Optimum Time of Use Program Proposal for Iranian Power Systems

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Abstract- **Recently implementation of Time of Use (TOU) program has been started in Iranian Power Systems by means of three tariffs digital meters. Time based rate Demand Response (DR) applicability, necessity of peak reduction (in peak hours) and increasing Load Factor (LF) are main reasons for installing the mentioned meters by Ministry of Energy. In this paper, TOU program is formulated based on economic models of DR by means of "price elasticity of demand" and "customer benefit function". Different scenarios such as various electricity pricing, changing interval of peak, off-peak and low load periods, different customer sensitivity versus prices and the programs' potential have been studied. Peak day load curve of Iranian power grid in 2007 has been considered as the base case for all of the numerical studies. Also, peak reduction, energy consumption and customers' benefits and losses are analyzed. The optimum scenario is selected using "Strategy Success Index" (SSI) method.**

Index Terms— Demand response, Elasticity, Load economic model, Time of Use

I. INTRODUCTION

Implementation of demand response (DR) programs will result in integration of retail and wholesale electricity markets. The lack of demand response to rapidly increasing prices in the California electricity market in 2000 and early 2001 have been identified as one significant factor in the descent of that market into dysfunction [1].

Market institutions and prices provide platforms through which buyers can discover their preferences in the face of potentially ever-changing technology and service offerings from competing retail providers, taking into account other changes that can affect their demand for particular electric services, sellers can discover their opportunity costs, their comparative advantage, and the potential value of new business models and new technologies. The independent system operator (ISO) can play a crucial role in this nexus of institutions because of the perpetual need for system balancing and coordination [2].

Simply put, a double-sided market is an institution that enables buyers and sellers to find each other and to consummate transactions for mutual benefit. A market without active bidding on the demand side, it is still only a single-side market. A single-sided market with passive, inelastic demand tends to have higher prices than a market with active demand and supply, a double-sided market. A recent study estimated prospective benefits of active demand response at $7.5 billion by 2010 [2].

Evaluation of customers' response to California energy shortages in 2000-2001 showed that customers make even deeper temporary reduction in peak load to prevent rotating outages.

For achieving the above DR advantages customer participation in DR programs should be encouraged. It is worth to mention that DR programs should properly be designed to provide enough motivation for customers to participate in the program [3]. Therefore, designing of proper DR programs including precise tariff engineering for time-based and incentive-based programs, which consider the requirements of different customers are of great importance. In order to evaluate the impact of participation of customers in DR program on load profile, development of responsive demand economic models are necessary for designing the above process. It can be expected that such an approach to DR program design will result in more participation of customers.

In [4], [5] and [6], economic models for Time of Use (TOU), Critical Peak Pricing (CPP), Real Time Pricing (RTP), Emergency Demand Response Program (EDRP) and Direct Load Control (DLC) programs have been developed. In this paper, the economic model for TOU program is applied to the load curve of the peak day of the Iranian power system grid in 2007. The remaining of the paper is organized as follows. In section II, a review of DR programs with emphasize on TOU program is discussed. In section III, the mathematical model of TOU program is based on price elasticity of demand and customer benefit function is introduced. Section IV is devoted for numerical studies considering different scenarios. Finally, section V concludes the paper.

II. DEMAND RESPONSE PROGRAMS

According to the Demand Side Management (DSM) strategic plan of International Energy Agency (IEA), for 2004- 2009 years [7], "demand side activities should be active elements and the first choice in all energy policy decisions designed to create more reliable and more sustainable energy systems". Success of any demand side management program depends on the extent of demand survey and analysis for identifying demand characteristics. In this regard, most of the power industries around the world have conducted demand study programs.

In the above strategic plan of IEA, DR (analysis and implementation) has been dedicated to the United State of America. Federal Energy Regulatory Commission (FERC) reported the results of DR investigations and implementations in US utilities and power markets [8]. In the mentioned report, DR is divided into two basic categories namely, time-based Rate (TBR) programs, and incentive-based programs (IBP). Each of these categories is composed of several programs as it is indicated in Fig. 1.

