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Optimal maintenance scheduling of thermal power unıts in a restructured nigerian power system

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The optimal preventive maintenance schedules of generating units for the purpose of maximizing economic benefits and improving reliable operation of 44 functional thermal generating units of Nigerian power system, subject to satisfying system load demand, allowable maintenance window and crew constraints over 52 weeks maintenance and operational period is presented. It uses HPSO algorithm to find the optimum schedule. The purpose of the algorithm is to orderly encourage moving maintenance outages from periods of low reliability to periods of high reliability, so that a reasonable reliability level is attained throughout the the year. The maintenance outages for the generating units were scheduled to minimize the sum of the squares of reserves and satisfy 2,943.8 MW system peak load with 6.5% spinning reserve of 2,403.8 MW, available manpower for maintenance per week of 22 and maximum generation of 3,028.8 MW. The reliability criterion of the power system was achieved by maximizing the minimum net reserves along with satisfaction of maintenance window, crew and load constraints. The population size of 30 particles and 2500 iterations were chosen. These were chosen as a trade-off between computational time and complexity. It was shown that the HPSO algorithm is not as time efficient as the standard PSO but it provides more consistent and reliable results. In the periods of low maintenance activities, with the PSO algorithm, the maximum generation is 2,753.8 MW while the HPSO produce 2,943.8 MW. It is glaring from the comparison that the HPSO algorithm shows better performance and produce optimal maintenance scheduling framework for the Nigerian power system that will achieve better utilization of available energy with improved reliability and reduction in energy cost.

Key words: Generator maintenance, deregulated market, optimization.

INTRODUCTION

Adequate power supply plays very important role in the socio-economic and technological development of every nation. The electricity demand in Nigeria far outstrips its supply which is epileptic (Sambo, 2007; Efenedo and Akalagboro, 2012). By the year 2020, the Government's policy objective is that Nigeria should posses a generating capacity of at least 40,000 MW (FGN, 2005). Given Nigeria's population growth rate, 40,000 MW would still be less than 25% of South Africa's generating capacity per capita; but it would be sufficient to allow for a significant growth in manufacturing industry and ultimately Gross Domestic Product (GDP) per capita (Sambo, 2007). However, the investiments required to finance an increase in total power station capacity from 12,000 to 40,000 MW is huge. On a conservative estimate, this growth in capacity would require 36 billion US dollar (Presidential Action Committee on Power, 2010) which the Government can ill-afford. Hence, the

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need to incentivize the private sector to partner with government in this endeavour. The unbundling of the Power Holding Company of Nigeria (PHCN) has been an important step. Restructured and liberalized power sectors promote increased competition through unbundling of generation, transmission and privatization of distribution or retailing function (Billinton and Abdulwahab, 2003; Conejo et al., 2005; Jin-ho et al., 2005). The purpose was to break the monopoly of the traditional electric power industry and encourage a competitive power industry. This can bring about reduced generation cost and retail price.

In this context, both generation company (GENCO) and distribution company (DISCO) or retailer may have open access to the transmission grid for negotiated power transfer. The coordination between the GENCO, transmission company (TRANSCO) and DISCO for technical operation of these sub-entities and the commercial arbitration among them will be carried out by Nigeria Electricity Regulatory Commission (NERC). In such environment, GENCO submit their maintenance plans and constraints to the NERC including maintenance time windows, available maintenance resources and generation price offers. The TRANSCO also submit their respective maintenance plans and constraints to NERC. The NERC will be responsible for the optimal coordination of maintenance for generation units and transmission lines to ensure security of power systems and maximize reliability (Presidential Action Committee on Power, 2010). The primary goal of generator maintenance scheduling (GMS) is the effective allocation of generating units for maintenance while ensuring high system reliability, reducing production cost, prolonging generator lifetime subject to some unit and system constraints. GMS problem is a hard combinational optimization problem and is classified as a deterministic cost-minization problem (Cagnina et al., 2011).

