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Water Wave Optimization Algorithm for solving Thermal Unit Maintenance Scheduling

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Abstract : *Maintenance scheduling of generating units is considered one of the vital power system problem for providing power in a reliable and economic way. In order to improve the overall availability of the generating units, chances of capacity shortage is to be reduced by performing preventive maintenance at regular intervals. In this paper, Hybrid integer coded Water Wave Optimization (HWWO) Algorithm is proposed for solving thermal unit maintenance scheduling (TUMS) problem. To demonstrate the efficacy of the proposed approach, two test systems having 4 units and 22 units are considered. The numerical simulation results prove the superiority of the proposed HWWO for solving TUMS problem.*

Keywords: *Cost minimization, Hybrid integer coded Water Wave Optimization Algorithm, Optimal maintenance schedule, Preventive maintenance, Thermal Unit Maintenance Scheduling*

I. Introduction

It is an important task for a power generating utilities to find out when its generating units should be taken off for planned preventive maintenance once in the prescribed time period. This is of primary importance because the decisions on Thermal Unit Maintenance Scheduling (TUMS) directly affects other short term and long term activities like unit commitment, economic dispatch and generation expansion planning. TUMS problem is a constrained optimization problem where the objective is minimizing the overall operation cost or maximizing the system reliability or both. In this paper, TUMS problem in a vertically integrated power system is considered with an objective of minimizing the overall operational cost subject to various set of equality and inequality constraints.

In general the TUMS problem has two types of variables; discrete and continuous. The discrete variables indicate the ON/OFF status of generating units and continuous variables indicate the real power output from the committed generating units. Thus, it is a mixed integer problem. In early literature, mathematical methods like Integer Programming (IP) [3], Dynamic Programming (DP) [4, 5] and Branch and bound approach (B&B) [6] have been used for solving TUMS problem. But these approaches are restricted only to solve small size systems due to “curse of dimensionality” [7]. In [7], the sum of production and maintenance costs are considered as objective and simulated annealing method is used for solving the **T**UMS. For the objective of levering the reserve and minimization of total generation operation cost, maintenance schedules has been obtained using Tabu-Search (TS) algorithm in [8]. In order to reduce the computational time, avoid infeasible solutions, manage the constraints efficiently and find optimal or near optimal solution for TUMS, an algorithm has been proposed which synthesizes logic programming; constraint satisfaction technique and B&B search [9]. Minimizing the expected energy production cost and level the net reserve were considered as objectives and the TUMS problem has been solved using Genetic Algorithm (GA) [10]. Algorithms such as Particle Swarm Optimization (PSO) [11], Harmony Search (HS) algorithm [12], Teaching Learning Based Optimization (TLBO) [13], Ant Colony Optimization (ACO) [14] have been proposed to solve TUMS problem. In [15], Lagrange Multiplier method is hybridized with Differential Evolution algorithm in order to find optimal solution for the TUMS problem.

As in most of the existing literature, in this paper, the starting period for maintenance of power generating units is considered as control variables to be optimized. The starting period denotes in which period (normally in week) a particular unit can be taken off for preventive maintenance that are integers. At first, the water wave theory was related to gravitational force and other forces dating back to Newton’s work in 1687 **[16]**. In this paper, Water Wave Optimization (WWO) algorithm **[17]** inspired by shallow water wave theory and the idea from wave motions controlled by wave-current-bottom interactions **[18, 19]** is considered for solving TUMS problem. To handle the integer variables, WWOA is suitably modified known as integer coded water wave optimization algorithm. In order to get exact overall operation cost which includes production and variable operation and maintenance cost that needs to be spent by the generating utilities to meet the weekly peak load demand, Lagrange Multiplier Approach (LMA) a mathematical approach is considered and is synthesized with integer coded WWOA. LMA tries to economically dispatch the available generation with minimum production cost which helps WWOA in finding exact maintenance schedule for the TUMS problem.

In this paper, hybrid integer coded water wave optimization (HWWO) algorithm is proposed for solving TUMS problem. The numerical simulation results show the capability of the proposed algorithm in finding optimal or near optimal solution for TUMS problem.

