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GENERATOR MAINTENANCE SCHEDULING IN A DEREGULATED ENVIRONMENT USING HYBRID DIFFERENTIAL EVOLUTION ALGORITHM

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ABSTRACT

In this paper, a new approach for preventive maintenance of generating units in a competitive market environment is proposed. The objective of the generator maintenance scheduling (GMS) problem is to find the precise time interval for maintenance of power generating units with an objective criterion of maximizing the profit of individual generation companies (GenCo's) present in an electricity market. The problem of scheduling of generating units for maintenance is formulated as a mixed integer optimization problem. Differential Evolution (DE) algorithm is suitably modified to handle the integer variables present in the GMS problem. The integer variables are the control variables that denotes the starting period of each generating unit for carrying out maintenance work. The lambda iteration approach is incorporated into the DE procedure in order to assists DE in finding the accurate starting period for maintenance of power generating units. This paper presents a hybrid differential evolution (HDE) to solve maintenance scheduling problem in a power system. The performance of the proposed algorithm is validated by considering 22 units test system. Numerical results obtained by the proposed HDE method are compared with hybrid particle swarm optimization (HPSO) algorithm. The test results reveal the capability of the proposed HDE algorithm in finding near optimal maintenance schedule for the GMS problem under competitive market environment.

Keywords: generator maintenance scheduling, competitive electricity market, profit maximization, hybrid differential evolution, lambda iteration approach, optimal maintenance schedule.

1. INTRODUCTION

Preventive maintenance scheduling of any equipment is important in order to extend the lifetime of it. Maintenance scheduling of power generating units is a significant and challenging task both in centralized and decentralized power system. The objective of generator maintenance scheduling (GMS) problem is to determine the exact time interval for planned preventive maintenance on a yearly time horizon. The main aim of the GMS in a centralized power system is to reduce the production cost, increase the system reliability whereas in decentralized power system, it aims at maximizing the profit of individual power generation companies (GenCo's) present in the market. The complexity of the problem increases with increase in system size. The problem has two types of variables, integer variables denoting the on/off status of the unit and continuous variables denoting the power generation of various units and hence it is a mixed integer problem. Lot of contribution are made by various authors towards GMS. Earlier, mathematical approaches like integer programming (IP) [1], Branch and Bound (B&B) algorithm [2], dynamic programming (DP) approach [3, 4] has been used for solving GMS problem. These mathematical approaches give optimal solution for small size systems. The increase in system size increases the solution space of the problem exponentially known as 'curse of dimensionality'. Due to the curse of dimensionality, mathematical approaches cannot be used

for solving large size systems. To overcome such difficulties, modern optimization techniques are introduced for solving GMS problem. The minimization of cost is considered as a goal and solved for the problem of generator maintenance scheduling [5-7]. A decomposition approach has been presented in [5] for solving GMS. The GMS problem is formulated as 0 -1 mixed integer problem with an objective of minimizing overall operational cost which includes production cost and maintenance cost and is solved using Simulated Annealing [SA] in [6]. In [7], the objective criterion of minimizing production cost is considered and GMS is solved using combination of logic programming, constraint satisfaction technique and B&B algorithm. In [8], minimization of fuel cost, maintenance cost and variation of spinning reserve rate are considered as objective and combined using weighting coefficients. To overcome the excessive execution time needed by SA for solving GMS and to combine the intensification and diversification aspects, Genetic Algorithm (GA) and Tabu search (TS) are synthesized with SA to solve GMS [8]. The reliability associated with a power system is a measure of its ability to provide an adequate supply of electrical energy for the period of time. The reliability criterion considered for solving the problem of maintenance scheduling of generating units is either deterministic or probabilistic. There are plenty of probabilistic reliability definitions like loss of load probability (LOLP), loss of load expectation (LOLE) etc.,

