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Modeling the Effects of Probabilistic Participation of Domestic and Industrial Customers' in the Time-of-Use Pricing and Interruptible Load Programs

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Abstract-Nowadays, demand response programs have gained importance due to their purpose of improving the operation of power systems. Demand response programs are divided into two main categories of incentive-based and price-based programs. The purpose of this paper is to model and analyze two practical and substantial demand response programs that correspond to the two types of customers in the distribution system. In this regard, the interruptible load program is intended for the industrial customers and the time-of-use (TOU) pricing program is intended for the domestic customers. The interruptible load program is a reward-based program specific to peak hours; while the time-of-use pricing program is based on three price tariffs throughout the day. An efficient model based on the information of customer price elasticity is used to analyze the customers' response. Moreover, the level of customers' participation is taken into account in each program using two parameters; and the effects of their probabilistic participation are evaluated in three different simulation cases. In order to analyze the proposed method, a case study is considered and the evaluation indices of the load curve are calculated and analyzed after executing the programs. The simulation results clearly indicate the efficiency of the proposed method.

Keywords- *Demand Response, Interruptible Load, Time-of-Use Pricing, Load Factor, Price Elasticity*

SYMBOLS

Δd : Energy changes (kWh)
$\Delta\rho$: Price changes (rial)
n, m : Time periods
E : Elasticity
$E(i,i)$: Self elasticity
$E(i,j)$: Cross elasticity
$d_0^{domestic}$: Initial domestic load
$d_0^{industrial}$: Initial industrial load
γ : Share of domestic loads from the total load
d_0^{total} : Total initial load
dr : Load consumption after the execution of each DR program
α_{TOU} : Participation factor of the domestic customer in the TOU program
α_{IL} : Participation factor of the industrial customer in the IL program
d^{after_DR} : Total load consumption after the execution of the two DR programs
$\rho(i)$: Spot electricity price (rial/kWh)
$\rho_0(i)$: Initial electricity price (rial/kWh)
β : Weight factor for reward and penalty
$A(i)$: The value of reward (rial/kWh)
$pen(i)$: The value of penalty (rial/kWh)
LF : Load factor
T : Studied time period

I. INTRODUCTION

Demand response program provides the basis of the customers' active presence in improving the performance of the power system operation. These programs can provide the demand reduction required by the system in a relatively short time period in critical conditions. According to the definition presented by the Federal Energy Regulatory Commission (FERC) of the United States, demand response is the ability of the industrial, commercial and residential customers to improve the consumption pattern of electric energy in order to achieve adequate prices and enhance system reliability. In other words, demand response can be defined as the changes made by customers in power consumption from their normal consumption pattern in response to the changes made in the price of power over time [1]. In general, demand response occurs in one of two ways based on the state of the consumers' participation:

- Price-based demand response programs
- Incentive-based demand response programs

Fig. 1 plots the types of programs in each category.

