Optimal Maintenance Scheduling in Power Systems 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 21-unit test system. The simulation results are compared with other optimization methods published in the literature. The comparison affirmed the robustness, fast convergence and proficiency 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, uncertainities 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]. Eventhough 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 system load demand and manpower constraints.
The primary contributions of this paper are:

- Solving the challenging GMS problem for 21-unit test 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.

Ti $\subset$ T is the set of periods when maintenance of unit i may start,
Ti = {t $\in$ T: $e_i \le t \le l_i - di + 1$} for each i.

We define,

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

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, $S_{it} = \{k \in T_i: t - d_i + 1 \le k \le t\}$. Let it be the set of units which are allowed to be in maintenance in period t, $I_t = \{i: t \in T_t\}$. 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).

$$\underset{X_{it}}{Min}\left\{\sum_t\left(\sum_i P_{it} - \sum_{i\in It}\sum_{K\in Sit} X_{ik}\cdot P_{ik} - L_t\right)^2\right\} \quad (2)$$

subject to the maintenance window constraint

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

the crew constraint

$$\sum_{i\in It}\sum_{K\in Sit} X_{ik}\cdot M_{ik} \le AM_t \quad \forall_t \quad (4)$$

and the load constraint

$$\sum_i P_{it} - \sum_{i\in It}\sum_{K\in Sit} X_{ik}\cdot P_{ik} \ge L_t \quad (5)$$

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. *Chemo*taxis

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^{th} bacteria at j^{th} chemotactic step, k^{th} reproduction step and l^{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 BFA optimization technique was employed to solve GMS problem on 21 unit test system [2, 9] 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. 21 unit test system

In order to investigate the performance of Bacterial foraging algorithm for the GMS problem, a test system comprising of 21 units over a planning period of 52 weeks is considered. During this period, all the 21 units need to undergo maintenance. The generator ratings, allowed maintenance period, maintenance duration of each unit and crew required per weekly for each unit are given data [2, 3]. The system peak load demand is 4739 MW and manpower requirement to carry out maintenance task is 35. The following bacterial foraging algorithm parameters, S (10), N_c (20), N_s (12), N_{re} (10) and N_{ed} (5) are considered for the simulation. Bacterial foraging algorithm is employed to solve the GMS problem for the 21 unit system and the simulation results are given table 5.1. Figures 5.1 and 5.2 show typical sum of squares of reserve margin and maintenance crew plots respectively obtained using Bacterial foraging algorithm.

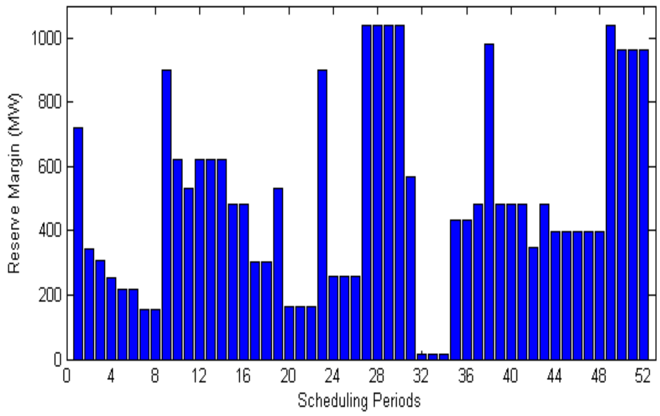

Figure 5.1. Reserve margin obtained from BFA for the 21 unit test system

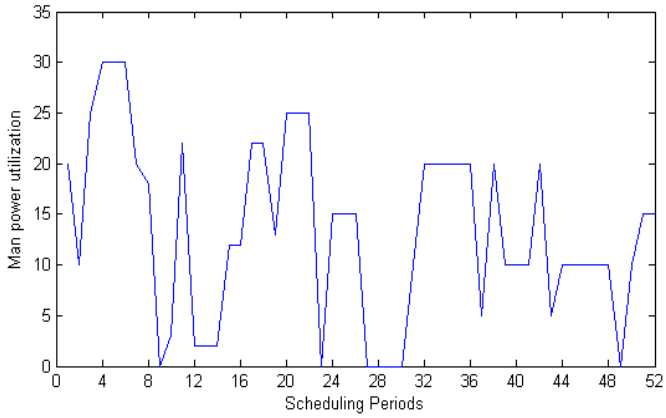

Figure 5.2. Manpower allocations obtained from BFA for the 21 unit test system

Table 5.1 Shows generator unit scheduled for maintenance in period of 52 weeks, obtained by BFA for the 21-unit test system. To illustrate the validity of the proposed method, the obtained results are compared with MDPSO and MS- MDPSO methods published recently in period of 52 weeks, obtained by bacterial foraging algorithm for the 21-unit test system.

To illustrate the validity of the proposed method, the obtained results are compared with MDPSO and MS-MDPSO methods published recently. It can be deduced from the typical maintenance schedules presented in table 5.1 that, weeks 9,23,27,28,29,30 and 49 indicate periods with low maintenance task (no unit is scheduled for maintenance) resulting in comparatively high available generation on same weeks 9,23, 27,28,29,30 and 49. On comparison with previously published methods, it is shown that the proposed Bacterial foraging algorithm shows improved performance in view of more number of maintenance free weeks. This ensures more reliable operation of the system. Within the maintenance window, a minimum of 5047MW (with spinning reserve) is sustained to meet the peak demand, whereas the crew is limited to a maximum of 30.

TABLE 5.1: TYPICAL GENERATOR MAINTENANCE SCHEDULERS OBTAINED BY BFA FOR THE 21-UNIT TEST SYSTEM

Week No	Generating units scheduled for maintenance		
	MDPSO [20,21]	MS-MDPSO [20,21]	BFA
1	1	12,13	3
2	1	12,13	1
3	1	4,13	1,11
4	1	4	1,1113
5	1	4	1,13,9
6	1	2,6	1,13,9
7	1,6	2,6	1,12
8	3,6,11	6	1,12
9	2,6,11	6	-----
10	2,6	6,7,8	6
11	6	6,7	6,8
12	6	6,7	6
13	6,13	6,7,11	6
14	6,10,13	6,11	6
15	6,10,13	6	6,7
16	6,7,10	6	6,7
17	7,10	5	6,7,2
18	7,9,12	5,9	6,7,2
19	7,9,12	5,9	6,10
20	4	1	10,4
21	4	1	10,4
22	4	1,10	10,4
23	5	1,10	-----
24	5	1,10	5
25	5	1,10	5
26	5,8	1	5
27	19	17,20	----
28	19,20	17,19	----
29	16	17,19	----
30	16	----	----
31	16	14	21
32	16	14	21,16
33	16	14	21,16
34	16	14	21,16
35	---	14	19,16
36	17	---	19,16
37	17	21	16
38	17	21	18
39	14	21	14
40	14	21	14
41	14	18	14
42	14	16	14, 20
43	14	16	14
44	21	16	15
45	21,18	16	15
46	21	16	15
47	21	16	15
48	15	15	15
49	15	15	----
50	15	15	17
51	15	15	17
52	15	15	17

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 21-unit test 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 modification operation adaptive while other powerful variants could be integrated into the Bacterial foraging algorithm to improve the present performance.

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