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A Novel Method for Implementing of Time-of-use to Improve the Performance of Electric Distribution Systems: A Case Study

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ABSTRACT

Increased electric energy consumption in recent years, associated economic problems, reduced reliability and increased power losses in electric networks. One of the main solutions in smart grids to overcome the mentioned problems is demand response programs. In demand response programs, operators apply time-varying tariffs to consumers, and convince them to change their consumption pattern. Among the demand response programs, the most effective program for subscribers who receive electricity at fixed price is time-of-use (TOU) pricing. This paper offers a new approach to implementing TOU program, which is determining the scheduling and pricing of TOU tariff simultaneously taking into account the objectives of smoothing the load profile, reducing the losses and energy not supplied. The proposed method is simulated in MATLAB, and has been evaluated on an urban distribution network in Yazd Electrical Distribution Company (YEDC) that feeds 35 distribution transformers (20/0.4kV) through a radial feeder. Results show that implementation of this method has only a minor increase in cost and reduction in consumption for subscribers, and makes load profile more smooth, improve reliability and reduce power losses.

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1. INTRODUCTION

Power consumption growth during recent years, in addition to increased power losses in electric networks, and due to the mismatch with the increase in production led to decreased reliability of electric distribution systems. We should not forget that even if all the problems caused by the necessity of heavy investments for the construction of power plants is resolved, with the current trend of increasing consumption and inappropriate patterns in the bilateral equation of consumption and production, they will be faced with serious and fundamental challenges. This matter shows the necessity of paying attention to the issue of consumption management more than before. Electric energy consumption management includes two groups of production-side and consumption-side. Since the demand-side options are more economical than the production-side options, demand response programs have been developed. Federal Energy Regulatory Commission (FERC) has divided demand response programs into two groups of Price-Based programs and Incentive-Based programs. Many electricity companies choose price-based programs to implement as the better option because Incentive-Based programs are also more complex than the other one and in addition to the initial costs, include running costs. For instance, a day-ahead real-time pricing (DA-RTP) tariff used by the Illinois Power Company in the United States, several critical peak pricing pilots in California, Idaho, and New Jersey, and the three-level (on-peak, mid-peak, off-peak) TOU pricing tariff in Ontario, Canada [1]. A large number of research articles have been published on real-time pricing [2-4], time-of-use pricing [5-7] and critical peak pricing [8-10]. Results show that the real-time pricing is more effective in reducing the consumption in peak times [11]. But TOU is the simplest form of administrative of demand response and needs slightest technological changes. It's difficult for consumers who are used to flat tariff to face with variable prices in RTP tariffs and even may lose their motivation to move

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consumption from peak hours to off-peak hours [12]. Hence, it is better that TOU tariffs apply. Some research articles have done TOU pricing [13-16], but what distinguishes this article is determining the scheduling and pricing of TOU tariff simultaneously taking into account the objectives of smoothing the load profile, reducing the losses and energy not supplied.

The remainder of the paper is organized as follows. Section 2 provides economic model of demand response. In section 3, the problem is formulated as objectives and constrains. The proposed algorithm for determining the timing pattern and pricing of TOU tariff is presented in section 4. Section 5 is devoted to numerical study and simulation results of the case study. Finally, section 6 concludes this paper.

2. DEMAND RESPONE MODEL

To assess consumer participation in demand response programs, development of a model which determines features of load profiles, profits and losses of consumers with respect to prices is necessary. Elasticity is defined as load sensitivity with respect to price changes [17]:

$$E(i,j) = \frac{\partial d(i)}{\partial \rho(j)} . \frac{\rho_0(j)}{d_0(i)} \qquad j = 1,2,3,...,24 \tag{1}$$

$$\begin{cases} E(i,j) \leq 0 & if \quad i = j \\ E(i,j) \geq 0 & if \quad i \neq j \end{cases} \tag{2}$$

Where, *E(i,j)* is load changes in *i*-th period with respect to price changes in *j*-th period, *ρ(j)* is electricity price in *j*-th period and *d(i)* is demand value in *i*-th period. Zero indexes in each of symbols represent their initial values.

