A New Solution for Maintenance Scheduling in Deregulated Environment based on Lost Opportunity Cost of Market Participation and Reliability

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Abstract— **This paper proposes a new method for maintenance scheduling of power generation units in deregulated environments by determining a fundamental index named Lost Opportunity Cost of Market Participation (LOCMP) based on dynamic game theory. Maintenance scheduling of power generation units in deregulated environments is a vital issue, because each Generation Company (GENCO) requires maximizing its benefits besides considering reliability concerns that is attended by Independent System Operator (ISO) side. Therefore, the paper offers a justice-oriented framework based on dynamic game theory for the maintenance scheduling problem. In this new solution, each generation company sets its strategy to minimizing the Lost Opportunity Cost of all Market Participators in a dynamic game theory by considering load uncertainty. On the other hand, ISO keeps safety of system based on its desirable reliability and its policy. The paper assessed the ISO activities by applying Monte-Carlo simulation for studying reliability indices. Numerical results are obtained by using IEEE Reliability Test System as the case study for testing correctness and applicability of the new mentioned solution.**

Keywords—Deregulated Environment, Lost Opportunity Cost of Market Participation, Maintenance Scheduling, Reliability.

I. Introduction

DEVELOPING competition in power electricity markets affects the planning of power systems in short-term horizon, and also has major impacts on mid-term and long-term operation and planning of power systems. Maintenance scheduling of power generation units is one of the main mid-term issues in planning of power systems that gets in touch with new challenges in deregulated environment.

Nowadays, decision making about maintenance scheduling in restructured power markets has been settled through players that have not the common targets presently. Thus, new solutions were required for optimizing strategies of market participants. On the other hand, preserving reliability in satisfactory limit has an important role in power system security studies. Therefore, suitable interactions between GENCOs and ISO may lead to desirable environment for competition with less reliability concerns.

Many researches have been presented through exploring applicable method for maintenance scheduling in power markets in Heuristic Levels I and II. Reference [1] offered a framework based on game theory to find Nash equilibrium for maintenance scheduling for generation units but this paper did not consider uncertainty of load and the effects of this uncertainty on reliability of system. Also, this paper did not attend to ISO managing roles in electricity market. Reference [2] obtained a criterion for risk assessment from ISO point of view. This paper presents a method that ISO ensures about reliability preservation, because of studying expected energy not supplied index in reliability calculation, but this paper didn't pay any attention to costs and benefits of other market participants such as GENCOs. In [3], taking advantage from a motivation method, the paper gives a solution for maintenance scheduling of generation units, but this paper simplify the maintenance problem by applying unreal assumptions. In order to find maintenance scheduling solution, [4] solved the problem with network considerations in about two year's horizon. This paper also didn't attend to the lost income of GENCOs because of maintenance scheduling. The maintenance scheduling in mid-term horizon has been assessed in [5], this paper also neglect the market oriented solution. Reference [6] studied a flexible maintenance solution with uncertainties and fuzzy method. Also, this paper didn't refer to power market and the lost opportunity cost of GENCOs in power electricity market. Reference [7] proposed a new solution for maintenance scheduling of generation units by presenting a maintenance market (MM). This paper used game theory for modeling the behaviors of market participants. In this method, each GENCO set its strategy solely. So, the paper did not consider any solution for justice observance in power market. In [8], a competition solution has been offered for respecting justice for GENCOs, but the paper simplified the role of reliability. In [8], each participant who tends to pay more gets the license to go for maintenance.

This paper presents a new model for maintenance scheduling of power generation units based on Lost Opportunity Cost of Market Participants (LOCMP) index and reliability indices by applying dynamic game theory and Monte-Carlo Simulation (MCS) technique. The new solution obtained in this paper is relying on modeling a fair-competitive environment by considering GENCOs and ISO that GENCOs adopt their strategies based on minimizing LOCMP to gain the Nash equilibrium. On the other hand, by using MCS, reliability indices such as energy index reliability (EIR) and energy not supplied (ENS) have been calculated through eighty thousand iterations.

Using IEEE 32-Unit reliability test system (IEEE-RTS), analytical results of solution have been checked. Therefore, this new method has many advantages such as offering a justice-oriented solution for maintenance scheduling in heuristic level I, based on network reliability assessment by considering load uncertainty, modeling the strategies of each GENCO by using dynamic game theory, presenting suitable interaction between ISO and GENCOs and determining penalties based on reliability indices, proportion to impact of each GENCO on reliability reduction of power system at each time stage. Fig. 1 presents the schema of interactions between market participants in proposed maintenance scheduling method.