Several optimization methods have been applied to solve the problem, which could be grouped into three categories namely, heuristic methods, mathematical programming methods and artificial intelligent methods. Heuristic methods provides the most primitive solution based on trial and error principles. Mathematical programming methods includes mixed integer programming (MIP), mixed integer linear programming (MILP), decomposition, branch and bound and dynamic programming (Kitayayama and Yasuda, 2006). The main problem with the exact mathematical methods is that the number of combinations of states that must be searched increases exponentially with the size of the problem and becomes computationally prohibitive (Talukder, 2011). Furthermore, these techniques are generally unsuitable for the nonlinear objective functions and constraints in their standard form and several assumptions are required to make the problem solvable using reasonable computational resources (Del Valle et al., 2008). Artificial intelligent methods include neural networks, artificial immune systems, genetic algorithm, fuzzy optimization, ant colony optimization and particle swarm optimization (PSO) algorithm. The PSO is a novel population-based stochastic search algorithm and an alternative solution to the complex nonlinear optimization problem (Yasuda et al., 2010).

The PSO algorithm basically learned from animal's activity or behaviour to solve optimization problems. In PSO, the population is called a swarm and each member of the population is called a particle. Each particle has three main characteristics: an adaptable velocity with which it moves in the search space, a memory where it stores the best position it ever visited in the search space (that is, the position with lowest function value), and the social sharing of information, that is, the knowledge of the best position ever visited by all particles in its neighbourhood. Starting with a randomly intialized population and moving in randomly chosen directions, each particle goes through the search space and remembers the best previous positions of itself and its neighbours. Particles of a swarm communicate good positions to each other as well as dynamically adjust their own position and velocity derived from the best position of all particles. The next step begins when all particles have been moved. Finally, all particles tend to fly towards better and better positions over the searching process until the swarm move close to an optimum of the fitness function $f: R^n \rightarrow R.$

Standard PSO performs well in the early iterations, but it has problems approaching a near-optimal solution (Yasuda et al., 2010). If a particle's current position accords with the global best and its inertia weight and previous velocity are different from zero, the particle will only fall into a specific position. If their previous velocities are very close to zero, then all the particles will stop moving around near-optimal solution, which may lead to premature convergence of the algorithm. In this situation, all the particles have converged to the best position discovered so far which cannot be the optimal solution. This is known as stagnation (Del Valle et al., 2008). Using hybrid particle swarm optimization (HPSO) by adding the mutation operator used in genetic algorithm (GA), the aforementioned problems can be solved (Yare et al., 2008; Yare and Venayagamoorthy, 2010). The aim of mutation is to introduce new genetic material into existing individual; that is, to add diversity to the genetic characteristics of the population.

The objective of this study is to schedule generator maintenance that will reduce the operational cost of generator which includes, the maintenance cost while satisfying all necessary constraints involved using PSO.

MATERIALS AND METHODS

The test problem is to schedule the maintenance of 44 functional generating units (Table 1) over planning period of 52 weeks. The

Table 1. Nigerian thermal grid system.

S/N	Plant	Plant type	Location (state)	Installed capacity (MW)	Available capacity (MW)	Installed units	Units available
1.	Egbin	Thermal	Lagos	1320	880	6	4
2.	Egbin AEs	Thermal	Lagos	270	270	9	9
3.	Sapele	Thermal	Delta	1020	102	10	1
4.	Okapi	Thermal	Cross River	480	320	3	2
5.	Afam	Thermal	Rivers	702	105.3	20	3
6.	Delta	Thermal	Delta	840	560	18	12
7.	Omoku	Thermal	Rivers	150	100	6	4
8.	Ajaokuta	Thermal	Kogi	110	110	2	2
9.	Geregu	Thermal	Kogi	414	414	3	3
10.	Omotosho	Thermal	Ondo	335	83.75	8	2
11.	Olorunsogo/ Papalanto	Thermal	Ogun	335	83.75	8	2
Total				5,976	3,028.8	93	44

Source: Sambo (2007).

