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## Uncertain Interruptible/Curtailable Services in Electricity Markets.

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### ABSTRACT

The focus of this paper is to model the interruptible/curtailable (I/C) services as the most prevalent priced-based DRPs with consideration of uncertainty. To achieve this goal, nonlinear behavioral characteristics of the elastic loads is considered which causes to more realistic modeling of demand response to I/C. In addition, elasticity uncertainty is applied in the proposed model through the normal distribution probability function. In order to evaluation of proposed model, the impact of running TOU programs on load profile of the peak day of the Iranian power system in 2007 is investigated. The results show the behavior of responsive demands to I/C option.

**Keywords:** Demand Response programs, Elasticity, Interruptible/curtailable services.

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## INTRODUCTION

Firm electricity services, also called uninterruptible services, are services that are intended to be available at all times during a period covered by an agreement. Also, the service is not subject to a prior claim from another customer and receives the same priority as any other firm service. Conditional firm service is similar to firm service in that it is reserved and has priority over interruptible service. However, it can have restrictions, such as times when it would be curtailed before firm service but after interruptible service. The cost per unit with this service is called a firm rate or uninterruptible rate. The opposite of firm service is non-firm service, also called interruptible service or as-available service. The cost per unit for this service is called a non-firm rate or interruptible rate. The interruptible load is the portion of a utility's load that comes from customers with interruptible service.

In this paper, we focus on Interruptible/curtailable services (I/C). I/C service integrated into retail tariffs that provide a rate discount or bill credit for agreeing to reduce load during system contingencies. Penalties maybe assessed for failure to curtail. Interruptible programs have traditionally been offered only to the largest industrial (or commercial) customers [1, 2].

Many researchers have modeled responsive load simply based on elasticity definition and they have not consider a very important issue as uncertainty in their model [3-6]. The previous models have two main defects. First the models are linear that could say customer behavior is not linear and could be more complicated than linear behavior in many real situations, and second is about demand elasticity which has modeled as a fixed value while there is some extent uncertainty in forecasted elasticity of demand. These problem have been solved in this paper because they could help the model becomes more realistic.

In this paper, a power model to describe price dependent loads is developed such that the characteristics of I/C programs can be imitated. The remaining parts of the paper are organized as following: the definition of elasticity is reviewed in section 2. Section 3 is about elasticity uncertainty. Power modeling of DR based on the concept of price elasticity of demand is developed in section 4. Section 5 is devoted to simulation results where the impact of I/C programs via proposed exponential model on load profile of the peak day of the Iranian power system in 2007 is investigated. Finally, the paper is concluded in section 5.

### 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. The customer marginal benefit from the use of  $d$  MWh of electrical energy is represented mathematically by:

$$B(d) = \int_0^d \rho(d) \cdot \partial d \quad (1)$$

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

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

For time varying loads, for which the electricity consumptions 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 consumptions 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,  $e_{t\hat{t}}$ , (with positive value) which relates relative changes in consumption during time period  $t$  to the price relative changes during time period  $\hat{t}$  are defined by following relations:

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

$$e_{t\hat{t}} = \frac{\partial d_t / d_t}{\partial \rho_{\hat{t}} / \rho_{\hat{t}}} \tag{4}$$

### Elasticity uncertainty

The expression for the probability density function of a normal distribution is always written as

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x - \mu)^2}{2\sigma^2}\right] \tag{5}$$

Where  $\mu$  is mean value and  $\sigma$  is standard deviation.

Typical normal density function curves are shown in Figure 1 for a given value of  $\mu$  and three values of  $\sigma$ . Similarly since the value of  $\sigma$  determines the amount of spread or dispersion and therefore the shape of the curve, it is referred to as the scale parameter.