which are used as reliability objective criteria for the formulation of GMS problem. In [9], maintenance of generator is scheduled so as to minimize the risk through the minimization of yearly value of LOLE is proposed and solved using GA. LOLP is taken as objective in formulating GMS problem and has been solved using method of cumulants [10]. The deterministic reliability criterion of minimizing the sum of the squares of the reserve is considered in [11] and the meta-heuristic based hybrid approach is used to solve the GMS problem in which heuristic approach is combined with GA / SA hybrid to seed the initial population. The objectives of minimizing the total operating cost and leveling the reserve are considered and solved using new TS algorithm in [12]. In [13], Leou proposed a new formulation in which the cost and reliability are considered as an index and GA is combined with SA and is implemented for solving the problem. Particle swarm optimization (PSO) is used for finding the good schedule for maintenance of generating units by considering leveling the reserve generation as objective [14, 15]. Ant colony optimization (ACO) inspired by the foraging behavior of ant colonies is implemented for solving GMS in [16]. Knowledge based expert system is applied in [17] to schedule the generator for maintenance in which the knowledge has been built in consultation with experienced operators and are expressed by rules and logic representations. To include the uncertainties present in the GMS, the objectives and constraints are expressed in fuzzy notation and embedded with dynamic programming to find the units maintenance schedule [18]. In [19], the objectives and constraints are fuzzified through the guidance of GA and the maintenance schedule for generating units is obtained with the help of fuzzy dynamic programming. Four objective criteria such as loss of load expectation, expected un-served energy, expected fuel cost and constraint violation are considered and has been solved using B & B algorithm [20]. In decentralized electricity environment, generation, transmission and distribution of power are done by separate entities like GenCos, transmission companies (TransCos) and distribution companies (DisCos) respectively. The major objective of these entities is maximizing their own profits while maintaining adequate level of system reliability is the objective of independent system operator (ISO). Marwali and Shahidehpour [21] proposed Bender's decomposition approach for finding the solution to the GMS problem with an objective of minimizing GenCo's total maintenance and production costs as well as the cost of purchasing additional energy from outside sources over the operational planning period. To satisfy the GenCo's objective of maximizing the profit and ISO's objective of maintaining appropriate level of reliability, Conejo, et al., described a sound coordination mechanism among GenCo and ISO in [22]. Samuel and Rajan [23] presented two new hybrid approaches based on PSO- GA and PSO- Shuffled frog leaping algorithm (SFLA) for solving long term GMS from the perspective

of GenCo. The major limitation of these modern optimization methods is that though it can be used for solving GMS of large size systems, it can find only sub optimal or near optimal solutions for the GMS problem. Differential evolution (DE) introduced by Storn and Price [24, 25] is another tool that is successfully applied for solving many real world optimization problems. The basic DE has the problem of premature convergence. In order to avoid premature convergence and to find optimal solution for a particular problem, the basic DE highly relies on population size. If the number of variables is high, then DE needs more population to find optimal solution. This motivates the authors to propose an algorithm that can find near global optimal solution for the GMS with considerable reduction in population size. Therefore in this paper, lambda iteration method is incorporated into the DE algorithm which supports DE in finding near global optimal solution for the GMS problem. The lambda iteration method is a mathematical method used to economically dispatch the available generation so as to get minimum production cost. The GMS problem is a mixed integer problem having continuous variables denoting the active power generation and binary integer variables denoting the on/off status of generating units. In the proposed methodology, variables are the starting periods for maintenance of generators which are integers. Thus the number of variables is considerably reduced. DE is suitably modified to handle the integer variables. The inclusion of lambda iteration approach into DE procedure helps to economically dispatch the available generation of committed generators with minimum production cost. It also meets the load demand due to bilateral contract and power for bid. Thus, this paper presents hybrid differential evolution (HDE) algorithm for solving GMS problem in decentralized power system with the objective criterion of maximizing GenCo's profit while satisfying numerous hard constraints. To validate the effectiveness of the proposed HDE algorithm, in this paper, the results obtained using HDE are compared with that obtained using hybrid particle swarm optimization (HPSO).

