Nuclear Power Plant Preventive Maintenance Scheduling Problem with Fuzziness

Samir A. Abass and Asmaa S. Abdallah
Math. and Theor. Phys. Department, Nuclear Research Centre, AEA, Cairo, Egypt.

Received: 10/6/2012 **Accepted: 5/7/2012**

ABSTRACT

Maintenance activity is regarded as the most important key factor for the safety, reliability and economy of a nuclear power plant. Preventive maintenance refers to set of planned activities which include nondestructive testing and periodic inspection as well as maintenance. In this paper, we address the problem of nuclear power plant preventive maintenance scheduling with uncertainty. The uncertainty will be represented by fuzzy parameters. The problem is how to determine the period for which generating units of an electric system should be taken off line for planned preventive maintenance over specific time horizon. Preventive maintenance activity of a nuclear power plant is an important issue as it designed to extend the plant life. It is more required to review the maintenance not only from the view point of safety and reliability but also economy. Preventive maintenance program exists to ensure that nuclear safety significant equipment will function when it is supposed to. Also this problem is extremely important because a failure in a power plant may cause a general breakdown in an electric network. In this paper a mixed integer programming model is used to express this problem. In proposed model power demand is taken as fuzzy parameters. A case study is provided to demonstrate the efficiency of the proposed model.

Keywords: preventive maintenance / scheduling / mixed Integer programming / Fuzzy parameters.

INTRODUCTION

For efficient operation of nuclear power plants timely shutdowns for maintenance are essential. Preventive maintenance is planned maintenance of the plant equipment and facilities that is designed to extend their life and avoid any unplanned maintenance activity. It consists of the periodic inspection of power plant to detect potential failures. The aim of preventive maintenance is to reduce the amount of unplanned maintenance work which consumes a large proportion of the cost of generating electricity needed in a power plant (1).

The electric energy demand must be supplied under an adequate reliability level (2, 3). Moreover the associated cost of shutdown an electric generator set has to be minimum possible. The problem of power plant preventive maintenance scheduling is perceived to be an important issue. The importance of the problem under study springs from the real necessity to shutdown power plants regularly and review the functioning of the machinery, the complementary equipment and the facilities. The main aim is to maintain efficiency. Because power plants are integrated into a global electric system, it is possible for an unexpected failure to affect the rest of the system. Hence, an unexpected shutdown in a power plant may cause an undesirable interruption in the electric supply. The problem of power plant preventive maintenance scheduling is usually dealt within the framework of the long term exploitation of electric energy production systems (4, 5).

Different authors have focused their attention on power plant preventive maintenance planning with a wide variety of methodologies. Namely, this problem has been solved by heuristic techniques [(6, 7)], mixed integer programming [(8 -11)], dynamic programming [(12, 13)], stochastic programming [(14 -16)], decomposition methods [(17 - 20)], tabu search [(21)], expert systems [(22)] and multiobjective optimization [(23)]. They apply different models to the concerned problem.

In the rest of this paper we will present an optimization model for nuclear power plant preventive maintenance scheduling problem with fuzzy parameters. In section 2, some basic definitions on fuzzy set theory are introduced. In section 3 we will formulate the problem of concern as mixed integer programming model with fuzziness. A case study is provided in section 4 to demonstrate the efficiency of our proposed model. Section 5 contains the conclusions.

FUZZY CONCEPTS

L. A. Zadeh, advanced the fuzzy theory at the university of California in 1965. The fuzzy set theory proposes a mathematical technique for dealing with imprecise concepts and problems that have many possible solutions. The concept of fuzzy mathematical programming was first proposed by Tanaka et al (1974) in the framework of the fuzzy decision of Zadeh and Bellman [(24)]. Now, we present some necessary definitions [(25)].

Definition 1. A fuzzy number is a convex normalized fuzzy set of the real line R^1 whose membership functions piecewise continuous.

Definition 2. Triangular fuzzy number is a fuzzy number whose membership function $m_M(x)$ satisfies the following conditions:

1. A continuous mapping from R^1 to the closed interval [0, 1].
2. $m_M(x) = 0 \; \forall x \in \left]-\infty, a\right]$.
3. Strictly increasing and continuous on [a, m].
4. $m_M(x) = 1$ at $x = m$.
5. $m_M(x)$ is strictly decreasing and continuous on [m, b].
6. $m_M(x) = 0 \; \forall x \in \left[b, \infty\right[$.

where a, b and m are real numbers and the triangular fuzzy number is denoted by (a, m, b).

