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Investigating Effect of Changes in Demand Response Programs on Emission Level of Thermal Power Plants and Market Player Profit

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Abstract: Because of potential benefits of Demand Side Management (DSM) at operation, economic and environmental levels, DSM is introduced as the first choice in all energy policy decisions. Under deregulation, the DSM programs have been expanded to include Demand Response Programs (DRPs). In the present study, in order to investigate effect of changes in DRPs on the emission level of thermal power plants and Supply Side Resources (SSRs) profit, an appropriate model of Unit Commitment (UC) problem incorporating Demand Side Resources (DSRs) with implementation of Time Based Rate (TBR) programs of DRPs (UC-DSRs with TBR programs) is presented and studied. The proposed model is applied to determine the optimal TBR program with the aim of lowest emission. In the other word, the amount of emission per day in UC-DSRs problem is used to prioritize the TBR programs from ISO's point of view.

Key words: Demand Side Resources (DSRs), emission reduction, Supply Side Resources (SSRs), UC-DSRs, Time-Based Rate (TBR) programs

INTRODUCTION

Generation of electricity from fossil fuel in thermal power plants releases several contaminants, such as NO_x, CO_2 and SO_2 into the atmosphere (Muslu, 2004). In the past decades, the environmental issues have become a society concern. So, emission effects should be taken into account for environmental friendly power production. The clean air act amendments passage a law to force the utilities to modify their design or operational strategies for reducing pollution and atmospheric emissions of the thermal power plants (Muslu, 2004; Marwali and Shahidehpour, 1999; Lamont and Obessis, 1995; Wang *et al*., 1995). One of the goals of Demand Side Management (DSM) is related to environmental issue that achieves environmental and/or social goals by reducing energy usage, deferring commitment of polluted units, leading to increased energy efficiency and/or reduced greenhouse gas emissions (IEA, 2012).

After restructuring, the performance of power systems have been changed a lot that one of these changes is related to DSM and implementation of Demand Response Programs (DRPs). In the previous decades, the generation scheduling of power plants has been obtained by considering constant value of demand whereas after restructuring, the value of demand can be changed according to variation of electricity prices. Khodaei *et al*. (2011), hourly demand response has been incorporated into unit commitment for economic and security purposes. The responsive loads are linked to the hourly market prices and curtailed or shifted to other operating hours. Rahmani-Andebili *et al*. (2011), an investigation of implementing emergency Demand Response Program (EDRP) in Unit Commitment (UC) problem has been studied. Also by Rahmani-Andebili and Rahmani-Andebili (2012), Time of Use (TOU) program in fuel cost reduction of UC problem has been applied. In all the mentioned study, the approach of studies is not environmental. In the present study, effect of changes in DRPs on emission level of thermal power plants and profit of Supply Side Resources (SSRs) is investigated. So, an appropriate model of UC problem incorporating Demand Side Resources (DSRs) with implementation of Time-Based Rate (TBR) programs (UC-DSRs with TBR programs) is presented and studied. The market model of responsive loads is derived based on price elasticity of demand and customers' surplus function. The proposed model is applied to determine the optimal TBR program with the aim of lowest emission.

DEMAND RESPONSE PROGRAMS IN SUMMARY

US Department Of Energy (DOE) defines demand response as: Changes in electric usage by end-user 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