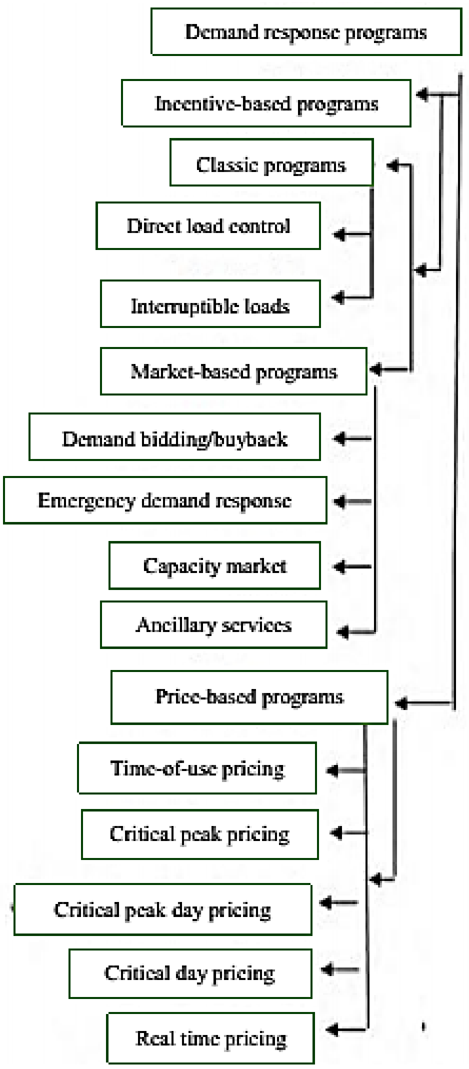

Figure 1. The categorization of demand response programs

A. *Time-of-Use (TOU) Pricing Progarm*

In TOU program, the selling price of electric energy in each period is dependent on the cost of production in that period. Therefore, the prices are low in low-load hours, medium in medium-load hours, and high at the time of peak. Executing this program leads the customers (specifically those who can transfer their load) to adapt their consumption to the price and transfer the load from peak hours to some other time, reducing the system's peak load as a result. According to Fig. 2, this tariff can be implemented in different times of the day, different days of the week, or different days of the year [2].

B. *The Interruptible/Curtailable (I/C) Load Program*

In this program, the consumer makes a contract with the power company, stating that they would reduce or cut their consumption in case of accidents. In this program, the customers are rewarded for reducing their consumption at the time of accident, and penalized if they don't do so [1].

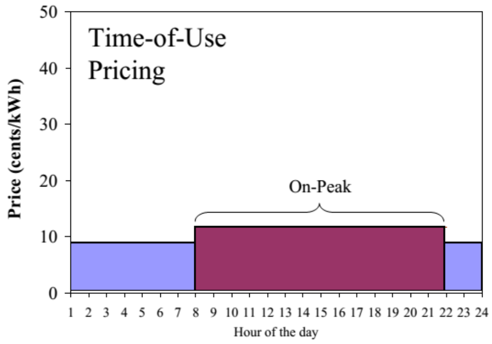

Figure 2. The time-of-use (TOU) pricing program

The operator gains benefit through the reduction of the peak load and thus the heavy cost of production, and the guaranteed reliability of the system. Moreover, the consumer gains benefit through the reduction of power consumption costs and especially the incentives offered by the independent system operator.

In the following, some articles on the subject of demand response are briefly reviewed. In the references [3,4] have studied the economic model of the demand response program with the price sensitivity factors and the customer utility function. They have also modeled and evaluated the TOU program. Reference [5] has studied responsive loads on the basis of price elasticity in order to improve the reliability, reduce power fluctuations, reduce the cost and improve the load curve.

Reference [2] has defined, categorized, implemented the costs and expressed the potential benefits of demand response. They have also simulated the demand response effect using a case study. Executing the DR program has resulted in the improvement of reliability and the reduction of costs and power fluctuations. Reference [6] has proposed an economic model for demand response. This model is based on price elasticity and determines the amount of customer consumption to gain the maximum benefit in a 24-hour period after participation in the DR program. It also prioritizes DR programs based on criteria such as improving the load factor, reducing the peak, reducing the peak and off-peak interval and satisfying the customers. An analytic hierarchy process has been used in order to choose the most effective DR program. Reference [7] has focused on interruptible loads and capacity market programs which are incentive-based. In this article, penalties are set for customers participating in the interruptible/curtailable load program if they don't reduce the load. Then, the effect of the program on the load curve is evaluated. The obtained results indicate the effect of these programs on the load shape and surface, customer utility and energy consumption reduction. Reference [8] has studied responsive loads on the basis of price elasticity.

Reference [9] has studied the nonlinear economic model of the demand response program which is based on the price elasticity of demand and the customer utility function in order to extract different mathematical models for the TOU program.

The goal of this paper, is to study the economic model of demand response programs using the price sensitivity factors of demand and the possible participation of domestic and industrial customers, with regards to the modeling of the time-of-use (TOU) pricing and the interruptible/curtailable (I/C) programs. In section II, the economic model of the proposed method is extracted and modeled using the price sensitivity factors of demand and the utility function. Section III examines the load curve of the studied system and the effect of the fixed and possible participations of domestic and industrial customers on the TOU and I/C programs. After that, the simulation results are presented and analyzed. Finally, the conclusions are articulated.