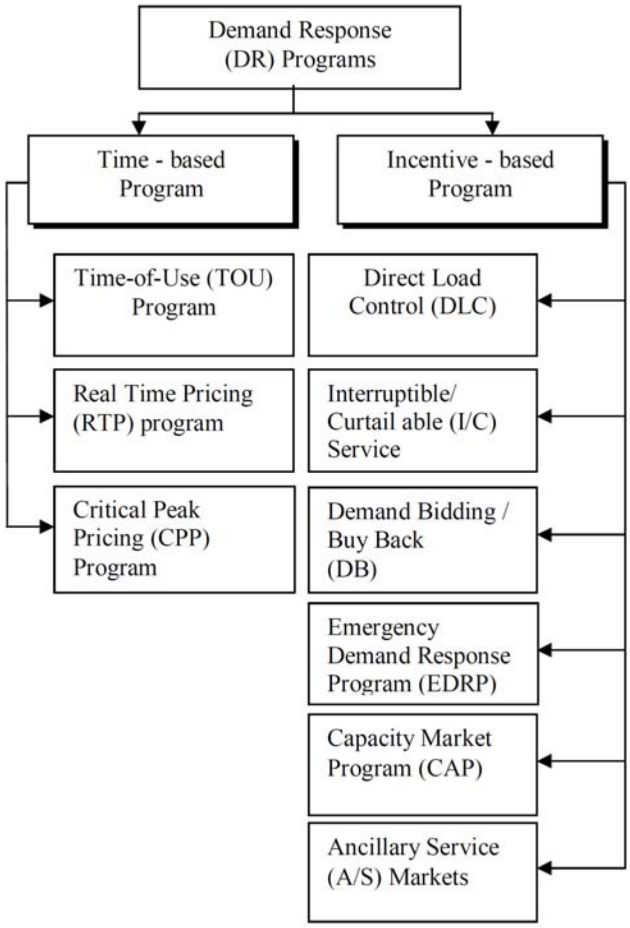

Fig. 1. Categories of demand response programs

In this paper, we have focused on TOU program. In the following, this program is briefly introduced. More detailed explanations of DR programs can be found in [8]. In TOU program the electricity price changes for different periods according to 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. Time-of-use (TOU) rates establish two or more daily periods those reflect hours when the system load is higher (peak) or lower (off-peak), and charge a higher rate during peak hours as shown in Fig. 2. Off-peak hours are usually some part of the night, as well as weekends. Definition of TOU periods differs widely among utilities based on the timing of their peak system demands over the day, week, or year [9].

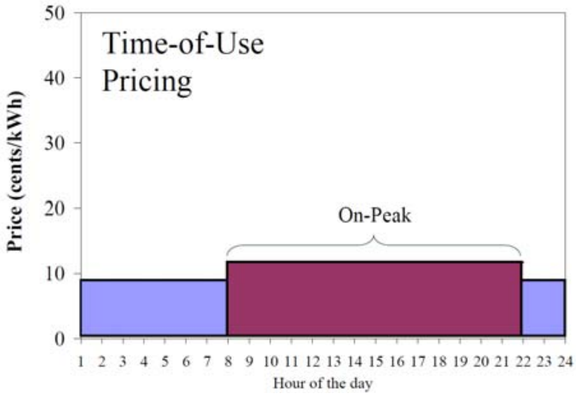

Fig. 2. TOU Program

III. Responsive Load Economic Model

In order to formulate the participation of customers in DR programs, an economic load model which represents the changes of the customer's demand with respect to changing of the electricity price and elasticity is developed here. More detailed explanations of this model are in our previous work reported in [4, 5, 6].

A. Price Elasticity of Demand

Elasticity is defined as the demand sensitivity with respect to the price [10]:

$$E = \frac{\rho_0}{d_0} \cdot \frac{\partial d}{\partial \rho} \tag{1}$$

According to equation (1), the price elasticity of the *i*-th period versus *j*-th period can be defined as:

$$E(i, j) = \frac{\rho_0(j)}{d_0(i)} \cdot \frac{\partial d(i)}{\partial \rho(j)} \tag{2}$$

If the electricity prices vary for different periods, then the demand reacts one of followings [10]:

Some loads are not able to move from one period to another (e.g. illuminating loads) and they could be only on or off. So, such loads have sensitivity just in a single period and it is called "self elasticity", and it always has a negative value.