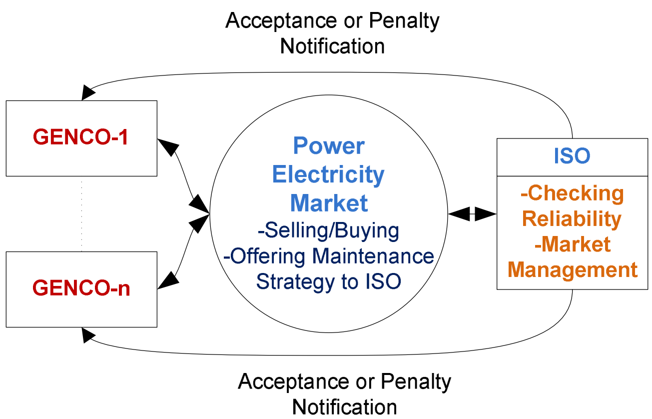

Fig. 1. Interactions between market participants in proposed maintenance solution.

II. THE MAINTENANCE SCHEDULING SOLUTION

In this section, the new maintenance scheduling method that results to a fair competition has been fully explained. Generally, the main participants of power market are GENCOs, and ISO. Independent system operator undertakes the reliability preservation of system. In this new solution, all GENCOs are going to maximize their own payoffs through minimizing the Lost Opportunity Cost of Market Participation in a dynamic game. This means that the players of market should schedule the maintenance in a way that the lost costs of all GENCOs that are derived from maintenance of each GENCO, be reduced optimally. This cost is the value of opportunity of selling electricity in power market that GENCO cannot attain it, because of its maintenance duration. After finding the Nash Equilibrium by minimizing the LOCMP, the best strategy of GENCOs has been offered to ISO. On the other hand, ISO assesses the offered Nash strategy in system reliability point of view by the MCS. ISO can accept the offer or can present a disincentive when reliability of system is lower than desired level. Further on, the roles of each market players have been discussed.

A. GENCOs Roles in Proposed Maintenance Scheduling Solution

In managing systems such as power electricity markets, main decision making variables are market participants. For modeling the participants and their behaviors in power market, a dynamic game theory has been applied. So, the strategy of each GENCO has been simulated through a dynamic tree-game based on market time stages and if the Nash equilibrium exits in the market, the market could be converged to this equilibrium point. At this point, all companies will not be sorry from their decision in market. So, in this paper strategy of GENCOs are based on maximizing GENCO's profits relying on minimizing LOCMP to attain a fair-oriented solution.

Therefore, the LOCMP of GENCOs has been written by (1):

$$LOCMP = \sum_{t}^{week}\sum_{g}^{G}(\Pr ice_t - (2aP_{\max,g,t} + b)) \times P_{\max,g,t} \times h_t \times Y_{g,t} \quad (1)$$

Where,

$\Pr ice_t$: Price for a strategy in specific time Stage (\$/MWh).

$P_{\max,g,t}$: Power generated by units in stage t (MW).

a,b : Cost Factors.

$Y_{g,t}$: Maintenance status of units in stage t (1 if unit goes to maintenance and 0 otherwise).

h_t : Maintenance hours of unit at stage-t.

The Objective function of each GENCO has been presented by (2):

$$obj = \sum_{t}^{week}\sum_{g}^{G}\begin{bmatrix}((\Pr ice_t - (C_{g,t})) \times P_{\max,g,t} \times (1 - Y_{g,t})) - \\ (mp_{g,t} \times (Y_{g,t}))\end{bmatrix} \quad (2)$$

Where,

obj : Objective Function of GENCO in specific stage.

$C_{g,t}$: Production Cost of generation units in stage t.

$mp_{g,t}$: Maintenance Cost of generation units.

The final aims of GENCOs from participating in market stages can be gained by (3):

$$Max : obj_{weeks}^{Units-of-GENCOs} \quad (3)$$

Equation (2) presents that strategy of each GENCO is relied on cost reduction and payoffs maximization in time stages of power market. So, considering all time stages, GENCOs solve their problem to determine the best strategy for maintenance. After finding the Nash strategy, GENCOs offer this strategy to ISO.

If ISO accepts the offer of GENCOs, the specified generators of each GENCO will go to maintenance.

Otherwise, ISO may determine penalties. In this method, GENCOs renew the Nash strategy based on determined disincentives for time stages (weeks). This process will not end unless reliability of system supplies by the offered strategy.

