MAINTENANCE COST MODELS IN DEREGULATED POWER SYSTEMS UNDER OPPORTUNITY COSTS

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ABSTRACT

Maintenance costs in deregulated power systems play an important role. This mainly includes direct costs associated with material and labor costs; and indirect costs associated with spare parts inventory, shipment, test equipment cost, indirect labor, and opportunity costs. The cost function is used as the sole or main component of the objective function in maintenance scheduling and planning activities. The cost has been modeled in literature with several representations for centralized power systems. With deregulation of power industries in many countries the costs representation to be used within the maintenance model in the decentralized power systems has become an important research question. This paper presents modeling of different components of maintenance costs that can be used within the main objective function of the maintenance scheduling and planning problem for the deregulated environment.

KEY WORDS

Maintenance, opportunity cost, deregulated power system

1. Introduction

The impact of failures varies over products and systems causing inconveniences, high costs, and significant economic losses. The main cause of these failures is poor maintenance. Maintenance is defined as any action which retains non-failed units in a reliability wise satisfactory and operational condition; and if they have failed, restores them to a reliability-wise satisfactory and operational condition [7]. There are different types of maintenance strategies used in practice. They include:

- Corrective Maintenance (CM),
- Predictive Maintenance (PdM),
- Preventive (Scheduled) Maintenance (PM),
- Reliability Centered Maintenance (RCM)

The application of these models depends on the nature of the system. In order to avoid premature failures of an important system leading to unplanned and costly outages, it is vital to carry out maintenance at regular intervals. The goal of maintenance modeling and scheduling in a system is to allocate a proper maintenance timetable for the system while maintaining its reliability, reducing total operating cost, extending equipment lifetime, etc. In this work, we concentrate on maintenance modeling of power generators of a generating company in the deregulated environment.

In power systems, generators must be maintained in order to supply electricity with a high reliability level. Regardless of the maintenance type carried out, the generator units must be taken out of service for a period of time ranging from several hours to several days for maintenance [16].

In the centralized power systems where the power utilities are vertically integrated, the operation and planning of generation and transmission are coordinated centrally among the integrated utilities, in order to improve the reliability and reduce the costs. The maintenance activities of generating units are coordinated centrally by sharing operating reserves [16]. In this case, full information is available for maintenance planning and scheduling of power generators. Depending on the load and the availability of other generators, the effect of maintenance outages can be minimal or critical. Therefore, maintenance will be performed at the most suitable time from reliability point of view (i.e. low load period). In the centralized power system, the operator is responsible for scheduling maintenance.

Nowadays, the electricity industries in many countries have moved from centralized structure separating the integrated power system entities into a deregulated power system. In doing so, the power segments which were vertically integrated in the centralized structure are unbundled into [20]:

- Generation companies (GENCOs);
- Transmission companies (TRANSCOs);
- Distribution companies (DISCOs).

An independent system operator (ISO) operates a power system and through which these three business entities participate in the operation through it. These segments can be considered as separate entities. Each one has certain responsibilities in order to run the system smoothly. Also, each segment has its own objective of maximizing profit. Restructuring is a very complex process and differs from one country to another. In general, the generation sector has been deregulated in many countries [16], while transmission and distribution sectors are still working within regulated environment in some countries. The main aim of restructuring is to let market forces drive the price of electric supply and reduce the cost of electricity through increased competition. Restructuring creates an open market environment by allowing competition in power supply and allowing consumers to choose their supplier of electric energy [16].

Changes in the power industries from a regulated to a deregulated structure result in invalidating the centralized maintenance system. In deregulated environment competition replaces cooperation of centralized system. The decision when to take the generator out of service depends on different criteria such as the effect of maintenance outages on the overall system, customer reliability (losing opportunity), and losses in revenue.

There are different costs associated with generator maintenance activities in deregulated power systems. These costs influence on generator maintenance scheduling and planning activities. Reducing the maintenance cost is one of the main objectives in power system maintenance scheduling problems. As the major factor in maintenance scheduling problem formulation the maintenance cost needs to be carefully modeled to reflect the real-world situations. It must be accurately quantified, and otherwise the optimal solution found need not match with the real optimum

The maintenance models in the deregulated power systems are formulated as a single- or multiple-objective optimization problem. The maintenance scheduling model for deregulated power systems should include various cost functions. This paper concentrates on modeling maintenance costs and opportunity costs for generating companies GENCOs in deregulated power system. We will also discuss the strengths and weaknesses of these cost representations as well as the assumptions made.