II. THE ECONOMIC MODEL OF THE DEMAND RESPONSE PROGRAM

Demand response programs are designed to increase the customers' sensitivity to market price changes. The sensitivity of the consumption amount to price is called the price elasticity of demand, which is defined by the following matrix:

$$\begin{bmatrix} \Delta d_1 \\ \Delta d_2 \\ \vdots \\ \Delta d_i \\ \vdots \\ \Delta d_m \end{bmatrix} = \begin{bmatrix} E_{11} & E_{12} & \cdots & E_{1n} \\ E_{21} & E_{22} & & \\ \vdots & & \mathrm{E}_{ij} & \vdots \\ & & \vdots & \\ E_{m1} & \cdots & E_{mj} & \cdots E_{mn} \end{bmatrix} \times \begin{bmatrix} \Delta \rho_1 \\ \Delta \rho_2 \\ \vdots \\ \Delta \rho_i \\ \vdots \\ \Delta \rho_m \end{bmatrix} \tag{1}$$

For example, m and n are equivalent to 24 for one day; so the elasticity matrix would be a 24×24 matrix. When the price of electric energy varies in different periods, the load (or demand) demonstrates two types of responses:

a) Loads those are not able to transfer between different periods and can only be on or off (such as lighting loads). This type of demand response to price is called single-period responsiveness and is evaluated through self-elasticity (the diagonal elements of the elasticity matrix). This factor is always negative; because as the price rises, the demand lowers in the same period.

b) Loads those are able to transfer between different periods; which means that the consumption can transfer from peak hours to medium-load or low-load hours (such as air conditioning loads, electric water heater loads, etc.). This type of demand response to price is called multiple-period responsiveness and is evaluated through cross elasticity (the non-diagonal elements of the elasticity matrix). This factor is always positive; because as the price rises in a specific period, the demand increases in other periods.

In the following, the mathematical models of the time-of-use pricing and the interruptible/curtailable load programs are presented and described using self and cross elasticities.

In (2) and (3), it is assumed that the domestic customers constitute a percentage of the total load, and the industrial customers make up the rest. The amounts of customer consumption after the execution of the TOU and I/C programs are obtained from (4) and (5) respectively. In (5), β is the weight factor of the reward and penalty (according to customer welfare), which is used to increase the maximum benefit of the customers and the distribution company.

$$\begin{cases} d_0^{domestic} = \gamma . d_0^{total} \\ d_0^{industrial} = (1-\gamma) . d_0^{total} \end{cases} \tag{2), (3}$$

$$dr^{domestic} = \alpha_{TOU} . d_0^{domestic} . \begin{Bmatrix} 1 + E_{TOU}(i,i) . \dfrac{[\rho(i) - \rho_0(i)]}{\rho_0(i)} \\ + \sum\limits_{\substack{j=1 \\ j \neq i}}^{24} E_{TOU}(i,j) . \dfrac{[\rho(j) - \rho_0(j)]}{\rho_0(j)} \end{Bmatrix} \tag{4}$$

i= 1,2,...,24

$$dr^{industrial} = \alpha_{IL} . d_0^{industrial} . \begin{Bmatrix} 1 + E_{IL}(i,i) . \dfrac{[\rho(i) - \rho_0(i) + \beta(A(i) + pen(i))]}{\rho_0(i)} \\ + \sum\limits_{\substack{j=1 \\ j \neq i}}^{24} E_{IL}(i,j) . \dfrac{[\rho(j) - \rho_0(j) + \beta(A(j) + pen(j))]}{\rho_0(j)} \end{Bmatrix} \tag{5}$$

i= 1,2,...,24

Equation (6) and (7), it is assumed that a percentage of the customers in each of the domestic and industrial sections participate in the demand response program. The total load consumption after the execution of the two programs is calculated through (8).

$$d^{domestic} = (1-\alpha_{TOU}) d_0^{domestic} + d_r^{domestic} \tag{6}$$

$$d^{industrial} = (1-\alpha_{IL}) d_0^{industrial} + d_r^{industrial} \tag{7}$$

$$d^{after\_DR} = d^{domestic} + d^{industrial} \tag{8}$$

In the following, the proposed models are executed on Iran's peak load curve and the results are evaluated and analyzed in terms of peak load reduction, load factor, percentage of the fixed and possible participation of customers, etc.

