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NOWE PODEJŚCIE DO HARMONOGRAMOWANIA CZYNNOŚCI OBSŁUGOWYCH SYSTEMÓW ELEKTROENERGETYCZNYCH WYKORZYSTUJĄCE ALGORYTM GENETYCZNY ORAZ SYMULACJĘ MONTE-CARLO

A NEW APPROACH FOR MAINTENANCE SCHEDULING OF POWER SYSTEMS, USING A GENETIC ALGORITHM AND MONTE-CARLO SIMULATION

Celem pracy jest przedstawienie nowego, całościowego rozwiązania w zakresie harmonogramowania czynności obsługowych jednostek wytwórczych w warunkach deregulacji, przy założeniu rocznego niezależnego rynku. Rozwiązanie otrzymano poprzez wykorzystanie algorytmu genetycznego (GA) oraz symulacji Monte-Carlo (MCS). W warunkach deregulacji, każde przedsiębiorstwo wytwórcze (Generation Company, GENCO) dąży do optymalizacji zysków, podczas gdy niezależny operator systemowy (Independent System Operator, ISO) troszczy się o niezawodność. Na ogół, zderzenie tych dwóch punktów widzenia stwarza wiele problemów. Dlatego też proponujemy metodę harmonogramowania czynności obsługowych opartą na GA. Zgodnie z tą metodą, przedsiębiorstwa GENCO ustalają swoje strategie uczestnictwa w rocznym rynku usług serwisowych (Annual Maintenance Market, AMM) biorąc pod uwagę niepewności związane z obciążeniem, umowy paliwowe oraz zachowania innych przedsiębiorstw. Z drugiej strony, ISO zarządza AMM w oparciu o niezawodność i daje przedsiębiorstwom premie lub nakłada na nie kary bazując na własnej polityce poprzez MCS. Trafność i stosowalność zaproponowanej metody harmonogramowania czynności obsługowych jednostek wytwórczych oceniono analizując system testowy wyposażony w magistralę IEEE-118.

Słowa kluczowe: *algorytm genetyczny, roczny rynek serwisowy, harmonogramowanie czynności obsługowych, symulacja Monte-Carlo, niezawodność.*

The aim of this study is to present a new comprehensive solution for maintenance scheduling of power generating units in deregulated environments by applying an annual independent market. The solution was obtained by using a Genetic Algorithm (GA) and a Monte-Carlo Simulation (MCS). In a deregulated environment, each Generation Company (GENCO) desires to optimize its payoffs, whereas an Independent System Operator (ISO) has its reliability solicitudes. In general, the two points of view create many problems. Therefore, we propose a method based on a GA for maintenance scheduling. In this method, GENCOs set their strategies to participate in an Annual Maintenance Market (AMM) by considering load uncertainties, fuel contracts and the behaviors of other companies. On the other hand, the ISO manages the AMM based on reliability and offers incentives/ penalties for companies relying on its policy through MCS. To evaluate the accuracy and applicability of our solution for maintenance scheduling of power generation units, an IEEE-118 bus test system was studied.

Keywords: *genetic algorithm, annual maintenance market, maintenance scheduling, Monte-Carlo simulation, reliability.*

1. Introduction

The development of economic competitiveness in power electricity markets necessitates a short-term economic optimization of power systems. It also affects the mid-term and long-term operation and planning of power systems. Maintenance scheduling of power generation units is one of the fundamental mid-term issues in the planning of power systems as it raises new challenges in deregulated environments.

In general, persons that do not have common objectives determine the maintenance scheduling in restructured power markets. Thus, new methods are needed to optimize market strategies.

Bilateral interactions between GENCOs and ISOs may result in considerable competition and trade, with few reliability concerns. Many studies have explored methods that are applicable to maintenance scheduling at Heuristic Levels I and II. For instance, reference [2] proposes a framework based on game theory to find the Nash equilibrium for maintenance scheduling of generation units. However, this paper did not consider load and fuel uncertainties or the effect of maintenance delay on the reliability of the system and the GENCO payoffs. This paper also did not discuss ISO managing responsibilities in the electricity market. Reference [5] provides a solution for maintenance scheduling of generation units by introducing a motivational method. However, this paper simplifies the maintenance problem and does not discuss load and resource uncertainties. In reference [13], a flexible maintenance solution was studied with a fuzzy method. This reference also does not refer to a power market or uncertainties. In reference [29], a competitive and fair solution for GENCOs is proposed. However, the reliability assessment of the system is simplified. Regarding optimization, many studies rely on linear/non-linear optimization techniques with conventional or advanced algorithms. On the other hand, the Genetic Algorithm (GA) has also been used as an optimization technique. In most studies, however, GAs have not been applied in deregulated environments. Table 1 summarizes certain studies on maintenance scheduling that use GAs and other optimization methods. As indicated in Table 1, most of these studies focused on conventional maintenance scheduling of generating units.

In this paper, we propose a new competitive model for maintenance scheduling of generating units that relies on the modeling of an independent Maintenance Market (MM) [11] using a genetic algorithm. The new method is based on the simulation of a competition environment by considering load and fuel uncertainties. Thus, each GENCO offers its own strategy by considering the behaviors of other GENCOs in an outright GA optimization. On the other hand, by applying a Monte-Carlo Simulation (MCS) technique [3, 4], reliability indices [25,26,27,28], such as the Energy Not Supplied (ENS) and the Energy Index Reliability (EIR), were obtained by considering the load uncertainty of each unit at specific times.