The reminder of this paper is arranged as follows. Section 2 is a literature review about deregulated power systems and maintenance modeling. Section 3 presents our investigations on maintenance cost representations within maintenance scheduling models for deregulated power systems. It details developed models where we consider direct, indirect and opportunity costs. An implementation of a small case study is illustrated in section 4. Section 5 concludes the paper.

2. Literature Review

In literature, different maintenance models have been established to consider the decision criteria of when to perform maintenance. Maintenance cost in power systems can be divided into two types: direct and indirect costs. Labor costs, spare parts costs, and maintenance cleaning material costs are examples of *direct maintenance costs*. On the other hand, *indirect maintenance costs* include inventory costs, shipment costs, indirect labor costs, test equipment costs, etc [14]. Most researchers concentrate only on total (constant or variable) maintenance direct costs [9, 16].

Finding the actual maintenance costs for deregulated power systems is not easy. In literature there are two approaches used to quantify maintenance costs; a) *fictitious* cost approach to penalize the deviation from the ideal maintenance schedules; and b) *window* approach assuming maintenance costs are constant over the planning horizon [31]. A variety of different models presented in literature considered different cost factors associated with maintenance. [16] presented a general model for maintenance scheduling. The authors used maintenance costs of generating units and the energy production cost within the objective function. This model has been described in different publications with different objective functions [17, 18, and 19], such as minimizing total operating cost, minimizing loss of revenue, etc., but using the same maintenance cost function. The authors also used the window approach to minimize the risk by using the fictitious cost. This however need not be the ideal situation where the actual maintenance cost is calculated from real data.

A simple representation of maintenance cost was given in [9]. The objective function was to minimize the sum of the overall fuel and maintenance costs. The maintenance cost was calculated using the same approach as discussed above.

The model in [25] focuses on improving reliability by maintaining the units as early as possible. The model is derived from an optional cost minimization model given in [29] to overcome maintenance cost.

[4] developed a model that considered the tradeoff between short and long-term objectives to determine optimal maintenance profile generators. All the major *costs* associated with maintenance, namely, direct maintenance expenses as well as opportunity costs such as, foregone spot market revenue, replacement costs and penalties for not meeting contractual obligations are explicitly recognized in the model. Clearly, maintenance cost representations in this model differ from those presented earlier.

The uncertainties associated with load forecast, price of fuels and maintenance costs, available recourses, and maintenance crew availability may affect the optimal solution of maintenance scheduling problems. [19] provided with two ways to handle the uncertainties; namely probabilistic modeling and fuzzy modeling. The uncertainties associated with the maintenance costs are due to changes in labor and spare parts availability and prices, weather conditions, and availability of maintenance crew. The authors presented a method for modeling maintenance cost uncertainties using fuzzy sets. The uncertainties of the maintenance cost have been modeled by triangular membership function, where the most probable cost value for each unit has a maximum membership.

In addition to the classical maintenance cost, the maintenance model for deregulated power systems should also include opportunity costs, and failure costs. The opportunity cost was introduced as influencing factor in modeling maintenance in restructured power system [20, 21]. A mathematical model for real-time pricing of electricity was given in [20]. It includes selected ancillary services and incorporates constraints on power quality and environment impact that often influence the operation of a power system. The same authors derived optimal nodal specific real-time prices both for real and reactive power that incorporate additive premia, or opportunity costs, reflecting the effects of the various engineering and environmental operating constraints [21]. The opportunity cost was introduced to the model of real-time price of electricity.

Recently, [12] has discussed maintenance costs in a different way. The model investigated three different costs associated with different maintenance methods. These costs are failure, preventive maintenance, and interruption costs. A risk model is introduced in [6]. It simulates the risk of losing revenue when facing random generator outages.

The cost of maintenance for applying a particular maintenance strategy is different from one GENCO to another. [10] conducted a survey on maintenance policies in electric utilities among different countries. Different maintenance strategies were used in different countries. These include reliability-centered maintenance (RCM), continuous monitoring of the generator units, predictive maintenance (when needed) periodic inspection, and scheduled maintenance (fixed intervals). These strategies are different in terms of quality and cost. The study shows that RCM, being the highest quality, provides longer uptimes, lower costs, better control and decisions, and better use of labor. [12] proposed reliability-centered asset maintenance (RCAM) method, and derived a quantitative relationship between PM of assets and total maintenance cost. The main stages of RCAM include system reliability analysis, component reliability modeling, and system reliability and cost/benefit analysis. In the proposed cost analysis, [12] considered the cost of failure, the cost of PM, and cost of interruptions. In modeling the cost of PM, [12] include the PM strategy. In [14], the cost of maintenance was unknown. Consequently, various cost functions (linear, quadratic, and exponential) were investigated to consider the behavior of the maintenance cost.