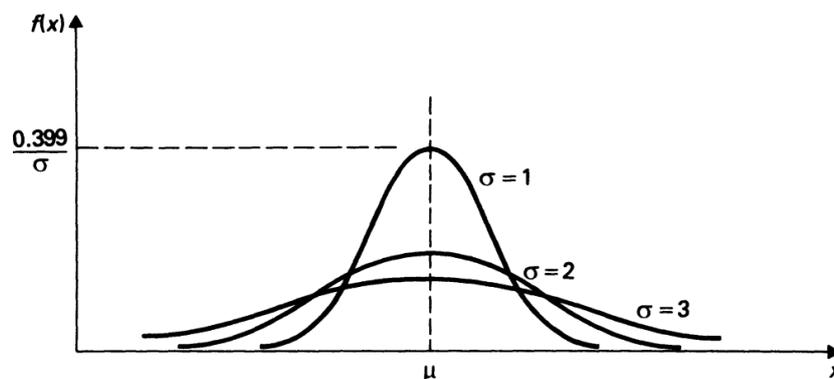


Figure 1: Normal density functions for three values of  $\sigma$  .

It is extremely difficult to obtain sufficient historical data to determine the distribution describing the elasticity coefficient uncertainty. Published data, however, has suggested that the uncertainty can be reasonably described by a normal distribution. The distribution mean is the forecasted elasticity coefficient. The distribution can be divided into a discrete number of class intervals. The elasticity representing the class interval mid-point is assigned the designated probability for that class interval. This is shown in Figure 2, where the distribution is divided into seven steps. A similar approach can be used to represent a non symmetrical distribution if required. It has been found that there is little difference in the end result between representing the distribution of elasticity coefficient uncertainty by seven steps or forty-nine steps. Here, we consider eleven intervals because our simulation showed that considering higher step numbers have no effect on the end result.

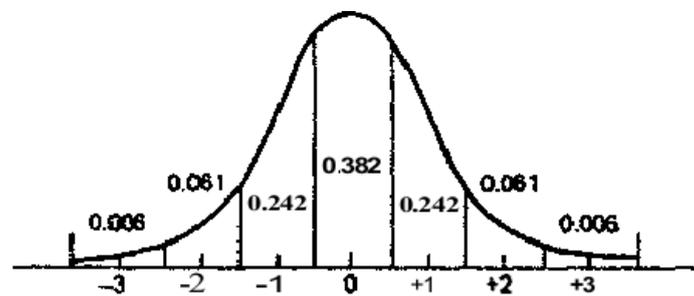


Figure 2: Seven-step approximation of the normal distribution

### Power modeling of elastic loads

The proper offered rates can motivate the participated customers to revise their consumption pattern from the initial value  $d_t^0$  to a modified level  $d_t$  in period t.

$$\Delta d_t = d_t - d_t^0 \tag{6}$$

I/C programs are included penalty terms for those enrolled customers who do not respond. Regarding the level of contract,  $L_t$  and penalty rate  $pen_t$  in time t, the total penalty which enrolled customers must pay is:

$$PEN(\Delta d_t) = pen_t \times (L_t + \Delta d_t) \tag{7}$$

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:

$$B[d_t] - d_t \cdot \rho_t - PEN(\Delta d_t) \tag{8}$$

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

$$\frac{\partial B[d_t]}{\partial d_t} - \rho_t - \frac{\partial PEN(\Delta d_t)}{\partial d_t} = 0 \tag{9}$$

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

$$\frac{\partial B[d_t]}{\partial d_t} = \rho_t + pen_t \quad (10)$$

Substituting (9) to (3) and (4), a general relation based on self and cross elasticity coefficients is obtained for each time period  $t$  as follows:

$$\frac{\partial d_t}{d_t} = e_{tt} \frac{\partial(\rho_t + pen_t)}{\rho_t + pen_t} \quad (11)$$

By assuming constant elasticity for NT-hours period,  $e_{tt} = \text{Constant}$  for  $\forall t, t \in NT$  integration of each term, we obtain the following relationship.

$$\int_{d_t^0}^{d_t} \frac{\partial d_t}{d_t} = \sum_{t=1}^{NT} \left\{ e_{tt} \left[ \int_{\rho_t^0}^{\rho_t} \frac{\partial \rho_t}{\rho_t + pen_t} + \int_0^{pen_t} \frac{\partial pen_t}{\rho_t + pen_t} \right] \right\} \quad (12)$$

