OPTI 2014
An International Conference on
Engineering and Applied Sciences Optimization
M. Papadrakakis, M.G. Karlaftis, N.D. Lagaros (eds.)
Kos Island, Greece, 4-6 June 2014

A MODEL FOR PREVENTIVE MAINTENANCE SCHEDULING OF POWER PLANTS MINIMIZING COST

Salvador Perez-Canto

School of Industrial Engineering, University of Malaga
Campus of Teatinos, 29071 Malaga, Spain
e-mail: spc@uma.es

Keywords: Preventive Maintenance, Power Plant, Scheduling, Cost, Optimization.

Abstract. *This paper presents an approach to preventive maintenance scheduling of power plants for electric systems. The problem under study is an optimization problem and has been formulated with a cost-based criterion. The main aim is to know which power plants must stop their operation of electricity production for periodic inspection over a time horizon. The management of this problem has a considerable impact on power system performance because an unexpected failure in a power plant may cause a general breakdown in an electric system. The main consequence would be that the electric demand could be unsatisfied. The global electric system modeled comprises the most important types of power plants: thermal, hydroelectric, nuclear, and wind power plants. A realistic application example is included.*

1 INTRODUCTION

This paper addresses the problem of preventive maintenance scheduling of power plants. This problem is usually treated in the long-term exploitation of electric production systems. It requires determining the period for which generating units of an electric power utility should be taken off-line for planned preventive maintenance over a time horizon. Preventive maintenance is an expensive activity for power generation companies and requires to be scheduled into the operating schedule [1]. The objective is to minimize the total cost while the power demand, certain reliability requirements and a number of other constraints are satisfied [2].

A review of the literature shows that diverse methods have been proposed and applied to solve the maintenance scheduling of power plants: Multi-objective optimization [3]; Linear programming [4]; Stochastic programming [5]; Mixed integer programming [6]; Decomposition methods [7, 8]; Genetic algorithms [9]; Heuristic techniques [10]; Particle swarm optimization [11]; Meta heuristic-based hybrid approaches [12]; and Simulated annealing [13, 14]

The contribution of this work is to present an approach to the problem of preventive maintenance scheduling of power plants, designing a model which is based on cost, and oriented towards an optimization perspective. The research encompasses a wide range of power plants: thermal, nuclear, hydroelectric, and wind power plants. In addition, a complete set of constraints is included to model the real world for power systems. To date, the great majority of power industries have been unable to reach optimal maintenance decisions. Thus, the main aim here is to formulate an improved model and establish an adequate maintenance strategy to be applied by those companies dealing with electric energy generation. The inclusion of renewable energy, such as hydroelectric and wind energy, is a way to get sustainable power systems, reducing the impact on the environment.

The remainder of the paper is organized as follows. Section 2 presents the conceptual framework. Section 3 presents the mathematical formulation of the problem. Section 4 establishes a model for the problem and the methodology for its resolution. An application example is shown in section 5. Finally, conclusions are drawn in section 6.

2 PROBLEM DESCRIPTION

The problem of preventive maintenance scheduling of power plants consists in disconnecting a power plant periodically to review its functioning and to detect potential failures. The planned maintenance activity is designed to lengthen the useful life of power plants and to maintain their safety. This strategy is a way to avoid system malfunctions and the subsequent corrective maintenance. Its importance emerges from the real necessity of maintaining high efficiency at a minimum cost to improve the reliability of power plants.

Power plants are integrated into a global electric system. For this reason, an unpredicted failure affects the rest of the system. As a consequence, an unforeseen shutdown in a power plant might cause an undesirable interruption in the power supply, a reduction in the quality service, and subsequent customer dissatisfaction. In view of these reasons, the problem of preventive maintenance scheduling of power plants is a very important topic to evaluate.

A double perspective can be distinguished in the problem analyzed: cost [13, 15] and reliability [9, 16]. Electric energy demand must be supplied at an appropriate reliability level. In addition, the associated cost of shutdown of power plants should be as low as possible.

The problem of preventive maintenance scheduling of power plants is generally categorized as a 0/1 mixed integer linear programming problem. Its complexity arises from the enormous size of the system to be modeled. A large number of variables are present in the formulation, especially considering the binary variables, which are the most difficult to handle.

