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A COORDINATION MECHANISM FOR MAINTENANCE SCHEDULING OF GENERATING UNITS IN THE RESTRUCTURED POWER SYSTEMS BASED ON GAME THEORY CONSIDERING PAY-AS-BID AND MCP PAYMENT MECHANISM

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Abstract- This paper presents a novel approach for Maintenance Scheduling of Generating Units (MSU) in competitive electricity markets. In this environment, Generation Companies (Gencos) seek to maximize their own profits from the market and they are not no longer concern about meeting the demands and system reliability. On the other hand, Independent System Operator (ISO) is still responsible for system security and reliability. ISO tries to preserve system security with setting penalties for Gencos which maintenance scheduling of their units make system unreliable. ISO computes these penalties with calculating Expected Energy Not Supply (EENS) index and considering Value Of Lost Load (VOLL). The final profits of Gencos achieve after subtracting these penalties from their revenues. Under this situation, the MSU problem is formulated as a dynamic noncooperative game with complete information and optimal strategies of Gencos is defined with Nash Equilibrium. From other point of view, considering the two payment mechanism in different markets, i.e. Pay-as-Bid and Market Clearing Price (MCP), Gencos face with different situation for computing their profits. Numerical results for a simple two-Genco system and Roy Billinton Test System (RBTS) indicate the basic concept and applicability of proposed method. These results depict that MSU problem is very vital for Gencos in order to maximize their own profits from the market. Otherwise, without ISO supervision system reliability may not be guarantee. Also different impact of ISO's regulation mechanism in Pay-as-Bid and MCP payment Mechanism is compared.

Keywords: Competitive Electricity Market, Maintenance Scheduling of Generating Units, Dynamic Noncooperative Game, Nash Equilibrium, Reliability Index, Expected Energy Not Supply.

I. INTRODUCTION

Maintenance scheduling of generating units play a very significant role in secure and economical operation of power systems. In centrally integrated systems, system operator derived maintenance scheduling of generating units with target of achieving a blend between improving power system reliability and decreasing whole system costs. The system operator imposed this program to all producers. Many researches have been done in this area considering different objective functions [1-4]. But this centralized framework is not anymore workable in restructured power systems. In new situation, each generation company seeks to maximize its own profit from the market and has no concern about providing demand, while ISO is still responsible for wide system reliability and security [5].

So in power market environment, maintenance scheduling has been done through different participants that they have not common goals necessarily. Therefore, new methods are needed in order to optimize goals of market participants and preserving system reliability. [6] presented a game theoretic framework for privatized Gencos to set maintenance schedule of their units in order to receive maximum profits from the market, but it did not point to system reliability and the role of ISO. Taking into account the both goals of Gencos and ISO, [7] proposed an iterative solution based on incentive/disincentive for MSU problem. It assumed individual Gencos as price-takers and did not consider market power and price forecasting condition.

The [8] addressed coordination maintenance scheduling in restructured power system based on bus-wise unserved energy. Coordination process is based on Genco's responsibility for unserved energy using concept of commons and domains. In [9], the objective function of each Genco is to sell electricity as much as possible while ISO goals are preserving reserve capacity and limiting energy purchase costs. This paper applied genetic algorithm for solving the MSU problem. The scheme proposed in [10] tries to access a balance between Genco's benefits and ISO's responsibility for reliability. Considering maintenance bidding costs and satisfaction degrees of Gencos for each maintenance window and also load curtailment conditions, ISO coordinates the Genco's maintenance requests.

However in this paper the gamic behavior of Gencos and price forecasting condition is not mentioned. The [11] investigated the effects of maintenance on economical risk of individual producers. The [12] addressed a regulation mechanism for coordinating generation and transmission maintenance scheduling in a deregulated power system. The [13] offered a coordination mechanism for long term generation and transmission maintenance facilities. Factor that may affect optimal maintenance outages such as, random outages of generators and transmission lines, load forecast errors and fuel price fluctuation are taking into account, too.