If electricity prices change in different periods, loads can respond in two ways to these price adjustments [18]:

- Some loads are not able to transfer to other periods (such as lighting) and can only be switched on and off. So such loads have sensitivity only in a single period, and their elasticity is called “self-elasticity" which always has a negative value, E(i,i).
- Some loads, unlike the first group, can be transferred from peak period to the off-peak period. Such behavior is called multi-period sensitivity, and their elasticity is “cross- elasticity” which always has a positive value, E(i,j).

2. 1. Modeling of Single Period Elastic Loads

If a consumer's consumption in *i*-th hour is equal to *d(i)*, *B (d(i))* considered consumer’s income resulting from the use of *d(i)* kW. Therefore, the consumer’s profit will be as follows:

$$S = B(d(i)) - d(i).\rho(i) \tag{3}$$

Under the rules of classical optimization, the maximum profit to the consumer can be calculated as:

$$\frac{\partial S}{\partial d(i)} = \frac{\partial B(d(i))}{\partial d(i)} - \rho(i) = 0 \tag{4}$$

$$\frac{\partial B(d(i))}{\partial d(i)} = \rho(i) \tag{5}$$

Linear structure of customer response function is the simplest and also the most widely used. However, the reality is the customer response function as a non-linear function. In this paper, the exponential structure of customer response function is used. For exponential structure of customer response function, the benefit function can be obtained by Taylor expansion of B(d(i)) as following [19]:

$$\begin{aligned} &B(d(i)) = B_0(i) + \\ &\rho_0(i).d(i).\left\{1 + \frac{1}{E(i,i)}\left[ln\left(\frac{d(i)}{d_0(i)}\right) - 1\right]\right\} \end{aligned} \tag{6}$$

By differentiation from the above equation with respect to d(i), we will have:

$$\begin{aligned} &\frac{\partial B(d(i))}{\partial d(i)} = \rho_0(i).\left\{1 + \frac{1}{E(i,i)}\left[ln\left(\frac{d(i)}{d_0(i)}\right) - 1\right]\right\} \\ &+ \rho_0(i).d(i).\left\{\frac{1}{E(i,i)} . \frac{1}{d_0(i)} . \frac{d_0(i)}{d(i)}\right\} \end{aligned} \tag{7}$$

Substituting Equation (7) in (5) results in:

$$\rho(i) = \rho_0(i) + \frac{\rho_0(i)}{E(i,i)}\left[ln\left(\frac{d(i)}{d_0(i)}\right) - 1 + 1\right] \tag{8}$$

$$\rho(i) - \rho_0(i) = \frac{\rho_0(i)}{E(i,i)}\left[ln\left(\frac{d(i)}{d_0(i)}\right) - 1 + 1\right] \tag{9}$$

Therefore, customer’s demand can be represented as following:

$$d(i) = d_0(i).EXP\left\{E(i,i)\,\frac{\rho(i) - \rho_0(i)}{\rho_0(i)}\right\} \tag{10}$$

2. 2. Modeling Multi Period Elastic Loads

In the multi period elastic loads, cross elasticity, *E(i,j)*, for *i*-th hour should be calculated to other periods (*i≠j*). So by changing the price in other periods and regardless of the increase in electricity price in *i*-th hour Equation (10) is changed as following:

$$d(i) = d_0(i).EXP\left\{\sum_{\substack{j=1 \\ j \neq i}}^{24} E(i,j)\,\frac{\rho(i) - \rho_0(j)}{\rho_0(j)}\right\} \tag{11}$$

It should be noted that a 24-h interval has been considered in Equation (11), however, longer or shorter intervals are also definable.