The time planning horizon selected is 1 year, which is expressed as 13 periods (52 weeks; 4 weeks per period). The periods for dividing the time horizon can be either 13 periods or 52 weeks. A time interval of 13 periods is the option selected for this study because an average maintenance lasts 4 weeks. The notation for periods of time will be “k”, which takes values from 1 to 13.

Preventive maintenance duration is established according to the type of power plant analyzed. The same maintenance duration will be considered for all of the power plants. It is assumed that preventive maintenance duration will be the typical value of 1 period or 4 weeks.

Regarding the electric demand, two parts are distinguished in each period of time, weekdays and weekends, according to the electric energy demand, with the larger demand occurring during weekdays. Each part is divided into three different subparts depending on the electric demand. The aforementioned subparts, from higher to lower demand are peak, shoulder, and valley. This distinction is made under a typical distribution profile of the electric demand. Thus, there are 6 subperiods with different durations. Its notation will be “n”, which varies from 1 to 6. The previous distribution is repeated three times because three possible electric demand scenarios are chosen: high (s_h), medium (s_m), and low (s_l). This set of possible scenarios is a way to model the stochastic nature of the power demand. A probability of occurrence has been assigned to each scenario.

3 MATHEMATICAL FORMULATION

This section gives a complete mathematical model to solve this problem. This problem is a complex optimization problem. Objectives such as cost minimization and consecution of a certain reliability level are proposed by imposing an objective function and satisfying a set of constraints.

The most relevant variable in this problem is the maintenance variable, whose notation is $x_{i,k}$. It is a binary variable (0/1) that indicates the following:

$x_{i,k}$=0: Power plant i is not in maintenance during period k.
$x_{i,k}$=1: Power plant i is in maintenance during period k.

Another 0/1 variable involved is $c_{i,k}$, which denotes the maintenance start-up and is indicated as follows:

$c_{i,k}$=0: Maintenance of power plant i does not start at the beginning of period k.
$c_{i,k}$=1: Maintenance of power plant i starts at the beginning of period k.

3.1 Objective function

The costs are the selected criteria for the objective function. The operating or exploitation costs are divided into five types:

a) Fixed cost
The fixed cost does not depend on the power production level;
b) Start-up cost
The start-up cost is the cost of putting a power plant into operation after being disconnected;
c) *Shut-down cost*
The shut-down cost is the cost of disconnecting a power plant off;
d) Production cost
The production cost is the cost of producing one megawatt-hour (MWh) in a power plant; and
e) Maintenance cost
The maintenance cost is the cost of putting a power plant into preventive maintenance.

These costs depend on the power plant considered. In general, fixed costs, shutdown costs and maintenance costs are not taken into consideration because they are not significant in comparison to start-up and production costs. Hydroelectric and wind power plants do not have start-up costs or production costs. The expression for the total cost is in the following:

$$\sum_{i\in I}\sum_{s\in S}\sum_{k\in K}\sum_{n\in N} q_s \cdot \left(h_{i,s,k,n} + w_{i,s,k,n}\right), \tag{1}$$

where
$h_{i,s,k,n}$ = The start-up cost of power plant i, subperiod n, period k, scenario s (€);
$w_{i,s,k,n}$ = The production cost of power plant i, subperiod n, period k, scenario s (€);
q_s = The probability of demand scenario s.

Substituting each cost for its value results in the following:

$$\sum_{i\in I}\sum_{s\in S}\sum_{k\in K}\sum_{n\in N} q_s \cdot \left(f_i \cdot y_{i,s,k,n} + g_i \cdot p_{i,s,k,n} \cdot \tau_n\right), \tag{2}$$

where
f_i = The start-up cost of power plant i (€);
$y_{i,s,k,n}$ = The start-up variable of power plant i, subperiod n, period k, scenario s;
g_i = The electric energy cost produced by power plant i (€/MWh);
$p_{i,s,k,n}$ = The output of power plant i, subperiod n, period k, scenario s (MW); and
τ_n = The duration of subperiod n (h).

$y_{i,s,k,n}$ is a 0/1 variable whose value is given by the next criterion:

$y_{i,s,k,n}=0$: Power plant i does not start at the beginning of subperiod n, period k, scenario s.
$y_{i,s,k,n}=1$: Power plant i starts at the beginning of subperiod n, period k, scenario s.

3.2 Constraints

The constraints considered are classified in five sets: maintenance constraints, production operation constraints, maintenance and connection constraint, generating volume constraints, and wind power constraints. All of them have to be satisfied to solve the problem under study.