Definition 3. a-level set of the fuzzy number A is defined as the ordinary set A_a for which the degree of their membership function exceeds the level a:

$$A_a = \left\{ x \left| m_M(x) \geq a \, , \; a \in [0,1] \right. \right\}.$$

From definition 3, the a-level set of the triangular fuzzy number (a, m, b) is

$$A_a = \left[a + a\,(m - a), \; b - a\,(b - m) \right].$$

Problem formulation

The nuclear power plant preventive maintenance scheduling problem is to determine the period for which generating units of an electric system should be taken off line for planned preventive maintenance over specific time horizon. The criterion is to minimize the general costs with different types of constraints. The general costs divided into three types [(18)]:

- **Start up cost:** this is the cost to put a generator into operation after being disconnected.
- **Production cost:** this cost refers to the cost of producing 1 MW h in a generator.
- **Maintenance cost:** this is the cost to put a generator into preventive maintenance.

Now, we will propose a mixed integer programming model for nuclear power plant preventive maintenance scheduling problem with fuzzy parameters in the constraints. The power demand is taken as fuzzy parameters. First, we introduce the notations:

Notations

Index sets

I : Index set for nuclear power plant.

K : Index set for periods.

K_n : Index that varies from period 1 until period k.

Parameters

f_i : Start up cost of generator i ($).

g_i : Electric energy cost produced by generator i ($/MW h).

$z_{i,k}$: Maintenance cost of generator i in period k ($).

b_i : Maintenance duration for generator i.

y_k : Maximum number of maintenances in period k.

$\underline{t_i}$: Nominal minimum power for generator i (MW).

$\overline{t_i}$: Nominal maximum power for generator i (MW).

$\tilde{d}_k$: Fuzzy power demand in period k (MW).

rr_k : Power reserve for period k (MW).

Decision variables

$y_{i,k}$: start up variable of generator i at the beginning of period k,

$$y_{i,k} = \begin{cases} 0 & \text{Generator } i \text{ does not start at the beginning of period } k, \\ 1 & \text{Generator } i \text{ starts at the beginning of period } k. \end{cases}$$

$t_{i,k}$: Output electric power of generator i in period k (MW).

$x_{i,k}$: Maintenance variable of generator i in period k,

$$x_{i,k} = \begin{cases} 0 & \text{Generator } i \text{ is not in maintenance in period } k, \\ 1 & \text{Generator } i \text{ is in maintenance in period } k. \end{cases}$$

$c_{i,k}$: Maintenance start up variable of generator i in period k,

$$c_{i,k} = \begin{cases} 0 & \text{Maintenance of generator } i \text{ does not start at the beginning of period } k, \\ 1 & \text{Maintenance of generator } i \text{ starts at the beginning of period } k. \end{cases}$$

$v_{i,k}$: Connecting variable for generator i in period k,

$$v_{i,k} = \begin{cases} 0 & \text{Generator } i \text{ is not connected in period } k, \\ 1 & \text{Generator } i \text{ is connected in period } k. \end{cases}$$

We formulate a mixed integer programming model for the nuclear power plant preventive maintenance scheduling problem with fuzzy parameters as follows:

$$\text{Minimize} \sum_{i \in I} \sum_{k \in K} \left(f_i y_{i,k} + g_i t_{i,k} + z_{i,k} x_{i,k} \right) \tag{1}$$

subject to

$$\sum_{k\in K} x_{i,k} = b_i, \qquad \forall i \in I \qquad (2)$$

$$\sum_{i\in I} x_{i,k} \le y_k, \qquad \forall k \in K \qquad (3)$$

$$x_{i,k} - x_{i,k-1} \le c_{i,k}, \quad \forall i \in I,\ k \in K, \ \text{ for } k=1 \text{ select } x_{i,0}=0 \qquad (4)$$

$$\sum_{k_n=1}^{k} c_{i,k_n} - c_{j,k} \ge 0, \qquad \forall k \in K,\ i,j \in I \qquad (5)$$