2. PROBLEM FORMULATION

The main objective of GMS problem is to find the exact time interval to carry out maintenance work of power generating units. In this paper, maintenance scheduling of generating units is considered from the perspective of GenCo's only. The objective criterion of GMS problem considered is maximizing the profit of each GenCo present in the electricity market. The profit can be calculated as the difference between GenCo's expected revenues and expenses. The objective function of maximizing profit of GenCo is formulated as

$$Max \sum_{t=1}^{T} \left(E_R(t) - E_E(t) \right) \qquad (1)$$

where

$$E_R(t) = H.C^C(t).p^C(t) + H.C^S(t).p^S(t) \quad (2)$$

$$E_E(t) = \sum_{i=1}^{N} H.(a_i + b_i P_{it} + c_i P_{it}^2).(1 - U_{it}) + \sum_{i=1}^{N} H.P_{it}.v_i.(1 - U_{it}) + \sum_{i=1}^{N} MC_i.R_i.U_{it} \quad (3)$$

In equation (2), the first term corresponds to the revenue due to the bilateral contract to meet out the load demand and second term corresponds to the revenue due to bidding of power for sale. The first term of (3) denotes the cost of production of power; the second term represents the variable operation and maintenance cost and the fixed maintenance cost are represented by the third term. The various constraints to be satisfied by the GMS problem are

2.1 Maintenance window constraint

The preventive maintenance work of each power generating unit must be scheduled between its earliest and latest period allowed for maintenance. The maintenance window constraint guarantees that once maintenance of unit *i* gets started, the maintenance work have to be continued without any interruption for the time period that is exactly equal to maintenance duration of unit *i* in weeks. The state variable is stated as follows

$$U_{it} = \begin{cases} 1, & t = S_i,...,S_i + M_i - 1 \\ 0, & otherwise \end{cases} \quad (4)$$

2.2 Covering of Bilateral contract and Power for Bid

In any sub period *t*, the total generated power must be sufficient to meet out the load pattern due to bilateral contract and power for sale in electricity market. This is given by

$$\sum_{i=1}^{N} P_{it} = p^C(t) + p^S(t) \quad (5)$$

2.3 Generators limit constraint

It ensures that the output of each generator in a GenCo lies within its minimum and maximum limit and is stated as follows

$$P_i^{min} \leq P_{it} \leq P_i^{max} \quad (6)$$

2.4 Crew constraint

It depends on the availability of man power for maintenance work. It guarantees that no two units can be maintained by the same maintenance crews. It is expressed in terms of U_{it} variables of the second unit *i2* as follows

$$\sum_{t=S_{i1}}^{S_{i1}+M_{i1}-1} U_{i2,t} = 0 \quad (7)$$

Equation (7), states that unit '2' should not be taken offline to carry out maintenance work when the duration on which unit '1' is under maintenance.

2.5 Precedence constraint

In some circumstances, some of the units need maintenance prior to other generating units. Such circumstances can be tackled using precedence constraints. This constraint specifies the order in which maintenance on the generators has to be carried out. For instance, if maintenance of unit '1' is to be completed before the starting of maintenance of unit '2', then this constraint is given by

$$S_1 + M_1 - 1 \leq S_2 \quad (8)$$

Equation (8) states that maintenance of unit '2' must be started only after the completion of maintenance of unit '1'.

3. PROPOSED METHODOLOGY

Differential Evolution (DE) algorithm is a simple evolutionary strategy, introduced by Storn and Price [24, 25]. It is a stochastic, population based optimization algorithm that is developed to optimize real parameter and real valued functions. DE creates new solutions by combining the parent individual and several other individuals of the same population. A candidate replaces the parent only if it has better fitness. Thus, the fittest offspring competes one-to-one with its parent, which is different from the other evolutionary algorithms. It has few control variables to steer the objective and are easy to choose. The control parameters of DE that have to be controlled by the user are number of population NP, scaling factor F and crossover factor CR. DE has been successfully applied to solve various difficult optimization problems and has been verified as a promising algorithm for solving real world optimization problems in diverse fields [26]. The GMS problem has two variables; one is binary integer which represents the on/off status of power generating units and another variable is continuous which represents the output of generating units. Thus GMS is a mixed integer problem. In this paper, DE is suitably modified to handle integer variables indicating the starting period for maintenance of generators. Thus population of vector of integers that denotes the starting period of maintenance of each and every generator (X) is randomly