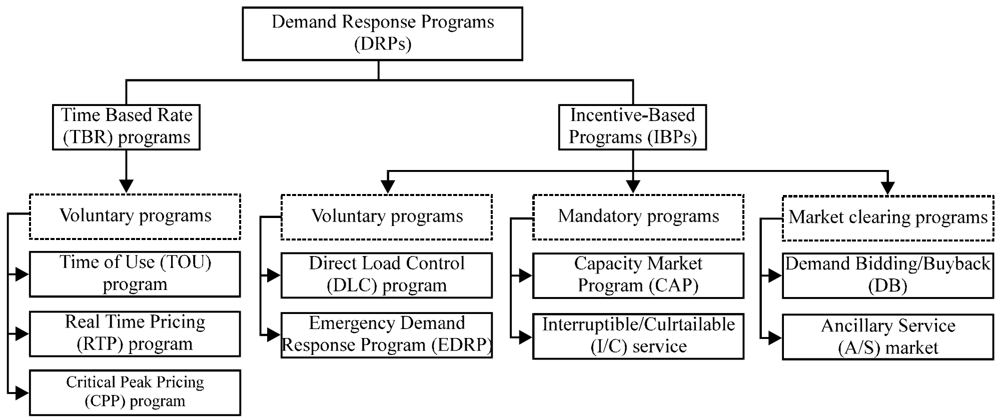

Fig. 1: Different categories of DRPs

use at times of high wholesale market prices or when system reliability is jeopardized. Federal Energy Regulatory Commission (FERC), reported the results of DRPs investigations and implementations in US utilities and power markets (FERC, 2006). In the mentioned report, DRPs is divided into two basic categories namely, TBR programs and IBPs. Also, IBPs are classified into 3 main subgroups namely; voluntary, mandatory and market clearing programs. Each of these categories and subgroups is composed of several programs as shown in Fig. 1.

In TBR programs the electricity price changes for different periods according to the electricity supply cost. TOU, RTP and CPP programs are voluntary programs and there is not any incentive or penalty for customer response.

A TOU tariff gives information on systematic variations in daily costs of production and defines blocks of hours with different rates reflecting average costs during each block. Typically, the 24 h day^{-1} are grouped into 3 blocks: Low, normal and peak hours. The purpose of using TOU tariffs is load shifting, decreasing consumption at peak hours and increasing consumption in normal and low price hours. TOU tariffs aim to reduce welfare losses by introducing levels of average pricing. Typically, the tariff is pre-determined for a year in advance and once determined, consumers know the rules and do not have to follow hourly price changes in the market (Andersen *et al*., 2006).

CPP program focuses at periods when marginal production costs and prices in the market are very high either due to very large demand or due to lack of production capacity and aim at reducing demand in high-price periods by super-imposing a pre-specified high rate. Normally, CPP rates are super-imposed on either a TOU tariff or a time-invariant rate. Utilities trigger CPP rates and call on consumers to react at relatively short notice, often for a limited number of hours per year. CPP programmes require that consumers receive information when CPP rates are triggered and are able to react to these (Andersen *et al*., 2006).

In systems with RTP, the price of electricity directly reflects the market price, typically on an hourly scale, determined on a day-ahead or an hour-ahead basis. On an hourly market, RTP removes the welfare losses associated with other tariff systems. However to make sense, RTP requires consumers to follow price developments in the market and carry the costs associated with this (Andersen *et al*., 2006).

In IBPs, DLC and EDRP are voluntary programs and if customers do not curtail consumption, they are not penalized. I/C and CAP are mandatory programs and enrolled customers are subject to penalties if they do not curtail when directed. DB and A/S are market clearing programs, where large customers are encouraged to offer or to provide load reductions at the posted prices. A/S programs allow customers to bid load curtailments in electricity markets as operating reserves.

In this study, the TBR programs (the highlighted blocks) will be investigated. More detailed explanations of DRPs can be found by Fahrioglu and Alvarado (2000), Kirschen *et al.* (2000), Kirschen and Strbac (2004) and Yusta *et al.* (2007).

ECONOMIC MODELLING OF RESPONSIVE LOADS

Elasticity is defined as the demand sensitivity respect to the price (Kirschen and Strbac, 2004):

$$E = \frac{\partial D}{\partial PR} = \frac{PR_0}{D_0}\frac{dD}{dPR} \tag{1}$$

Where:

- E = Demand elasticity
- PR_0 = Initial price
- D_0 = Initial demand
- PR = New price
- D = New demand

If electric energy prices vary for different periods, then the demand reacts one of the following:

