GENERATORS MAINTENANCE SCHEDULING USING HARMONY SEARCH ALGORITHM

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ABSTRACT

Music-based harmony search algorithm is a relatively new meta-heuristic technique. It is used to solve multi-objective optimization problems. Generators maintenance schedules (GMS) play the most significant role for the economical and reliable operation of a power production system. This paper presents the application of harmony search (HS) algorithm for solving generators maintenance scheduling problem. HS algorithm is quite efficient, because, the convergence rate of this algorithm is very fast. HS algorithm is based on the concept of music improvisation process of searching for a perfect state of harmony. To verify the great power of this method, HS algorithm is applied to solve GMS problem of different power production systems. Simulation results reveal that the proposed algorithm is a powerful search algorithm for various optimization problems.

Keywords: *Harmony Search, maintenance scheduling, reserve margin, maintenance window*

INTRODUCTION

GMS is a complex constrained optimization problem. Maintenance ensures the long life and good performance of generators. To avoid premature failure of generators in a power production system, it is important to perform maintenance at consistent intervals. Optimized GMS solution is vital to provide secure and reliable operation of a power production system. The main aim of GMS is to specify an optimized generators maintenance timetable in order to achieve system reliability, decrease total operating costs, maximize the reserve margin and enhance generator life time, while, satisfying maintenance window constraints, crew constraints and load constraints.

Generator maintenance scheduling (GMS) is a large-scale, nonlinear and stochastic optimization problem with many constraints and conflicting objective functions[1]. To obtain optimized solution for complex GMS problem a number of different solutions exist. Yamayee et al. used the dynamic programming approach for formulating the optimal maintenance scheduling, which combines the system reliability and the production cost[2]. Kothari has presented a three-step method for the maintenance scheduling, based on the dynamic programming[3]. Bala's algorithm has been used to solve the GMS problem[4]. Mukerji et al. have discussed that the integer programming is only true optimal and practical approach for solving GMS problem[5]. Edwin and Curtius presented a method for the GMS, in which the production cost is minimized by integer linear programming[6]. Chen and Toyoda have presented multi area maintenance scheduling with network constraints by decomposing the problem into a master and several sub-problems using branch and bound technique[7]. J. Yellen et al. presented a decomposition approach based on duality theory for optimized generators maintenance schedule by decomposing the problem into one master problem and one sub-problem[8]. Stremel presented a method to simulate weekly maintenance schedules[9]. Eon Duval and Poilpot have described a heuristic approach to the GMS which is seen here as a combinatorial model[10]. GMS is done on priority basis. EI-Sheikhi and Billinton presented a method for GMS in two interconnected power systems[11]. Contaxis et al. presented a software package for interactive risk calculation and GMS by using two approximation techniques: levelized effective reserve and levelized incremental risk[12]. C.E. Lin et al. have presented a prototype knowledge based expert system for solving the optimized generators maintenance scheduling problem in Taiwan Power Corporation (TPC) system[13]. In fact C.E. Lin et al. and C.J. Huang et al. were the fist to introduce a fuzzy concept to solve the GMS problem[14-15].

The heuristic approach is based on trial-and-error method to calculate the GMS objective function, generally by considering each unit on individual ba-

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sis. It needs momentous operator input and often, it fails to create feasible solutions. Whereas, the mathematical techniques are rigorously limited with handling the nonlinear objective and constraint functions that exemplify the GMS problem. Expert systems become inappropriate in case when heuristic suppositions are applied on rules. Fuzzy approach can be applied to practical power systems, but cannot be generalized.

To overcome the limitations of heuristic, mathematical, expert system and fuzzy methods a number of meta-heuristic techniques for solving GMS problem are studied. These include genetic algorithm[16-17], simulated annealing[18] and evolutionary programming[19]. It is observed that the performance of meta-heuristic approaches for solving GMS problem is more promising as compared with other techniques. This paper presents a robust meta-heuristic technique (HS) to solve complex GMS problem. HS is quite efficient and distinct from that of conventional methods.

The rest of the paper is organized in six main sections. Section 2 describes the HS algorithm and its search procedure. GMS mathematical model is presented in section 3. The case studies for which GMS problem is solved are discussed in section 4. HS implementation to solve these case studies is mentioned in section 5. Finally, results and some conclusion remarks are presented in section 5 and 6 respectively.

HS ALGORITHM

HS algorithm comprises of three main factors, which are: harmony memory (HM), pitch adjustment and randomization. HM is used to store the best harmonies, which are selected as new solution vectors. HM accepting rate α_{accept} is responsible to store the best harmonies in memory. Pitch adjustment is used to generate slightly different notes by adjusting the frequency. There are two important pitch adjustment parameters, which are: pitch bandwidth $p_{bandwidth}$ and pitch adjusting rate pa_{rate}. In HS, pitch is adjusted linearly using the following equation:

$$h_{new} = h_{old} + p_{bandwidth} * \gamma \tag{1}$$

Randomization is the last important component of the HS algorithm. It is used to increase the diversity of the solutions. The probability of randomization is computed by using the following equation:

$$R_{prob} = 1 - \alpha_{accept} \tag{2}$$

The pitch adjustment probability is:

$$p_{prob} = \alpha_{accept} * pa_{rate} \tag{3}$$

Generally, HM and pitch adjustment explores the local best solutions, while the randomization computes the global best solutions.

HS Search Procedure

The HS search procedure includes the following important steps:

- The lower and upper limits of the given parameters are defined. The parameters are initialized with random solutions and these solutions are stored in HM.
- Each harmony is evaluated.
- New harmonies are improvised using the existing best harmonies.
- HM is updated with these new harmonies.

This procedure is continued until optimal solution is achieved. The conceptual framework of harmony search algorithm is shown in Figure 1.

