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جدول ۱۲- ردیف ۹

A New Approach for Maintenance Scheduling of Generating Units in Power Market

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Abstract--This paper presents results of modeling and solving a maintenance scheduling problem of generating units in competitive environment. In this environment, management of GENCOs and grid is separated, each maximizing its own benefit. The objective function for the GENCO is to sell electricity as much as possible, according to the market clearing price forecast. The objective function of ISO is to maximize the reserve capacity of the system with equal ratio of reserve capacity in each period; provided the energy purchase cost should be smaller than a pre-determined amount when the units of GENCOs are out for maintenance. Therefore there are two objective functions for finding an optimum maintenance schedule in restructured power systems. In this paper we apply Genetic Algorithm methodology for finding the optimum preventive maintenance schedule of generating units.

***Index Term*--genetic algorithm; maintenance scheduling; market clearing price; energy purchase cost**

I. NOMENCLATURE

The main mathematical symbols used throughout this paper are classified below.

Variables:

$R(t)$	Reserve capacity in stage t.
$I^{ISO}(t)$	Reliability index of grid in stage t.
$P_{Gij}(t)$	Power generated (MW) by unit j of GENCOi in stage t.
$x_{ij}(t)$	Maintenance status for unit j of GENCOi in stage t (1 if unit j is under maintenance in stage t and 0 otherwise).
$x_1(t)$	Ratio of power generated to demand in stage t.

Constants:

$MCP_i(t)$	Energy price estimate ($\$/MWh$) by GENCOi for stage t.
$I_v^{GENCOi}(t)$	Reliability index related to maintenance scheduling of GENCOi in stage t at iteration v.
$P_{Gij}^{\max}$	Capacity (MW) of unit j of GENCOi.
$P_{Gij}^{\min}$	Minimum power output (MW) of unit j of GENCOi.
$C(P_{Gij}(t))$	Production cost ($\$/h$) of unit j of GENCOi in stage t.
FC_{ij}	Fixed cost ($\$/Kw/YR$) of unit j of GENCOi.
VC_{ij}	Variable cost ($\$/MWh$) of unit j of GENCOi.
$L_D(t)$	Power demanded (MW) in stage t.
$C(t)$	Predicted market clearing price ($\$/MWh$) in stage t by ISO.
$P_v^M(t)$	The permissible and impermissible maximum power for maintenance of units in stage t at iteration v.
$C_v^{GENCOi}(t)$	Metaphorical cost of GENCOi in stage t at iteration v.

Numbers:

I	Number of GENCOs. (I=1)
T	Number of stages. (T=52)
HW	All hours of the week. ($24 \times 7 = 168$ hour)
k_1	Constant used by the ISO. ($k_1 = 0.5$)
C_{max}	The upper limit of power price. ($C_{max} = 50$ $\$/MWh$)
C_{min}	The least unit cost of power. ($C_{min} = 25$ $\$/MWh$)
d	The upper limit of energy purchase cost in research cycle. ($d = 1.35 \times 10^7$ $\$/h$)

II. INTRODUCTION

Maintenance scheduling is a complicated discrete stochastic non-linear optimization problem, especially when independent entities such as GENCOs and TRANSCOs and their self-interested objectives are taken into account. In a broad sense, there are two kined of facility maintenance in power system: generating unit maintenance and transmission line maintenance. Theoretically, maintenance of generation and transmission may be studied independently. The generating unit maintenance scheduling problem is first proposed when engineers try to optimize the operational scheduling of a large power system. With the appearance of restructuring and deregulation of modern power systems, unit maintenance scheduling in restructured power systems has got new characteristics and becomes quite different from that in traditional power systems [1,2]. A deregulated power system can be divided into three main segments: generation (GENCOs), transmission (TRANSCOs) and distribution (DISCOs). The main tasks of these three components will remain the same as before, however, to comply with FERC orders, new types of unbundling, coordination and rules are to be established to guarantee competition and non-discriminatory open access to all users. Each segment has certain responsibilities so that the system would have the required reliability. Therefore, each segment is responsible for performing the necessary maintenance on their facilities in order to sustain the competitive energy market. In this system, unit maintenance scheduling will not be decided only by ISO any more but will be mainly decided by GENCOs [3]. It is naturally the goal of GENCOs to maximize their benefit. All of them hope to minimize the maintenance investment loss (MIL) from their own interests. So every GENCO hopes to put its maintenance on the weeks when the market clearing price (MCP) is lowest, so that MIL is minimized. Therefore, objective function for the GENCO is to sell electricity as much as possible, according to the market clearing price forecast. The goal of ISO is to maximize the reserve capacity of the system with equal ratio of reserve capacity in each period provided the energy purchase cost should be smaller

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than a pre-determined amount when the units of GENCOs are out for maintenance.

