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Generator Maintenance Scheduling Models in Power Systems

Integrated Cost Models for Generator Maintenance Strategy
under Market Environment

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Abstract

Change from a regulated to deregulated structure means that, the centralized maintenance system is not valid any more. In the surveyed published literature, there is not a single model which incorporates all maintenance cost components to analyze the effect of different maintenance strategies for generator companies (GENCOs). The work enclosed in this thesis demonstrates that there is a considerable requirement for accurately modelling cost components of the maintenance model, to be used in maintenance scheduling for deregulated power system, in order to attain a superior schedule with major financial and operational impact.

This research investigates and models most cost factors that affect the maintenance activities of the deregulated GENCOs, and demonstrates the utilization of the developed cost models in maintenance scheduling. It also presents the data gathering process for the developed maintenance cost model. A generator maintenance scheduling model that considers direct and indirect maintenance costs, opportunity costs (i.e. loss of customer goodwill), effective maintenance strategies, failures, and interruptions is developed.

A Genetic Algorithm (GA) based approach is employed to achieve maintenance schedules to various generators maintenance scenarios. An Analytical Hierarchy Process (AHP) approach is proposed for modelling customer goodwill. The maintenance model was redeveloped under the Reliability Centred Maintenance (RCM) strategy to analyze the effect of a maintenance strategy on maintenance costs. Case studies are presented to demonstrate the utilisation of the developed models.

The investigation shows that the market prices, opportunity costs and maintenance strategy have an effect on the final maintenance schedule. The research demonstrates that the cost components are critical factors to achieve an effective maintenance schedule, and they must be considered and carefully modelled in order to reflect more realistic situation for maintenance scheduling of generator units in deregulation environment.

Keywords: Deregulate, Power systems, Generator maintenance scheduling, Maintenance costs, Opportunity costs, Customer goodwill, Genetic algorithm (GA), Analytical Hierarchy Process (AHP), Reliability Centred Maintenance (RCM).

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List of Symbols

| | |
|-------------------|-------------------------------------------------------------------------------------------------------|
| 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 (MW) of generator i at time t |
| y_{it} | Generator maintenance status, 0 if generator i is off-line for maintenance; 1 if it is on |
| x_{it} | Generator maintenance starts week, 1 if generator i maintenance starts, 0 otherwise |
| $oppl_{it}$ | Loss of profit (\$) due to maintenance or a failure of generator i at time t |
| opp_{it}^i | Loss of customer goodwill cost (\$) due to planned generator maintenance of generator i at time t |
| opp_{it}^f | Loss of customer goodwill cost (\$) due to failure of generator i at time t |
| opp_{it}^p | Penalty (\$) to the pool due to failure of generator i at time t |
| $ICf_{it}(s)$ | Interruption cost (\$) due to failure of generator i at time t for maintenance strategy s |
| VLP_{it} | Value of lost production (\$) for generator i at time t |
| ORC_{it} | Outage related costs (\$) for generator i at time t |
| ORS_{it} | Outage related savings (\$) for generator i at time t |
| 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 |
| $Cma_{it}(s)$ | Cost (\$) of maintenance actions for generator i at time t for maintenance strategy s |
| $Cf_{it}(s)$ | Cost (\$) of failure for generator i at time t for maintenance strategy s |
| $Cr_{it}(s)$ | Repair (or replacement) cost (\$) for generator i at time t for maintenance strategy s |
| $\lambda_{it}(s)$ | Failure rate for generator i at time t for maintenance strategy s |
| $g_{it,sched}$ | Power (MW) scheduled to be supplied by generator i at time t |
| MCP_t | Day-ahead market clearing price at time t (\$/MWh) |

| | |
|----------------------|---------------------------------------------------------------|
| SMP_t | Real time hourly spot market price (\$) at hour t |
| λ_{\max} | Maximum Eigen-value |
| CI | Consistency index |
| CR | Consistency ratio |
| \overline{CR} | Overall consistency ratio |
| RI | Random consistency index |
| e_i | Earliest period to begin maintenance of generator unit i |
| l_i | Latest period to begin maintenance of generator unit i |
| d_i | Duration of maintenance for generator unit i |
| s_i | Time period in which maintenance of generator unit i starts |
| \tilde{f} | Time to failure |
| \tilde{r} | Time to repair |
| u | Repair rate |
| f_i | The probability of generator unit failure |
| X_1, X_2, N_1, N_2 | Random variables |
| MPC_{it} | Market production cost \$/MW of generator i at time t |

List of Abbreviations

GENCOs Generation companies

TRANSCOs Transmission companies

DISCOs Distribution companies

GMS Generator Maintenance Scheduling

AHP Analytical Hierarchy Process

ISO Independent System Operator

CM Corrective Maintenance

PdM Predictive Maintenance

PM Preventive Maintenance

RCM Reliability Centred Maintenance

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Chapter 1

Introduction

Chapter 1: Introduction

1.1 Introduction

1.1.1 Overview

Electricity is a very effective and flexible form of energy. It is produced, then delivered and finally converted to light, heat, motion, or other forms of energy. The basic function of an electric power system is to supply its customers with electrical energy economically and continuously. Different countries have different power industry structures such as vertically integrated and unbundled electric power utilities. In a vertically integrated utility, the generation, transmission and distribution facilities are owned by that company. One of the disadvantages of the traditionally regulated industry is the lack of competition, which creates monopoly. Competition has become the key factor driving the deregulation process in the electric power industry. The key concept behind deregulation in almost every country is that no one company should have a monopoly. The deregulated power industry is faced with many problems such as how to operate the unbundled power systems economically and reliably, and how to minimize production and maintenance costs under the market competition. The market price is a factor that needs to be addressed in maintenance cost of a deregulated system. Maintenance cost is a major concern in the newly deregulated power industry due to the competitive framework in which companies operate. The cost function is used as the sole or main component of the objective function in maintenance scheduling and planning activities. With deregulation of power industries in many countries the representation of costs to be used within the maintenance model in the decentralized

power systems has become an important research question. The research described in this thesis is focused on market price considerations in maintenance costs in the deregulated industry environment.

1.1.2 Power Systems

In power systems, generators must be maintained in order to supply electricity with a high reliability level. Regardless of the maintenance strategies used the generating units must be taken out of service for a period of time ranging from several hours to several days for maintenance. Power systems world-wide significantly changed in the last decade following the decomposition of the centralized structure.

In the centralized power systems where the power utilities are vertically integrated, the operation, maintenance and planning of generation and transmission systems are coordinated centrally, in order to improve overall reliability and reduce cost. Depending on the load and the availability of other generators, the effect of maintenance outages can be minimal or critical. In the centralized power system, the operator is responsible for scheduling maintenance.

The electricity industries in many countries have moved from a centralized structure by separating the integrated power system entities into a deregulated power system (Shahidehpour and Marwali 2000). In doing so, the power segments which were vertically integrated in the centralized structure are unbundled. The main segments in the deregulated environments are:

1. Generation companies (GENCOs),
2. Transmission companies (TRANSCO's),

3. Distribution companies (DISCOs).

Each one of these segments has its own objectives for maximizing profit and each has certain responsibilities to the other in order for the system to operate smoothly. An independent system operator (ISO) operates the power system. 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.

The centralized maintenance system used in a vertical structure is not valid for deregulated structure. In a deregulated environment competition replaces the cooperation of a 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 and revenue lost. Also, customer goodwill (customer reliability or opportunity cost) is a factor that affects maintenance decisions in a deregulated environment, therefore this factor should be considered in maintenance costs. In the literature different maintenance models have been established to consider the criteria used in the decision of when to perform maintenance.

1.1.3 Maintenance Strategies

In order to avoid premature failure of an important system leading to unplanned and costly outages, it is vital to carry out maintenance at regular intervals. The goal of maintenance modelling and scheduling in a system is to allocate a proper maintenance timetable for the system while maintaining its reliability, reducing total operating cost and extending equipment lifetime. There are different types of maintenance strategies used in practice. They include:

1. Corrective Maintenance (CM),
2. Predictive Maintenance (PdM),
3. Preventive (Scheduled) Maintenance (PM),
4. Reliability Centred Maintenance (RCM).

CM corresponds to the actions that occur after systems failure. PM is a planned activity which is performed in order to increase overall system availability and reliability. PdM is periodic inspections or continuous monitoring performed when it is deemed necessary. The PdM routines contain a set of programs named RCM. RCM is a sophisticated maintenance strategy. It is the concept of developing a maintenance method based on the reliability of a variety of critical components of a system.

Application of these strategies depends on the nature of the system. Several types of maintenance models exist, for example predictive maintenance and preventive maintenance models addressing different maintenance strategies. In this thesis the effect of RCM strategy on modelling maintenance scheduling of the deregulated power system environment will be investigated.

1.1.4 Maintenance Scheduling Problems

Infrequent maintenance of equipment increases the number of failures. However, recurrent maintenance may increase maintenance cost. Therefore, an optimal maintenance schedule is imperative. The optimal maintenance policy can be defined as a schedule for maintenance activity such that overall cost of maintenance is reduced. The main objective in maintenance scheduling is to search for the lowest production and maintenance costs (Silva et al. 2001).

In a power system, maintenance is either generator units or transmission lines. Because of its impact on other planning activities, it is very important for the successful operation of a power system to determine when its facility should be taken off-line for maintenance. The ISO is responsible for maintenance scheduling in a power system utility. In a centralized structure the operator is able to solve the maintenance scheduling problem centrally and produce a maintenance schedule. When developing maintenance schedules for a deregulated structure, the schedules will be driven more by market prices than other costs. Researchers have classified power system unit maintenance scheduling (long-term and short-term) as a large scale problem. Maintenance scheduling objectives are either economically based or reliability based (Endrenyi et al. 2001), (Dahal et al. 1999), (Dahal et al. 2000a), and (Dahal et al. 2000b). There are some typical constraints for maintenance scheduling problems such as maintenance window, crew, load and resource. In a deregulated power systems market constraints such as contractual commitments and the electricity market should be taken into consideration (Bier and Glyer 2002), (Sanders 2002), (Shahidehpour and Marwali 2000), and (Stephenson and Paun 2001). This research develop a market oriented maintenance scheduling model which minimizes the total expected maintenance costs subject to system and maintenance constraints.

1.2 Objectives of the Thesis

1.2.1 Research Motivation and Justification

An accurate and realistic cost model is vital in order to plan maintenance activities for deregulated GENCOs. In a competitive market environment the cost model needs to consider not only the direct maintenance cost, but also costs associated with missed

opportunities, effective maintenance strategies, and interruptions. The cost model for a centralized system is no longer valid. The recent literature has reported some work towards formulating the maintenance scheduling problem using limited factors.

This thesis will investigate the opportunity costs in modelling maintenance scheduling for a deregulated environment to reflect the inconvenience due to system unavailability. The opportunity costs may be qualitatively assessed by estimating the loss the owners and customers incur during the system downtime.

1.2.2 Research Objectives

As noted earlier, power systems can be divided into three functional zones. This research concentrates on the development of maintenance and opportunity cost models and investigates solutions. The basic objective of the research described in this thesis is to investigate and model all cost factors that affect the maintenance activities of the deregulated GENCOs, and demonstrate the utilization of the developed cost models in maintenance planning and scheduling. The objectives of this research have been accomplished by focusing on the following tasks.

1. Analyzing a wide range of maintenance modelling approaches for maintenance of generators in power systems.
2. Analyzing a wide range of maintenance scheduling approaches for maintenance of generators in power systems.
3. Developing maintenance models for generator units.
 - a. Investigating and modelling all direct and indirect maintenance costs for different maintenance strategies.

- b. Investigating and modelling the opportunity cost, generation loss, interruption cost, and loss of customer goodwill cost.
4. Formulating maintenance scheduling problems with the use of the developed cost models for GENCOs.
5. Investigating a wide range of Mathematical, Heuristic or Decision Making techniques and developing an appropriate method for formulating maintenance scheduling problems.
6. Demonstrate the use of the developed cost model using different case studies.

Initially this thesis will review and analyze a wide range of maintenance modelling and scheduling approaches reported in the literature for maintenance of generators in power systems. Maintenance strategies will be formulated and their co-ordination in a deregulated electricity market will be investigated. These formulations will be based on potential revenue maximization and opportunity costs minimization while meeting constraints such as maintenance windows, crew availability, load demands, electricity market as well as technical issues related to power systems. Different maintenance strategies will be studied in this thesis. We start by presenting the famous GMS models. Then, maintenance costs, opportunity costs and failure costs will be defined and quantified in the maintenance model. In this thesis we develop a model that covers most of the uncertainties under opportunity cost. GENCOs losses of profit and customer goodwill are factors that will be introduced to the maintenance model. A technique to solve the final model will be developed to create a solution. Then we formulate case studies to solve the GMS model.

1.3 Thesis Contributions

The contributions of this thesis are as follows:

1. Review of the existing maintenance scheduling and maintenance cost models of generating units in centralized and deregulated power systems.
2. Development of cost components associated with generator maintenance activities in a deregulated environment and inclusion of them within an integrated maintenance cost model.
3. Data gathering process for the integrated maintenance cost model.
4. Formulation and solution of generator maintenance scheduling problems using the maintenance cost models for GMS case studies of different size.
5. Application of Analytical Hierarchy Process in modelling loss of customer goodwill for a GENCO to stay competitive in the market environment.
6. Formulation and solution of market oriented maintenance scheduling model for a GENCO under RCM strategy.

1.4 Thesis Outline

This thesis establishes a framework for maintenance cost modelling and scheduling of a deregulated power system. A wide range of case studies are presented to illustrate the possible application of the proposed models using GA and MCDM techniques. There are seven chapters in this thesis. A brief introduction on centralized and deregulated power systems structure and of maintenance costs are presented in Section 1.1.2. The basic concepts related to power system maintenance modelling, maintenance strategies and scheduling are given in Sections 1.1.3 and 1.1.4. Chapter 1 also outlines the aim,

objectives and the main contributions of the thesis. The associated publications are listed in the last section. The rest of the thesis is organized as follows:

- Chapter 2 introduces a wide range of general maintenance strategies. It also reviews the available literature on maintenance scheduling and maintenance cost models. The basic power system maintenance modelling and scheduling techniques such as deterministic and heuristics are presented in this chapter.
- The formulation of maintenance cost models is presented in Chapter 3. First, the operation and maintenance of centralized and deregulated power systems is described in this chapter. Then, the maintenance scheduling problem objectives and constraints for deregulated power systems are presented. In this chapter opportunity costs, failure costs, and interruption costs are modelled. Finally, the complete cost model under both failure/no failure scenarios is developed.
- Chapter 4 reviews GA applications used in maintenance scheduling of the power system. Also, it illustrates the design and the implementation of GA for generator maintenance scheduling problems. This chapter also examines the effects of various parameters of the developed models through two (small and large)-case studies. Results and sensitivity analysis are also presented in this chapter.

- Chapter 5 introduces decision making methods. Aspects related to opportunity cost modelling are considered in this chapter. These include: a discussion of the opportunity cost of loss of customer goodwill which is one of the factors that need to be considered in the deregulated competitive environment, and AHP the technique employed to model loss of customer goodwill. The proposed technique is illustrated and applied to a case study.
- Chapter 6 presents a practical methodology for the implementation of RCM strategy on the developed model. First, it introduces relation between preventive maintenance policies and RCM. Then, it explains the methodology of RCM strategy. The formulation of the maintenance cost model under RCM is presented in this chapter. Finally, an implementation of the developed model in a case study is illustrated.
- Chapter 7 summarizes the thesis and highlights both the conclusions and the future work

1.5 Associated Publications

The following papers resulted directly from the research activities presented in this thesis.

Journal papers:

1. Al-Arfaj, K. A. and Dahal, K. P. (2009) “Modelling Generator Maintenance Costs in Deregulated Power Systems”, submitted to *Journal of Electric Power Systems Research*.

Conference papers:

1. Al-Arfaj, K., Dahal, K. P. and Azaiez, M. N. (2007) “Maintenance Cost Models in Deregulated Power systems Under Opportunity Costs”, *Proceedings of the 7th IASTED International Conference on Power and Energy Systems (EuroPES)*.
2. Al-Arfaj, K. A. and Dahal, K. P. (2008) “Modelling Loss of Customer Goodwill due to Generator Maintenance using Analytical Hierarchy Process”, *presented in the 19th International Conference on Multiple Criteria Decision Making*.

Workshop papers:

1. Al-Arfaj, K. and Dahal, K. (2005) *Modelling of Power System Preventive Maintenance Policies*, Sixth Informatics Workshop for Research Students, School of informatics, University of Bradford.
2. Al-Arfaj, K. and Dahal, K. (1006) *Cost representations for maintenance scheduling models in deregulated power system*, Seventh Informatics Workshop for Research Students, School of informatics, University of Bradford.
3. Al-Arfaj, K. and Dahal, K. (2007) *Review of optimization techniques applied on maintenance scheduling problem of power systems*, Eighth Informatics Workshop for Research Students, School of informatics, University of Bradford.
4. Al-Arfaj, K. and Dahal, K. (2008) *Modelling Loss of Customer Goodwill due to Generator Maintenance Using Analytical Hierarchy Process*, Ninth Informatics Workshop for Research Students, School of informatics, University of Bradford.