initialized between its earliest and latest staring period as follows

$$\left(X_i^k\right) = round\left(E_i^k + random(0,1).\left(L_i^k - E_i^k\right)\right) \quad (9)$$

where, $k = 1, 2, …, NP$. The integer variables are checked for satisfying crew and precedence constraints. If any of the constraint is violated for a generating unit, the integer variable is selected randomly between its earliest and latest starting period until the crew constraint and precedence constraint are satisfied and then the integer variables are checked for maintenance window constraint. After satisfying all the above mentioned constraints, the status of each unit i is set at '1' from the starting period up to its corresponding maintenance duration period (M_i) to denote that the unit i is taken offline for planned preventive maintenance and '0' during other periods. The lambda iteration method is used to obtain optimal generation schedule for the committed generating units in each and every week of the planning horizon in order to meet the load demand due to bilateral contract. The optimal generation schedule of each committed generating units yields minimum production cost which in turn maximizes the profit. The computational procedure to find the optimal generation schedule using lambda iteration method has the following steps.

Step 1: with an initial value of λ, power output to be generated by each committed generator (P_i) in sub period t is calculated using

$$P_{it} = \frac{\lambda - b_i}{2c_i} \quad (10)$$

The generated output power is set at its maximum value if it exceeds the maximum limit of that generator.

Step 2: The change in power output is calculated using

$$\Delta P^K = p^C(t) - \sum_{i=1}^{NCG} P_{it} \quad (11)$$

where, NCG is number of committed generators.

Step 3: The change in λ can be found as follows

$$\Delta\lambda^K = \frac{\Delta P^K}{\sum_{i=1}^{NCG} \frac{1}{2c_i}} \quad (12)$$

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:

$$\lambda^{K+1} = \lambda^K + \Delta\lambda^K \quad (13)$$

The steps (10) - (13) are repeated until ΔP is zero. Thus optimal generation of committed generating units with minimum production cost can be found. The remaining power that can be generated from the available generators is the selling power ($p^S(t)$) on market.

The fitness function of the GMS problem to be minimized using DE is

$$\psi = -\left(\sum_{t=1}^{T}\left(E_R(t) - E_E(t)\right) + \sum_{nc=1}^{NOC} \omega_{nc}\left|CV_{nc}\right|\right) \quad (14)$$

After initializing the population of vectors, there are three operators that are very crucial for the successful working of DE. They are mutation, crossover and selection. These operators are explained below

3.1 Mutation

A mutated individual is generated during the mutation operation. In this paper, most frequently used DE variant, DE/rand/1/bin has been employed for obtaining perturbed individual. Three vectors $r1$, $r2$ and $r3$ are randomly chosen between [1, NP] which are mutually different and is also different from base index j. The donor vector is created by adding weighted difference between two population vectors to a third vector as given below

$$\left(V_j^{G+1}\right) = \left(X_{r1}^G + round\left(F.\left(X_{r2}^G - X_{r3}^G\right)\right)\right) \quad (15)$$

where, the scaling or mutation factor $F \in [0.1,1]$. The scaling factor F ensures the fastest possible convergence. The obtained donor vector is checked in order to satisfy crew and precedence constraint. If any of the constraint is violated for a unit, the integer variable is selected randomly between its earliest and latest starting period until the crew constraint and precedence constraint are satisfied and then the integer variables are checked for maintenance window constraint. The perturbed individual V_j^{G+1} thus obtained is a mutated integer vector for its parent integer vector X_j^G.