- Some of loads are not be able to move (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 valley period. Such behaviour is called multi period sensitivity and it is evaluated by cross elasticity. This value is always positive. According to Eq. 1, the self elasticity and cross elasticity could be written as (Kirschen and Strbac, 2004):

$$E(t,t) = \frac{\Delta D(t)}{\Delta PR(t)} \leq 0 \tag{2}$$

$$E(t,t') = \frac{\Delta D(t)}{\Delta PR(t')} \geq 0 \tag{3}$$

Electricity is a particular commodity that small consumers are not considerably being sensitive to its price variation. But, commercial and industrial consumers are more sensitive to the price variation for earning more income. The electricity customers who participate in TBR programs adapt their demands with the prices and shift their demand from expensive hours to cheaper ones. In addition, the customers produce their commodities by consuming the electricity. So, they generate incomes and pay the electricity bills. Hence, the Consumer's Net Surplus Function (CNSF) can be formulated as:

$$CNSF(t) = CGSF\left(D_{TBR}(t)\right) - D_{TBR}(t)PR^{E}(t) \tag{4}$$

In the earliar equation, CGSF is Consumer's Gross Surplus Function (CGSF) which is related to the customer's income due to electricity consumption and producing their commodities. D_{TBR} (t) is the value of demand after implementing TBR programs and PR^E (t) is the modified prices of electricity related to TBR programs after implementation of TBR programs. According to the classical optimization rules to maximize the CNSF, researchers have:

$$\frac{\partial CNSF(t)}{\partial D_{TBR}(t)} = \frac{\partial CGSF\left(D_{TBR}(t)\right)}{\partial D_{TBR}(t)} - PR^{E}(t) = 0 \tag{5}$$

Therefore:

$$\frac{\partial CGSF\left(D_{TBR}(t)\right)}{\partial D_{TBR}(t)} = PR^{E}(t) \tag{6}$$

By using Taylor Series Expansion for CNSF considering, researchers have (Yusta *et al*., 2007):

$$\begin{aligned} CNSF(D_{TBR}(t)) = {} & CGSF(D_0(t)) + PR_0^E(t)(D_{TBR}(t) - \\ & D_0(t)) + \frac{PR_0^E(t)}{2E(t,t)D_0(t)}(D_{TBR}(t) - D_0(t))^2 \end{aligned} \tag{7}$$

By differentiating the Eq. 7, researchers have:

$$\frac{\partial CGSF(D_{TBR}(t))}{\partial D_{TBR}(t)} = PR_0^E(t) \times \left(1 + \frac{D_{TBR}(t) - D_0(t)}{D_0(t)E(t,t)}\right) \tag{8}$$

With combining Eq. 8 and 6, researchers have the single period elastic load model:

$$D_{TBR}(t) = D_0(t) \times \left(1 + \frac{PR^{E}(t) - PR_0^E(t)}{PR_0^E(t)} E(t,t)\right) \tag{9}$$

Therefore, the value of demand after implementation of TBR programs that composed of single and multi period elastic load model is as Eq. 10.

$$\begin{aligned} & D_{TBR}(t) = D_0(t) \times \\ & \left(1 + \frac{PR^{E}(t) - PR_0^E(t)}{PR_0^E(t)} \sum_{t'=1}^{T} E(t,t')\right) \end{aligned} \tag{10}$$

According to Eq. 10, if the prices in different hours before and after implementing TBR programs are equal, then the customers will have no encouragement to modify their demand pattern and shift it from peak hours to other hours.

PROPOSED MODEL FOR UC-DSRS WITH IMPLEMENTATION OF TBR PROGRAMS

In this study, among DRPs, all the voluntary TBR programs, i.e., TOU program, RTP program and CPP program are selected to implement in UC-DSRs problem. Because of predetermination of incentive amounts and price of electricity and also because no penalty is considered for the consumers who do not reduce or curtail their consumption in the announced hours, participation in TBR programs have had good results in some power markets (FERC, 2006).

In this study, the target of SSRs is maximizing their profit by minimizing the cost of electricity generation. In the other hand, the SSRs run the cost-based UC. Also, the target of DSRs is maximizing their CNSF by using electricity in cheaper hours. By running TBR programs, the consumers, especially who able to move their consumption will adjust their demand with different prices. But, the target of ISO is minimizing the emission level of thermal power plants. So, ISO modifies the price of electricity in different hours to achieve to this aim. By running TBR programs, the demand in peak hours will be shifted to off-peak and valley hours. So, the emission level of thermal power plants will be decreased. Because by running TBR programs, the commitment of polluted units will be deferred and the more polluted units will be kept off and the less polluted units will be kept on in the scheduling period. Moreover, the emission of thermal power plants has a quadratic polynomial manner and the emission level of them in high generation is more than low generation.