Papers are indirectly resulted from the research activities presented in this thesis:

1. Azaiez, M. N. and Al-Arfaj, K. A. (2004) “A Quality-Dependent PM Model with Opportunity Costs”, *Journal of Industrial Cooperation in the Arabian Gulf*, vol. 94, pp. 15-25.
2. Al-Kubi, G., Al-Arfaj, K., and Sultan, A. (2008) “Analytic Hierarchy Process for Decision Making for e-Government Transformation Success”, *Proceedings of the Saudi 19th National Computer Conference (NCC19)*.

Chapter 2

Literature Review

Chapter 2: Literature Review

2.1 Chapter Overview

Maintainability, Reliability, and Availability are very important criteria's for any system. These criteria are different in terms of definition, but very much related to each other. Maintainability is defined as the probability that a failed system/component will be restored or repaired to a specific condition within a period of time when maintenance is performed in accordance with the prescribed procedure. Reliability is the probability that a system/component will perform a requested function for a given time when used under a stated operational condition. Availability is defined as the probability that a system/component is operational at a given point in time or is the percentage of time over some interval in which the system/component is operational (Ebeling 1997).

The impact of systems failures varies between minor/major inconveniences, high costs, and significant economic loss. The main cause for these failures is poor maintenance. Maintenance is defined as any action which retains non-failed units in a satisfactory reliable and operational condition; and if they have failed, restores them to a reliable and, operational condition (Kececioglu 1995).

Generally, there are two kinds of facility maintenance in power systems: (1) generator maintenance, (2) transmission line maintenance, which can be studied independently. Maintenance scheduling defines a maintenance schedule within a specific time horizon usually 52 weeks. In 1970, generating unit maintenance scheduling was proposed in order to optimize the operational schedule of a power system. In centralized power

systems structure, the electricity generation, transmission and distribution facilities are vertically integrated where the operator has full control of maintenance scheduling. In a deregulated environment the power system facilities are decomposed into three main segments; GENCOs; TRANSCOs; and DISCOs. An Independent System Operator (ISO) operates the system and coordinates maintenance scheduling between the segments. The decision when to put generators off for maintenance becomes a critical decision in a deregulated environment.

In this chapter we present a literature review for maintenance modelling and scheduling. In section 2 maintenance strategy and policies are discussed and different types of general and power system related maintenance cost models are explained. Generators maintenance scheduling in power system is presented section 3. In Section 4 maintenance modelling and scheduling techniques are presented. Observation and justification are presented in section 5. Section 6 is a chapter summary.

2.2 Review of Maintenance

Maintenance is defined as a combination of activities performed to restore a system to a satisfactory condition in which the system can perform its intended functions. Inspections, replacements, repairs are possible maintenance actions. Maintenance is necessary for the long life of machines, equipment, instruments etc. A general estimate is that maintenance costs are about one-third of the total operating cost of any equipment (Leachman 2007). In this section we define different maintenance strategies, and will present general maintenance models. Then, maintenance cost classifications will be explained. Also, we review different maintenance scheduling models.

2.2.1 Maintenance Strategies

In general maintenance is either planned or unplanned, as shown in Figure 2.1. Planned maintenance strategies are proactive in nature and can be either predictive or preventive (or scheduled). PdM is carried out when it is necessary, while PM is carried out at regular intervals. Unplanned maintenance strategies are reactive in nature, such as CM which is carried out after failure has occurred. These strategies are used in modelling maintenance for different systems.

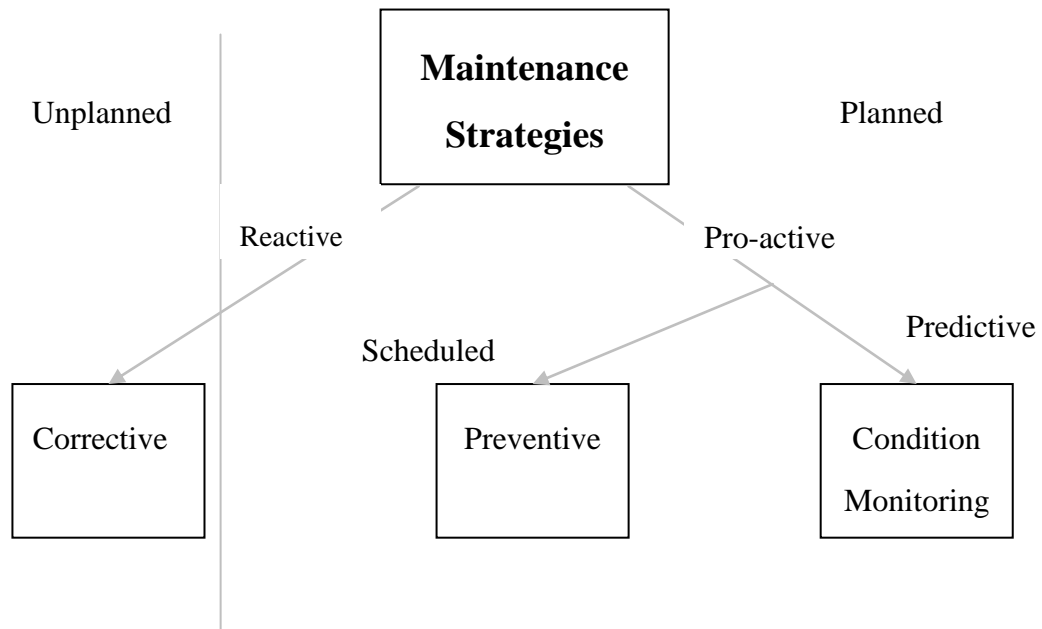


Figure 2.1 Maintenance strategies (Asgarpoor and Doghman 1999)

2.2.1.1 Corrective Maintenance

CM corresponds to the actions that occur after the system breaks down. It is performed on failed systems. Also, it is performed at unpredictable intervals because the time to any specific system failure cannot be determined ahead of time. The purpose of CM is

to restore the system to a satisfactory condition within the shortest time possible (Billit 1964). Such a strategy has not been used in modelling maintenance of a power system.

2.2.1.2 Preventive (Scheduled) Maintenance

In order to avoid premature aging and failure of an important system leading to unplanned and costly outages, it is vital to carry out preventive maintenance at regular intervals. PM is a planned activity usually performed in order to increase overall system availability and reliability and/or decrease unexpected outages. Also, PM can reduce the effect of aging or wear-out and has a significant impact on the life of a system. The main objectives of PM are to increase a unit's reliability, decrease the numbers of secondary failures, its downtime, overall spare parts requirements, and its life-cycle cost. The preventive maintenance involves scheduling and executing the actual maintenance works. This is vital for the planning of the secure and reliable operation of the system, primarily because other short-term activities are directly affected by such decisions (Camarata 1963).

The concepts of PM have changed with time. Previously, PM has dealt with rebuilding the equipment at some given calendar periods. However, PM nowadays includes among other things like the following actions: (1) servicing periodically, (2) inspecting, checking over, repairing or replacing failed items, (3) replacing items before prescribed wear-out, and (4) overhauling aged items. There are different PM policies, where a PM policy can be defined as a schedule for maintenance activity such that the overall cost of system failure, maintenance, and replacement during its expected life cycle is minimized.

Preventive maintenance is divided into two types: time-driven PM and condition driven PM. Condition-driven PM is basically the same as predictive maintenance. Various versions of time-driven preventive maintenance policy have been proposed in the literature.

Most of the PM models available incorporate time-driven PM policies such as:

- i) Age replacement,
- ii) Block replacement,
- iii) Minimal repair.

Performing PM on a very frequent basis will result in a substantial increase in maintenance costs. It also affects system downtime. Moreover, it may result in maintenance induced failures. On the other hand, infrequent PM actions increase the chance of system failures, reduce the system life, and may result in early system wear-out. Therefore, PM policies attempt to trade-off maintenance costs and effects on system performance. It is important to notice that selecting a PM policy is very dependent on the system in question, the types of maintenance tasks involved, as well as the objectives considered. Consequently, an optimal PM policy for some particular system need not be optimal, or even applicable for other systems. Optimal PM policies are determined for repairable devices by minimizing total maintenance cost, maximizing availability, or optimizing some other objectives. For very important systems such as power system, PM must be planned carefully in conjunction with other operational requirements to minimize the risk of system breakdown.

2.2.1.3 Predictive Maintenance

PdM is carried out when it is deemed necessary, based on periodic inspections, analysis of needs and priorities, diagnostic tests or other means of periodic or continuous condition monitoring. It is the most often used strategy to establish the need for maintenance (Endrenyi et al. 2001).

2.2.1.4 Reliability Centred Maintenance (RCM)

Since the 1930's, the evolution of maintenance can be traced through three generations. In the first, there was no need for systematic maintenance beyond simple cleaning, servicing and lubrication routines. The second generation, the 1960's, is consisted mainly of equipment overhauls done at fixed intervals. RCM is rapidly becoming a foundation of the third Generation. RCM is a structured process used to determine optimal maintenance requirements for equipment in a particular operating environment.

RCM originated in the civil airline industry with the introduction of the Boeing 747 series in 1963, and led to major reductions in labor, material and inventory costs. In 1975, because of RCM's successful results, the U.S. Department of Commerce mandated that RCM should be used in all major military systems (Nowlan and Heap 1978). Further, it was applied to the nuclear power industry in the 1980's. RCM is a sophisticated maintenance strategy that relates PM to reliability. It is a qualitative systematic approach to organizing maintenance. RCM merges the strategies of preventive maintenance, predictive maintenance and, corrective maintenance and adapts these strategies where each is appropriate. Quality, benefits, and progress must be measured carefully to ensure effective implementation of RCM. These three parameters are not independent and they must be continuously measured to show a complete picture

of RCM implementation health. Data collecting mechanisms are very important, in order to implement evaluation of these parameters for RCM. Johnston (2002a) has used three sources to draw data for RCM implementation: a web-enabled RCM logic database, a computerised maintenance management system (CMMS), and bottom-line benefits data drawn from financial management systems. The author was able to develop a procedure to help organisations make decisions about RCM implementation. He created prototype software of RCM logic diagrams to determine the optimal maintenance policy. Failure mode data is input to this decision diagram. The Diagram produces five possible policies. The result shows that the software has captured the logic of RCM and led to the most effective maintenance policy for each situation analyzed.

2.2.2 General Maintenance Models

In the literature some of these strategies were used to model maintenance for different systems. There are different types of maintenance models addressing different maintenance strategies and policies. Among these models are breakdown maintenance models, maintenance after failure models; preventive maintenance models, monthly or yearly maintenance models; predictive maintenance models, emergency maintenance models.

A PM model is used to measure the effects of a PM activity. Minimal repair and perfect repair, discussed extensively in the reliability and maintenance literature, represent two extreme types of repairs. Many repair or maintenance activities may not fall into these two extreme cases. The more realistic assumption is that the system after PM lies somewhere between as good as new (perfect repair) and as bad as old (minimum repair).

This kind of PM is called imperfect PM. There are two main alternatives for modelling an imperfect PM activity. The first one assumes that PM is equivalent to minimal repair with probability p and equivalent to replacement with probability $1-p$ (Brown and Proschan 1983). The second one models the PM's effects directly in terms of how the hazard rate function or the effective age of the equipment is changed by the PM (Jayabalan and Chaudhuri 1992). Using the concept of effective age, we may say that a certain PM has restored the health condition of a piece of equipment with a calendar age of 5 years to "as good as a 4-year old." Such a statement indicates that the PM has made the equipment younger and thus healthier.

Chan and Asgarpoor (2006) have compared the two preventive maintenance policies: full repair after random failure and minimal repair after random failure. The optimal policy was determined with the help of the Markov Decision Process. This process is characterized by a set of states; in each state there are several actions the decision maker may choose. For the first policy, as the mean time to Poisson failure (failure occurs at a constant rate) increases, the demand for preventive maintenance decreases. For the second policy, variation of mean time to Poisson failure has no effect on mean time to preventive maintenance. The result shows that in the case of availability and the mean time to maintenance the first policy is better than the second.

Another set of repair and replacement policies was presented by Nguyen and Murthy (1981). They studied two policies of optimal preventive maintenance for a repairable system. The first is for single item system (replacement of a system after a few repairs) and the second for multi-item system (restore a system after minimal repair). An algorithm was used for computing the optimal policies. The result illustrated that under

certain reasonable assumptions; both policies have distinctive solutions and are easily computable. Both policies were compared using maintenance cost and failure rate of the system, as optimal solutions depend on these parameters. The practical advantage of the first over the second policy is the periodic maintenance of the system.

Some other authors went further by comparing large numbers of policies. For example, Lam and Yeh (1994) have studied five maintenance policies where degrees of deterioration can be found through inspection. These policies are: failure replacement, age replacement, sequential inspection, periodic inspection and continuous inspection. Using the multi-state continuous-time Markov process the deterioration has been modelled. For acquiring the optimal maintenance policy and the corresponding cost rate for each policy an iterative algorithm has been derived. After comparing the optimal cost rates of the first four maintenance policies it was found that sequential inspection was preferred over the other three policies and that continuous inspection was preferred over sequential inspection.

Degbotse and Nachlas (2003) have presented the idea of a Nested renewal process to define availability models for equipment subject to age-based opportunistic preventive maintenance policies. The reported research argues that the nested renewal concept provides an effective means of representing availability behaviour under policies that have not previously been successfully modelled. Opportunistic maintenance is defined as follows: when a piece of equipment is undergoing maintenance, there could be an opening to perform maintenance on another piece of equipment at a lower overall cost.

Using hazed rate in modelling, PM was addressed in a different publication. Lie and Chun (1986) have proposed the concept of adjustment factors in hazard rate function

and effective age to model the effects of PM. They introduced the adjustment factor (k) to investigate the age restoration of a system. The imperfect PM can reduce a system's age from t to t/k and is ensuing in restoring the system's reliability from $R(t)$ to $R(t/k)$. The restoration result is affected by a number of factors, such as, age, time interval, and cost of PM.

Nakagawa (1988) has considered different policies in his paper. He has discussed two sequential PM policies using the concept of improvement factors. The first PM policy is to reduce the hazard rate while increasing the number of PM's and the second is to reduce the age of the system. The result shows that in the age case it would be better to perform PM as late as possible because the system should be replaced at the next PM period. In the case of hazard reduction rate the PM is done at scheduled intervals, but the system may fail and be replaced. Thus, it costs more in terms of time and money compared to the reduced age policy. It is concluded that reduced age is more practical than the hazard rate policy.

Other PM models under an optimal PM policy for both single component and dual component systems were obtained by (Wells and Bryant 1985). They analyzed both systems, which were put through preventive maintenance policies over a random horizon. In the prior system certain assumptions were taken and the optimal PM policy was recognized which maximized the expected accumulated uptime. The second system was an example of PM policy with standby redundancy. When an operating component fails or undergoes PM, the standby component starts operating. The analysis which was carried out helps establish the effect of PM on system performance measures, in

designing the systems and in detailing the effect of changes in parameters on system performance.

Different to the previously discussed PM model, Amari and McLaughlin (2004) have considered a simplified Condition Based Maintenance (CBM) model concentrating on soft failures (Deterioration Failure). The deterioration process is defined as the process in which all the essential parts of the machine become worse as the machine is left unattended leading to total failure. The result shows that optimal designs of CBM models will maximize system availability.

Most of these maintenance models were applied on production systems in different scenarios; for example, the maintenance of an unreliable M/G/1 queue-like production system was discussed in Hsu's paper (Hsu 1992). M/G/1 as a system comprises a problem of repair and maintenance operations for a production system. The author introduced a conceptual and analytical framework for integrating the monitoring and maintenance activities for an unreliable production system. They derived a general mathematical model using renewal theory to determine an optimal maintenance policy. The result shows that if a system has good monitoring technology then PM and inspections are not necessary and repair actions must be performed on any monitored failure. If the system does not have a monitoring technology then both the inspection and PM become very important.

Budai et al. (2006) have studied the relation between production and maintenance for different strategies such as opportunity maintenance, preventive and corrective maintenance, for different sectors for example railways, roads, airlines and electric

power systems. The model deals with quality and failure aspects.

In another publication, Tseng (1996) incorporated the PM policy into the deteriorated production system, for computational simplicity and system reliability enhanced. This production process produces defective items when it shifts from 'in-control' to 'out-of-control' states. The proposed model is based on two IFR (Increasing Failure Rate) distributions, Weibull and extreme value distributions. The inspection policy is useful for a deteriorating system but it does not enhance the system reliability. By comparing both the PM policy developed in this paper and the inspection policy derived by (Lin et al. 1991), it is found that the PM policy is better than the inspection policy and cheaper as well.

Preventive maintenance policies for serial production systems are discussed by (Hsu 1991). In his paper a mathematical analysis is conducted to reduce the rate of system failure and optimize system utilization. Through mathematical examples, managerial implications for maintaining such a system have been provided. The result shows that the operating characteristic of the stations are interrelated therefore it is important to observe the joint effects of a maintenance policy on the different stations simultaneously rather than study each station individually.

As we can see, finding the optimum PM policy was the aim of previous publications. The best policy is the policy that minimizes the total maintenance cost. Maintenance cost models will be discussed in the next section.

