumption from peak hours to the other hours.

SIMULATION RESULTS

In this section numerical study for evaluation of proposed model of TOU programs are presented. For this purpose the peak load curve of the Iranian power grid on 28/08/2007(annual peak load), has been used for our simulation studies. Also the electricity price in Iran in 2007 was 150 Rials. This load curve, shown in Fig. 3, divided into three different periods, namely valley period (00:00 am-9:00 am), off-peak period (9:00 am-7:00 pm) and peak period (7:00 pm-12:00 pm).

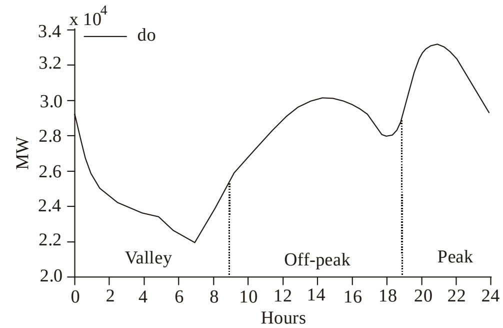

Fig. 3: Initial load profile

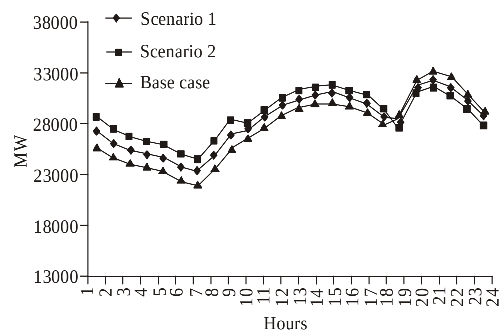

Fig. 4: The impact of adopting scenarios 1 and 2 on load profile

Table 1: self and cross elasticities

	Low	Off-Peak	Peak
Low	- 0.10	0.010	0.012
Off-Peak	0.010	- 0. 10	0.016
Peak	0.012	0.016	- 0. 10

The selected values for the self and cross elasticities have been shown in Table 1.

Two scenarios are considered as Table 2.

The impact of adopting scenarios 1 and 2 on load profiles have been shown all together in Fig. 4. As seen, the load of peak periods is reduced and shifted to other periods. Hence, the load of low and off-peak periods is increased. By increasing the value of demand response potential according to scenario 1 and 2, the peak reduction and load shifting are increased.

Technical characteristics of the load profile in scenario 1 and 2 have been given in Table 3. It is seen that the technical characteristics such as peak reduction, load factor have been improved by adopting scenario 1 and more in scenario 2 while daily energy change is positive. Also the values of peak to valley are improved.

According to data reported in Table 4 which are economical characteristics of the load profile in scenario 1 and 2, running TOU program is profitable for participated customers. Also by increasing demand response potential customers' profit is increased and it leads to more satisfaction of customers to participate in TOU program.

Table 2: The considered scenarios

Scenario no.	TOU rates (Rials/MWh)	Demand response potential (%)
1	20, 80, 300 at valley, off peak and peak periods respectively	5
2	20, 80, 300 at valley, off peak and peak periods respectively	10

Table 3: Technical characteristics of the load profile in scenarios 1 and 2 in comparison with the base case

	Energy (MWh)	Energy change (%)	Peak (MW)	Peak reduction (%)	load factor	Load factor improvement (%)	Peak to valley (MW)
Base Case	662268	0	33286	0	0.8290	0	11318
Scenario 1	676962.3657	2.2	32403.2	2.7	0.8705	5.0	9161.3
Scenario 2	691656.7313	4.4	31851.1	4.3	0.9048	9.1	7335.3

Table 4: Economical characteristics of the load profile in scenarios 1 and 2 in comparison with the base case

	Bill in scenario 1 (Rials/Day)	Bill reduction (Profit) (%)
Base case	99340200	0
Scenario 1	82333410.8	17.1
Scenario 2	81755901.6	17.7

CONCLUSION

In this study, an exponential model of demand response program has been introduced. It has been shown that this model could imitate customers' response to TOU program as prevalent DRPs. This model can help sponsor's TOU programs to simulate the behavior of customers for the purpose of improvement of load profile characteristics as well as satisfaction of customers.

NOMENCLATURE

- 0 Initial state index (Superscript)
- t,t' Time period indices (subscript)
- NT Number of hours within period of study
- d Load (MW)
- ρ Price (Rials/MWh)
- Δd Demand change (MW)Demand change (MW)
- $\Delta\rho$ Price change Price change (Rials/MWh)
- $B[d_t]$ Benefit of consumer at time period *t by* consuming d_t
- e_{tt} Self elasticity
- $e_{tt'}$ Cross elasticity
- η Demand response potential (%)

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