II. Problem Formulation

The TUMS problem considered here is classified as a deterministic cost-minimization problem in which the overall operation cost includes three types of cost functions namely production, fixed maintenance cost of offline units and variable operation and maintenance costs of committed generators. The fixed maintenance cost is constant and does not have influence on maintenance schedule and hence it is neglected in the formulation. Thus the objective of minimizing the overall operation cost that combines production and variable operation and maintenance costs of online units over the planning period is given by

$$Min\, C = \sum_{t=1}^{T}\sum_{u=1}^{U} H.\, F_u(P_{ut}).(X_{ut}) \tag{1}$$

where

$$F_u(P_{ut}) = a_u + (b_u + v_u)P_{ut} + c_u P_{ut}^2 \tag{2}$$

The solution obtained for the TUMS problem must satisfy the following set of equality and inequality constraints.

Maintenance window constraint

In order to let the units operate in good condition, units should be maintained after a certain period of operation. This constraint ensures that once unit ‘u’ is taken offline for maintenance work, it should be continued without any interruption for the time period that is exactly equal to maintenance duration of that unit ‘u’.

$$X_{ut} = \begin{cases} 1 & t = 1, 2, \dots, S_u - 1 \\ 0 & t = S_u, \dots, S_u + M_u - 1 \\ 1 & t = S_u + M_u, S_u + M_u + 1, \dots, T \end{cases} \tag{3}$$

Crew constraint

Due to lack of availability of man power, many thermal generating units cannot be maintained by the same maintenance crew. This can be achieved with the inclusion of crew constraint. Here crew constraint restricts maintenance of unit 1 and 2 simultaneously i.e., during the maintenance of unit 2, unit 1 must be under running condition.

$$\sum_{t=S_{u1}}^{S_{u1}+M_{u1}-1} X_{u2,t} = 1 \tag{4}$$

Priority constraint

Some of the generating units need priority during maintenance i.e., the maintenance activities of such units required to be completed before the starting of the maintenance of other units. Such requirements in maintenance scheduling problem can be handled using priority constraint. This constraint gives the order in which maintenance on the generators has to be carried out. For example, if unit 1 must be completed maintenance prior to the beginning of that of unit 2, this constraint is given by

$$S_2 > S_1 + M_1 - 1 \tag{5}$$

Resource constraint

In every sub-period of planning horizon, the sum of capacity of thermal generating units that are taken out for maintenance must be lesser than gross reserve in that sub-period. The gross reserve in every week can be obtained by taking the difference between the total installed capacity and load demand on that week. In this paper, it is assumed that the rating of unit ‘u’ is exactly equal to the maximum power that can be generated by unit ‘u’. This can be achieved by using resource constraint as given in

$$\sum_{u=1}^{U} R_u \,.\, (1 - X_{ut}) \le \left(\sum_{u=1}^{U} P_u^{\max} - LD_t \right) \tag{6}$$

Generator limit constraint

For each unit, the operating capacity is denoted by P_u^{max}. The power output from each committed unit ‘u’ must be within their lower and upper limits. This can be achieved with the help of generator limit constraint. The power output is zero during maintenance.

$$0 \le P_{ut} \,.\, X_{ut} \le P_u^{\max} \,.\, X_{ut} \tag{7}$$

Load balance constraint

It guarantees that output power generated by the committed generating units is exactly equal to the weekly peak load demand.

$$\sum_{u=1}^{U} P_{ut} \, . \, X_{ut} = LD_t \quad (8)$$

III. Water Wave optimization Algorithm

3.1. Introduction

Nature is the main source of inspiration for the majority of the population-based stochastic optimization techniques. Water wave optimization algorithm is a nature inspired algorithm proposed by Zheng **[17]**.

Initially a set of random solutions are created for the optimization process. Later these initial solutions are combined, moved or evolved over a number of generations or iterations which is predefined. This is the common framework for almost all the population based algorithms.

In this work, the implementation of WWOA is proposed to solve the Thermal Unit Maintenance Scheduling (TUMS) problems subject to few important constraints as mentioned above.

The first paragraph under each heading or subheading should be flush left, and subsequent paragraphs should have a five-space indentation. A colon is inserted before an equation is presented, but there is no punctuation following the equation. All equations are numbered and referred to in the text solely by a number enclosed in a round bracket (i.e., (3) reads as "equation 3"). Ensure that any miscellaneous numbering system you use in your paper cannot be confused with a reference [4] or an equation (3) designation.

3.2. Mathematical model of WWOA

3.2.1. Initialization

As similar to other population based algorithms, population of initial water waves are generated randomly as given below for continuous variable problems.

$$X_{np} = L_d + \rho.(U_d - L_d)$$

where L and U are the lower and upper bounds of the variable 'd'. $\rho \in [0,1]$, d = 1, 2,…, D.