3.2 Crossover

After the mutation operation, crossover phase is applied to create the trial vector. The trial integer vector is created by applying uniform binomial crossover operation to each pair of parent or target integer vector X_j^G and its corresponding mutant or donor integer vector V_j^{G+1} as follows:

$$V_{hj}^{G+1} = \begin{cases} X_{hj}^{G}, & random(0,1) > CR \\ V_{hj}^{G+1}, & otherwise \end{cases} \qquad (16)$$

where, h = 1, 2, …, NI and the crossover factor $CR \in$ [0, 1]. If the random number is greater than CR, the parameters of the trial integer vector are inherited from the parent integer vector; otherwise it is copied from the donor integer vector. The individual gene in the trial integer vector symbolizes the starting period of each generating unit. The status of each unit i is set at '1' from the starting period up to its corresponding maintenance duration period (M_i) to denote that the unit i is taken offline for planned preventive maintenance and '0' during other periods. The committed generators in each week are then economically dispatched using equations (10) - (13) in order to satisfy the weekly load demand due to bilateral contract with minimum production cost. The remaining power that can be generated from the available generators is the selling power ($p^S(t)$) on market. Then the fitness function value can be calculated using equation (14).

3.3 Selection

The fitness function value of each offspring or trial vector $\psi(V_j^{G+1})$ is compared to that of its corresponding parent vector $\psi(X_j^{G})$ in the current population. If the trial vector has lesser or equal fitness function value than the corresponding parent vector, the trial vector will replaces the parent vector otherwise the parent vector is retained for the next generation. The selection operation can be expressed as follows

$$X_j^{G+1} = \begin{cases} V_j^{G+1}, & if\ \psi\left(V_j^{G+1}\right) \le \psi\left(X_j^{G}\right) \\ X_j^{G}, & otherwise \end{cases} \qquad (17)$$

The above steps are repeated until some specific stopping criterion is satisfied.

4. RESULT AND DISCUSSIONS

In this paper, a new methodology is proposed to obtain optimal maintenance schedule for generator maintenance scheduling problem. In the proposed methodology, DE is employed as a primary optimizer in solving GMS problem. The use of lambda iteration method economically dispatches the available generation and minimizes the expenses of the GenCo's in turn maximizes their profit and based on these information DE tries to find the optimal maintenance schedule for planned preventive maintenance of power generating units. To validate the effectiveness of the proposed HDE algorithm, real size system of having 22 generating units [12] is considered. The 22 units belongs to a GenCo has to be scheduled for maintenance just once during the planning horizon of 52 weeks. The number of integer variables of the 22 units system is 22 that indicate the starting period of 22 generators. Due to precedence constraint, the maintenance work of unit 2 must be completed before starting of maintenance of unit 3. Similarly the maintenance of unit 6 must be started only after the completion of maintenance work of unit 5. Due to crew constraint, the maintenance activities of units 15 and 16, units 21 and 22 should not be initiated simultaneously. The program is developed using MATLAB 7.7 on a personal computer with 2 GHz Core 2 Duo CPU. The simulation results are compared with that achieved via HPSO optimization scheme. The maintenance costs are assumed as in Table-1.The generator data of 22 units system is given in Table-1.

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Table-1. Generator data of 22 unit system.

