A Novel Hybrid Symbiotic Organism Search for Solving Generator Maintenance Scheduling in a Power System

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A Novel Hybrid Symbiotic Organism Search for Solving Generator Maintenance Scheduling in a Power System

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Abstract- The generator maintenance scheduling (GMS) problem is a high-dimensional complex constrained non linear optimization problem that determines the schedule for carrying out planned preventive maintenance on generating units in a power system. Here, GMS is modelled from the perspective of vertically integrated utility system subject to different set of system and operational constraints. Over the last few decades, a number of solution techniques, including nature inspired algorithms, have been developed and proposed to solve this problem. In this paper, a new nature inspired algorithm; symbiotic organism search is proposed to solve the generator maintenance scheduling problem. To examine the efficiency of the proposed algorithm, two test systems, 4-units and 22-units system are considered. The simulation results are compared with that of other existing algorithms, which reveal that the proposed method has merit in terms of solution quality.

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Nomenclature

i - Power generating unit index
I - Total number of generating units
t - Time period index (week)
T - Total number of sub periods (weeks) in the planning horizon
nc - Constraint index
NC - Total number of constraints
k - Population index
K - Iteration index in Lagrange Multiplier method
NP - Population Size
a_i, b_i, c_i - Fuel cost coefficients of unit i
CV - Constraint violation
v_i - Variable operation and maintenance cost of unit i in \$/MWh
H - Number of hours in a sub-period (week) = 168
X - Vector of variables

P_{it} - Power output from generating unit i in sub-period t, MW
$P_i^{min.}$ - Minimum limit generating unit i, MW
$P_i^{max.}$ - Maximum limit generating unit i, MW
R_i - Rating of unit i
U_{it} - State variable equal to 0 if the unit i in sub-period t is offline for maintenance and 1 otherwise
S_{Ei} - Earliest period in which maintenance of unit i can start
S_{Li} - Latest period in which maintenance of unit i can start
S_i - Starting period of maintenance of unit $i \in [S_{Li}, S_{Ei}]$
M_i - Maintenance duration of unit i
PD_t - Active power load demand in week t
ω - Penalty factor
ψ - Fitness function to be minimized

I. Introduction

The generator maintenance scheduling problem is a large scale, stochastic, nonlinear combinatorial optimization problem which is a sub problem of integrated long term operations planning problem. The objective of the GMS problem is to find the exact time interval for preventive maintenance of power generating units with the intention of minimizing the operating cost, maximizing the system reliability and extending the life time of it. In earlier literature, mathematical approaches have been used for solving GMS [1, 2, 3]. These methods are limited to small size systems having few numbers of generators. For the case of large size systems, the number of intermediate solutions exponentially increases known as curse of dimensionality that restricts the use of mathematical methods to solve GMS. Local search methods such as Simulated annealing (SA) [4], Tabu search (TS) algorithm [5] has been proposed for the solution of GMS problem. For obtaining timetable for the purpose of maintenance of generators, nature inspired algorithms like Particle swarm optimization (PSO) [6], Artificial bee colony (ABC) algorithm [7], Ant colony optimization (ACO) [8], Shuffled frog leaping algorithm (SFLA) [9] have been used. Evolutionary algorithms such as Genetic algorithm (GA) [10], Evolutionary programming (EP) [11], Differential evolution (DE) [12]

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and other meta heuristic approaches such as Harmony Search (HS) [13], Teaching Learning Based Optimization (TLBO) [14] have also been applied for the solution of GMS.

In this paper, to solve the GMS problem, a new nature inspired algorithm; Symbiotic Organism Search (SOS) [15] is proposed. To get exact production cost that is to be spent by generating company to meet the weekly active peak load demand, Lagrange multiplier method (LMM) is hybridized with SOS, which helps SOS in finding minimum production cost based maintenance schedule for GMS. To examine the efficacy of the proposed approach, a small size system having 4 generating units and a medium size system having 22 generating units are considered and simulation results are compared with that obtained using well admired techniques such as PSO and TS.

