Generation Maintenance Scheduling in Power Market Based on Genetic Algorithm

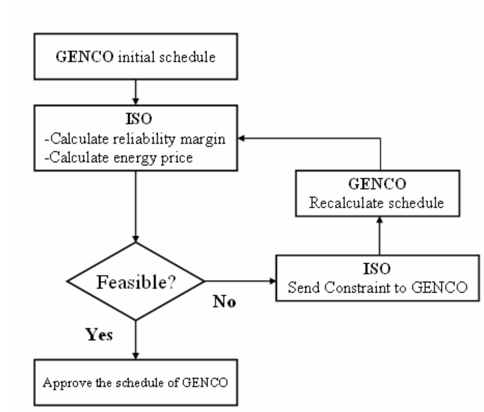
R. Eshraghnia, M.H. Modir Shanechi, *Senior Member IEEE* and H. Rajabi Mashhadi [1]

Abstract--This paper presents a Genetic Algorithm methodology for finding the optimum preventive maintenance schedule of generating units of a GENCO in a restructured power system. In this environment, management of GENCOs and grid is separated, each maximizing its own benefit. Therefore, the principle to draw up the unit maintenance scheduling will be changed significantly. The profit of a GENCO is defined as the total profit, which is the sum of the individual units' profits from the auctions over the horizon. So every GENCO hopes to put its maintenance on the weeks when the market clearing price (MCP) is lowest, so that maintenance investment loss (MIL) descends. Therefore, objective function for the GENCO is to sell electricity as much as possible, according to the market clearing price forecast. Various technical constraints such as generation capacity, duration of maintenances and maintenance continuity are being taken in to account. The objective function of ISO is to maximize the reserve capacity of the system at every time interval, subject to the energy purchase cost doesn't increase from a pre-determined amount when the units of GENCOs are in outage for maintenance. Therefore two objective functions will be finding for fairly maintenance scheduling in restructured power systems. Each GENCO specifies optimum maintenance scheduling according to its objective 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.

***Index Term*-- genetic algorithm; maintenance scheduling; market clearing price; maintenance investment loss.**

I. Introduction

Recently, the electric utility industry in the whole world has been facing pressure to be deregulated or restructured in order to increase its efficiency, to reduce operational cost or to give consumers more alternatives. For this aspect, a great deal more research is needed to achieve better intelligent knowledge process. The present centralized system for the power system control; operation and planning must be remodeled to cope with these situations. With the promotion for the deregulation of electric power systems, maintenance scheduling in a restructured power system is becoming critical [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. GENCOs will try to schedule their units maintenance according to the operating conditions of their units [3]. Flowchart for maintenance scheduling problem is shown in below.



The algorithm for maintenance scheduling of GENCO

It is naturally the goal of GENCOs to maximize their benefit. All of them hope to minimize the MIL from their own interests. So every GENCO hopes to put its maintenance on the weeks when the MCP is lowest, so that MIL descends [3]. Therefore, objective function for the GENCO is to sell electricity as much as possible, according to the market clearing price forecast. Various constraints such as generation capacity, duration of maintenance and maintenance continuity are being taken in to account. The goal of ISO is to maximize the reserve of the system at every time interval subject to the purchase cost doesn't increase from a pre-determined amount when the units of GENCOs are in outage for maintenance [4, 5].

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

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R. Eshraghnia is with the Deputy of engineering and market plans of Iran Grid Management Co., Tehran, Iran. (E-mail: roozbeh_eshraghnia@yahoo.com)

M.H. Modir Shanechi and H.R. Mashhadi are with Electrical Engineering Department, Faculty of Engineering Ferdowsi University of Mashhad, Mashhad, Iran. (e-mails:, shanechi@gmail.com, h_mashhadi@um.ac.ir)

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 that violate the constraints will be identified and ISO asks for time rescheduling. 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.

II. GENETIC ALGORITHM

Recently, genetic algorithms have received a lot of attention, and they currently account for many successful applications. Genetic algorithms are search algorithms that reflect in a primitive way some of the processes of natural evolution. Genetic algorithms often provide very effective search mechanisms that can be used in optimization and classification applications. Genetic algorithms work with a population of points, rather than a single point; each point is actually a vector in hyperspace representing one potential, or candidate, solution to the optimization problem. A population is thus, just an ensemble, or set, of hyperspace vectors. Each vector is called an individual or sometimes a choromosome in the population.

