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A NEW SOLUTION FOR MAINTENANCE SCHEDULING OF DISTRIBUTED GENERATIONS BASED ON MONTE-CARLO SIMULATION AND GAME THEORY

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Abstract. This paper presents a new solution for maintenance scheduling of Distributed Generation (DG) in deregulated power markets by applying an independent market for DG maintenance scheduling based on game theory. Maintenance scheduling is one of the important issues in restructured power electricity markets, because each distribution generation company desires to maximize its own payoffs and independent system operator (ISO) has its own reliability concerns that mostly, these two points of view are against with each other. The paper presents a dynamic Distribution Resources Maintenance Market (DRMM) based on dynamic game theory for resolving maintenance scheduling problem of distributed generation resources in deregulated environment. In this market, distribution generation companies are set their strategies to participate in DRMM by considering load, primary resources and seasonal forced outage rate uncertainties and behaviour of other DG companies that participate in market. On the other hand, ISO manages the maintenance market based on reliability and offering incentives /penalties for DG companies. This paper studied the ISO acts by using Monte-Carlo simulation for reliability indices assessment relying on load and resources uncertainties and interactions between DG companies. Numerical results are determined by using an applicable case study for testing accuracy and applicability of the new proposed solution.

Key words

Distributed Generation, Maintenance Scheduling, DG Maintenance Market, Monte-Carlo, Game Theory.

1. Introduction

Maintenance scheduling of distributed generation units is one of the most important mid-term issues in planning that has faced with new challenges in deregulated power electricity markets. Nowadays, maintenance scheduling costs of distributed generation grows by requesting higher reliability for a network.

On the other hand, decision making about specific problem such as maintenance scheduling in restructured environment has been done through different participants that have not the common goals necessarily. This issue and other DG maintenance scheduling issues such as uncertainty of resources, leads to considered that new methods were needed for optimizing costs and benefits of DG companies besides preserving desired reliability of system. Many researches have been done through finding most suitable solution for maintenance scheduling issue in deregulated structure in Hierarchical I and II levels (HLI, HLII) but most of them did not attend to the distributed resources maintenance scheduling problems [1]- [8].

Reference [1] offered a framework based on game theory to find Nash equilibrium 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 roles and distributed resources. Reference [2] obtained a criterion for risk assessment from ISO point of view. This paper didn't pay any attention to costs and benefits of other market participants such as GENCOs. In [3], by a motivational method, the paper presents a solution for maintenance scheduling of generation units, but this paper simplify the maintenance issue. In order to find maintenance scheduling solution, [4] solved the problem with network considerations. This paper also didn't attend to the lost income of GENCOs because of maintenance scheduling. The maintenance scheduling in a mid-term horizon has been considered in [5], this paper, neglects the market considerations and effects. Reference [6] studied a flexible maintenance solution with uncertainties with fuzzy evaluation. This paper didn't refer to power 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. This paper also did not assess distributed generation resources. In [8], a competitive solution has been proposed for respecting fairness for GENCOs, but in [8], each participant who desires to pay more gets the maintenance licence.

This paper proposes a new competitive model in HLI for DG maintenance scheduling of distributed generation units based on simulating an independent distribution resources maintenance market (DRMM) using dynamic game theory. The new method presented in this paper is accordance to simulating a competition environment by considering load and resource uncertainties.

So, each participant regulates its decision based on strategy of other players to gain the Nash equilibrium. On the other hand, by applying Monte-Carlo Simulation (MCS) technique, reliability indices such as expected energy not supplied (EENS) and energy index reliability (EIR) have been obtained by considering uncertainties of load and forced outage rate of each DG unit. Taking benefit from these indices, incentives or disincentives of ISO have been explored. In this paper, the number of iterations for MCS considered about 100000.

Therefore, by applying a sample test system numerical results of market performance have been presented. So, this new solution has many advantages such as presenting a comprehensive market oriented solution for DG maintenance scheduling based on precise computations and covering network reliability by considering load uncertainty and uncertainty of primary resources, simulating the strategies of each DG company in DRMM by using dynamic game theory, interactions between ISO and DG companies and retailers, and determining incentives or penalties based on EIR index. Generally, the initial schema of DRMM is based on Fig. 1.