It follows from the above discussion that different cost components have an affect on maintenance scheduling. However, there is a need for a single model which incorporates all cost components to analyze the effect of different maintenance strategies for GENCOs. Also, many of the cost components suggested in the literature are assigned to fixed values, restricting their use in optimization models. In the current work, we investigate and model all cost factors that affect maintenance activities of deregulated GENCOs, and demonstrate the utilization of the developed cost models in maintenance planning and scheduling.

3. Maintenance Models for Deregulated Power Systems Using Opportunity Costs

The maintenance models in the deregulated power systems are formulated as an optimization problem with single and multiple objectives and a set of constraints. The following notations are used to describe the formulation in this sections and maintenance cost representation in the following sections.

Notations:

C_{it} : Generator maintenance cost for generator *i* at time *t* ($)

c_{it} : Generation cost of generator *i* at time *t*

g_{it} : Power generation of generator *i* at time *t*

x_{it} : Generator maintenance status, 0 if generator is off-line for maintenance; 1 if it is on.

opl_{it} : Losses of profit for GENCO(*i*) during maintenance at time *t*

opi_{it} : Inconvenience to the user due to planned generator maintenance at time *t*, which will affect the decision in the next electricity supply contract (cost of losses of goodwill of a GENCO(*i*))

$oplf_{it}$: Losses of profit for GENCO(*i*) during failure at time *t*

$opif_{it}$: Inconvenience to the user due to generator failure which will affect the decision in the next electricity supply contract (cost of losses of goodwill of a GENCO(*i*))

$oppf_{it}$: Penalty that GENCO(*i*) should pay to the pool in case of a failure at time *t*

ICf_{it} : Interruption cost because of failure

VLP_{it} : Value of lost Production

ORC_{it} : Outage-Related Costs

ORS_{it} : out-Related Savings

P_{ij} : Generator output of generator-*i* at period-*j*

L_{it} : Labor cost for generator *i* at time *t* ($)

M_{it} : Material cost for generator *i* at time *t* ($)

IM_{it} *:* Indirect material cost for generator *i* at time *t* ($)

IL_{it} *:* Indirect labor cost for generator *i* at time *t* ($)

Cpm_{it} : Cost of preventive maintenance (PM) for generator *i* at time *t* ($)

Cf_{it} : Cost of failure (CM) for generator *i* at time *t* ($)

f^{i} : Cost of repair or replacement of generator *i* ($)

λ^{it} : Failure rate for generator *i* at time *t* ($)

MSC^{i} : Different maintenance strategy

$\tilde{f}$: Time to failure

$\tilde{r}$: Time to repair

u : Repair rate

f_i : Probability of failure for generator *i*

$g^{t}_{i,sched}$: Power (MW) scheduled to be supplied by generator *i* at time *t*

MCP^{t} :. Day-ahead market clearing price at time *t($/MWh)*

S^{t} : Real time hourly spot market price at hour *t*

x : Random variable over (-∞,∞)

Y_1, Y_2, M_1 and M_2 : Random variables

$\bar{g}_i$: Upper real power limit of unit *i*

N_f : Number of failures

[16] developed the following model:

$$Min\sum_{t}\sum_{i}\{C_{it}(1-x_{it})+c_{it}g_{it}\} \tag{1}$$

This is subject to system and maintenance constraints. This formulation is a mixed–integer programming since x_{it} is an integer variable and g_{it} is continuous. In the objective function the first term represents maintenance cost of generator units and the second is the energy production cost. The overall objective is to minimize the total maintenance and production costs over the scheduling period. The maintenance constraints considered include maintenance windows, crew and recourses availability, seasonal limitations, desirable schedule, fuel and emission. System constraints represent the peak load balance, transmission flow limits and allowable unreserved energy checked by ISO.

The production cost is usually the dominant part of the objective function (1). Production cost calculation however, often requires many approximations or computationally intensive methods. It was reported in the literature that minimizing production cost (which is the main part of the operating cost for thermal plants) is an insensitive objective for the maintenance scheduling problem [28]. There are other cost components that can be sensitive to be considered in the maintenance model in the competitive deregulated market. The modeling of these other costs along with the maintenance costs are discussed in the following sub-sections.