Unit (I)	L	E	M	$P_{Min.}$ MW	$P_{Max.}$ MW	v $/MWh	MC $/MW	Fuel cost			Cost		
								a_1	b_1	c_1	$a = a_1$ $/h	$b = b_1 + v_i$ $/MWh	$c = c_1$ $/MW^2/h
1	1	47	6	0	100	0.25	93	70	8.00	0.00585	70	8.25	0.00585
2	1	50	3	0	100	0.20	93	70	8.00	0.00580	70	8.20	0.00580
3	1	50	3	0	100	0.20	93	70	8.00	0.00580	70	8.20	0.00580
4	1	50	3	0	100	0.20	93	70	8.00	0.00580	70	8.20	0.00580
5	1	47	6	0	90	0.35	93	60	8.00	0.00610	60	8.35	0.00610
6	1	49	4	0	90	0.30	93	60	8.00	0.00610	60	8.30	0.00610
7	1	50	3	0	95	0.20	93	68	8.00	0.00579	68	8.20	0.00579
8	1	49	4	0	100	0.20	93	72	8.00	0.00565	72	8.20	0.00565
9	27	48	5	0	650	0.52	137	525	7.00	0.00120	525	7.52	0.00120
10	6	11	12	0	610	0.50	137	510	7.20	0.00142	510	7.70	0.00142
11	1	49	4	0	91	0.20	93	62	8.25	0.00600	62	8.45	0.00600
12	1	45	8	0	100	0.30	93	74	8.15	0.00578	74	8.45	0.00578
13	1	50	3	0	100	0.20	93	70	8.00	0.00580	70	8.20	0.00580
14	1	47	6	0	100	0.25	93	70	8.00	0.00585	70	8.25	0.00585
15	1	48	5	0	220	0.25	117	85	7.90	0.00460	85	8.15	0.00460
16	1	47	6	0	220	0.25	117	87	7.95	0.00464	87	8.20	0.00464
17	1	48	5	0	100	0.20	93	69	8.18	0.00570	69	8.38	0.00570
18	1	48	5	0	100	0.25	93	69	8.17	0.00572	69	8.42	0.00572
19	1	50	3	0	220	0.25	117	81	7.90	0.00463	81	8.15	0.00463
20	1	50	3	0	220	0.25	117	82	7.95	0.00462	82	8.20	0.00462
21	1	50	3	0	240	0.30	117	82	7.40	0.00410	82	7.70	0.00410
22	1	48	5	0	240	0.30	117	80	7.42	0.00415	80	7.72	0.00415

It is assumed that there is a bilateral contract between GenCo and market participants (large consumers). The contracted power profile to be met out by GenCo and prices that has to be paid to GenCo by market participant for weekly bases is given in Table-2. The price data are taken from [27].

Table-2. Bilateral contract with weekly power profile and price.

Week (t)	$p^C(t)$ (MW)	$C^C(t)$ $/MWh	Week (t)	$p^C(t)$ (MW)	$C^C(t)$ $/MWh	Week (t)	$p^C(t)$ (MW)	$C^C(t)$ $/MWh	Week (t)	$p^C(t)$ (MW)	$C^C(t)$ $/MWh
1	1694	41.4	14	1396	35.4	27	1737	34.5	40	1982	33.5
2	1714	41.4	15	1443	35.4	28	1927	34.5	41	1672	38.6
3	1844	41.4	16	1273	35.4	29	2137	34.9	42	1782	38.6
4	1694	41.4	17	1263	35.4	30	1927	34.9	43	1772	38.6
5	1684	41.4	18	1655	35.4	31	1907	34.9	44	1556	38.6
6	1763	41.4	19	1695	35.4	32	1888	34.9	45	1706	38.6
7	1663	41.4	20	1675	35.4	33	1818	33.5	46	1806	38.6
8	1583	41.4	21	1805	35.4	34	1848	33.5	47	1826	38.6
9	1543	35.4	22	1705	35.4	35	2118	33.5	48	1906	38.6
10	1586	35.4	23	1766	35.4	36	1879	33.5	49	1999	38.6
11	1690	35.4	24	1946	35.4	37	2089	33.5	50	2109	48.1
12	1496	35.4	25	2116	34.5	38	1989	33.5	51	2209	48.1
13	1456	35.4	26	1916	34.5	39	1999	33.5	52	1779	48.1