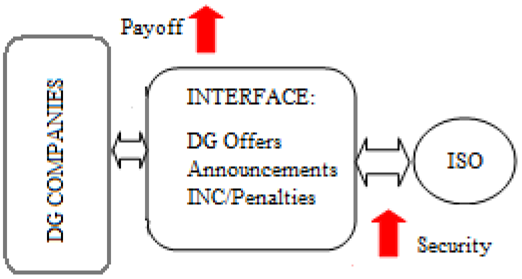

Fig. 1. Schema of Maintenance Market and its Interface.

The main participants of DRMM are DG Companies and ISO. ISO is responsible for market management. Each DG company is going to maximize its own payoffs in both main electricity market and DRMM through its uncertainties. On the other hand, ISO covers the network reliability concerns by the DRMM. At first, each DG company gives its offer in DRMM to the ISO. Then, ISO informs the DRMM participants by a Market Interface. In cases such as opening/closing time of DRMM, announcing acceptance or rejection of offers in time stages and incentive/disincentive to DRMM participants.

2. The Maintenance Scheduling Solution

In this section, the new maintenance scheduling method for distributed generation companies (DGENCOs) that result to a competitive DRMM has been fully explained.

A. GENCOs in DG Maintenance Market

In this paper, the strategy of each participant has been modeled through a game based on market conditions. If the equilibrium point exits in the market, the market should be converged to the Nash equilibrium. So, in this paper strategy of each DG company is based on maximizing DG company's profits considering both auction and DG maintenance markets and the decisions of other DG companies. Herein, the objective function of each DGENCO has been written by (1):

$$Max \prod_{g,w}^{G,week} = \sum_{w}^{week}\sum_{g}^{G}\left[\begin{array}{l}((Price_w - C_g)\times P_{\max,g}\times(1-\lambda_{g,w}))\\ -(\theta_{g,w}\times(\lambda_{g,w}))\end{array}\right] \quad (1)$$

Where,

$Price_w$: Weekly Price of selling power to Retailer for a strategy ($/MWh).

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

C_g : Cost Function of each DG unit.

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

$\theta_{g,w}$: Maintenance Cost of generation units ($).

Therefore, the strategy of each DG company is based on decreasing its costs and maximizing its own payoffs in both main market and DRMM. So, each DG company solves its own problem by considering game of other DG companies and determines its best strategy in DRMM and main market. By considering all existing strategies for themselves, DG companies announce ISO if they desire to participate in DRMM in specific stage or not. If ISO accepts the offer of a DG company, the specified units of this DG Company will go to maintenance. Otherwise, ISO may propose incentives or penalties for DG companies before closing the annual DRMM. In this situation, each DG company obtains its new strategy by optimizing its objective function based on determined incentives or disincentives. This process continues until ISO announce closing the DRMM and find the Nash equilibrium at the specific market stage.

On the other hand, one of the main distributed resources that have been assessed in this paper is the wind. Because of high initial resource uncertainty, the cost and benefit evaluation of wind resources is a complicate issue. The output power of wind farm plant continuously changes with the wind speed. Thus, the amount of selling power to retailers is completely depends on wind regime. Also, the maintenance scheduling of wind power plants has a vital role in final payoffs of distributed generation companies. The DGENCOs desire goes to maintenance in weeks that the selling price of auction market is in the lowest level or the wind regime doesn't in a suitable power producible situation. This situation specially occurs when the speed of wind is very low. Thus, in this paper, each DGENCO has wind farms and tries to maximize their payoffs that will gain through their wind turbines. The objective function of wind turbine that is a part of (1) can be written as (2):

$$Max \prod_{w}^{week} = \sum_{w}^{week}\left[\begin{array}{l}((Price_w - C_{wind})\times P_{\max,m}\times(1-\lambda_w))\\ -(\theta_w\times(\lambda_w))\end{array}\right] \quad (2)$$

Where,

$\Pr ice_w$: Weekly price of selling power to Retailer for a strategy ($/MWh).