A. *Load Factor*

In order to evaluate the different cases of DR programs and compare the response of the domestic and industrial customers, the evaluation index of load factor (LF) is calculated for each case. According to the definition of evaluation indices, load factor is the average load to maximum load ratio in a time period; which is given by (9):

$$LF = \frac{\frac{1}{24} \times \sum_{t=1}^{T} (d^{after\_DR}(t))}{\max \left\{ d^{after\_DR}(t) \right\}} \quad (9)$$

III. SIMULATION RESULTS

A load curve similar to the one in the reference [6] is used in order to study and test the TOU and I/C demand response programs. According to Fig. 3, the three tariffs of the used TOU program are as follows: low-load from 1:00 to 9:00, medium-load from 10:00 to 19:00 and peak load from 20:00 to 24:00. Moreover, the amount of customer consumption after the execution of the I/C program can be calculated through (5). In this program, the customer's response depends on the price of power, the incentives and the penalty. Therefore, the demand can be obtained in every period by changing the price of power, the incentives and the penalty in each of the demand response programs. The tariff prices and the amount of reward and penalty are in accordance with the reference [7].

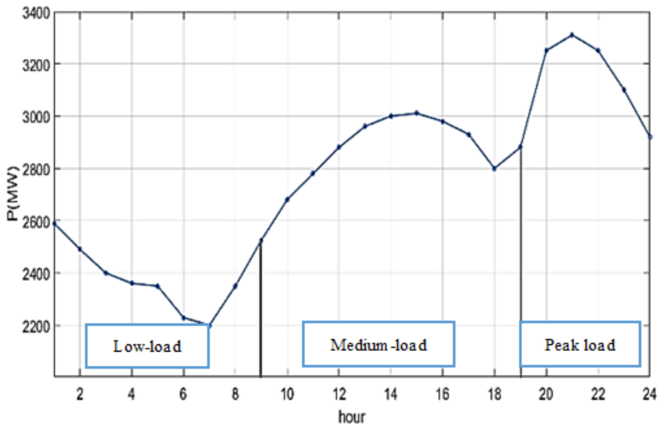

Figure 3. Load curve used in the simulations

According to the reference [7], the self and cross elasticities for the TOU program are plotted in table I. However, the self and cross elasticities of the I/C program are considered to be 20% higher than the TOU program, due to the difference between the responses of domestic and industrial customers.

TABLE I. SELF AND CROSS ELASTICITIES

	Low load	Medium load	Peak load
Low load	-0.01	0.016	0.012
Medium load	0.016	-0.01	0.01
Peak load	0.012	0.01	-0.01

First, it is assumed that 15% of the total domestic loads are participating in the TOU program; while 5% of the total industrial loads are participating in the I/C program. Then, participation in the programs is considered to be probable; and the results obtained by the execution of the proposed model are analyzed.

In these simulations, the amounts of the domestic and industrial loads are each assumed to constitute 50% of the total load of the system. The initial calculations indicate a load factor of 83.36%, a valley-to-peak distance of 1110 MW and a peak load of 3310 MW for the initial load curve (d0).

A. Analyzing Fixed Participation in The TOU and I/C Programs

Fig. 4 and Fig. 5 illustrate the initial load curve and the obtained load curve after the execution of each of the TOU and interruptible load programs.