2.2.3 Maintenance Cost Models

A large number of maintenance cost models have been discussed in the literature address cost minimization as the objective of selecting a maintenance strategy or policy. In situations where system failures may have severe consequences, maximizing system reliability may become a higher priority in choosing a maintenance strategy or policy. Maintenance policies are determined for repairable systems by minimizing total cost, maximizing availability or optimizing some other purposes such as age replacement, block replacement and minimal repair.

Maintenance costs can be divided into two types of cost; direct and indirect. Labor, spare parts and maintenance cleaning material costs are examples of *direct maintenance costs*. On the other hand, *indirect maintenance costs* can be one or all of the following costs; inventory cost, shipment cost, indirect labor cost, test equipment cost, etc. (Jardine 1973).

Minimizing maintenance cost models are available in the literature, for example, Bris et al. (2003) have developed a method for minimizing the PM cost of series–parallel systems. The proposed method was based on the solution techniques such as Monte Carlo simulation and genetic algorithms. The problem of reliability assurance, which comprises both the availability constraint and cost evaluation, was also theoretically solved. The main objective of the research was to minimize the cost function with the help of a maintenance policy. Jayabalan and Chaudhuri (1992) have considered the cost minimization model. The authors have shown that when the system becomes new it requires less maintenance due to the lower failure rates and when the system becomes

old it requires more maintenance due to higher failure rates. As the system is old it costs more to maintain than the new system. The objective of the cost model is to minimize the average total cost over a finite time horizon. Other types of maintenance models are available in the literature. For example, Leachman (2007) in paper tried to find the cost of replacement of equipment before failure (planned replacement) and after failure (unplanned replacement) by applying the renewal method. Practically it is difficult to find that cost but it is possible to accumulate and examine data concerning the time required for planned and unplanned maintenance. The author also found that individual replacement costs are more than the group replacement costs because the rate of equipment replacement will never be the same, more probably it increases. Also, Lim and Park (1999) have evaluated the average maintenance cost for the imperfect repair model. A minimal repair is defined as: if any part of the system fails and only that part is replaced leaving the other parts intact the unit remains at the same stage as it was before failure. On the other hand, perfect repair makes the system up to the new state after replacing the whole unit. After evaluating the cost rates for the exponential and Weibull distributions, it is found that the cost of perfect repair is higher than the cost of imperfect (minimal) repair. It is also found that at each failure the probability of a perfectly repaired system to become new is more than the minimally repaired system.

Usher et al. (1998) have used an approach for envisaging a cost-optimal maintenance policy for a maintainable system with an increasing Rate of Occurrence of Failure (ROCOF), also known as deterioration, over a distinct number of periods. For each period, three possible activities (do nothing to the system, replace the system and maintain the system) should be taken, such that the total present value of all future costs

are reduced. The model has been developed for determining a cost optimal maintenance and replacement schedule for a new system, which is subject to deterioration. The method suitably suggests planning future maintenance activities such as spare parts provisioning, workforce allocation and overall system performance issues.

2.2.4 Maintenance Scheduling

Adequate maintenance of equipment is essential for the stable operation of systems. Maintenance costs and expected losses due to failures have an inverse relationship. The maintenance cost is increased due to frequency of maintenance, and the expected loss caused by failures is decreased due to reduction in failure probability. On the other hand, vice versa is true. Hence, the existing trade off would give rise to an optimal maintenance schedule. Maintenance scheduling for systems is usually based on that trade off plus other different constraints.

There are different PM policies, where a PM policy can be defined as a schedule for maintenance activity such that the overall cost of maintenance is minimized. Determination of a PM policy is an important issue in optimal maintenance planning. PM policies can be divided into two main categories: periodic and sequential. Periodic PM defines that a system is maintained at integer multiples of some fixed period and undergoes only minimal repair at failures between these PMs. Sequential PM is the same as periodic PM except that the system is maintained at a sequence of intervals which may have unequal lengths. Periodic PM is more convenient to schedule, whereas sequential PM is more realistic when the system requires more frequent maintenance as it ages (Lin et al. 2000).

In general, there are four cycles for repair and maintenance of equipment, which are illustrated in Figure 2.2. In cases (a) and (c) a breakdown of the equipment will cause a forced outage just before its maintenance period. The cases (b) and (d) consider a failure during the maintenance period. In all cases, the equipment will be up and running after finishing the maintenance or repair tasks, depending on which of them takes more time. The main objective of the scheduling algorithm is to search for the lowest total costs (production, loss of load, and maintenance cost) among several different maintenance schedules (Silva et al. 2001).

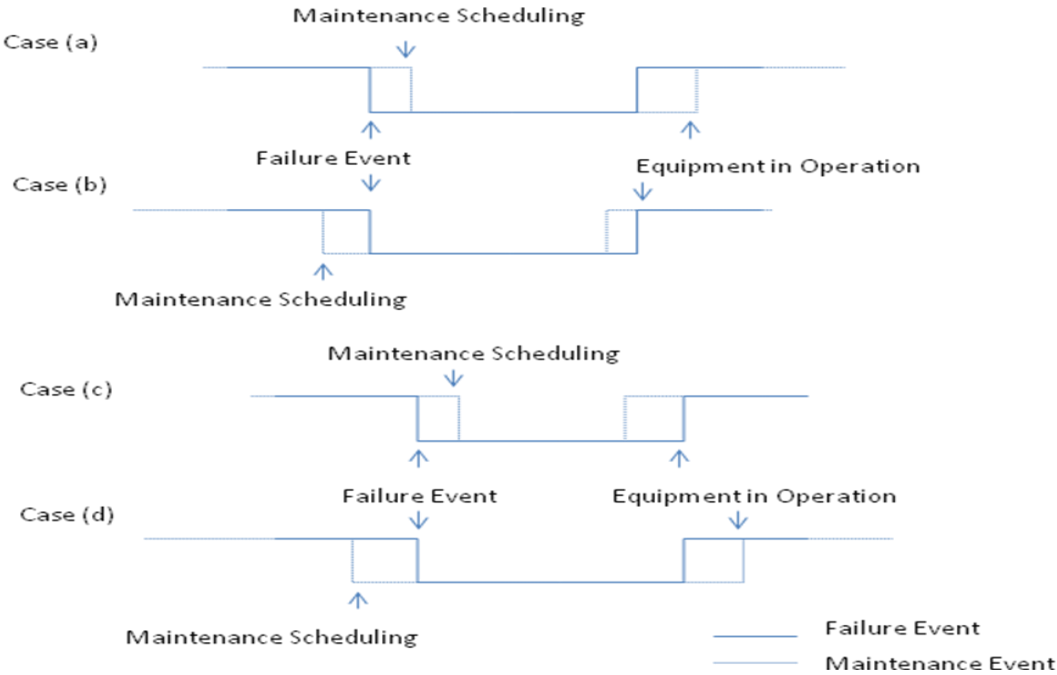


Figure 2.2 Equipment Repair and Maintenance Cycles (Silva et al. 2001)

Preventive maintenance and production scheduling are related to each other in different publications. Cassady and Kutanoglu (2005) in their paper have studied the integration of preventive maintenance planning and production scheduling for a single machine and the benefits from the integration of both activities. The result shows that preventive

maintenance should be scheduled on a weekly/monthly basis for making equipment new and it makes equipment safe from failure. It is unnecessary to do PM after every production. The proposed integrated model can be used as a combined planning tool for integrating production scheduling and PM planning decisions. Sloan and Shanthikumar (2000) comprise the advantages of combining the elements of both the production and maintenance scheduling into a single machine production system. They developed a Markov decision model and structural optimal policy followed by comparing the combination of threshold maintenance policy and dispatching policy. The result shows that it is suitable to use both production scheduling and maintenance scheduling in a combined state because in that way it is easy to know what step should be taken at what time.

Other scheduling models have considered deterioration of the systems. Berk and Moinzadeh (2000) have considered the maintenance scheduling of M identical machines, the performance of which deteriorates with usage but not from random failure. These conditions are found in heavy machine tooling, petro-chemical and semiconductor industries. The authors have developed a model in which it is assumed that machines are monitored constantly and offer a general control policy class. This policy utilizes the information about the number of machines in operation and their ages. The expressions for the operating characteristics of the system and optimization outcomes for the cases when maintenance times are deterministic and exponentially distributed have been developed. The result shows that the operating cost of a machine related to performance increases due to deterioration and there is impact of maintenance time variability on system performance.

A new reliability-based optimal maintenance scheduling method which considers the “maintenance effects” for reducing costs was introduced by (Zhang and Nakamura 2005). This method is based on the list ordering of element maintenance effects with various maintenance-interval types. The system availability can be increased by shortening the maintenance interval of elements with high maintenance effects. On the other hand, the number of maintenance tasks can be decreased by lengthening the maintenance interval of elements with low maintenance effects.

2.3 Generator Maintenance Scheduling in Power Systems

Power generating companies must generate sufficient electrical power to cater for the varying demands of consumers. Electricity cannot be cheaply and easily stored, so it must be continuously generated based on the customers’ demand. Maintenance scheduling of generating units is usually conducted on a short-term or long term basis. A sufficient reserve power margin should be available against any equipment failure taking into consideration generating units under maintenance (Nimura et al. 1996) and (Hayashi et al. 2001).

The generating company has a declared capacity at any given instant and must supply this contracted demand from its generating units. There are many types of segments that collectively constitute the power system such as generating units and transmission lines. The generating units should be periodically maintained to avoid deterioration which results from prolonged usage. Maintenance is necessary in order to extend the life and improve the overall availability of the generators. The manner of scheduling this maintenance is of utmost importance from economic and engineering perspectives. The optimum schedule is one, which satisfies the many constraints yet maximizes service

reliability and minimizes maintenance and operation costs. Finding the optimal schedule has been a topic of study by researchers over the past decades.

In a centralized electric power system, an appropriate generation maintenance schedule is derived by the system operator and imposed on producers. The objective is to achieve an appropriate blend between maximum reliability and minimum cost. However, this centralized framework is no longer valid in currently deregulated electric energy systems. To guarantee reliability is still the duty of the operator, as known as an Independent System Operator (ISO) in the new framework, but generator profits or costs are not anymore its business. The ISO strategy leads generally to schedule units for maintenance in low demand weeks while the independent strategies of the producers' leads to schedule units for maintenance in low price weeks. The ISO is entitled to negotiate with the generator a generating unit's mandatory maintenance schedule that guarantees an appropriate level of system availability. Removal from service of generating units for maintenance will reduce the available capacity and increase the system risk. Maintenance requests, therefore, in both vertically integrated and deregulated power systems, must be carefully coordinated.

Centralized maintenance scheduling objectives are either economically based or reliability based. From an economic point of view, production (i.e. fuel cost) and operation costs such as maintenance cost must be minimized.

Levelling of the reserve generation over the operational planning period which can be realized by maximizing the minimum net reserve of the system during any time period is one of the most common reliability criterions in vertically integrated structures (Endrenyi et al. 2001). Minimizing the sum of squares of the reserves can be an

effective approach for large variations of reserve (Dahal et al. 1999), (Dahal et al. 2000a) and (Dahal et al. 2000b). The maintenance scheduling for thermal generating units in a power system is a long-term scheduling problem. Thermal units take a relatively long duration of maintenance and particularly for a captive power plant, it is crucial to maintain a proper level of reserve margin between available supply capacity and estimated load demand from the system reliability point of view (Mohanta et al. 2006).

Katafuchi et al. (2003) proposed reliability-based optimal maintenance scheduling by considering the decision of maintenance intervals of equipment in thermal power stations based on the working rate of the power stations and the repair/replacement rates. These previously proposed methods also required a monotonously increasing relationship between the number of maintenance periods and reliability. On the other hand, Chattopadhyay et al. (1995) proposed least-cost generating unit maintenance scheduling for interconnected power systems. A mixed integer programming model was developed for analysis of the fuel supply decisions, generation and maintenance scheduling decisions, as well as inter-utility transfer schedules in a comprehensive way. Also, Chattopadhyay (1998) employed linear programming for maintenance scheduling of fuel supply and inter-utility transfer decisions. Bretthauer et al. (1998) proposed the integrated maintenance scheduling system which considers device and system-specific data in order to coordinate the maintenance activities for constrained maintenance schedules.

The most common economic objective in maintenance scheduling of deregulated power systems is minimizing production and maintenance costs (Shahidehpour and Marwali

2000). However, the production cost alone could be an objective (Huang and Yang 2002).

There are typical constraints for maintenance scheduling problems such as maintenance window constraints, crew constraints, resource constraints, load constraints and reliability constraints. The constraints in deregulated power systems are similar to the centralized systems. Market constraints such as contractual commitments, maintenance policy and electricity market rules are additional constraints (Sanders 2002), (Shahidehpour and Marwali 2000) and (Stephenson and Paun 2001). The maintenance scheduling models for a deregulated power system uses different maintenance strategies such as RCM strategy which was presented in (Bier and Glycer 2002).

2.4 Review of Maintenance Modelling and Scheduling Techniques

Many maintenance-scheduling methods have been proposed using conventional mathematical programming methods or heuristic techniques. Heuristic approaches provide the most primitive solution based on trial-and-error approaches. These techniques may not generally lead to the global optimal for a complex problem, i.e. the procedure tends to fall into a local minimum if a starting point is not carefully chosen. Heuristic methods were used earlier in solving maintenance scheduling problems for centralized power systems because of their simplicity and flexibility.

Mathematical optimization based techniques such as integer programming (Dopazo and Merrill 1975), dynamic programming ((Zurn and Quintana 1975) and (Yamayee et al. 1983)) and branch-and-bound (Egan et al. 1976) have been proposed to solve maintenance scheduling problems. For small problems these methods give an exact

optimal solution. However, as the size of the problem increases, the size of the solution space increases greatly and hence the running time of these algorithms. These approaches tend to suffer from an excessive computational time with the increase of variables. To overcome this difficulty, modern techniques such as simulated annealing (Cerny 1985) and (Kirkpatrick et al. 1983), stochastic evolution (Saab and Rao 1991), genetic algorithms (Goldberg 1989) and Tabu search (Reeves 1993) have been proposed as alternatives where the problem size precludes traditional techniques. These techniques are completely distinct from classical programming and trial-and-error heuristic methods. The GA method mimics the principles of natural genetics and natural selection to constitute search and optimization procedures. Simulated annealing mimics the cooling phenomenon of molten metals to constitute a search procedure. The GA and SA approaches have been reported to solve a range of optimization problems in electrical power systems with encouraging results (Mirinda et al. 1998).

The following sections review the some of common math-base and modern heuristic based techniques.

2.4.1 Mathematical Techniques

Mathematical approaches are mainly based on linear, Integer, Mixed-Integer Programming (LP, IP, and MIP), Decomposition, Branch-And-Bound (BaB) and Dynamic Programming (DP). In the following pages we describe several mathematical solution techniques, which were used in the literature for solving maintenance scheduling problems.

2.4.1.1 Linear, Integer, and Mixed-Integer Programming

The most basic mathematical programming technique is linear program (LP). It has been applied with impressive success to problems ranging from familiar cases in industry, economics and transportation to the more extreme cases in behavioural sciences (Taha 1987). The LP model refers to an optimization problem in which the objective function and the constraint function are linear variables. Integer programming (IP) is essentially LP with the additional requirement that the variables have to be an integer. If only some of the variables are required to be integer and the others are real, then it became mixed integer programming (MIP). Combinatorial scheduling problems can often be formulated as IP or MIP problems (Pinedo 1995), (Bellman et al. 2001) and (Dopazo and Merrill 1975).

The cutting plane (polyhedral) technique deals with IP by focusing on LP relaxation. The techniques aim at generating additional linear constraints that have to be satisfied for the variables to be integer. These additional inequalities constraint the feasible set more than the original set of linear inequalities without cutting off integer solutions. Solving the LP relaxation of the IP with additional inequalities then yields a different solution, which may be integer. If the solution is integer, the procedure stops, because the solution obtained is an optimal solution for the original IP. If the variables are not integer, more inequalities are generated (Pinedo 1995). In any LP there is a dual problem to the primary one. These two problems are related to each other with interesting applications. The duality in LP has been used in another solution technique, Benders decomposition. Shahidehpour and Marwali (2000) in their book have used MIP and the Benders decomposition technique to coordinate and optimize maintenance

scheduling in a deregulated system. Yao et al. (2001) have developed a model based on mixed integer programming and it is helpful in resource limitations in manufacturing. The non linear functions appearing in the MIP model can be transformed into linear functions with the help of decision variables. This can be solved by using any LP/IP software. The result shows that in the PM based model scheduling system, the equipment availability would increase and become profitable to the manufacturer.

2.4.1.2 Dynamic Programming

In 1957, Dynamic Programming (DP) originates from Bellman and is applicable to a lot of optimizing problems, not just those arising in scheduling (French 1982). It is one of the more widely used techniques for solving combinatorial optimization problems. DP can be applied to problems that are solved in polynomial time as well as problems that can't be solved in polynomial time. It has proven to be applicable to stochastic problems as well (Pinedo 1995).

Dynamic programming is basically a complete enumeration scheme that attempts, with a divide-and-conquer approach, to minimize the amount of computation to be done. The approach solves a series of sub problems until it finds the solution of the original problem. It determines the optimal solution for each sub problem and its contribution to the objective function. At each iteration, it determines the optimal solution for a sub problem, which is better than the previously solved sub problems. It finds a solution for the current sub problems by utilizing all the information obtained before in the solutions of all previous sub problems as well (Pinedo 1995).