Nigerian thermal grid system comprising of 44 generating units spread across 11 generation stations is as depicted in Table 1. Table 2 gives the generating capacities, maintenance allowed periods, maintenance duration, available manpower, and the crew needed for each generator. The GMS problem has a number of units and system constraints to be satisfied. The constraints include: the maintenance window, crew, demand and reserve constraints. The objective function to be minimized is given by:

$$Min\left[\sum_{t=1}^{T}\left(\sum_{i=1}^{I} g_{i,t} - \sum_{i\in I_t}\sum_{r\in s_{i,t}} x_{i,t} g_{i,t} - D_t\right)^2\right] \qquad (1)$$

Subject to: maintenance window constraint:

$$\sum_{t\in T_i} x_{i,t} = 1, \text{ for all } i = 1,2,....,I \qquad (2)$$

Crew constraint:

$$\sum_{i\in I_t}\sum_{k\in s_{i,t}} x_{i,r} M_{i,r} \le A_t, \text{ for all } t = 1,2,.....,T \qquad (3)$$

Load constraint:

$$\sum_{i=1}^{I} g_{i,t} - \sum_{i\in I_t}\sum_{k\in s_{i,t}} x_{i,r} g_{i,r} \ge D_t, \text{ for all } t = 1,2,.....,T \qquad (4)$$

Where t = index of period, $t = 1,2,.....,T$; T = total number of planned horizons; i = index of the generators number, $i = 1,2,....,I$; I = total number of generators; $g_{i,t}$ = generating capacity for each generator (MW); I_t = the set of indices of generators in maintenance at time t; r = index of start periods of maintenance for each generator, $r = t,....,s$; $s_{i,t}$ = set of start period r such that if the maintenance generator i starts at period r that generator will be in maintenance at period t, $s_{i,r} = [r \in T_i : t - N_i \le r \le t]$; T_i = set of periods when maintenance of generator i may start, $T_i = [t \in T : e_i \le t \le l_i - N_i + 1]$; e_i = earliest period for generator i to start maintenance; l_i = latest period for generator i to start maintenance; $x_{i,r}$ = variable for the start of maintenance for each generator i at time r; if generator i is on maintenance $x_{i,r} = 1$, otherwise $x_{i,r} = 0$; D_t = demand per period; $M_{i,r}$ = number of crew used for maintenance of generator i at time r; A_t = available number of crew at every time t; N_i = duration of maintenance on each generator i.

The augmented objective function $F(x)$ formulated for this study is a weighted sum of the objective function and the penalty functions for violations of the constraints; hence:

$$F(x) = \omega_o SSR + \omega_m TMV + \omega_l TLV \qquad (5)$$

Where SSR is the sum of squares of reserves as in Equation 1, TMV is the total manpower violation as in Equation 3 and TLV is the total load violation as in Equation 4.

The weighting coefficients ω_o, ω_m and ω_l were chosen so that the violation of the relatively hard load constraint (Equation 4) gives a greater penelty value than for soft crew constraint (Equation 3). As in Khan et al. (2010), ω_o, ω_m and ω_l were chosen as 10^{-5},

Table 2. Maintenance data of 44 functional units.

S/N	Power station	Capacity (MW)	Earliest period	Latest period	Outage (weeks)	Available manpower	Required manpower
	Egbin						
1	ST1	190	7	23	5	22	6+5+5+4+2
2	ST2	190	29	45	5	22	6+5+5+4+2
3	ST3	190	36	52	5	22	6+5+5+4+2
4	ST4	190	24	50	5	22	6+5+5+4+2
5	ST5	190	39	52	5	22	6+5+5+4+2
6	ST6	190	1	20	5	22	6+5+5+4+2
7	GT1	30	42	52	2	7	4+3
8	GT2	30	8	21	2	7	4+3
9	GT3	30	1	20	2	7	4+3
10	GT4	30	1	20	2	7	4+3
11	GT5	30	13	36	2	7	4+3
12	GT6	30	16	39	2	7	4+3
13	GT7	30	16	41	2	7	4+3
	Sapele						
14	ST1	120	20	45	4	12	4+3+3+2
15	ST2	120	1	14	4	12	4+3+3+2
16	ST3	120	1	20	4	12	4+3+3+2
17	ST4	120	1	15	4	12	4+3+3+2
	Okapi						
18.	GT1	160	1	9	5	20	6+5+4+3+2
19.	GT2	160	1	16	5	20	6+5+4+3+2
	Afam						
20	GT18	138	30	45	4	20	7+6+4+3
21	GT19	138	14	36	4	20	7+6+4+3
22	GT20	138	7	27	4	20	7+6+4+3
	Delta						
23	GT3	19.6	11	26	2	7	4+3
24	GT4	19.6	1	19	2	7	4+3
25	GT6	19.6	35	51	2	7	4+3
26	GT7	19.6	35	51	2	7	4+3
27	GT8	19.6	1	23	2	7	4+3
28	GT15	85	33	52	4	14	4+4+3+3
29	GT16	85	40	52	4	14	4+4+3+3
30	GT17	85	30	52	4	14	4+4+3+3
31	GT18	85	29	52	4	14	4+4+3+3
	Omuku						
32	GT1	25	40	52	2	7	4+3
33	GT3	25	26	52	2	7	4+3
34	GT5	25	20	40	2	7	4+3
35	GT6	25	11	31	2	7	4+3
	Ajaokuta						
36	GT1	50	2	22	4	15	5+4+3+3
37	GT2	50	31	51	4	15	5+4+3+3