GMS PROBLEM FORMULATION

The following notations are used in GMS mathematical model:

$T_{(weeks)}$ = Total number of weeks (periods) in the planning horizon

$N_{(units)}$ = Total number of generators/units in the power production system

$I_{(units)}$ = Set of generators indices

ind = Index of generators

tnd = Index of weeks

ear_{ind} = Earliest week of generator *ind* to start maintenance

lat_{ind} = Latest week of generator *ind* to end maintenance

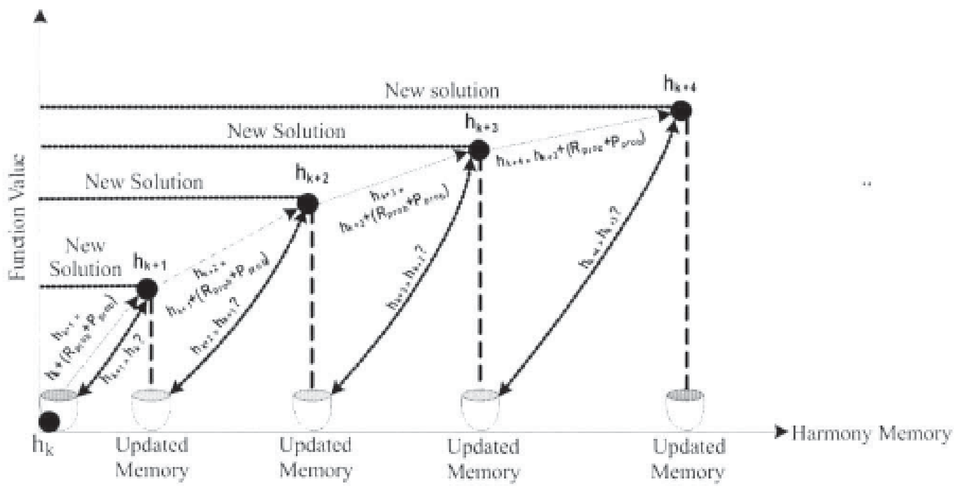

Figure 1: Conceptual framework of harmony search algorithm

dur_{ind} = Duration of maintenance of *ind* generator

$cap_{ind\ tnd}$ = Generating capacity of generator in week

lod_{tnd} = Load demand for period *tnd*

$NM_{ind,tnd}$ = Man power needed by generator *ind* at period *tnd*

AM_{tnd} = Man power available at period *tnd*

Objective Function and Constraints Formulation

Reserve based objective function is the most appropriate to solve the GMS problem. So, GMS objective function maximizes the minimum reserve margin during each generation. Let $T_{(weeks)ind} \subset T_{(weeks)}$ is the set of weeks when maintenance of generator ind may start. So, for each unit ind:

$$T_{(weeks)ind} = \left\{ \begin{array}{l} tnd \in T_{(weeks)} : ear_{ind} \le tnd \\ \le lat_{ind} - dur_{ind} + 1 \end{array} \right\} \qquad (4)$$

Eqn. 4 gives the specified time period during which a generator is maintained. If a generator is off-line for maintenance then '1' is used to represent that the generator is on maintenance whereas, '0' indicates that generator is not on maintenance.

$$U_{ind,tnd} = \begin{cases} 1 & if\ unit\ ind\ starts\ maintenance \\ & in\ tnd\ week \\ 0 & otherwise \end{cases} \qquad (5)$$

For each unit $ind \in I_{(units)}$ and $tnd \in T_{(weeks)ind}$. Let $S_{ind,tnd}$ is the set of start time periods. If maintenance of a unit *ind* starts at week *j*, that unit must be maintained at period *tnd* So,

$$S_{ind,tnd} = \left\{ \begin{array}{l} j \in T_{(weeks)ind} : tnd - dur_{ind} \\ +1 \le j \le tnd \end{array} \right\} \qquad (6)$$

The net reserve of the power production system during generators maintenance scheduling can be formulated as:

$$net\_reserve = \underset{U_{ind,tnd}}{Min} \left(\begin{array}{l} \sum_{ind \in I_{(units)}} cap_{ind,tnd} - \sum_{ind \in I_{(units)ind}} \\ \left(\sum_{j \in S_{ind,tnd}} U_{ind,j} cap_{ind,j} \right) - lod_{tnd} \end{array} \right) \qquad (7)$$

Subject to the maintenance window constraint,

$$\sum_{tnd \in T_{(weeks)ind}} U_{ind,tnd} = 1 \quad \forall ind \in I_{units} \qquad (8)$$

The crew constraint,

$$\sum_{ind \in I_{(units)ind}} \sum_{j \in S_{ind,tnd}} U_{ind,j} NM_{ind,j} \le AM_{tnd} \quad \forall tnd \in I_{(weeks)} \qquad (9)$$

The load constraint,

$$\sum_{ind \in I_{(units)}} cap_{ind,tnd} - \sum_{ind \in I_{(units)tnd}} \sum_{j \in S_{ind,tnd}} U_{ind,j} cap_{ind,j} \le lod_{tnd} \quad \forall tnd \in T_{(weeks)} \tag{10}$$

In case of constraints violation some penalty value is added in the objective function.

CASE STUDIES

In order to investigate the performance of HS algorithm, five case studies are solved.

Case Study-1: 8-Units Test System

This system comprises of 8 units over a planning period of 6 weeks is used, which is obtained from the example presented in[20]. During this period, 8 units need to undergo maintenance, and table 1 lists the generator capacities, maintenance duration of each unit and predicted load of each week. The maintenance outages for the generating units are scheduled to maximize the minimum net reserves mentioned in Eqn. 7 and satisfy the maintenance window constraint, crew constraint and load constraint presented in Eqns. 8, 9 and 10 respectively.

Table 1: Data of Case Study-1
(a: Generation and durations, b: Predicted loads)

Unit #	Unit Capacity (MW)	Duration (weeks)
1	30	1
2	25	1
3	35	1
4	40	1
5	50	1
6	45	2
7	40	2
8	35	2

a.

Interval #	Load (MW)
1	165
2	160
3	190
4	245
5	250
6	180

b.

Case Study-2: 13-Units Test System

The proposed optimization approach is used to solve a test system consists of 13 units over a planning period of 26 weeks, which is obtained from example presented in[21]. Table 2 gives the unit capacities, maintenance duration and manpower needed for each week. A constant system peak load 2500 MW is used. The available crew is limited to 40 in each week. Maintenance window constraint, crew constraint and load constraint is needed to satisfy in each week. The objective is to levelize the reserve margin in each generation by minimizing the sum of square of net reserve, which can be calculated as:

$$\min_{U_{ind,tnd}} \left\{ \sum_{tnd \in T_{(weeks)}} \left[\left(\sum_{ind \in I_{(units)}} cap_{ind,tnd} - \sum_{ind \in I_{(units)tnd}} \left(\sum_{j \in S_{ind,tnd}} U_{ind,j} cap_{ind,j} \right) - lod_{tnd} \right) \right]^2 \right\} \tag{11}$$

Case Study-3: 21-Units Test System

The test problem consists of scheduling of the maintenance of 21 generating units over a planning period of 52 weeks presented in[22]. Table 3 lists the generator capacity, allowed maintenance period, outage duration of each unit and crew needed weekly for

