

# Generator Maintenance Scheduling in Power System using Bacterial Foraging Algorithm

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**Abstract**—This paper presents a novel optimization approach to constrained generator maintenance scheduling (GMS) problem using bacterial foraging algorithm (BFA). The approach utilizes the natural selection of global optimum bacterium having successful foraging strategies in the fitness function. The bacterial foraging algorithm appears to be a robust and reliable optimization algorithm for the solution of the GMS problems. The performance and effectiveness of the bacterial foraging algorithm in solving the GMS problem is illustrated on 49-unit Nigerian hydrothermal power system. The simulation results are compared with other optimization methods published in the literature. The comparison affirmed the robustness, fast convergence and ability of proposed methodology over other existing techniques.

**Keywords** – Generator maintenance scheduling, bacterial foraging algorithm, maintenance window, load and spinning reserve and manpower.

## I. INTRODUCTION

The economic operation of an electric utility system requires the simultaneous solution of all aspects of the operation scheduling problem in the face of system complexity, different time-scales involved, uncertainties of different order, and dimensionality problems. Utilities spend billions of dollars per year for maintenance. The reliability of system operation and production cost in an electric power system is affected by the maintenance outage of generating units. Optimized maintenance schedules could save millions of dollars and potentially defer some capital expenditure for new plants in times of tightening reserve margins, and allow critical maintenance work to be performed which might not otherwise be done. Therefore, maintenance scheduling in the electric utility system is a significant part of the overall operations scheduling problem. Power system components are made to remain in operating conditions by regular preventive maintenance. The task of generator maintenance is often performed manually by human experts who generate the maintenance schedule based on their experience and knowledge of the system, and in such cases there is no guarantee that the optimal or near optimal solution is found.

Various methods exist in the literature that addresses GMS as an optimization problem under different conditions. Different optimization techniques are classified based on the type of the search space and the objective function. The simplest method is linear programming (LP) which concerns the case where the objective function is linear [1, 2, 6]. For a special case, where some or all variables are constrained to

take on integer values, the technique is referred to as integer programming [1]. Even though deterministic optimization problems are formulated with known parameters, real world problems almost invariably include some unknown parameters. This necessitates the introduction of dynamic programming (DP). Although the DP technique has been mathematically proven to find an optimal solution, it suffers from dimensionality problem. The complexity is even further increased when moving from finite horizon to infinite horizon problems, while also considering the stochastic effects, model imperfections and the presence of the external disturbances [4, 5]. Genetic algorithm (GA) can provide solution to GMS and the above optimization problems [7- 9]. While GA can rapidly locate good solutions, it may have a tendency to converge towards local optima rather than the global optimum of the problem. Recently, new approximation and heuristic approaches have been used to solve the MS problem.

These methods include the application of modern optimization techniques such as simulated annealing, particle swarm, expert systems, fuzzy logic sets, evolutionary programming, and genetic algorithms [10-17]. The developed bacterial foraging algorithm is used to determine the active power to be generated by the generating units in power generation systems, which are subjected to a number of inequality and equality constraints in order to achieve minimum generation cost while satisfying the load demand simultaneously. This paper presents a bacterial foraging algorithm to solve optimal generator maintenance scheduling for economical and reliable operation of a power system while satisfying the system load demand and manpower constraints.

The primary contributions of this paper are:

- Solving the challenging GMS problem for 49-unit Nigerian hydrothermal power system using bacterial foraging algorithm.
- Improving the quality of the maintenance schedules generated during GMS in terms of reliability by including the crew and sum of reserve margins.
- Comparison of simulation results with other optimization methods published recently

## II. PROBLEM FORMULATION

Generator maintenance schedule is a preventive outage schedule for generating units in a power system within a specified time horizon. The GMS over this planning period is important for resource management and future planning. Generally, there are two main categories of objective functions in GMS, namely, based on reliability and economic cost [3]. This study applies the reliability criteria of leaving reserve generation for the entire period of study. This can be realized by minimizing the sum of squares of the reserve over the entire operational planning period. The problem has a series of unit and system constraints to be satisfied. The constraints include the following:

- *Maintenance window and sequence constraints*-defines the starting of maintenance at the beginning of an interval and finishes at the end of the same interval. The maintenance cannot be aborted or finished earlier than scheduled.
- *Crew and resource constraints* - for each period, number of people to perform maintenance schedule cannot exceed the available crew. It defines manpower availability and the limits on the resources needed for maintenance activity at each time period.
- *Load and reliability constraints* - total capacity of the units running at any interval should not be less than predicted load at that interval. The load demand on the power system is considered during the scheduling period.
- *Spinning reserve* - in order to maintain the electric power supply normally, there must be a spinning reserve to meet unexpected load demand.