$P_{\max,m}$: Average Power generated by units in each month (MW).

C_{wind} : Cost Function of wind unit.

λ_w : Wind maintenance status in stage t (1 if unit goes to maintenance and 0 otherwise).

θ_w : Maintenance Cost of wind plant ($).

It should be mentioned that the wind payoff maximization is being done through weekly stages. So, the weekly maximum power of wind turbines considered as mean power of each month that is estimated by the wind turbine characteristics [9] (3).

$$P_w = \begin{cases} 0 & 0 \le S_w \le V_{ci} \\ [A + B \times S_w + C \times S_w^2] P_r & V_{ci} \le S_w \le V_r \\ P_r & V_r \le S_w \le V_{co} \\ 0 & V_{co} \le S_w \end{cases} \quad (3)$$

Where,

P_w : Total Power Generation of Wind Turbine (MW).

P_r : Nominal Power of Wind Turbine (MW).

S_w : Wind Speed (m/s).

V_{ci} : Cut-in Wind Speed (m/s).

V_r : Rated Wind Speed (m/s).

V_{co} : Cut-out Wind Speed (m/s).

A, B, C : Constant Factors that can be calculated by (4), (5) and (6):

$$A = \frac{1}{(V_{ci} - V_r)^2} \left\{ V_{ci}(V_{ci} + V_r) - 4\, V_{ci} V_r \left[\frac{(V_{ci} + V_r)}{2V_r} \right]^3 \right\} \quad (4)$$

$$B = \frac{1}{(V_{ci} - V_r)^2} \left\{ 4 V_{ci} V_r \left[\frac{(V_{ci} + V_r)}{2V_r} \right]^3 - (3V_{ci} + V_r) \right\} \quad (5)$$

$$C = \frac{1}{(V_{ci} - V_r)^2} \left\{ 2 - 4 \left[\frac{(V_{ci} + V_r)}{2V_r} \right]^3 \right\} \quad (6)$$

Therefore, in this paper, by applying (3) besides considering monthly regime of wind, the mean power for each month has been obtained. This regime can be simply modeled by Weibull distribution [10]. Each generation company estimated its total payoffs considering behaviors of other companies in order to offer the Nash strategy.

B. ISO in DG Maintenance Market

ISO is responsible for DRMM supervision, protection and improvement of power system reliability and security. For these reasons, this paper has applied the Monte-Carlo Simulation for assessing comprehensive reliability indices of system and also determining accurate incentives or penalties for DRMM. By using MCS, important reliability indices such as Loss of Energy Expectation (LOEE), Expected Energy Not Supplied (EENS) and Energy Index Reliability (EIR) have been obtained. EIR shows the reliability level of a power system. Equation (7) shows the EIR [11]:

$$EIR = 1 - EENS_{p.u} \quad (7)$$

That,

$$EENS_{p.u} = \sum_{k=1}^{n} \frac{E_k P_k}{E} \quad (8)$$

Where,

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

E : Total energy under the load duration curve.

Also it can compare the allowed energy not supplied with EENS index for assessing the reliability of power system. The advantage of using this method is considering forced outage rates and their uncertainties of distributed generation units in reliability assessment.

Therefore, ISO calculates initially the reliability at each time stage. ISO calculates the reliability indices with considering offers of DG companies. If the offers are feasible, closure of the DRMM will be announced by ISO. Otherwise, ISO starts the assessment if it can present a public incentive or disincentive in specific stage to notify to DRMM participants.

The important advantage of this method is that incentives or penalties have been made based on a cost that ISO should pay for preserving reliability in satisfaction level. Also, reliability of system has been calculated by considering units that have been gone to maintenance in previous stages. (9) & (10) show the method of determining incentives/ disincentives based on ENS and EIR indices.

$$\gamma_i = \left| EIR_{base_i} - EIR_{offered_i} \right| (EIR_{base_i} - EIR_{offered_i}) \quad (9)$$

Where,

γ : 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.

$$\eta_t = \left[\frac{\gamma_i}{\sum_{t=1}^{52} \gamma_i} \right] \times C_{ISO-imp-weeks,t} \quad (10)$$

Where,

η_t : Incentive/Penalty Index.