Table 2: Data of case study-2

Unit #	Capacity (MW)	Duration (Weeks)	Crew Required in Each Week	Unit #	Capacity MW	Duration (Weeks)	Crew Required in Each Week
1	555	7	10+10+5+5+5+5+3	8	90	1	20
3	180	1	20	10	94	4	10+10+10+10
4	640	3	15+15+15	11	39	2	15+15
5	640	3	15+15+15	12	188	2	15+15
6	276	10	3+3+2+2+2+2+2+2+2+2	13	52	3	10+10+10
7	140	4	10+10+5+5				

Table 3: Data of case study-3

Unit #	Capacity (MW)	Allowed perod (weeks)	Outrage (weeks)	Required manpower	Unit #	Capacity (MW)	Allowed period (weeks)	Outrage (weeks)	Required manpower
1	555	1-26	7	10+10+5+5+ 5+5+3	12	76	27-52	3	10+15+15
2	555	27-52	5	10+10+10+ 5+5	13	76	1-26	2	15+15
3	180	1-26	2	15+15	14	94	1-26	4	10+10+10+10
4	180	1-26	1	20	15	39	1-26	2	15+15
5	640	27-52	5	10+10+10+ 10+10	16	188	1-26	2	15+15
6	640	1-26	3	15+15+15	17	58	27-52	1	20
7	640	1-26	3	15+15+15	18	48	27-52	2	15+15
8	555	27-52	2	10+10+10+ 5+5+5	19	137	27-52	1	15
9	276	1-26	10	3+3+2+2+2+ 2+2+2+2+2	20	469	27-52	4	10+10+10+10
10	140	1-26	4	10+10+5+5	21	52	1-26	3	10+10+10
11	90	1-26	1	20					

each unit. The test system peak load is 4739 MW. A 20 technical staff are available in each week during maintenance. The maintenance outages for the units scheduled to minimize the sum of squares of reserves and satisfy the maintenance window constraint, crew constraint and load constraint mentioned in eqns. 8, 9 and 10 respectively. The objective is to minimize the sum of square of reserve per generation by using Eqn. 11.

Case Study-4: 62-Units Test Power Production System

The system consists of 62 units, which are to be maintained in 26 intervals (weeks) during a year[23]. Table 4 gives the unit capacity, maintenance duration of each unit and system peak load of each interval. The proposed optimization approach is used to maximize the minimum net reserve by using Eqn. 7 along with satisfying the maintenance window constraint, crew constraint and load constraint mentioned in eqns. 8, 9 and 10 respectively.

Case Study-5: 136-Units Power Production System (WAPDA System)

Water and power development authority Pakistan (WAPDA) GMS problem consists of scheduling the maintenance of 136 generators over a time period of 52 weeks (one year). Table 5 gives the generating capacities, maintenance allowed periods, maintenance durations, available manpower and the crew needed for each generator of WAPDA system. The power system weekly peak loads are given in Table 6. The reliability criterion of power system is achieved by maximizing the minimum net reserves by using Eqn. 7, along with the satisfaction of maintenance window constraint, crew constraint and load constraint presented in Eqns. 8, 9 and 10 respectively.

HS IMPLEMENTATION

HS implementation to solve GMS problem for different small and large power production systems

Table 4: Data of case study-4 (a: Generation and durations, b: Predicted loads)

Unit #	Capacity (MW)	Outage (weeks)	Unit #	Capacity (MW)	Outage (weeks)	Unit #	Capacity (MW)	Outage (weeks)
1	10	1	22	30	1	43	50	2
2	10	1	23	30	1	44	50	2
3	10	1	24	30	1	45	50	2
4	10	1	25	30	1	46	55	3
5	10	1	26	30	1	47	55	3
6	10	1	27	30	1	48	55	3
7	10	1	28	30	1	49	55	3
8	10	1	29	30	1	50	55	3
9	10	1	30	30	1	51	60	4
10	10	1	31	40	2	52	60	4
11	20	1	32	40	32	53	60	4
12	20	1	33	40	33	54	60	4
13	20	1	34	40	34	55	60	4
14	20	1	35	40	35	56	70	3
15	20	1	36	40	36	57	70	3
16	20	1	37	40	37	58	70	3
17	20	1	38	40	38	59	70	3
18	20	1	39	40	39	60	70	3
19	20	1	40	40	40	61	85	4
20	20	1	41	50	41	62	90	4
21	30	1	42	50	42			

a.

Inter-val #	Load	Inter-val #	Load
1	2100	14	1700
2	2100	15	1700
3	1900	16	1900
4	1900	17	1900
5	1750	18	1900
6	1750	19	2000
7	1750	20	2000
8	1650	21	2000
9	1650	22	2200
10	1600	23	2200
11	1600	24	2200
12	1600	25	2100
13	1700	26	2100

b.

comprise of the selection of solution encoding, evaluation function and HS parameters.

HS Solution Encoding

A harmony represents a complete solution for GMS problem, which consists of the maintenance start period of each generator of the power system. The size of a harmony depends upon the number of generators used in the power production system. The start week of each generator in the harmony is bounded by the earliest and latest start period (week).

A power production system consists of number of generators, the harmony is:

$$nt_1, nt_2, \ldots, nt_i, \ldots, nt_N \tag{12}$$

Where nt_i is a generator and is bounded by:

$$ear_i \leq nt_i \leq (lat_i + dur_i + 1) \tag{13}$$

Where ear_i is the earliest start week, lat_i is the latest start week and is the outage duration of generator i:

Evaluation Function

The fitness of every virtual harmony is calculated by using evaluation function. The evaluation function for the proposed GMS solution is:

Table 5: Data of WAPDA system (Generations, duration etc,)