The paper is organized as follows. In section 2, GMS problem formulation is discussed. Section 3 presents the detailed explanation of proposed SOS for solving GMS. The simulation results and discussions of using the proposed technique to solve GMS for 4- and 22- units system are included in Sections 4. Section 5 ends with the concluding remarks and future scope of the work.

II. GMS Problem Formulation

The cost objective considered here is to minimize the overall operational cost over a planning horizon is stated as

$$F = \sum_{t=1}^{T}\sum_{i=1}^{I} H.\left(a_i P_{it}^2 + b_i P_{it} + c_i\right).U_{it} + \sum_{i=1}^{I} H.P_{it}.v_i.U_{it} \tag{1}$$

The first part of (1) is production cost and second part signifies the variable operation and maintenance cost. The fixed maintenance cost is constant and does not have influence on maintenance schedule and hence it is neglected in the formulation.

The solution obtained for the GMS problem must satisfy the following set of system and operational constraints.

$$U_{it} = \begin{cases} 0 & t = S_i,...,S_i + M_i - 1 \\ 1 & otherwise \end{cases} \tag{2}$$

$$\sum_{t=S_{i1}}^{S_{i1}+M_{i1}-1} U_{i2,t} = 1 \tag{3}$$

$$S_2 \geq S_1 + M_1 \tag{4}$$

$$\sum_{i=1}^{I} R_i.\left(1 - U_{it}\right) \leq \left(\sum_{i=1}^{I} P_i^{max} - PD_t\right) \tag{5}$$

$$P_i^{min} \leq P_{it} \leq P_i^{max} \tag{6}$$

$$\sum_{i=1}^{I} P_{it}.U_{it} \geq PD_t \tag{7}$$

The constraint (2) is the maintenance window constraint which ensures that once maintenance of the unit i begins, the work have to be continued without any break off for the time period that is exactly equal to maintenance duration of unit i. To ensure no two generators is maintained by same crew, it is stated in terms of U_{it} variables of second unit i2 as in (3). Crew constraint restricts maintenance of unit 1 and 2 in unison. In some situation, the maintenance works on some of the power producing units should be initiated only after the completion of maintenance activities of other generators. This can be achieved with the inclusion of precedence constraint. For instance, if maintenance of unit '2' is to be started only after the completion of maintenance of unit '1', then this constraint is given by (4). In every sub-period of planning horizon, the sum of capacity of generating units that are switched off for maintenance must be lesser than gross reserve in that sub-period. This can be achieved by using resource constraint as given in (5). Constraint (6) guarantees the real power output from every generator is within its minimum and maximum limits. Load balance constraint is given by (7).

III. Proposed Solution Methodology

The GMS problem have two types of variables; continuous and binary integer variables. The continuous variables denote the power output from the online generating units and binary integer variables indicates the on/off status of power producing units. Here, as in most of the literature, the staring period for maintenance of each generator is considered as variables which are integers. The number of integer variables is exactly equal to number of generators present in the system. To solve the problem, symbiotic organism search (SOS) a population based new meta-heuristic nature inspired algorithm is proposed. The SOS is initially developed by Cheng and Prayogo in 2014 [15]. Basically SOS has been proposed for solving the problem in continuous domain. This algorithm requires only common control parameter such as population size and maximum number of generations to be tuned and does not have any algorithm specific control parameters. It mimics the symbiotic interaction strategies adopted by two organisms to stay alive and propagate in the ecosystem. To evolve to a good solution, SOS uses three important phases; mutualism, commensalism and parasitism. The flowchart of the SOS is shown in Fig. 1.
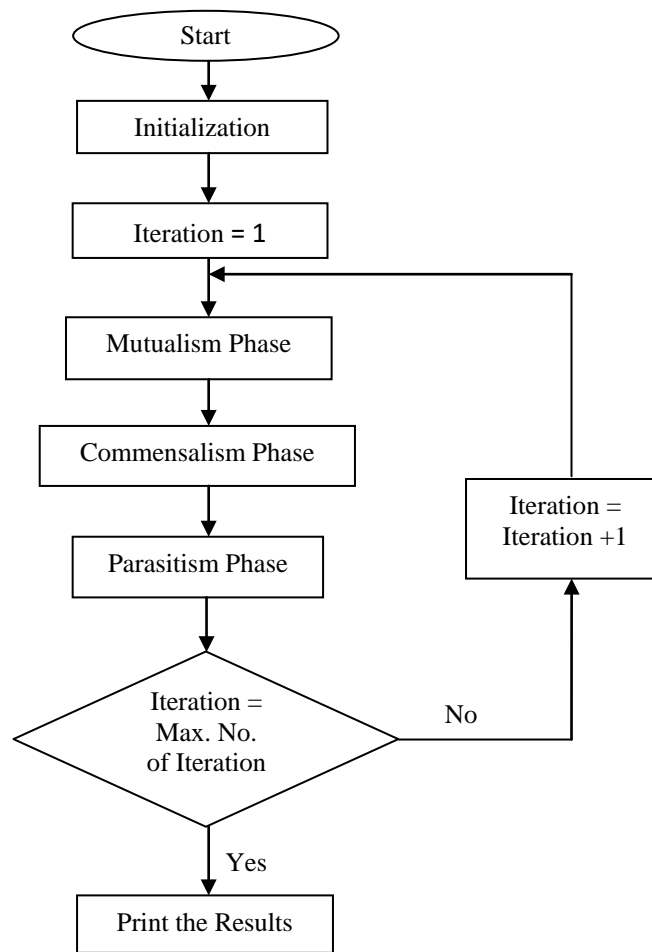
Fig. 1: Flowchart of Symbiotic Organism Search