The framework of implementation of TBR programs in UC-DSRs problem from ISO's point of view is shown in Fig. 2. The important point is to link the DSRs and the SSRs to the generation scheduling problem. As can be seen, ISO in a day-ahead power market announces the amount of electricity prices of different hours to the DSRs. Then, based on the price elasticity of demand, the amount of implementation potential of DRPs and a feedback from DSRs, ISO predicts the level of demand. After that the UC-DSRs problem is solved and the level of emission is determined. Based on emission level reduction, this loop continues until the optimum TBR program is determined by the ISO.

Here, UC-DSRs problem is solved using Simulated Annealing (SA) algorithm. In this algorithm, the value of total cost of UC-DSRs is defined as internal energy of molten metal and then tries to minimize the internal energy of molten metal. The proposed algorithm consists of several steps that have been explained by Rahmani-Andebili *et al.* (2011) and Rahmani-Andebili and Rahmani-Andebili (2012).

THE FORMULATION OF UC-DSRS WITH IMPLEMENTATION OF TBR PROGRAMS

In this part, the mathematical formulation of cost-based UC-DSRs is presented. Here, the target of SSRs is minimizing the total cost of UC-DSRs problem. The cost terms of objective function of problem are consisting of the fuel cost of generating units, the start-up cost of de-committed units and shut-down cost of the committed units. So, the objective function of the UC-DSRs problem in general form is formulated as:

$$\min\{TC\} = \min\left\{\sum_{t=1}^{T} TC(t)\right\}$$
$$\min\left\{\sum_{t=1}^{T}\sum_{i=1}^{Ng}\left\{\begin{array}{l} FC(i,t)u(i,t) + STUC(i,t)(1- \\ u(i,t-1))u(i,t) + SHDC(i,t) \\ u(i,t-1)(1-u(i,t)) \end{array}\right\}\right\} \quad (11)$$

The constraints of the problem are as following: The power balance constraints in all the scheduling hours with and without implementing TBR programs.

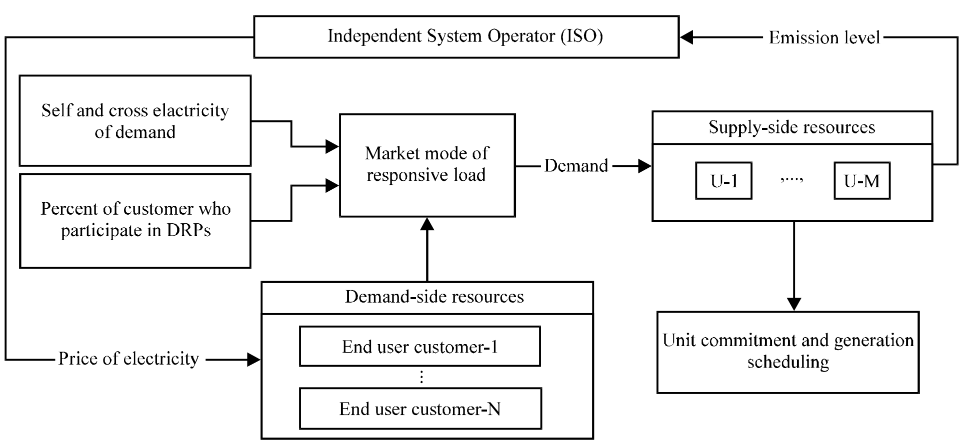

Fig. 2: Framework of UC-DSRs with implementation of TBR programs

$$\sum_{i=1}^{Ng} P(i,t)u(i,t) = D_0(t), \;\forall t = 1,...,T \quad (12)$$

$$\sum_{i=1}^{Ng} P(i,t)u(i,t) = D_{TBR}(t), \;\forall t = 1,...,T \quad (13)$$

The constraints of minimum level of load at any hour with and without implementing TBR programs:

$$\sum_{i=1}^{Ngz} P_{min}(i,t)u(i,t) \le D_0(t), \;\forall t = 1,...,T \quad (14)$$

$$\sum_{i=1}^{Ngz} P_{min}(i,t)u(i,t) \le D_{TBR}(t), \;\forall t = 1,...,T \quad (15)$$