3.2.2. Propagation

From the initial water wave population, each wave is allowed to propagate only once in each iteration. The propagation operator shifts the original wave x in each dimension to produce a new propagated wave x'. The new wave is modelled by the following equation:

$$x'(d) = x(d) + round\ [rnd(-1,1).\delta.L(d)] \quad (9)$$

where $rnd(-1,1)$ is a uniformly distributed random number within the range [-1, 1] and $L(d)$ is the length of the d^{th} dimension. δ be the wavelength of Wave x, which is updated after each generation as

$$\delta = \delta.\alpha^{-(f(x)-f_{min}+\epsilon)/(f_{max}-f_{min+\epsilon})} \quad (10)$$

where α is the wavelength reduction coefficient, where $f(x)$ is the fitness of the original wave, $fmax$ and $fmin$ are respectively the maximum and minimum fitness values among the current population and ϵ is a very small positive number to avoid division-by-zero. The equation (10) ensures that the waves with higher fitness value have lower wavelengths and thus propagate with smaller ranges.

3.2.3. Breaking

In WWOA, the breaking operation is performed only on a wave x that finds a new best solution (i.e., x becomes the new x^*) and conduct a local search around x^* using 'k' solitary waves to simulate wave breaking using the following equation.

$$x'(d) = x(d) + round\ [N(0,1).\beta.L(d)] \quad (11)$$

where β is the breaking coefficient. N is the gaussian random number, *L(d)* is the length of the d^{th} dimension. If none of the solitary waves are better than x^*, x^* is retained; otherwise x^* is replaced by the fittest one among the solitary waves. Totally k number of solitary waves x' are generated at each dimension d and the value of k is generated randomly between 1 and k_{max}. Overall the Breaking process helps in exploitation for a better solution.

3.2.4. Refraction

During wave propagation, if the wave path is not perpendicular to the isobaths the wave gets deflected and the wave converges in shallow regions and diverges in deep regions. In WWOA, refraction is performed on the waves whose height decreases to zero. The position of the wave after refraction is calculated as,

$$x'(d) = N\left(round\ \left[\frac{x^*(d)+x(d)}{2}\right], round\ [\frac{|x^*(d)-x(d)|}{2}]\right) \quad (12)$$

where N is a Gaussian random number, x^* is the best solution found so far and d is the dimension of the problem. So the new position of the wave is a random number midway between the original and the current best known position. Once the refraction phase is ended, the wave height of x' is reset to its maximum value h_{max} and its wavelength is set by,

$$\delta' = \delta \frac{f(x)}{f(x')} \quad (13)$$

Overall the refraction process supports exploration capability of the algorithm.

3.3. Implementation of WWOA for Thermal Unit Maintenance Scheduling

WWOA is initialized with population of waves randomly. Here each wave denotes a set of Starting period (SP) for maintenance of all the thermal generating units of the test system considered.

The initial wave population of ('NP') individuals is randomly selected for all variables ('D') by uniform probability distribution to cover the entire search space uniformly using equation (14). In the thermal unit maintenance scheduling problem the state variables (X) are integers which represents the starting period of each unit for offline maintenance between the earliest start and the latest start period and is randomly generated as

$$\boldsymbol{X_0^{np}} = round\left(S_{Eu}^{np} + \rho.\left(S_{Lu}^{np} - S_{Eu}^{np}\right)\right) \quad (14)$$

where $np = 1, 2, \ldots, NP$ and $\rho \in [0,1]$. The crew and priority constraints are checked with the integer state variables to satisfy. If any of the constraint is violated for a thermal unit, the integer variable is selected randomly between its earliest and latest starting period until both the above constraints are satisfied. The $\boldsymbol{X_o^{np}}$ is the integer variable vector denoting the starting period for each thermal unit during the planning period. Up to the maintenance duration period (week) from the starting period, the status of each unit is set at '0' for units taken off for planned maintenance and '1' during other periods. The optimal generation schedule is obtained by LMA for thermal units which are not under maintenance in every week to meet the weekly load demand as follows,

Step 1: With an initial value of λ, the power output of each committed thermal unit (P_i) in the sub-period 't' is calculated as,

$$P_u = \frac{\lambda - b_u}{2c_u} \quad (15)$$

If the power output of a particular thermal unit exceeds the maximum allowed value, it is fixed at its maximum value.