Because real numbers are often encoded in genetic algorithms using binary numbers, the dimensionality of the problem vector might be different from the dimensionality of the bit string chromosome. The number of elements in each vector (individual) equals the number of real parameters in the optimization problem. A vector element generally corresponds to one parameter, or dimension, of the numeric vector. Each element can be encoded in any number of bits, depending on the representation of each parameter. The total number of bits defines the dimension of hyperspace being searched.

The series of operations carried out when implementing a genetic algorithm paradigm is:

1. Initialize the population,
2. Calculate fitness for each individual in the population,
3. Reproduce selected individuals to form a new population,
4. Perform crossover and mutation on the population,
5. Loop to step 2 until some condition is met.

The two main steps for the translation of an optimization problem to an evolutionary optimization problem are chromosome representation and chromosome evaluation. In the first step, which is problem specific, the solution of the optimization problem is represented in the form of a binary string, i.e. a chromosome. In the second step, an evaluation function serving as fitness function is introduced in order to compare the chromosomes in the evolution process. The encoding of the problem and the selection of a proper fitness function has important effects on the success of the GA method.

III. PROBLEM FORMULATION

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 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 i could be represented by a string of zeros and ones, x_{it}, where one means the unit i 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 the 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 sigle point crossover) and exchanges the parent genes after the cut. Mutation changes randomly the values of some bits (genes) in each selected chromosome [6].

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 [7]. Each GENCO solves its corresponding maintenance scheduling problem seeking to maximize its own profit. Therefore the objective function of GENCO_i in maintenance scheduling can be formulated as follows:

Objective function of GENCO_i:

$$\begin{aligned} Max \prod_{GENCO_i} = \sum_{i=1}^{N} \sum_{t=1}^{T} \left[(MCP_t \times P_{it} - C(P_{it})) \times (1 - x_{it}) \right] HW \\ - \sum_{i=1}^{N} \sum_{t=1}^{T} \{ [FMC_i \times \frac{1000}{8760} \times x_{it} \times P_{i\max}] \\ + [VMC_i \times P_{i\max} \times x_{it}] \} \, HW \end{aligned} \quad (1)$$

where,

MCP_t : Energy price estimate ($\$/MWh$) for stage t.

P_{it} : Power generated (MW) by unit i in stage t.

$P_{i\max}$: Capacity (MW) of unit i.

$C(P_{it})$: Production cost ($\$/h$) of unit i in stage t.

FMC_i : Fixed maintenance cost $(\$/Kw/YR)$ of unit i.

VMC_i : Variable maintenance cost $(\$/MWh)$ of unit i.

N : Number of units in GENCOi.

T : Number of stages. (T=52)

HW : All hours of the week. (24×7=168 hour)

x_{it} : Maintenance status for unit i in stage t (1 if unit i is under maintenance in stage t and 0 otherwise).

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 cost and variable maintenance cost [1].

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.

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

In this paper it is assumed that GENCOi offers the price in a way that wins all the auctions and in all the period uses its energy. 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.

We use the weekly electricity price of norpool deregulated power system [8]. Table 1 show these weekly electricity prices and Table 2 shows a list of generating unit data and operating cost data.

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

It should 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.

From the ISO view point that 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 reliability throughout the weeks of the year. Sufficiently accurate demand forecasts for the whole year assumed to be known [8]. 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.

Table 2
Generating Unit Data and Operating Cost Data

No	Unit Size MW		Number Of Units	Maintenance Duration (Week)	Maintenance Costs	
	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

Therefore ISO should arrange the units for maintenance by maximizing the system capacity reserve in the whole year. So, the objective function of the ISO can be defined as follow:

Objective function of ISO:

$$Maximize\ \min R_t = \sum_{i=1}^{N} P_{i\max} - L_t - \sum_{i=1}^{N} P_{i\max} x_{it} \qquad (2)$$

where, L_t is predicted load for period t and R_t is system reserve capacity. The set of constraints of the maintenance scheduling problem of the ISO are specified below.

***1) Minimum Net Reserve**:* This constraint ensures a net reserve above a specified threshold for all periods [9].

$$\sum_{i=1}^{N} P_{i\max}(1-x_{it}) - L_t \geq R_t^{\min} \qquad \forall t \qquad (3)$$

where, $R_t^{\min}$ is net minimum reserve (MW) in period t. The percentage reliability index in all period is above 50%.