Taking advantage of the reliability indices, incentives or disincentives of ISOs were explored using a new justice-oriented solution. Thus, this method has many advantages. For example, a competitive solution for maintenance scheduling [24] at Heuristic Level I that considers load and fuel uncertainty can be determined based on network reliability assessment. The benefits of GENCOs in auction and MMs can also be optimized through GAs. Furthermore, suitable interactions between ISOs and GENCOs can be achieved, incentives/penalties based on reliability indices can be determined, and the impact of each GENCO on the reliability reduction of a power system at each time stage can be assessed.

2. The maintenance scheduling solution

In this section, a new maintenance scheduling method that results in a fair competition is explained in detail. Generally, the main participants of AMMs are GENCOs and ISOs. The independent system operator is responsible for the reliability preservation of the power system. In the new solution, all GENCOs maximize their own payoffs in the power market while minimizing their costs in the AMM by GA optimization. Once the maintenance strategy of the GENCOs is found, this strategy is proposed to the ISO. On the other hand, the ISO evaluates the reliability of the system of the proposed strategy by using MCS.

After reliability assessment, the ISO accepts the offer or presents an incentive/disincentive in GENCO offers using a new method for each time stage when the reliability of the system is higher/lower than the desirable level and also offer its desirable strategy to GENCOs for more assessment. (fig. 1) depicts the interactions between market participants in the proposed maintenance scheduling solution. The role of each market player is also thoroughly discussed.

A. GENCOs in Annual Maintenance Markets

In power electricity markets, the main variables for a decision-making process are market participants. To simulate the participants and their behaviors in a power market, a genetic algorithm optimization technique was applied.

This technique has many advantages in comparison with game theory techniques. For instance, in GAs, a dimensional problem does not occur. Further, GAs lead to solutions more rapidly as compared to game theory techniques. Thus, the strategy of the GENCOs was modeled using a comprehensive ob-

Tab. 1. A brief literature review of maintenance scheduling issues

Method	Obj. Function	Market-Oriented	System Reliability	Fuel & Load Uncertainty	Maintenance Delay Penalty	Inc/Penalty Policy	Reference
CPLEX	Maximizing Payoffs	Yes	Yes	No	No	Yes	[5]
GA	Reserve Minimization	No	Just Reserve	No	No	No	[23]
GA+Fuzzy Function	Reserve Minimization	No	Just Reserve	No	No	No	[6]
GA/SA	Reliability /Reserve	No	LOLP	No	No	No	[21]
Multi-Layer GA	Minimizing Costs	No	No	No	No	No	[17]
Deterministic Approach	Maximizing Payoffs	No	Yes	Seasonal Limits	No	No	[15]
GA	Maximizing Reliability	No	Yes/LOLE	No	No	No	[22]
Fuzzy	Reserve	No	LOLP	For Uncertainty	No	No	[16]
GA/SA	Reliability /Operation Expense	No	Yes	No	No	No	[12]
GA/SA Heuristic	Reserve Minimization	No	Yes	No	No	No	[7]
GA	Maximizing Payoffs	Yes	Yes	No	No	No	[10]
PSO	Reserve Minimization	No	No	No	No	No	[18]
Fuzzy	Minimizing Costs	No	No	Yes	No	No	[8]
Markov Process	Minimizing Costs	No	Yes	Energy Cost	No	No	[20]
Game Theory	Maximizing Payoffs	Yes	Yes/MCS	Load Uncertainty	No	Yes	[14]
GA	Maximizing Payoffs	Yes	Yes/MCS	Yes	Yes	Yes	[This Paper]

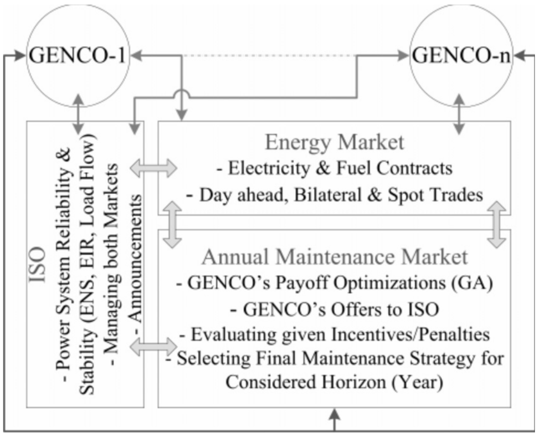

Fig. 1. Schema of the proposed maintenance market

jective function that is optimized by a GA for each time stage. In other words, the strategy of the GENCOs reported in this paper is based on maximizing the GENCO profits by minimizing costs in auction and annual maintenance markets to attain an admissible solution. The objective function of the GENCOs is given by Eq. (1).

Considering all time stages, the GENCOs solve their maintenance problem by an improved GA to determine the best strategy, considering the behaviors of the other GENCOs. After finding the best strategy that estimates the activities of GENCOs in both power electricity market and the AMM, they present their strategy to the ISO as an offer for the maintenance.