I. Maintenance constraints
Twelve types of constraints are considered in this first group.

1) Maintenance window constraint

The maintenance of the power plant i has a duration of β_i periods.

$$\sum_{k \in K} x_{i,k} = \beta_i \qquad \forall\, i \in I \tag{3}$$

2) Period constraint

A maximum number of maintenance ψ_k is imposed in period k.

$$\sum_{i \in I} x_{i,k} \le \psi_k \qquad \forall\, k \in K \tag{4}$$

3) Maintenance continuity

When a power plant is removed from the electric production system for maintenance, it completes the maintenance with no interruption during its maintenance duration.

$$x_{i,k} - x_{i,k-1} \le c_{i,k} \qquad \forall\, i \in I \quad \forall\, k \in K \tag{5}$$

For k=1, select $x_{i,0}=0$.

4) Precedence constraint

This constraint establishes the order to follow in maintenance. If the maintenance for power plant i precedes the maintenance for power plant j, then

$$\begin{aligned} &\sum_{k_n=1}^{k} c_{i,k_n} - c_{j,k} \ge 0 \qquad \forall\, k \in K \\ &c_{i,k} + c_{j,k} \le 1 \qquad \forall\, k \in K \end{aligned} \quad , \tag{6}$$

where k_n is an index that varies from period 1 to period k.

5) Exclusion constraint

Power plants i and j cannot be in maintenance at the same time.

$$x_{i,k} + x_{j,k} \le 1 \qquad \forall\, k \in K \tag{7}$$

6) Interval constraint

A number of "e" periods are introduced between maintenances of power plants i and j. A sequence is provided. If δ is the time horizon, then the formula is

$$\begin{aligned} &c_{i,k} = c_{j,k+\beta_i+e} \qquad 1 \le k \le \delta - \beta_i - e \\ &\sum_{k=1}^{\delta-\beta_i-e} \left(c_{i,k} + c_{j,k+\beta_i+e}\right) = 2 \end{aligned} \quad . \tag{8}$$

7) Overlap constraint

There is an overlap of “u” periods between the maintenance of power plants i and j. Power plant i is the first plant that is out of service.

$$c_{i,k} = c_{j,k+\beta_i-u} \qquad 1 \le k < \delta - \beta_i + u \tag{9}$$

8) One-time maintenance constraint

Each power plant has only one outage for maintenance over the time horizon considered.

$$\sum_{k \in K} c_{i,k} = 1 \qquad \forall\, i \in I \tag{10}$$

9) Deadline constraint

The maintenance for power plant i must be concluded before the end of period T_i.

$$\sum_{k=1}^{T_i - \beta_i + 1} c_{i,k} = 1 \qquad \forall\, i \in I_d \tag{11}$$

I_d is the set of power plants that are affected by this constraint. β_i represents the duration of the maintenance of power plant i.

10) Maintenance working hours constraint

The number of maintenance working hours used is less than the number of working hours available within each period of time. This constraint arises from the limited resources, human and materials, to perform the preventive maintenance.

$$\sum_{i \in I} WHN_i \cdot x_{i,k} \le WH_k \qquad \forall\, k \in K \tag{12}$$

WHN_i is the number of working hours that are needed for the maintenance of unit i and WH_k is the total number of working hours that are available at period k.

11) Geographical location constraint

This constraint enforces a maximum number of maintained wind power plants in a specific region. Its purpose is to avoid the reduction of electric capacity in a region during the time horizon because wind farms are aimed at compensating peak electricity demand.

$$NPM_R \le NPM_R^{max}$$

Where NPM_R is the number of plants that are under maintenance activities in region R and NPM_R^{max} is the maximum number of plants in maintenance allowed in region R.

Considering G as the set of regions, the previous expression can be rewritten as follows:

$$\sum_{i \in R} \sum_{k \in K} c_{i,k} \le NPM_R^{max} \qquad \forall\, i \in R \quad \forall\, R \in G, \tag{13}$$

II. Production operation constraints

Four types of constraints are considered in this second group.

1) Production level bounds constraint
Each power plant works between minimum and maximum power capacity (MW).

$$v_{i,s,k,n} \cdot \underline{p}_i \leq p_{i,s,k,n} \leq v_{i,s,k,n} \cdot \overline{p}_i \quad \forall i \in I \quad \forall s \in S \quad \forall k \in K \quad \forall n \in N \tag{14}$$

where
$\underline{p}_i$ = Nominal minimum power or technical minimum for power plant i (MW);
$\overline{p}_i$ = Nominal maximum power or technical maximum for power plant i (MW); and
$v_{i,s,k,n}$ = Connecting variable for power plant i, subperiod n, period k, scenario s.