Some consumption could be transferred from the peak period to the off-peak or low periods (e.g. process loads). Such behavior is called multi period sensitivity and it is evaluated by "cross elasticity". This value is always positive [11]. Accordingly, the self elasticity *E(i,i)* and the cross elasticity *E(i,j)* can be classified as:

$$\begin{cases} E(i, j) \leq 0 & if \quad i = j \\ E(i, j) \geq 0 & if \quad i \neq j \end{cases} \tag{3}$$

B. Modeling of Single Period Elastic Loads

Suppose that the customer changes his demand from *d0(i)* (initial value) to *d(i),* based on the electricity price in *i*-th hours.

$$\Delta d(i) = d(i) - d_0(i) \tag{4}$$

If it is assumed that B(d(i)) be the income of customer during hour *(i)* from the use of *d(i)* kWh of electric energy, then the customer's benefit, *S*, for the *i*-th hour will be as follows:

$$S = B(d(i)) - d(i).\rho(i) \quad (5)$$

According to classical optimization rules, to maximize the customer's benefit, we should have,

$$\frac{\partial S}{\partial d(i)} = \frac{\partial B(d(i))}{\partial d(i)} - \rho(i) = 0 \quad (6)$$

$$\frac{\partial B(d(i))}{\partial d(i)} = \rho(i) \quad (7)$$

The benefit function, most often used, is the quadratic benefit function (second-order Taylor Series extension of *B(d(i)* versus *d(i)*) as following [12]:

$$B(d(i)) = B_0(i) + \rho_0(i)[d(i) - d_0(i)]\left\{1 + \frac{d(i) - d_0(i)}{2E(i).d_0(i)}\right\} \quad (8)$$

By differentiating the above equation and substituting the result in (7) we will have:

$$\rho(i) = \rho_0(i)\left\{1 + \frac{d(i) - d_0(i)}{E(i)\ d_0(i)}\right\} \quad (9)$$

Therefore, customer's consumption will be as following:

$$d(i) = d_0(i)\left\{1 + E(i,i).\frac{[\rho(i) - \rho_0(i)]}{\rho_0(i)}\right\} \quad (10)$$

The above equation represents single period elastic load model.

C. Modeling of Multi Period Elastic Loads

According to the definition of the cross elasticity in (2) with the linearity assumption we have:

$$\frac{\partial d(i)}{\partial \rho(j)} : \text{Constant for } i, \qquad j=1,2,\ldots 24 \quad (11)$$

This results in the following linear relationship between prices and demands:

$$d(i) = d_0(i) + \sum_{\substack{i=1 \\ i \neq j}}^{24} E\ (i,j).\frac{d_0(i)}{\rho_0(j)}.[\rho(j) - \rho_0(j)] \quad (12)$$

In (12), we have considered a 24 hours interval.

D. Load Economic Model

By combining (10) and (12), we will have the responsive load economic model as following:

$$d(i) = d_0(i).\left\{1 + E(i,i).\frac{[\rho(i) - \rho_0(i)]}{\rho_0(i)} + \sum_{\substack{j=1 \\ j \neq i}}^{24} E(i,j).\frac{[\rho(j) - \rho_0(j)]}{\rho_0(j)}\right\} \quad (13)$$

The above equation shows how much should be the customer's consumption to achieve maximum benefit in a 24 hours interval while participating in TOU program.

E. Strategy Selection

Beyond the broad improvements in market efficiency and market linkages, demand response creates multiple, specific benefits for market participants and for the general efficiency and operation of electricity markets. To achieve the above benefit, ISO considers different strategies for reduction of load during system peak, reduction of energy consumption, improvement of system load factor and reduction of distance between peak and valley, etc. On the other hand, different scenarios for price, elasticity, program's potential and duration of periods are compared with each other. Here it is proposed that ISO prioritize these scenarios by using Simple Multiple Weighted (SMW) method which is named Strategy Index *(SI)* and Strategy Success Index *(SSI)* as defined by the following equations, respectively [13].

$$SI = \sum_{i=1}^{24} \left(\prod_{j=1}^{k} [St_k(i)]^{\alpha} \times [C(i)]^{\beta}\right) \quad (14)$$

$$SSI = \frac{\sum_{i=1}^{n} SI\ (i)}{\sum_{i=1}^{n} SI\ (\max)} \quad (15)$$

In which, *C(i),* represents the electricity cost of customer in *i*-th period, $St_k(i)$ represents the value of performance of strategy for *k*-th criterion of load profile characteristic in *i*-th period, α and *β* are criteria weightings, and *n* represents the total days of running the programs. The lower the *SSI* coefficient the better the profit. In next section, we will use the proposed economic model and these indices to evaluate different scenarios.