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

t : Symbol for time stages.

$$C_{ISO-imp-weeks,t} \equiv CENS_t \quad (11)$$

Where,

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

Therefore, DGENCOs recalculate their strategies based on represented incentive/disincentive by ISO for attaining a new Nash by (12).

$$\underset{g,w}{Max}\prod^{G,week} = \sum_{w}^{week}\sum_{g}^{G}\begin{bmatrix}((\text{Pr}ice_w - C_g)\times P_{\max,g}\times(1-\lambda_{g,w})) \\ -(\theta_{g,w}\times(\lambda_{g,w}))-\eta_t\end{bmatrix} \quad (12)$$

Where,

η_t : Disincentives Index for stage t.

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

3. Case Study and Simulation Results

The sample test system, inspired from Roy Billinton Test System (RBTS) [12] consists of two DG companies, with overall forty two generators. Three types of generators have been considered: Wind power plants, Combined heat & Powers (CHPs) and Gas Turbines (G.T). The annual peak load of test system is about 185 MW with uncertainty. The load uncertainty is considered 5% with normal distribution situation. The uncertainty of wind plants has been considered as Weibull distribution. The DRMM runs in 52 weeks (a year) and ISO studies the reliability in important weeks. The important weeks are weeks when the load level is high or the maximum power that goes to maintenance increases considerably. TABLE I, presents the uncertainty factors of sample test system. TABLE II, III and IV show the generation data, the demand and the price data of sample test system respectively. Additional information about single line diagram of RBTS and the annual load duration curve is mentioned in [12].

On the other hand, TABLE V presents the general information of wind turbines of DGENCOs. Based on TABLE V and Fig. 2 [14], TABLE VI has obtained which determines the monthly estimated power for considered wind turbines. It should be mentioned that in TABLE II, the number of generation units of DGENCOs are 25 and 17 respectively. For simplifying the Dynamic-Game and for reducing the curse of dimensionality issue, this paper integrates these units as DG power plants. So, as it is seen in TABLE II, approximately eleven DG plants are in the case study.

Table I. 5% Load Uncertainty data

Standard Deviation	Demand (MW) RBTS	Probability
-3	157.25	0.006
-2	166.5	0.061
-1	175.75	0.242
0	185	0.382
1	194.25	0.242
2	203.5	0.061
3	212.75	0.006

In fact, each DGENCO solves its problem using (1) for optimizing its own benefit in a dynamic game applying GAMS based programming software. Final numerical results for RBTS are shown in Table VII. The basic strategy is offered by DGENCOs to the ISO.

Table II. General Information of Case Study

No. of DG Plants	Pmax	FOR	Type	Maintenance Duration
DGENCO-1				
1	40 MW	0.04	Conv.	2 Weeks
2	4*5 MW	0.04	CHP	2 Weeks
3	4*5 MW	0.04	CHP	2 Weeks
4	4*5 MW	0.05	G.T	2 Weeks
5	5*4 MW	0.05	G.T	2 Weeks
6A	1*4 MW	0.04	CHP	2 Weeks
6B	1*1 MW	0.03	G.T	2 Weeks
7	5*1 MW	seasonal	Wind	2 Weeks
DGENCO-2				
8	40 MW	0.04	Conv.	2 Weeks
9	40 MW	0.04	Conv.	2 Weeks
10A	3*4 MW	0.04	CHP	2 Weeks
10B	2*4 MW	0.05	G.T	2 Weeks
11	10*1 MW	seasonal	Wind	2 Weeks

Table III. Weekly Peak Demand information for case study

No.	Demand(MW)	No.	Demand(MW)	No.	Demand(MW)
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 IV. Weekly Price (\$/MWh) for case study