#	Power Stations	Capacity MW	Earliest Period	Latest Period	Outage Weeks	Available Manpower	Required Manpower
1	**TPS Guddu** ST-1	50	7	23	4	40	10+10+10+10
2	ST-2	75	29	45	4	40	10+10+10+10
3	ST-3	150	36	52	10	100	20+20+20+10+5+5
4	ST-4	150	24	50	14	150	20+20+20+20+10+10+10
5	CC-5 (GT7-8)	70	39	52	3	30	10+10+10
6	CC-6 (GT9-10)	65	1	20	10	100	20+20+20+10+5+5+5
7	GT-7	75	42	52	1	30	30
8	GT-8	80	8	21	1	30	30
9	GT-9	75	1	20	10	100	20+20+20+10+5+5+5
10	GT-10	75	1	20	10	100	20+20+20+10+5+5+5
11	GT-11	80	13	36	11	110	20+20+20+10+10+5+5
12	GT-12	115	16	39	11	110	20+20+20+10+10+5+5
13	CC-13(GT11-12)	95	16	41	13	145	20+20+20+20+10+10+10
14	**TPS Jamsoro** : ST-1	180	20	45	13	200	25+25+25+25+20+20+20
15	ST-2	180	1	14	6	200	50+50+25+25+25+25
16	ST-3	170	1	20	4	200	50+50+50+50
17	ST-4	170	1	15	4	200	50+50+50+50
18	**GTPS Kotri**: GT-1	10	1	9	3	15	5+5+5
19	GT-2	10	1	16	3	15	5+5+5
20	GT-3	20	30	45	3	25	10+10+5
21	GT-4	20	14	36	10	65	10+5+5+5+5+5+5+5
22	GT-5	20	7	27	8	50	10+10+5+5+5+5+5+5
23	GT-6	20	11	26	3	25	10+10+5
24	GT-7	40	1	19	13	65	10+10+5+5+5+5+5+5
25	**TPS M.Garh**: ST-1	185	35	51	4	125	50+25+25+25
26	ST-2	200	35	51	4	175	50+50+50+25
27	ST-3	160	1	23	13	155	50+25+20+10+10+5+5
28	ST-4	245	33	52	13	155	50+25+20+10+10+5+5
29	ST-5	170	40	52	4	200	50+50+50+50
30	ST-6	170	30	52	13	155	50+25+20+10+10+5+5
31	**NGPS Multan**: ST-1	30	29	52	17	81	10+10+5+5+5+5+5
32	ST-2	30	40	52	4	20	5+5+5+5
33	ST-4	30	26	52	4	20	5+5+5+5
34	**GTPS F. Abad** : GT-1	19	20	40	8	30	5+5+5+3+3+3+3+3
35	GT-2	19	11	31	8	30	5+5+5+3+3+3+3+3
36	GT-3	19	2	22	8	30	5+5+5+3+3+3+3+3
37	GT-4	19	31	51	8	30	5+5+5+3+3+3+3+3

#	Power Stations	Capacity MW	Earliest Period	Latest Period	Outage Weeks	Available Manpower	Required Manpower
38	GT-5	23	2	20	4	20	5+5+5+5
39	GT-6	23	3	15	5	19	5+5+3+3+3
40	GT-7	23	2	17	1	20	20
41	GT-8	23	5	25	3	11	5+3+3
42	CC-9	42	40	52	4	30	10+10+5+5
43	**SPS F. Abad** : ST-1	50	37	52	4	40	20+10+5+5
44	ST-2	50	42	52	4	40	20+10+5+5
45	**KEL** : U # 1	15	21	36	3	20	10+5+5
46	U # 2	15	15	30	3	20	10+5+5
47	U # 3	15	20	35	3	20	10+5+5
48	U # 4	15	5	20	3	20	10+5+5
49	U # 5	10	1	13	3	20	10+5+5
50	U # 6	15	2	17	3	20	10+5+5
51	U # 7	15	1	9	3	20	10+5+5
52	U # 8	15	41	52	3	20	10+5+5
53	STG	6	2	18	4	12	3+3+3+3
54	**FKPCL:** Full Complex	151	24	37	1	50	50
55	Full Complex	151	37	52	3	150	50+50+50
56	**LIBERTY**	211	1	12	2	200	100+100
57	**UCH**	551	37	52	4	250	100+50+50+50
58	**HUBCO** : U # 1	300	22	39	5	255	50+50+50+50+25
59	U # 2	300	38	52	2	100	50+50
60	U # 3	300	33	50	5	255	50+50+50+50+25
61	U # 4	300	4	26	10	200	50+25+25+20+20+20
62	**KAPCO** : GT-1	93	28	43	3	95	50+25+20
63	GT-2	92	1	20	10	97	25+20+20+10+5+5+3
64	GT-3	81	1	18	7	49	20+10+5+5+3+3+3
65	GT-4	80	1	18	8	50	10+10+5+5+5+5+5+5
66	GT-5	78	28	46	6	35	10+5+5+5+5+5
67	GT-6	78	28	46	6	35	10+5+5+5+5+5
68	GT-7	79	33	52	8	50	10+10+5+5+5+5+5+5
69	GT-8	77	38	52	3	20	10+5+5
70	SGT-9 (GT1,3)	105	28	43	3	20	10+5+5
71	SGT-10 (GT2,4)	99	1	18	8	50	10+10+5+5+5+5+5+5
72	SGT-11 (GT5,6)	86	28	46	6	35	10+5+5+5+5+5
73	SGT-12 (GT7,8)	84	38	52	3	20	10+5+5
74	GT-13	113	32	52	9	125	25+25+20+20+10+10
75	GT-14	115	33	52	9	125	25+25+20+20+10

#	Power Stations	Capacity MW	Earliest Period	Latest Period	Outage Weeks	Available Manpower	Required Manpower
76	SGT-15 (GT13,14)	126	33	52	9	125	25+25+20+20+10+10
77	**HCPC**	129	35	48	1	50	50
78	**AES PAKGEN**	350	28	48	4	250	100+50+50+50
79	**AES LALPIR**	350	24	40	4	250	100+50+50+50
80	**SABA**	125	30	46	4	120	50+25+25+20
81	**ROUSCH** : Half Complex	197	1	12	1	100	100
82	Half Complex	197	7	20	1	100	100
83	Half Complex	197	16	27	1	100	100
84	Half Complex	197	24	37	1	100	100
85	Half Complex	197	33	46	1	100	100
86	Half Complex	395	38	52	2	200	100+100
87	**SEPCOL** : U # 1	21	15	30	3	20	10+5+5
88	U # 2	21	15	30	3	20	10+5+5
89	U # 3	21	15	30	3	20	10+5+5
90	U # 4	21	20	35	3	20	10+5+5
91	U # 5	21	20	35	3	20	10+5+5
92	U # 6	17	20	35	3	15	5+5+5
93	**Japan**	120	7	21	2	100	50+50
94	**CNPP**	300	30	52	3	200	100+50+50
95	**Terbela** 1	175	1	16	4	150	50+50+25+25
96	2	200	10	25	4	150	50+50+25+25
97	3	200	5	20	4	150	50+50+25+25
98	4	175	1	13	4	150	50+50+25+25
99	5	200	30	52	4	150	50+50+25+25
100	6	200	30	52	4	150	50+50+25+25
101	7	200	10	26	4	150	50+50+25+25
102	8	175	5	21	4	150	50+50+25+25
103	9	175	46	52	1	100	100
104	10	432	36	52	4	150	50+50+25+25
105	11	432	1	12	3	150	50+50+50
106	12	432	43	52	3	150	50+50+50
107	13	432	2	17	3	150	50+50+50
108	14	432	5	21	3	150	50+50+50
109	**G.Barottha** : 1	240	1	25	5	110	50+25+20+10+5
110	2	290	1	10	4	120	50+25+25+20
111	3	290	43	52	3	125	50+50+25
112	4	290	1	14	4	120	50+25+25+20
113	5	290	2	17	3	125	50+50+25