Table 2. Contd.

				Geregu			
38	GT1	138	2	20	4	20	7+6+4+3
39	GT2	138	3	15	4	20	7+6+4+3
40	GT3	138	2	17	4	20	7+6+4+3
				Omotosho			
41	GT1	40	5	25	3	8	3+3+2
42	GT2	40	40	52	3	8	3+3+2
				Olorunsogo			
43	GT1	40	37	52	3	8	3+3+2
44	GT2	40	42	52	3	8	3+3+2

4 and 2 respectively.

Particle swarm optimization (PSO)

The PSO algorithm is an iterative optimization process and repeated iterations will continue until a stopping condition is satisfied. Within one iteration, a particle determines the personal best position, the local or global best position, adjusts the velocity, and a number of function evaluations are performed. If N is the total number of particles in the swarm, then N function evaluations are performed at each iteration. The algorithm is terminated when there is no significant improvement over a number of iterations. That is, if the average change of the particles' positions are very small or the average velocity of the particles is approximately zero over a number of iterations. It can also be terminated when the maximum number of iterations has been attained. The updating rule of the positions and velocities are given as:

$$x_{jd}(k+1) = x_{jd}(k) + v_{jd}(k+1) \tag{6}$$

Where:

$$v_{jd}(k+1) = \omega v_{jd}(k) + c_1 rand(\ )\left(P_{jd}(k) - x_{jd}(k)\right) + c_2 rand(\ )\left(P_{gd}(k) - x_{jd}(k)\right) \tag{7}$$

and $v_{jd}(k)$ is the velocity vector of particle j in dimension d at iteration k; $x_{jd}(k)$ is the position vector of particle j in dimension d at iteration k; $P_{jd}(k)$ is the personal best position of particle j in dimension d found from initialization through iteration k. ω is the inertia weight used to weigh the last velocity; c_1 is a variable used to weigh the particle's knowledge and c_2 is a variable used to weigh the swarm's knowledge. $rand(\ )$ are uniformly distributed random numbers between zero and one. The best position of each particle is updated at each iteration by setting $P_{jd}(k+1) = x_{jd}(k+1)$, if $f(x_{jd}) < f(P_{jd})$, otherwise it remains unchanged.

An update of the index g is also required at each iteration. The recommended relationship between c_1 and c_2 (Talukder, 2011) is:

$$c_1 + c_2 \leq 4 \tag{8}$$

The parameters c_1 and c_2 are usually set fixed and equal, so that the particle is equally influenced by its best position P_{jd}, as well as the best position of its neighbourhood P_{gd}. ω often decrease linearly from 0.9 to 0.4 during each iteration (Yasuda et al., 2010). Its values are set according to:

$$\omega(k) = \omega_{\max} - \frac{k(\omega_{\max} - \omega_{\min})}{k_{\max}} \tag{9}$$

Where $\omega_{\max}$ and $\omega_{\min}$ are the initial and final values of the inertia weight respectively.

Herein, the mutation operator is introducted into the PSO algorithm. The main goal is to increase the diversity of the population by preventing the particles from moving too close to each other thus converging prematurely to local optima (Song et al., 2012). This in turn improves the PSO's search performance. The mutation operator is defined as follows:

$$\alpha_m(k) = \alpha_m^{\max} - \left(\frac{\alpha_m^{\max} - \alpha_m^{\min}}{k_{\max}}\right) \times k \tag{10}$$

Table 3. Parameters used in this study.

Parameter	c_1	c_2	$\omega_{\max}$	$\omega_{\min}$	$\alpha_m^{\max}$	$\alpha_m^{\min}$	N	$k_{\max}$
Value	2	2	0.9	0.4	0.01	0.001	30	2500

Where $k_{\max}$ is the maximum iteration number and k is th current iteration number (Table 3).