A flowchart of the activities of the GENCOs in the AMM is shown in (fig. 2). The first week of maintenance for each unit was considered as a GA chromosome, and each GENCO regards the behavior of the other GENCOs. Thus, each chromosome has some genomes equal to the total number of generation units.

$$Max \overset{W,G}{\underset{w,g}{Z}} = \sum_{w=1}^{52} \sum_{g\in i}^{G,I} \left[\begin{array}{l} (\pi_w - \left\{ OC_{g,i} + F_{g,i} \right\}) \times P_{max,g,i} \times (1 - Y_{g,i,w}) \times t_{g,i,w}) - \\ ((FC_{g,i} + (VC_{g,i} \times 168)) \times P_{max,g,i} \times (Y_{g,i,w})) + \\ (SR_{g,i,w} \times (1 - Y_{g,i,w})) - (\delta_{g,i,w} \times (Y_{g,i,w}) \times a_w) + \\ (fp_{g,i,w} \times (1 - Y_{g,i,w}) \times F_{g,i} \times P_{max,g,i} \times av_{g,i,w} \times h) \end{array} \right] \quad (1)$$

Where: π_w - Weekly forecasted price (\$/MWh), $P_{max,g,i}$ - Power generated by unit-g of GENCO-i (MW), $OC_{g,i}$ - Operational Costs of unit-g of GENCO-i excluding fuel costs (\$/MWh), $F_{g,i}$ - Fuel buying contract of unit-g of GENCO-i (\$/MWh), $Y_{g,i-,w}$ - Maintenance status of units in stage t (1 if unit goes to maintenance and 0 otherwise), $FC_{g,i}$ - Fixed maintenance cost of unit-g of GENCO-i (\$/MW), $VC_{g,i}$ - Variable maintenance cost of unit-g of GENCO-i (\$/MWh), $t_{g,i,w}$ - Operation hours of unit -g of GENCO-s in stage-w (~168), $SR_{g,i,w}$ - Stability-Reliability factor that is gained from the inherit stability and reliability characteristics of the Network (\$), $\delta_{g,i,w}$ - Probability of delay in maintenance duration of unit-g of GENCO-i at week-w, a_w - Penalty of maintenance delay for stage-w (\$), $fp_{g,i,w}$ - Probability of non-supplying fuel to unit-g in stage-w, $av_{g,i,w}$ - Average days of unexpected unit shutdown caused by fuel network disconnection, h - Daily factor (=24 hour).

As shown by Eq. (1), the objective function of the GENCOs maximizes the amount of sold electricity in the power market at each time stage, considering maintenance costs, stability indices, penalties of maintenance delays, and fuel uncertainties. On the other hand, the main constraints of this new maintenance approach are as follows;

a. The Generation and Load balance constraint:

$$\sum_{g\in i}^{G} Y_{g,i,w} \times P_{max,g,i} \geq d_w \quad (2)$$

Where: d_w - Total demand of stage-w.

b. The consecutive maintenance duration:

$$\sum_{w}^{W+U_{g,i}-1} (1 - Y_{g,i,w}) \geq (U_{g,i} \times (Y_{g,i,w-1} - Y_{g,i,w})) \quad (3)$$

Where: $Y_{g,i,w-1}$ - Status of unit-g in stage (w-1), $U_{g,i}$ - Maintenance duration of unit-g of GENCO-i.

c. The number of shut-downs for maintenance:

$$\sum_{w=1}^{W=52} Y_{g,i,w} = (1 \times 52) - U_{g,i} \quad (4)$$

If the ISO accepts the offer of the GENCOs, the specified generators of each GENCO will go to maintenance. Otherwise, the ISO may determine incentives/penalties for received offers of GENCOs and send its desirable strategy to GENCOs in order to re-assess their offer. In this method, the GENCOs re-new their strategies based on determined incentive/penalty policy for the time stages (weeks).

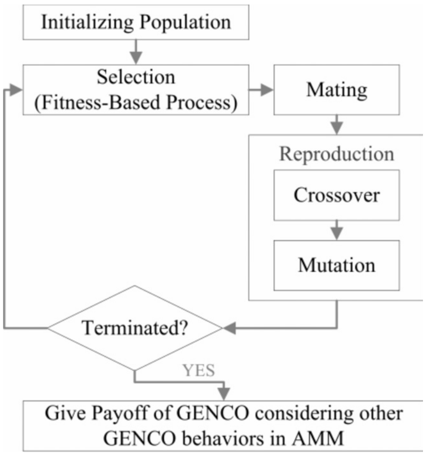

Fig. 2. Flowchart of GENCO payoff calculations in an AMM by a GA

B. ISO in the Proposed Maintenance Market

The ISO is responsible for preservation of the power system reliability. The Monte-Carlo simulation technique was used to accurately assess the reliability of the system and to determine suitable motivational policies. MCSs calculate important reliability indices, such as ENS for the ISO. Eq. (5) presents the ENS [1]:

$$\begin{aligned} ENS_{total} &= \sum_{w=1}^{52} C_w \times f_w \times D_w = \\ &= \sum_{w=1}^{52} C_w \times P_w \times t_w = \sum_{w=1}^{52} E_w P_w \end{aligned} \quad (5)$$

Where: C_w - Load Curtailment of network at week-w, f_w - Frequency of curtailment of network at week-w, D_w - Duration of curtailment of network at week-w, P_w -Probability of network energy lost at week-w, E_wP_w - Energy Curtailed × Probability of energy lost, t_w - Curtailment duration (hour) at week-w (=168).