2. 3. Modeling Composite Period Elastic Loads

For i = constant, and j = 1, 2… 24 (including i), the composite period load model can be obtained by combining Equations (10) and (11) as follows:

$$d(i) = d_0(i).EXP\left\{\sum_{j=1}^{24} E(i,j)\,\frac{\rho(i) - \rho_0(j)}{\rho_0(j)}\right\} \tag{12}$$

3. PROBLEM FORMULATION

TOU tariff is one of the most effective methods of demand-side management. The purpose of this paper is determining the scheduling and pricing of TOU tariff simultaneously taking into account the objectives of smoothing the load profile, reducing the losses with energy not supplied.

3. 1. Objective Functions

In this part, the goals of this research are expressed:

A) Smoothing the load profile

From the perspective of network operators, with a smoother load profile the operating of system is more desirable. One criterion for the measurement of the smoothness of the load profile is the difference between the maximum and minimum of load profile. The less the difference is, the load profile is smoother. Thus minimizing this difference is intended as one of the objectives:

$$F_1 = max\left(d\left(i\right)\right) - min\left(d\left(i\right)\right);\ i = 1,2,...,24 \tag{13}$$

where, d is the consumption value (kW).

B) Power losses

The economic consequences and high costs which are paid caused the issue of power losses to be an update debate in power engineering community. The power loss minimization problem in distribution systems has traditionally focused on network reconfiguration [20] and reactive power support through capacitor placement [21]. However, power loss minimization is considered as another objective, which is expressed as following [22]:

$$F_2 = P_{Loss} = \sum_{T=1}^{24}\sum_{B=1}^{N_r}\left(I_{B,T}^{2}.R_B\right) \tag{14}$$

where P_{Loss} is the total power loss of the distribution system in a day (kW), R_B is the resistance of branch B, $I_{B,T}$ is the current of branch B at hour T and N_r is the number of total branches.

C) Energy Not Supplied

The ability to secure the customer electricity supply with an acceptable quality is called reliability to the power system. One of the main objectives of demand response programs is to improve the reliability of the distribution system. There are various indices for assessing the reliability of the distribution systems. However, here the index of Energy Not Supplied (ENS) has been selected as another objective, which is defined as follows [23]:

$$F_3 = ENS = \sum_{i=1}^{N} L_{avg}(i).U(i) \tag{15}$$

$$U\left(i\right) = \lambda\left(i\right).r\left(i\right) \tag{16}$$

where $L_{avg}(i)$ is the average load connected to load point i, λ_i is the failure rate at load point i, $r(i)$ is average outage time at load point i, $U(i)$ is annual outage time of load point i and N is the total number of load points.

D) Combination of Smoothing the load profile, Power losses and ENS

Finally combine all three objectives presented and is considered as the main objective. For this purpose, the objective functions first normalized and then using weighting coefficients have been converted to a single function as following:

$$F = W_1\left(\frac{F_1 - F_{1,min}}{F_{1,max} - F_{1,min}}\right) + W_2\left(\frac{F_2 - F_{2,min}}{F_{2,max} - F_{2,min}}\right) + W_3\left(\frac{F_3 - F_{3,min}}{F_{3,max} - F_{3,min}}\right) \tag{17}$$

Where, the minimum of each objective is its optimum level, the maximum of each objective is its value before the implementation of TOU program, and W_i shows the weight of the importance of each parameter, that are assumed as: $W_1=0.5$, $W_2=0.25$, and $W_3=0.25$.