In this paper the maintenance scheduling is analyzed from the ISO point of view. Each GENCO specifies optimum maintenance scheduling according to its objective function and hands it over to ISO. The ISO compares its own reliability index with reliability index related to maintenance schedule of GENCOs. If they are close enough in terms of reliability, it will be approved; otherwise the units, which violate the constraints, will be identified and ISO asks for time rescheduling. The GENCOs rescheduling will be possible by the information, which is provided by the ISO from permissible and impermissible maximum power for maintenance of generating units in all of the periods. This scheduling is quite unbiased and depends upon system conditions [2]. In this paper the maintenance scheduling of a specific GENCO is considered. The results for a simple system are analyzed and the application of the proposed method to IEEE-RTS (Reliability Test System), which consists of 24-bus, 32 generation units, and 38 transmission lines, is discussed.

III. PROBLEM FORMULATION

In order to solve an optimization problem using GA, first the possible solutions of the problem have to be coded in chromosomes. Next a fitness function to compare the chromosomes has to be defined. The period of maintenance scheduling is usually one year and is divided into T stages. When a stage is one week, T is equal to 52. In solving the generation maintenance scheduling problem, the main variables to be identified are maintenance states of the generating units. The schedule for unit j could be represented by a string of zeros and ones, $x_{ij}(t)$, where one means the unit j is under maintenance in stsge t. We take the maintenance schedule corresponding to an individual generating unit as a gene and build the chromosome from these genes. Therefore, a single chromosome will completely describe the maintenance schedules for power generating units. In other words, each chromosome is a possible solution for the problem. Since not every randomly built string will make a valid gene, a proper description of gene pools for each unit is necessary to ensure that the chromosomes satisfy the constraints. When chromosomes are built form valid genes, Crossover and Mutation as genetic operators are used to generate new possible solutions. Crossover cuts parent chromosomes at a point between two genes (called single poiht crossover) and exchanges the parent genes after the cut. Mutation changes randomly the values of some bits (genes) in each selected chromosome [4].

The profit of a GENCO is defined as the total profit which is the sum of the individual unit profits from the auctions over the scheduling horizon [5]. Each GENCO solves its corresponding maintenance scheduling problem seeking to maximize its own profit. Therefore the objective function of GENCOi in maintenance scheduling can be formulated as follows:

$$\begin{aligned} Max \prod_{GENCO} = & \sum_{j\in G_i}\sum_{t=1}^{T}\left[(MCP_i(t)\times P_{Gij}(t)-C\,(P_{Gij}(t)))\times(1-x_{ij}(t))\right]HW \\ & -\sum_{j\in Gi}\sum_{t=1}^{T}\{[FC_{ij}\times\frac{1000}{8760}\times x_{ij}(t)\times P_{Gij}^{\max}] \\ & +[VC_{ij}\times P_{Gij}^{\max}\times x_{ij}(t)]\}HW \end{aligned} \qquad (1)$$

The objective function (1) represents the profit of GENCOi, which is calculated as the difference between its total revenues and its corresponding costs which include production cost, fixed and variable costs. To compute the objective function accoring (1), the market clearing price should be determined . For the sake of simplicity, no uncertainty is considered, which means that is assumed the market clearing price forecasts are known and forced outage rate for each generating unit is zero.

In order to make the maitenance schedule feasible certain constraints should be satisfied. Some of basic constraints which should be set up are the continuity of maintenance activity, spesific time interval for maintenance of some generating units, maintenance crew constraint and the maximum & minimum capacity of each generating unit. The set of constraints of the maintenance scheduling problem of the GENCOi are specified below.

1) Maintenance Outage Duration: This constraint ensures for each unit that is maintained the required number of time periods. It shoud be noted that units 4,14,32 's maintenance start are not at interval 24 and units 6,15 are not to be maintained at interval 13.