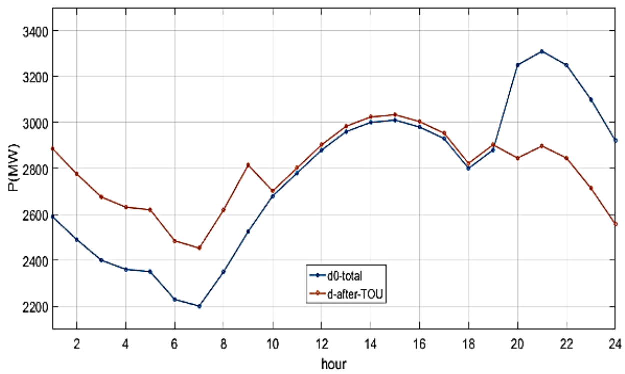

Figure 4. Effect of the TOU program on the initial load

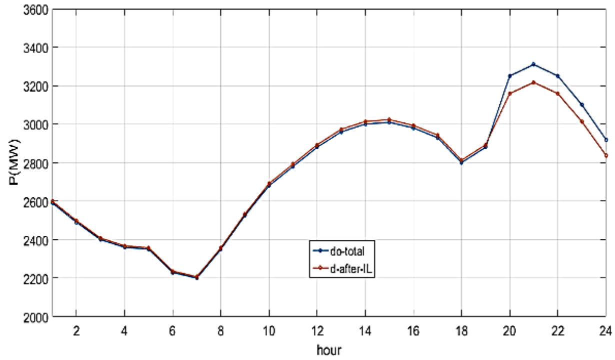

Figure 5. Effect of the I/C program on the initial load

After the execution of the TOU program according to Fig. 4, the peak power consumption demand has decreased from 3310 MW to 3034 MW in comparison with the initial case; and the load factor has increased from 83.36% to 87.28% in comparison with the initial case. Moreover, Fig. 5 indicates that the peak power consumption demand has decreased from 3310 MW to 3217 MW after the execution of the I/C program; and the load factor has increased from 83.36% to 84.36%.

Fig. 6 illustrates the initial load curve and the load curve obtained after the simultaneous execution of the TOU and I/C programs.

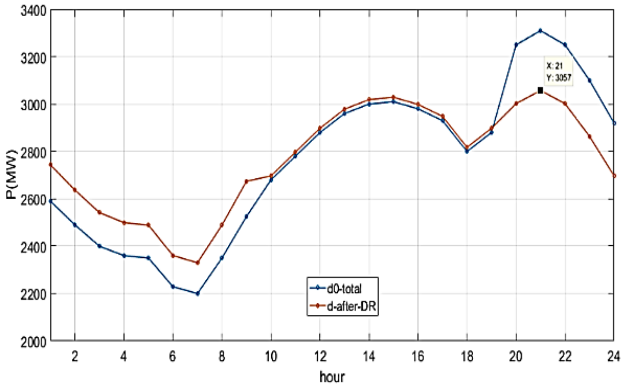

Figure 6. The effect of TOU and I/C programs execution

After the simultaneous execution of the TOU and I/C programs according to Fig. 6, the peak power consumption demand has decreased from 3310 MW to 3057 MW in comparison with the initial case; and the load factor has increased from 83.36% to 90.58%. Therefore, the simultaneous execution of the TOU and I/C programs results in the maximum power demand reduction with respect to the peak day.

B. Analyzing Possible Participation in Demand Response Programs

In the simulations conducted in this section, 30% of the total load is considered to be domestic, and the remaining 70% is considered to be industrial.

1) Possible Participation in The TOU Program

In this case, the percentage of participation in the interruptible load program is considered to be fixed and equivalent to 5%; however, the percentage of participation in the TOU program is assumed to have random values with a normal distribution around an average of 15%. The simulations are executed for 500 random samples and the results are presented and analyzed in the following.

Fig. 7 plots the values obtained for the load factor index for all the implemented random samples. According to the results, the average value is 84.98 and the variance is 0.0269.

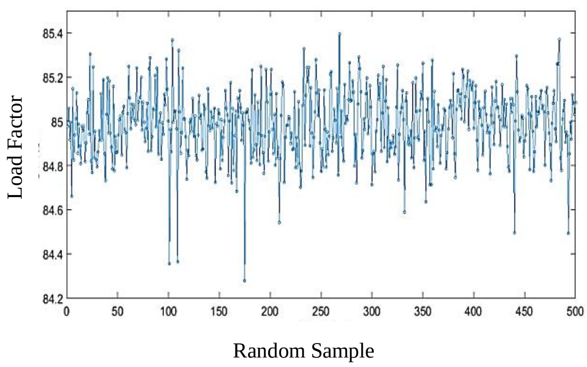

Figure 7. Load factor for probabilistic participation in TOU program

Fig. 8 and Fig. 9 illustrate the "participation level/ peak power consumption" and the "participation level/ load factor" diagrams.