3. 2. Constraints

In this section, constraints of the proposed objectives are presented as follows:

$$\max(d(i)) \le \max(d_0(i)) \tag{18}$$

$$\cos t \le 1.05 * \cos t_0 \tag{19}$$

$$\begin{cases} \max(T_p) = 5 \\ \max(T_m) = 12 \end{cases} \tag{20}$$

$$\begin{cases} 0 \le d(i) - d_0(i) \le 0.2 \times d_0(i); \\ i \in \text{low peak time} \\ -0.1 \times d_0(i) \le d(i) - d_0(i) \le 0.1 \times d_0(i); \\ i \in \text{middle peak time} \\ -0.2 \times d_0(i) \le d(i) - d_0(i) \le 0; \\ i \in \text{peak time} \end{cases} \tag{21}$$

According to Equation (18) scheduling and pricing need to be done as the daily peak after the implementation of TOU program does not exceed the previous amount. In Equation (19), $cost_0$ is the charge that subscribers pay before the implementation of TOU program and cost is the charge that subscribers pay after the implementation of TOU program. TOU program implementation results in increasing the cost of subscribers, in order to avoid excessive increase Equation (19) is intended. Equation (20) is considered to satisfy customers, where T_P and T_m are the number of peak hours and middle peak hours, respectively. Equation (21) shows the limits of load changes in peak, middle peak and low peak times. It is here assumed that the consumers are able to have 20% changes in their loads.

4. OPTIMIZATION ALGORITHM

There are various optimization algorithms to solve the above optimization problem, but here Genetic algorithm (GA) is used to solve the problem. GA is greatly empowered to finding the solution of the non-linear problems and it is very convenient for optimization problems with discrete quantities [24, 25]. GA is available in MATLAB toolbox and can easily be used.

As previously said, the problem is determining the scheduling and pricing of TOU tariff simultaneously by considering mentioned objectives. So, a day is divided into three time intervals (low peak, middle peak, and peak). A chromosome with 27 genes is considered to solve the optimization problem. Genes from 1 to 24 are related to determining the time pattern that each of these genes can choose values of 1or 2 or 3. Numbers 1, 2 and 3 represent periods of low peak, middle peak and peak, respectively. The remaining three genes are to determine the optimum tariffs. Genes 25, 26, and 27 represent the tariffs of low peak, middle peak and peak, respectively. It is assumed that operator has the upper and lower bound of electricity price in each period, as Table 1 shows:

The flowchart of the propose algorithm is shown in Figure 1.

5. NUMERICAL STUDY AND RESULTS

In order to analyze the goals of power losses and ENS reduction an urban distribution network in YEDC (Yazd-Iran) is studied. The network, as shown in Figure 2, feeds 35 distribution substations (20/0.4 kV) through a radial feeder. The network technical data are accessible in appendix. It should be noted that all consumers in this feeder are household. Iran's electricity market is one-way and Power is supplied to household consumers with a fixed price of 1770 ℛ/kWh. A daily load profile of this feeder is shown in Figure 3.

TABLE 1. Bound of electricity price in each period

Period	Min (R[2]/kWh)	Max (R/kWh)
Low peak	600	1000
Middle peak	1400	2000
peak	2500	4000