$T_i \subset T$  is the set of periods when maintenance of unit  $i$  may start,

$T_i = \{t \in T: e_i \leq t \leq l_i - d_i + 1\}$  for each  $i$ .

We define,

$$X_{it} = \begin{cases} 1 & \text{if unit } i \text{ starts maintenance} \\ & \text{in period } t \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

to be the maintenance start indicator for unit  $i$  in period  $t$ . Let  $S_{it}$  be the set of start time periods  $k$  such that if the maintenance of unit  $i$  starts at period  $k$  that unit will be in maintenance at period  $t$ ,  $S_{it} = \{k \in T_i: t - d_i + 1 \leq k \leq t\}$ . Let  $I_t$  be the set of units which are allowed to be in maintenance in period  $t$ ,  $I_t = \{i: t \in T_i\}$ . Then the problem can be formulated as a quadratic 0-1 programming problem as below.

The objective function to be minimized as given in (2).

$$\text{Min}_{X_{it}} \left\{ \sum_t \left( \sum_i P_{it} - \sum_{i \in I_t} \sum_{k \in S_{it}} X_{ik} \cdot P_{ik} - L_t \right)^2 \right\} \quad (2)$$

subject to the maintenance window constraint

$$\sum_{t \in T_i} X_{it} = 1 \quad \forall_i \quad (3)$$

the crew constraint

$$\sum_{i \in I_t} \sum_{k \in S_{it}} X_{ik} \cdot M_{ik} \leq AM_t \quad \forall_t \quad (4)$$

and the load constraint

$$\sum_i P_{it} - \sum_{i \in I_t} \sum_{k \in S_{it}} X_{ik} \cdot P_{ik} \geq L_t \quad (5)$$

In this paper, the reliability in the above formulation is quantified by the sum of squares of reserves (SSR). A solution with a high reliability (low SSR) but requiring some extra manpower (TMV > 0) may well be acceptable to a power utility as the unavailable manpower may be hired. Here we take account of this flexibility by assuming that extra manpower of about 5% of the total available man-weeks can be hired if this leads to better system reliability. A bacterial foraging algorithm system is used to find the best compromise between the values of SSR and TMV, using knowledge of typical trade-offs in maintenance schedules for the test problem.

## III. BACTERIAL FORAGING ALGORITHM (BFA)

BFA is an optimization method developed by Kevin M. Passino [18], based on the foraging strategy of Escherichia Coli (E. Coli) bacteria that live in the human intestine. Foraging strategy is a method of animals for locating, handling and ingesting their food. The foraging strategy of E.Coli is governed basically by four processes, namely chemotaxis, swarming, reproduction, elimination and dispersal.

### A. Chemotaxis

Chemotaxis process is the characteristics of movement of bacteria in search of food and consists of two processes namely swimming and tumbling. A bacterium is said to be 'swimming' if it moves in a predefined direction, and 'tumbling' if moving in an altogether different direction. Let  $j$  be the index of chemotactic step,  $k$  be the reproduction step and  $l$  be the elimination dispersal event. Let  $\theta^i(j, k, l)$  is the position of  $i^{\text{th}}$  bacteria at  $j^{\text{th}}$  chemotactic step,  $k^{\text{th}}$  reproduction step and  $l^{\text{th}}$  elimination dispersal event. The position of the bacteria in the next chemotactic step after a tumble is given by

$$\theta^i(j+1, k, l) = \theta^i(j, k, l) + C(i) * \frac{\Delta(i)}{\sqrt{\Delta^T(i) * \Delta(i)}} \quad (6)$$

If the health of the bacteria improves after the tumble, the bacteria will continue to swim in the same direction of the specified steps or until the health degrades.

### B. Swarming

Bacteria exhibits swarm behaviour, i.e. healthy bacteria try to attract other bacteria, so that together they reach the desired location (solution point) more rapidly. The effect of Swarming is to make the bacteria congregate into groups and move as concentric patterns with high bacterial density.

$$J_{cc}(\theta, P(j, k, l)) = \sum_{i=1}^n J_{cc}(\theta, \theta^i(j, k, l))$$

$$= \sum_{i=1}^s \left[ -d_{attract} \exp \left( -W_{attract} \sum_{i=1}^n (\theta_m - \theta_m^i)^2 \right) \right] +$$

$$\sum_{i=1}^s \left[ -d_{repellant} \exp \left( -W_{repellant} \sum_{i=1}^n (\theta_m - \theta_m^i)^2 \right) \right] \quad (7)$$

#### C. Reproduction

In this step, population members who have had sufficient nutrients will reproduce and the least healthy bacteria will die. The healthier half of the population replaces with the other half of the bacteria which gets eliminated, owing to their poorer foraging abilities. This makes the population of bacteria constant in the evolution process.