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		

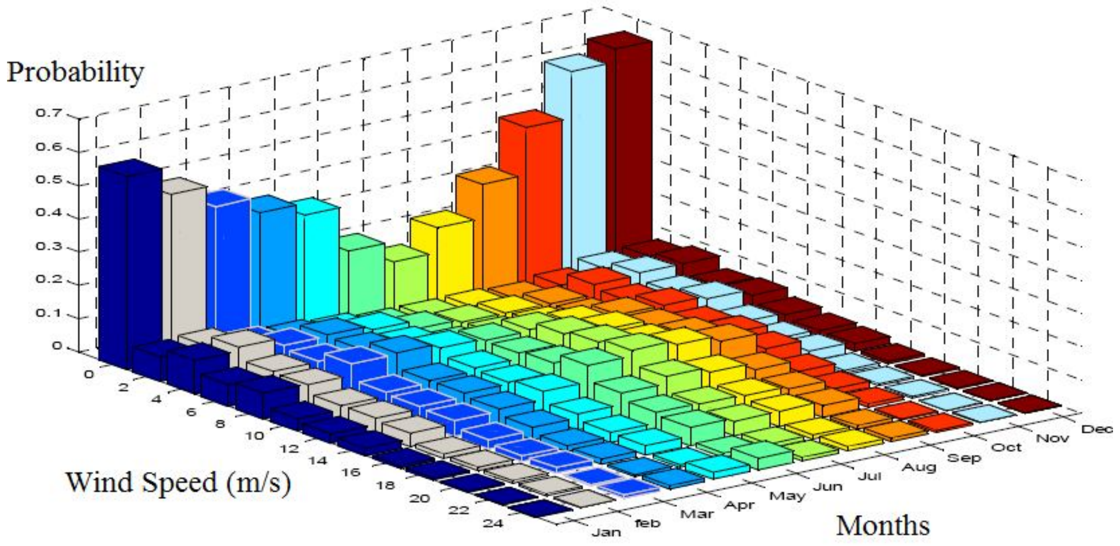

Fig. 2. Schema of Monthly Wind Regime in Considered Case Study [14].

Table V. WW1-Model Wind Turbine Characteristics

WTG (WW1)		Dimension	Value
Rated Power		kW	1000
cut-in wind speed (V_{ci})		m/s	4
rated wind speed (V_r)		m/s	12.5
cut-out wind speed(V_{co})		m/s	22
A		---	0.11765
B		---	-0.07647
C		---	0.01176
Forced Outage Rate (F.O.R)	Season 1	/year	0.06
	Season 2	/year	0.05
	Season 3	/year	0.045
	Season 4	/year	0.05

Table VI. Monthly Estimated Power of WW1-Wind Turbines

Month	Probabilities and Power				Monthly Estimated Power (MW)
Jan	Probability	0.75	0.22	0.03	0.424
	MW	0	0.346	1	
Feb	Probability	0.64	0.28	0.08	0.293
	MW	0	0.091	1	
March	Probability	0.6	0.31	0.09	0.301
	MW	0	0.098	1	
April	Probability	0.52	0.38	0.1	0.286
	MW	0	0.098	1	
May	Probability	0.45	0.29	0.26	0.560
	MW	0	0.166	1	
June	Probability	0.25	0.47	0.28	0.469
	MW	0	0.153	1	
July	Probability	0.18	0.22	0.6	0.760
	MW	0	0.107	1	
Aug	Probability	0.28	0.04	0.68	0.950
	MW	0	0.104	1	
Sept	Probability	0.45	0.03	0.52	0.951
	MW	0	0.105	1	
Oct	Probability	0.6	0.12	0.28	0.733
	MW	0	0.111	1	
Nov	Probability	0.78	0.08	0.14	0.674
	MW	0	0.105	1	
Dec	Probability	0.85	0.07	0.08	0.612
	MW	0	0.170	1	

Then, ISO notifies incentives/disincentives for the strategy using MCS for reliability assessment and by considering 5% weekly load duration curve uncertainty. ISO calculates weekly EENS and EIR indices by MCS technique and compares these results with the results that show the weekly acceptable EENS and EIR values for ISO. Fig. 3, shows the EENS value of 51th week by 100000 iteration as a sample of EENS calculations.