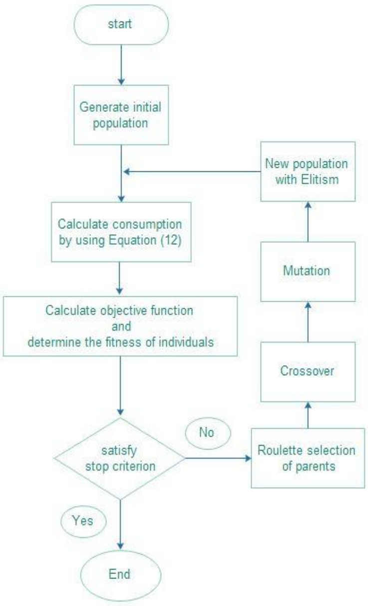

Figure 1. Flowchart of proposed algorithm

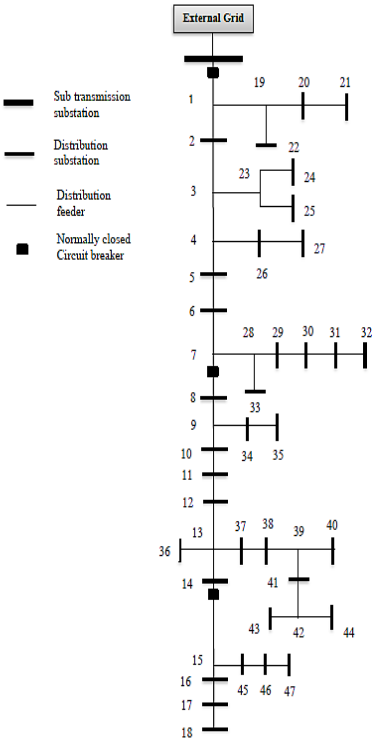

Figure 2. Single line diagram of distribution feeder under study

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[2]- Unit of Iranian currency denoted by ℛ .

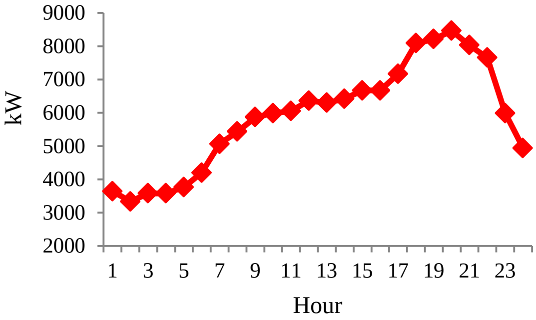

Figure 3. Daily load profile of feeder under study

The price elasticities of the demand are considered as listed in Table 2 [26].

It should be noted that, for calculating power losses backward-forward sweeping method is used, which is easy to be implemented in MATLAB, and power factor is constant before and after the implementation of TOU program. To compute ENS, the failure rate for each line is equal to 0.06 (f/year.km). Repair time and total isolation and switching time are considered 5 and 0.5 h, respectively. ENS is calculated in MATLAB.

A) Smoothing the load profile analysis

Scheduling and optimum tariff for this purpose are shown in Figure 4. Load profile of before and after TOU implementation is shown in Figure 5. The difference between the maximum and minimum of load profile in base case was 5128.8 kW, and after TOU implementation is 3040.5 kW which 40.7% is decreased.

TABLE 2. Self and cross elasticities

	Peak	Middle Peak	Low Peak
Peak	-0.1	0.016	0.012
Middle Peak	0.016	-0.1	0.01
Low Peak	0.012	0.01	-0.1

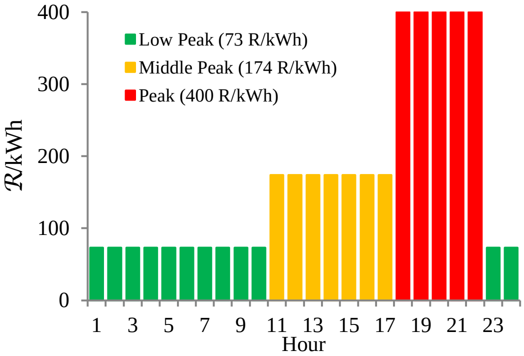

Figure 4. Scheduling and optimum tariff for Smoothing the load profile

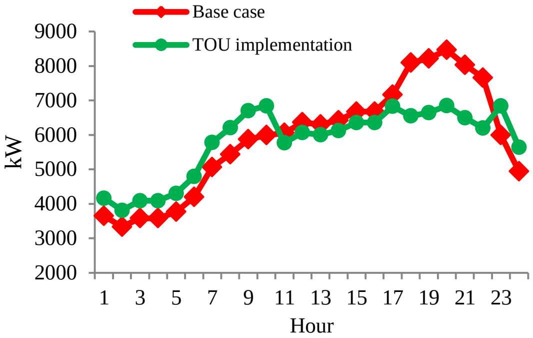

Figure 5. Load profile before and after TOU implementation for Smoothing the load profile

B) Power losses analysis

Figures 6 and 7 illustrate scheduling and optimum tariff and load profile of before and after TOU implementation, respectively. Power losses in base case were 1799.4 kW, and after TOU implementation is 1623.1 kW. As result shows, power losses are decreased 9.8%. As consumption decreases, losses are also decreased. But, for the hours of 1 to 7 consumption has increased because of transfer consumption from peak hours to low peak hours (Equation 21).