Step 2: The change in power output is calculated as

$$\Delta P^K = LD_t - \sum_{i=1}^{NCG} P_u \quad (16)$$

where 'LD_t' is the real power demand in sub-period 't' and 'NCG' is the number of committed thermal generating units.

Step 3: For the next iteration, the new λ = old λ + $\Delta\lambda$ where,

$$\Delta\lambda^K = \frac{\Delta P^K}{\sum_{i=1}^{NCG} \frac{1}{2c_i}} \quad (17)$$

$$\lambda^{K+1} = \lambda^K + \Delta\lambda^K \quad (18)$$

The above steps are repeated until ΔP becomes zero.

The fitness function Ψ for the thermal unit maintenance scheduling problem is given as,

$$\Psi = \sum_{t=1}^{T}\sum_{u=1}^{U} H.F_u(P_{ut}).X_{ut} + \sum_{nc=1}^{NC} \omega_{nc}|CV_{nc}| \quad (19)$$

1. Read the system data and WWOA parameters.
2. Randomly initialize the initial wave population ($'NP'\ wave\ vectors$ and $'D'\ no.of\ variables$) between the earliest starting (Es) and the latest starting (Ls) that represents the starting period of each thermal generating unit over the entire scheduling horizon using equation (14).
3. For each wave vector in the population,

a. Check (& Fix) for constraints (3, 4 & 5) agreement.

b. Generate the discrete thermal unit scheduling matrix. Check for constraint 6 to be satisfied.

['0' – Generator taken out for maintenance. '1'– Generator under working condition.]

c. Perform (weekly) economic dispatch for each vector by LMA to meet out the weekly load demand satisfying the constraints 7 and 8 which gives the corresponding production cost. The sum of all the weekly cost is the objective function of the corresponding population vector. Then find the fitness using equation (19).

4. Select the wave from the initial population with which we get the maximum fitness (minimum fuel cost) as the best solution wave (x^*) so far.
5. Set *iter = 1*
6. While (*iter <= iter_max*).
7. Wave = 1;
8. Perform Propagation on the Wave (only once) in each iteration by equation (9).

a. Check (& Fix) for constraints (3, 4 & 5) agreement.

b. Generate the discrete generator scheduling matrix (DGSM) for the propagated wave and check the constraint 6 to be satisfied.

c. Perform (weekly) economic dispatch for each vector by LMA to meet out the weekly load demand satisfying the constraints 7 and 8 which gives the corresponding production cost. The sum of all the weekly cost is the objective function of the corresponding population vector. Then find the fitness using equation (19).

9. Evaluate the fitness, $f(x')$ of the new wave using equation (19).
10. If $f(x') > f(x)$ then go to **step 11.** Else, go to **step 13.**
11. If $f(x') > f(x^*)$ then go to **step 11.a.** Else, go to **step 12.**

a. Perform Breaking based on equation (11) on the wave (x') to obtain k number of solitary waves (x_k), Where, $k = 1 \ to \ k_{max}$ (a random number predefined based on the dimension of the problem).

b. Compare fitness of the Solitary waves (x_k), $k = 1 \ to \ k_{max}$, with the best wave fitness $f(x^*)$

i.e., If $max(f(x_k)) > f(x^*)$ then

Update (x^*) with $best \ of \ (x_k)$.

Else,

Replace (x^*) with (x').

12. Replace (x) with (x') and go to **step 15.** (i.e., Return the best solution obtained)
13. Wave (x) remains the same and decrease the wave height $(x.h)$ by 1. If $(x.h = 0)$ then go to **step 14.** Else, go to **step 15.**
14. Perform Refraction on wave (x) to a new wave (x') based on equations (12) and (13). Reset the new wave height $(x'.h)$ to h_{max}.
15. If Wave < NP, then Wave = Wave + 1. Go to **step 8.** Else, go to **step 16.**
16. Update the wavelengths (λ) of the population using equation (10).
17. **Return** the best solution wave (x^*) obtained so far.
18. Stop and Print the global Thermal Unit Maintenance Schedule (TUMS) results.

IV. Numerical Results and Discussions

To test and validate the effectiveness of the proposed HWWO Algorithm, two test systems are considered [8, 15]. The first system is a small system having 4 generators to be completed maintenance within a planning period of 8 weeks. The second system is a medium size system having 22 generating units to be finished maintenance within a planning horizon of 52 weeks. The results obtained for the TUMS problem by the proposed hybrid integer coded water wave optimization algorithm are compared with the results attained through well known algorithms present in the literature.