GMS procedure using standard PSO are as follows:

Step 1: the initial parameters, the number of particles j, where $j = 1,2,....,N$ the maximum number of iterations $k_{\max}$ and the iteration counter $k = 1$ were set. The position x_j and volcity v_j at random for every particle were set;

Step 2: set iteration counter $k = 1$

Step 3: evaluate the augmented objective function of the GMS problem (Equation 5) for every particle;

Step 4: determined P_j and P_g. Here P_j is the value of x particle i that gives the minimum evaluated GMS result from initial iteration to the present iteration. P_g is the value of x that gives the minimum evaluated result in the whole swarm from initial to present iteration;

Step 5: increase the iteration counter $k = k + 1$;

Step 6: compared the iteration counter with the preset maximum number $k_{\max}$. When $k < k_{\max}$, the algorithm returns to step 3. Otherwise P_g is output as the optimal solution and the search terminated.

The procedure for the hybrid PSO (HPSO) method is as follows:

Step 1: initialize the volocity, position, local best position and global best position;

Step 2: set iteration counter $k = 1$;

Step 3: evaluate the objective function;

Step 4: update $\omega(k)$ and j^{th} particle velocity using Equations 9 and 7 respectively;

Step 5: update the local best position and global best position;

Step 6: calculate the mutation operator using Equation 10;

Step 7: if rand ( ) < $\alpha_m(k)$, then 7(a): if $k < k_{\max}$, then new global best position = $x_{j\min} + rand(\ ) \times (x_{j\max} - x_{j\min})$, where $x_{j\min}$ represents the lower bound and $x_{j\max}$ represents the upper bound of the parameter if objective value $_{\text{at global best position}}$ > objective value $_{\text{at new global best position}}$, then $P_g = P_{gnew}$ and the search terminated; otherwise $P_j = P_{jnew}$

Step 8: the iteration number k was increased to $k = k + 1$ and algorithm returns to step 3.

RESULTS AND DISCUSSION

The PSO algorithm was simulated with different number of population sizes and iterations over the 52 weeks period. The algorithm was implemented using Matlab on a Intel (R) core (TM)^2 Duo 2.10 GHZ personal computer. Matlab does not have any PSO programming function and as such the mixed integer PSO programme was written using the M-file. An M-file was created and edited in the Editor/Debugger Window of the Matlab programme (Zimmerman and Gan, 2005). The effect of population size on time of computational time is shown in Figure 1. The population size of 30 particles has a lower computational time than that of 40 particles population but generates the same results. It is noteworthy, that the number of iteration was used as a stopping criterion for the optimization and as such the smaller the iteration value used to obtain the optimal results the better. In view of the forthgoing, the population size of 30 particles and 2500 iterations were chosen for this study. The chosen population and iteration ensure that the search space was fully utilized without putting strain on the computation time and complexity. The variation of objective function with the number of iteration is depicted in Figure 2. The population sizes of 30 and 40 particles gave relatively lower values under each iteration. But population size of 30 particles has egde over that of 40 particles because it has a lower computation time.

Choosing the population size determines the diversity and search space for each particle. More particles in the swarm provide a good uniform initialization scheme but at the expense of the computational complexity (Yasuda et al., 2010), as a result the search degrades to a parallel random search. The convergence iteration is a little late in the HPSO algorithm because it takes more time for particles to mutate around feasible areas (Song et al., 2012). In other words, a particle has a higher possibility than PSO algorithm to find better optimized solution. The HPSO algorithm has a better performance related to maintenance scheduling problem having higher accessibility to search the optimal solution. As maintenance scheduling is an annual planning problem in a long horizon over one year, emphasis has to be not on convergence time but a set of optimal solution. Hence, the HPSO is not time efficient as the standard PSO but it provides more consistent and reliable results. Figure 3 shows the reserve margin. The reserve margin is non negative because the load constraint (Equation 4) is satisfied. The addition of the generation limits (Equation 4) ensures that the load constraint is never violated and thus reduces the SSR. NERC may employ penalty factor to patronize unit not to have maintenance in peak load. By this strategy, NERC will have more effect on unit