The revenue to GenCo is through bilateral contract and due to sale of power on bid. The market clearing price is the price of the electricity that is forecasted based on electricity demand and supply, fuel costs, etc [28]. The forecasted market clearing price [27] at which the power can be sold out for every time period (week) in the planning horizon of one year is given in Table-3. Table 4 and 5 shows the maintenance schedule of GenCo having 22 power generating units obtained through HDE and HPSO algorithm respectively. In table 4 and 5, it can be seen that both algorithms satisfies crew and precedence constraints. Each and every unit of GenCo is maintained just once during the entire planning period and is under continuous maintenance for the duration specified by maintenance duration of unit i satisfying maintenance window constraint. The schedule is attained with an objective of maximizing the profit of GenCo's present in the electricity market. In the objective, the revenue due to bilateral contract arrangement is going to be constant for the entire planning period [27]. The fixed maintenance cost does not have that much influence on minimizing overall operational cost when compared to production and variable O and M costs [7, 29]. Thus overall operational cost can be minimized by minimizing the production cost and variable operation and maintenance cost. The incorporation of lambda iteration approach into DE and PSO results in minimum production cost which in turn maximizes the profit. But, based on this information, when compared to HPSO, the proposed HDE finds optimal maintenance schedule as shown in Table-4.

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Table-3. Forecasted weekly market clearing price.

Week (*t*)	MCP $C^S(t)$ $/MWh	Week (*t*)	MCP $C^S(t)$ $/MWh	Week (*t*)	MCP $C^S(t)$ $/MWh	Week (*t*)	MCP $C^S(t)$ $/MWh
1	40.4	14	34.4	27	36.9	40	32.9
2	41.7	15	34.2	28	36.6	41	31.7
3	40.9	16	37.8	29	38.8	42	33.3
4	40.4	17	33.4	30	37.7	43	37.8
5	42.8	18	37.7	31	31.6	44	43.6
6	40.1	19	41.9	32	32.8	45	43.5
7	41.9	20	41.5	33	34.4	46	47.6
8	39.0	21	38.6	34	32.7	47	48.3
9	37.4	22	42.6	35	31.5	48	46.6
10	36.3	23	42.5	36	32.4	49	49.9
11	36.5	24	44.7	37	35.3	50	53.3
12	35.6	25	42.8	38	31.7	51	60.2
13	36.7	26	39.1	39	30.6	52	51.2

Table-4. Maintenance schedule (HDE).

Week	$P^S(t)$	Units on maintenance
1	2292	-----
2	2272	-----
3	2142	-----
4	2292	-----
5	2302	-----
6	2223	-----
7	2323	-----
8	1793	10
9	1833	10
10	1790	10
11	1686	10
12	1560	10,13,19
13	1400	10,13,14,18,19
14	1460	10,13,14,18,19
15	1542	2,10,11,14,18
16	1712	2,10,11,14,18
17	1722	2,10,11,14,18
18	1530	10,11,14
19	1681	10
20	2311	-----
21	2181	-----
22	2281	-----
23	2220	-----
24	2040	-----
25	1870	-----
26	1975	7
27	2154	7
28	1964	7
29	1849	-----
30	1859	4,8
31	1229	4,8,9
32	838	4,5,8,9,12,15
33	1008	5,8,9,12,15
34	1078	5,9,12,15
35	568	5,9,12,15,21
36	1257	1,5,12,15,17,21
37	1047	1,5,12,16,17,21
38	1047	1,3,6,12,16,17,22
39	817	1,3,6,12,16,17,20,22
40	934	1,3,6,16,17,20,22
41	1444	1,6,16,20,22
42	1744	16,22
43	2214	-----
44	2430	-----

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45	2280	-----
46	2180	-----
47	2160	-----
48	2080	-----
49	1987	-----
50	1877	-----
51	1777	-----
52	2207	-----

Table-5. Maintenance schedule (HPSO).