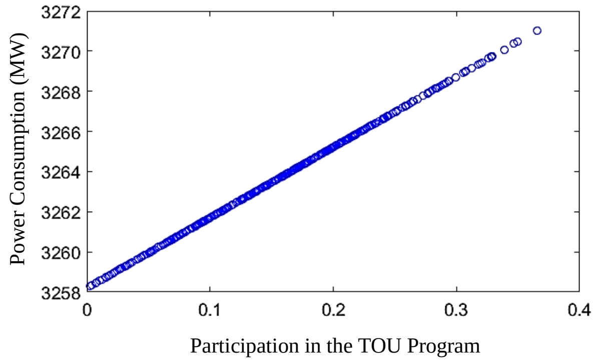

Figure 8. Peak consumption as a function of possible participation in the TOU program

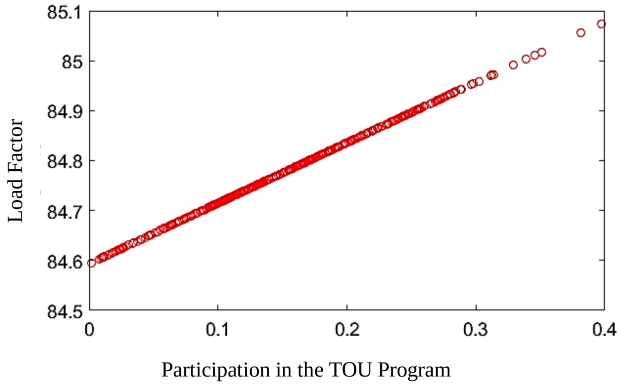

Figure 9. Load factor versus participation level in the TOU program

According to Fig. 8, the amount of power consumption rises with the increase of participation in the TOU program. In addition, Fig. 9 indicates that the load factor index also improves significantly with the increase of participation.

2) Possible Participation in The Interruptible Load Program

In this case, the percentage of participation in the TOU program is considered to be fixed and equivalent to 15%; however, the percentage of participation in the interruptible load program is assumed to have random values with a normal distribution around an average of 5%. The simulations are executed for 500 random samples and the results are presented and analyzed in the following. Fig. 10 plots the changes of the load factor for the random samples. According to the results, the average value is 84.99 and the variance is 0.0073.

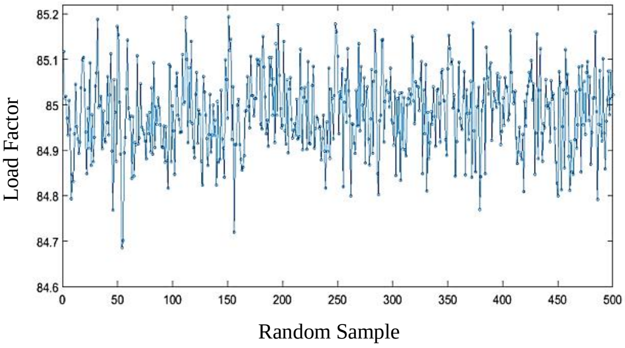

Figure 10. Load factor for participation level in the IL program

Fig. 11 and Fig. 12 illustrate the "participation level/ peak power consumption" and the "participation level/ load factor" diagrams.

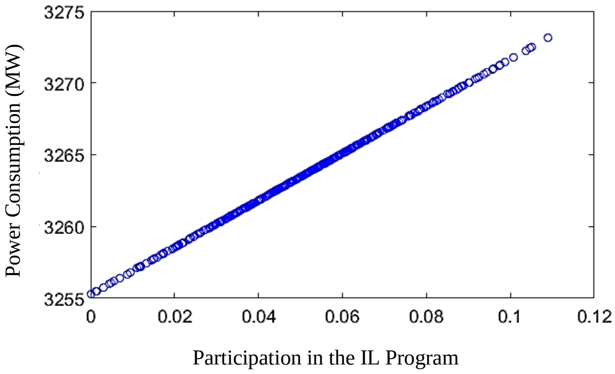

Figure 11. Peak versus participation level in the IL program

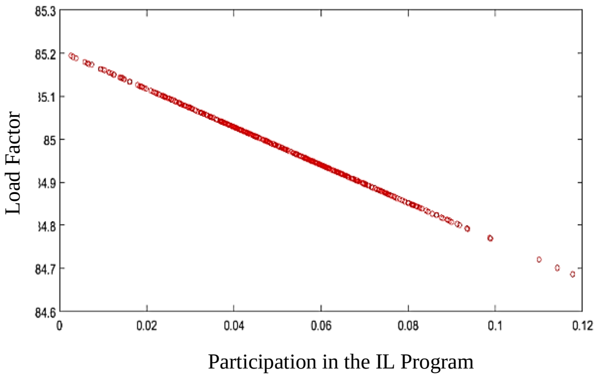

Figure 12. Load factor versus participation level in the IL program

It is evident that the amount of power consumption rises with the increase of participation in the IL program; however, the load factor index falls. This is due to the limited hours of demand response in the interruptible load programs (high-load hours only) and the nonlinear equation of the load factor.