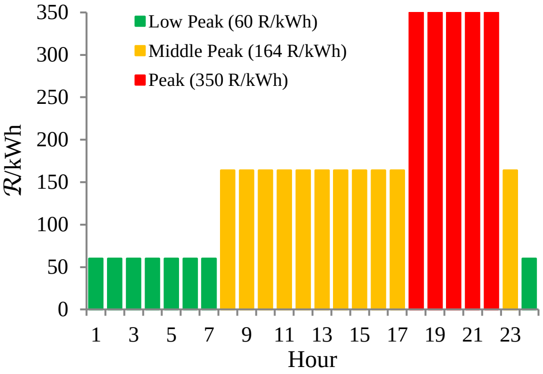

Figure 6. Scheduling and optimum tariff for power losses

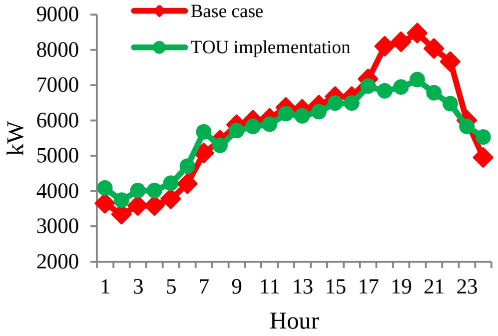

Figure 7. Load profile of before and after TOU implementation for power losses

C) ENS analysis

The results of this purpose are presented in Figures 8 and 9. Quantity of ENS in base case was 10494kW/year, while with the implementation of TOU it decreases to 10155kW/year (3.2%). It may seem small amounts but in the context of outage cost, this amount will be invaluable.

D) Combination of Smoothing the load profile, Power losses and ENS analysis

Results can be seen in Figures 10 and 11.

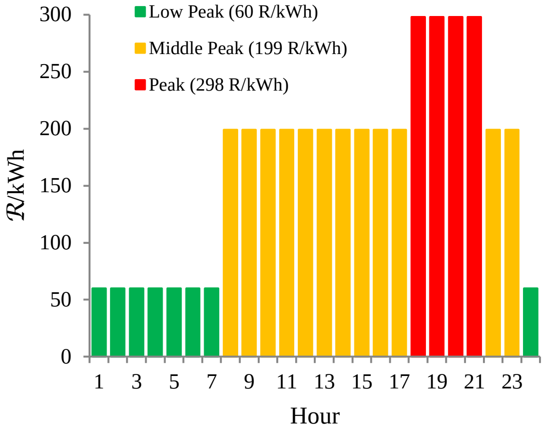

Figure 8. Scheduling and optimum tariff for ENS

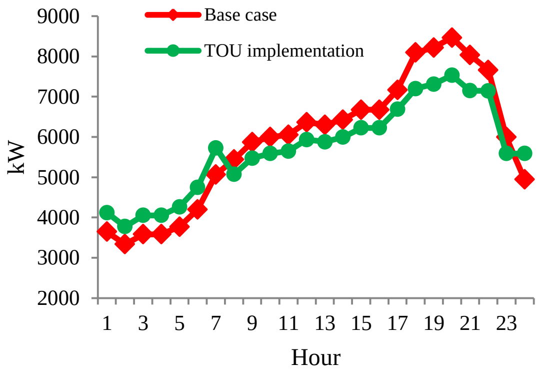

Figure 9. Load profile of before and after TOU implementation for ENS

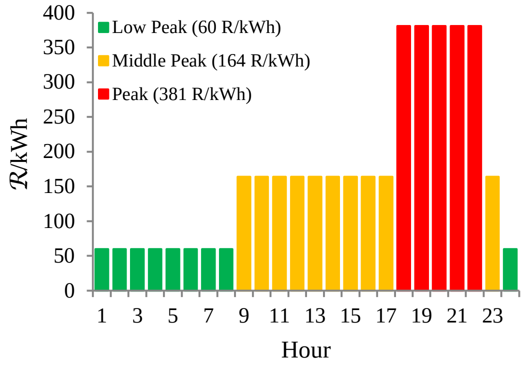

Figure 9. Scheduling and optimum tariff for Combination of Smoothing the load profile, Power losses and ENS