The constraints of maximum level of load and spinning reserve in all the scheduling hours with and without implementing TBR programs:

$$\sum_{i=1}^{Ngz} P_{max}(i,t)u(i,t) \ge D_0(t) + R(t), \;\forall t = 1,...,T \quad (16)$$

$$\sum_{i=1}^{Ngz} P_{max}(i,t)u(i,t) \ge D_{TBR}(t) + R(t), \;\forall t = 1,...,T \quad (17)$$

The constraints of unit output limit in all the scheduling hours:

$$[P_{min}(i,t) \le P(i,t) \le P_{max}(i,t)]u(i,t), \;\forall t = 1,...,T \quad (18)$$

The constraints of minimum up/down time limit for each generation unit:

$$T_{OFF}(i) \ge MDT(i), \;\forall i = 1,...,Ng \quad (19)$$

$$T_{ON}(i) \ge MUT(i), \;\forall i = 1,...,Ng \quad (20)$$

The emission of units is a quadratic polynomial and emission level of units (ton/day) is defined as following:

$$EL = \sum_{t=1}^{T} EL(t) = \sum_{t=1}^{T}\sum_{t=1}^{Ng}\{a_E(i) + b_E(i)P(i,t) + c_E(i)P^2(i,t)\} \quad (21)$$

NUMERICAL STUDIES

In this part, the proposed algorithm is applied on the 10 unit system with a scheduling time horizon of 24 h. The value of demand of system at any hour is shown in Table 1.

The amount of spinning reserve at any hour is considered as 10% of demand at same hour. The technical data of generation units are shown in Table 2. Table 2 consist of start-up/shut-down costs of units, minimum up/down time of units, maximum/minimum generation of units and fuel/emission coefficients of units.

The self and cross elasticity of demand in different hours of a typical day are brought in Eq. 22-24 which is extracted by Kirschen *et al.* (2000) with some modification. Also, the implementation potential of DRPs is considered 50%.

$$E = \begin{bmatrix} [A]_{9\times 9} & [0.016]_{9\times 9} & [0.049]_{9\times 6} \\ [0.040]_{9\times 9} & [-0.020]_{9\times 9} & [0.010]_{9\times 6} \\ [0.033]_{6\times 9} & [0.010]_{6\times 9} & [B]_{6\times 6} \end{bmatrix} \quad (22)$$

Table 1: Value of hourly demand (MW)

h	D	h	D	h	D	h	D
1	1145	7	1011	13	1458	19	1792
2	1120	8	1047	14	1539	20	1963
3	1086	9	1087	15	1579	21	1972
4	1025	10	1367	16	1579	22	1955
5	1027	11	1488	17	1397	23	1752
6	1002	12	1492	18	1469	24	1597

h = Hour; D = Demand

Table 2: Generation units' data

Unit No. (i)	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
STUC (i) ($)	4500	5000	5500	560	400	210	160	190	150	180
SHDC (i) ($)	4500	5000	5500	560	400	210	160	190	150	180
MDT (i) (h)	8	8	6	6	5	3	3	1	1	1
MUT (i) (h)	8	8	6	6	5	3	3	1	1	1
P_{max} (i) (MW)	300	300	240	240	220	220	180	180	160	160
P_{min} (i) (MW)	150	150	50	50	30	25	25	20	20	20
a_F (i) ($/h)	460	470	480	580	650	1770	1880	1960	1965	1995
b_F (i) ($/MWh)	17.19	18.86	22.3	24.6	27.5	30.26	32.94	36.42	39.97	43.19
c_F (i) ($/MW2h)	0.0111	0.0118	0.0122	0.0131	0.0138	0.014	0.02	0.021	0.0221	0.0232
a_E (i) (ton/h)	10.339	11.454	12.682	12.752	12.857	13.339	13.531	35.0005	35.0005	36.0001
b_E (i) (ton/MWh)	-0.2744	-0.2684	-0.2434	-0.2318	-0.2181	-0.2344	-0.2444	-0.3952	-0.3952	-0.3986
c_E (i) (ton/MW2h)	0.0031	0.0031	0.0033	0.0033	0.0033	0.0035	0.0036	0.0046	0.0046	0.0047