2) Continuous Maintenance: This constraint ensures that the maintenance of any unit must be completed once it begins.

In order to accelerate the genetic algorithm, the constraints (1) and (2) are laid in chromosome.

3) Maximum and Minimum Power Output: The power generated for each online unit must be within a certain range represented by its minimum power output $P_{Gij}^{\min}$ and its capacity $P_{Gij}^{\max}$.

$$(1-x_{ij}(t))P_{Gij}^{\min} \le P_{Gij}(t) \le (1-x_{ij}(t))P_{Gij}^{\max} \qquad \forall j\in Gi, \forall t \qquad (2)$$

We use the weekly electricity price of nordpool deregulated power system [6]. Table 1 shows these weekly electricity prices and Table 2 shows a list of generating unit data and operating cost data. If needed, a more detailed cost modeling can be used [1].

Table 1
Weekly Electricity Market Clearing Price

Week	MCP	Week	MCP	Week	MCP	Week	MCP
1	36.7	14	28.8	27	29.2	40	25.5
2	39.3	15	25.2	28	34.1	41	27.7
3	37.2	16	33.2	29	33.2	42	27.9
4	35.6	17	29.1	30	38.1	43	33.1
5	37.9	18	35.7	31	25.2	44	38.1
6	35.9	19	37	32	30.9	45	38.2
7	35.4	20	37.8	33	33.1	46	40.3
8	33.5	21	36.4	34	26	47	42.2
9	27.2	22	33.7	35	25.8	48	38.7
10	26.7	23	39.7	36	25	49	42.8
11	25.1	24	38.3	37	31.1	50	45
12	25.9	25	39	38	23.8	51	58
13	24.9	26	36.6	39	25.6	52	43.4

Table 2
Generating Unit Data and Operating Cost Data

No	Unit Size MW		Number Of Units	Maintenance Duration (Week)	Maintenance Cost	
	Pmax	Pmin			Fixed $/kw/YR	Variable $/MWh
1-5	12	2.4	5	1	10.0	5.0
6-9	20	4.0	4	1	0.3	5.0
10-13	76	15.2	4	3	10.0	0.9
14-19	100	25	6	4	8.5	0.8
20-23	155	54.25	4	5	7.0	0.8
24-29	197	68.95	6	6	5.0	0.7
30	350	140	1	8	4.5	0.7
31-32	400	100	2	8	5.0	0.3

From the ISO view point who is responsible for system reliability another objective function should be defined and optimized. The ISO solves a maintenance scheduling problem involving all units, independently on which GENCO owns each unit, with the target of maximizing the reserve throughout the weeks of the year. Sufficiently accurate demand forecasts for the whole year assumed to be known. It should be noted that the ISO role is to ensure system reliability. Therefore, it must agree with GENCO on a generation maintenance plan that preserves system reliability. The power system reliability is closely related to the system reserve capacity. Therefore ISO should arrange the units for maintenance by maximizing the system capacity reserve in the whole year [7]. So, the objective function of the ISO can be defined as follow [8]:

$$\text{Maximize} \quad F = \min R(t) \qquad t = \{1,2,3,\dots T\} \tag{3}$$

$$R(t) = \sum_{i=1}^{I} \sum_{j \in G_i} P_{Gij}^{\max} - L_D(t) - \sum_{i=1}^{I} \sum_{j \in G_i} P_{Gij}^{\max} x_{ij}(t) \qquad \forall t \tag{4}$$

The set of constraints of the maintenance scheduling problem of the ISO are specified below.

1) Net Reserve: This constraint ensures a net reserve above a specified threshold for all periods.

$$\sum_{i=1}^{I} \sum_{j \in Gi} P_{Gij}^{\max} x_{ij}(t) + L_D(t) + R(t) \le \sum_{i=1}^{I} \sum_{j \in Gi} P_{Gij}^{\max} (1 - x_{ij}(t)) \qquad \forall t \tag{5}$$

2) Maintenance Outage Duration

3) Continuous Maintenance

In order to accelerate the genetic algorithm, the constraints (2) and (3) are laid in chromosome.