$v_{i,s,k,n}$ is a 0/1 variable whose value is given according to the next criterion:

$v_{i,s,k,n}$=0: Power plant i is not connected in subperiod n, period k, scenario s.
$v_{i,s,k,n}$=1: Power plant i is connected in subperiod n, period k, scenario s.

Nuclear and wind power plants have similar lower and upper bounds because of technical reasons. Hence, the power generated is constant.

2) Demand supply constraint
This constraint establishes a power balance: power production in each subperiod must meet the electric demand, with a constant value in the considered subperiod of time.

$$\sum_{i \in I} p_{i,s,k,n} = d_{s,k,n} \quad \forall s \in S \quad \forall k \in K \quad \forall n \in N \tag{15}$$

$d_{s,k,n}$ is the power demand in subperiod n, of period k, in scenario s (MW).

3) Reserve constraint
The reserve is a margin of action if some eventuality occurs. It allows the power generated and the electric demand to meet in a continuous way. If $rr_{s,k,n}$ (MW) is the reserve in subperiod n, of period k, in scenario s, then the results is as follows:

$$\sum_{i \in I} v_{i,s,k,n} \cdot \overline{p}_i \geq d_{s,k,n} + rr_{s,k,n} \quad \forall s \in S \quad \forall k \in K \quad \forall n \in N. \tag{16}$$

The term $rr_{s,k,n}$ is usually calculated as a percentage of the electric demand.

4) Start-up constraint
This constraint establishes the start-up logic for thermal and nuclear power plants. The variable $y_{i,s,k,n}$ must satisfy the following constraint to correctly model the start-up costs:

$$y_{i,s,k,n} \geq v_{i,s,k,n} - v_{i,s,k,n-1} \quad \forall i \in \{I - I_2 - I_4\} \quad \forall s \in S \quad \forall k \in K \quad \forall n \in N. \tag{17}$$

I_2 is the index set for hydroelectric power plants and I_4 for wind power plants. When n is equal to 1, the applied contour condition is the condition that corresponds to the last subperiod of the previous period (in the case of k equal to 1, 0 is selected for the connecting variable).

III. Maintenance and connection constraint

It models the correlation between the maintenance variables $x_{i,k}$ and the connection variables $v_{i,s,k,n}$: $x_{i,k} + v_{i,s,k,n} \le 1$. For nuclear power plants, only equality exists because they are always connected, except when in maintenance. Therefore:

$$
\begin{array}{lllll}
x_{i_1,k} + v_{i_1,s,k,n} \le 1 & \forall\, i_1 \in I_1 & \forall\, s \in S & \forall\, k \in K & \forall\, n \in N \\
x_{i_2,k} + v_{i_2,s,k,n} \le 1 & \forall\, i_2 \in I_2 & \forall\, s \in S & \forall\, k \in K & \forall\, n \in N \\
x_{i_3,k} + v_{i_3,s,k,n} = 1 & \forall\, i_3 \in I_3 & \forall\, s \in S & \forall\, k \in K & \forall\, n \in N \\
x_{i_4,k} + v_{i_4,s,k,n} \le 1 & \forall\, i_4 \in I_4 & \forall\, s \in S & \forall\, k \in K & \forall\, n \in N
\end{array}, \qquad (18)
$$

where

I_1 = Index set for thermal power plants and

I_3 = Index set for nuclear power plants.

IV. Generating volume constraints

Three types of constraints are considered in the fourth group.

1) Minimum volume constraint

This constraint is related to a particular country. Its application depends on the electric system under consideration. It is used for coal thermal power plants. A minimum production using national coal is required to maintain jobs in the sector, even though this is not profitable.

$$\sum_{n\in N} p_{i_1,s,k,n} \cdot \tau_n \ge \underline{E}_{i_1} \cdot \left(1 - x_{i_1,k}\right) \quad \forall\, i_1 \in I_1 \quad \forall\, s \in S \quad \forall\, k \in K \qquad (19)$$

$\underline{E}_{i_1}$ is the minimum energy (MWh) to be produced by power plant i_1. The parameter τ_n is the duration of subperiod n (h).