2.4.1.3 Branch-and-Bound

Apart from heuristic methods, the Branch-and-Bound (BaB) technique is probably the most widely used technique in scheduling. Like DP it is an enumeration technique and used to optimize large class problems (French 1982). It is a type of implicit enumeration method or tree search method, which can find an optimal solution by systematically examining subsets of feasible solutions (Egan et al. 1976) and (Chestienne et al. 1995).

The Branch-and-Bound procedure consists of the repeated application of the following steps. First, that portion of the solution space (i.e. set of decision variables under consideration) in which the optimal solution is known to lie is partitioned into subsets. Second, if all of the elements in a subset violate the constraints of the minimization problem, then that subset is eliminated from further consideration (fathomed). Third, an upper bound on the minimum value of the objective function is computed. Finally, lower bounds are computed on the value of the objective function when the decision variables are constrained to lie in each subset still under consideration. A subset is then fathomed if its lower bound exceeds the upper bound of the minimization problem, since the optimal decision variable cannot lie in that subset. Convergence takes place when only one subset of decision variables remains and the upper and lower bounds are equal for that subset (Padhy 2004).

2.4.1.4 Benders Decomposition

Bender's method, based on LP duality theory, decomposes the scheduling optimization problem into a master problem and several sub-problems. The master problem in this case involves only the integer variables of the problem, and the sub-problems involve only the continuous variables. The solution process of the master problem starts with

almost no constraints. Then the sub-problem is used as a test to check if this solution satisfies the remaining constraints. If so, then the solution is optimal, since the objective has been minimized over all constraints. Otherwise, the most unsatisfied constraint (i.e. the deepest cut) will be added to the master problem, and it will be resolved with the added constraint. The main disadvantages of this approach are the long computational time requirement and the suitable problem model (Shahidehpour and Marwali 2000).

Because of the combinational nature of the GMS problem, MIP and Bender's decomposition methods are used to coordinate and optimize maintenance schedules. Marwali and Shahidehpour (1998) use Benders decomposition for solving maintenance scheduling problems for centralized power system structures. They use Benders decomposition to decompose a complex Integrated Maintenance Scheduler (IMS) problem that represents a network constrained generation and transmission maintenance-scheduling problem, into a master problem and operation sub-problems. By using an IMS, several and complex constraints which bound the selection of scheduling times, are included into the solution method. In this problem, at each iteration, the solution of sub-problems generate dual multipliers, which are used to form one or more constraints that will be added to the master problem for the next iteration until a feasible solution is found. Benders approach has been used in different publications (Shahidehpour and Marwali 2000) and (Marwali and Shahidehpour 2000b) for solving different problems in deregulated systems. Also, Marwali and Shahidehpour (2000a) have used Benders decomposition method to solve a short-term transmission maintenance problem.

2.4.2 Artificial Intelligence Approach

Various Artificial Intelligence (AI) techniques for solving the maintenance-scheduling problems of a power system can be found in the literature with different presentations. Artificial Intelligence (AI) includes expert systems, Simulated Annealing (SA), fuzzy logic theory, neural network, evolutionary optimization including evolutionary programming, evolutionary strategy and Generic Algorithm (GA), simulated evolution and their hybrids (Shahidehpour and Marwali 2000). This section will present some of these AI techniques.

2.4.2.1 Simulated Annealing

Kirkpatrick et al. (1982) and Cerny (1985) independently introduced simulated annealing. Satoh and Nara (1991) and Burk et al. (1997) have considered SA algorithms in solving thermal generator maintenance scheduling problems. The problems were formulated using the economic objective and typical problem constraints. The authors found that SA was faster than integer programming (IP) in finding the same solution for their small and medium-sized problems. Also, the SA approach was able to find a solution for the large system where IP could not be realised due to combinatorial explosion. They used a binary string representation to encode a trial solution and penalty approach to take account of the problem constraints (Dahal et al. 2000b).

Annealing, physically, refers to the process of heating up a solid to a high temperature followed by slow cooling achieved by decreasing the temperature of the environment in steps (Wong and Wong 1994) and (Annakkage et al. 1995). By making similarity

between the annealing method and the optimization problem, an enormous class of combinatorial optimization problems can be solved following the same procedure of conversion from one equilibrium condition to another, reaching minimum energy of the system (Padhy 2004). The initialization of the SA method involves the selection of an initial temperature (T_0) and an initial solution in the search. The initial solution may be generated at random or by any other means. If the final solution is to be independent of the starting solution, the initial temperature T_0 must be high enough to permit an almost free switch of neighbouring solutions. Generally the value of T_0 is chosen in such a way that it is greater than the maximum possible difference between the evaluation values of two solutions (Downsland 1993).

Then, the temperature is decreased as the algorithm progresses according to a cooling schedule. The cooling schedule may be adapted by using a large number of iterations at a small number of temperatures or vice versa. The number of iterations at each temperature and the rate at which the temperature is reduced are significant factors in controlling the performance of the SA method. The number of iterations increases with successive temperatures since it is important to spend more time searching at lower temperatures to guarantee that the neighbourhood of a local optimum has been entirely explored. Then, the move operator specifies the algorithm for generating a new trial solution from the current solution. Randomly, the move operator selects one variable from the integer strings to be changed. The selected variable is then changed to a random value in the allowed range.

Finally, the criterion for stopping the algorithm can be articulated either in terms of a minimum value of the temperature, or in terms of the ‘freezing’ of the system at the

current solution. ‘Freezing’ may be recognized by the number of iterations (or ‘temperatures’) that have passed without a move being acknowledged that has exceeded a given limit, or by the number of accepted moves in a stage falling below a given value. However, the simplest rule of all is to fix the total number of iterations. The number of iterations needs to be carefully tuned with other parameters to make sure that it corresponds to a satisfactorily low temperature to ensure convergence (Dahal et al. 2000b).

2.4.2.2 Genetic Algorithms

During the last years, there has been a growing interest in problem-solving systems based on the principles of evolution and machine learning (Orero and Irving 1997) and (Sood et al. 2003); where such systems maintain a population of potential solutions. They have some selection process based on fitness of individuals and some “genetic” operators (Padhy 2004). In the 1970s, Holland (1975) introduced the concept of a genetic algorithm (GA). Like other AI the basic idea behind GA was to make computers do what humans do. In order to apply a genetic algorithm to solve an optimization problem, candidate solutions must be encoded using an appropriate representation, such as a numeric string, and an evaluation function must be formulated to assign a quality value to every solution produced.

The GA represents an iterative process, where each iteration is called a *generation*. Population size specifies how many individuals there are in each generation. With a large population size, the genetic algorithm searches the solution space more thoroughly, thereby reducing the possibility that the algorithm will return a local minimum that is not a global minimum. However, a large population size also causes

the algorithm to run more slowly. Each population contains a number of chromosomes, and a chromosome consists of several "genes", and each gene is represented by 0 or 1.

There are two basic mechanisms that link a GA to the problem it is solving: *encoding* and *evaluation*. The encoding is carried out using binary strings (chromosomes) of ones and zeros in each bit, which is the most popular representation. An evaluation function is used to measure the chromosome's performance, or *fitness*, on the problem to be solved. The GA uses a measure of fitness of individual chromosomes to carry out reproduction.

Genetic algorithms apply three genetic operators: selection, crossover and mutation.

I. Selection

There are different types of selection methods such as the followings (Back et al. 1997):

- Tournament selection: where a small subset of individuals is chosen at random, then choosing the best individual from that set to be a parent.
- The roulette wheel selection

The most common chromosome selection technique is the roulette wheel selection (Goldberg 1989) and (Davis 1991). Roulette selection chooses parents by simulating a roulette wheel, in which the area of the section of the wheel corresponding to an individual is proportional to the individual's expectation. For example, for a given population each chromosome is given a slice of a circular roulette wheel equal to the chromosome fitness ratio. To select a chromosome for mating, a random number is generated, and the chromosome whose segment spans the random number is selected. It

is like rotating a roulette wheel where each chromosome has a section on the wheel proportional to its fitness. The roulette wheel is spun, and when the arrow comes to stop on one of the slices, the corresponding chromosome is chosen.

II. Crossover

Crossover specifies how the genetic algorithm combines two individuals, or parents, to form a crossover child for the next generation. The crossover operator is applied with a certain crossover probability, once a pair of parent chromosomes is selected. Generally, a value of 0.7 for the crossover probability produces good results (Negnevitsky 2005). First, the crossover operator randomly chooses a crossover point where two parent chromosomes "break", and then exchanges the chromosome parts after that point. As a result, two new offspring are created. There are different types of crossovers for example (Back et al. 1997):

- Single point crossover: where a single locus chosen at random then a parent chromosome break and all bits after that point be swapped.
- Two point crossover: this involves choosing two points at random and swapping the corresponding parts from the two parents defined by the two points.

III. Mutation

Mutation specifies how the genetic algorithm makes small random changes in the individuals in the population to create mutation children. Mutation can occur at any gene in the chromosome with some probability. Typically, the mutation probability is in the range between 0.001 and 0.01.

Mutation provides genetic diversity and enables the genetic algorithm to search a broader space (Negnevitsky 2005). Genetic algorithms guarantee the continuous improvement of the average fitness of the population, and after a certain number of generations the population evolves to an optimal or near-optimal solution.

Given a clearly defined problem and a binary string representation for candidate solutions, a basic GA can be represented in the following steps (Davis 1991) and (Mitchell 1996):

Step 1: Represent the problem variable domain as a chromosome of and define the population size, the crossover *and* the mutation probability, and the evaluation function.

Step 2: Randomly produce an initial population of chromosomes.

Step 3: Compute the fitness of each one.

Step 4: Choose a couple of chromosomes for mating.

Step 5: Generate a pair of offspring chromosomes by applying genetic operators.

Step 6: Position the formed offspring chromosomes in the new population, then repeat *Step 4*, until the size of the new population becomes equivalent to the size of the initial population.

Step 7: Substitute the initial (parent) chromosome population with the new (offspring) population.

Step 8: Go to *Step 3*, and repeat the process until the termination criterion is fulfilled.

Genetic algorithms become popular as a powerful optimization tool appropriate for a diversity of problems. Both GA by it self or a combination of GA and other techniques are broadly addressed in the literature for solving maintenance scheduling for power

systems. Negnevitsky and Kelareva (1999) have used GA in solving maintenance scheduling in power systems. The objective was to maximize reserve margins subject to maintenance and system constraints. They have designed a representation which is suitable for a variety of problems and appropriate chromosome evaluation is suggested. A case study was solved using GA, and the result shows that chromosome representation plays an important role in GA where it may reduce problem complexity by including constraints. Abdulwhab et al. (2004) use the genetic algorithm optimization technique to maximize the overall system reliability for a specified future time period in which a number of generating units are to be removed from service for preventive maintenance.

Basker et al. (2003) has used GA with modified genetic operators, such as string reversal and reciprocal exchange mutation, to solve the generator maintenance scheduling (GMS) problem. They have used three types of encoding; integer encoding, binary for integer encoding, and real encoding. The GMS problem is solved to minimize the expected energy production cost and maximizing the reserve objectives subject to maintenance windows, consecutive periods of maintenance, crew, demand reserve and reliability. The result shows that only integer coding GA finds the global optimum solution, irrespective of the nature of the objective function and system size. Also, modified genetic operators were shown to be effective in reducing computation time and improving search efficiency of the GA.

It has been reported that the performance of the GA approach can be improved by combining it with other techniques (Reeves 1993). The GA/SA hybrid approach has been employed to solve a maintenance scheduling problem by (Kim et al. 1996) and

(Kim et al. 1994). The hybrid approach presented by Mohanta et al. (2006) use the integer encoding for solving the captive power plant maintenance scheduling problem with leveled reserve reliability objective function. From the comparison of results obtained from application of only GA and from hybrid GA/SA techniques for scheduling, can be seen that the hybrid GA/SA solution technique yields better results.

Dahal et al. (2000b) investigated the applications of GA and SA using an integer representation to encode candidate solutions to GMS test problems with a reliability criterion. The evaluation function is a weighted sum of the objective function and the penalty function for violations of the constraint. The authors concluded that the SA and GA are robust and stable techniques for solving GMS problems. Also, Dahal et al. (1999) propose solving centralized maintenance problems using GA with integer's representation using fuzzy evaluation functions. Since fuzzy logic can be used to deal with multiple objectives, it was used to combine the objective of maximizing reliability and considering the flexibility in the manpower constraint. The fuzzy evaluation function is developed as a combination of a crisp penalty function for inflexible load constraint and a fuzzy penalty function for the objective and the flexible manpower constraints. The results obtained using the fuzzy logic evaluation function were compared with those obtained from GAs with crisp evaluation functions, and the fuzzy logic method was shown to achieve an effective trade-off between reliability and manpower within the allowed flexibility.

Burke and Smith (2000) presented a technique named Memetic approach for solving real scale maintenance scheduling problems in centralized structures. The objective was to minimize the sum of the overall fuel and maintenance costs. Memetic is a genetic

algorithm combined with Tabu search. Tabu search is a powerful optimization procedure that has been successfully applied to a number of combinatorial optimization problems. Memetic takes the concept of evolution as employed in GA. It has a memory as unit of information instead of gene in GA (Dawkins 1976). A population of information can be created and a good one has a better chance of survival than a bad one, and they can be combined to form new ideas. They investigated the use of Memetic algorithms for solving thermal generator maintenance scheduling problems. A comparison between Tabu search and Memetic algorithm shows that Tabu is more affective for small problems and Memetic algorithm will outperform Tabu search for large problems. Also, they show that the Memetic algorithm using Tabu search as the local optimizer yields greater benefits than simulated annealing which was used previously in solving thermal generator maintenance scheduling problems (Satoh and Nara 1991).

2.4.2.3 Multi-stage approach

A new solution approach was developed by Burke and Smith (1999) for solving large size thermal generator maintenance scheduling problems for centralized structures. It is named multi-stage approach. The problem which has been solved by the authors has been tackled by different researchers using different solution techniques such as SA, GA, Memetic and Tabu. Among these algorithms the Memetic algorithm alone can produce quality solutions at the expense of extended run-time. The authors addressed the problem of extended run-times by using a multi-stage approach. Instead of solving the problem in one step, the multi-stage approach segregates the main problem into a series of sub-problems, each can be solved consecutively then the results recombined to

form the solution of the original problem. It is not suitable for indivisible problems. It is similar to the rolling-horizon technique, which has been applied to problems such as multipurpose plant scheduling, commercial fishing fleet scheduling and production scheduling.

The first task of the multi-stage algorithm is to order the units according to some measure of difficulty. An example of the difficulty measure is ordering the units with the least number of possible maintenance starting periods first. Another example is scheduling the units with the highest operating capacity first. In doing so the chance of creating difficulties later on in the process is decreased. Then, the algorithm will fit the easier units in the available gaps.

The multi-staging approach picks the first N units and schedules them using the Tabu search or Mimetic algorithm. All other units are left unscheduled. The next N units (most difficult units to schedule) are then placed in the schedule, and so on, until all units have been scheduled. Therefore, each evaluation function can re-use data acquired from the previous evaluation very effectively. This approach differs from other rolling horizon approaches in that the problem is divided into sub-problems which contain a reduced number of units to be scheduled, rather than sub-problems with a look-ahead set of a further M units from the list to the units currently being scheduled. However at the end of the scheduling, only the first N units are fixed into the schedule. This enables the algorithm to schedule the current set of N units based not only on the units already scheduled (if any), but also to utilize additional information based from looking ahead at the next M units (Burke and Smith 1999).

2.5 Observation and Justification

In this chapter we have concentrated on different research areas which are maintenance strategies, maintenance models, maintenance costs models, maintenance scheduling, generators maintenance scheduling, and maintenance scheduling techniques. In literature, Billit (1964), Camarata (1963), Endrenyi et al. (2001), Nowlan and Heap (1978) and Johnston (2002b) have presented different type of maintenance strategies ranging from time based strategy (i.e. PM) or condition based strategy (i.e. PdM) or a combination of them (i.e. RCM). These strategies were employed in different maintenance model, either by combining two strategies which happens rarely, or by addressing different PM policies such as failure replacement, age replacement, sequential inspection or minimal repair policies (Brown and Proschan 1983), (Chan and Asgarpoor 2006), (Nguyen and Murthy 1981), (Lam and Yeh 1994), (Degbotse and Nachlas 2003), (Lie and Chun 1986), (Nakagawa 1988), (Wells and Bryant 1985) and (Atthirawong and McCarthy 2002). Theses policies can be defined as a schedule for maintenance activities (Lin et al. 2000), (Silva et al. 2001), (Cassidy and Kutanoglu 2005), (Sloan and Shanthikumar 2000), (Berk and Moinzadeh 2000) and (Zhang and Nakamura 2005). Different maintenance models were applied on different systems such as production or manufacturing systems (Hsu 1992), (Budai et al. 2006), (Tseng 1996) and (Lin et al. 1991). In literature large number of maintenance cost models address cost minimization or maximizing system reliability as the objective of selecting maintenance strategy or policy (Bris et al. 2003), (Jayabalan and Chaudhuri 1992), (Leachman 2007), (Jae-Hak and Dong 1999), (Usher et al. 1998) and (Jardine 1973).