4.1 Test System 1: 4 Units System

The generator data for 4 units system is given in **[15].** The weekly peak load data is given in Table 1. The total installed capacity is 790 MW. Due to crew constraint, units 1 and 2 should not be under maintenance simultaneously. Due to priority constraint, the maintenance activities of unit 1 must be completed before the beginning of the maintenance of unit 2.

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

The maintenance outage schedule obtained using proposed HWWO is given in table 4.2. Since this system is a small system, the same schedule has been attained for TUMS using HPSO [15] as shown in Table 2.

Table 2: Maintenance Schedule of 4 units system

Week	Units on Maintenance	Capacity on Maintenance (MW)	Gross Reserve (MW)
1	3	300	541
2	3	300	525
3	1	200	514
4	1	200	511
5	1	200	534
6	1	200	483
7	2, 4	290	603
8	2	200	495

From Table 2, it is evident that each of the 4 units are under maintenance continuously for the period equal to its corresponding maintenance duration weeks only once during the entire planning period of 8 weeks, thereby satisfying maintenance window constraint. Also the sum of capacity of units that are taken offline for maintenance in every week is lesser than the gross reserve in that week, satisfies resource constraint. Also it can be seen that, units 1 and 2 are not under simultaneous maintenance, thereby satisfying crew constraint. The maintenance of unit 1 has been finished before the starting of maintenance of unit 2, thereby satisfying priority constraint. The power output from units 1, 2, 3 and 4 in each week is given in figure 1, 2, 3 and 4 respectively.