4) Maximum energy purchase cost: The reliability and economic objectives often conflict with the operation of power systems, and are very difficult to be integrated in one mathematical formulation. In most cases, it seems more acceptable to consider the reliability as an optimization objective and the cost as a constraint. This constraint can be formulated as follow:

$$\sum_{t=1}^{T} C(t)\, L_D(t) \le d \tag{6}$$

Assuming the relationship of the MCP forecast and the ratio between supply and demand of power is an exponential function, which is showed in Fig. 1. This expression can be formulated as follow [9]:

$$x_1(t) = \frac{\sum_{i=1}^{I} \sum_{j \in G_i} P_{Gij}(t)}{L_D(t)} \qquad \forall t \tag{7}$$

$$C(x_1(t)) = C_{\min} + (C_{\max} - C_{\min})\, e^{-k_1 (x_1(t) - 1)} \tag{8}$$

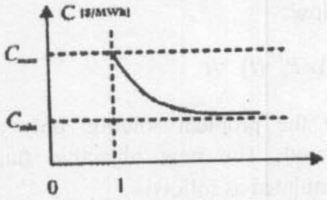

Fig. 1. The relationship of the MCP forecast and the ratio between supply and demand of power

The annual peak load for the test system is 2850 MW. Table 3 gives data on weekly peak load in percentage of annual peak load. The annual peak load occurs in week 51.

Table 3
Weekly Peak Load in Percent of Annual Peak

Week	Peak Load	Week	Peak Load	Week	Peak Load	Week	Peak Load
1	86.2	14	75.0	27	75.5	40	72.4
2	90.0	15	72.1	28	81.6	41	74.3
3	87.8	16	80.0	29	80.1	42	74.4
4	83.4	17	75.4	30	88.0	43	80.0
5	88.0	18	83.7	31	72.2	44	88.1
6	84.1	19	87.0	32	77.6	45	88.5
7	83.2	20	88.0	33	80.0	46	90.9
8	80.6	21	85.6	34	72.9	47	94.0
9	74.0	22	81.1	35	72.6	48	89.0
10	73.7	23	90.0	36	70.5	49	94.2
11	71.5	24	88.7	37	78.0	50	97.0
12	72.7	25	89.6	38	69.5	51	100
13	70.4	26	86.1	39	72.4	52	95.5

IV. A SOLUTION ALGORITHM FOR MAINTENANCE SCHEDULING IN COMPETITIVE ENVIRONMENT

The ISO solves the maintenance scheduling problem with the target of maximizing the reserve throughout the weeks of the year. Each GENCO specifies optimum maintenance scheduling according to its target function and hands it over to ISO. The ISO compares its reliability index with reliability index related to maintenance scheduling of GENCOs. If they are close enough in terms of reliability, it will be approved; otherwise the units, which violate the constraints, will be identified and ISO asks for time rescheduling. The GENCOs rescheduling will be possible by the information, which is provided by the ISO from permissible and impermissible maximum power for maintenance of generating units in all of the periods. This information calculated as follow:

$$I(t) = \frac{\sum_{i=1}^{I} \sum_{j \in G_i} \left[P_{Gij}^{\max} (1 - x_{ij}(t)) \right] - L_D(t)}{\sum_{i=1}^{I} \sum_{j \in G_i} P_{Gij}^{\max} - L_D(t)} \tag{9}$$

$$P_v^M(t) = \left[\sum_{i=1}^{I} \sum_{j \in G_i} P_{Gij}^{\max} - L_D(t) \right] \times \left[I_v^{GENCOs}(t) - I^{ISO}(t) \right] \qquad \forall t \tag{10}$$

Each GENCO, calculates its new maintenance scheduling including metaphorical cost in the objective function. The metaphorical cost can be calculated by using MCP in each period. This cost can be considered as a criteria for maintenance rescheduling of GENCO. Metaphorical cost can be formulated as follow:

$$C_v^{GENCOi}(t) = MCP_i(t) \times P_v^M(t) \ \forall t \tag{11}$$

In this paper in the problem solution only a specific GENCO is considered. The new objective function for GENCOi can be formulated as follow:

$$\begin{aligned} Max \prod_{GENCO} = & \sum_{j \in G_i} \sum_{t=1}^{T} \left[(MCP_i(t) \times P_{Gij}(t) - C(P_{Gij}(t))) \times (1 - x_{ij}(t)) \right] HW \\ & - \sum_{j \in Gi} \sum_{t=1}^{T} \{ [FC_{ij} \times \frac{1000}{8760} \times x_{ij}(t) \times P_{Gij}^{\max}] \\ & + [VC_{ij} \times P_{Gij}^{\max} - C_v^{GENCOi}(t)] x_{ij}(t) \} HW \end{aligned} \tag{12}$$

After ISO's purposes are met, benefit of GENCOi decreases. Now the final decision by GENCO is whether it accepts the scheduling or acts according to the previous scheduling and compensates its generation loss by buying from other GENCOs. It's obvious that the decision depends on the rate of benefit loss and the condition of GENCO. Flowchart of the proposed approach for maintenance scheduling problem is shown in fig. 2.