The [14] presented a game theoretic model to determine the best maintenance decision or dispatch strategy for Gencos. The [15] discussed only maintenance scheduling of transmission lines in market environment. The purpose of this paper is to determine optimal time interval for maintenance outages of transmission lines, within a yearly time horizon, considering two constraints: First the transmission system adequacy and second market operation. The [16] solved generation maintenance scheduling problem in power market. This paper introduced ISO as a responsible organization for scheduling facilities maintenance and did not consider independent goals of individual Gencos.

In this paper a new method based on game theory for MSU problem is presented. In power market environment Gencos aim to schedule their units for maintenance in order to maximize their own profit from the market. But if the maintenance scheduling of generating units determine only by Genco's decisions the system security could not be guarantee. Therefore ISO tries to encourage producers to regulate their maintenance intervals in a manner which assure system reliability. For this reason ISO specifies penalties for units which their maintenance caused unreliable conditions. Also we consider different situation of pay-as-bid and MCP payment mechanism and distinct effect of these situations on Gencos profits and their decision for maintenance scheduling of their units.

The rest of this paper is organized as follows. Section II describes the proposed method and solution methodology. Section III presents simulation results for a simple two-Genco system and RBTS. The conclusion is drawn in section IV.

II. PROBLEM FORMULATION

A. Gencos Problem

In restructured power systems, power producers' target is to achieve as much as possible from selling their energy in a given horizon time and maximize their profits. In this environment, MSU problem has a vital role in final profits that Gencos catch from the market. Different maintenance windows can affect the available resources and electricity selling price and so Genco's profits. On the other hand, different market prices and Genco's profits affect Genco's decision for maintenance scheduling of their units. Thus the profit of a Genco and its strategy for maintenance scheduling of its unit could not determine by its own decision only and other Gencos decisions can affect it, too. Therefore game theory is a good tool for modelling MSU problem. In this paper MSU problem is modelled as a dynamic noncooperative game with complete information in which individual Gencos corresponds to players.

The time horizon is one year that can divide into 52 weeks or stages. The state of a unit can be defined as {0, 1}. 0 means that the unit is out for maintenance and 1 means that the unit is available for generating. Mention that a week is the minimum time required for maintenance so the unit state stay invariant in each stage. In each stage we have 168 Hourly Energy Auction (HEA) in the spot market.

The objective function of Gencos is making their profits maximum from the market. The profit of a Genco is the sum of its cumulative profit from HEAs. This profit can be defined by both maintenance and bidding strategies of Gencos [17]. But bidding strategy is not the main contribution of this paper and we only focus on maintenance strategy. For simplification we assume that the offer of each Genco is equal to marginal cost of it. In other words we model the market as complete information and perfect competition market. The profit of each Genco in each stage is defined as (1).

$$\prod_i^k (x^k) = \sum_{t=1}^{168} \{ \sum_{j=1}^{N_i} [p^t(x^k).q_{i,j}^t(x^k) - f_{i,j}(x^k)] \} - \sum_{j=1}^{N_i} m_{i,j}(x_i^k) \quad (1)$$

where $\prod_i^k (x^k)$ is the profit of ith Genco in kth week, x^k is the unit state in kth week, N_i is the number of ith Genco units, p^t is the hourly price in each hour, $q_{i,j}^t$ is the power that jth unit of ith Genco produce, $f_{i,j}$ is the cost function of jth unit of ith Genco, $m_{i,j}$ is the maintenance cost of jth unit of ith Genco.

The first part of Equation (1) indicates the revenue of each unit from selling their energy in market. The second part shows operating cost and the third part maintenance cost.

The profit of each Genco in whole time horizon is the sum of its revenue in all stages.

$$\prod_i = \sum_{k \in K} \prod_i^k (x^k) \quad (2)$$

The cost function of each unit is modelled as a quadratic function and is presented as (3)

$$f_{i,j}(q_{i,j}^t) = a_{i,j} + b_{i,j}.q_{i,j}^t + c_{i,j}(q_{i,j}^t)^2 \quad (3)$$

where $a_{i,j}$, $b_{i,j}$ and $c_{i,j}$ are cost coefficients. In this model we suppose that HEA market is operated as a completely competitive market and generating units offer prices are equal to their marginal costs.