#	Power Stations	Capacity MW	Earliest Period	Latest Period	Outage Weeks	Available Manpower	Required Manpower
114	**Mangla**: 1	100	1	14	5	95	25+20+20+10+10
115	2	100	42	52	3	125	50+50+25
116	3	100	30	46	3	120	50+50+20
117	4	100	25	40	3	120	50+50+20
118	5	100	43	52	3	125	50+50+25
119	6	100	1	9	3	125	50+50+25
120	7	100	1	12	2	100	50+50
121	8	100	41	52	1	50	50
122	9	100	40	52	2	100	50+50
123	10	100	30	52	2	100	50+50
124	**Warsak** : 1	40	37	52	6	29	10+5+5+3+3+3
125	2	40	41	52	4	21	10+5+3+3
126	3	40	1	14	6	29	10+5+5+3+3+3
127	4	40	2	17	3	18	10+5+3
128	5	41	2	16	2	15	10+5
129	**Chashma** : 1	23	1	12	2	15	10+5
130	2	23	1	14	6	22	5+5+3+3+3+3
131	3	23	7	21	2	15	10+5
132	4	23	1	14	2	15	10+5
133	5	23	42	52	3	18	10+5+3
134	6	23	41	52	4	16	5+5+3+3
135	7	23	4	18	2	15	10+5
136	8	23	1	16	4	16	5+5+3+3

$$fx\_val + net\_reserve + w_1 * con_1 + w_2 * con_2 + w_3 * con_3 \quad (14)$$

where fx_val is the fitness value and $net\_reserve$ represents the net reserve of a harmony. w_1, w_2 and w_3 represent the weights of violations of con_1, con_2 and con_3. con_1 represents the maintenance window constraint, con_2 represents the crew constraint and con_3 represents the load constraint.

RESULTS

HS important parameters are listed in Table 7. The proposed algorithm is tested, validated and compared for five different power production systems. HS generates optimal and best possible generators maintenance schedule for all systems, while satisfying maintenance window constraint, crew constraint and load constraint. Figure 2 shows the result of case study-1, which includes the convergence of objective function, generation versus load demand, net reserves in each generation and the best schedule for generators maintenance. Figure 3 gives the Objective values, no violation of load constraint, reserve margin, crew constraint, manpower required and the optimal schedule for 13-unit system. Results for 21-units, 62-units and 136-units power systems are presented in Figures 4, 5 and 6 respectively.

Figures 2a, 3a, 4a, 5a, 6a show the objective function convergence of HS algorithm. Optimal solution is obtained very quickly. Figures 2b, 3b, 4b, 5b, 6b represent that load constraint is completely satisfied, means available power

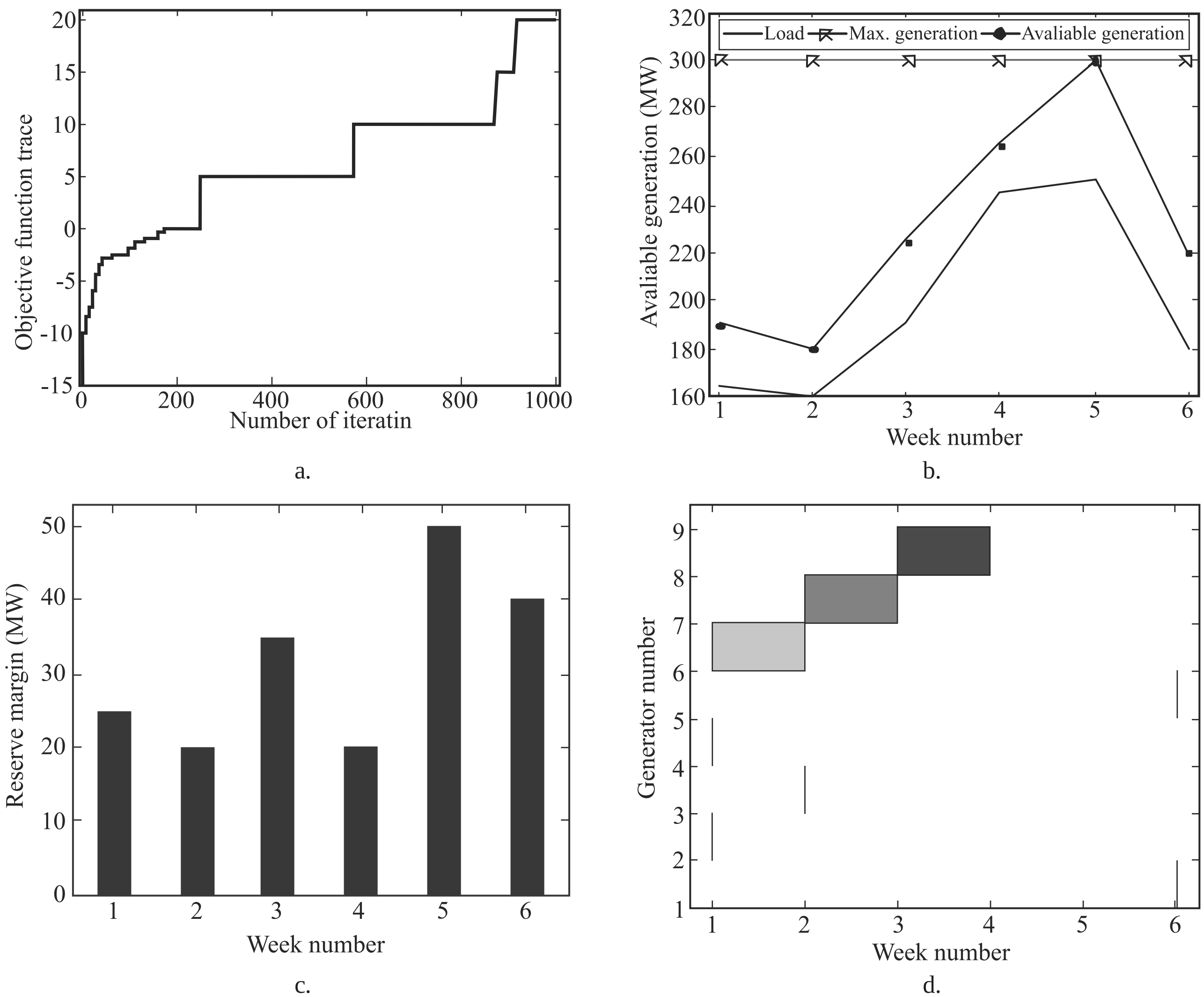

Figure 2: Results for 8-units system (a: Objective function trace, b: Available generations and loads, c: Reserve margin, d: Optimal maintenance schedule)