$$c_{i,k} + c_{j,k} \le 1, \qquad \forall k \in K,\ \ i,j \in I \qquad (6)$$

$$\sum_{k\in K} c_{i,k} \le 1, \qquad \forall i \in I \qquad (7)$$

$$v_{i,k}\underline{t}_i \le t_{i,k} \le v_{i,k}\overline{t}_i, \qquad \forall i \in I,\ k \in K \qquad (8)$$

$$\sum_{i\in I} t_{i,k} \ge \tilde{d}_k, \qquad \forall k \in K \qquad (9)$$

$$\sum_{i\in I} v_{i,k}\overline{t}_i \ge \tilde{d}_k + rr_k, \qquad \forall k \in K \qquad (10)$$

$$y_{i,k} \ge v_{i,k} - v_{i,k-1}, \ \forall i \in I,\ k \in K, \ \text{ for } k=1 \text{ select } v_{i,0}=0 \qquad (11)$$

$$x_{i,k} + v_{i,k} = 1, \qquad \forall i \in I,\ k \in K \qquad (12)$$

$$y_{i,k}, x_{i,k}, c_{i,k}, v_{i,k} \in \{0,1\}, \quad \forall i \in I,\ k \in K \qquad (13)$$

$$t_{i,k} \ge 0, \qquad \forall i \in I,\ k \in K \qquad (14)$$

The power demands $\tilde{d}_k$ $, k=1,\ldots K$ represent fuzzy parameters involved in the constraints with their membership functions are $m_{\tilde{d}_k}$. Therefore problem (1)-(14) can be understood as the following nonfuzzy problem:

(**Nonfuzzy problem**)

$$\text{Minimize} \sum_{i\in I}\sum_{k\in K}\left(f_i y_{i,k} + g_i t_{i,k} + z_{i,k}x_{i,k}\right) \qquad (15)$$

subject to

$$\sum_{i\in I} t_{i,k} \ge d_k, \qquad \forall k \in K \qquad (16)$$

$$\sum_{i\in I} v_{i,k}\overline{t}_i \ge d_k + rr_k, \qquad \forall k \in K \qquad (17)$$

$$d_k \in L_a(\tilde{d}_k), \qquad \forall\ k \in K \qquad (18)$$

set of constraint (2)-(8), (11)-(12)

$L_a(\tilde{d}_k)$ are the a-level set of the fuzzy numbers $\tilde{d}_k$, where $L_a(\tilde{d}_k) = [d_k^1 + a(d_k^2 - d_k^1),\ d_k^3 - a(d_k^3 - d_k^2)]$ with triangular fuzzy numbers $\tilde{d}_k = (d_k^1, d_k^2, d_k^3)$ and $a \in [0,1]$. The nonfuzzy problem can be written in the following equivalent form:

$$\text{Minimize} \sum_{i\in I}\sum_{k\in K}\left(f_i y_{i,k} + g_i t_{i,k} + z_{i,k}x_{i,k}\right) \qquad (19)$$

subject to

$$n_k \le d_k \le N_k, \qquad \forall\ k \in K \qquad (20)$$

set of constraint (2)-(8), (11)-(12), (16)-(17)

It is should be noted that the set of constraint (18) have been replaced by the set of constraint (20). n_k and N_k are lower and upper bounds on d_k respectively and they are constants.

CASE STUDY

In order to check the efficiency of the proposed model, it is tested by the following system. Four nuclear generators in a nuclear power plant are chosen to apply our model Time planning horizon is accepted as nine months. It divided into six equal periods. Each period is equal to six weeks. The nuclear generators are supposed to be disconnected before the time horizon starts. Power demands are considered as uncertainty parameters. This uncertainty is represented by triangular fuzzy numbers as shown in table 1. The power reserve values (rr_k) are chosen as 10% of power demands. The economical data of the case study are shown in table 2. The technical data are $b_1 = b_4 = 1$ and $b_2 = b_3 = 2$. Also $\overline{t_1} = \overline{t_2} = \overline{t_3} = \overline{t_4} = 1000\text{MW}$ while $\underline{t_1} = \underline{t_2} = \underline{t_3} = \underline{t_4} = 500\text{MW}$. $y_1 = y_2 = y_3 = y_4 = y_5 = y_6 = 1$.