Combining the customer optimum behavior that leads to (9), (10) with (11) yields the power model of elastic loads, as follows:

$$d_t = d_t^0 \prod_{t=1}^{NT} \left[ \frac{(\rho_t + pen_t)^2}{\rho_t(\rho_t^0 + pen_t)} \right]^{e_{tt}} \quad (13)$$

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

$$d_t = d_t^0 + \eta d_t^0 \left\{ \prod_{t=1}^{NT} \left[ \frac{(\rho_t + pen_t)^2}{\rho_t(\rho_t^0 + pen_t)} \right]^{e_{tt}} - 1 \right\} \quad (14)$$

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

Elasticity uncertainty based on details explained in the previous section could be considered in the equation number (14) as follow:

$$d_t = \sum_{i=1}^{ND} \left[ prob_i \left( d_t^0 + \eta d_t^0 \left( \prod_{t=1}^{NT} \left[ \frac{(\rho_t + pen_t)^2}{\rho_t(\rho_t^0 + pen_t)} \right]^{e_{tt,i}} - 1 \right) \right) \right] \quad (15)$$

Where  $ND$  is the number of class intervals,  $prob_i$  is probability of class interval  $i^{th}$  and  $e_{tt,i}$  is mid-point of class interval  $i^{th}$ .

## Simulation results

In this section numerical study for evaluation of proposed model of EDRP 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 [7]. Also the electricity price in Iran in 2007 was 150 Rials (Unit in Iranian Currency). This load curve, shown in figure 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).

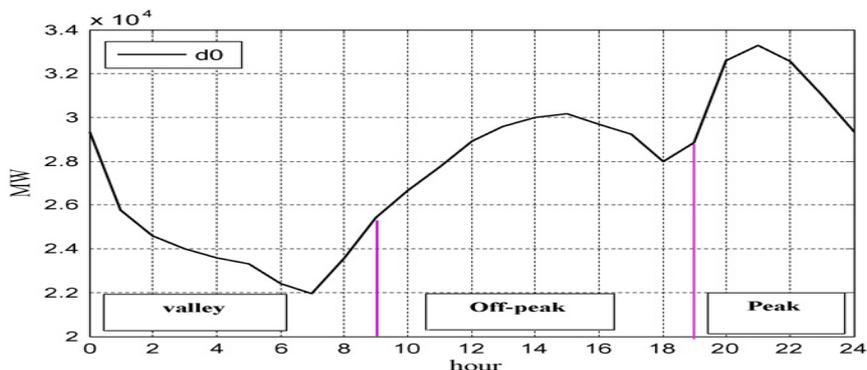


Figure 3: Initial load profile

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

Table 1: self and cross elasticities

	Low	Off-peak	Peak
Low	-0.10	0.014	0.016
Off-peak	0.014	-0.10	0.012
Peak	0.016	0.012	-0.10

Different scenarios are considered according to Table 2.

Table 2: The considered scenarios

Scenario number	I/C rates (Rials/MWh)	Penalty rate in peak periods (Rials/MWh)	Demand reduction level of contract (in peak periods)	Demand response potential (%)
1	Flat 160	200	40%	10%
2	Flat 160	200	40%	20%
3	Flat 160	200	40%	30%