In the MCS, the generation on/off situation was modeled by generating random numbers between zero and one. The considered number of iterations is 70000. To calculate the ENS index by MCS with a random generation of numbers and to compare FORs, the existence capacity of the system was assessed. By intersecting this capacity with the Load Duration Curve (LDC), the energy lost value was determined as the area underneath the annual load curve. The value was obtained using MCS and Eq. (5).

The ISO obtains the reliability of the system for each time stage. Then, the ISO calculates the ENS index by considering the offers of the GENCOs. If the presented unit offer is feasible, a maintenance solution is determined. Otherwise, the ISO assesses whether he can present incentives/disincentives for a specific time stage to the GENCOs. An appropriate policy of giving incentives/penalties is proposed in this paper. It is based on reliability and economical indices. The main advantage of this method is that the policy relies on costs that the ISO should pay for keeping the reliability of the power system on a satisfactory level. Eq. (6) to Eq. (10) detail the determination method of incentives/disincentives based on reliability indices.

$$\eta_w = ENS_{expected,w} - ENS_{offered,w} \tag{6}$$

Where: η_w - Index for incentive/penalty,
$ENS_{expected,w}$ - Energy not supplied calculated by the ISO shows desirable (expected) reliability at week-w, $ENS_{offered,w}$ - Energy not supplied considering offers of the GENCOs at week-w.

$$\underset{at:w=w_i}{\theta_{total,w}} = \sum_{h=1}^{H}((K_{j,w} \times CC_{j,g,w}) + \\ + ((\eta_{j,w} \times V_{j,w})) \times (1+\alpha)^h \times \beta^h \tag{7}$$

Where: $\underset{at:w=w_i}{\theta_{total,w}}$ - Total Incentive/penalty ($) index for week=i (if +: Incentive/if -: Penalty), $K_{j,w}$ - Curtailment Cost normalized factor depends on types of consumers in a specific area or a country (In this paper assumed: 3.25 $/KW), $CC_{j,g,w}$ - Difference Curtailment Capacity (MW), $\eta_{j,w}$ - Index for incentive/penalty for week=i, $V_{j,w}$ - Cost of Curtailed energy that is related to unavailability cost of generating units at week-w ($/MWh), α, β - Load growth rate per year (5%), Economic Factor for Net Present Value of Incentive/Penalty calculation, ^{h} - denotes horizon scheduling year (in this paper: h=H=1), ^{j} - denotes the scheduled outages.

$$\underset{at:w=w_i}{CC_{j,g}} = P_{cr,expected} - \sum_{g}^{r} P_{cr,g} \tag{8}$$

$P_{cr,expected}$ - The expected curtailed power that calculates by ISO in order to make $ENS_{expected,w}$ (MW), $\sum_{g}^{r} P_{cr,g}$ - Sum of curtailed powers of generating units for week=i.

$$\beta = \frac{1+\sigma}{1+\mu} \text{ (In this paper considered: } \sigma\text{=2.3\%, } \mu\text{=0.25\%)} \tag{9}$$

σ, μ - Inflation Rate, Interest Rate.

$$\underset{at:w=w_i}{\theta_{g=g_n}} = \frac{P_{cr,g=g_n}}{\sum_{g}^{r} P_{cr,g}} \times \theta_{total,w} \tag{10}$$

$\theta_{g=g_n}$ - Incentive/Penalty for generating unit number-n ($).

In Eq. (7) Curtailment Cost has been determined in order to get a money factor to the incentive/penalty formula based on share of each type of consumers in a specific area or a country. For instance, most consumers in area-A are industrial consumers but most consumers in area-B are residential. It is clear that curtailment cost factors for these two areas are different due to the types of consumers. Thus, $K_{j,w}$ can create different incentive/penalty factors for these mentioned areas. It is obvious that the Incentive/Penalty of a GENCO in a considered week obtains from summing incentives/penalties of generating units of GENCO.

The GENCOs re-calculate their strategies based on the presented incentives/disincentives that are provided for important stages (weeks) by the ISO to find a new optimal strategy using Eq. (11).

$$Max \underset{w,g}{\overset{W,G}{Z}} = \sum_{w=1}^{52}\sum_{g\in i}^{G,I} \begin{bmatrix} (\pi_w - \{OC_{g,i} + F_{g,i}\}) \times P_{max,g,i} \times (1 - Y_{g,i,w}) \times t_{g,i,w}) - \\ ((FC_{g,i} + (VC_{g,i} \times 168)) \times P_{max,g,i} \times (Y_{g,i,w})) + \\ (SR_{g,i,w} \times (1 - Y_{g,i,w})) - (\delta_{g,i,w} \times (Y_{g,i,w}) \times a_w) + \\ (fp_{g,i,w} \times (1 - Y_{g,i,w}) \times F_{g,i} \times P_{max,g,i} \times av_{g,i,w} \times h) - \theta_{g,i,w} \end{bmatrix} \tag{11}$$

Where: $\theta_{g,i,w}$ - Incentive/disincentive index for GENCO-i at stage-w.