We consider the both MCP and pay-as-bid payment mechanism and evaluate the effects of these two different payment mechanisms on Genco's maintenance strategies and impact of ISO's regulation mechanism on Gencos' profits.

In MCP mechanism the market clearing price at each hour is calculated by the offer price of marginal costs that results in supply quantity meeting the forecast demand at the time.

$$p^t = \max_{i \in N, j \in N_i} \{ p_{i,j}(q_{i,j}^t) : q_{i,j}^t > 0 \} \quad (4)$$

where

$$p_{i,j}(q_{i,j}^t) = b_{i,j} + 2c_{i,j} q_{i,j}^t \quad (5)$$

But in pay-as-bid mechanism the amount that each producer receives is equal to its offer price and its expression is given by (5). The constraints of this problem are:

- Load demand
- Maintenance interval
- Maintenance continuity
- Maintenance window
- Maximum and minimum power generation

B. ISO Problem

ISO's main duty is to guarantee system reliability. ISO must check the Genco's maintenance schedules. If their proposed maintenance program leads to unreliable situation ISO makes Gencos to change their maintenance program. For this purpose ISO set penalties and Gencos see these penalties in their final profits and then calculate their optimal strategies.

ISO computes the Expected Energy Not Supply (EENS) for each maintenance feasible state at each stage and then compare it with the base criteria. If EENS related to maintenance schedules of Gencos' proposed program was higher than the base criteria, ISO set the penalties. These penalties are based on EENS in each time interval and the Value of Lost Load (VOLL). The value of energy curtailment is much more than supplying it, for example 50 times bigger than it [18].

So for evaluating the price of energy curtailment we use the product of EENS and VOLL. The penalties are allocated to generating units based on their capacity on maintenance in each time interval. After subtracting these penalties from their revenues, Gencos compute their final profit from the market in whole time horizon and base of these final profits they find their optimal maintenance strategies.

C. Solution Procedure

For analyzing each Genco's strategy in MSU problem we use game theory. We model MSU problem as a noncooperative dynamic game with complete information and Nash Equilibrium is used as the solution of this game. So the game solution is:

$$X^{Nash} \triangleq [x_1^{Nash}, x_2^{Nash}, ..., x_N^{Nash}]^{tr} \quad (6)$$

which

$$\prod_i^j (x_i^{Nash}, x_{-i}^{Nash}) \geq \prod_i^j (x_i, x_{-i}^{Nash}) \quad (7)$$

For $i = 1, 2, ..., N \quad \forall j, \forall x_i \in X$ and X is the total feasible solutions, where

$$x_{-i}^{Nash} = [x_1^{Nash}, x_2^{Nash}, ..., x_{i-1}^{Nash}, x_{i+1}^{Nash}, ..., x_N^{Nash}] \quad (8)$$

At each stage, Gencos decide about their maintenance and bidding offers simultaneously. We used game tree model to represent the concept of dynamic games. We use backward induction method to solve this problem. In this method we begin from the last node of the game and in each node the respective player choose the strategy that has best payoff for him.

III. SIMULATION RESULTS

A. Simple Test System

Here we introduce a small test system consist of two Gencos which Genco1 owns two units and Genco1 one unit. The generators' data is presented in Table 1.

Table 1. Generating units' data of simple test system

Genco	units	$w_{i,j}$	P_{max} [MW]	P_{min} [MW]	$a_{i,j}$	$b_{i,j}$	$c_{i,j}$
Genco 1	$G_{1,1}$	1	120	30	0.005	0.1	7.5
	$G_{1,2}$	2	95	10	0.0025	0.5	0.1
Genco 2	$G_{2,1}$	1	100	5	0.002	0.6	0.05

In Table 1, $w_{i,j}$ stands for the time intervals needed for unit maintenance. P_{max} and P_{min} express the maximum and minimum power produced by each unit and $a_{i,j}$, $b_{i,j}$ and $c_{i,j}$ are the cost coefficient in cost function introduced by (3).

In this case we consider four weeks as time horizon and the Gencos schedules maintenance of their units in these four weeks. Totally we have 672 HEA in this time horizon and Gencos calculate their profits in these 672 HEA. The peak load of these four weeks is presented in Table 2 and the load curve in these four weeks is displayed in Figure 1.