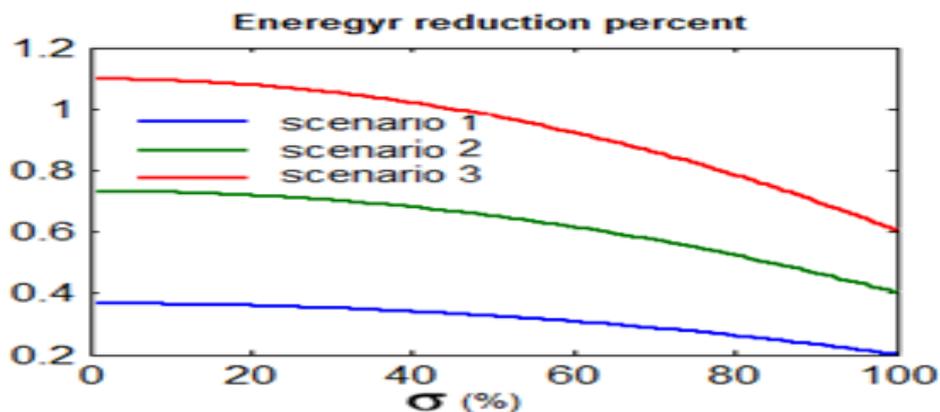


Figure 4: Energy reduction (%) in different scenarios

Figure 4 depicts the percent of energy reduction in different scenarios. Scenario 3 has the highest energy reduction effect and after that scenario 2 and 1 have located, respectively. This can be concluded that when demand response potential grows up in electricity markets we can expect more reduction of electrical energy consumption. Another

thing that could be concluded from the figure is that increasing  $\sigma$  which demonstrates higher uncertainty, leads to more energy increasing.

Figure 5 shows energy shifting (in percent) in different scenarios. The order of priority for different scenarios is the same as the former. Increasing demand response potential could increase energy shifting. Keep in mind that increasing  $\sigma$  has a slight increasing effect on energy shifting.

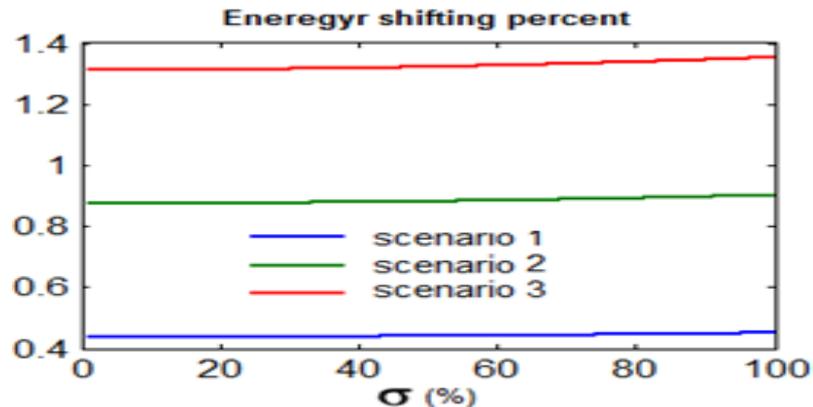


Figure 5: Energy shifting (%) in different scenarios

Figure 6 shows peak reduction (in percent) in different scenarios. The order of priority for different scenarios is the same as the former. Increasing demand response potential makes this effect weaker.

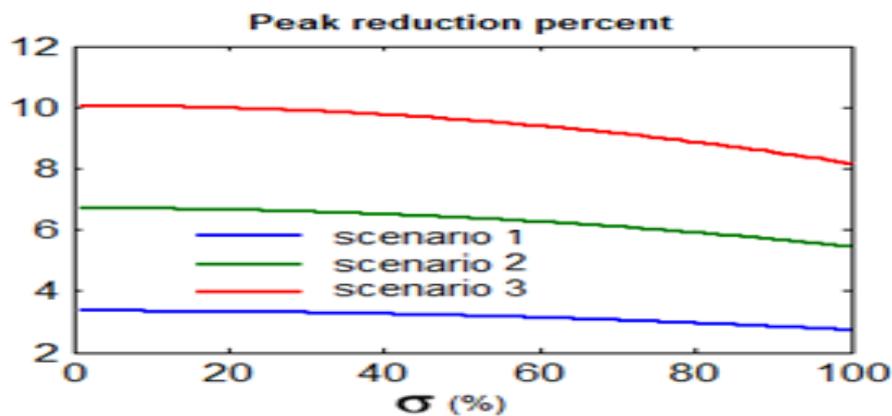


Figure 6: Peak reduction (%) in different scenarios

Figure 7 shows scenario priority from load factor improvement aspect. As seen, scenario 3 has the highest priority and after that scenario 2 and 1 have located, respectively. As seen, in scenario 1, increasing uncertainty through increasing  $\sigma$  leads to a bad result which is load factor decreasing, in scenario 2, we achieve to lower load factor when  $\sigma$  increases, and in scenario 3 we have increasing trend of load factor during increasing  $\sigma$ .