A. Direct Maintenance Costs

These are the costs of preventive maintenance (PM) actions such as planned maintenance, replacement of a component before failure. This includes:

- Labor cost: This can be quantified by multiplying the duration of the maintenance in hour by the hourly rate of the technicians who perform the generator maintenance.
- Maintenance material cost: This is equal to the cost of the materials being used while carrying out the generator maintenance.

B. Indirect Maintenance Costs

The indirect costs can be divided into two:

- Indirect labor costs: These are other labor costs. For example, health care, social security, and training. This can be quantified by a percentage of labor yearly salary.
- Indirect material costs: These are other material costs. For example, inventory, test equipment, and shipment cost. These can be quantified by a percentage of spare part/material acquisition cost.

Considering the direct and indirect maintenance costs, the cost of maintenance is represented by the following:

$$Cpm_{it} = \sum_{i}\sum_{t}[L_{it} + M_{it} + IM_{it} + IL_{it}] \qquad (2)$$

C. Cost of Failure

This is the cost of corrective maintenance (CM) due to failures. This includes repair cost and loss of revenue due to no generation of energy. Refereeing to [15] the cost of failure can be modeled as,

$$Cf_{it} = \lambda^{it}(MSC^{i}) \cdot f^{i} \qquad (3)$$

Fitting a probabilistic distribution of a generator failure data to represent its operating cycle may be not appropriate, because a probabilistic distribution requires a large statistical data which is not available since generator failure rarely happens. In contrast, with fuzzy representation, the inherent uncertainty of the transition rates resulting from insufficient data collocation can be handled more appropriately [3]. The failure rate using fuzzy representation ($\tilde{\lambda}$) can be modeled as follows:

$$\tilde{P}_{up} = 1/[1 + \tilde{r}\cdot(1/\tilde{f})); \qquad (4)$$

$$\tilde{P}_{down} = 1/[1 + (1/\tilde{r})\cdot(\tilde{f})] \qquad (5)$$

Where, $\tilde{P}_{up}$, $\tilde{P}_{down}$ are the probability that a generator unit being in the success and failure rate, respectively. Also $\tilde{f}$, $\tilde{r}$ are time to failure and time to repair, respectively. The failure rate $\tilde{\lambda}$ and repair rate $\tilde{u}$ can be represented as follows:

$$\tilde{\lambda} = 1/\tilde{f} \qquad (6)$$

$$\tilde{u} = 1/\tilde{r} \qquad (7)$$

D. Opportunity Costs

The opportunity costs can be found in the two scenarios when generator is subject to planned maintenance or when it fails between the maintenance periods. We consider the following cases for modeling the opportunity costs:

- The losses of profit when the generator is under maintenance and when it went down because of a failure.
- The penalty which the GENCO has to pay to the pool (the alternative power provider) in case of generator failure. Since the pool (where all the generation companies feed their production of electricity) will go for another GENCOs with the higher market price
- The inconvenience that the user may incur during generator failure or planned maintenance which will affect the decision in the next electricity supply contract (losses of a goodwill of a GENCO).
- Cost of interruption, due to unavailability of electricity for customers.

E.1 The Losses of Profit of GENCO

Using the result obtained in [9], the expected losses of GENCO can be expressed in the following way:

$$Losses = [g_{i,sched}^{t} S^{t} - g_{i,sched}^{t} MCP^{t}] \qquad (8)$$

This term represents the GENCO losses when the generator goes down for planned maintenance or because of a failure. The Market Clearing Price (MCP) is given by the cost of last expensive bid offered to meet the final increment of load in that hour. The day-ahead MCPs are assumed to follow a normal distribution. Therefore, the generators can then estimate MCP for each hour of the day from normal distribution of historical MCP. The Real-time hourly spot market price can vary randomly from low values during the off-peak periods to very large values during peak loads. The spot market price is assumed to be a few times more than the MCP in most cases but can reach very high values occasionally and can even be less than the MCP during the off-peak periods [9]. The real-time hourly spot market price (S) is modeled using:

$$S^{t} = MCP^{t}[1 + z] \qquad (9)$$

Random variable z is generated as follows. Let Y_1 be a standard Normal random variable and Y_2 be another random variable following the standard Cauchy distribution [24]. Let $M = (M_1, M_2)^T$ be a bivariate random variable that takes the value $(0,1)^T$ with probability 0.1 and the value $(1,0)^T$ with probability 0.9. Let