B. ISO Activities in Proposed Maintenance Scheduling Solution

ISO as a market supervisor is responsible for power system reliability preservation. This paper has used the Monte Carlo Simulation for reviewing comprehensive reliability of system and determining suitable penalties. MCS gives important reliability indices such and EIR to ISO for reliability assessment. EIR shows the reliability level of a power system. (4) shows the EIR equation [9]:

$$EIR = 1 - ENS_{p.u} \tag{4}$$

That,

$$ENS_{p.u} = \sum_{k=1}^{n} \frac{E_k P_k}{E} \tag{5}$$

Where,

$E_k\ P_k$: Energy Curtailed × Probability of energy lost.

E : Total energy under the load duration curve.

In MCS, modeling of generation on/off condition is done through generating random numbers between zero and one. For calculating the loss of load expectation (LOLE) index in each step of simulation, with calculating whole generation of system and by intersecting this with load duration curve (LDC), the unavailability time of system will be gained and also the probability of availability of system in mentioned state will be calculated. With multiplication of these two values, LOLE can be obtained. The number of iterations has been considered about 80000. For calculating ENS index by MCS, with random generation of numbers and comparing FORs, existence capacity of system are assessed. By intersecting this capacity with LDC, the energy lost value has been obtained through underneath area of annual curve. So, with (5) this value will be obtained accurately through MCS.

Therefore, ISO initially obtains the reliability of system at each time stage. Then, ISO calculates the reliability indices with considering offers of GENCOs. If the offer is feasible, maintenance solution will be gained. Otherwise, ISO starts the assessment if it can present a disincentive policy in specific stage for GENCOs. The main advantage of this method is that the penalties have been made relying on a cost that ISO should pay for keeping reliability in a satisfactory level. (6) & (7) show the method of determining disincentives based on ENS and EIR indices.

$$S_i = \left| EIR_{base_i} - EIR_{offered_i} \right|^2 \tag{6}$$

Where,

S : Quadratic Index for penalty.

EIR_{base_i} : Energy Index Reliability calculated by ISO shows desirable reliability.

$EIR_{offered_i}$: Energy Index Reliability calculated by ISO considering offers of GENCOs.

$$pen_t = \left| \frac{S_i}{\sum_{t=1}^{52} S_i} \right| \times C_{ISO-Payment,t} \tag{7}$$

Where,

pen_t : Penalty Index.

$C_{ISO-Payment,t}$: Cost paid by ISO for penalty ($).

t : Symbol for time stages.

$$C_{ISO-Payment,t} \equiv CENS_t \tag{8}$$

Where,

$CENS_t$: Cost of energy not supplied ($/MWh) in t.

Therefore, GENCOs recalculate their strategies based on presented disincentive by ISO for attaining a new Nash strategy by (9).

$$obj = \sum_{t}^{week} \sum_{g}^{G} \begin{bmatrix} ((Price_t - (C_{g,t})) \times P_{\max,g,t} \times (1 - Y_{g,t})) - \\ (mp_{g,t} \times (Y_{g,t})) - Pen_t \end{bmatrix} \tag{9}$$

Where,

Pen_t : Disincentives Index for stage t.

This process continues until reliability considerations of system have been respected.

III. Simulation Results

IEEE RTS [10] has 2850 MW annual peak load with 32 generation units. Two GENCOs are the owners of these 32 generators that participate in power market in a year (52 weeks). Table I, presents the uncertainty factors of IEEE-RTS. Table II, III and IV show the generation data, the weekly peak demand and the price data of IEEE-RTS, respectively. Additional information about schematic of IEEE-RTS and the annual LDC is considered in [10]. As it is known, ISO offers penalties to the GENCOs from (6), (7) & (8) considering the weekly value of reliability. Table V gives the penalty calculations for ISO important weeks that reliability risk of system increases during these time stages. After calculation of penalties, ISO notifies it to the GENCOs.