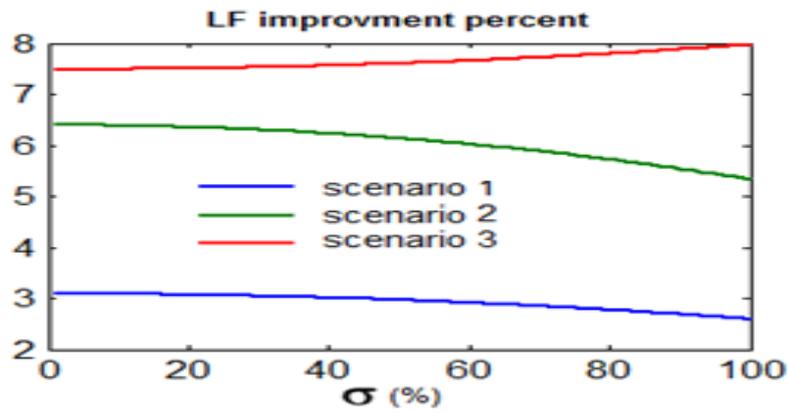


Figure 7: Load factor improvement (%) in different scenarios

Figure 8 shows economical aspect as bill reduction (%) in different scenarios. Scenario 3 has the highest energy reduction effect and after that scenario 2 and 1 have located, respectively. This can be concluded that when demand response potential grows up in electricity markets we can expect the more bill reduction and this could more satisfy customers.

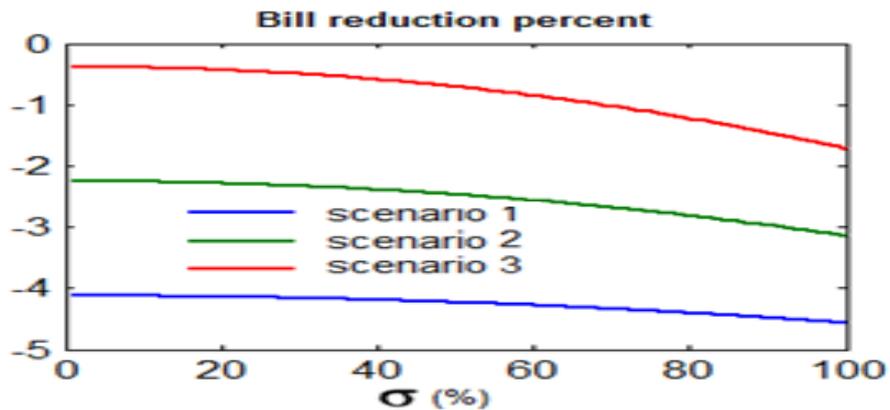


Figure 8: Bill reduction (%) in different scenarios

### CONCLUSION

The effect of considering unreliable elasticity in demand response modeling based on power model has investigated in this paper. The propose model could simulate the customers' response to I/C program. This model can help sponsor's I/C programs to simulate the behavior of customers for the purpose of improvement of load profile characteristics as well as satisfaction of customers. The studies were carried out on Iranian power system. Validate of the proposed technique showed by many simulation results.

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## Nomenclature

0	Initial state index (Superscript)
$t, \hat{t}$	Time period indices (subscript)
ND	Number of class intervals of normal density function
NT	Number of hours within period of study
d	Load (MW)
$\rho$	Price (Rials/MWh)
$\Delta d$	Demand change (MW)
$\Delta \rho$	Price change ( Rials/MWh)
$B[d_t]$	Benefit of consumer at time period $t$ by consuming $d_t$
$e_{tt}$	Self elasticity
$e_{t\hat{t}}$	Cross elasticity
$e_{tt,i}$	Self elasticity in interval class $i^{th}$
$e_{t\hat{t},i}$	Cross elasticity in interval class $i^{th}$
$prob_i$	Probability of class interval $i^{th}$
$pen_t$	Penalty rate in period t
$\eta$	Demand response potential (%)

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