Only direct maintenance cost under PM was addressed in previous cost models. In a centralized electric power system, these maintenance cost models can be applied and an appropriate generation maintenance schedule is derived by the system operator. However, in deregulated systems, in order for the independent system operator to produce a market oriented schedule, we need to include other maintenance costs and address the affect of different strategies on maintenance activities.

Direct maintenance cost is not the only important item in maintenance cost modelling for a deregulated system. There are other different costs that play a role in modelling maintenance costs, for example, indirect maintenance costs, opportunity costs and failure costs. Indirect maintenance costs can be one or all of the following costs; inventory cost, shipment cost, indirect labor cost, test equipment cost, etc (Jardine 1973). On the other hand, opportunity costs can be found in two scenarios, when the system goes for planned maintenance or when it fails between maintenance periods. It includes inconvenience and interruption costs. In Chapter 3 we talk about modelling maintenance and opportunity costs. The inconvenience cost that the user may incur during system failure or during planned maintenance can be represented as the loss of goodwill.

The cost of loss of goodwill in many publications was presented as a constant value; on the other hand, it can be measured by the probability of losing it due to bad service (Lim 2001), (Frank et al. 2003), (Tsay 1999), (Milner and Rosenblatt 2001), and (Ng and Bjornsson 2001). In Chapter 5 we review these papers when we talk about modelling loss of customer goodwill. However, the interruption cost is the economic loss that the customer may incur during system failure. Interruption cost includes the value of lost

production, direct costs incurred because of outage, and the saving cost of unused raw materials (Sullivan et al. 1996). Also, the maintenance scheduling models for a deregulated power system uses different maintenance strategies such as RCM strategy which was presented in (Bier and Glyer 2002). In Chapter 6 we review and investigate the modelling of this strategy.

Heuristic methods were used previously in solving maintenance scheduling problems for centralized power systems because of their elasticity, but they may not lead to optimal solution for a complex problem. Mathematical techniques such as MIP (Bellman et al. 1982) and (Dopazo and Merrill 1975) and Bender's Decomposition (Shahidehpour and Marwali 2000) and (Marwali and Shahidehpour 1998), have been proposed to solve generator maintenance scheduling problems for small problems. However, for NP-complete scheduling problems traditional deterministic techniques can fail due to time limits (Negnevitsky and Kelareva 1999).

Genetic algorithms become a powerful optimization tool appropriate for a diversity of problems. GAs are based on natural genetic and evolution mechanisms which can be used to solve complicated optimization problems. The key success of GA lies in defining a fitness function that incorporates all constraints. In the literature Negnevitsky and Kelareva (1999), Abdulwhab et al. (2004), Kim et al. (1996), Kim et al. (1994), Reeves (Reeves, 1993), Mohanta et al. (2006), Baskar et al. (2003), Dahal et al. (2000b), Dahal et al. (1999), Burke and Smith (2000), Dawkins (1976) use both GA or a mixture of GA and other techniques for solving maintenance scheduling for power systems. In this thesis we employ genetic algorithm (GA) as an optimization technique for solving Generator Maintenance Scheduling GMS problems.

2.6 Chapter Summary

In this chapter we have presented many maintenance cost and scheduling models for power systems. Most of these models considered maintenance costs only under a specific maintenance strategy and are not integrated with other costs such as opportunity costs which are influencing factors on the maintenance schedule. In following chapters, we integrate different cost models in order to form a single maintenance cost model which incorporates all cost factors and we illustrate the utilization of that model for different maintenance strategies. There are many solution methods, in this chapter we reviewed a wide range of mathematical and artificial intelligence approaches. In the literature, these techniques were used to solve different maintenance scheduling problems. Genetic Algorithm (GA) was found to be a powerful optimization tool for solving maintenance scheduling for power systems. In this research we used the GA as a scheduling approach.

Chapter 3

Maintenance Scheduling Models in Power Systems

Chapter 3: Maintenance Scheduling Models in Power Systems

3.1 Chapter Overview

The goal of maintenance modelling and scheduling in a system is to allocate an effective maintenance timetable for the system equipment while optimizing system reliability, reducing total operating cost, and extending equipment lifetime. Currently, the electric power industry throughout the world is shifting toward deregulation where maintenance scheduling becomes very critical. The aim of this chapter is to investigate and model all cost factors that affect the maintenance activities of the deregulated GENCOs. In this framework we propose a full model which considers not only direct maintenance cost, but also all indirect maintenance costs, opportunity costs and cost of failure.

We start this chapter by providing a description of regulated and deregulated power systems. Also, we explain all deregulated power segments and their functions. Next, we talk about generator maintenance scheduling (GMS) problems and will explain maintenance scheduling models for both systems. Then, a classification of costs associated with generator maintenance activities will be presented. In the last part of this chapter, we investigate and model mainly cost factors that affect maintenance activities of deregulated GENCOs under no-failure and failure scenarios.

3.2 Regulated and deregulated power systems

The local vertically integrated utility (VIU) consists of generation facility, transmission facility, and distribution facility. The VIUs operate their own system, perform the economic dispatch of generation and manage trades with other utilities. Most of the electric power industries throughout the world are experiencing deregulation. Restructuring is unbundling power utilities into three different entities, generation companies (GENCOs), transmission companies (TRANCOs), and distribution companies (DISCOs). The main reason for that is to introduce competition and to allow customers to choose from different suppliers.

An independent system operator (ISO) operates a power system and these three business entities participate in the trading of power through it. These segments can be considered as separate entities. Changes on the power industries from a regulated to deregulated structure result in a sub-optimal centralized maintenance system which is not ideal any more. In the next section we describe both vertically integrated utilities and deregulated power systems.

3.2.1 Centralized Power System Operations

Each utility in VIUs structure controls and owns the generation facility, transmission facility, and distribution facility within its arena. Also, it exercises a monopoly on selling electricity to regional customers and is obligated to meet their needs. The VIU is either publicly owned and not operated for profit, or has a price which is set by regulatory organizations. A huge power grid is formed by interconnecting the VIUs via tie-lines (see Figure 3.1).

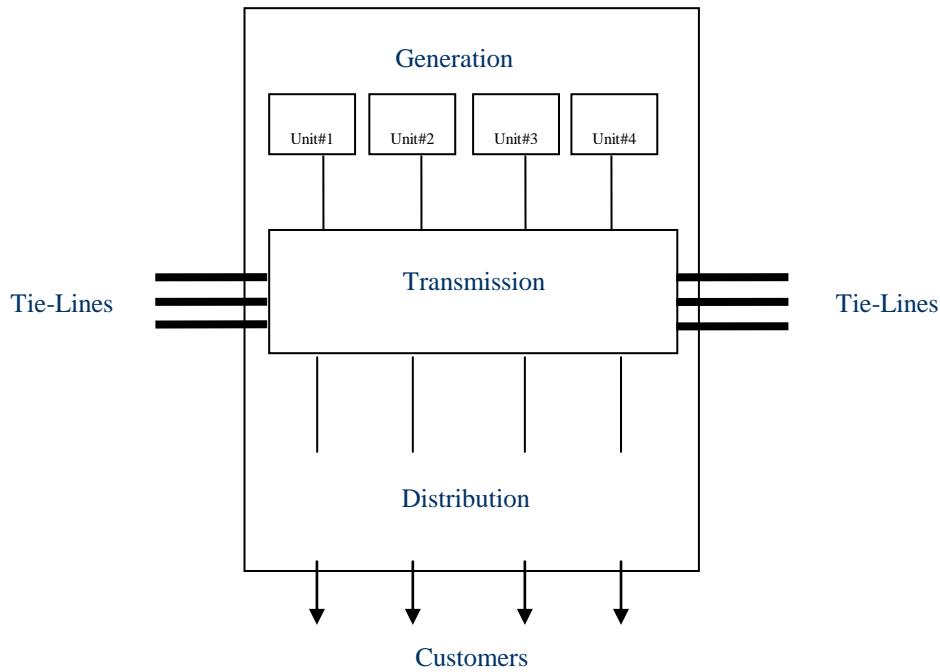


Figure 3.1 Vertically Integrated Utilities (Wood and Wollenberg 1996)

In this network high-voltage transmission lines transfer power from central generating facilities which are located in far distant areas to load central locations. The transmission lines will also, facilitate transfers of energy from one control zone to another to share reserve capacity, take advantage of load diversity, increase system reliability, and transfer power at times of emergency or for economic reasons (Wood and Wollenberg 1996).

3.2.2 Deregulated Power System Operation

In a deregulated environment the power system facilities are decomposed into three main segments: GENCOs, TRANSCO, and DISCO in order to improve the economic posture of the generating and transmission companies. Restructuring is a very complicated process and differs from one country to another for different reasons (Shahidehpour and Marwali 2000). In the case of a deregulated structure the GENCOs

will be separately owned and compete to sell energy. The TRANSCOs will carry the power from one place to another using high-voltage line. The DISCOs will distribute the energy at retail level and may aggregate retail loads. A deregulated power system is shown in figure 3.2.

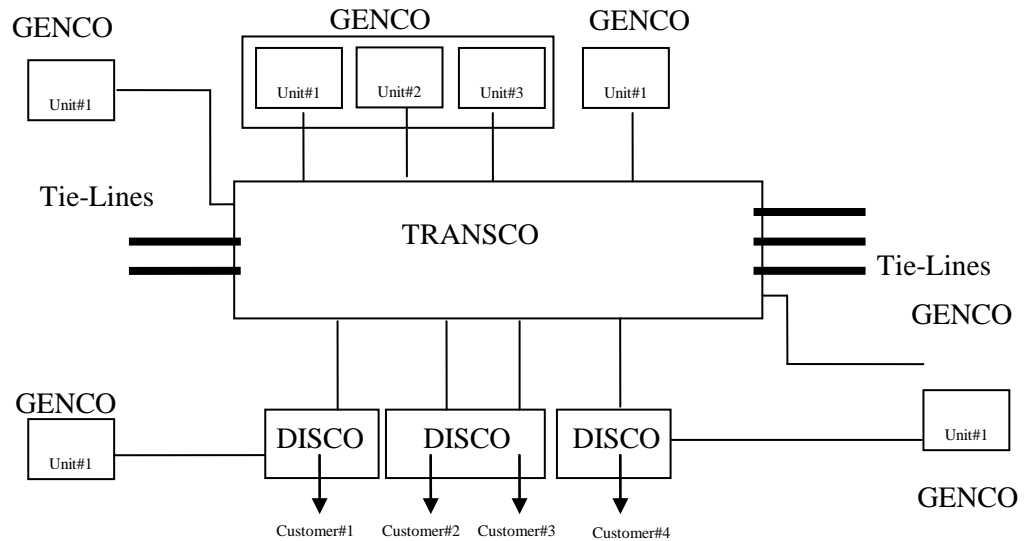


Figure 3.2 Deregulated Power Systems (Shahidehpour and Marwali 2000)

3.2.2.1 GENCOs

The main function of a GENCO is to maintain the existing generating plants. GENCOs may offer electricity to different locations using TRANSCOs and DISCOs to customers. It may own the generating plants or be delegated by plants owners to interact with short term markets such as spot market, pool, and power exchange. It can directly sell electricity to entities. Also, it can sell electricity to power exchanges where DISCO and other customers can purchase electricity to meet their demand. GENCOs will coordinate maintenance activities for generating units with the Independent System Operator (ISO) (Shahidehpour and Marwali 2000).

3.2.2.2 TRANSCOs

A TRANSCO has the role of building, owning, maintaining, and operating the transmission system in a certain geographic region. To provide services for maintaining the overall power system reliability it transmits electricity via high-voltage lines from GENCOs to DISCOs to deliver to customers. TRANSCOs provide the wholesale transmission of electricity and have no common ownership with GENCOs or other market entities. The use of TRANSCO facilities will be under the control of the regional ISO. The transmission maintenance is coordinated between TRANSCOs and the ISO (Shahidehpour and Marwali 2000).

3.2.2.3 DISCOs

Distribution companies (DISCOs) move energy via its facilities to customers in a certain geographic region. It is charged with building and operating its electric system to maintain a certain degree of quality, reliability, and availability. DISCOs must coordinate their functions with both TRANSCOs and the ISO to ensure the flow of energy and delivery to final customers. They are responsible to coordinate with the ISO for maintenance (Shahidehpour and Marwali 2000).

3.2.2.4 ISO

An Independent System Operator (ISO) operates the system. Its primary objective is to control the generation to the extent necessary to maintain reliability, optimize transmission efficiency, and maintain stability of the power system. Co-ordination (using the ISO) for long-term and short-term maintenance scheduling between the segments and within each segment in the deregulated environment is crucial to its success. Therefore, each part is responsible for performing the required maintenance on

their systems in order to sustain the power market. In some market structures the Power Exchange (PX) is under the control of the ISO, and the ISO is responsible for dispatching all generators and setting the price of energy (Billinton and Abdulwhab 2003).

3.3 Generator Maintenance Scheduling Problem

There are two types of facility maintenance in a power system: generating unit's maintenance and transmission lines maintenance. They may be evaluated independently. Maintenance scheduling creates a preventive outage schedule within a planning horizon for a given facility. The solution process will drive the time horizon to short periods and then determine the starting time for each facility outage in order to optimize the given objective (Marwali and Shahidehpour 2000a). It is very important for the effective operation of a power system to determine when its generators should be taken off-line for preventative maintenance or when is the best time for the transmission line maintenance, or when both need to happen. This is primarily because other planning activities are directly affected by such decisions.

The ISO, in a deregulated system will resolve maintenance scheduling conflicts between GENCOs and TRANSCOs, when their competitive interests are not met. The market driven scheduling should consider the electricity prices rather than the operating costs, whilst still optimizing the maintenance activities. GENCOs and TRANSCOs owners tend to perform maintenance only when the market price is low. In doing so, the decision of when to maintain a facility is driven by profit incentive rather than by the optimal cost of maintenance.

3.4 Maintenance Scheduling Models in a Centralized System

The maintenance scheduling has been modelled in literature with several representations for centralized power systems. In the vertically integrated power systems structure the operator has full control of the power system as well as complete technical and costing information of each operation and maintenance activity, and solves the maintenance scheduling problem centrally. A centralized maintenance schedule is produced coordinating with other planning activities using the complete costing and technical information. Researchers have classified the power system unit maintenance scheduling problem as a large scale problem. It includes long-term and short-term scheduling and co-ordination of maintenance activities of generators and transmission systems (El-Sarkh and El-Keib 2003) and (Marwali and Shahidehpour 2000b). In most scenarios the generators maintenance scheduling and transmission maintenance scheduling are treated as separate problems, for simplicity.

3.4.1 Objectives in Solving Maintenance Scheduling Problem in centralized structure

Power systems maintenance scheduling can be modelled as a multi-criterion constrained combinatorial optimization problem, with non-linear objectives and constraint functions (Baskar et al. 2003). One of the most common reliability objectives in a centralized structure is the levelling of the reserve generation over the entire operational planning horizon. In the case of a large variation of reserve, minimizing the sum of squares of the reserves can be an effective approach (Dahal et al. 2000b). Alternatively, the quality of reserve is considered, whereby the risk of exceeding the available capacity is levelled over the entire period by using the equivalent load carrying capacity for each unit and an

equivalent load for each interval. Minimizing the sum of the individual loss of load probabilities for each interval can also be a reliability objective under the conditions of load uncertainty and random forced outages of units (Endrenyi et al. 2001). Minimizing production (i.e. fuel cost) and operation costs (i.e. maintenance cost) is considered to be the most common economic objectives.

3.4.2 Constraints of Maintenance Scheduling Problem in centralized structure

There are typical constraints for maintenance scheduling problems. Any maintenance timetable must satisfy a given set of constraints. The following are some of the constraints presented in the literature (Dahal and McDonald 1997):

- Maintenance window constraints: allowable times and the duration of maintenance tasks for each component.
- Crew constraints: manpower availability to carry out maintenance work.
- Resource constraints: limits on the resources needed for maintenance at each interval.
- Exclusion constraints: prevent simultaneous maintenance of a set of components.
- Sequence constraints: restriction of beginning of maintenance of some equipment before maintenance of some other equipment.
- Load constraints: demand on the power system during the scheduling horizon.
- Reliability constraints: risk level of a given maintenance schedule.
- Generation capacity constraints: generating unit's limitations.
- Transmission capacity constraints: transmission capacity limitations in an interconnected power system.

- Geographic constraints: limitations of total number of unit under maintenance in one zone.

3.5 Maintenance Scheduling Models in a Deregulated Power System

Maintenance scheduling of generating units in a deregulated power system is usually conducted on a short-term or long term basis. The difference between short-term and long-term maintenance scheduling is the time horizon and time increment. In long-term scheduling, the horizon is one year or more with increment of a week. However, in short-term the horizon is weeks with hour as an increment. In this research a short -term and long term GMS problem in a deregulated power system will be investigated.