Week	$P^S(t)$	Units on maintenance
1	2292	-----
2	2272	-----
3	2142	-----
4	2292	-----
5	2302	-----
6	2223	-----
7	2223	1
8	1693	1,10
9	1733	1,10
10	1590	1,10,13
11	1486	1,10,13
12	1680	1,10,13
13	1920	10
14	1980	10
15	1933	10
16	2103	10
17	2113	10
18	1721	10
19	1681	10
20	2311	-----
21	2181	-----

22	2281	-----
23	2220	-----
24	2040	-----
25	1870	-----
26	2070	-----
27	2249	-----
28	2059	-----
29	1849	-----
30	1859	8,14
31	1559	8,12,14,15
32	1478	4,8,12,14,15
33	1357	2,4,8,11,12,14,15
34	1007	2,4,11,12,14,15,17,18,19
35	287	2,5,11,12,14,15,17,18,19,20,21
36	946	5,11,12,17,18,19,20,21
37	947	3,5,12,17,18,20,21
38	637	3,5,9,12,16,17,18
39	687	3,5,9,16,22
40	804	5,9,16,22
41	1019	6,7,9,16,22
42	909	6,7,9,16,22
43	1569	6,7,16,22
44	2340	6
45	2280	-----
46	2180	-----
47	2160	-----
48	2080	-----
49	1987	-----
50	1877	-----
51	1777	-----
52	2207	-----

The comparison of results obtained through HDE and HPSO in terms of cost is shown in Table-6.

Table-6. Comparison of results in terms of cost.

	Revenue due to bidding $	Production cost of p^S $	Production cost to meet p^C $	Profit $
HDE	626407924.8	168080613.74	148731823.32	884721819.14
HPSO	626705973.6	169118332.85	148766095.77	883947876.37

From the results of Table-6, it can be concluded that maximizing the profit of GenCo highly depends on minimization of production cost. The use of lambda iteration method yields in minimum production cost with economically dispatching the available generation to meet out the bilateral contract. The production cost found using proposed HDE is less when compared to that obtained through HPSO in turn HDE gives better maintenance schedule in terms of profit maximization. This shows the applicability of the proposed HDE algorithm in finding optimal maintenance schedule for the GMS problem in deregulated electricity environment.

5. CONCLUSIONS

In this paper, generator maintenance scheduling problem in a market environment is considered with an objective of maximizing the profit of generation companies is considered. A conceptually simple yet efficient methodology to solve generator maintenance scheduling problem in electricity market environment is proposed. In the proposed approach, the lambda iteration method is included into the DE procedure to find the optimal maintenance schedule. The efficiency of the proposed HDE is validated by considering 22 units system. To compare the results of the HDE, HPSO is considered. The simulation results shows that DE effectively utilizes the results of lambda iteration method and finds better maintenance schedule interms of maximizing the profit of GenCo's present in the market when compared to that of PSO.

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Nomenclature

H - Number of hours in a sub period (week) = 168
t - Time period index (week)
T - Total number of sub periods (weeks) in the planning horizon
i - Power generating unit index
N - Total number of power generating units
ω - Penalty factor
nc - Constraint index
NCG - Number of committed generating units
NOC - Number of constraints
CV - Constraints violation
NI - Number of integers equal to number of units in the system
a, b, c - Fuel cost coefficients

v_i - Variable operation and maintenance cost of unit i, \$/MWh
MC_i - Fixed maintenance cost of unit i, \$/MW
R_i — Rating of unit i, MW
$E_R(t)$ - Expected revenue of GenCo
$E_E(t)$ - Expenses made by the GenCo
U_{it} - State variable equal to 1 if the unit i in sub period t is under maintenance and 0 otherwise
P_{it} - Power output from unit i in sub period t, MW
$C^C(t)$ - Price to be paid to GenCo due to bilateral contract in sub period t, \$/MWh
$C^S(t)$ - Market clearing price for energy in sub period t, \$/MWh
$p^C(t)$ - Power to meet out the load demand due to bilateral contract in sub period t, MW
$p^S(t)$ - Power for bid in sub period t, MW
E_i - Earliest period in which maintenance of unit i can start
L_i - Latest period in which maintenance of unit i can start
S_i - Starting period of maintenance of unit $i \in [L_i, E_i]$
M_i - Maintenance duration of unit i
P_i^{min} - Minimum limit generating unit i
P_i^{max} - Maximum limit generating unit i

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