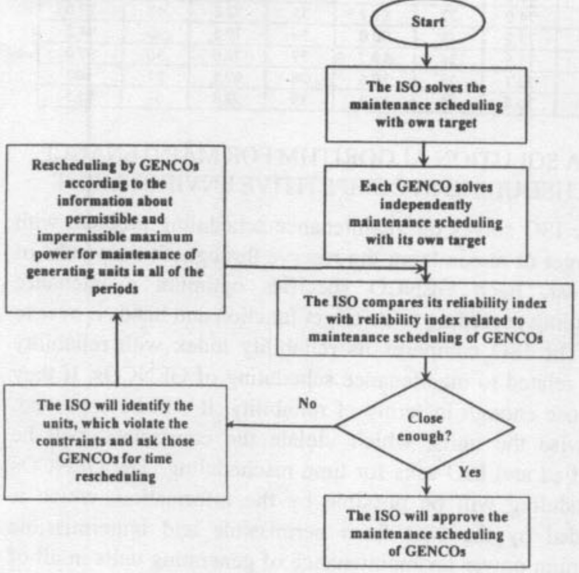

Fig. 2. The algorithm of proposed approach for maintenance scheduling of GENCOs

V. OUTPUT RESULTS

Fig. 3 shows performance of the GA over 1000 generations when maintenance scheduling of the GENCO solved from ISO viewpoint. In this figure, the fitness of the best individual and the average fitness of the population are illustrated. First of all, note that the maintenance schedule of GENCOi by the ISO (see Fig.4) schedules most units for maintenance during weeks 9-16 and 31-42, which are the weeks with the lowest loads. Its reliability profile is depicted in Fig. 5. Table 4 shows possible solution to this problem that covers ISO's purposes.

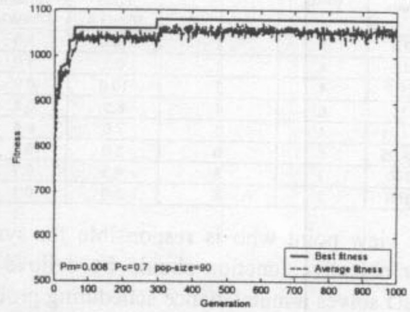

Fig. 3. Performance of GA based on ISO objective function

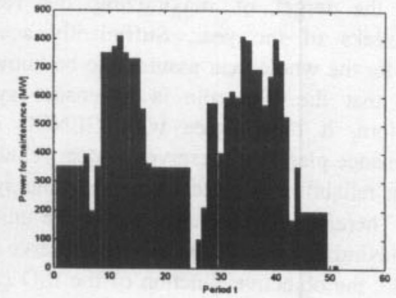

Fig. 4. Maintenance schedule of GENCOi from ISO viewpoint

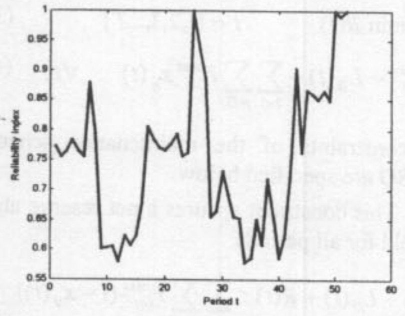

Fig. 5. Reliability index corresponding to ISO objective function

Table 4
Generation Maintenance Scheduling by ISO (52-weeks horizon)

Unit	Start of Outage (Week)	Unit	Start of Outage (Week)	Unit	Start of Outage (Week)
21-27	1	19	26	10	38
26	6	1-6-12	27	18	39
23	8	32	28	13-20	40
31	9	25	31	3	43
7	11	8	32	24	44
16-22	12	2-14-15	34	5	51
9-11	13	17-28	36	-	-
4-30	17	29	37	-	-

Fig. 6 shows performance of the GA over 500 generations when the scheduling of GENCOi generating units formulated based on its desired objective function. This approach of as shown in Fig. 7, schedules most units for maintenance during weeks 8-19 and 31-43 which are the weeks with the lowest energy prices. The reserve capacity profiles corresponding to both approachesare compared in Fig. 8 and the maintenance schedule based on GENCOi desired objective function is shown clearly in Table 5. Reliability index clearance of 15% in each period will be approved by ISO.