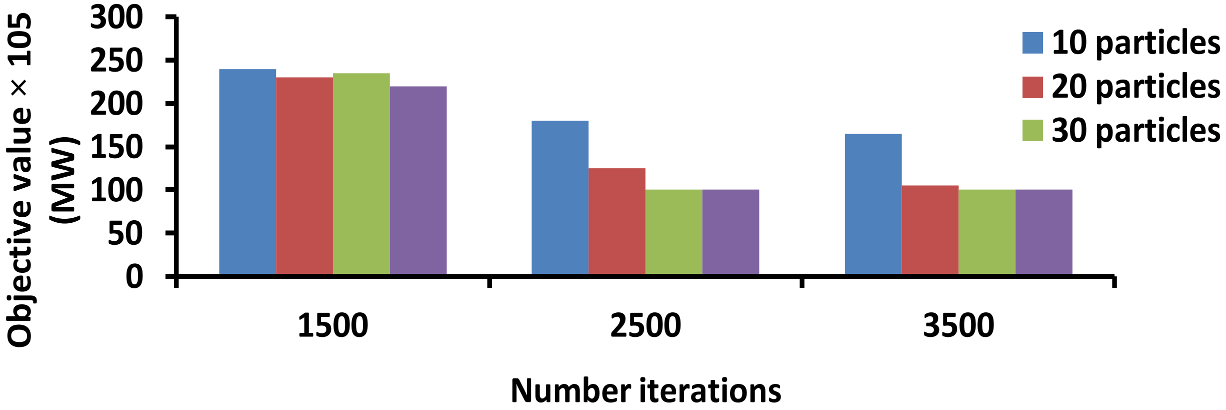

Figure 1. Variation of objective function with number of iteration.

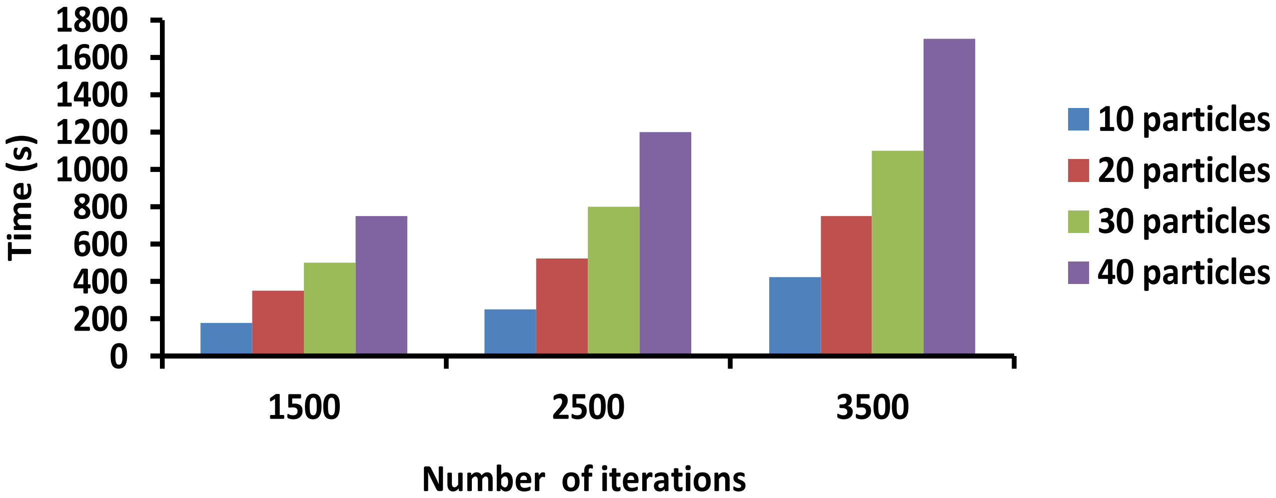

Figure 2. Comparison of population size with computational time.