Table 2. Weekly peak load of simple test system

Week	1	2	3	4
Peak load [MW]	150	180	165	90

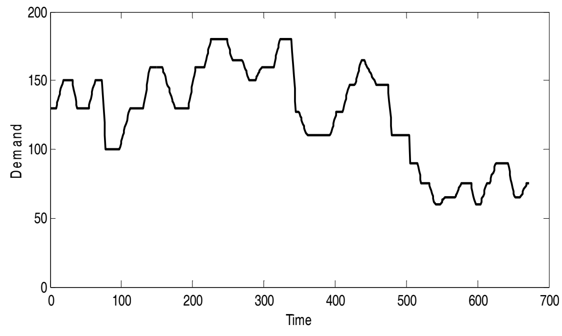

Figure 1. Load curve of simple test system

Considering generation units' capacities and the peak load of each week, 12 feasible states are existed. These states are shown in Table 3.

Table 3. Gencos' strategies in feasible states

Feasible state	Gencos' strategy
X^1	{[(0,1,1,1)(1,0,0,1)],(1,1,1,0)}
X^2	{[(0,1,1,1)(1,1,0,0)],(1,1,1,0)}
X^3	{[(0,1,1,1)(1,0,0,1)],(1,0,1,1)}
X^4	{[(1,0,1,1)(1,1,0,0)],(0,1,1,1)}
X^5	{[(1,0,1,1)(1,1,0,0)],(1,1,1,0)}
X^6	{[(1,1,0,1)(0,0,1,1)],(1,1,1,0)}
X^7	{[(1,1,1,0)(0,0,1,1)],(1,1,0,1)}
X^8	{[(1,1,1,0)(0,0,1,1)],(1,1,1,0)}
X^9	{[(1,1,1,0)(1,1,0,0)],(0,1,1,1)}
X^{10}	{[(1,1,1,0)(1,0,0,1)],(0,1,1,1)}
X^{11}	{[(1,1,1,0)(1,0,0,1)],(1,1,1,0)}
X^{12}	{[(1,1,1,0)(1,1,0,0)],(1,0,1,1)}

In this modulation the first bracket shows Genco1's units strategies for maintenance. For example X^1 has the maintenance strategy like: [(0, 1, 1, 1), (1, 0, 0, 1)]. It shows that $G_{1,1}$ goes in maintenance at first week. $G_{1,2}$ is off for maintenance in second and third weeks. The term (1, 1, 1, 0) shows maintenance strategy of $G_{2,1}$. The maintenance interval of this unit is last week and so on for other strategies. The game tree model of this game is illustrated in Figure 2 for X^2 and X^{10}. As mentioned before, we consider both MCP and pay-as-bid payment mechanism and at the end we compare the simulation results for these two conditions.

B. MCP Mechanism

In MCP mechanism the amount received by each Genco is equal to maximum offer price of Gencos that meet the demand. For more investigation, at first we do not consider the ISO's penalties in Gencos' profits. In this situation, the profits of two Gencos in 12 feasible states are as Table 4. After solving this game with backward induction method the Nash equilibrium is in first state. The profits of Gencos in this state are as Table 5. In this state the reliability indexes in four weeks are as Table 6.