To deal with integers, a rounding off operator is used in SOS called integer coded symbiotic organism search (ICSOS). The detailed explanation of proposed solution methodology for solving GMS problem is given below.

a) Hybrid SOS for Cost based GMS

The cost objective is given in (1). The aim is to obtain a maintenance schedule for the GMS problem such that the overall operation cost should be minimized. To obtain the exact production cost involved to meet the weekly peak load demand, a LMM is hybridized with ICSOS called hybrid SOS (HSOS). The following are the steps involved in HSOS for solving cost based GMS.

i. *Initialization*

Initialize NP population called ecosystem. Each vector of ecosystem called organism represents one candidate solution of the problem. Each organism (X^k) has integers decision variables equal to number of generators present in the system which is generated randomly between every generator's earliest and latest allowed starting period for maintenance as follows

$$\left(X_i^k\right) = round\left(S_{Ei}^k + random(0,1).\left(S_{Li}^k - S_{Ei}^k\right)\right) \quad (8)$$

The integer variables are checked for precedence and crew constraints. If any of the above constraint is violated for a particular generator, the corresponding integer variable is chosen randomly until the constraints are satisfied and then the integer variables are checked for maintenance window constraint. After satisfying all the constraints, the status of each unit is set at '0' from the starting period up to its corresponding maintenance duration period to indicate that the unit *i* is switched off for preventive maintenance and '1' during other periods. The LMM is used to achieve optimal generation schedule from the online generators in every week to meet the weekly load demand as follows.

Step 1: With initial value of λ, power output from each committed generator (P_i) in sub-period *t* can be calculated using

$$P_{it} = \frac{\lambda - b_i}{2c_i} \quad (9)$$

The generated output power is checked to satisfy constraint (6).

Step 2: The change in power output (ΔP) can be calculated using

$$\Delta P^K = PD_t - \sum_{i=1}^{NCG} P_{it} \qquad (10)$$

Step 3: The change in λ ($\Delta\lambda$) can be found as follows

$$\Delta\lambda^K = \frac{\Delta P^K}{\displaystyle\sum_{i=1}^{NCG} \frac{1}{2c_i}} \qquad (11)$$