3.5.1 Objectives in Solving Maintenance Scheduling Problem in Deregulated structure

The available literature on generating unit maintenance scheduling for deregulated power systems is largely focused on two aspects, which are economic criteria and reliability criteria of the power system. From the reliability perspective, a sufficient reserve power margin must be maintained against any equipment failure that may happen during the operation period, with a certain combination of generating units under maintenance. The reserve generation is the difference between the total capacity of the units not being under maintenance and the demand over the planning period. The reserve margins should be levelled through the schedule horizons determined for robust operation of the power system (Nimura et al. 1996). In the case of reliability criteria, Billinton and Abdulwhab (2003) proposed a hybrid approach for a short-term generator maintenance scheduling in a competitive power market. The methodology combines a deterministic criterion within a probabilistic framework (well-being approach). The

scheduling objective is to ensure the resulting risk does not exceed a predetermined acceptable level. In a deterministic approach, the acceptable margin is either a percentage of the available capacity or load, or a value equal to the largest loaded unit. This methodology is named as the health levelization technique. It creates a maintenance schedule for participating GENCOs that satisfies specified health criteria for the entire period under study. The authors demonstrated the effect of conducting preventive maintenance with different load profiles. Hayashi et al. (2001) have presented a long-term generator maintenance scheduling problem for a GENCO. The problem was to determine the best maintenance time intervals, within one year, to take generators off-line for planned maintenance, while it's ISO meets the power demand and system reliability.

Kim et al. (2003) formulated generators maintenance scheduling, where each individual GENCO is modelled as a profit seeking player. Each player seeks to maximize their cumulative profit from the energy action over a scheduling horizon. This type of maintenance strategy is one of the main components in determining the cumulative profit. Each GENCO tries to set up the optimal maintenance period of their generators in a sequential fashion. Bier and Glyer (2002) uses the Reliability Centred Maintenance (RCM) view of the importance of the reliability of power system equipment on the profitability of the company. Usually the forced outages have direct financial consequences for the utilities as they may affect the cost of required reserves to cover possible forced outages.

Abdulwhab and Billinton (2002) have illustrated the effect on maintenance scheduling by using time dependent unit unavailability rather than using Forced Outages Rate (FOR). They proposed a methodology that incorporates probabilistic quantities such as unit unavailability and load forecast uncertainty with deterministic consideration factors such as load levels and reliability criteria. This is a RCM approach where a maintenance schedule is developed in a way to maintain an acceptable reliability level measured by probability of health.

From an economic prospective, fuel and operating costs such as maintenance and energy production costs must be minimized in the long term time-scale. Minimizing the total production and maintenance costs are the most common economic objective in maintenance scheduling for deregulated environment (Shahidehpour and Marwali 2000). If outage durations are allowed to vary, this results in a trade-off between the energy production cost and the maintenance cost. Shorter outage durations lead to higher maintenance costs but reduce the load of expensive generation and possible energy purchases, resulting in lower energy production costs. The production cost alone could also be chosen as the objective function by minimizing the total energy replacement cost due to preventive maintenance scheduling (Huang and Yang 2002). On the other hand, Chattopadhyay (2004) tried to develop a life-cycle maintenance (LCM) policy by maximizing the earning before income tax (EBIT). The model explicitly recognizes all the major *costs* associated with maintenance while considering the technical *benefits* of maintenance.

3.5.2 Constraints of Maintenance Scheduling Problem in deregulated structure

The set of constraints for generator maintenance scheduling problems in deregulated power systems have a similar formulation to the constraints of the centralized power systems. For example, maintenance windows, crew/resource availability, and equipment/power system are related constraints. The other constraints are seasonal limitations, desirable schedule, fuel and emissions. Where the system constraints represent the peak load balance, transmission flow limits and allowable reserved energy will be checked by ISO. In addition to these the schedule should also take into account market constraints such as the following:

- **Contractual commitments:** There are several types of financial contracts such as future contracts, forward contracts and option contract. These contracts include contractual comments related to the supply volume, price and time (Bajpai and Singh 2004).
- **Electricity market rules:** Different market rules are applied for different market. There are important features of market rules choice which are flexibility of bid functions, price determination process including demand-side, impact of hedge contracts on bidding and mandatory versus voluntary pools (Wolak 2000).
- **Market switch and fuel switch capabilities:** Provide opportunity to select lower cost fuel and sell electricity into higher price markets to maximize profited (Sun and Liu 2007).

3.6 Maintenance Cost Models for GMS Problems

The maintenance scheduling problem in the deregulated power systems are formulated as an optimization problem with single and multiple objectives and a set of constraints. The economic criteria based objective functions for deregulated power systems should include various costs (especially maintenance cost) functions. The cost function is used as the sole or main component of the objective function in maintenance scheduling and planning activities. 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. We have attempted to model these components for the deregulated power system. We also discuss the strengths and weaknesses of these cost representations as well as the assumptions made (i.e. assuming the profit of GENCO equal to the penalty that the GENCO should pay to the pool in case of failure).

Shahidehpour and Marwali (2000) and Marwali and Shahidehpour (2000a) have presented a basic formulation for long term GMS problem using a planning horizon in order to minimize total operating costs and satisfying other constraints such as system energy and reliability requirements. Their formulation is a mixed–integer programming model. The objective function includes the total maintenance and production costs. In this case the objective is based on an economic criterion which is minimizing total operating cost, which includes the costs of maintenance and energy production.

In some other publications the authors have introduced different costs to the maintenance modelling. For example the opportunity cost was introduced as an influencing factor in modelling maintenance for power systems. Baughman et al.

(1996a) set a mathematical formulation of a model for real-time pricing of electricity that included selected ancillary services and extended the theory to incorporate constraints on power quality and environment impact that often influence the operation of a power system. They presented an advanced stochastic control model of the for real-time electricity prices. The formulation is novel in that it combines the dynamic equations for load-frequency control with the static equations of a constrained optimal power flow. Baughman et al. (1996b) in their second publication an optimal nodal specific real-time price for both real and reactive power are derived that incorporate additive premia, or opportunity costs, reflecting the effects of the various engineering and environmental operating constraints, such as voltage regulation, maintenance of generation and transmission reserves, regulation of frequency and tie-line flows, removal and/or control of power harmonics, and others, are included in the model. In this publication, they explain the implications that emanate from the necessary first order conditions for the problem presented in part I for pricing of retail and wholesale electricity services.

Chattopadhyay (2004) presents a stochastic optimization framework to optimize the selection of maintenance items over the life of the generating unit to maximize the net revenue of the unit. The model recognizes direct maintenance expenses as well as opportunity costs such as, foregone spot market revenue, replacement costs and penalties for not meeting contractual obligations. It also recognizes the other maintenance advantages such as, avoided degradation of heat rate, unit output and forced outage rate and how such benefits translate into additional profits in the future years.

The opportunity costs and optimal PM strategies are factors, which may influence the over all maintenance cost. Therefore, these factors should be carefully investigated in modelling maintenance scheduling of power systems. However, there is a need for a single model which incorporates all maintenance cost components to analyze their effect on GENCOs. Also, many of the cost components suggested in the literature are assigned to fixed values, restricting their use in optimization models.

3.7 Modelling Maintenance Costs for GENCOs

The maintenance cost model consists of maintenance costs, failure costs, and opportunity costs. These costs will be mathematically modelled to form a complete market oriented maintenance cost model in the following sub-sections.

3.7.1 Cost of Maintenance

The cost of maintenance is an item which was introduced in almost all GMS problems. It is the cost of maintenance actions such as labor cost and maintenance material cost, and indirect cost. Maintenance costs in power systems can be divided into two types: direct and indirect costs.

I. Direct Maintenance Costs

- Labor cost
- Maintenance material cost

The direct costs of maintenance are the costs of preventive maintenance (PM) actions such as planned maintenance, replacement of a component before failure. This includes labor costs which can be quantified by multiplying the duration of the maintenance in hours by the hourly rate of the technicians who perform the generator maintenance.

Direct maintenance material costs are equal to the cost of the materials being used while carrying out the generator maintenance.

II. Indirect Maintenance Costs

- Indirect labor costs
- Indirect material cost

The indirect labor costs are other labor costs for example, health care, social security, and training. This can be quantified by a percentage of labor yearly salary. The indirect material costs are other material costs such as inventory, test equipment, and shipment cost. These can be quantified by a percentage of spare part/material acquisition costs.

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

$$Cma_{it}(s) = [L_{it} + M_{it} + IM_{it} + IL_{it}](s) \quad (3.1)$$

The first term and the last term represents the direct and indirect labor costs for generator i at time t . The second term and third term shows direct and indirect material costs for generator i at time t . The cost of maintenance for applying a particular maintenance strategy is different from one GENCO to another. Different maintenance strategies such as RCM, continuous monitoring of the generator units, predictive maintenance (as needed) periodic inspection, and scheduled maintenance (fixed intervals) were used in different countries. These strategies are different in terms of quality and cost (Endrenyi et al. 2001).

3.7.2 Cost of Failure

This is the cost of repair or replacement due to failures. Referring to Bertling et al. (2005), the failure cost for a distribution system was modelled as follows:

$$Cf_{it}(s) = \lambda_{it}(s) \cdot Cr_{it}(s) \quad (3.2)$$

The first term shows the failure rate for different maintenance strategy for different units in different time interval and the second term represents costs of repair or replacement for different units in different time interval.

Fitting a probabilistic distribution for generator failure data to represent its operating cycle may be not appropriate, because a probabilistic distribution requires a large amount of statistical data which is not available since generator failure rarely happens. Therefore some authors used alternative approach, such as fuzzy representation to taking consideration the inherent uncertainty of the transition rates resulting from insufficient data collection (Eua-Arporn and Karunanoon 2000). The probability that a generator unit is in operation or down because of failure can be presented as follows:

$$\tilde{P}_{up} = 1/[1 + \tilde{r} \cdot (1/\tilde{f})]; \quad (3.3)$$

$$\tilde{P}_{down} = 1/[1 + (1/\tilde{r}) \cdot (\tilde{f})] \quad (3.4)$$

Where, \tilde{P}_{up} , \tilde{P}_{down} are the probability that a generator unit is operating successfully and the probability that a generator unit has failed. And \tilde{f} , \tilde{r} are time to failure and time to repair.

The failure rate $\tilde{\lambda}$ and repair rate \tilde{u} can be modelled as follows:

$$\tilde{\lambda} = 1/\tilde{f} \quad (3.5)$$

$$\tilde{u} = 1/\tilde{r} \quad (3.6)$$

3.7.3 Opportunity Costs

In the proposed model the opportunity costs will be seriously addressed. It can be found in the two scenarios, when the generator is subject to planned maintenance or when it fails between the maintenance periods. We consider the following cases for modelling the opportunity costs:

- Losses of profit when the generator is under planned maintenance and when it went down because of a failure.
- Penalty which the GENCO has to pay to the pool in case of generator failure.
- The inconvenience that the customer may incur during generator failure or planned maintenance (losses of goodwill).
- Cost of interruption, due to unavailability of electricity for customers (economic losses).

3.7.3.1 GENCO Losses

Using the result obtained from Das and Wollenberg (2005), the expected losses for GENCO can be modelled as follows:

$$opp_{it}^l = g_{it,sched}(SMP_t - MCP_t) \quad (3.7)$$

This equation represents the GENCO losses when generator goes down for planned maintenance or because of a failure. The first term represents the amount of scheduled power to be generated multiplied by spot market price. The second term shows the amount of scheduled power to be generated multiplied by market clearing price.

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 (Das and Wollenberg 2005). The real-time hourly spot market price is modelled using:

$$SMP_t = MCP_t(1 + \alpha) \quad (3.8)$$

Where, α is a random variable generated as follows:

Let X_1 be a standard normal random variable and X_2 be another random variable following the standard Cauchy distribution (Hoel et al. 1971). Let $N = (N_1, N_2)^T$ 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.

$$\alpha = \begin{cases} |\beta| & \forall t \in (5,20) \\ \beta & \forall t \in (1,4) \cup ((21,24)) \end{cases} \quad (3.9)$$

Where, $\beta = N_1 X_1 + N_2 X_2$

This ensures that the real-time hourly spot market price is greater than the day-ahead *MCP* between the 5th and the 20th hour but can be lower between the first and the fourth hour and between the 21st and the 24th hours, which are assumed to be off-peak periods. A few random spikes in hourly spot market prices are accounted for by the standard Cauchy distribution (Das and Wollenberg 2005).

In reality *SMP* varies within a range (the range can be very big if the market is very volatile). This means the value of α is also varies within a range. We can calculate the upper bound and lower bound of α using historical data of *SMP* and average *MCP* for a period. If we have maximum value of *SMP* (SMP_{max}) and minimum value of *SMP* (SMP_{min}) and average *MCP* for a representative period, then the minimum and maximum value of α can be calculated using equation 3.8 as follows:

For the lower bound $\alpha_{min} = (SMP_{min} / MCP_{ave}) - 1$; and for the upper bound $\alpha_{max} = (SMP_{max} / MCP_{ave}) - 1$

The value of *SMP* is somehow related to, but can be very different than the average value of *MCP*. In the absence of historical data for *SMP* in our case we assume that *SMP* can be within the range of (0.1* average *MCP*) and (10* average *MCP*). Based on these values α varies in the range of (-0.9, 9).

3.7.3.2 Penalty of Failure

The GENCO penalty cost to the pool is the amount of cost the GENCO should pay to the pool in case of a failure. This amount can be assumed as the profit that the GENCO will gain. Using the result obtained from (Das and Wollenberg 2005), the expected profit of a GENCO can be modelled in the following way:

$$oppf_{it} = g_{it,sched}MCP_t - C_i(g_{it,sched}) \quad (3.10)$$

This equation will represent the penalty cost that the GENCO will pay to the pool in case the generator goes down because of a failure. The first term represents the amount of scheduled power to be generated multiplied by market clearing price and the second term shows the cost of scheduled power to be generated.

3.7.3.3 Inconvenience Costs (Losses of Goodwill)

The inconvenience costs that the user may incur during a generator failure or during planned maintenance will affect the decision in the next electricity supply contract. It can be represented as the losses of customer goodwill. The goodwill is like customer's loyalty to the company due to its good service/reputation.

$$\text{Lose of goodwill} = \begin{cases} oppi & \text{in case of no failure} \\ oppif & \text{, otherwise} \end{cases} \quad (3.11)$$

In case of no failure the customer will be aware of the planned maintenance and the customer may arrange for that, however that still may cause minor inconvenient to the customer. For example, if the customer in direct contract with electricity supplier planned maintenance may cause him lost of sales. In case of failure the customer will experience the outage which may cause him a major of inconvenient. Therefore, the

supplier will incur different costs for loss of customer goodwill as a result of customer inconvenient for the two cases. The cost of losses of goodwill in many publications is presented differently. The cost of lost sales, penalty of lost demand, damaged cost or holding and stock out costs are different representations of losses of goodwill (Frank et al. 2002), (Milner and Rosenblatt 2001) and (Ng and Bjornsson 2001). On the other hand, loss of goodwill can be measured by the probability of losing it due to bad services. 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. With the GENCO's, each generator may have different costs of losses of goodwill depending on the importance of supplying electricity to priority customers and the amount of power they consume. Losses of customer goodwill costs will be investigated and modelled in detailed in Chapter 5.

3.7.3.4 Interruption Costs

The interruption cost is the economic losses that the customer may incur during generator failure. Interruption costs were estimated by trained engineering auditors using an accounting methodology that involved collecting detailed information from plant management about the market value of products and production costs for 210 facilities in the USA (Sullivan et al. 1996). An example of the interruption costs for a large industrial customer can be expressed as follows:

Interruption cost because of failure = $ICf_{it} = \{ \text{Value of lost Production} + \text{Outage Related Costs} - \text{Outage Related Savings} \}$.

$$ICf_{it}(s) = [VLP_{it} + ORC_{it} - ORS_{it}](s) \quad (3.12)$$

The Value of lost Production is equal to the customer's expected revenue without outage minus its revenue with outage. The outage-related costs are the direct costs incurred because of outage. The outage-related saving costs are cost savings resulting from the outage, such as cost of unused fuel and cost of unused raw materials. The outage-related costs can be obtained from real data or can be modelled by regression models (Sullivan et al. 1996). From above, the opportunity costs can be modelled as follows:

- In the case of no failure: $opp_l^i + opp_i^i$
- In the case of a failure: $opp_l^i + opp_i^i + (opp_l^i + opp_i^i f_{it} + opp_f^i + ICf_{it})$

3.7.4 Energy Production Cost

The energy production cost (PC_{it}) is a term that exists in almost all GMS problem formulation. It can be represented as follows:

$$(PC_{it}) = c_{it} g_{it} \quad (3.13)$$

In this research, since we consider the market oriented model, the generation cost will be replaced by Market Clearing Price (MCP); therefore, market production cost (MPC) is equal:

$$(MPC_{it}) = MCP_t \cdot g_{it} \quad (3.14)$$

3.8 Complete Cost Model

Based on the discussion earlier, we have two different models as discussed in the following sub-sections.