Table 6: Peak loads of WAPDA system

Inter-val #	Peak Load	Inter-val #	Peak Load	Inter-val #	Peak Load
1	6043	19	6796	37	7429
2	5888	20	6798	38	7510
3	6410	21	7146	39	7592
4	6440	22	7183	40	7539
5	6396	23	7251	41	7431
6	6650	24	7134	42	7352
7	6674	25	7467	43	7499
8	6408	26	7467	44	7566
9	6620	27	7351	45	7464

Inter-val #	Peak Load	Inter-val #	Peak Load	Inter-val #	Peak Load
10	6604	28	7525	46	7401
11	6436	29	7513	47	7354
12	6550	30	7351	48	7354
13	6514	31	7584	49	6839
14	6478	32	7589	50	6701
15	6502	33	7653	51	6600
16	6631	34	6964	52	6691
17	6587	35	7364		
18	6791	36	7514		

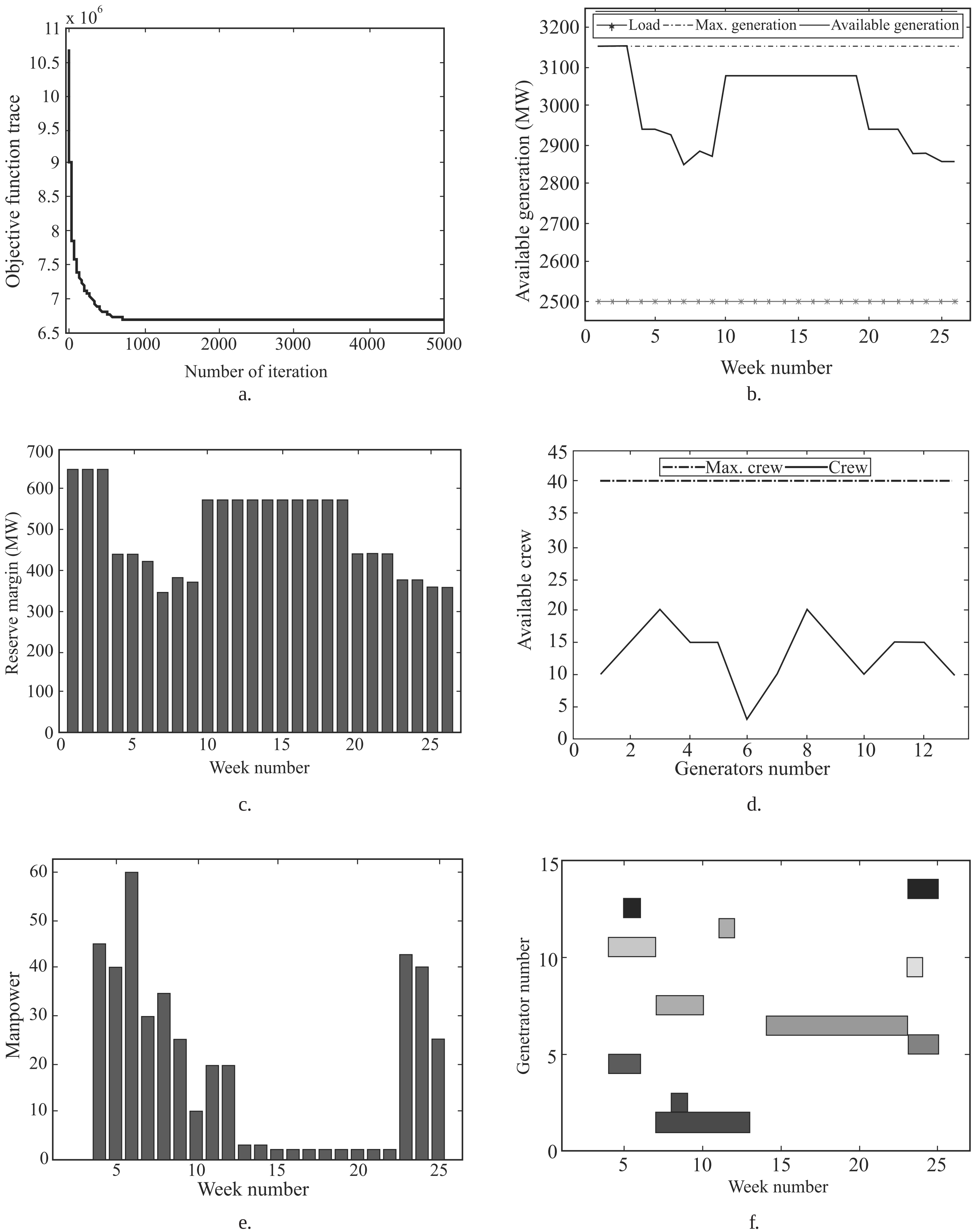

Figure 3: Results for 13-units system (a: Objective function trace, b: Available generations and loads, c: Reserve margin, d: Crew required, e: Manpower, f: Optimal maintenance schedule)