Step 4: The new value of λ for the next iteration (K+1) can be found by adding change in λ with previous value of λ as follows

$$\lambda^{K+1} = \lambda^K + \Delta\lambda^{K+1} \qquad (12)$$

$$X_{y\,new} = X_y + round\left(random(0,1).\left(X_{best} - \left(\frac{X_y + X_z}{2}\right).BF_1 \right)\right) \qquad (14)$$

$$X_{z\,new} = X_z + round\left(random(0,1).\left(X_{best} - \left(\frac{X_y + X_z}{2}\right).BF_2 \right)\right) \qquad (15)$$

where X_{best} is the best organism in the ecosystem which is used in SOS to model the highest degree of adaptation, that is the objective of both organisms. After creating the starting period for maintenance of each generator using equations (14) and (15) they are checked for any constraints violation. If all the constraints are satisfied, the status of each unit is set at '0' from the starting period up to its corresponding maintenance duration period to indicate that the unit *i* is taken out for preventive overhauling work and '1' during other periods. The minimum production cost for new organisms that denotes the starting period for maintenance of thermal units is calculated with the help of LMM. The fitness function is calculated for new organisms using equation (13). If these organisms have better fitness, the current organism is replaced by the new one.

iii. *Commensalism Phase*

During this phase, an organism X_y gets benefited by interacting with randomly generated another organism X_z in the ecosystem. But X_z is neither suffered nor benefited. A new solution of X_y is determined based on the commensalism operation among the organisms X_y and X_z, which can be expressed as

$$X_{y\,new} = X_y + round\left(rand(-1,1).\left(X_{best} - X_z \right)\right) \qquad (16)$$

Once the new organism that indicates the starting period for maintenance of power generating units is determined, it is checked in order to satisfy constraints (2) – (5). After satisfying all the constraints, the status of each unit is set at '0' from the starting

The above steps are repeated until ΔP becomes zero. Thus constraint (7) is satisfied. The fitness function of the GMS problem to be minimized by HSOS is

$$\psi = \sum_{t=1}^{T}\sum_{i=1}^{I} H.\left(a_i P_{it}^2 + b_i P_{it} + c_i\right).U_{it} + \sum_{nc=1}^{NC} \omega_{nc}\left|CV_{nc}\right| \qquad (13)$$

ii. *Mutualism Phase*

In mutualism phase, two participating organisms of the ecosystem get benefited. In SOS, two organisms X_y and X_z are selected. They interacts each other with the aim of increasing mutual survival advantage in the ecosystem. The new solution after mutual relationship is given by

period up to its corresponding maintenance duration period to indicate that the unit *i* is taken out for planned preventive maintenance and '1' during other periods.

Then LMM is used to obtain optimum generation schedule from the online generators in every sub-period to meet the weekly peak load demand with minimum production cost. The fitness function is calculated for new organisms using equation (13). The new organism $X_{y,new}$ is accepted, if it has better fitness, than the current organism.

iv. *Parasitism Phase*

In this phase, a parasite vector $X_{y,new}$ is created in the search space by duplicating organism X_y and its dimensions are perturbed using a random number as follows

$$X_{y,\,new} = round\left(random(0,1).\,X_y\right) \qquad (17)$$

The parasite vector that indicates the starting period for maintenance of generating units is checked in order to satisfy constraints (2) – (5). After satisfying all the constraints, the status of each unit is set at '0' from the starting period up to its corresponding maintenance duration period to indicate that the unit *i* is taken offline for maintenance and '1' during other periods. Then LMM is used to obtain optimum generation schedule from the online generators in every sub-period to meet the weekly peak load demand with minimum production cost thus satisfying generator limit and load balance constraints given by equations (6) and (7). The fitness function is calculated for new organisms using equation (13). An organism X_z is chosen randomly from the ecosystem that serves as a host for the parasite vector $X_{y,new}$. If the

parasite vector has better fitness function value, then it occupies the space of its corresponding host by killing them. The above phases are repeated until maximum number of generations.

IV. Simulation Results And Discussions

In order to prove the superiority of the proposed HSOS algorithm, two test systems; one is small system having 4 generators and another one is medium size system having 22 power generating units are considered [5, 12]. In the proposed approach, Lagrange Multiplier method is hybridized with ICSOS in order to solve large scale generator maintenance scheduling problem. In HSOS approach, ICSOS tries to find an optimal starting period for maintenance of power generating units with the help of LMM which tries to economically dispatch the available generation from committed generators to meet the weekly peak active

load demand with minimum production cost. The program is developed using MATLAB on a personal computer with 3 GHz core i5 CPU. The simulation results are compared with that achieved via particle swarm optimization scheme.

a) Test System 1: 4 Units System

There are 4 thermal generating units to be maintained within a planning period of 8 weeks. Among 4 generating units, due to precedence constraint, the maintenance of unit 1 must be completed before the starting of maintenance of unit 2. Due to crew constraint, units 1 and 2 should not be under maintenance simultaneously. The generator data is given in [12]. The gross reserve in every week can be calculated by taking difference between installed capacity and load demand in that week. The weekly peak load data is given in Table 1.