Table (1): Triangular fuzzy power demands

Periods	Power demand (MW)
Period 1	$\tilde{d}_1$=(1500,2000,4000)
Period 2	$\tilde{d}_2$=(1200,3000,4000)
Period 3	$\tilde{d}_3$=(1000,2500,4000)
Period 4	$\tilde{d}_4$=(2000,3000,4000)
Period 5	$\tilde{d}_5$=(1750,3000,4000)
Period 6	$\tilde{d}_6$=(1500,2500,4000)

Table (2): The economical data

Periods	Start up cost f_i (\$)	Electric energy cost g_i (\$/MW h)	Maintenance cost z_{ik} (\$)
Period 1	5	6	5
	5	6	4
	5	6	5
	5	6	5
Period 2	5	6	4
	5	6	6
	5	6	6
	5	6	4
Period 3	5	6	5
	5	6	3
	5	6	4
	5	6	6
Period 4	5	6	6
	5	6	5
	5	6	5
	5	6	7
Period 5	5	6	5

	5	6	4
	5	6	6
	5	6	3
Period 6	5	6	6
	5	6	5
	5	6	3
	5	6	5

By followed the proposed approach which is described through section 3, we get a deterministic integer programming model of the nuclear power plant preventive maintenance scheduling problem. For $a = 0.5$ and by using Win QSB software for solving integer programming models, we get the following results as shown in table 3:

Table (3): The results of case study

$y^*_{1,1} = y^*_{2,1} = y^*_{3,1} = y^*_{4,2} = y^*_{1,3} = y^*_{2,5} = 1,\ y^*_{4,1} = y^*_{1,2} = y^*_{2,2} = y^*_{3,2} = y^*_{2,3} = y^*_{3,3} =$ $y^*_{4,3} = y^*_{1,4} = y^*_{2,4} = y^*_{3,4} = y^*_{4,4} = y^*_{1,5} = y^*_{3,5} = y^*_{4,5} = y^*_{1,6} = y^*_{2,6} = y^*_{3,6} = y^*_{4,6} = 0$
$t^*_{1,1} = t^*_{3,1} = t^*_{4,2} = t^*_{1,3} = t^*_{4,3} = t^*_{4,4} = t^*_{4,5} = t^*_{1,6} = t^*_{2,6} = 500$ MW, $t^*_{2,1} = t^*_{3,3} = 750,\ t^*_{3,2} =$ $t^*_{1,4} = t^*_{3,4} = t^*_{2,5} = t^*_{4,6} = 1000$ MW, $t^*_{2,2} = 600$ MW, $t^*_{1,5} = 875$ MW, $t^*_{4,1} = t^*_{1,2} = t^*_{2,3} =$ $t^*_{2,4} = t^*_{3,5} = t^*_{3,6} = 0$
$x^*_{4,1} = x^*_{1,2} = x^*_{2,3} = x^*_{2,4} = x^*_{3,5} = x^*_{3,6} = 1,\ x^*_{1,1} = x^*_{2,1} = x^*_{3,1} = x^*_{2,2} = x^*_{3,2} = x^*_{4,2} = x^*_{1,3} =$ $x^*_{3,3} = x^*_{4,3} = x^*_{1,4} = x^*_{3,4} = x^*_{4,4} = x^*_{1,5} = x^*_{2,5} = x^*_{4,5} = x^*_{1,6} = x^*_{2,6} = x^*_{4,6} = 0$
$c^*_{4,1} = c^*_{1,2} = c^*_{2,3} = c^*_{3,5} = 1,\ c^*_{1,1} = c^*_{2,1} = c^*_{3,1} = c^*_{2,2} = c^*_{3,2} = c^*_{4,2} = c^*_{1,3} = c^*_{3,3} = c^*_{4,3} = c^*_{1,4} =$ $c^*_{2,4} = c^*_{3,4} = c^*_{4,4} = c^*_{1,5} = c^*_{2,5} = c^*_{4,5} = c^*_{1,6} = c^*_{2,6} = c^*_{3,6} = c^*_{4,6} = 0$
$v^*_{1,1} = v^*_{2,1} = v^*_{3,1} = v^*_{2,2} = v^*_{3,2} = v^*_{4,2} = v^*_{1,3} = v^*_{3,3} = v^*_{4,3} = v^*_{1,4} = v^*_{3,4} = v^*_{4,4} = v^*_{1,5} = v^*_{2,5} =$ $v^*_{4,5} = v^*_{1,6} = v^*_{2,6} = v^*_{4,6} = 1,\ v^*_{4,1} = v^*_{1,2} = v^*_{2,3} = v^*_{2,4} = v^*_{3,5} = v^*_{3,6} = 0$
The value of objective function =74906$ in time horizon.