2) Maximum volume constraint

This constraint is applied to thermal power plants. Legislation enforces a maximum limit of energy production to reduce the environmental impact.

$$\sum_{n\in N} p_{i_1,s,k,n} \cdot \tau_n \le \overline{E}_{i_1} \cdot \left(1 - x_{i_1,k}\right) \quad \forall\, i_1 \in I_1 \quad \forall\, s \in S \quad \forall\, k \in K \qquad (20)$$

$\overline{E}_{i_1}$ is the maximum energy (MWh) to be produced by thermal power plant i_1.

3) Water volume constraint

The water volume constraint is related to hydroelectric power plants. A basin water reserve cannot be used only to produce electricity (for instance: human consumption and irrigation).

$$\sum_{n\in N} p_{i_2,s,k,n} \cdot \tau_n = E_{i_2,s,k} \cdot \left(1 - x_{i_2,k}\right) \quad \forall\, i_2 \in I_2 \quad \forall\, s \in S \quad \forall\, k \in K \qquad (21)$$

$E_{i_2,s,k}$ is the energy (MWh) to be produced by hydroelectric power plant i_2 in period k of scenario s.

V. Wind power generation constraints
Two types of constraints are considered here, which are specific for wind power plants.

1) Maximum energy allowance constraint
When the electricity produced by a wind power plant reaches certain level, it must be stopped because of the impossibility to disconnect other power plants, such as nuclear power plants.

$$\sum_{n\in N} p_{i_4,s,k,n} \cdot \tau_n \leq \overline{E}_{i_4,s,k} \cdot \left(1 - x_{i_4,k}\right) \qquad \forall\, i_4 \in I_4 \quad \forall\, s \in S \quad \forall\, k \in K \tag{22}$$

$\overline{E}_{i_4,s,k}$ is the maximum energy (MWh) to be produced by wind power plant i_4 in period k of scenario s.

2) Functioning hours constraint
The number of hours that a wind power plant works is dependent on the wind regime, which is specific to the geographical area under consideration. An average percent of the total number of hours over the time horizon is imposed.

$$\sum_{k\in K} FH_{i_4,k} \cdot x_{i_4,k} \leq r_{i_4} \cdot TNH \qquad \forall\, i_4 \in I_4 \tag{23}$$

$FH_{i_4,k}$ represents the working hours that are associated with wind power plant i_4 during period k. TNH is the global number of hours of the time horizon, and r_{i_4} expresses the percentage applied according to the wind regime in the geographical area where i_4 operates.

4 MODEL AND METHODOLOGY

The problem analyzed is modeled as a 0/1 mixed integer linear programming problem because of its linearity and the inclusion of real and integer variables. The integer variables considered are binary. The model in this paper also includes real variables.

4.1 Model for the problem

According to the description in Section 3, the problem is modeled in the following form:

Minimize (2)
subject to (3-23)

4.2 Solving process

The solving process is shown in Figure 1.

FORMULATION OF THE PROBLEM
↓
USE OF AN OPTIMIZER
↓
FINAL OPTIMAL SOLUTION, IF FEASIBLE

Figure 1: Procedure for the solving process.

GAMS (General Algebraic Modeling System) [17] was the optimizer used.

5 APPLICATION EXAMPLE

An application example based on a high-dimensioned realistic power system, similar to the Spanish power system, was undertaken to validate the efficiency of the model.

5.1 Problem description

The power system characterized for the application of the model and the methodology presented here has the following features:

a) 90 power plants (45 thermal, 20 hydroelectric, 8 nuclear and 17 wind) and

b) 3 power demand scenarios, 13 periods, and 6 subperiods.

Wind power plants are grouped by geographical areas or regions because they are usually dispersed. The number of wind power plants is the result of this assumption.