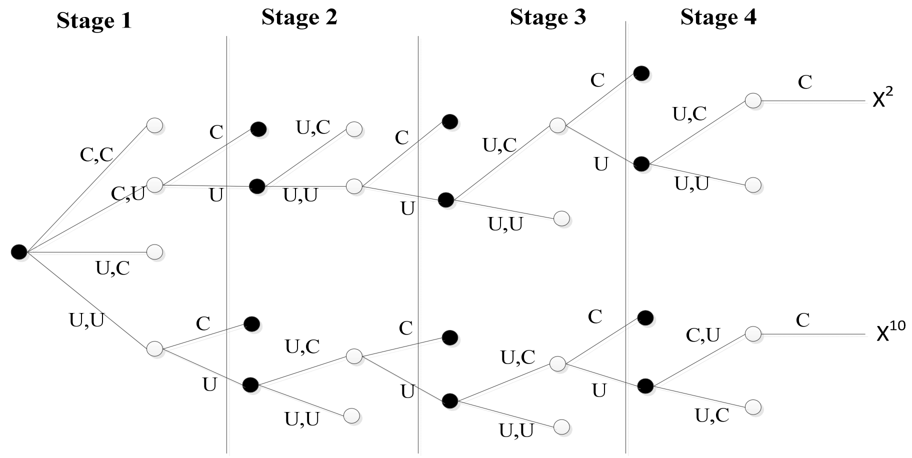

Figure 2. Game tree and Gencos' payoffs of the two feasible states

Table 4. Gencos' profits in feasible states in MCP mechanism and without considering ISO's penalties

Feasible State	Profit [$]	
	Genco1	Genco2
X^1	6700435.39	14366842.80
X^2	6251987.73	13822217.04
X^3	10462507.39	10177255.80
X^4	10206761.40	10230545.77
X^5	5948561.30	12314767.32
X^6	6699738.27	14633946.92
X^7	9999739.70	14585226.47
X^8	5875135.76	19732052.20
X^9	12952043.90	13797459.09
X^{10}	10149149.20	14316048.67
X^{11}	5973111.45	19657947.40
X^{12}	12904363.45	12236719.40

Table 5. Gencos' profits in Nash equilibrium in MCP mechanism and without considering ISO's penalties

Genco	Genco 1	Genco 2
Profit [$]	6700435.39	14366842.80

Table 6. Reliability indexes in four weeks in Nash equilibrium in MCP mechanism and without considering ISO's penalties

Week	1	2	3	4
EENS	442.71	494.19	226.38	7.38
EIR	0.994715	0.994100	0.997297	0.999911

It is obvious that the reliability indexes in these four weeks are not same. In forth week the EENS is very lower than other weeks. So ISO set penalties for states in which reliability constraints do not satisfy. ISO set these penalties for each unit based on the capacity that is off for maintenance in each time interval. The penalties that ISO set for units in MCP mechanism in each state for each unit are illustrated in Table 7.

Table 7. ISO's penalties for units in each feasible state and in MCP payment mechanism

Feasible State	Unit 1	Unit 2	Unit 3
X^1	166018.20	9729916.12	99611.63
X^2	166018.20	6377207.64	1617624.77
X^3	166018.20	3189635.45	5521865.50
X^4	364529.08	3189635.45	2868760.96
X^5	364529.05	6377207.64	1617624.77
X^6	196122.16	10193015.01	99611.63
X^7	2906.53	10193015.01	2475796.65
X^8	204711.75	10193015.01	90454.02
X^9	141638.40	3121201.03	2868760.96
X^{10}	2906.53	9729916.12	2868760.96
X^{11}	204711.75	9729916.12	90454.02
X^{12}	141638.40	3121201.03	5521865.50

Gencos must consider these penalties in their final profits and after that they can find their optimal maintenance strategy. The final profits of Gencos are shown Table 8. Comparing previous state the Gencos' profits are decreasing and in some states Gencos' profits are negative. It shows that in these weeks network reliability is too low and ISO set restrict penalties for these states. In these states ISO's penalties dominate Genco's profits. In this situation the Nash equilibrium is achieved in 9th state. Gencos's profits are presented in Table 9. In this state the reliability indexes are as Table 10. After imposing ISO's penalties, reliability indexes in four weeks are much more in an acceptable range.

Table 8. Gencos' profits in MCP mechanism after imposing ISO's penalties

Feasible State	Profit [$]	
	Genco 1	Genco 2
X^1	-3195498.92	14267231.17
X^2	-291238.10	12204592.26
X^3	7106853.74	4655390.29
X^4	6652596.86	7361784.81
X^5	-793175.42	10697142.55
X^6	-3689398.90	14534335.29
X^7	-196127.84	12109429.82
X^8	-4522591.00	19641598.17
X^9	9689204.47	10928698.13
X^{10}	416326.54	11447287.711
X^{11}	-3961516.41	19567493.37
X^{12}	9641524.02	6714853.89