This process continues until the reliability considerations of the power system are fully respected. (fig. 3) presents a flowchart of interactions between the ISO and the GENCOs in the expressed solution.

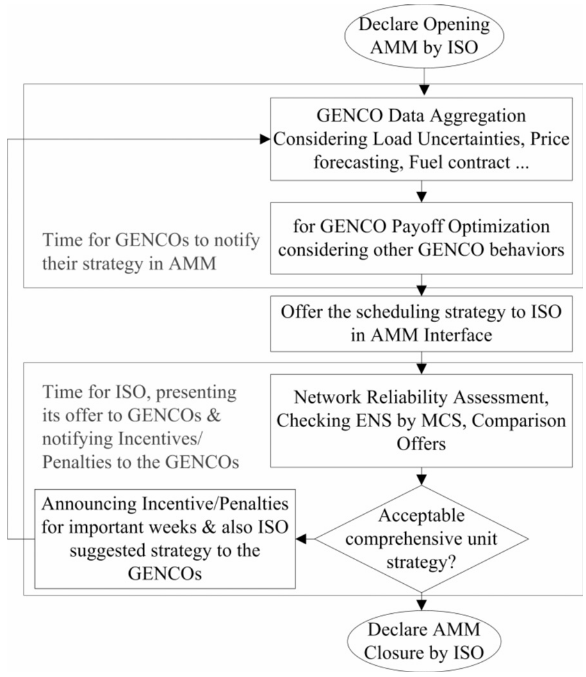

Fig. 3. Flowchart of interactions between the ISO and GENCOs in an AMM

3. Simulation results

IEEE-118 Bus Test System [9, 19] has a 6000-MW annual peak load with 54 generation units. Three GENCOs are the owners of these 54 generators, which participate in the power market over one year (52 weeks). Table II presents the uncertainty factors of IEEE-118 Bus Test System applying seven-step normal distribution curve [1]. Tables 3, 4, 5, and 6 show the general information of the units, the weekly peak demand, the fuel data, and the price data of IEEE-118 Bus Test System, respectively. Additional information on a schematic of IEEE-118 Bus Test System can be found in [9].

All of the GENCOs maximize their own payoffs using a GA in both the power market and the AMM. In this paper, the first week of maintenance for each generating unit was considered as a GA chromosome. On the other hand, each GENCO considers the behavior of the other GENCOs. Thus, each chromosome has 54 genomes because IEEE-118 Bus Test System has 54 generation units in total. In addition, the duration and continuity of maintenance were fully considered.

Tab. 2. 7% load uncertainty data with 7-step normal distribution

Probability	Demand (MW) IEEE RTS	Standard Deviation
0.006	4740	-3
0.061	5160	-2
0.242	5580	-1
0.382	6000	0
0.242	6420	1
0.061	6840	2
0.006	7260	3

Tab. 3. General information of generating units in IEEE-118 Bus Test System

GENCO-1			GENCO-2			GENCO-3	
Unit No.	P_{max} (MW)	FOR	Maintenance Duration	Unit No.	P_{maX} (MW)	FOR	Maintenance Duration
1	30	0.08	3	28	420	0.12	4
2	30	0.08	3	29	300	0.12	4
3	30	0.08	3	30	80	0.08	3
4	300	0.12	4	31	30	0.08	3
5	300	0.12	4	32	30	0.08	3
6	30	0.08	3	33	20	0.08	2
7	100	0.10	3	34	100	0.10	3
8	30	0.08	3	35	100	0.10	3
9	30	0.08	3	36	300	0.12	4
10	300	0.12	4	37	100	0.10	3
11	350	0.12	4	38	30	0.08	3
12	30	0.08	3	39	300	0.12	4
13	30	0.08	3	40	200	0.12	4
14	100	0.10	3	41	20	0.08	2
15	30	0.08	3	42	50	0.08	3
16	100	0.10	3	43	300	0.12	4
17	30	0.08	3	44	300	0.12	4
18	30	0.08	3	45	300	0.12	4
19	100	0.10	3	46	20	0.08	2
20	250	0.12	4	47	100	0.10	3
21	250	0.12	4	48	100	0.10	3
22	100	0.10	3	49	20	0.08	2
23	100	0.10	3	50	50	0.08	3
24	200	0.12	4	51	100	0.10	3
25	200	0.12	4	52	100	0.10	3
26	100	0.10	3	53	100	0.10	3
27	420	0.12	4	54	50	0.08	3

Tab. 4. Weekly peak demand for IEEE-118 Bus Test System

No.	Demand (MW)	No.	Demand (MW)	No.	Demand (MW)
1	5172	19	5280	37	4680
2	5400	20	5280	38	4170
3	5400	21	5136	39	4344
4	5280	22	4866	40	4344
5	5280	23	5376	41	4458
6	5046	24	5280	42	4464
7	4992	25	5376	43	4800
8	4836	26	5166	44	5310
9	4440	27	4530	45	5310
10	4422	28	4896	46	5454
11	4290	29	4806	47	5640
12	4362	30	5166	48	5340
13	4224	31	4332	49	5652
14	4500	32	4656	50	5820
15	4326	33	4800	51	6000
16	4800	34	4374	52	5730
17	4524	35	4356		
18	5136	36	4230		