5.2 General data

In this section, typical example data are provided for the problem.

a) Probabilities for power demand scenarios: Low: 0.1. Medium: 0.6. High: 0.3.
b) Power demand order for periods: P1>P8>P13>P7>P12>P2>P11>P3>P10>P4>P9>P6>P5
c) Peak, middle, and low duration in a period: Peak: 10%. Middle: 60%. Low: 30%.
d) Fuel cost: Thermal power plants: 0.0054093 €/Te. Nuclear power plants: 0.001503 €/Te.
e) Power reserve: 10% of the electric demand is chosen for the power reserve value.
f) Energy to be produced by hydroelectric power plants in water volume constraint

$$E_{i_2,s,k} = 0.12 \cdot \frac{\overline{p}_{i_2}}{\sum_{i_2 \in I_2} \overline{p}_{i_2}} \cdot \sum_{n \in N} d_{s,k,n} \cdot \tau_n \qquad \forall\, i_2 \in I_2 \quad \forall\, s \in S \quad \forall\, k \in K$$

g) Geographical distribution of the power plants: This is related to the location of the 90 power plants in the regions of the country. In this case, 17 regions have been considered.
h) Initial situation for the power plants: The different power plants are disconnected when the time horizon starts. This arrangement means that they do not produce any electricity.
i) Entry data: Owing to space limitations, the information concerning entry data (costs, power demand, power plant capacity, and nominal maximum power) is not detailed in this document.

5.3 Problem constraints

Table 1 shows some of the constraints imposed: precedence, exclusion, interval, and overlap constraints. Other constraints are not reported here owing to space limitations.

Power plants	*Precedence*	*Exclusion*	*Interval*	*Overlap*
1,52		1		
2,17			1	
4,13	1			
5,19		1		
6,29			3	
7,28			2	
9,18	1			
11,39	1			
12,23				1
14,22			8	

15,65		1		
18,81				1
19,2	1			
22,10				1
23,90		1		
24,42	1			
26,68				1
29,32		1		
30,41			4	
31,17			0	
35,66	1			
38,45	1			
40,73				1
42,11	1			
45,22	1			
50,87			2	
52,7	1			
53,62		1		
56,72		1		
57,25	1			
59.2	1			
62,37			3	
64,25	1			
65.28			5	
66,72			2	
67,53	1			
68,90		1		
69,21			0	
70,22		1		
72,77		1		
73,49			2	
74,76	1			
75,71	1		8	
75,89				1
76,19			6	
77,9	1			
78,75				1
79,25	1			
80,2	1			
82,11			4	
85,22				1
87,37				1
88,90			3	
90,27				1

Table 1: Constraints imposed.

For example, power plants 11 and 39 are affected by the precedence constraint. Power plants 53 and 62 are affected by the exclusion constraint. Power plants 75 and 71 are affected by the interval constraint, with 8 periods between their respective maintenances. Power plants 87 and 37 are affected by the overlap constraint.

5.4 Findings

After running the model, the findings obtained are described below.

1) Objective function

The value reached for the objective function is €1,071.73 million (total cost of the system).

2) Maintenance schedule

The time-plan for outages is displayed on Table 2. The power plants labelled 1-45 are thermal, 46-65 are hydroelectric, 66-73 are nuclear, and 74-90 are wind.

PP/Per	1	2	3	4	5	6	7	8	9	10	11	12	13
1													■
2											■		
3						■							
4				■									
5													■
6				■									
7		■											
8							■						
9								■					
10												■	
11											■		
12					■								
13							■						
14			■										
15									■				
16										■			
17													■
18									■				
19										■			
20						■							
21													■
22												■	
23					■								
24			■										
25												■	
26										■			
27									■				
28												■	
29								■					
30		■											
31												■	
32													■
33					■								
34												■	
35			■										
36					■								
37									■				
38										■			
39												■	
40		■											
41							■						
42						■							
43									■				
44				■									
45											■		
46							■						
47		■											
48		■											
49					■								
50						■							
51											■		
52	■												
53										■			
54											■		
55												■	
56											■		
57									■				
58											■		
59										■			
60						■							
61				■									
62					■								
63		■											
64											■		
65						■							
66				■									
67				■									

68										■			
69												■	
70									■				
71							■						
72							■						
73		■											
74	■												
75				■									
76			■										
77					■								
78				■									
79			■										
80					■								
81									■				
82						■							
83												■	
84			■										
85												■	
86					■								
87									■				
88					■								
89				■									
90									■				

Table 2: Maintenance schedule.

3) Computational time

The execution time is 117.58 s. Computer used: Intel Core i7, CPU 860, 2.80 GHz RAM.

6 CONCLUSIONS

This paper has explored the problem of preventive maintenance scheduling of power plants of an electric grid. Its importance derives from the necessity to maintain them to get a high quality level service. The objective is determining the periods of time to take down a set of power plants for planned preventive maintenance over a time horizon, at minimum cost.