$$[A]=\begin{bmatrix} -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 \\ -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 \\ -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 \\ -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 \\ -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 \\ -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.230 & -0.030 & -0.030 & -0.030 \\ -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.230 & -0.030 & -0.030 \\ -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.230 & -0.030 \\ -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.030 & -0.230 \end{bmatrix} \quad (23)$$

$$[B]=\begin{bmatrix} -0.060 & -0.060 & -0.060 & -0.060 & -0.060 & -0.060 \\ -0.060 & -0.160 & -0.060 & -0.060 & -0.060 & -0.060 \\ -0.060 & -0.060 & -0.160 & -0.060 & -0.060 & -0.060 \\ -0.060 & -0.060 & -0.060 & -0.160 & -0.060 & -0.060 \\ -0.060 & -0.060 & -0.060 & -0.060 & -0.060 & -0.060 \\ -0.060 & -0.060 & -0.060 & -0.060 & -0.060 & -0.060 \end{bmatrix} \quad (24)$$

Scenarios' details are shown in Table 3. As can be seen in the scenarios 1-4, the UC without TBR programs (Sc. 1), the UC-DSRs with implementation of RTP program (Sc. 2), the UC-DSRs with implementation of TOU program (Sc. 3) and the UC-DSRs with implementation of CPP program (Sc. 4) are run and investigated. Figure 3 shows the different scheme of TBR programs. In the other word, this graph demonstrates the hourly electricity prices of RTP, TOU and CPP programs that are announced by ISO to DSRs in a day-ahead power market. As can be seen, the price of electricity before implementing TBR programs is constant and just about 0.06792 $/KWh. Moreover, the electricity price in RTP is almost different at each hour. Also, the electricity price in TOU program and CPP program are in three and four level, respectively.

The results of simulation of scenarios 1-4 have been shown in Table 4. As can be seen in all the scenarios the value of income of SSRs remains constant but the emission level of thermal power plants decrease by implementing the TBR programs. In the other word, a negative effect on the income of SSRs. As can be shown in Table 4, by running the problem of UC without TBR programs, the emission level of thermal power plants is obtained about 23,347 ton day^{-1}. Here, the amount of emission per day is used to prioritize the TBR programs from ISO's point of view. By implementing the CPP program the emission level of thermal power plants is in the lowest level. Therefore, the first priority goes for CPP program.

Figure 4 and 5 demonstrate the daily and hourly emission level of UC without TBR programs, UC-DSRs with implementation of RTP, TOU and CPP programs, respectively. As can be shown in Fig. 5, the emission level of thermal power plants without implementation of TBR programs at peak hours is high. By implementing TBR programs the emission level of thermal power plants decreases at peak and off-peak hours and increases in

Table 3: Details of different scenarios

Scenario No.	Description
1	UC without DRPs
2	UC-DSRs with Implementation of RTP Program
3	UC-DSRs with Implementation of TOU Program
4	UC-DSRs with Implementation of CPP Program

Table 4: Results of simulation of UC without TBR programs, UC-DSRs with implementation of RTP, TOU and CPP programs (Sc. 1-4)

Scenario No.	Emission level (ton day^{-1})	Income of SSRs ($/day)	Cost of SSRs ($/day)	Profit of SSRs ($/day)	Prioritizing the TBR programs
1	23,347	2,305,800	1,176,100	1,129,700	-
2	23,208	2,305,800	1,149,600	1,156,200	3
3	22,973	2,305,800	1,126,100	1,179,700	2
4	22,956	2,305,800	1,124,200	1,181,600	1

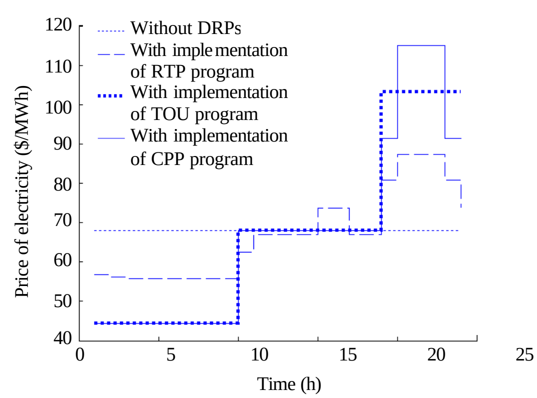

Fig. 3: The hourly electricity prices of RTP, TOU and CPP programs ($/Mwh)