Tab. 5. Weekly fuel contract, maintenance costs information for IEEE-118 Bus Test System

Unit No.	Fuel Contract ($/MWh)	$FC_{g,i}$ ($/KW)	$VC_{g,i}$ ($/MWh)	Unit No.	Fuel Contract ($/MWh)	$FC_{g,i}$ ($/KW)	$VC_{g,i}$ ($/MWh)
1	22.1845	10	0.9	28	8.5325	5	0.3
2	22.1845	10	0.9	29	8.5325	4.5	0.7
3	8.5325	10	0.9	30	8.5325	8.5	0.8
4	8.5325	4.5	0.7	31	8.5325	10	0.9
5	8.5325	4.5	0.7	32	29.0105	10	0.9
6	22.1845	10	0.9	33	29.0105	10	0.9
7	8.5325	8.5	0.8	34	29.0105	8.5	0.8
8	22.1845	10	0.9	35	8.5325	8.5	0.8
9	22.1845	10	0.9	36	8.5325	4.5	0.7
10	8.5325	4.5	0.7	37	8.5325	8.5	0.8
11	8.5325	4.5	0.7	38	8.5325	10	0.9
12	22.1845	10	0.9	39	29.0105	4.5	0.7
13	22.1845	10	0.9	40	8.5325	5	0.7
14	8.5325	8.5	0.8	41	8.5325	10	0.9
15	22.1845	10	0.9	42	25.5975	10	0.9
16	8.5325	8.5	0.8	43	25.5975	4.5	0.7
17	22.1845	10	0.9	44	8.5325	4.5	0.7
18	22.1845	10	0.9	45	8.5325	4.5	0.7
19	8.5325	8.5	0.8	46	8.5325	10	0.9
20	8.5325	5	0.7	47	29.0105	8.5	0.8
21	8.5325	5	0.7	48	8.5325	8.5	0.8
22	8.5325	8.5	0.8	49	8.5325	10	0.9
23	8.5325	8.5	0.8	50	29.0105	10	0.9
24	8.5325	5	0.7	51	29.0105	8.5	0.8
25	8.5325	5	0.7	52	8.5325	8.5	0.8
26	8.5325	8.5	0.8	53	8.5325	8.5	0.8
27	22.1845	5	0.3	54	8.5325	10	0.9

The optimal strategies of GENCOs were determined and were then offered to the ISO. Table 7 and Table 8 show the offered strategies of three GENCOs without incentive/penalty calculations. GENCO-1 and GENCO-2 offer the strategy of Table 7 but GENCO-3 find the strategy of Table 8 more suitable. Considering the weekly value of the system reliability, the ISO then presented incentives/penalties to the GENCOs using Eq. (6) to Eq. (10) and a Monte-Carlo simulation technique. By applying this method, a desirable reliability level of the system was obtained for each week. (Fig. 4) shows ENS value for week 10 that was calculated by MCS with 70000 iterations as an example. Additionally, Table 9 gives the incentive/penalty calculations for ISO important weeks in which the reliability risk

Tab. 6. Weekly forecasted price ($/MWh) for IEEE-118 Bus Test System

No.	Price ($/MWh)	No.	Price ($/MWh)	No.	Price ($/MWh)
1	56.90	19	57.43	37	51.48
2	59.40	20	58.08	38	45.88
3	57.94	21	56.51	39	47.77
4	55.05	22	53.52	40	47.77
5	58.08	23	59.40	41	49.05
6	55.51	24	58.54	42	49.09
7	54.91	25	59.15	43	52.80
8	53.19	26	56.83	44	58.15
9	48.84	27	49.84	45	58.40
10	48.63	28	53.87	46	60.00
11	47.20	29	52.87	47	62.04
12	47.98	30	58.08	48	58.75
13	46.45	31	47.66	49	62.18
14	49.51	32	51.23	50	64.03
15	47.59	33	52.80	51	66.00
16	52.80	34	48.12	52	62.83
17	49.77	35	47.91		
18	55.23	36	46.52		

Tab. 7. Offer proposed by GENCO-1 AND GENCO-2 to the ISO for maintenance scheduling

Unit No.	Maintenance Start Week	Unit No.	Maintenance Start Week	Unit No.	Maintenance Start Week
1	40	19	38	37	36
2	37	20	10	38	26
3	30	21	38	39	10
4	10	22	36	40	34
5	36	23	39	41	26
6	11	24	38	42	38
7	34	25	11	43	10
8	12	26	27	44	38
9	36	27	11	45	38
10	38	28	38	46	31
11	10	29	35	47	9
12	11	30	10	48	37
13	35	31	29	49	17
14	34	32	14	50	31
15	35	33	8	51	12
16	34	34	34	52	36
17	37	35	39	53	40
18	20	36	10	54	10
GENCO-1 Payoff= 2.9665×10^8		GENCO-2 Payoff= 17.714×10^8		GENCO-3 Payoff= 2.2527×10^8	