$$Y = M_1 Y_1 + M_2 Y_2 \text{ and let} \qquad (10)$$

$$z = |Y| \quad \forall \quad t \in (Peak \quad hours) \qquad (11)$$

$$z = Y_1 \quad \forall \quad t \in (Offpeak \quad hours) \qquad (12)$$

This ensures that the real-time hourly spot market price is greater than the day-ahead MCP for peak hours but can be lower than the day-ahead MCP for off-peak periods. A few random spikes in hourly spot market prices are accounted by Cauchy distribution [6].

E.2 The GENCO Penalty Cost to Pool

The GENCO penalty cost to the pool is the cost that GENCO should pay to the pool in case of a failure. This amount can be assumed to be the profit that the GENCO would gain. Using the result obtained from [6], the expected profit of a GENCO can be expressed in the following way:

$$Penalty = [g_{i,sched}^{t} MCP^{t} - C_{i}(g_{i,sched}^{t})] \qquad (13)$$

This term represents the penalty cost that the GENCO will pay to the pool in case where the generator goes down because of a failure.

E.3 The Inconvenience Cost (Losses of Customer Goodwill)

The inconvenience cost that the user may incur during generator failure or during planned maintenance will affect the decision in the next electricity supply contract. It can be represented as the losses of GENCO goodwill. The goodwill is like customer's loyalty to the company due to its good service/reputation. The cost of lost sales, penalty of lost demand, damaged cost or holding and stockout costs are different representations of losses of goodwill in many publications [1, 11, 16 and 28]. Using decision theory terminology, goodwill cost may be assessed through *pricing-out* the loss of customer loyalty. This may be interpreted as the maximum price that the supplier is willing to pay in order to avoid losing customer loyalty. In GENCO, each generator may have different cost of losses of goodwill depending on their importance in supplying electricity to very important customers and the amount of power they produce. These costs can form the cost of losses of goodwill for specific

GENCO. For, simplicity, we will content by assuming that the losses of goodwill will be constant.

$$\text{Losses of goodwill} = \pi \tag{14}$$

E.4 Interruption Cost

The interruption cost is the economic losses that the customer may incur during generator failure [13]. An example of the interruption cost for large industrial customer can be expressed as follows:

$$ICf_{it} = VLP_{it} + ORC_{it} - ORS_{it} \tag{15}$$

The Value of lost Production is equal to customer's expected revenue without outage minus its revenue with outage. The outage-related costs are the direct costs incurred because of outage. And the outage-related saving costs are cost savings from the outage, such as cost of unused fuel and cost of unused raw materials. The outage-related cost can be obtained from real date or can be approached by regression models [13]. In GENCO each generator may have different interruption costs depending on their importance in supplying electricity to very important customers and the outages/saving costs. These costs will form the cost of losses of goodwill for a specific GENCO.

From above, the opportunity costs can be modeled as follows:

- In case of no failure:

$$\text{Opportunity costs} = (opl_{it} + opi_{it}) \tag{16}$$

- In case of a failure:

$$\begin{aligned}\text{Opportunity costs} &= (opl_{it} + opi_{it} + oplf_{it} + \\ &\quad opif_{it} + oppf_{it} + ICf_{it})\end{aligned} \tag{17}$$

E. The Complete Model

In this section, we summarize the complete cost model.

E.1 Complete Cost Model under no Failure

$$CostA = \sum_i \sum_i \{[Cpm_{it} + (opl_{it} + opi_{it})](1 - f_i)\}$$

$$= \sum_i \sum_i \left[\begin{array}{l} \{(L_{it} + M_{it} + IL_{it} + M_{it}) + \\ \{(g^t_{i,sched}\ S^t - g^t_{i,sched}\ MCP^t) \\ + \pi_{it})\} * (1 - f_i) \end{array}\right] \tag{18}$$