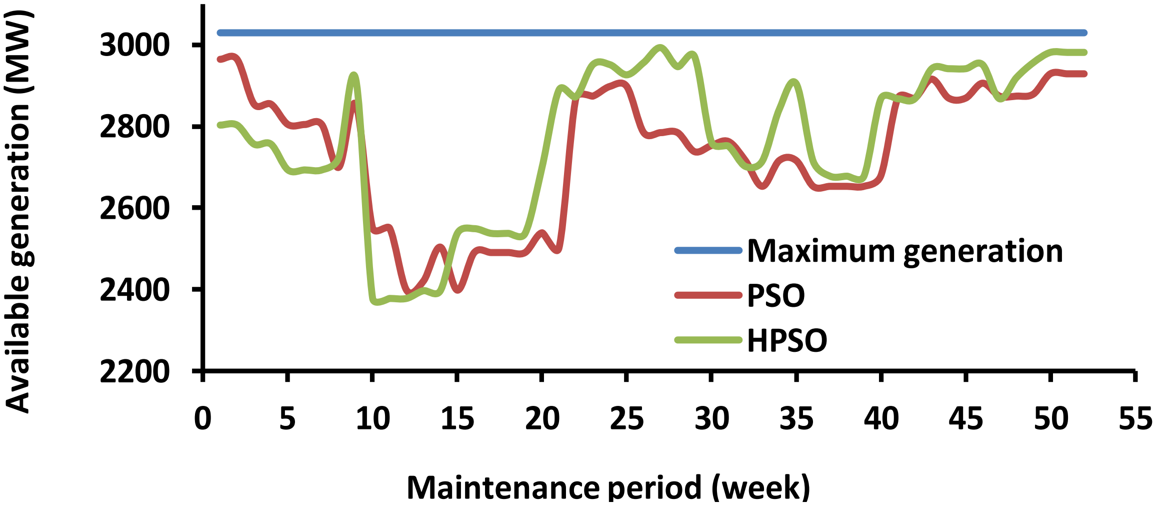

Figure 3. Available generation versus maintenance period.

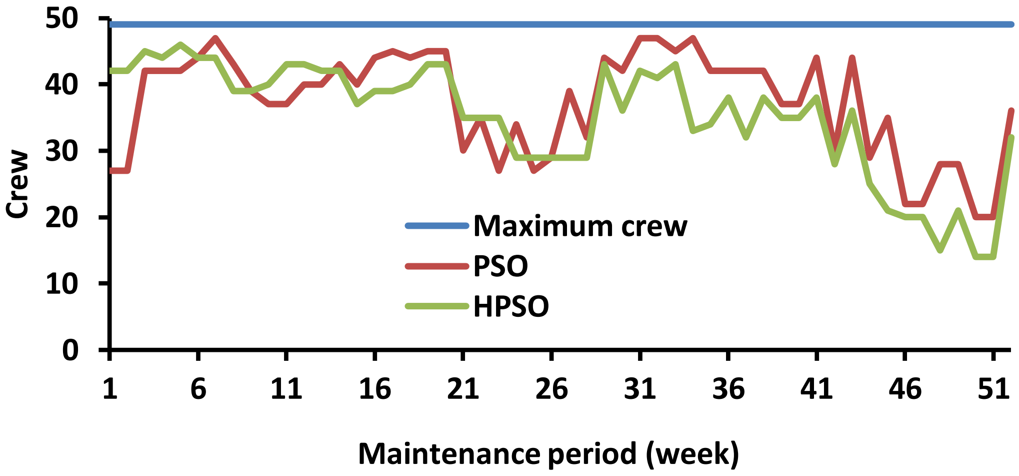

Figure 4. Crew requirement against maintenance period.

Table 4. Generator maintenance schedule.