3.8.1 Cost Model under No Failure

Cost A = {[Cost of maintenance (labor + material + indirect cost)] + [losses for not submitting bid to ISO (pool) because of maintenance + (losses of customer goodwill)]* probability of no failure

$$CostA = \sum_{i=1}^N \sum_{t=1}^T [Cma_{it}(s) + (opp_{it}^l + opp_{it}^i)](1 - f_i) \quad (3.15)$$

$$= \sum_{i=1}^N \sum_{t=1}^T \left[\begin{array}{l} (L_{it} + M_{it} + IL_{it} + M_{it})(s) + g_{it,sched} \\ (SMP_t - MCP_t) + opp_{it}^i \end{array} \right] * (1 - f_i) \quad (3.16)$$

3.8.2 Cost Model with Failures

Cost B = {Cost A} + {Cost of failure (actual cost of failure) + losses for not submitting bid to ISO (pool) because of failure + losses of customer goodwill because of failure + customer interruption cost (economic losses) because of failure + GENCO payment to the pool because of failure (GENCO profit)}* probability of failure

$$CostB = \sum_{i=1}^N \sum_{t=1}^T \left[\begin{array}{l} \{Cma_{it}(s) + (opp_{it}^l + opp_{it}^i)\} + opp_{it}^l + opp_{it}^f + \\ opp_{it}^f + ICf_{it}(s) + Cf_{it}(s) \end{array} \right] * (f_i) \quad (3.17)$$

$$= \sum_{i=1}^N \sum_{t=1}^T \left[\begin{array}{l} \{(L_{it} + M_{it} + IL_{it} + M_{it})(s) + \\ g_{it,sched}(SMP_t - MCP_t) + opp_{it}^i\} + \\ \{(g_{it,sched}MCP_t - C_i(g_{it,sched})) + \\ g_{it,sched}(SMP_t - MCP_t) + \\ opp_{it}^f + ICf_{it}(s) + \lambda_{it}(s) Cr_{it}(s)\} \end{array} \right] * (f_i) \quad (3.18)$$

3.8.3 The Expected Total Maintenance Cost Model

The total expected maintenance cost ($Exp(C_{it})$) = Probability of no failure * Cost A + Probability of failure * Cost B

$$Exp(C_{it}) = \sum_{i=1}^N \sum_{t=1}^T \left[\begin{array}{l} \left[(L_{it} + M_{it} + IL_{it} + M_{it})(s) + g_{it,sched} \right. \\ \left. (SMP_t - MCP_t) + oppi_{it} \right] * (1 - f_i) \\ + \left[\{ (L_{it} + M_{it} + IL_{it} + M_{it})(s) + \right. \\ g_{it,sched} (SMP_t - MCP_t) + oppi_{it} \} + \\ \{ (g_{it,sched} MCP_t - C_i(g_{it,sched})) + \\ g_{it,sched} (SMP_t - MCP_t) + \\ oppif_{it} + ICf_{it}(s) + \lambda_{it}(s) Cr_{it}(s) \} \end{array} \right] * (f) \quad (3.19)$$

$$Exp(C_{it}) = \sum_{i=1}^N \sum_{t=1}^T \left[\begin{array}{l} \left[(L_{it} + M_{it} + IL_{it} + M_{it})(s) + g_{it,sched} \right. \\ \left. (SMP_t - MCP_t) + oppi_{it} \right] * (1 - f_i) \\ + \left[\{ (L_{it} + M_{it} + IL_{it} + M_{it})(s) + \right. \\ 2(g_{it,sched} (SMP_t - MCP_t)) + oppi_{it} \} + \\ \{ (g_{it,sched} MCP_t - C_i(g_{it,sched})) + \\ oppif_{it} + ICf_{it}(s) + \lambda_{it}(s) Cr_{it}(s) \} \end{array} \right] * (f) \quad (3.20)$$

The formula 3.19 represent the total expected maintenance cost. The first term represent cost A which includes cost of maintenance (direct and indirect labor and material costs), losses because of maintenance, and losses of customer goodwill multiplied by probability of no failure. The second term represent Cost B which includes Cost A, actual cost of failure, losses because of failure, losses of customer goodwill because of failure, customer interruption cost (economic losses) because of failure, and penalty of failure (CENCO profit) multiplied by probability of failure.

3.9 Justification of Maintenance Cost Model

As discussed in Chapter 2, most of the maintenance cost models for deregulated GENCO include only direct maintenance cost. Therefore, that maintenance cost need to be replaced with the total expected maintenance cost presented in (3.20). For example, if we consider a GMS problem with an objective function of minimizing total maintenance cost and production cost (Shahidehpour and Marwali 2000), then the developed expected maintenance cost can replace the traditional (direct) maintenance cost presented in objective function of as follows:

$$\text{Min} \sum_{i=1}^N \sum_{t=1}^T \left[\begin{array}{l} \left[(L_{it} + M_{it} + IL_{it} + M_{it}) + g_{it,sched}(SMP_t) \right] * (1 - f_i) \\ \left[-MCP_t + oppi_{it} \right] \\ \left[\{ (L_{it} + M_{it} + IL_{it} + M_{it}) + \right. \\ \left. 2(g_{it,sched}(SMP_t - MCP_t)) + oppi_{it} \} + \right. \\ \left. \{ (g_{it,sched}MCP_t - C_i(g_{it,sched})) + \right. \\ \left. oppif_{it} + ICf_{it}(s) + \lambda_{it}(s) Cr_{it}(s) \} \right] * f_i \end{array} \right] (1 - x_{it}) + c_{it} g_{it} \quad (3.21)$$

The objective function (3.21) shown above include an integrated maintenance cost model where all factors that affect maintenance activities in deregulated power structure are considered. As we stated before, in deregulation environment where completion exists, maintenance cost model needs to consider not only the direct maintenance cost, but also opportunity and interruption costs and the effect of maintenance strategies. This cost model is more realistic cost where all cost factors are market driven. Therefore, in deregulation power system the GENCOs should utilize this cost model to replace the traditional cost model, in order to account for market conditions when developing a generator maintenance schedule.

3.10 Chapter Summary

In this chapter, we can see that researchers have focused much attention on maintenance scheduling problems for deregulated power systems in order to improve the economic posture of the generation companies. Reducing the maintenance cost is one of the main objectives in power system maintenance scheduling. So, the maintenance scheduling model for deregulated power systems should include various cost (especially maintenance cost) functions.

There are many sensitive cost components that can be considered in the maintenance scheduling model in the deregulated environment. In this chapter, we have analyzed maintenance cost representations considering direct, indirect and opportunity costs. Two models were developed reflecting failure and no failure status of generators. We have shown that there are many costs that affect the decision of when to take a generator out for maintenance. Also, the models took account of any sudden failure which may happen before or after any planned maintenance event. The opportunity costs which reflect customers or GENCO inconvenience in the case of a failure were considered. We demonstrate the utilization of the developed cost models maintenance planning and scheduling in the following chapters.

Chapter 4

GA Based Approach for Generator Maintenance Scheduling

Chapter 4: GA Based Approach for Generator Maintenance Scheduling

4.1 Chapter Overview

Three types of main optimization techniques have been used to solve maintenance scheduling problems for power systems; these are Mathematical approaches, Heuristic approaches and Artificial Intelligence approaches, as discussed earlier in Chapter 2.

Heuristics methods were used earlier in solving maintenance scheduling problem for centralized power systems, although they do not guarantee an optimal solution. Scheduling and planning tasks are often considered difficult for two reasons; scheduling problems are NP-complete and traditional deterministic search techniques can fail due to time limits. Also, these problems are usually not accurately formalized (Negnevitsky and Kelareva 1999).

Mathematical approaches such as, mixed integer programming and Bender's decomposition approaches are used to coordinate and optimize maintenance schedule. The main disadvantages of these approaches are the large computational time required and the suitability of the problem model (Shahidehpour and Marwali 2000).

In this thesis we employ GA as an optimization technique. GAs are based on natural genetic and evolution mechanisms which can be used to solve complicated optimization problems. In different publications (Dawkins 1976), (Dahal and McDonald 1997), (Dahal et al. 1999), (Dahal et al. 2000b), (Negnevitsky and Kelareva 1999) and (Baskar et al. 2003) GA was considered to solve the maintenance scheduling problem.

In this chapter the procedure of developing a basic GA will be given and a description of some GA applications in deregulated power systems will be presented. Also designing GA applications for a GMS problem will be explained in detail. Experimental results and discussion of case studies will be illustrated in the last sections.

4.2 Design and Implementation of Genetic Algorithm to GMS Problems

4.2.1 Experimental Process

The general GA method has been specialized for application to the maintenance scheduling problem, and it will be used to solve GMS problems in this chapter.

4.2.2 Problem Design

In Chapter 3, maintenance cost models have been developed with and without failure scenarios. Both models include different maintenance cost components which may capture a realistic scenario in a real market environment. In order to demonstrate the solution methodology using the genetic algorithm (GA) technique for solving GMS problems, a test system with three generating units which must be maintained over a 4 week planning horizon is described in detail here. The system and relevant data are taken from (Dopazo and Merrill 1975). The main objectives of this case study are the following:

1. Demonstration of data gathering process.
2. Development of GA encoding and setting GA operators.

3. Formulation of maintenance schedule and evaluation function.
4. Implementation of the market oriented maintenance scheduling model.

In this case study a three generating units system and four time intervals (weeks) will be considered. The generating units encompass a single GENCO. All maintenance costs components that form $\text{Exp}(C)$ as define in section 3.8.3 will be calculated. The objective function is to minimize total maintenance cost and production cost subject to maintenance and system constraints (Shahidehpour and Marwali 2000).

$$\text{Min} \quad \left[\sum_{i=1}^N \sum_{t=1}^T \{ \text{Exp}(C)_{it} (1 - y_{it}) + c_{it} g_{it} \} \right] \quad (4.1)$$

The first term represents maintenance cost and the second term represents production cost. The generation cost c_{it} may not reflect the real situation since GENCO may have low or high generation cost regardless of the electricity market price. Therefore, in order for the objective function to be electricity market oriented the second term needs to be modified, as discussed in Chapter 3. In doing so, the MCP_t will be used to replace the generation cost which result in that the production cost depends on the electricity market price during each time period.

Therefore, the objective function considered in this example is to minimize the market maintenance and production cost subject to maintenance and system constraints:

$$\text{Min} \quad \left[\sum_{i=1}^N \sum_{t=1}^T \{ \text{Exp}(C)_{it} (1 - y_{it}) + MCP_t g_{it} \} \right] \quad (4.2)$$

$$\text{Min} \sum_{i=1}^N \sum_{t=1}^T \left[\begin{array}{l} \left[\begin{array}{l} (L_{it} + M_{it} + IL_{it} + M_{it})(s) + g_{it,sched} \\ (SMP_t - MCP_t) + oppi_{it} \end{array} \right]^{*(1-f_i)} \\ \left[\begin{array}{l} \{(L_{it} + M_{it} + IL_{it} + M_{it})(s) + \\ 2(g_{it,sched}(SMP_t - MCP_t)) + oppi_{it}\} + \\ \{(g_{it,sched}MCP_t - C_i(g_{it,sched})) + \\ oppif_{it} + ICf_{it}(s) + \lambda_{it}(s)Cr_{it}(s)\} \end{array} \right]^{*(f_i)} \end{array} \right] (1 - y_{it}) + MCP_t \quad g_{it} \quad (4.3)$$

Subject to:

- Maintenance window: Each unit must be maintained exactly once and the maintenance for each unit must occupy the required time duration without interruption.
- Sequence constraint: Maintenance on unit 3 must begin immediately after maintenance on unit 2 is completed.
- Non-simultaneous maintenance constraint: Maintenance cannot be done on unit 1 and unit 2 simultaneously.
- Load constraint: The total capacities available for maintenance in weeks 1-4 are 150, 170, 180, 130 MW respectively.

The other system and maintenance data is presented in table 4.1 below.

| Unit | Capacity MW | Allowed maintenance period (weeks) | Maintenance duration |
|------|-------------|------------------------------------|----------------------|
| 1 | 80 | 1-4 | 2 |
| 2 | 110 | 1-3 | 1 |
| 3 | 50 | 2-4 | 2 |

Table 4.1 System and maintenance DATA (Dahal and McDonald 1975)

4.2.3 Data Gathering

There are four type of data need to be gathered for this case study, beside the system and maintenance data presented in table in table 4.1. These are direct/indirect maintenance costs, failure cost, *MCP* (to calculate *SMP*, GENCOs losses, penalty of failure and *MPC*), and interruption cost. Both, direct/indirect maintenance costs and failure cost are collect from a power generation company in Saudi Arabia. However, the *MCP* is collected from a published historical data for some GENCO's in California (Klein and Grix 1998), and the interruption cost was obtained from a survey conducted for large industries in USA and it was published in (Sullivan et al. 1996). We have assumed these values do not vary geographically and the actual labor and material costs in both countries are the same.

Actual maintenance, material and labor data have been gathered from an electricity generating company in Saudi Arabia (name withheld for privacy reasons). Referring to (Azaiez and Al-Arfaj 2004) the labor and material costs will be assumed constant through out four week horizon. Referring to Chapter 3 section 3.7.1; direct labor cost is equal to the cost of contracted labor per year. While, indirect labor cost is equal to the cost of rented labor per year. The maintenance material cost is equal to the cost of material used during one year and indirect material cost is equal to the cost of indirect material used during one year. The direct/indirect labor and material costs per week can be obtained by dividing over 52 weeks, for example direct labor is equal to; $3,563,480/52 = 68,528$ \$/week . Table 4.2 summarize direct/indirect maintenance cost for a Saudi electricity company.

| Maintenance costs | Yearly | Weekly |
|-----------------------------------------|-------------|-----------|
| Direct labor cost | \$3,563,480 | \$ 68,528 |
| Indirect labor cost | \$889,580 | \$17,107 |
| Direct material cost | \$2,857,160 | \$54,945 |
| Indirect material cost | \$3,853,052 | \$74,097 |
| Total Direct/Indirect Maintenance costs | | \$215,226 |

Table 4.2 Maintenance data (Saudi electricity Company)

Before calculating opportunity costs the *MCP*, Spot Market Prices (*SMP*), and generation costs functions need to be obtained.

The Day-Ahead *MCPs* are assumed to follow a normal distribution. The GENCO can then estimate *MCPs* for each time period from the normal distribution. Historical data for *MCPs* for different years (1998-2001) for some GENCO's in California were found (Klein and Grix, 1998). The *MCPs* data for each week were fitted to a normal distribution, and the mean values for weeks 1 to 4 were 6,120\$, 6840\$, 7,272\$ and 6,336\$ respectively.

Both *MCPs* and *SMP* change with time. The *SMP*'s are assumed to be a few times more than the *MCPs* in most cases but can reach very high values occasionally and can even be less than the *MCPs* during the off-peak periods (Das and Wollenberg 2005). The spot market price is equal to *MCP* multiplied by $(1 + \alpha)$, where α takes a random value between (-0.9, 9) for each time period. It is generated based on the methodology described in section 3.7.3.1. Using random number generation functions 'randn' and 'cauchy' (in MATLAB) the generated random numbers for X1 and X2 are 0.82 and 5.8

respectively, and N_1, N_2 are equal to 1 and 0 respectively. Therefore, β is obtained as follows:

$$\beta = N_1 X_1 + N_2 X_2 = 0.82.$$

In this problem the value of α is assumed to be the same for peak/off-peak period and equal to β . The values for *SMPs* for weeks are presented in table 4.3.

| Week | <i>MCPs</i> | <i>SMPs</i> |
|------|-------------|-------------|
| 1 | \$ 6,120 | \$ 11,138 |
| 2 | \$ 6840 | \$ 12,449 |
| 3 | \$ 7,272 | \$ 13,235 |
| 4 | \$ 6,336 | \$ 11,532 |

Table 4.3 Summaries of *MCP* and *SMP*

Using the data and the cost curve function presented in (Das and Wollenberg 2005) each generator is assumed to supply its capacity in MW (g_i) and the cost curve function is a quadratic cost function as follows:

$$C_i(g_i) = 0.10g_i^2 + 12g_i + 100 \quad (4.4)$$

The cost curve function for each generator is as follows:

$$C_1(80) = 0.10(80)^2 + 12(80) + 100 = 1,700\$/\text{MW-hr} * 168\text{hr}/\text{Week} = 285,600\$/\text{MW-Week}$$

And, performing the same calculation for other unit's yields:

$$C_2(g^2) = 441,840\$/\text{MW-Week} \text{ and } C_3(g^3) = 159,600\$/\text{MW-Week}$$

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The opportunity costs for each unit at $t = 1$ can be calculated using the formula below:

$$opp^l_{it} = g_{it,sched}(SMP_t - MCP_t) \quad (4.5)$$

Losses for generating unit 1 = $80(11,138) - 80(6,120) = 401,440$ \$/MW-Week

And for generating unit 2 = $552,024$ \$/MW-Week.

And for generating unit 3 = $250,920$ \$/MW-Week.

The penalty to pool can be calculated using the formula below:

$$opp^f_{it} = g_{it,sched}MCP_t - C_i(g_{it,sched}) \quad (4.6)$$

The penalty to pool for generating unit 1 = $80(6,120) - 285,600 = 204,000$ \$/MW-Week.

And for generating unit 2 = $231,360$ \$/MW-Week.

And for generating unit 3 = $146,400$ \$/MW-Week.

Using the data presented in the reference (Sullivan et al. 1996) the interruption cost for a large commercial and industrial customer is assumed to be equal $74,835$ \$/week. The cost of losses of customer goodwill is unknown; therefore it needs to be modelled. Neither interruption costs nor losses of customer goodwill costs will be included in the calculation of the expected maintenance cost in these experiments. Because these costs are more loyalty related, they will be thoroughly investigated in Chapter 5.