Tab. 8. Offer proposed by GENCO-3 to the ISO for maintenance scheduling

Unit No.	Maintenance Start Week	Unit No.	Maintenance Start Week	Unit No.	Maintenance Start Week
1	37	19	38	37	36
2	13	20	38	38	39
3	11	21	38	39	10
4	10	22	12	40	37
5	36	23	13	41	30
6	38	24	33	42	40
7	40	25	11	43	13
8	38	26	34	44	39
9	9	27	10	45	38
10	11	28	34	46	14
11	10	29	35	47	8
12	9	30	15	48	11
13	39	31	12	49	19
14	13	32	32	50	12
15	7	33	12	51	37
16	36	34	38	52	39
17	39	35	13	53	12
18	36	36	36	54	39
GENCO-1 Payoff= 2.9660×10^8		GENCO-2 Payoff= 17.7078×10^8		GENCO-3 Payoff= 2.2535×10^8	

of the system could increase. After calculating the incentives/penalties for GENCO strategies, the ISO notifies them. On the other hand, ISO send its offer for maintenance to the GENCOs. After reliability assessment, ISO finds that the offered strategy of GENCO-3 is completely adequate for maintenance scheduling. Thus, ISO send this strategy as its offer for the GENCOs.

The GENCOs re-calculate their payoffs by Eq. (11) considering ISO offered strategy and also incentive/penalties of their offered solution to find a new strategy. Thus, the GENCOs agree to follow the ISO suggested strategy because, if GENCO-1 and GENCO-2 insist on their strategy, they should pay 437533$ and 3363158$ as penalties for the ISO important weeks. So, the GENCO-1 and GENCO-2 payoffs were reduced to 296212467$ and 1768006842$, respectively. Thus, they found another strategy (ISO offered strategy) that would give them better payoffs through GA calculations. Table 8 presents the final strategy for the ISO and the GENCOs, and Table 10 indicates the incentives/penalties for this strategy.

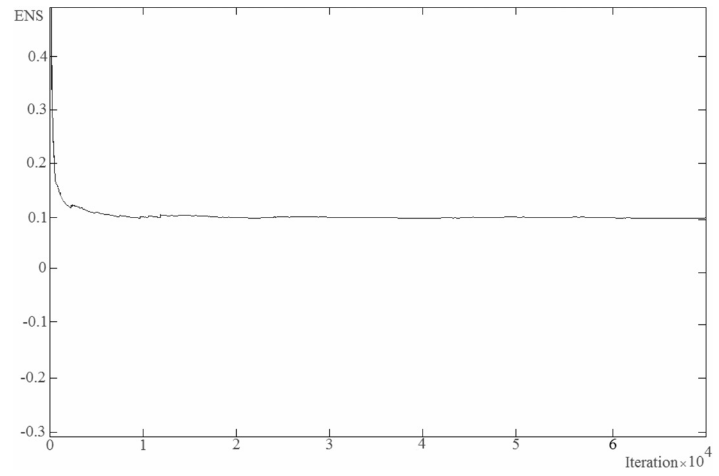

Fig. 4. Sample ENS Calculation for Week No.10 of offered Strategy in IEEE-118 Bus Test System, Applying Monte-Carlo Simulation Technique

According to the proportion of the role of each GENCO in reducing the reliability of the ISO important weeks, the incentive/penalty values are divided between GENCOs. On the other hand, the reliability was acceptable for the ISO important weeks. As a result, this IEEE-118 Bus Test System case study shows that competitiveness of maintenance scheduling for participants can be achieved in both maintenance and power electricity markets by using the proposed method.

As a result, accepting the ISO strategy by the GENCOs raises the final payoffs of GENCOs. Considering incentive/penalties for the final accepted strategy, GENCO-1 and GENCO-2 received 296951979$ and 1771528722$ respectively and GENCO-3 gained 225129409$ as their final payoffs for participating in both power auction market and AMM. Thus, a minimization of costs in the objective functions of the GENCOs led to minimal lost costs of the GENCOs in the power electricity market in IEEE-118 Bus Test System.

Finally, (fig. 5) presents the payoffs of the GENCOs in the final selected strategy obtained by the GA. Table 10 and (fig. 5) show that, in the final strategy, the maintenance weeks are weeks in which the load values and weekly prices are lower than those of other weeks of the same year beside choosing weeks for maintenance which keep reliability of system in acceptable level.

Tab. 9. Incentive/Penalty calculations of ISO important weeks for the proposed strategies of GENCO-1 and 2.

Week No.	$ENS_{offered,w}$ **(MWh)**	$ENS_{expected,w}$ **(MWh)**	$V_{j,w}$ **($/MWh)**	**GENCO-1 ($)**	**GENCO-2 ($)**	**GENCO-3 ($)**
10	0.1080	0.1000	5000000	-236984	-443807	-150808
11	0.0147	0.0130	3000000	-24471.1	-530206	0
34	0.0124	0.0120	1000000	-45229.8	-226149	0
36	0.0152	0.0135	4000000	-26637.6	-266376	-266376
38	0.1474	0.1000	7000000	-104210	-1896620	0
			Total Incentive/Penalty ($):	-437533	-3363158	-417184

Tab. 10. Incentive/Penalty calculations based on reliability assessment of ISO important weeks for the final strategy