E.2 Complete Cost Model with Failures

$$CostB = \sum_i \sum_i \left[\begin{array}{l} \{Cpm_{it} + (opl_{it} + \\ opi_{it})\} + oplf_{it} + \\ opif_{it} + oppf_{it} \\ + ICf_{it} + (Cf_{it}) \end{array}\right] * (f_i) * (N_f) \tag{19}$$

$$= \sum_i \sum_i \left[\begin{array}{l} \{(L_{it} + M_{it} + IL_{it} + M_{it}) + \\ (g^t_{i,sched}\ S^t - g^t_{i,sched} \\ MCP^t) + \pi)\} + \{(g^t_{i,sched} \\ MCP^t - C_i(g^t_{i,sched})) + \\ (g^t_{i,sched}\ S^t - g^t_{i,sched} \\ MCP^t) + \pi_{it} + ICf_{it}\} + \\ (MSC^i)(\lambda^{it})f^i \end{array}\right] * (f_i) * (N_f) \tag{20}$$

E.3 The Expected Total Maintenance Cost Model

Now the total expected maintenance cost (Exp(C)) can be expressed as follows:

Exp (C) = Probability of no failure * Cost A + Probability of failure * Cost B * number of failures

$$\begin{aligned} &= \sum_i \sum_t \left[\begin{array}{l} \{(L_{it} + M_{it} + IL_{it} + M_{it}) + \\ \{(g^t_{i,sched}\ S^t - g^t_{i,sched}\ MCP^t) \\ + \pi_{it})\} \end{array}\right] * (1 - f_i) \\ &+ \left[\begin{array}{l} \{(L_{it} + M_{it} + IL_{it} + M_{it}) + \\ (g^t_{i,sched}\ S^t - g^t_{i,sched}\ MCP^t) \\ + \pi)\} + \{(g^t_{i,sched}\ MCP^t - \\ C_i(g^t_{i,sched})) + (g^t_{i,sched}\ S^t - \\ g^t_{i,sched}\ MCP^t) + \pi_{it} + \\ ICf_{it}\} + (MSC^i)(\lambda^{it})f^i \end{array}\right] * (f_i) * (N_f) \end{aligned} \tag{21}$$

4. Case Study

In the previous section, we have presented a full maintenance model with many maintenance cost factors. These cost factors are time dependent and considering them separately in maintenance time intervals is very difficult. In this section we consider a simple and small case study of maintenance scheduling using only the opportunity cost factors of the presented maintenance cost model (i.e. by omitting all other maintenance cost components of the cost model except the opportunity cost factors). This example is not very realistic; however, it can give some flavor on how the general case would look like.

In this case study, we will consecrate on the following opportunity costs:

1. *The losses of profit for GENCO*
2. *The GENCO penalty cost to the Pool*
3. *The inconvenience cost (Customer goodwill)*
4. *The interruption cost*

In doing so, the customized maintenance cost model is as follows:

$$= \sum_{i}\sum_{t}\left[(g_{i,sched}^{t}S^{t} - g_{i,sched}^{t}MCP^{t}) + \pi_{it}\right]^{*(1-f_{i})} + \begin{bmatrix}(g_{i,sched}^{t}S^{t} - g_{i,sched}^{t}MCP^{t}) + \\ (g_{i,sched}^{t}MCP^{t} - C_{i}(g_{i,sched}^{t})) \\ +(g_{i,sched}^{t}S^{t} - g_{i,sched}^{t}MCP^{t}) + \pi_{it}\end{bmatrix}^{*(f_{i})*(N_{f})} \quad (22)$$

Figure 4.1 Three-Bus System Example

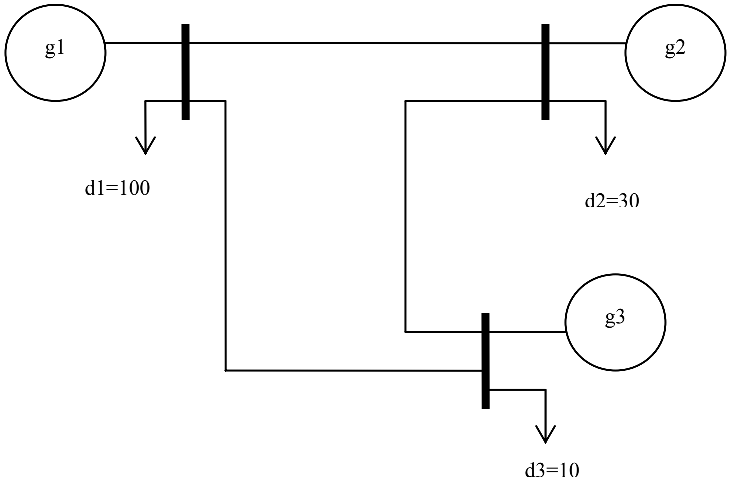


Table 4.1 Line Data for 3-bus System

Line	Ω/line	No. of lines	Cap/line (p.u.)
1-2	0.2	2	0.25
2-3	0.25	2	0.5
1-3	0.4	2	0.25