IV. NUMERICAL RESULTS

The proposed economic model is used for evaluation of TOU program which is presently implemented in IRAN. Furthermore the model is adopted for developing an optimal TOU program. In this regard the load profile of the peak day of the Iranian Grid in 2007 is used for our numerical study. Fig. 3 shows peak load curve which has been occurred on 27 August 2007. In a three tariffs system, this curve is divided into three different periods: Low load (23:00 to 7:00), off-peak load (7:00 to 19:00) and peak load (19:00 to 23:00) [14]. Average price of electric energy has been considered 400, 160 and 40 Rials[1]/kWh, in peak, off-peak and low load periods, respectively [14].

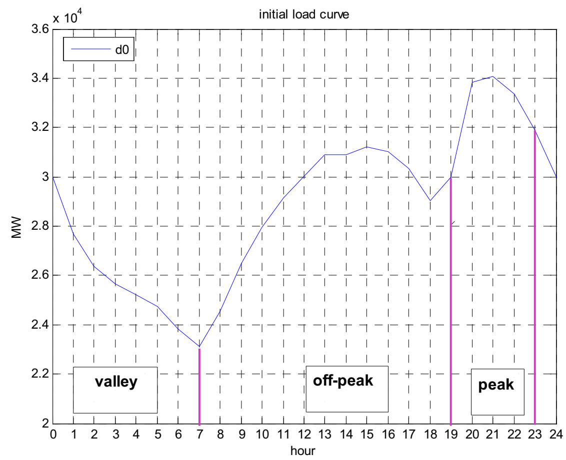

Fig. 3. Initial load curve (27 August 2007) [14]

[1] . Unit of Iranian currency equal to 0.1 cent

Price elasticity of demand values are considered as Table 1.

TABLE 1
SELF AND CROSS ELASTICITY VALUES

	Peak	Off-Peak	Low
Peak	-0.10	0.016	0.012
Off-Peak	0.008	-0.10	0.01
Low	0.006	0.008	-0.10

There is a high potential for energy saving in IRAN. It has been estimated that the potential of DR programs is more than 30% in IRAN [15]. In our study we have assumed 10% as implementation potential of TOU program. In other words, it assumed that 10% of the total load would participate in the program. Table 2 shows nine different scenarios which are considered for our numerical study.

TABLE 2
DEFINITION OF SCENARIOS

Group No	Scenario No	Program	Price*	Period**	Program's Potential	Elasticity
1	1	Flat Rate (Base Case)	present	Present	10%	As Table1
2	2	TOU	Present	Present	10%	As Table1
	3	TOU	Present	Suggested	10%	As Table1
	4	TOU	Suggested	Present	10%	As Table1
	5	TOU	Suggested	Suggested	10%	As Table1
3	6	TOU	Present	Present	20%	As Table1
	7	TOU	Suggested	Suggested	20%	As Table1
4	8	TOU	Present	Present	10%	0.5*Table1
	9	TOU	Suggested	Suggested	10%	0.5*Table1

*Present Price: 400, 160 and 40 Rials/kWh, in peak, off-peak and low load periods, respectively

*Suggested Price: 450, 200 and 0 Rials/kWh, in peak, off-peak and low load periods, respectively

**Present period: Low load (23:00 to 7:00), off-peak load (7:00 to 19:00) and peak load (19:00 to 23:00)

**Suggested period: Low load (24:00 to 9:00), off-peak load (9:00 to 20:00) and peak load (20:00 to 24:00)

1) Scenario 1: In this scenario, electricity price is fixed and Fig. 3 represents initial load curve without running TOU program.

2) Scenario 2: In this scenario, TOU pricing of the Ministry of Energy is used (present price). After implementing TOU program, the peak load which was occurred on hour 21:00 is reduced about 2500 MW, but load is increased about 1800 MW on hour 24:00. So it is better to consider the hour 24:00 in the peak period. On the other hand, it can be seen that hour 7:00 has the lowest load value, but the Ministry of Energy has considered hour 7:00 in the off-peak period. That is why the load is not increased on this hour and the deepest point of the curve has not moved as shown in Fig. 4. Load profile characteristics and benefit/loss of customers can be found in Table 3 and Table 4.

3) Scenario 3: In order to solve disadvantages of Ministry of Energy's TOU program, scenario 3 has been defined with same electricity prices as scenario 2, but time intervals are defined as 24:00 to 9:00 as the low load period, 9:00 to 20:00 as the off-peak period and 20:00 to 24:00 as the peak load period. The results of TOU program implementing TOU program can be seen in Fig. 4. As it can be seen the Peak load is reduced by 3000MW, load spike on 24:00 is prevented and load valley is increased by 2000 MW.