Table 1: Load data of 4 units system

Week	1	2	3	4	5	6	7	8
Load (MW)	249	265	276	279	256	307	187	295

In order to compare the results of proposed HSOS and mathematical approach assisted particle swarm optimization (MAPSO) [12], the population size and maximum number of generations for both the algorithms are set at 10 and 500 respectively. Since the test system 1 is a small system, both the algorithms produce the same maintenance schedule. Table 2 shows the maintenance schedule of 4 units system. Here, '0' indicates the unit is taken out for maintenance and '1' indicates that the unit is available to serve the load. From the table, it can be seen that unit 1 and 2 are not under maintenance in unison, thereby satisfying crew constraints. Also, the maintenance of unit 2 begins only after the completion of maintenance of unit 1, thereby satisfying precedence constraint. In Table 2, it is clear that each generator is under maintenance only

once during the planning period and is equal to corresponding maintenance duration week, thereby satisfying maintenance window constraint.

Table 2: Maintenance Schedule of 4 Units System

Unit/Week	1	2	3	4	5	6	7	8
1	1	1	0	0	0	0	1	1
2	1	1	1	1	1	1	0	0
3	0	0	1	1	1	1	1	1
4	1	1	1	1	1	1	0	1

Fig. 2. shows the capacity on maintenance in every week. From the figure, it can be seen that, in every week, the capacity of units that are taken out for maintenance is lesser than the gross reserve in that week, thereby satisfying resource constraint.
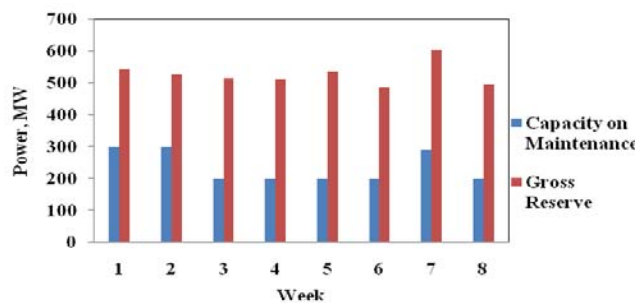
Fig. 2: Capacity on Maintenance

Table 3 shows the power output from online generators obtained using LMM. From the table, it can be seen that power output from committed generators are within their lower and upper bounds, thereby satisfying generator limit constraint. The sum of the

power output from available generators in every week is exactly equal to corresponding active power load demand, thus satisfying load balance constraint.

Table 3: Power Output from Committed Generators

Unit/Week	1	2	3	4	5	6	7	8
1	102.5031	108.1499	0	0	0	0	85.4857	120.9644
2	125.3387	131.23	129.1009	130.1914	121.8306	140.3698	0	0
3	0	0	122.8916	123.9751	115.6682	134.0878	101.5143	138.29
4	21.1582	25.6201	24.0075	24.8335	18.5012	32.5424	0	35.7456

For the maintenance schedule of 4 unit system that is obtained through Tabu Search (TS) algorithm [5], the authors have not given the overall production cost. For the same schedule, using LMM the overall operation cost is found. Table 4 shows the comparison of overall operational cost between proposed method with other existing methods.