CONCLUSION

In this paper, the nuclear power plant preventive maintenance scheduling problem has been formulated under uncertainty. The concerned problem is formulated as mixed integer programming model. In our proposed model the power demand is represented by fuzzy parameters. The obtained results proved that the fuzzy programming approach is more realistic for practical problems such as the nuclear power plant preventive maintenance scheduling problem. A case study has been given to clarify the efficiency of the proposed approach.

REFERENCES

(1) P. C. Salvador; Optim. Eng.; 12, 333 (2011).
(2) I. B. Gertsbakh; "Reliability theory with applications to preventive maintenance", Springer, Berlin, Germany (2000).

(3) H. H. Zurn, and V. H. Quintana; IEEE Transactions on Power Apparatus and Systems; 96, 984 (1977).
(4) L. B. Kralj, and R. Petrovic; European Journal of Operational Research; 35, 1 (1988).
(5) Z. A. Yamayee; IEEE Transactions on Power Apparatus and Systems; 101, 2770 (1982).
(6) W. R. Christiaanse, and A. Palmer; IEEE Transactions on Power Apparatus and Systems; 91, 137 (1972).
(7) K. Shimomura, H. Ishitoku, S. Sakurai, and F. Hirose; Hitachi Review; 51, 137 (2002).
(8) M. Ben-Daya, S. O. Duffuaa, and A. Raouf; "Maintenance, Modeling and Optimization", Kluwer, Boston, USA (2000).
(9) J. F. Dopazo, and H. M. Merill; IEEE Transactions on Power Apparatus and Systems; 94, 1537 (1975).
(10) L. F. Escudero, J. W. Horton, and J. F. Scheiderich; IEEE Winter Meeting; 264 (1980).
(11) V. Gurevich, S. Frant, and A. Bianu; "Generating units maintenance scheduling optimizing production cost and reliability", Power Systems Computation Conference, Dresden, Germany, (1996).
(12) A. M. Agogino, S. Y. Chao, and Z.Lee; "Development of Decision Strategies for Scheduling Outages of Power Plant", Final Report 1997-98 for MICRO project 97-2004,(1999).
(13) H. H. Zurn, and V. H. Quintana; IEEE Transactions on Power Apparatus and Systems; 94, 665 (1975).
(14) D. Chattopadhyay; IEEE Transactions on Power Systems; 19, 1181 (2004).
(15) E. K. Doyle; European Journal of Operational Research; 154, 673 (2004).
(16) E. L. Silva, M. Morozowski, L. G. S. Fonseca, G. C. Oliveira, A. C. G. Melo, and J. C. O. Melo; IEEE Transactions on Power Systems; 10, 695 (1995).
(17) M. K. C. Marwali, and S. M. Shahidehpour; IEEE Transactions on Power Systems; 13, 3 (1998).
(18) P. C. Salvador; European Journal of Operational Research; 184, (2008).
(19) P. C. Salvador; International Journal of Manufacturing Technology and Management; 22, 1 (2011).
(20) J. Yellen, T. M. Al-Khamis, S. Vemuri, and L. Lemonidis; IEEE Transactions on Power Systems; 7, 2 (1992).
(21) I. M. El-Amin, S. O. Duffuaa, and M. T. Abbas; Journal of Electric Power Systems Research; 54, 2 (2000).
(22) C. E. Lin, C. J. Huang, C. L. Huang, C. C. Liang, and S. Y. Lee; IEEE Transactions on Power Systems; 7, 3 (1992).
(23) L. B. Kralj, and N. Rajakovic; Electric Power and Energy System; 16, 4 (1994).
(24) R. E. Bellman, and L. A. Zadeh; Management Science; 17, (1970).
(25) D. Dubois, and H. Parade; "Fuzzy sets and systems, Theory and Aplplications", Academic Press, New York (1980).