4) Scenario 4: This scenario is designed to study the effect of price changes on the load curve. Time intervals are considered based on Ministry of Energy definition, but 0, 200 and 450 Rials/kWh have been considered as the electricity prices for the low, off-peak and peak periods, respectively. According to Fig.4 the peak load on hour 21:00 is reduced to 31000 MW, but a new peak is created on hour 24:00 (32500 MW) and load valley has become deeper by 600 MW.

5) Scenario 5: In this scenario, load economic model has been established based on suggested prices and periods. As it can be seen from Fig. 4 and Tables 3 and 4, load curve characteristics and customers' benefits are much better comparing with other scenarios.

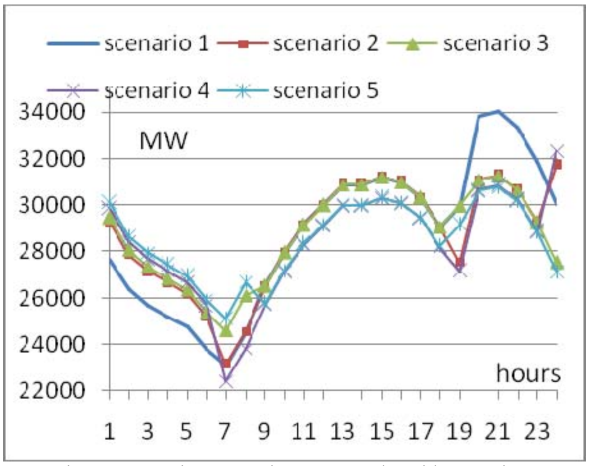

Fig. 4. Comparing scenarios 2, 3, 4 and 5 with scenario 1

Scenarios 6 and 7 are designed in order to analyze the effects of variations in the program potential.

6) Scenario 6: In this scenario it has been assumed that number of installed digital meters is increased and so the potential of running the program will be increased to 20%. The results of Fig. 5 Show that the Peak load on 21:00 is reduced about 5000 MW (two times of scenario 2). Load spike is occurred on hour 24:00, in addition the peak load is shifted from hour 21:00 to hour 24:00 with a value around 33000 MW.

7) Scenario 7: This scenario is same as scenario 6, but the suggested periods and prices are considered. The results are shown in Fig. 5.

Scenarios 8 and 9 are designed to investigate about the effects of elasticity variations on the load curve.

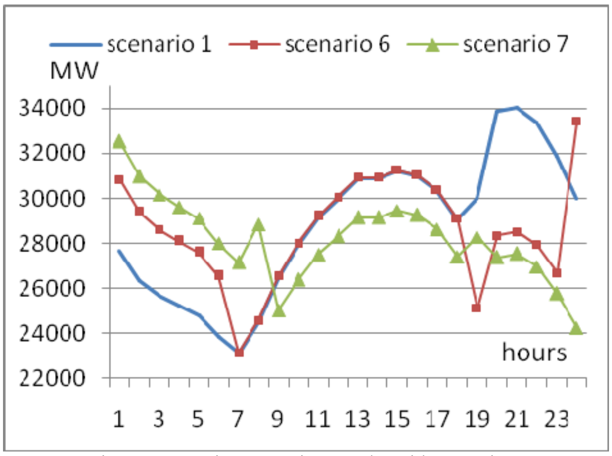

Fig. 5. Comparing scenarios 6 and 7 with scenario 1

8) Scenario 8: In this scenario the elasticity values are taken as half value of Table 1 and the results of implementing TOU program are shown in Fig. 6. As it was expected, the value of peak reduction and other changes are decreased.
9) Scenario 9: Repeating scenario 8 by considering suggested periods and prices. The results can be seen in Fig. 6.