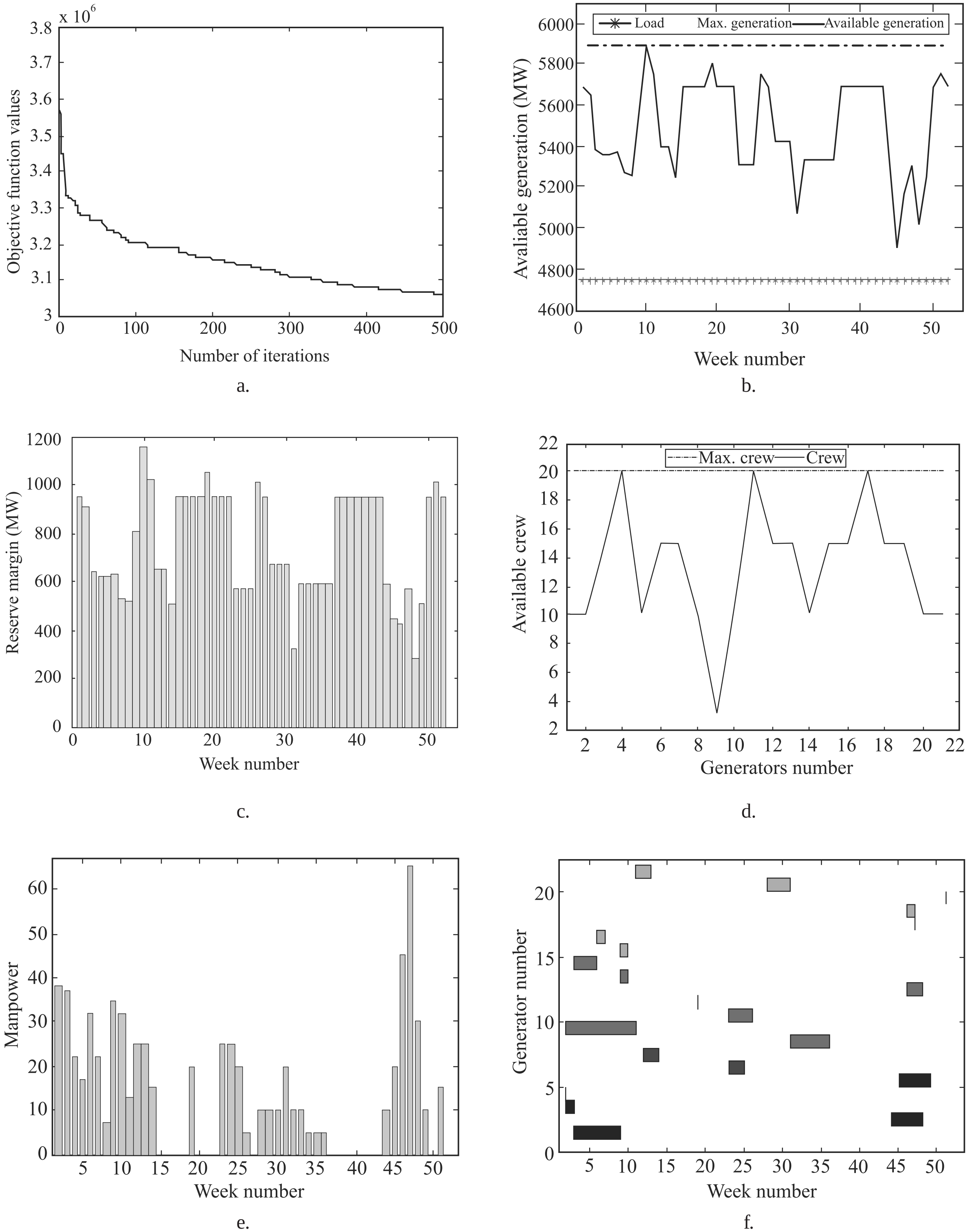

Figure 4: Results for 21-units system (a: Objective function trace, b: Available generations and loads, c: Reserve margin, d: Crew required, e: Manpower, f: Optimal maintenance schedule)

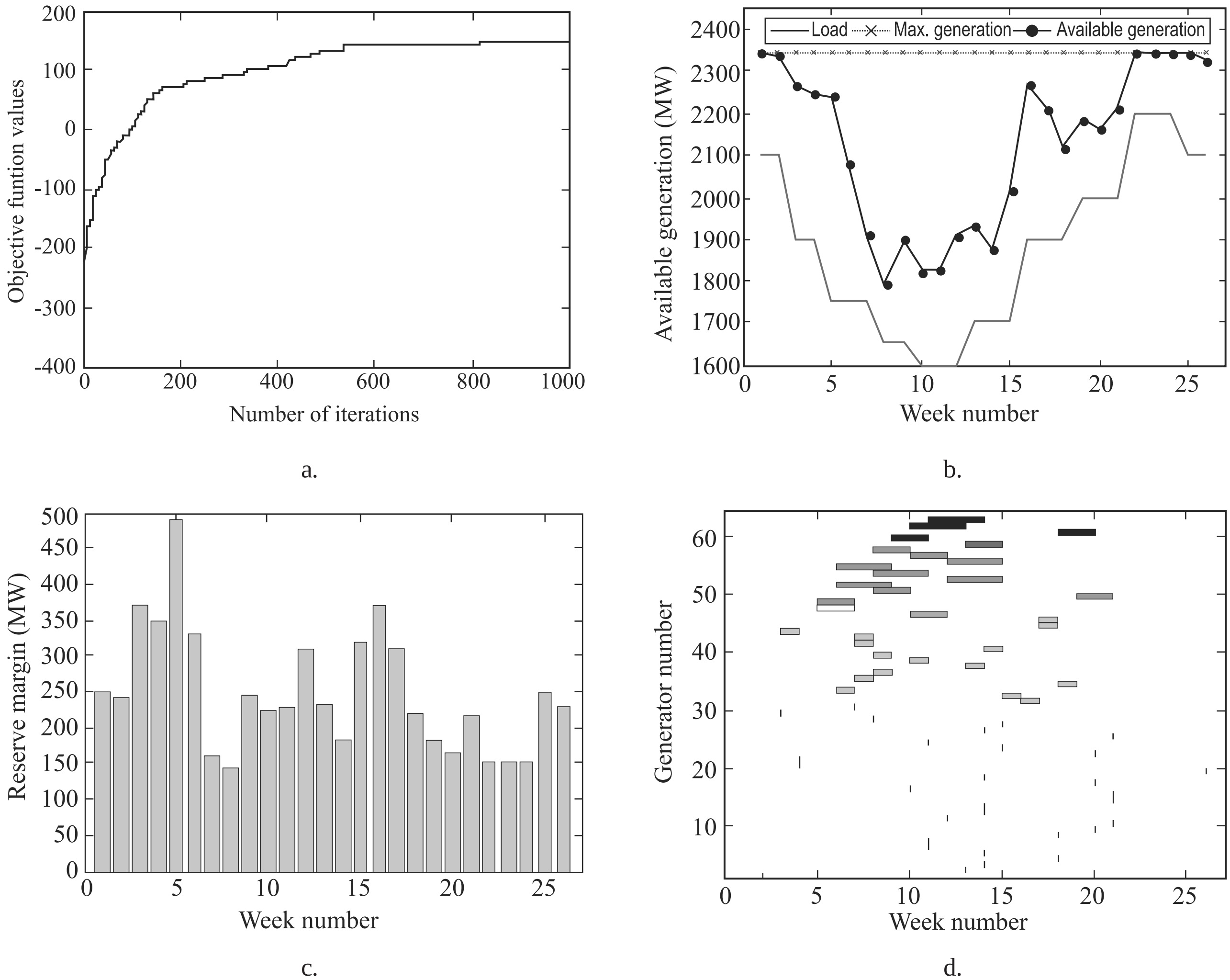

Figure 5: Results for 62-units system (a: Objective function trace, b: Available generations and loads, c: Reserve margin, d: Optimal maintenance schedule)