Week No.	Generating unit scheduled for maintenance		Week No.	Generating unit scheduled for maintenance	
	PSO	**HPSO**		**PSO**	**HPSO**
1	10, 18	6, 15, 18	27	14, 21, 33	4, 33
2	10, 18	6, 15, 18	28	14, 21	4, 35
3	6, 18, 36	6, 15, 18, 24	29	4, 14, 21	2, 31, 35
4	6, 18, 36	6, 15, 18, 24	30	4, 21	2, 31
5	6, 16, 18	6, 16, 18, 36	31	4, 20, 30	2, 31, 37
6	6, 16, 17	9, 16, 17, 36	32	4, 20, 30	2, 31, 37
7	6, 16, 17	9, 16, 17, 36	33	4, 20, 30	2, 20, 37
8.	8, 16, 17, 40	16, 17, 36	34	2, 20, 30	13, 20, 37
9	8, 17, 40	10, 17, 22	35	2, 28, 37	13, 20, 25
10	11, 19, 40	10, 22, 39	36	2, 28, 37	3, 20, 25
11	11, 19, 40	1, 22, 39	37	2, 28, 37	3, 26, 43
12	15, 19, 39	1,19, 22, 39	38	2, 28, 37	3, 26, 43
13	15, 19, 39	1, 19, 39	39	5, 26, 43	3, 28, 43
14	9, 19, 23, 39	1,19, 40	40	5, 26, 43	3, 28, 42
15	9, 23, 39	1, 19, 40	41	5, 29, 43	5, 28, 42
16	1, 24, 38	8, 19, 40	42	5, 44	5, 28, 42
17	1, 24, 38	8, 21, 40	43	5, 29, 44	5, 14, 30
18	1, 27, 38	11, 21, 38	44	7, 29, 44	5, 14, 30
19	1, 27, 38	11, 21, 38	45	7, 29	5, 14, 30
20	1, 34, 41	12, 21, 38	46	25, 32, 42	7, 14, 44
21	12, 34, 41	12, 38, 41	47	25, 32, 42	7, 30, 44
22	12, 22, 41	27, 34, 41	48	3, 31, 42	32, 44
23	13, 22	27, 34, 41	49	3, 31	29, 32
24	13, 22, 35	4, 23	50	3, 31	29
25	22, 35	4, 23	51	3, 31	29
26	14, 33	4, 33	52	3, 31	29

maintenance schedules. Figure 4 illustrates the effectiveness of the generator limits constraint. The reliability criterion of the power system was achieved by maximizing the minimum net reserves along with satisfaction of maintenance window, crew and load constraints.

The complete maintenance schedules obtained by PSO and HPSO are presented in Table 4. It presents the corresponding crew availability needed to carry out the scheduled shutdown maintenance of the generating units. The proposed algorithm attains the maximum generation in weeks 49, 50, 51 and 52. However, the PSO algorithm has also low maintenance activities in those weeks resulting in high available generation. With the PSO algorithm, the maximum generation is 2,753.8 MW in those weeks whilst HPSO algorithm produce 2,911.8 MW in week 49 and 2,943.8 MW in others. It is evident from the comparison that the HPSO algorithm shows great potential for effective energy management, short and long term generation scheduling, system planning and operation.

Conclusion

Annual maintenance scheduling of generating units of GENCOs in deregulated power system was formulated and validated. It uses HPSO algorithm to find the optimum schedule. GENCO's objective is to sell electricity as much as possible and the goal of NERC is to maximize the reserve of the system at every time interval, provided the energy purchase cost is smaller than a pre-determined amount when the units of GENCOs are out for maintenance. In fact, NERC may employ penalty factor to patronize unit not to have maintenance in peak loads. By this strategy, NERC will have more effect on maintenance schedules. The purpose of the algorithm is to orderly encourage moving maintenance outages from periods of low reliability to periods of high reliability, so that a reasonable reliability level is attianed throughout the year. The algorithm was applied to GMS problem with 44 generating units. The maintenance outages for the generating units were scheduled to minimize the sum of the squares of reserves and satisfy 2,943.8 MW system peak load with 6.5% spinning reserve of 2,403.8 MW, available manpower for maintenance per week of 22 and maximum generation of 3,028.8 MW. The reliability criterion of the power system was achieved by maximizing the minimum net reserves along with satisfaction of maintenance window, crew and load constraints. The population size of 30 particles and 2500 iterations were chosen. The chosen population size and iteration ensure that the search space was utilized to the fullest without putting strain on computation time and complexity. It was shown that the proposed algorithm satisfied the load and crew requirements. It was evident that the HPSO algorithm has a better performance related to maintenance scheduling problem having higher accessibility to search the optimal solution. Although, the HPSO is not as time efficient as the standard PSO, it provides more consistent and reliable results.

In the periods of low maintenance activities, with the PSO algorithm, the maximum generation is 2,753.8 MW while the HPSO produce 2,943.8 MW. It is glaring from the comparison that the HPSO algorithm shows better performance and produce optimal maintenance scheduling framework for the Nigerian power system that will achieve better utilization of available energy with improved reliability and reduction in energy cost. The proposed algorithm can be modified to accommodate the maintenance unit requirements of emerging independent power producers and future generation additions.

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