Table 4: Overall Operational Cost

	Cost ($)
HSOS	3391993.59
MAPSO	3391993.59
TS	3392728.13

The available reserve in every week can be calculated by taking difference between installed capacity and sum of capacity on maintenance and weekly load demand. The minimum reserve obtained for the above maintenance schedule is 225 MW in 2nd week.

b) Test System 2: 22 Units System

In this system, there are 22 generating units that have to be maintained once within a planning horizon of one year. The planning period is divided into 52 sub-periods (weeks). The generator data is provided in [12]. The weekly load data is given in Fig. 3.
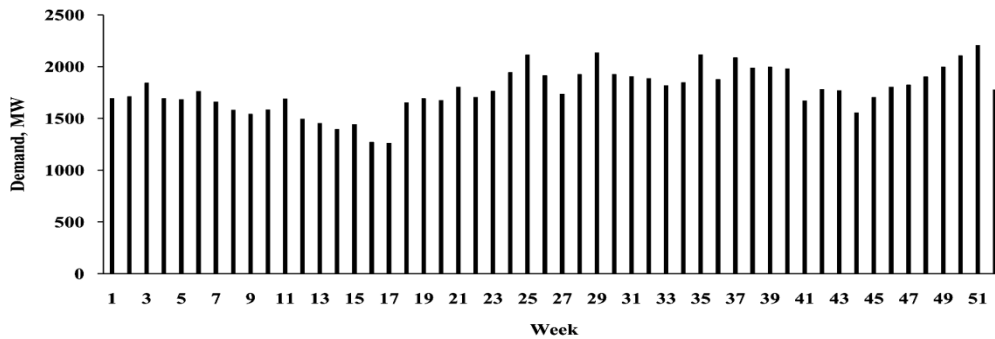

Fig. 3: Load Data of 22 units system

Due to precedence constraint, units 2 and 5 should be taken out for maintenance before the commencement of maintenance of units 3 and 6 respectively. Due to crew constraints, units 15 and 16, units 21 and 22 should not be under maintenance at the same time.

To make the comparison between proposed HSOS and MAPSO, population size and maximum number of iterations are fixed at 50 and 2500 respectively. The convergence characteristics of 22 units system is shown in Fig. 4.
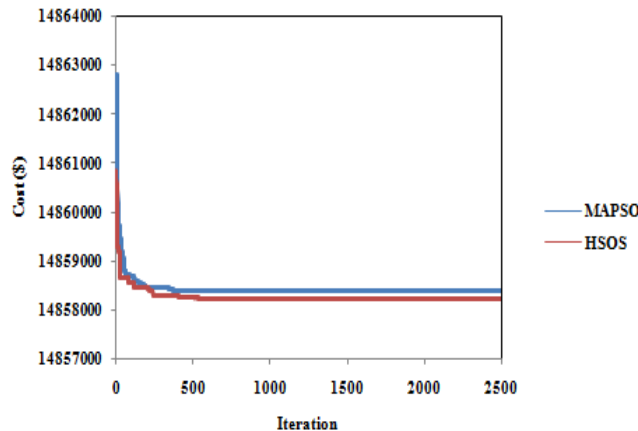

Fig. 4: Convergence Characteristics of 22 units system

From the characteristics, it can be seen that though HSOS have speed of convergence lower than MAPSO, it produces better maintenance schedule in terms of overall operational cost which includes production as well as variable operation and maintenance costs than MAPSO. Table 5 and 6 shows the maintenance schedule obtained through proposed HSOS algorithm and MAPSO. From Table 5 and 6, it can be seen that in both the schedules, each unit is taken out for maintenance only once during the planning horizon and is under maintenance without any interruption for the period equal to corresponding maintenance duration weeks. Thus, the maintenance window constraint gets satisfied. The gross reserve in every week is given in [5]. In every week, the capacity on maintenance is lesser than the gross reserve in that week. Thus resource constraint is satisfied. In Table 5 and 6, it is evident that the maintenance on units 2 and 5 gets completed before the starting of maintenance on units 3 and 6 respectively satisfying precedence constraint. Also units 15 and 16, units 21 and 22 are not under maintenance in same duration satisfying crew constraint.

The comparison of overall operational cost for 22 units system satisfying generator limit and load balance constraints are given Table 7.