Table 4.2 Generator Data for 3-bus System

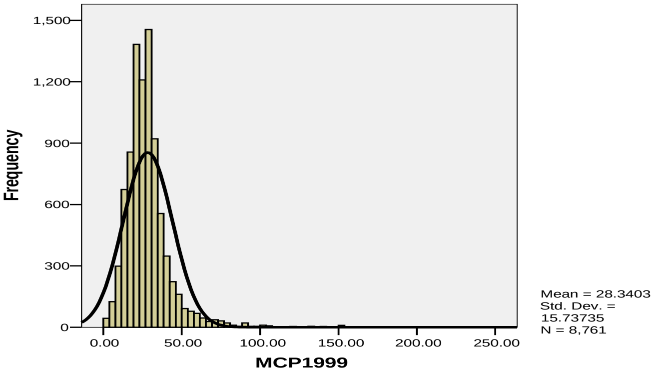
Unit	Min Cap (p.u.)	Max Cap (p.u.)	Cost ($)
1	0.5	2.5	10 g1
2	0.6	2.5	10 g2
3	0.6	3.0	10 g3

Assumptions:

- This study is done for one period of time
- Direct/Indirect maintenance costs are constant
- Minimal repair strategy is considered during failure with small repair time
- Failure rate is very small (ε)
- MCP obtained using market data of California State
- MCP is less than spot market price
- Interruption cost data obtained from [13]

In order to calculate opportunity costs, the MCP, Spot market prices, and Generation costs functions parameters must be obtained. The Day-Ahead MCP was estimated for each hour of the day from the normal distribution, using a historical data for MCPs for some GENCO in California (Fig. 4.1):

Figure 4.2 MCP for year 1999 of California State



The cost curve function is a quadratic cost function and each generator is assumed to supply 1 p. u. (MW)**.** The losses for generating units and the penalty to pool were calculated using equations (8 and 13), respectively. Using equation (22) the expected total costs of each generator, under a 90% reliability of the generator are as follows:

Table 4.3: Total expected costs for the three generating units

Costs	Generator 1	Generator 2	Generator 3
Cost A * 0.90	$360.9	$369.9	$405.9
Cost B * 0.1	$52.5	$54.5	$60.5
Total expected costs	$413.4	$424.4	$466.4

The expected maintenance cost for each generator where all opportunity costs are included are used with data in Tables 4.1 and 4.2 to formulate the maintenance model of the following form:

$$Min\sum_{t}\sum_{i}\{C_{it}(1-x_{it}) + c_{it}g_{it}\}$$

Benders Algorithm was used to solve this case. The optimal solution obtained in the 2^{nd} iteration with different schedule and value of objective function than the example presented in [16].

The solution is: Cost = 413, X_1=0, X_2=1, X_3=1

When comparing this result with the one obtained in [16] for the same three bus system, we can see that both the value of the schedule and the objective function were different. This is because of the opportunity cost factors mainly by incorporating loss of goodwill and interruption costs. Both goodwill and interruption costs affect the generators maintenance schedule. Also, both market clearing price and spot market price are critical factors which affect the price of electricity and indirectly affect the generators maintenance schedule. This yields the conclusion that any changes in the new maintenance cost components will be reflected in the initial schedule, and the final solution. Therefore, these costs components must be considered and carefully modelled and obtained to find an initial schedule for the GMS problem.

5. Conclusions

In the literature, researchers have focused much attention on maintenance scheduling problems for deregulated power systems in order to improve the economic posture of the generation companies. There are many cost components that can be sensitive to be considered in the maintenance scheduling model in the deregulated environment. In this paper, we have analyzed maintenance cost representations considering direct, indirect and opportunity costs to include in a maintenance scheduling model. Two models were developed in this paper reflecting failure and no failure status of a generator. The paper has shown that there exist other costs that affect the decision of when to take generator for maintenance. Also, the models took care of any sudden failure which may happen before or after any planned maintenance event. The opportunity costs which reflect customers or GENCO inconvenience in case of a failure are considered.

These cost models can be used to schedule more accurately maintenance activities of generators as well as to identify the best maintenance strategies over a period of time as they consider failure and opportunity costs. This will be one direction of our future research.

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