The problem under study is a complex problem framed into 0/1 mixed integer linear programming The large number of variables and constraints regarding maintenance, production operation, generating volume, and wind power, make this study quite detailed and realistic.

The proposed model and methodology was applied to a large-sized and realistic electric production system to check on its efficiency. The results are consistent and reflect the expected behavior and good performance. The final maintenance schedule obtained is adequate for the modeled requirements in terms of cost and the constraints imposed.

This study could be useful for electric companies with production activity. Cost, which is a parameter of first importance in the functioning of an electric system, is included in the model, apart from the fulfillment of the electric demand. This result indicates that the cost is minimized and a specific quality service level is maintained, avoiding potential failures. The first point is crucial for companies and the second one for customers.

REFERENCES

[1] T.N. Mohammadi, M. Pirmoradian, S.B. Hassanpour, Implicit enumeration based 0-1 integer programming for generation maintenance scheduling. *Proceedings of the International Conference on Computational Technologies in Electrical and Electronics Engineering*, Novosibirsk, Russia, 151-154, 2008.

[2] F. Besnard, M. Patriksson, A.B. Stromberg, A. Wojciechowski, K. Fischer, L. Bertling, A stochastic model for opportunistic maintenance planning of offshore wind farms. *Proceedings of the IEEE PowerTech conference*, Trondheim, Norway, 2011.

[3] Y. Colette, P. Siarry, *Multiobjective Optimization: Principles and Case Studies*. Springer, 2003.

[4] D. Chattopadhyay, A practical maintenance scheduling program: mathematical model and case study. *IEEE Transactions on Power Systems*, **13**, 1475-1480, 1998.

[5] E.K. Doyle, On the application of stochastic models in nuclear power plant maintenance. *European Journal of Operational Research*, **154 (3)**, 673-690, 2004.

[6] M. Ben-Daya, S.O. Duffuaa, A. Raouf (eds), *Maintenance, Modeling and Optimization*. Kluwer, 2000.

[7] S.P. Canto, Application of Benders' decomposition to power plant preventive maintenance scheduling. *European Journal of Operational Research*, **184(2)**, 759-777, 2008.

[8] R. Lusby, L. Flindt Muller, B. Petersen, A solution approach based on Benders decomposition for the preventive maintenance scheduling problem of a stochastic large-scale energy system. *Journal of Scheduling*, **16(6)**, 605-628, 2013.

[9] G.G. Samuel, C.C.A. Rajan, A modified genetic approach to long-term generation maintenance scheduling to enhance the reliability of the units, *Proceedings of the IEEE International Conference on Advances in Engineering, Science and Management*, Nagapattinam, India, 789-793, 2012.

[10] K.Y. Lee, M.A. El-Sharkawi, *Modern heuristic optimization techniques: theory and applications to power systems*. IEEE Press, 354-359, 2008.

[11] Y. Yare, G.K. Venayagamoorthy, U.O. Aliyu, Optimal generator maintenance scheduling using a modified discrete PSO. *IET Journal on Generation, Transmission and Distribution*, **2(6)**, 834-846, 2008.

[12] K.P. Dahal, N. Chakpitak, Generator maintenance scheduling in power systems using metaheuristic-based hybrid approaches. *Electric Power Systems Research Journal*, **77**, 771-779, 2007.

[13] J.T. Saraivaa, M.L. Pereira, V.T. Mendes, J.C. Sousa, A simulated annealing based approach to solve the generator maintenance scheduling problem. *Electric Power Systems Research*, **81**, 1283-1291, 2011.

[14] E.B. Schlünz, J.H. Van Vuuren, An investigation into the effectiveness of simulated annealing as a solution approach for the generator maintenance scheduling problem. *International Journal of Electrical Power and Energy Systems*. **53**, 166-174, 2012.

[15] H.H. Balci, J.F. Valenzuela, Scheduling electric power generators using particle swarm optimization combined with the lagrangian relaxation method. *International Journal of Applied Mathematics and Computer Science*, **14(3)**, 411-421, 2004.

[16] D.K. Mohanta, P.K. Sadhu, R. Chakrabarti, Deterministic and stochastic approach for safety and reliability optimization of captive power plant maintenance scheduling using GA/SA-based hybrid techniques: a comparison of results. *Reliability Engineering & System Safety*, **92**, 187-199, 2007.

[17] GAMS, General Algebraic Modeling System, [online], http://www.gams.com. 2013.