Table 7: Overall Operational Cost

	Cost ($)
HSOS	148582246.21
MAPSO	148584093.45
TS	148705625.34

V. Conclusion

A new nature inspired algorithm for the optimization of generator maintenance scheduling problem in vertically integrated system is presented in this paper. In the proposed approach, conventional lambda iteration approach or Lagrange Multiplier method is hybridized with integer coded symbiotic organism search algorithm. The lambda iteration approach assists symbiotic organism search algorithm in finding optimal starting period for maintenance of generating units. The proposed approach provides a feasible maintenance schedule for the generating units by considering minimization of overall generator operation cost as objective which includes production and variable operation and maintenance cost while satisfying system and operational constraints. The proposed method is validated by considering two test systems. The superiority of the proposed HSOS algorithm is demonstrated by comparing the results with the results obtained from MAPSO algorithm. The results conclude that both HSOS and MAPSO are well suited for solving generator maintenance scheduling of small system. For solving large scale generator maintenance scheduling problem, HSOS outperforms MAPSO in terms of finding the overall generation operation cost. Thus, test results reveal the capability of the proposed algorithm in finding the optimal solution for the GMS problem. The proposed approach can be extended for the solution of GMS problem in the competitive environment without any difficulty.

Table 5: Maintenance Schedule (HSOS)

Weeks	Load	Maintenance Capacity	Units on Maintenance
1	1694	585	1,5,7,8,17,18
2	1714	585	1,5,7,8,17,18
3	1844	585	1,5,7,8,17,18
4	1694	810	1,4,5,8,17,18,19
5	1684	710	1,4,5,17,18,19
6	1763	510	1,4,5,19
7	1663	610	10
8	1583	610	10
9	1543	610	10
10	1586	610	10
11	1690	610	10
12	1496	910	2,10,13,14
13	1456	910	2,10,13,14
14	1396	1001	2,10,11,13,14
15	1443	1041	10,11,14,21
16	1273	1261	10,11,14,15,21
17	1263	1261	10,11,14,15,21

18	1655	830	10,15
19	1695	460	15,22
20	1675	560	12,15,22
21	1805	440	3,12,22
22	1705	440	3,12,22
23	1766	440	3,12,22
24	1946	100	12
25	2116	100	12
26	1916	320	12,20
27	1737	320	12,20
28	1927	220	20
29	2137	0	-----
30	1927	0	-----
31	1907	220	16
32	1888	220	16
33	1818	220	16
34	1848	220	16
35	2118	220	16
36	1879	220	16
37	2089	0	-----
38	1989	0	-----
39	1999	0	-----
40	1982	0	-----
41	1672	650	9
42	1782	650	9
43	1772	650	9
44	1556	650	9
45	1706	650	9
46	1806	90	6
47	1826	90	6
48	1906	90	6
49	1999	90	6
50	2109	0	-----
51	2209	0	-----
52	1779	0	-----

Table 6: Maintenance Schedule (MAPSO)

Weeks	Load	Maintenance Capacity	Units on Maintenance
1	1694	511	8,11,15,17
2	1714	511	8,11,15,17
3	1844	511	8,11,15,17
4	1694	511	8,11,15,17
5	1684	320	15,17
6	1763	610	10
7	1663	610	10
8	1583	610	10
9	1543	610	10
10	1586	610	10
11	1690	610	10
12	1496	710	10,14
13	1456	950	10,14,21
14	1396	950	10,14,21
15	1443	950	10,14,21
16	1273	1350	4,10,12,13,14,18,22

17	1263	1350	4,10,12,13,14,18,22
18	1655	730	4,5,12,13,18,22
19	1695	630	1,5,12,18,22
20	1675	730	1,2,5,12,18,22
21	1805	610	1,2,5,12,19
22	1705	610	1,2,5,12,19
23	1766	510	1,5,12,19
24	1946	100	1
25	2116	0	-----
26	1916	320	3,20
27	1737	320	3,20
28	1927	320	3,20
29	2137	0	-----
30	1927	0	-----
31	1907	90	6
32	1888	185	6,7
33	1818	185	6,7
34	1848	185	6,7
35	2118	0	-----
36	1879	0	-----
37	2089	0	-----
38	1989	0	-----
39	1999	0	-----
40	1982	0	-----
41	1672	650	9
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43	1772	650	9
44	1556	650	9
45	1706	650	9
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47	1826	220	16
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49	1999	220	16
50	2109	220	16
51	2209	220	16
52	1779	220	16

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