Table 7: HS parameters

Sr. #	Parameter	Value
1	HS size	20-40
2	HM accept rate	0.95
3	Pitch adjusting rate	0.7
4	Pitch adjusting range	200
5	Time steps	100 to 10000

generation is much greater than load demand in each case, so, there in no need for load shedding. The aim of this research is to maximize the reserve margin in each week and HS is quite efficient to maximize the reserve margin in each week as shown in Figures 2c, 3c, 4c, 5c, 6c. Figures 2d, 3f, 4f, 5d, 6f show the allowed periods for which planned maintenance of generating units could be possible. Thermal and steam turbines could be shut down for maintenance only when the hydro plants are operating at their maximum generation. This corresponds to the months of January to April and November to December each year. The hydro plants can be scheduled for maintenance during low water level corresponding to the months of May to October. Within these months no thermal plant should be shut down for maintenance. Figures 3d, 4d, 6d mention that the crew constraint is completely satisfied, means the crew required for maintenance in each week is less than or equal to available crew. Figures 3e, 4e, 6e show that the maximum manpower required by each generator for maintenance.

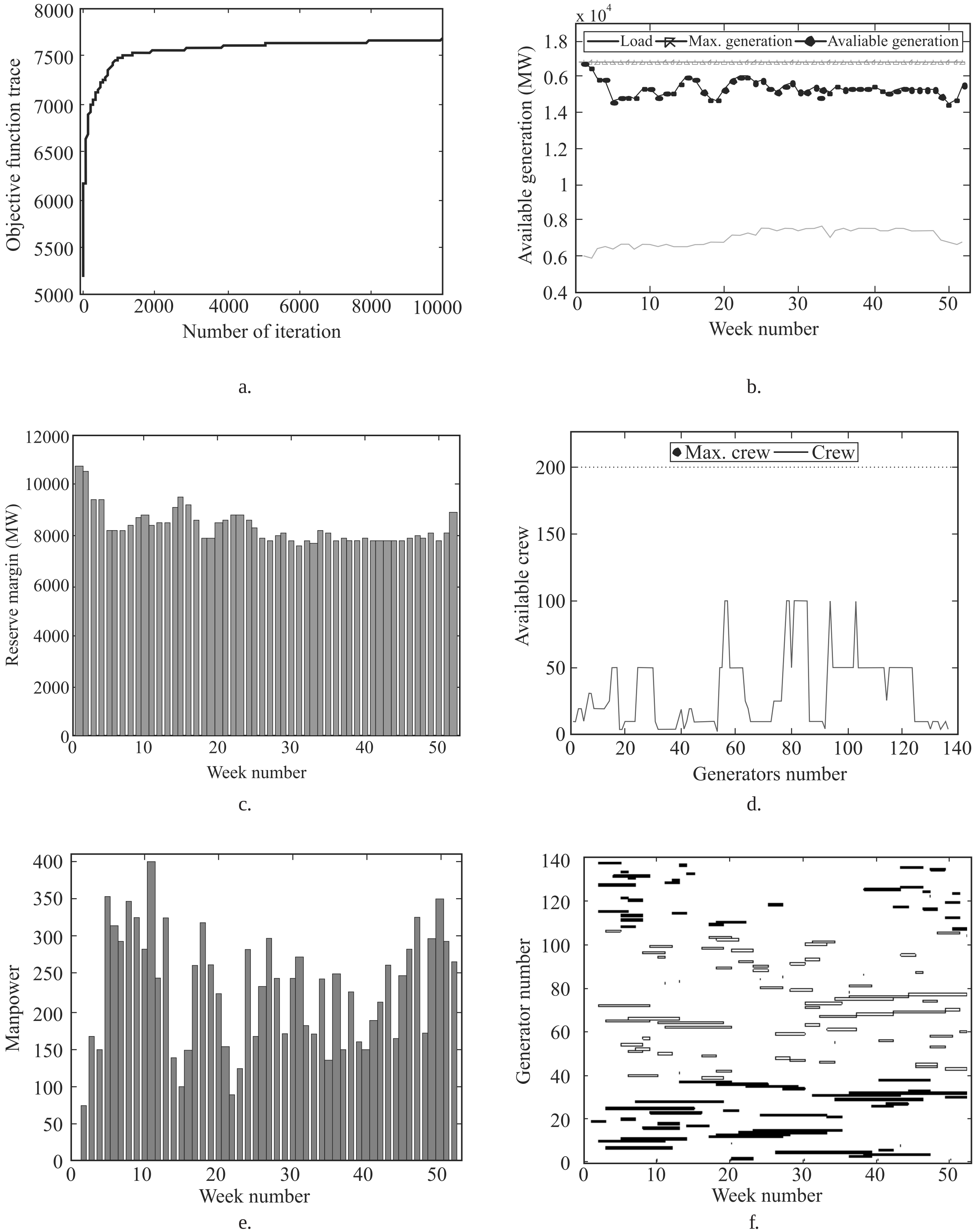

Figure 6: Results for 136-units system (a: Objective function trace, b: Available generations and loads, c: Reserve margin, d: Crew required, e: Manpower, f: Optimal maintenance schedule)

CONCLUSION

The GMS optimal solution is very essential for economical and reliable operation of a power system. A HS algorithm is proposed to give the optimal schedule. Five different case studies are solved with the proposed optimization technique. Case studies are used to investigate the performance of this proposed optimization algorithm. Recently developed HS algorithm is successfully applied to GMS problem of the power production systems. Simulation results show that the HS algorithm is potentially a powerful search and optimization technique in order to find the best solutions and convergence history. The results offered a feasible and more promising optimal generators maintenance schedule that can be implemented in small as well as real large power production systems.

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