Table 9. Gencos' profits in MCP mechanism and after imposing ISO's penalties in Nash Equilibrium

Genco	Genco 1	Genco 2
Profit [$]	9689204.47	10928698.13

Table 10. Reliability indexes in four weeks in MCP mechanism and after imposing ISO's penalties in Nash Equilibrium

Week	1	2	3	4
EENS	212.45	22.63	226.38	491.80
EIR	0.997463	0.999729	0.997297	0.994129

C. Pay-as-Bid Mechanism

In pay-as-bid mechanism the amount each producer receives is equal to its offer. Again in pay-as-bid mechanism, at first we do not consider the role of ISO and its penalties. In this mechanism without considering ISO's penalties, Gencos' profits are shown in Table 11. Here the Nash equilibrium is the 5th state. The Gencos' profits are in Table 12. In this state the reliability indexes are in Table 13. In this state the EENS index in second week is too higher than other weeks and system is unreliable. In this situation ISO set penalties to regulate reliability. The ISO's penalties for each unit are exploited in Table 14.

In this mechanism the units with lower offer price are affected more, because the amount that they receive corresponds to their offer price. On the other the units with higher offer price affected less and maybe they do not motivate enough to change their maintenance time.
After considering these penalties the final profits of Gencos can be calculated.

Table 11. Gencos' profits in Pay-as-Bid mechanism and before imposing ISO's penalties

Feasible State	Profit [$]	
	Genco1	Genco2
X^1	3472155.393	221830.405
X^2	3463359.848	211323.667
X^3	3590131.393	154652.406
X^4	3610697.804	168112.378
X^5	3489044.571	196390.994
X^6	3471458.271	223272.928
X^7	3546429.904	181062.478
X^8	3512208.826	2031202.272
X^9	3567352.415	190675.717
X^{10}	3567352.415	175146.278
X^{11}	3513594.726	199911.072
X^{12}	3572470.726	162283.0072

Table 12. Gencos' profits in Pay-as-Bid mechanism and after imposing ISO's penalties in Nash Equilibrium

Genco	Genco 1	Genco 2
Profit [$]	3489044.571	196390.994

Table 13. Reliability indexes in four weeks in Pay-as-Bid mechanism in Nash Equilibrium and before imposing ISO's penalties

Week	1	2	3	4
EENS	12.31	736.42	226.38	245.90
EIR	0.999852	0.991202	0.907297	0.997064

Table 14. ISO's penalties for units in each feasible state and in Pay-as-Bid payment mechanism

Feasible State	Unit 1	Unit 2	Unit 3
X^1	5533.94	324330.53	3320.38
X^2	5533.94	212573.58	53920.82
X^3	5533.94	106321.18	184062.18
X^4	12150.96	106321.18	95625.36
X^5	12150.96	212573.58	53920.82
X^6	6537.40	339767.16	3320.38
X^7	96.88	339767.16	82526.55
X^8	6823.72	339767.16	3015.13
X^9	4721.28	104040.03	95625.36
X^{10}	96.88	324330.53	95625.36
X^{11}	6823.72	324330.53	3015.13
X^{12}	4721.28	104040.03	184062.18

Table 15. Gencos' profits in Pay-as-Bid mechanism after imposing ISO's penalties

Feasible State	Profit [$]	
	Genco 1	Genco 2
X^1	3142290.91	218510.01
X^2	3245252.32	157402.84
X^3	3478276.27	-29409.77
X^4	3492225.65	72487.01
X^5	3264320.01	142470.16
X^6	3125153.69	219952.54
X^7	3206565.85	98535.92
X^8	3165617.93	200105.13
X^9	3458591.10	95050.35
X^{10}	3228658.18	79520.91
X^{11}	3182440.46	196895.93
X^{12}	3463709.41	-21779.11

The Nash equilibrium is the 11th state. The reliability indexes in four weeks are as Table 16. The payoffs of Gencos in 11th state are as Table 17. Table 19 shows the weekly peak load. The maintenance window for each unit is as Table 20.