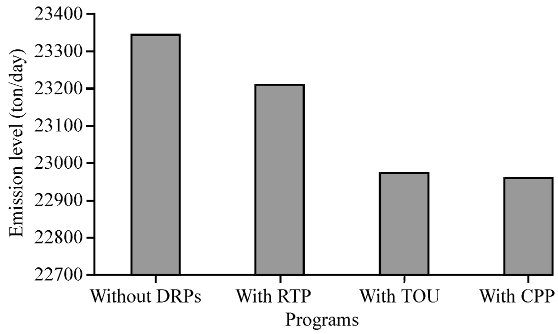

Fig. 4: The daily emission level of thermal power plants (ton/day) without TBR programs with implementation of RTP, TOU and CPP programs

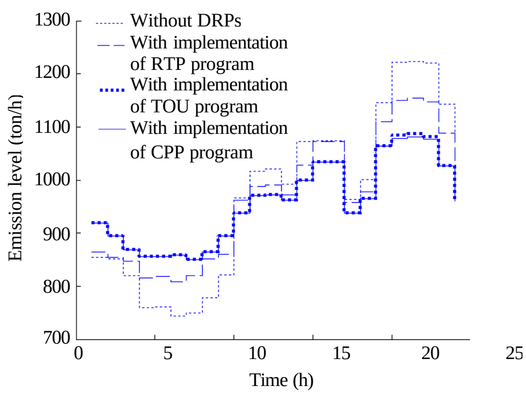

Fig. 5: The hourly emission level of thermal power plants (ton/day) without TBR programs with implementation of RTP, TOU and CPP programs

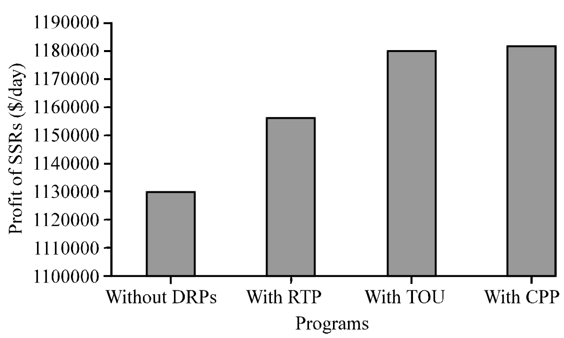

Fig. 6: The daily profit of SSRs without TBR programs, with implementation of RTP, TOU, and CPP programs

valley hours. However as can be shown in Fig. 4, the daily emission level decreases by implementing TBR programs.

On the other hand, implementing TBR programs not only decrease the emission level of thermal power plants but also increase the profit of SSRs by decreasing the cost of electricity generation. As can be shown in Table 4, by implementing the CPP program the most reduction in the cost of electricity generation is occurred and so the most profit is obtained for SSRs. Figure 6 demonstrates the profit of SSRs without TBR programs with implementation of RTP, TOU and CPP programs.

Table 5: Commitment and generation schedule of units in Cost-Based UC without DRPs (Sc. 1)

h	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
1	300	300	240	240	65	0	0	0	0	0
2	300	300	240	240	40	0	0	0	0	0
3	300	300	240	216	30	0	0	0	0	0
4	300	300	240	155	30	0	0	0	0	0
5	300	300	240	157	30	0	0	0	0	0
6	300	300	240	132	30	0	0	0	0	0
7	300	300	240	141	30	0	0	0	0	0
8	300	300	240	177	30	0	0	0	0	0
9	300	300	240	217	30	0	0	0	0	0
10	300	300	240	240	220	67	0	0	0	0
11	300	300	240	240	220	163	25	0	0	0
12	300	300	240	240	220	167	25	0	0	0
13	300	300	240	240	220	133	25	0	0	0
14	300	300	240	240	220	214	25	0	0	0
15	300	300	240	240	220	220	39	20	0	0
16	300	300	240	240	220	220	39	20	0	0
17	300	300	240	240	220	72	25	0	0	0
18	300	300	240	240	220	144	25	0	0	0
19	300	300	240	240	220	220	180	72	20	0
20	300	300	240	240	220	220	180	180	63	20
21	300	300	240	240	220	220	180	180	72	20
22	300	300	240	240	220	220	180	180	55	20
23	300	300	240	240	220	220	180	32	20	0
24	300	300	240	240	220	220	57	20	0	0