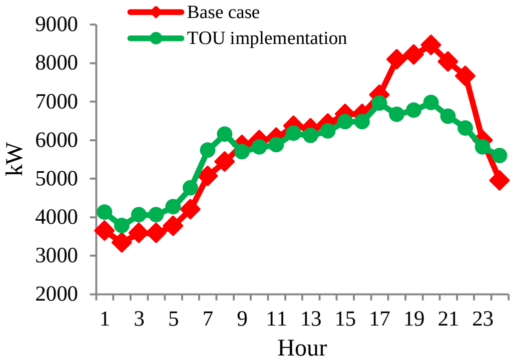

Figure 10. Load profile before and after TOU implementation for Combination of Smoothing the load profile, Power losses and ENS.

The difference between the maximum and minimum, power losses and ENS are decreased 37.7%, 9.6% and 2.9% respectively. The results of TOU implementation with the mentioned purposes are shown in Table 3. Results indicate the lowest reduction in consumption is 3.4%, and the greatest increasing in cost is about 1.2%. According to these results, values of cost increasing and consumption reduction are low and reasonable. So, Consumers will have the motivation to do TOU program and shift their loads from peak to low peak periods.

TABLE 3. Results of TOU implementation

	Cost (1000R)	Consumption (kW)	Max-min (kW)	Power losses (kW)	ENS (kW/year)
Base case	250570	141570	5128.8	1799.4	10494
Smoothing load profile	252910	139550	3040.5	1675.1	10345
Power losses	251090	137140	3415.7	1623.1	10166
ENS	251000	136990	3759	1626.6	10155
Composite	253600	137480	3197.4	1625.2	10191

6. CONCLUSIONS

In this paper, a new method is presented to implement the TOU program where determining the scheduling and pricing of TOU tariff is done simultaneously. For this purpose, the behavior of consumers are modeled as demand response model, and different purposes have been proposed such as smoothing the load profile, reducing the losses and energy not supplied. In this method provisions intended to increase customer satisfaction and boost the participation of consumers in TOU program. This method is carried out on a distribution feeder that the consumers are domestic. Results show that reduction in consumption is 3.4%, and increasing in cost is about 1.2%. These values are low and reasonable. It can be concluded from the results that for implementation of TOU program, timing and pricing should be done simultaneously till consumers' costs don't rise highly.