Table 16. Reliability indexes in four weeks in Pay-as-Bid mechanism and after imposing ISO's penalties in Nash Equilibrium

Week	1	2	3	4
EENS	112.31	494.19	226.38	368.85
EIR	0.999852	0.994100	0.907297	0.995597

Table 17. Gencos' profits in Pay-as-Bid mechanism and after imposing ISO's penalties in Nash Equilibrium

Genco	Genco 1	Genco 2
Profit [$]	3182440.46	196895.93

D. RBTS system

RBTS system is consisting of 11 units. The units' data are discussed in Table 18.

Table 18. Generating units' data for RBTS

Genco	Unit	P_{max} [MW]	FOR	$w_{i,j}$
Genco 1	1	40	0.02	2
	2	20	0.015	2
	3	20	0.015	2
	4	20	0.015	2
	5	20	0.015	2
	6	5	0.01	2
	7	5	0.01	2
Genco 2	8	40	0.03	2
	9	40	0.03	2
	10	20	0.025	2
	11	10	0.02	2

Table 19. Weekly peak load for RBTS

Week	Peak Load	Week	Peak Load	Week	Peak Load
1	159	19	161	37	144
2	167	20	163	38	129
3	162	21	158	39	134
4	154	22	150	40	134
5	163	23	167	41	137
6	156	24	164	42	138
7	154	25	166	43	148
8	149	26	159	44	163
9	137	27	140	45	164
10	136	28	151	46	168
11	132	29	148	47	174
12	134	30	163	48	165
13	130	31	134	49	174
14	139	32	144	50	179
15	133	33	148	51	185
16	148	34	135	52	176
17	139	35	134		
18	155	36	130		

Table 20. Maintenance windows of generating units for RBTS

Unit	Maintenance window
1	35-39
2	35-39
3	32-36
4	9-13
5	32-36
6	9-13
7	9-13
8	9-13
9	9-13
10	35-39
11	9-13

E. MCP mechanism

In MCP mechanism and without considering role of ISO, in Nash equilibrium the maintenance intervals of each unit is as Table 21. Reliability indexes in affected weeks are shown in Table 22. The EENS index in some weeks is too low and instead in some weeks EENS index is too high and more than allowed amount. In this state the Gencos profits are displayed in Table 23. After considering ISO's penalties the maintenance intervals are defined as Table 24. The reliability indexes are shown in Table 25. We can see that after imposing ISO's penalties the reliability indexes in all weeks are in same range and in an acceptable area. The profits of Gencos are decreased and are as Table 26.

Table 21. Maintenance intervals of generating units in Nash Equilibrium without considering ISO's penalties in MCP mechanism for RBTS

Unit	Maintenance interval
1	35-36
2	35-36
3	34-35
4	12-13
5	34-35
6	12-13
7	12-13
8	9-10
9	11-12
10	35-36
11	12-13

Table 22. Reliability indexes in Nash Equilibrium without considering ISO's penalties and in MCP mechanism for RBTS

Week	EENS	EIR
9	11.05	0.9999
10	11.03	0.9999
11	304.71	0.9964
12	11729.19	0.8610
13	674.38	0.9920
32	33.67	0.9998
33	33.45	0.9998
34	2.87	1.0000
35	2.34	1.0000
36	13335.08	0.9679
37	1182.98	0.9872
38	2.56	1.0000
39	43.22	0.9997

Table 23. Genco's profits in Nash Equilibrium without considering ISO's penalties and in MCP mechanism for RBTS

Genco	Genco 1	Genco 2
Profit [$]	22622320.01	17469470.16

Table 24. Maintenance intervals of generating units in Nash Equilibrium after considering ISO's penalties in MCP mechanism for RBTS

Unit	Maintenance interval
1	36-37
2	35-36
3	34-35
4	12-13
5	32-33
6	12-13
7	11-12
8	12-13
9	10-11
10	36-37
11	9-10

Table 25. Reliability indexes in Nash Equilibrium after considering ISO's penalties and in MCP mechanism for RBTS

Week	EENS	EIR
9	67.0	0.9992
10	1421.8	0.9831
11	271.9	0.9968
12	738.3	0.9907
13	56.9	0.9993
32	33.30	0.9998
33	32.83	0.9998
34	2.43	1.0000
35	59.61	0.9996
36	56.88	0.9996
37	31.27	0.9998
38	49.18	0.9996
39	59.61	0.9996