Table 6: Commitment status of units in cost-based UC with implementation of RTP program (Sc. 2)

Unit	H1-24
U1-5	111111111111111111111111
U6	111000000111111111111111
U7	000000000011111111111111
U8	000000000000000000111111
U9	000000000000000000011100
U10	000000000000000000000000

The commitment and generation schedule of units in cost-based UC without TBR programs (Sc. 1) has been shown in Table 5. Moreover, the commitment status of units in cost-based UC with implementation of RTP program (Sc. 2) has been shown in Table 6. The shaded boxes show the difference in the output power of generating units between the UC without TBR programs and the UC with RTP program. As can be seen by running the RTP program the commitment of polluted units has been differed. In the other word, the most polluted Unit (U10) is kept off in the whole scheduling period. Also, the commitment of other more polluted units (U8-9) is decreased and the commitment of other less polluted Unit (U6) is increased.

The commitment status of units in cost-based UC with implementation of TOU or CPP program (Sc. 3, 4) has been shown in Table 7. The highlighted boxes show the difference in the output power of generating units

Table 7: Commitment status of units in cost-based UC with implementation of TOU program or CPP program (Sc. 3, 4)

Unit	h1-24
U1-5	111111111111111111111111
U6	111000111111111111111111
U7	000000000111111111111111
U8	000000000000000000011100
U9	000000000000000000000000
U10	000000000000000000000000

between the UC without TBR programs and the UC with TOU or CPP program. As can be seen by implementing TOU or CPP program the commitment of polluted units has more been differed in comparison with the UC with CPP program. Because, the TOU and CPP programs are more popular than the RTP program and responsive loads have more responded to these programs and have more shifted their demand from peak hours to other hours.

CONCLUSION

In this study, effect of changes in DRPs on emission level of thermal power plants and profit of SSRs were investigated. It was observed that implementing TBR programs has a good potential for decreasing the emission level of thermal power plants and also for increasing the profit of SSRs. By implementing TBR programs the commitment of polluted units is differed. In the other word, the commitment of more polluted units is decreased and the commitment of less polluted units is increased. With prioritizing TBR programs form ISO's point of view with the aim of lowest emission level, the CPP program had the first priority. Also, this program made the most profit for SSRs.

NOMENCLATURE

a_E-c_E (i)	=	Emission level coefficients of unit i
a_F-c_F (i)	=	Fuel cost coefficients of unit i
CGSF	=	Consumers' gross surplus function
CNSF	=	Consumers' net surplus function
D_0 (t)	=	Initial demand of system before implementation of TBR programs
D_{TBR} (t)	=	Value of demand after implementation of TBR programs
E (t, t)	=	Self elasticity of demand
E (t, t')	=	Cross elasticity of demand
EL (i, t)	=	Emission level of unit i
FC (i, t)	=	Fuel cost of unit i
MDT (i)	=	Minimum down time of unit i
MUT (i)	=	Minimum up time of unit i
Ng	=	Number of units of SSRs
P (i, t)	=	Value of generation of unit i
P_{max} (i, t)	=	Maximum generation of unit i
P_{min} (i, t)	=	Minimum generation of unit i
PR_0^E (t)	=	Initial price of electricity before implementation of TBR programs
PR^E (t)	=	Modified price of electricity related to TBR programs after implementation of TBR programs
R (t)	=	Value of spinning reserve of system
STUC (i, t)	=	Start-up cost of unit i
SHDC (i, t)	=	Shut-down cost of unit i
TC	=	Total cost of UC
T	=	Number of hours for the scheduling period
T_{OFF} (i)	=	Number of hours which the unit i is continuously off
T_{ON} (i)	=	Number of hours which the unit i is continuously on
u (i, t)	=	Unit status indicator at hour t where 1 means on and 0 means off

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