In conclusion, ISO obtained the incentives/penalties using (9), (10) & (11) for the considered strategy. Table VIII represents the incentives/disincentives calculations for ISO important weeks. Then, ISO notifies the incentives/disincentives to the DGENCOs.

Therefore, DGENCOs re-calculate their payoffs by (12) and find the final Nash strategy. In this strategy, DGENCOs accept the incentives of weeks 12 & 13. Then they accept the disincentives of weeks 35, 36, 38, 39. So, they accept to pay 109992$ to ISO as penalty of mentioned weeks. As a result, DGENCO-1 and DGENCO-2 have obtained 50893515$ & 43865006$ respectively as their payoff by participating in both auction and DRMM.

On the other hand, ISO pays 2387.29$ as incentives considering the roles of each DGENCO in maintaining reliability.

Table VII. Results for RBTS Simulation

GENCO-1		GENCO-2	
No.	Maintenance Period (weeks)	No.	Maintenance Period (weeks)
1	38-39	8	12-13
2	38-39	9	38-39
3	35-36	10A	12-13
4	12-13	10B	12-13
5	35-36	11	12-13
6A	12-13		
6B	12-13		
7	12-13		
Payoff ($): 50951801		Payoff ($): 43914325	

Table VIII. Incentives/Penalties for ISO Important Weeks in RBTS

ISO important Weeks	CENS × Inc/Pen. Factor	Value of Reliability for Each week ($×168)	Final Inc/Pen. ($)
12	6.8E-05	16800	1.1424
13	7.3E-02	17880	1305.24
35	-0.4228	5480	-2426.54
36	-0.9137	4160	-3800.99
38	-14.2590	5440	-77568.96
39	-2.8474	9200	-26196.08
51	0.9651	19120	1080.91

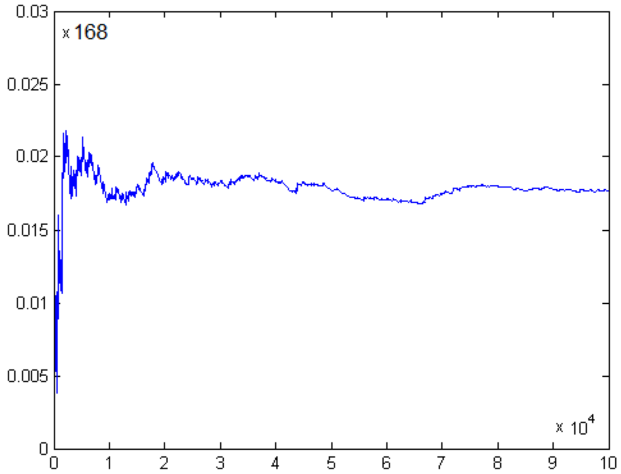

Fig. 3. ENS of 51th week by 100000 iteration of Monte-Carlo simulation.

As Table VIII shows, in this strategy maintenance weeks are weeks that the price and the load values are lower in comparison with other weeks. In this situation EIR is acceptable for the whole 52 weeks so this strategy can be the final maintenance strategy from ISO point of view.

4. Conclusion

This paper proposes a new comprehensive solution for maintenance scheduling of distributed generation resources in HLI based on establishing a competitive maintenance market by using game theory and considering uncertainties of load, primary resources and forced outage rates of DG units (specially wind resources) determining strategies of DG companies for achieving Nash equilibrium, presenting incentives/penalties to them by ISO and also, supplying the main target of ISO that is the reliability of system by using Monte-Carlo Simulation technique in order to calculate EENS and EIR indices.

For unfolding the accuracy and the applicability of this new solution for maintenance scheduling of DG units, a case study has been discussed that is inspired by RBTS. Therefore, the best applicable strategy of a DG company for maintenance scheduling problem can be obtained through proposed new solution.

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