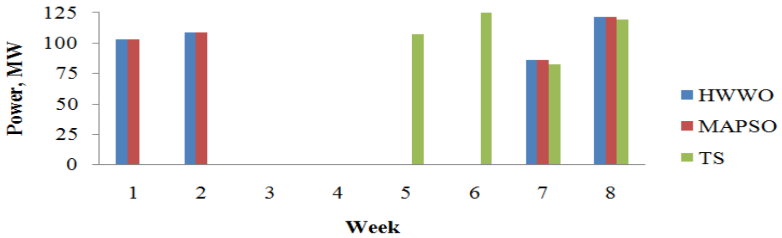

Fig.1. Power output from Unit 1

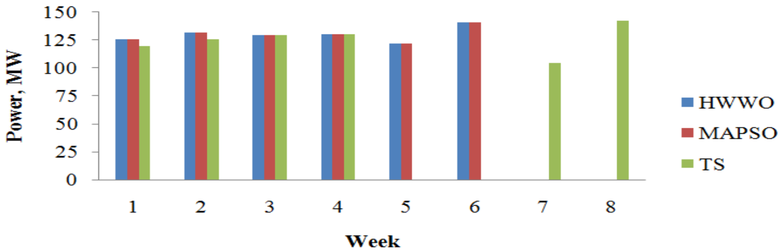

Fig.2. Power output from Unit 2

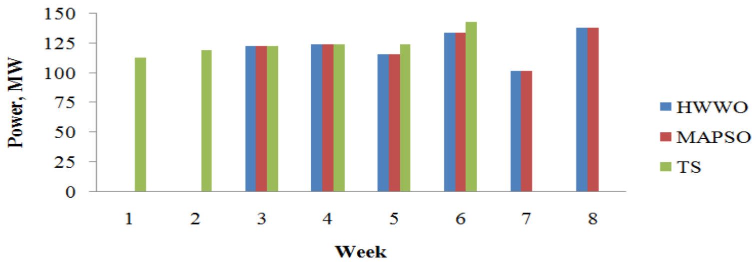

Fig.3. Power output from Unit 3

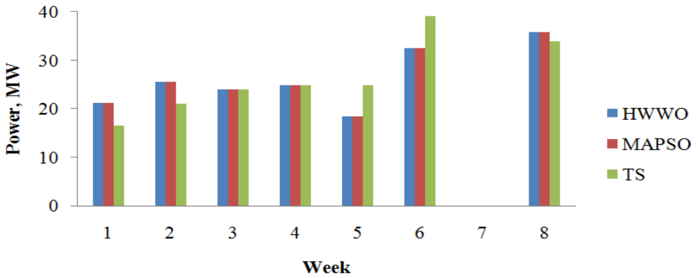

Fig.4. Power output from Unit 4

From Fig. 1 – Fig.4, it can be observed that both HWWO and MAPSO give same generation schedule. Also it can seen from the above figures that the active power output from all generators are within their lower and upper limits thereby satisfying generator limit constraint. The sum of the power output of all generating units in each week is equal to load demand on that week, thus load demand constraint is satisfied. For the maintenance schedule of 4 unit system attained with the objective of minimizing overall operation cost that is obtained through Tabu Search (TS) algorithm [8], the authors have not given the overall production cost. For the same schedule, using LMA the overall operation cost is found. Table 3 shows the comparison of overall operational cost between the proposed algorithm with other existing methods in [15].

Table 3: Overall Operational Cost

	Cost ($)
HWWO	3391993.59
MAPSO	3391993.59
TS	3392728.13

4.2 Test system 2: 22 Units system

This system has 22 generators on which the maintenance must be completed within the planning horizon of 52 weeks [8, 15]. The generator data is provided in **[15]**. The total installed capacity is 3986 MW. Due to crew constraint, units 15 and 16, units 21 and 22 should not be under maintenance simultaneously. Due to priority constraint, the maintenance activities of units 2 and 5 should be finished before the commencement of maintenance of units 3 and 6 respectively. The weekly peak load data is given in Fig.5. In the figure, it can be seen that there is peak load of 2209 MW in week 51 and low load of 1263 MW in week 17.

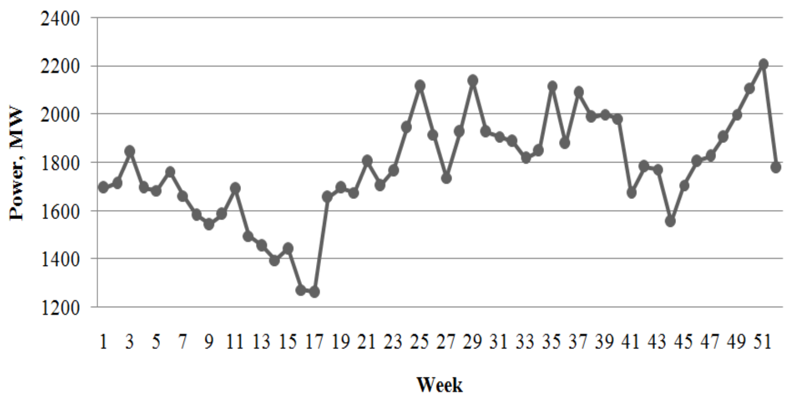

Fig.5. Load data of 22 units system

The gross reserve in each week is given in Table 4. It is obtained by subtracting the weekly load demand from the total installed capacity.

Table 4: Weekly gross reserve

Week	**Gross Reserve (MW)**	**Week**	**Gross Reserve (MW)**	**Week**	**Gross Reserve (MW)**	**Week**	**Gross Reserve (MW)**
1	2292	**14**	2590	**27**	2249	**40**	2004
2	2272	**15**	2543	**28**	2059	**41**	2314
3	2142	**16**	2713	**29**	1849	**42**	2204
4	2292	**17**	2723	**30**	2059	**43**	2214
5	2302	**18**	2331	**31**	2079	**44**	2430
6	2223	**19**	2291	**32**	2098	**45**	2280
7	2323	**20**	2311	**33**	2168	**46**	2180
8	2403	**21**	2181	**34**	2138	**47**	2160
9	2443	**22**	2281	**35**	1868	**48**	2080
10	2400	**23**	2220	**36**	2107	**49**	1987
11	2296	**24**	2040	**37**	1897	**50**	1877
12	2490	**25**	1870	**38**	1997	**51**	1777
13	2530	**26**	2070	**39**	1987	**52**	2207