#### D. Elimination and Dispersal

Gradual or sudden changes in the local environment where a bacterium population lives may occur due to various reasons, e.g. a significant local rise of temperature may kill a group of bacteria that are currently in a region with a high concentration of nutrient gradients. Events can take place in such a fashion that all the bacteria in a region are killed or a group is dispersed into a new location. To simulate this phenomenon in BFA some bacteria are liquidated at random with a very small probability while the new replacements are randomly initialized over the search space.

### IV. SIMULATION RESULTS AND DISCUSSION

The developed bacterial foraging algorithm was employed to solve GMS problem on 49 unit's Nigerian power system [20, 21]. The maintenance outages for the generating units are scheduled to minimize the sum of squares of reserves that satisfy the following constraints:

- Maintenance window – each unit must be maintained exactly once in every 52 weeks without interruption.
- Load constraint and spinning reserve – the system's peak load including 6.5% spinning reserve [19] is 5047MW.
- Crew constraint – there are only 40 crew available in each week for the maintenance work.

#### A. 49 units of the Nigerian power system

The Nigerian power system consists of a total of 49 functional units distributed among seven generating stations at the following locations: AFAM, DELTA, EGBIN, SAPELE, JEBBA, KAINJI and SHIROR. The data summarizes the name and type of power station, its capacity, maintenance duration and manpower requirement by generating unit for each maintenance week [20, 21]. In 49 functional units which are divided into three categories, first 20 units require maintenance during the period of January to April (1-17 weeks), second 18 units require maintenance during the period of May to October (18-43 weeks), and third

11 units require maintenance during the period of November to December (44-52 weeks). Over 25 years of operational experience and available historical data on hydrological conditions reveal that inflow variation profile at each hydro station location significantly impacts the generated power output of each hydro plant [12]. This inflow profile also dictates the allowed periods for the maintenance of the three hydro plants. These scenarios have been taken into consideration in solving the GMS problem using the Bacterial foraging algorithm.

In this case study gas turbines and steam turbines are to be shut down for maintenance only when the hydro plants are operating at their maximum generation. This corresponds to the months of January to April and November to December each year. The hydro plants can then be scheduled for maintenance during low inflow period corresponding to the months of May to October of each year. Within these months no thermal plant is allowed to be shut down for maintenance [12]. A maximum power demand of 3625MW plus 5% load increase is considered during the hot season of March to July every year. In this case study, the advantage and cost benefits of appropriate combination of thermal and hydro plants for maintenance within the period of low water level from May to October is investigated.

Figure 5.1 and 5.2 shows typical sum of squares of reserve margins and maintenance crew plots, respectively, for the Nigerian power system obtained using the Bacterial foraging algorithm. Table 5.1 shows the generator maintenance schedules obtained by Bacterial foraging algorithm for the 49 unit system. 17<sup>th</sup> week indicate periods with low maintenance task (no unit is scheduled for maintenance) resulting in comparatively high available generation on same week 17. Within the maintenance window, a minimum of 3625 MW (with spinning reserve) is sustained to meet the peak demand. The crew is limited to a maximum of 28. The maximum available generation is 3388.5 MW.

Similarly in the second 18 units the Nigerian power system. The weeks of 42 and 43 indicate periods with low maintenance task (no unit is scheduled for maintenance) resulting in comparatively high available generation on same weeks 42 and 43. The crew is limited to a maximum of 23. Similarly in the third 11 units of the Nigerian power system. The weeks are with maintenance task within the maintenance window (with spinning reserve). The crew is limited to a maximum of 26 and is compared with previously published work [20, 21]. Comparison shows that the proposed method yields improved performance than MDPSPSO and MS-MAPSO methods.

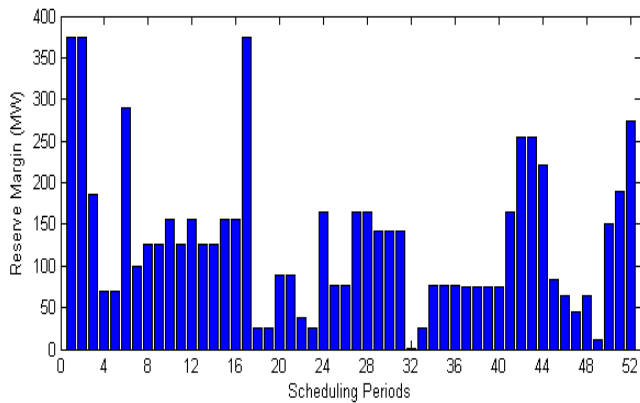


Fig 5.1. Reserve margin obtained from BFA for 49 units of the Nigerian power system