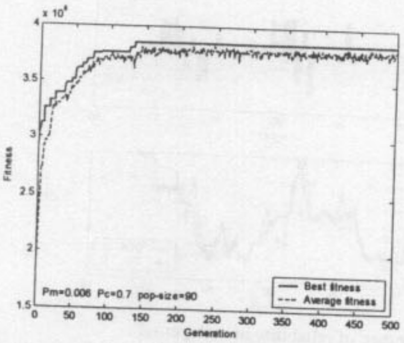

Fig. 6. Performance of GA based on GENCOi objective function

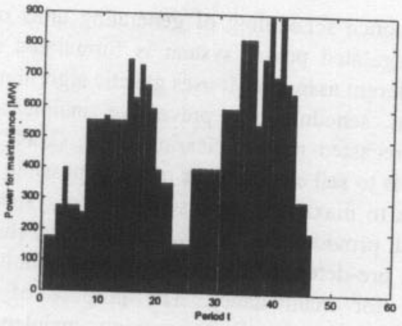

Fig.7. The schedule of GENCOi units from its desired objective function

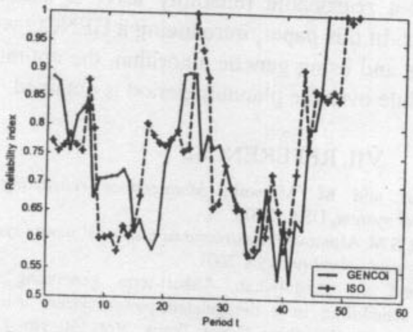

Fig. 8. Comparing reliability indices

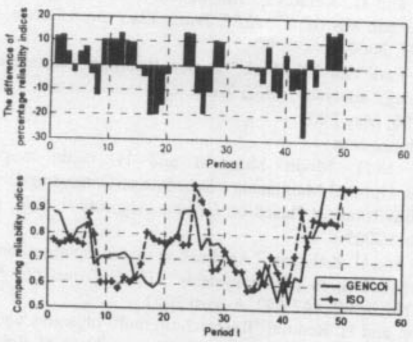

Fig. 9. The initial percentage of residual reliability and violated reliability

Fig. 9 depicts the percentage of residual reliability and violated reliability in each period, which is calculated by the ISO considering the initial scheduling. According to this percentage the maximum power for carrying out the maintenance of the units or ending it is calculated in each period. This is clearly shown in Fig. 10. In this figure the negative power means that the maintenance is impermissible according to the calculated power in each period and the positive power means that it is permissible.

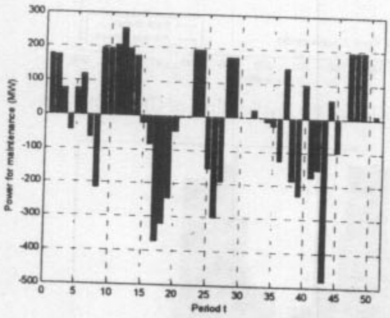

Fig. 10. The maximum permissible or impermissible power for maintenance of the units (initial iteration)

Table 5
The initial Generation Maintenance Scheduling by GENCOi

Unit	Start of Outage (Week)	Unit	Start of Outage (Week)
11-15	1	1-2-8-9-25	17
19	3	23	21
6-10-14	4	32	26
21	7	24	31
31	8	13-28-30	34
5	11	3-26	38
20	12	22	39
29	15	27	41
12-16-18	16	4-7-17	42

The GENCOi's benefit would be $3.8137\times10^{8}\$$. The achieved results with the results of other GENCOs are handed over to ISO. According to Fig. 8 reliability index of ISO is violated in some periods. Therefore scheduling of some units will not be approved according to ISO constraints. Each GENCO will be informed by ISO about its rejected schedules and then rescheduling process is executed by each GENCO. In this case study the maintenance schedules of some units of the studied GENCO, i.e. 17, 25, 26, 29, 32 will not be approved. This is because some of ISO constraints have been violated and therefore these units should be rescheduled by GENCOi. Fig.11 shows Performance of GA over 500 generations for the rescheduling based on GENCOi problem formulation with new constraints. This process should be repeated till the stopping condition is met. The stopping condition is satisfied when the profiles of reliability indices are sufficient close. The final maintenance scheduling plan and its reliability profile are illustrated in Fig. 12 and 13. The final maintenance schedule of GENCOi is shown clearly in Table 6.