3) Combined Possible Participation in TOU and Interruptible Demand Response Programs

In this case, the percentages of participation in the interruptible load and TOU programs are assumed to have random values with normal distributions around the average values of 5% and 15%, respectively. The simulations are executed for 500 random samples and the results are presented and analyzed in the following.

Fig. 13 plots the load factor index for the random samples. According to the results, the average value is 84.96 and the variance is 0.0432.

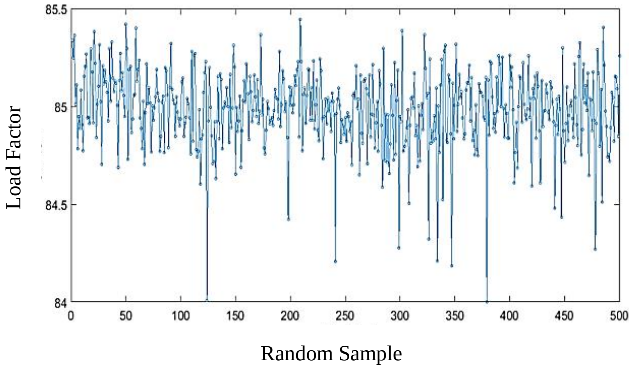

Figure 13. Load factor in combined participation in the TOU and IL programs

Fig. 14 and Fig. 15 illustrate the three-dimensional diagrams regarding the level of participation in each program, the peak power consumption and the load factor index. It is evident that the load factor improves significantly by considering a combined possible participation in the TOU and interruptible load programs.

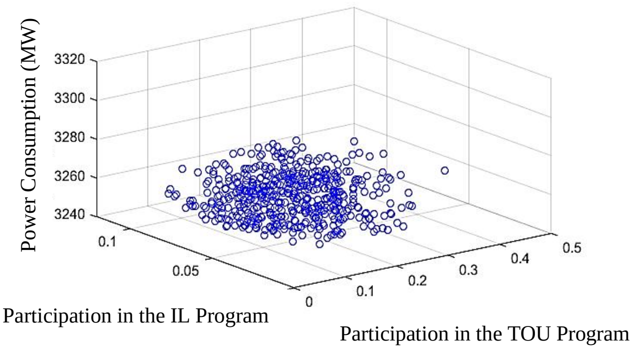

Figure 14. Peak power consumption as a function of combined participation in the TOU and IL programs

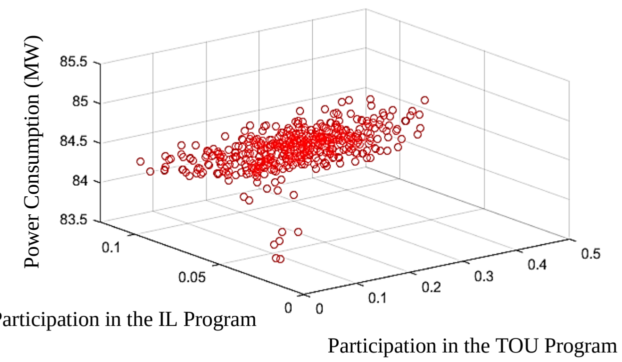

Figure 15. Load factor as a function of combined participation in the TOU and IL Programs

IV. CONCLUSION

With the development of smart grids and the application of demand response programs, the behavior of customers in power consumption changes has gained importance. Demand response can have a significant role in the utilization of the power grid. In this paper, a model is presented for demand response programs by taking into account the price elasticity matrix. Meanwhile, the effect of the fixed and possible participations of the domestic and industrial customers is investigated on two types of demand response programs in order to reduce the load in peak hours and improve the load factor of the system. The programs used in the paper are the TOU and I/C programs which are intended for the domestic and industrial customers respectively. The simulation results fairly indicate the importance of the level of customer participation and the type of the executed program on the evaluation indices of the system.

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