2) Maintenance Outage Duration

3) Continuous Maintenance

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

4) Maximum Energy Purchase Cost: The energy purchase cost doesn't increase from a pre-determined amount when the units of GENCOs are out for maintenance. This constraint can be formulated as follow [10]:

$$\sum_{t=1}^{T} C_t L_t \leq d \qquad (4)$$

where, C_t is predicted market clearing price for period t by ISO and d is the upper limit of energy purchase cost. (d= 1.35×10^7 *$/h*)

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 [3]:

$$x_t = \frac{\sum_{i=1}^{N} P_{it}(1-x_{it})}{L_t} \qquad \forall t \qquad (5)$$

$$C_t(x_t) = C_a + (C_b - C_a)e^{-k(x_t - 1)} \quad (6)$$

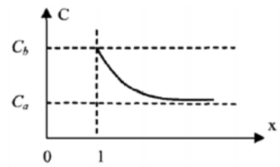

Fig. 1. The relationship of the MCP forecast and the ratio between supply and demand of power

In Fig. 1, C_a is the least unit cost of power (C_a=25 \$/MW) and C_b is the upper limit of power price (C_b=50 \$/MW), which is announced by the supervising department and must be obeyed in bidding. 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 RESTRUCTURED POWER SYSTEMS

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. This scheduling is quite unbiased and depends upon system conditions. In this paper in the problem solution only a specific GENCO is considered. Flowchart of the proposed approach for maintenance scheduling problem is shown in fig. 2. After ISO's purposes are met, benefit of GENCOi decreases. Now the final decision by GENCOi 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 GENCOi.

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. 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.