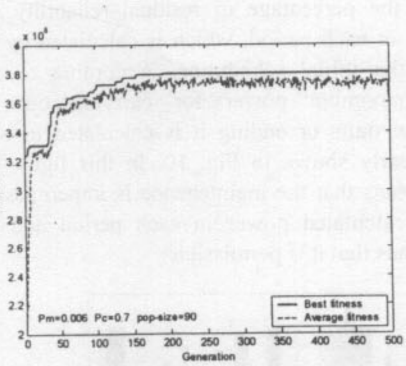

Fig. 11. Performance of GA for the rescheduling of GENCOi

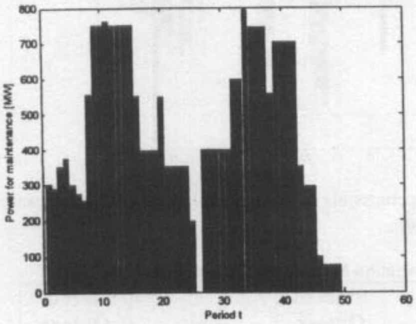

Fig. 12. The final maintenance scheduling of GENCOi

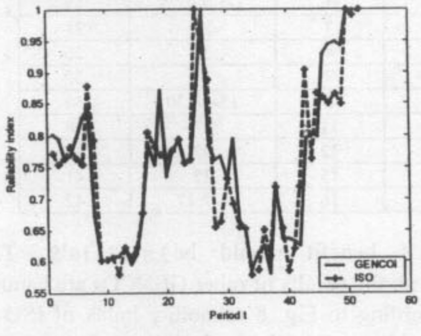

Fig. 13. comparing reliability indices

Table 6
The final Generation Maintenance Scheduling of GENCOi (52-weeks horizon)

Unit	Start of Outage (Week)	Unit	Start of Outage (Week)
4-8-9-11-13-15	1	16-18	16
6-7	2	23-26	20
19	3	32	27
10-14	4	24	32
1-2	5	28	34
21	7	30	35
31	8	3	38
29	9	22	39
5	11	27	40
20	12	17	44
25	15	12	47

After ISO's purposes are met, the results of table 6 will be achieved and by this new scheduling the benefit of GENCOi decreases by 400000$ and equals 3.8097×10^8\$. Now the final decision by GENCOi is whether it accepts the rescheduling or acts according to the its previous scheduling (Table 5), and compensates its generation loss by buying from other GENCOs. Fig. 14 depicts the final percentage of reliability in each period.

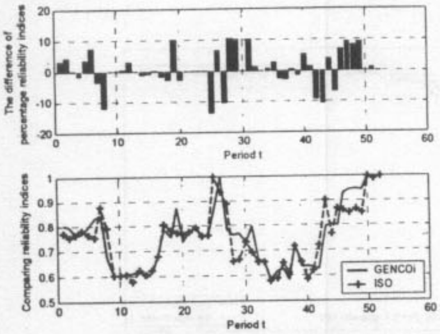

Fig. 14. The final percentage of reliability in each period

VI. CONCLUSION

Annual maintenance scheduling of generating units of a GENCO in a deregulated power system is formulated and discussed from different aaspects . It uses genetic algorithm to find the optimum schedule for preventive maintenance concerning the forecasted market clearing price. GENCO's objective function is to sell electricity as much as possible and the goal of ISO is to maximize the reserve of the system at every time interval, provided the energy purchase cost should be smaller than a pre-determined amount when the units of GENCOs is out for maintenance. The purpose of this algorithm is to orderly encourage moving maintenance outages from periods of low reliability to periods of high reliability, so that a reasonable reliability level is attained throughout the year. In this paper, introducing a GENCO with 32 generating units and using genetic algorithm, the optimum maintenance schedule over the planning period is obtained.

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