Table 5: Maintenance schedule obtained using HWWO

Weeks	Load	Maintenance Capacity	Units under Maintenance
1	1694	640	12,15,17,19
2	1714	740	8,12,15,17,19
3	1844	840	8,12,13,15,17,19
4	1694	620	8,12,13,15,17
5	1684	620	8,12,13,15,17
6	1763	710	10,12
7	1663	710	10,12
8	1583	710	10,12
9	1543	610	10
10	1586	610	10
11	1690	610	10
12	1496	830	10,16
13	1456	1050	10,16,20
14	1396	1150	10,14,16,20
15	1443	1150	10,14,16,20
16	1273	1265	7,10,14,16,21
17	1263	1365	1,7,10,14,16,21
18	1655	625	1,5,7,14,21
19	1695	530	1,5,14,22
20	1675	430	1,5,22
21	1805	430	1,5,22
22	1705	530	1,4,5,22
23	1766	430	4,5,22
24	1946	191	4,11
25	2116	91	11
26	1916	191	2,11
27	1737	191	2,11
28	1927	100	2
29	2137	0	*****
30	1927	190	6,18
31	1907	190	6,18
32	1888	190	6,18
33	1818	190	6,18
34	1848	100	18
35	2118	0	*****
36	1879	0	*****
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	100	3
47	1826	100	3
48	1906	100	3
49	1999	0	*****
50	2109	0	*****
51	2209	0	*****
52	1779	0	*****

The maintenance schedule obtained using HWWO is shown in Table 5. From Table 5, it is clear that units 15 and 16, units 21 and 22 are not in simultaneous maintenance, thereby crew constraint gets satisfied. The maintenance of generating units 2 and 5 gets completed before the starting of maintenance of generators 3 and 6 which shows that priority constraint is satisfied. Also the sum of capacity of all units that are under maintenance in every week is lesser than the gross reserve, thereby satisfying resource constraint. From Table 5, it is evident that each unit is under maintenance continuously for the period equal to its corresponding maintenance duration weeks only once during the entire planning horizon of 52 weeks, thereby satisfying maintenance window constraint. Table 6 shows the comparison of the overall operation cost that includes production and variable operation and maintenance costs. For the maintenance schedule of 22 unit system attained with the objective of minimizing overall operation cost that is obtained through Tabu Search (TS) algorithm [8], the authors have not given the overall production cost. For the same schedule, using LMA the overall operation cost is found.

Table 6: Overall Operational Cost

	Cost ($)
HWWO	148583060.09
MAPSO	148584093.45
TS	148705625.34

V. Conclusion

In this paper a new approach for optimization of the thermal generating unit maintenance scheduling problem is presented. In the proposed approach LMA is hybridized with water wave optimization algorithm. The LMA helps WWOA in finding the optimal starting period for maintenance of thermal generating units. This approach provides a feasible maintenance schedule for the thermal units by considering minimization of overall generator operation cost which includes production and variable operation and maintenance cost while satisfying the system and operational constraints. The validation of the proposed method is done by considering two test systems. The superiority of the proposed HWWO Algorithm is demonstrated by comparing it with the results obtained from existing algorithms. The simulation results emphasize the effectiveness of the proposed algorithm in finding optimal or near optimal solution for thermal generating units maintenance scheduling problem.

Appendix

Nomenclature

u - Power generating unit index	U - Total number of generating units
t - Time period index (week)	T - Total number of sub periods (weeks) in the planning horizon
LD_t - Real power load demand in week 't'	np - Population index
nc - Constraint index	NC - Total number of constraints
NP - Population Size	K - Iteration index in Lagrange Multiplier approach
C - Objective function	a_u, b_u, c_u - Fuel cost coefficients of unit *u*
CV - Constraint violation	NCG - Number of committed thermal units
D - Number of variables	v_u - Variable operation and maintenance cost of unit *u* in $/MWh
$P_u^{min.}$- Minimum limit generating unit *u*,0 MW	H - Number of hours in a sub-period (week) = 168
$P_u^{max.}$ - Maximum limit generating unit *u*, MW	P_{ut} - Power output from generating unit *u* in sub-period *t*, MW
R_u - Rating of unit *u*	X_{ut} - State variable equal to 0 if the unit *u* in sub-period *t* is switched off for maintenance and 1 otherwise
M_u - Maintenance duration of unit *u*	S_{Eu} - Earliest period in which maintenance of unit *u* can start
ω - Penalty factor	S_{Lu} - Latest period in which maintenance of unit *u* can start
ψ - Fitness function to be minimized	S_u - Starting period of maintenance of unit $u \in [S_{Lu}, S_{Eu}]$
α - Wavelength reduction coefficient	f_{max} - Maximum fitness among the population
β - Wave breaking coefficient	f_{min} - Minimum fitness among the population
δ - Wavelength of the wave	*L(d)*- Length of the d^{th} dimension
h_{max} - Maximum height of the wave	∈ - very small positive number to avoid divide-by-zero error
N - Gaussian random number	

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