Week No.	$ENS_{offered,w}$ **(MWh)**	$ENS_{expected,w}$ **(MWh)**	$V_{j,w}$ **($/MWh)**	**GENCO-1 ($)**	**GENCO-2 ($)**	**GENCO-3 ($)**
10	0.1022	0.1000	5000000	0	-481170	-134907
11	0.0114	0.0130	3000000	0	527472	26373.6
13	0.0135	0.0136	2000000	14388	71940	4316.4
36	0.0141	0.0135	4000000	-116374	-89220	-116374
38	0.0813	0.1000	7000000	453964.7	719700.1	0
			Total Incentive/Penalty ($):	351978.8	748722.5	-220591

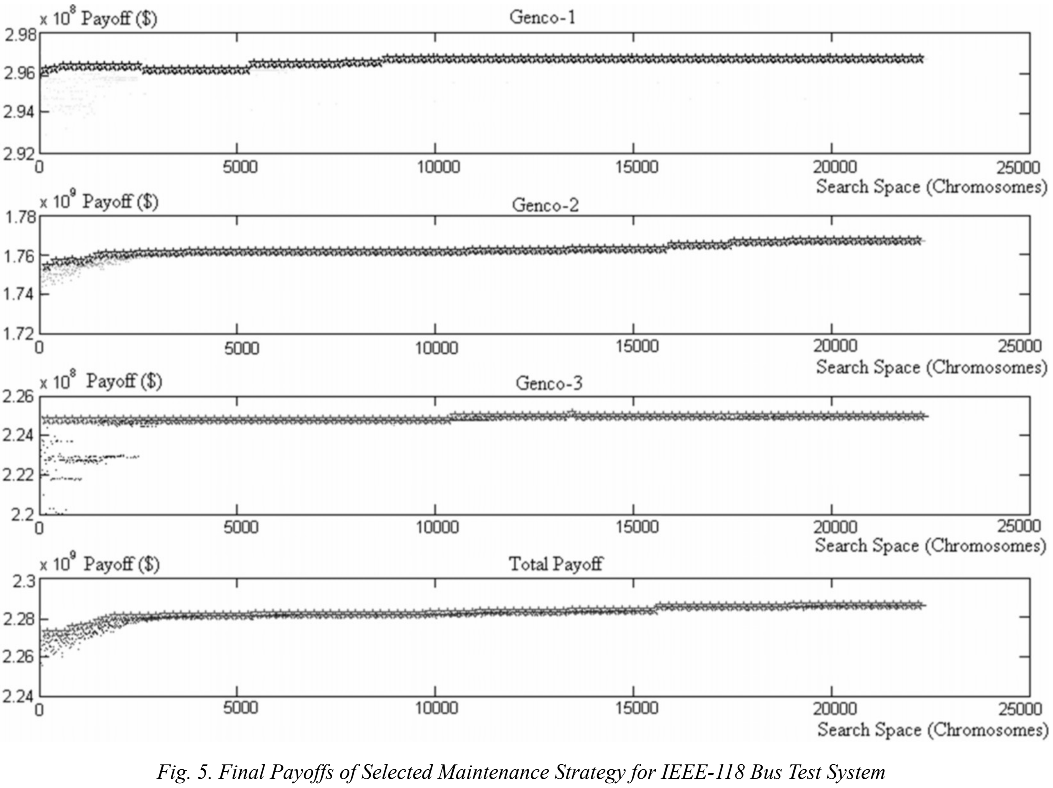

Fig. 5. Final Payoffs of Selected Maintenance Strategy for IEEE-118 Bus Test System

4. Conclusion

This paper proposes a new solution for scheduling power generating units' maintenance based on maximizing payoffs and minimizing costs in each GENCO's electricity and annual maintenance markets by applying an improved genetic algorithm. The best strategy in terms of maintenance issues (including load), fuel and maintenance time uncertainty, and the system's reliability was determined by using a Monte Carlo simulation in order to study ENS and EIR reliability indices.

First, the GENCOs' optimal strategy was determined and offered to the ISO. Based on the system's weekly reliability, the ISO presented incentives/penalties to the GENCOs. A desirable reliability level for the system was obtained for important weeks through 50,000 Monte Carlo simulation iterations.

After providing incentives/penalties, the ISO notifies the GENCOs of them. Then the GENCOs re-determine their payoffs to find a new strategy. The GENCOs are reluctant to pay $14,029,795 and $52,079,376, respectively, as penalties for the ISO's important weeks because those penalties would have reduced GENCO-1's and GENCO-2's payoffs considerably. Therefore, they decided to find a better strategy that would improve their payoffs through GA. In the final strategy, the GENCOs accept the ISO's incentive/penalty policy. According to each GENCO's role in reducing the reliability during the important weeks, the incentive/disincentive values are divided proportionally between the two GENCOs. To specify the new solution's correctness and applicability for scheduling power generation units' maintenance, IEEE-RTS was studied. The IEEE-RTS study shows that competitiveness of maintenance scheduling for the GENCOs can be gained in both the maintenance and power electricity markets by using the method this paper proposes.

After considering the penalties in the payoffs, GENCO-1 and GENCO-2 received $3,263,881,739 and $2,763,269,323, respectively, as their final payoff for participating in the power auction and maintenance markets.

As a result, the most efficient and adequate strategy for the GENCOs and the ISO was obtained by using this new comprehensive method, which also kept the system's reliability at a desirable level.

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