TABLE I
5% Load uncertainty data

Standard Deviation	Demand (MW) IEEE-RTS	Probability
-3	2422.5	0.006
-2	2565	0.061
-1	2707.5	0.242
0	2850	0.382
1	2992.5	0.242
2	3135	0.061
3	3277.5	0.006

Therefore, GENCOs re-calculate their payoffs by (9) to find the final Nash Equilibrium. Table VI shows the final strategy for ISO and GENCOs. Moreover, in this strategy, GENCOs accept the penalties of weeks 11, 12, 13, 38, 39, 40. Thus, they accept to pay totally 12876581$ as penalty for mentioned important weeks. Proportion to the role of each GENCO in reducing reliability of ISO important weeks, the penalty value divides between two GENCOs. Therefore, GENCO-1 pays 6675473.77$ and GENCO-2 pays 6201106.74$ to ISO as penalty. As a result, GENCO-1 and GENCO-2 have obtained 27950036075$ & 23935174316$ respectively as their payoffs for participating in power Market. On the other hand, ISO gets 12876581$ as the penalty proportion to the reliability reduction of each GENCO. Minimizing of LOCMP in IEEE-RTS, leads to least lost opportunity costs of two mentioned GENCOs in power electricity market. Thus, by applying this method, the fairness of maintenance scheduling of generation units of IEEE-RTS has been obtained.

TABLE II
Capacity, Forced Outage Rates and Maintenance Duration for IEEE-RTS

GENCO-1				GENCO-2			
No.	Pmax (MW)	FOR	Maintenance Duration	No.	P_{max} (MW)	FOR	Maintenance Duration
1	400	0.12	6	18	400	0.12	6
2	350	0.08	5	19	197	0.05	4
3	197	0.05	4	20	197	0.05	4
4	155	0.04	4	21	155	0.04	4
5	155	0.04	4	22	155	0.04	4
6	100	0.04	3	23	100	0.04	3
7	100	0.04	3	24	76	0.02	3
8	76	0.02	3	25	76	0.02	3
9	76	0.02	3	26	50	0.01	2
10	50	0.01	2	27	50	0.01	2
11	50	0.01	2	28	50	0.01	2
12	50	0.01	2	29	20	0.1	2
13	20	0.1	2	30	20	0.1	2
14	20	0.1	2	31	12	0.02	2
15	12	0.02	2	32	12	0.02	2
16	12	0.02	2				
17	12	0.02	2				

TABLE III
Weekly Peak Demand information for IEEE-RTS

No.	Demand(MW)	No.	Demand(MW)	No.	Demand(MW)
1	2457	19	2480	37	2223
2	2565	20	2508	38	1981
3	2502	21	2440	39	2063
4	2377	22	2311	40	2063
5	2508	23	2565	41	2118
6	2397	24	2528	42	2120
7	2371	25	2554	43	2280
8	2297	26	2454	44	2511
9	2109	27	2152	45	2522
10	2100	28	2326	46	2591
11	2038	29	2283	47	2679
12	2072	30	2508	48	2537
13	2006	31	2058	49	2685
14	2138	32	2212	50	2765
15	2055	33	2280	51	2850
16	2280	34	2078	52	2713
17	2149	35	2069		
18	2385	36	2009		

Fig. 2 shows ENS value for 12^{th} week that has been calculated by Monte-Carlo simulation with 80000 iterations as a sample. Finally, Fig. 3 presents the final accepted maintenance strategy through weekly peak load curve. Table VI and Fig. 3 show the concept that in final strategy, maintenance weeks are weeks that the load values and weekly prices are lower than other weeks of mentioned year. On the other hand, EIR is on the acceptable level for the 46 weeks and for 6 other weeks, ISO determines penalties for compensating cost of energy not supplied.

TABLE IV
Weekly Price ($/MWh) for IEEE-RTS

No.	Price ($/MWh)	No.	Price ($/MWh)	No.	Price ($/MWh)
1	57	19	57	37	51
2	59	20	58	38	46
3	58	21	57	39	48
4	55	22	54	40	48
5	58	23	59	41	49
6	56	24	59	42	49
7	55	25	59	43	53
8	53	26	57	44	58
9	49	27	50	45	58
10	49	28	54	46	60
11	47	29	53	47	62
12	48	30	58	48	59
13	46	31	48	49	62
14	50	32	51	50	64
15	48	33	53	51	66
16	53	34	48	52	63
17	50	35	48		
18	55	36	47		

TABLE V
Penalty Calculation Based on Reliability assessment for ISO important weeks

Imp. Weeks	11	12	13	38	39	40
ENS (MWh)	1951.06	2525.30	2503.99	3123.12	3044.16	708.75
EIR	0.99001	0.98744	0.98682	0.98319	0.98475	0.99645
EIR_{Base}	0.996	0.996	0.996	0.997	0.997	0.997
S	0.00003	0.00007	0.00008	0.00019	0.00015	3.0E-07
$C_{ISO\text{-}PAY}$ Million$	10	10	10	12	12	12
Pen Million$	0.7655	1.5648	1.8000	4.8889	3.84934	0.00778