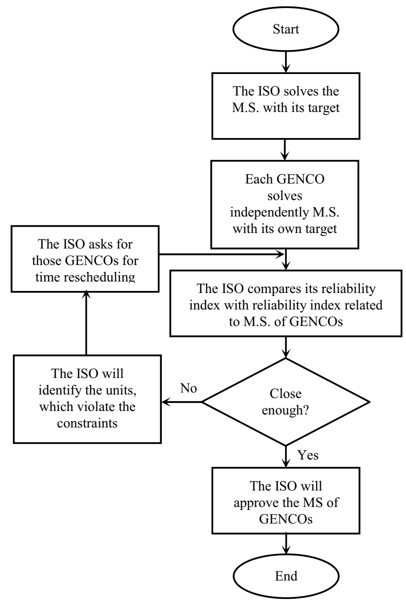

Fig. 2. The algorithm of proposed approach for maintenance scheduling of GENCOs

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	-	-

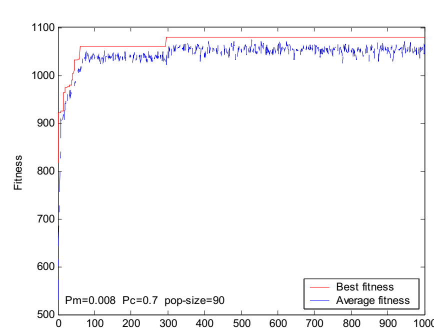

Fig. 3. Performance of GA based on ISO objective function

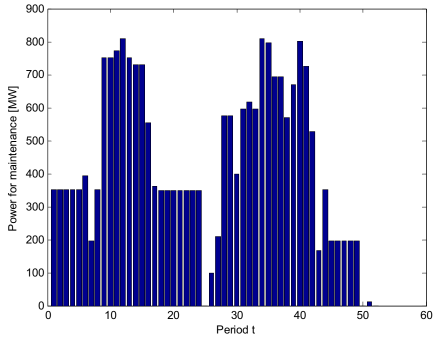

Fig. 4. Maintenance schedule of GENCOi from ISO viewpoint

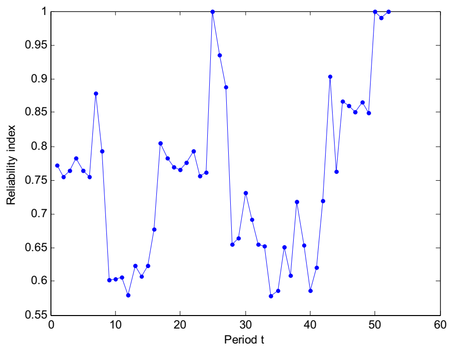

Fig. 5. Reliability index corresponding to ISO objective function

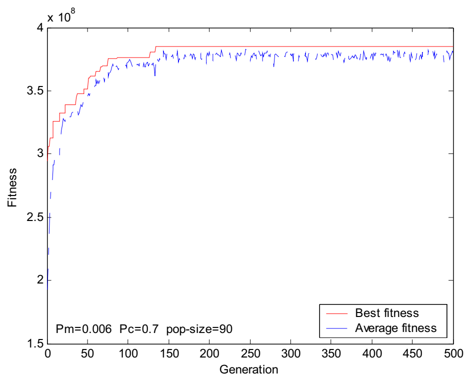

Fig. 6. Performance of GA based on GENCO objective function

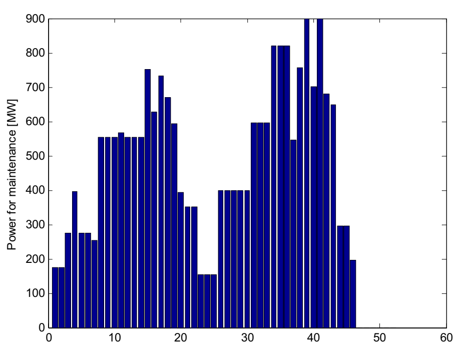

Fig.7. The schedule of GENCOi units from its desired objective function

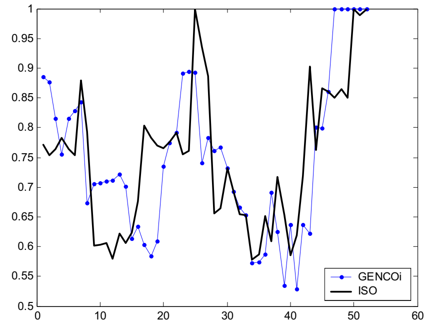

Fig. 8. Comparing reliability indices

Table 5
The Generation Maintenance Scheduling by GENCOi (52-weeks horizon)

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 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. The GENCOi's benefit would be $3.8137\times10^{8}\$$. The achieved results with the results of other GENCOs are handed over to ISO. The main responsibility of ISO is power system security guarantee so it approves or rejects the GENCOs offering by considering its constraints. 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.

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

Unit	Start of Outage (Week)	Unit	Start of Outage (Week)
11-15	1	26	20
19	3	23	21
6-10-14	4	32	27
21	7	24	32
31	8	13-28	34
29	9	30	35
5	11	3	38
20	12	22	39
25	15	27	40
12-16-18	16	4-7	42
1-2-8-9	17	17	43

Fig.9 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. 10 and 11. The final maintenance schedule of GENCOi is shown clearly in Table 6.

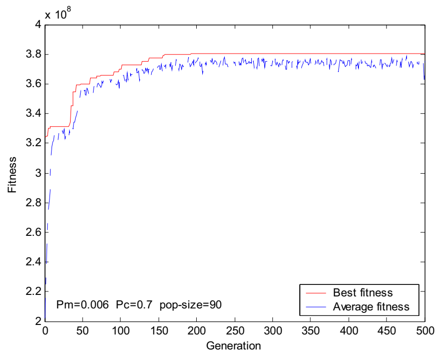

Fig. 9. Performance of GA for the rescheduling of GENCOi

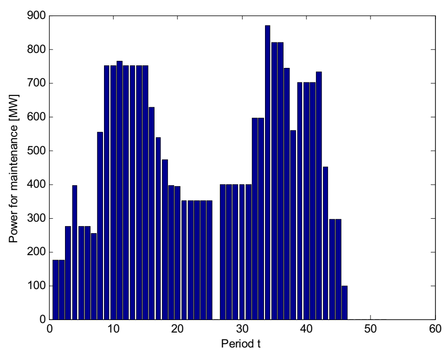

Fig. 10. The final maintenance scheduling of GENCOi

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 190000$ and equals $3.8118\times10^{8}\$$. 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. It's obvious that the decision depends on the rate of benefit loss and the condition of GENCOi.

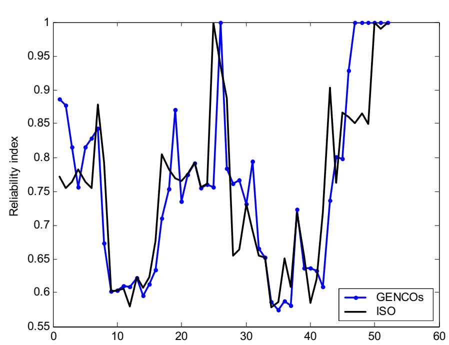

Fig. 11 comparing reliability indices

VI. CONCLUSION

Annual maintenance scheduling of generating units of a GENCO in a deregulated power system is formulated and discussed from different asspects. 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, subject to the energy purchase cost doesn't increase from a pre-determined amount when the units of GENCOs is in outage for maintenance. 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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