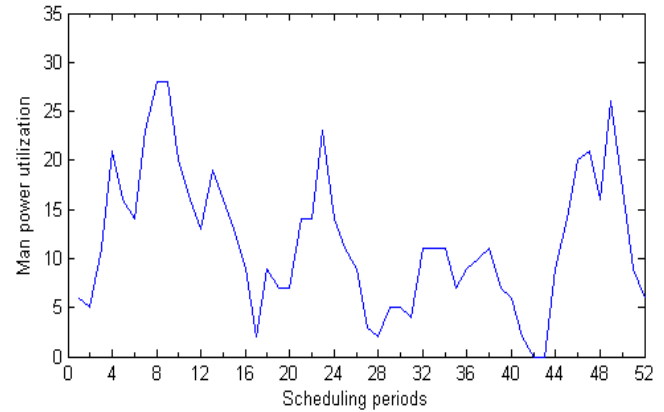


Fig 5.2. Manpower allocations obtained from BFA for 49 units of the Nigerian power system

TABLE 5.1 TYPICAL GENERATOR MAINTENANCE SCHEDULERS OBTAINED BY BFA FOR THE 49 NIGERIAN POWER SYSTEMS

Week No	Generating units scheduling for maintenance		
	MDPSO [20, 21]	MS-MDPSO [20, 21]	BFA
1	1,9,11,17	1,4,15	2,7,12
2	1,9,11,14,16,17	1,4,15	2,7,12,6
3	1,3,14,16,17	1,4,15	2,6,14
4	1,3,16,17	1,4,15	2,6,14,9,15
5	1,3,10,16	1,4,16	2,6,9,15,20
6	3,4,10	3,5,16	6,15,20,5,11,19
7	3,4	3,5,16	15,20,5,11,19,3,8
8	2,4	3,5,16	20,5,19,3,8
9	2,4,7	3,5	5,19,3,16,17
10	2,4,7,8	3,5	5,3,16,17,10,12
11	2,6,8,12	2,8,10,11,14	3,16,17,10,13,4
12	2,6,12	2,8,10,11,14	16,17,4,1,18
13	5,6,15	2,6	4,1,18
14	5,6,15	2,6,17	4,1,18
15	5,6,15	2,6,17	4,1,18
16	5,13,15	6,7,9,12,13,17	1
17	5,13	6,7,9,12,13,17	----
18	20,23,29,39	18,19,21,39	21,36
19	20,23,29,39	18,19,21,39	21,36
20	18,20,23,29,39	18,19,21,39	21,32,
21	18,20,23,28,39	18,19,21,30,39	21,32,28,29
22	18,28,36,39,40	24,30,39	32,28,29,37
23	18,28,36,40	24,28,30,38	28,29,37,23,34,38
24	28,33,40	24,28,31,38	28,23,34,38
25	31,33,40	24,28,29,31	23,34,26
26	31,32,33,40	20,22,27,28,29,31	23,34,26
27	26,31,32,33	20,22,27,29	26
28	26,32	20,22,27,34	26
29	22,26	20,22,27,34	27
30	22,26	34,35	27



31	19, 22, 24, 38	32,34,35	27
32	19, 22, 24, 38	32,37	27,31,35
33	19, 24, 27	32,37	31,35,25
34	19, 24, 27	25,33	31,35,22
35	27	25,33	25,22
36	27	25,33,40	25,22,30
37	35	25,33,40	22,30,33
38	21,30,35	36,40	30,33,24
39	21,30	36,40	33,34
40	21,25,30,34	23,26,40	33,34
41	21,25,34	23,26	24
42	25,34,37	23,26	----
43	25,34,37	23,26	-----
44	48,49	47,48	39,47
45	44,48,49	44,47,48	39,47,40
46	44,48,49	44,47,48	39,47,40,41,45
47	41,48,49	41,47,48	39,47,40,41,45,44
48	41,43	41,42	39,40,45,44,49
49	43,45,46,47	42,45,46,49	40,45,49,42,43,46,48
50	45,46,47	45,46,49	49,42,43,46,48
51	42,45,46,47	43,45,46,49	49,46,48
52	42,45,46,47	43,45,46,49	46,48

## V. CONCLUSIONS

The problem of generating optimal preventive maintenance schedule of generating units for economical and reliable operation of a power system while satisfying system load demand and crew constraints over one year period has been presented on a practical 49-unit test system of the Nigerian power system. To validate the proposed method, the results are compared with previously published work. The Bacterial Foraging Optimization technique has gained popularity in solving optimization problems. The results reflect a feasible and practical optimal solution that can be implemented in real time. Future work is to test on a large test system having different specifications over to a composite power system. The resulting optimal schedules will form part of overall system planning operation of a power utility. Future work will also seek to make the mutation operation adaptive while other powerful variants could be integrated into the Bacterial foraging algorithm to improve the present performance.

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