TABLE VI
Final Results for IEEE-RTS Maintenance Scheduling

Unit No.	Maintenance Weeks	Unit No.	Maintenance Weeks
1	35,36,37,38,39,40	19	10,11,12,13
2	11,12,13,14,15	20	10,11,12,13
3	10,11,12,13	21	38,39,40,41
4	10,11,12,13	22	10,11,12,13
5	38,39,40,41	23	36,37,38
6	13,14,15	24	34,35,36
7	38,39,40	25	34,35,36
8	34,35,36	26	11,12
9	34,35,36	27	40,41
10	38,39	28	38,39
11	35,36	29	38,39
12	35,36	30	38,39
13	12,13	31	38,39
14	13,14	32	38,39
15	35,36		
16	35,36		
17	35,36		
18	35,36,37,38,39,40		

As a result, IEEE-RTS case study gives the fact that by considering this new method, the fairness of maintenance scheduling for all participants in market has been achieved considerably. Therefore, this new solution could be successfully applied for maintenance scheduling issue in a justice-oriented competitive market environment.

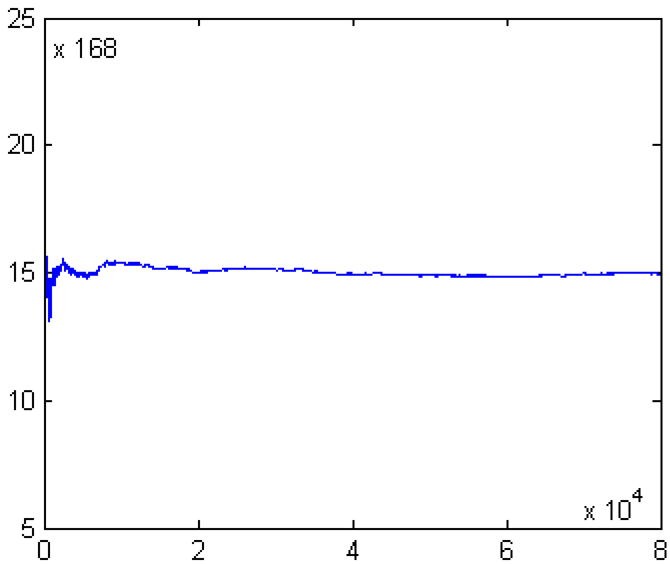

Fig. 2. ENS calculation of 12th week in IEEE-RTS by Monte Carlo Simulation with eighty thousand iterations.

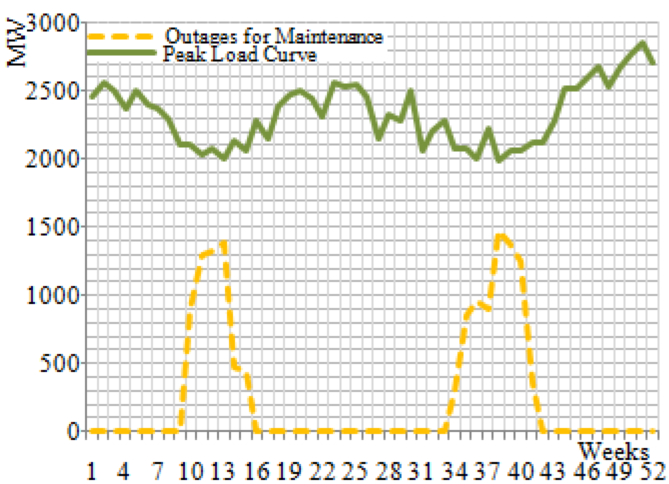

Fig. 3. Final maintenance strategy and peak load curve in IEEE-RTS.

IV. Conclusion

This paper presents a new justice-oriented solution for maintenance scheduling for power generation units based on minimizing lost opportunity costs of all market participants by applying dynamic game theory for achieving Nash equilibrium of market by Backward Induction method and also, supplying the main goal of ISO that is the preserving reliability of system by using Monte Carlo Simulation technique in order to study ENS and EIR indices.

For testing the correctness and the accuracy of this mentioned solution for maintenance scheduling of power generation units, IEEE Reliability Test System has been studied as an applicable case study. As a result, the best efficient and fair strategies for GENCOs in IEEE-RTS are obtained through this new presented method besides keeping reliability of system in a desirable level.

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