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9. APPENDIX

TABLE 4. Network Parameters

Send point	Receive Point	R(Ω)	X(Ω)	Length (km)
EG	1	0.133236	0.131386	0.560217
1	2	0.075725	0.075725	0.302899
2	3	0.124971	0.124971	0.499884
3	4	0.00928	0.00928	0.03714
4	5	0.12843	0.12843	0.513718
5	6	0.033991	0.036917	0.148577
6	7	0.024289	0.029924	0.121444
7	8	0.034499	0.027415	0.1554
8	9	0.3034	0.037379	0.151702
9	10	0.00598	0.00737	0.02991
10	11	0.035133	0.043284	0.175664
11	12	0.063765	0.028462	0.104766
12	13	0.141431	0.05012	0.176879
13	14	0.308846	0.109447	0.386057
14	15	0.080391	0.028489	0.100489
15	16	0.086166	0.030535	0.107707
16	17	0.220466	0.078128	0.275583
17	18	0.21849	0.077428	0.273113
1	19	0.01731	0.00613	0.02164
19	20	0.136024	0.048204	0.17003
20	21	0.025325	0.008974	0.031656
19	22	0.053048	0.03533	0.132619
3	23	0.012074	0.008041	0.030185
23	24	0.056187	0.061997	0.249081
23	25	0.010192	0.012557	0.050962
4	26	0.070385	0.044769	0.156156
26	27	0.132175	0.050125	0.177859
7	28	0.043666	0.03903	0.153845
28	29	0.00882	0.00587	0.02206
29	30	0.0159	0.01059	0.03975
30	31	0.01681	0.0112	0.04204
31	32	0.006536	0.00437	0.016
28	33	0.123751	0.04428	0.193516
9	34	0.211619	0.080021	0.285944
34	35	0.225836	0.080031	0.282295
13	36	0.071845	0.01579	0.089806
13	37	0.02637	0.00934	0.03296
37	38	0.181869	0.06445	0.227336
38	39	0.00365	0.00129	0.00456
39	40	0.166423	0.058976	0.208029
39	41	0.286661	0.10141	0.357707
41	42	0.01876	0.00664	0.02345
42	43	0.140474	0.049781	0.175593
42	44	0.287805	0.101991	0.359756
44	45	0.057021	0.031265	0.117362
45	46	0.109915	0.073204	0.274788
46	47	0.032635	0.030306	0.120079

TABLE 5. Load data

Load point	Active power (kW)	Reactive power (kW)
2	176	95
5	220	118.7
6	440	237.5
8	352	190
10	277.2	149.6
11	88	47.5
12	88	47.5
14	88	47.5
16	277.2	149.6
17	277.2	149.6
18	277.2	149.6
20	176	95
21	176	95
22	88	47.5
24	22	11.87
25	220	118.7
26	277.2	149.6
27	440	237.5
29	277.2	149.6
30	277.2	149.6
31	220	118.7
32	88	47.5
33	704	380
34	220	118.7
35	220	118.7
36	277.2	149.6
37	277.2	149.6
38	277.2	149.6
40	220	118.7
41	277.2	149.6
43	176	95
44	277.2	149.6
45	220	118.7
46	277.2	149.6
47	220	118.7

A Novel Method for Implementing of Time-of-use to Improve the Performance of Electric Distribution Systems: A Case Study

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چکیده

افزایش مصرف انرژی الکتریکی در سال‌های اخیر مشکلات اقتصادی، قابلیت اطمینان و تلفات توان را به همراه داشته است. یکی از مهم‌ترین راه‌حل‌های ارائه شده در شبکه هوشمند برق، برنامه‌های پاسخگویی بار است. در برنامه‌های پاسخگویی بار، بهره‌بردار با اعمال تعرفه‌های متغیر با زمان مشترک را مجاب به تغییر الگوی مصرف می‌کند. در میان برنامه‌های پاسخگویی بار، برنامه قیمت‌گذاری زمان استفاده (TOU) مؤثرترین روش برای مشترکینی است که برق را با قیمت ثابت دربافت می کنند. در این مقاله، تقسیم‌بندی زمانی و تعیین تعرفه بهینه به‌صورت همزمان به‌منظور هموارسازی منحنی بار، بهبود قابلیت اطمینان سیستم و کاهش تلفات ارائه گردیده است. روش پیشنهادی در نرم افزار متلب پیاده سازی شده است و سپس بر روی یک شبکه توزیع شهری از شرکت توزیع برق یزد که ۳۵ ترانس توزیع (۰,۴/۲۰ کیلوولت) را از طریق یک فیدر شعاعی تغذیه می‌کند، مورد ارزیابی قرار گرفته است. نتایج نشان می دهد اجرای این روش کمترین افزایش هزینه و کاهش مصرف را برای مشترکین در پی دارد و باعث هموار شدن منحنی بار، بهبود قابلیت اطمینان و کاهش تلفات سیستم می‌گردد.

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