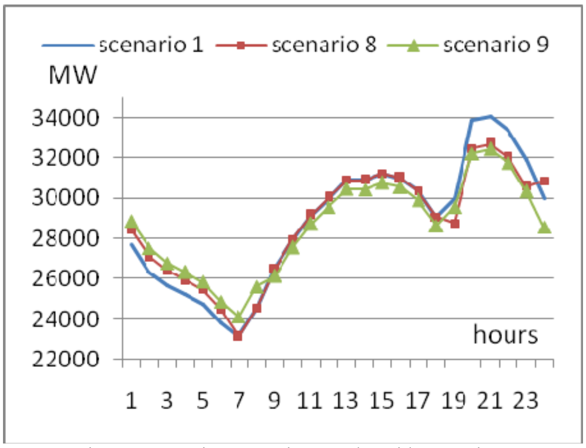

Fig. 6. Comparing scenarios 8 and 9 with scenario 1

A. Analysis of the results and choosing the optimum scenario

We have analyzed the results from two points of view: economical and technical. From economic point of view, we have analyzed cost of consumed electricity energy, customers' benefit/loss and utility's revenues in Table 3. From technical point of view, peak reduction, energy consumption reduction, load factor and peak to valley distance are compared in Table 4. As it can be concluded from Table 3, implementing of TOU program has been resulted in increasing of utility revenue and customers have paid more money for their consumptions. The highest and the lowest revenue of the utility and customer losses are occurred in scenario 9 and scenario 1, respectively.
Based on the results in Table 4, the worst load curve characteristics is belong to the base scenario, in which TOU program has not been implemented. But in other scenarios these characteristics are improved. The highest value of peak reduction and the lowest distance between peak and valley and the highest load factor is belonging to scenario 5 (suggested values). Also, the lowest energy consumption is occurred in scenario 7.

TABLE 3
ECONOMICAL COMPARISON OF SCENARIOS

Group No	Scenario No	Bill (Million Rials)	Customer loss (Million Rials)
1	1	110603	0
2	2	122886	12283
	3	120774	10171
	4	133365	22762
	5	137210	26607
3	6	118041	7438
	7	128117	17514
4	8	125308	14705
	9	141758	31155

For considering customers' benefits and also ISO goals (in implementing TOU program), and in order to obtain the optimum scenario, we have used "Strategy Success Index" (SSI), in which the cost of electricity usage (from customers' point of view), peak value, peak energy consumption, load factor and distance between peak and valley (from ISO's point of view) have been encountered in (15). The results show that the minimum value of SSI is belonging to scenario 5 which reveal that the suggested prices and periods are the optimum value. Ordering of scenarios is shown in Fig. 7.

TABLE 4
COMPARISON OF LOAD PROFILE CHARACTERISTICS

Group No	Scenario No	Peak (MW)	Peak Reduction (%)	energy consumption (MWh)	Load factor (%)	peak to valley distance (MW)
1	1	34058	0	691273	85	10951
2	2	31713	6.9	688730	90	8589
	3	31258	8.2	690835	92	6661
	4	32338	5.0	679933	88	9918
	5	30794	9.6	684029	93	5662
3	6	33423	1.9	686186	86	10281
	7	32526	4.5	676791	87	8273
4	8	32674	4.0	690002	88	9558
	9	32426	4.8	687654	88	8306

V. CONCLUSION

In this paper, TOU program of Iranian Ministry of Energy is evaluated using an economic model of demand response and the drawback of this program has been highlighted. It was shown that the suggested optimum TOU program could improve the load curve characteristics with lower cost of customers' electricity consumptions.

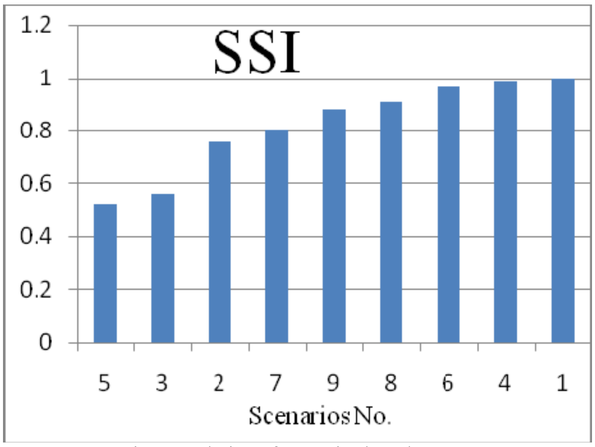

Fig. 7. Ordering of scenarios based on SSI

By using the proposed economic load model it was shown that how the load curve could be affected by elasticity values, energy prices, customers' participation and the periods of the peak, off peak and low load. Also the producer of determining the optimum scenario by means of "strategy success index" was addressed. The proposed method would be interesting for regulators or ISOs, because they could design an optimum TOU program in which load curve characteristics and customers satisfactory be considered, simultaneously.

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