Table 26. Genco's profits in Nash Equilibrium after considering ISO's penalties and in MCP mechanism for RBTS

Genco	Genco 1	Genco 2
Profit [$]	3264320.45	142470.19

F. Pay-as-Bid Mechanism

In pay-as-bid mechanism and without considering ISO's penalties the maintenance intervals for two Gencos in Nash Equilibrium are as Table 27. In Nash Equilibrium the reliability indexes in affected weeks are illustrated in Table 28. Reliability indexes in affected weeks change in a wide range and obviously in some weeks power system is unreliable. Gencos' profits are shown in Table 29. ISO set penalties and after that the maintenance intervals of Gencos change as Table 30. This time the reliability indexes are as Table 31. It is obvious that this time reliability indexes in all weeks are in an acceptable range and ISO's penalties make system reliable. And finally Gencos' profits decrease and shown in Table 32.

Table 27. Maintenance intervals of generating units in Nash Equilibrium without considering ISO’s penalties in Pay-as-Bid mechanism for RBTS

Unit	Maintenance interval
1	35-36
2	35-36
3	33-34
4	12-13
5	33-34
6	9-10
7	12-13
8	12-13
9	12-13
10	38-39
11	10-11

Table 28. Reliability indexes in Nash Equilibrium without considering ISO’s penalties and in Pay-as-Bid mechanism for RBTS

Week	EENS	EIR
9	1.6623	1.0000
10	1.5015	1.0000
11	0.5920	1.0000
12	209.3423	0.9975
13	135.8179	0.9984
32	0.3588	1.0000
33	0.5952	1.0000
34	0.1253	1.0000
35	0.1150	1.0000
36	58.7466	0.9996
37	359.5042	0.9974
38	0.1193	1.0000
39	0.1150	1.0000

Table 29. Genco’s profits in Nash Equilibrium without considering ISO’s penalties and in Pay-as-Bid mechanism for RBTS

Genco	Genco 1	Genco 2
Profit [$]	507520	3611200

Table 30. Maintenance intervals of generating units in Nash Equilibrium after considering ISO’s penalties in Pay-as-Bid mechanism for RBTS

Unit	Maintenance interval
1	38-39
2	36-37
3	32-33
4	11-12
5	33-34
6	12-13
7	12-13
8	9-10
9	9-10
10	38-39
11	10-11

Table 31. Reliability indexes in Nash Equilibrium after considering ISO’s penalties and in Pay-as-Bid mechanism for RBTS

Week	EENS	EIR
9	28.5566	0.9997
10	26.1798	0.9997
11	4.0131	1.0000
12	17.8057	0.9998
13	1.4017	1.0000
32	0.3588	1.0000
33	0.5952	1.0000
34	0.1253	1.0000
35	3.1022	1.0000
36	0.1992	1.0000
37	0.6935	1.0000
38	3.2142	1.0000
39	3.1022	1.0000

Table 32. Genco’s profits in Nash Equilibrium after considering ISO’s penalties and in Pay-as-Bid mechanism for RBTS

Genco	Genco 1	Genco 2
Profit [$]	345630	250450

IV. CONCLUSIONS

In this paper, a new method for the MSU problem in a competitive electricity market is introduced based on game theory. This method involves both Gencos’ and ISO’s individual desires. Explicitly, Gencos seek to maximize their own profit from the HEA market in defined time horizon, which may conflict ISO’s goals for assuring reliability constraints of system. So with setting penalties based on EENS, ISO makes Gencos to change their unit maintenance time in order to keep system in a reliable manner. We use game theory to formulate MSU problem and the competition between Gencos. The MSU problem is modelled as a dynamic game with complete information. The solution is the Nash equilibrium and can be obtained from backward induction method.

For further understanding, we use a two-Genco test system and for showing the applicability of the proposed method RBTS is used, too. We also consider both pay-as-bid an MCP payment mechanism. The numerical results depicts that ISO’s penalties can improve system reliability, however profits of Gencos will decrease.

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