Both interruption and goodwill costs will be considered in optimizing total expected maintenance costs in other experiments later.

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Using the data presented in (Eua-Arporn and Karunanoon 2000) the time to failure (IEEE-RTS generation system) is assumed to be 1200 hours (7 weeks). So, the failure rate is equal to $1/7 = 0.1429$ failure/week; and the cost of repair or replace is assumed to be \$ 1000,000 (using data of Saudi Company). So, the cost of failure = $0.1429 * 1000,000 = \$142,900$. Different maintenance strategies may have different failure rates. In this example a planned maintenance strategy with minimal repair in case of failure was considered. A different maintenance strategy will be considered in Chapter 6.

Now, we can calculate the two maintenance costs, and obtain the total expected maintenance cost. The expected maintenance cost will replace the previous direct maintenance cost presented in GMS problems. The total expected maintenance costs for the three generation units during a four weeks horizon will be calculated assuming that the probability of failure equal to 5%.

Table 4.4 represents the estimated values for maintenance cost components for the 3 generating units for four weeks. The third and the sixth columns represent generators losses obtained using formula (4.5). The fifth column represents the failure cost. Column number nine represent penalty of failure which is calculated using formula (4.6). The direct and indirect maintenance cost is presented in column ten as it shown in table 4.2. The last two columns represent cost A and cost B which were calculated using the formulas (3.16) and (3.18), respectively. The interruption cost and goodwill losses are not considered in this case study.

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| W E E K | U N I T | Other Maintenance Costs/Unit (\$) | | | | | | Indirect/ Direct Main. costs \$ | Main. cost under no failure (Cost A) \$ | Main. cost under failure (Cost B) \$ | |
|------------------|------------------|-----------------------------------|-----------------------------------------|--------------------|-------------------|-----------------------------------------|-----------------------------------------|------------------------------------------|--------------------------------------------------------|--------------------------------------------------|--------------------|
| | | Because of Maintenance | | Because of Failure | | | | | | | |
| | | No bids losses | goodwill losses | Cost of failure | No bids losses | goodwill losses | Interruption cost | | | | Penalty to pool |
| 1 | 1 | 401,440 | Not Considered in this Example | 142,900 | 401,440 | Not Considered in this Example | Not Considered in this Example | 204,000 | 215,226 | 616,666 | 1,365,006 |
| | 2 | 552,024 | | 142,900 | 552,024 | | | 231,360 | 215,226 | 767,250 | 1,693,534 |
| | 3 | 250,920 | | 142,900 | 250,920 | | | 146,400 | 215,226 | 466,146 | 1,006,366 |
| 2 | 1 | 448,704 | | 142,900 | 448,704 | | | 261,600 | 215,226 | 663,930 | 1,517,134 |
| | 2 | 310,560 | | 142,900 | 310,560 | | | 310,560 | 215,226 | 525,786 | 1,289,806 |
| | 3 | 280,440 | | 142,900 | 280,440 | | | 182,400 | 215,226 | 495,666 | 1,101,406 |
| 3 | 1 | 477,043 | | 142,900 | 477,043 | | | 296,160 | 215,226 | 692,269 | 1,608,372 |
| | 2 | 655,934 | | 142,900 | 655,934 | | | 358,080 | 215,226 | 871,160 | 2,028,075 |
| | 3 | 298,152 | | 142,900 | 298,152 | | | 204,000 | 215,226 | 513,378 | 1,158,430 |
| 4 | 1 | 415,642 | | 142,900 | 415,642 | | | 221,280 | 215,226 | 630,868 | 1,410,689 |
| | 2 | 571,507 | | 142,900 | 571,507 | | | 255,120 | 215,226 | 786,733 | 1,756,260 |
| | 3 | 259,776 | | 142,900 | 259,776 | | | 157,200 | 215,226 | 475,002 | 1,034,878 |

Table 4.4 Maintenance cost components

Table 4.5 illustrate the maintenance costs for all units/weeks. Columns three and four represent cost A and cost B multiplied by probability of no failure (0.95) and probability of failure (0.05), respectively. The last column represents the total expected maintenance cost which is equal to the summation of the two costs A and B.

| Week | Unit | Main. cost under no failure \$ (Cost A) * 0.95 | Main. cost under failure (\$ Cost B) * 0.05 | Total expected maintenance costs (\$) |
|------|------|------------------------------------------------|---------------------------------------------|---------------------------------------|
| 1 | 1 | 585,833 | 68,250 | 654,083 |
| | 2 | 728,888 | 84,677 | 813,564 |
| | 3 | 442,839 | 50,318 | 493,157 |
| 2 | 1 | 630,734 | 75,857 | 706,590 |
| | 2 | 499,497 | 64,490 | 563,987 |
| | 3 | 470,883 | 55,070 | 525,953 |
| 3 | 1 | 657,656 | 80,419 | 738,074 |
| | 2 | 827,602 | 101,404 | 929,006 |
| | 3 | 487,709 | 57,922 | 545,631 |
| 4 | 1 | 599,324 | 70,534 | 669,859 |
| | 2 | 747,397 | 87,813 | 835,210 |
| | 3 | 451,252 | 51,744 | 502,996 |

Table 4.5 Total expected maintenance costs for 3 generating unit

4.2.4 Scheduling Formulation

Let Y_{it} is the maintenance status of generator i in week t , such that

$$Y_{it} = \begin{cases} 0, & \text{if unit } i \text{ is off for maintenance at week } t \\ 1, & \text{otherwise} \end{cases} \quad (4.7)$$

In this example, there are 12 decision variables for the three units over four time periods (weeks). They are:

$$Y_{11}, Y_{12}, Y_{13}, Y_{14}, Y_{21}, Y_{22}, Y_{23}, Y_{24}, Y_{31}, Y_{32}, Y_{33} \text{ and } Y_{34}$$

Chapter 4. GA Based Approach for Generator Maintenance Scheduling

Let us consider the allowed start time for maintenance for each unit instead of maintenance status. The unknowns for this problem with maintenance start variables are as follows:

$$X_{11}, X_{12}, X_{13}, X_{21}, X_{22}, X_{23}, X_{32} \text{ and } X_{33}$$

Where;

$$X_{it} = \begin{cases} 1, & \text{if week } t \text{ is the start week of maintenance of unit } i \\ 0, & \text{otherwise} \end{cases} \quad (4.8)$$

The unknowns represent the start week of maintenance not the status of maintenance which reduces the number of unknowns from 12 to 8.

If we know X_{it} , then Y_{it} can be easily derived or vice versa, for the given maintenance durations. Using system and maintenance data presented in table 4.1 and following the methodology presented in (Dahal and McDonald 1997) the mathematical expressions for the above constraints can be written as follows:

- Maintenance window:

$$X_{11} + X_{12} + X_{13} = 1;$$

$$X_{21} + X_{22} + X_{23} = 1;$$

$$X_{32} + X_{33} = 1. \quad (4.9)$$

- Sequence constraint:

$$X_{21} - X_{32} = 0;$$

$$X_{22} - X_{33} = 0; \quad (4.10)$$

$$X_{23} = 0.$$

- Non-simultaneous maintenance constraint:

$$\begin{aligned}
 X_{11} + X_{21} &\leq 1; \\
 X_{11} + X_{12} + X_{22} &\leq 1; \\
 X_{12} + X_{13} + X_{23} &\leq 1.
 \end{aligned} \tag{4.11}$$

- Load constraint:

$$\begin{aligned}
 80X_{11} + 110X_{21} &\leq 150; \\
 80X_{11} + 80X_{12} + 110X_{22} + 50 X_{32} &\leq 170; \\
 80X_{12} + 80X_{13} + 110X_{23} + 50 X_{32} + 50X_{33} &\leq 180; \\
 80X_{13} + 50X_{33} &\leq 130.
 \end{aligned} \tag{4.12}$$

Where, X_{11} represent generator 1 with start time of week 1, and X_{12} represent generator 1 with start time of week 2, and X_{13} represent generator 1 with start time of week 3, and so on for other variables.

The objective function depends on the maintenance status of the generating units using maintenance status unknowns as follows:

$$\text{Min} \sum_{i=1}^N \sum_{t=1}^T \left[\left[\begin{aligned} & \left[\begin{aligned} & (L_{it} + M_{it} + IL_{it} + M_{it})(s) + g_{it,sched} \\ & (SMP_t - MCP_t) + opp_{it} \end{aligned} \right]^{*(1-f_i)} \\ & \left[\begin{aligned} & \{(L_{it} + M_{it} + IL_{it} + M_{it})(s) + \\ & 2(g_{it,sched}(SMP_t - MCP_t)) + opp_{it}\} + \\ & \{(g_{it,sched}MCP_t - C_i(g_{it,sched})) + \\ & opp_{it}f_{it} + ICf_{it}(s) + \lambda_{it}(s) Cr_{it}(s)\} \end{aligned} \right]^{*(f_i)} \end{aligned} \right] (1 - y_{it}) + MCP_t \quad g_{it} \tag{4.13}$$

4.2.5 Encoding

The encoding of the problem using an appropriate representation is a very important task in the implementation of a GA for solving an optimization problem. It defines the size and the structure of the search space. Three types of representations can be used in solving GMS problems (Dahal and McDonald 1997). These are binary representation, binary for integer representation, and integer representation. The integer encoding representation consists of a string (chromosome) of integers, each of which indicates the maintenance start period of a unit and the string length is equal to a number of units. The integer formulation of the problem can be encoded using 'Binary for Integer' representation in which, if the number of variable values is not a power of 2, some of the binary values will simply be redundant (Baskar et al. 2003).

The integer representation was found to be more effective for GMS problems as this respects the maintenance window constraint and reduces the size of the search space (Dahal and McDonald 1997). The advantage of this approach is the possibility of using an integer encoding for these new variables in a genetic structure consisting of a string of integers, each one of which represents the maintenance start period of a unit. Therefore, the integer strings are used here to represent candidate solutions of this problem.

4.2.6 Evaluation Function

As in Dahal et al. (2000b), the evaluation function is formulated as a weighted sum of the objective function and the penalty function for violations of the constraints in this example. The penalty value for each constraint violation is proportional to the amount

by which the constraint is violated (Dahal et al. 2000b). The objective is to minimize the evaluation function, which is formulated as following:

$$\sum_c W_c \times (\text{The amount of constraint 'k' violation}) + w_o \times (\text{Objective function}) \quad (4.14)$$

Where, W_c and W_o are the weighting coefficients for k^{th} constraint violation and the objective function respectively. These coefficients are chosen in such way that the violation of harder constraints (i.e. system constraints) pay greater penalty values than the violation of the soft constraints (i.e. maintenance constraints), as shown in figure 4.2. So, the unfit solutions with the violation of constraints contribute a high penalty value to the whole evaluation function value. The penalty value for the constraint violations dominate over the cost function. This leads to the hard constraints being satisfied first, followed by the soft constraints, and subsequently the minimization of the cost function (Dahal 2000).

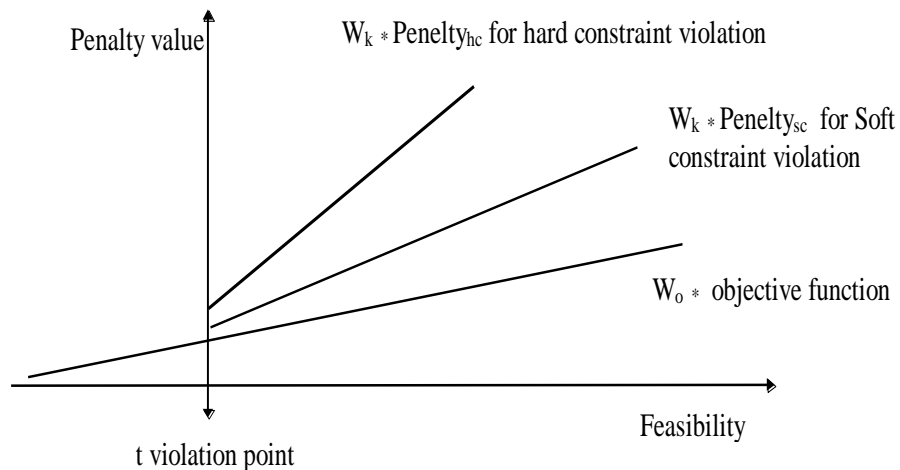


Figure 4.1 Weighting coefficients representations (Dahal 2000)

In order to obtain these weighting coefficients a number of experiments will be conducted to find the average values of the coefficients before running the first GMS experiment. The evaluation function for our test GMS problem was constructed as follows:

- Maintenance window constraints - The encoding automatically includes these constraints.
- Sequence constraints:

$$\text{Penalty}_1 = W_{c1} (|X_{21} - X_{32}| + |X_{22} - X_{33}| + X_{23}) \quad (4.15)$$

- Non-simultaneous maintenance constraints :

$$\begin{aligned} \text{Penalty}_2 = W_{c2} \{ & \max [(X_{11} + X_{21} - 1), 0] + \max [(X_{11} + X_{12} + X_{22} - 1), \\ & 0] + \max [(X_{12} + X_{13} + X_{23}), 1), 0]\}; \end{aligned} \quad (4.16)$$

- Load constraints :

$$\begin{aligned} \text{Penalty}_3 = W_{c3} \{ & \max [(80X_{11} + 110X_{21} - 150), 0] \\ & + \max [(80X_{11} + 80X_{12} + 110X_{22} + 50 X_{32} - 170), 0] \\ & + \max [(80X_{12} + 80X_{13} + 110X_{23} + 50 X_{32} + 50X_{32} - 170), 0] \\ & + \max [(80X_{13} + 50X_{33} - 130), 0]\}; \end{aligned} \quad (4.17)$$

- Cost function = $Min \sum_{i=1}^N \sum_{t=1}^T [\text{Exp} (C)_{it} (1 - y_{it}) + MCP_t g_{it}]$ (4.18)

- Evaluation function = $\{W_c \sum_k \text{Penalty}_k + W_o (\text{Objective function})\}$ (4.19)

4.2.7 Weighting Coefficients

The weighting coefficients were chosen in such a way violation of penalty has a higher value over the objective value. For this we need an indication of maximum constraints violation value. In order to obtain weighting coefficients for constraints violation, five GA runs were carried out using random weights coefficients.

| run | Objective | penalty for sequencing constraints violations | penalty for load constraints violations | penalty non-simultaneous maintenance constraints violations |
|------------------------|------------|-----------------------------------------------|-----------------------------------------|-------------------------------------------------------------|
| 1 | 10,158,467 | 100 | 250 | 650 |
| 2 | 10,188,683 | 450 | 350 | 850 |
| 3 | 10,158,67 | 200 | 250 | 350 |
| 4 | 10,187,983 | 100 | 150 | 75 |
| 5 | 10,158767 | 250 | 300 | 550 |
| Average | 10,170,513 | 220 | 260 | 395 |
| Weighting coefficients | 1 | 46,230 | 39,117 | 25,748 |

Table 4.6 Weighting coefficients

All constraints are soft constraints, in order to make the magnitude of each term in such a way that constraints penalties dominate objective, the weighting coefficients for sequencing constraints violations, load constraints violations, and simultaneous maintenance constraints violations are chosen 46,230, 39,117, and 25,748 respectively as shown in Table 4.6.

4.2.8 Experimental Design

In this section a set of experiments for the 3 generator units test problem was carried out. We use “Roulette wheel” selection method and “one-point” crossover operator as they are popular operators for small and simple application like here. Each experiment

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consists of 5 runs. After a number of experimentations we found that there is a slight changes in the solution, however the best solution found with Crossover Probability (CP) = 0.8, Mutation Probability (MP) = 0.01, and Population Size (PS) =100, these are in line with the recommendations made in the GA literature (Negnevitsky 2005). Therefore, these value where used in all three units case studied. We define the stopping criteria at 100 generation, which seems enough to assure solution convergence. The number of generations kept 100 for all studies. For the 21 unit’s problem, the same GA operator’s probabilities were used.

The experiments were run using MATLAB GA tool box version (7.5.0.324 (R2007b)). The result of each experiment consists of an evaluation function best value and a maintenance schedule that shows start week of maintenance.

Each GA run started from a different initial population pool. In the first experiment only 4 runs out of 5 yielded to an optimum solution that satisfied all constraints which is 2-1-2 with an evaluation function equal to \$9,599,226. The other experiments results are summarized in Table 4.7 and the best solution decoding presented in Table 4.8.

| No. | Solution | Exp-1 | Exp-2 | Exp-3 |
|-----|------------------------------------------------------------------------------------|-------------|-------|-------|
| 1 | No of runs out of 5 runs that reach optimum solution without violating constraints | 4 | 3 | 3 |
| 2 | The best value of evaluation function | \$9,599,226 | | |
| 3 | Corresponding schedule to best evaluation function | 2-1-2 | | |

Table 4.7 Maintenance status per week

| Unit | Evaluation Function Value | Best maintenance start week schedule | Maintenance status per week (1= generator on; 0 = off for maintenance) | | | |
|------|---------------------------|--------------------------------------|---------------------------------------------------------------------------|-------|-------|-------|
| | | | Week1 | Week2 | Week3 | Week4 |
| 1 | \$9,599,226 | 2 | 1 | 0 | 0 | 1 |
| 2 | | 1 | 0 | 1 | 1 | 1 |
| 3 | | 2 | 1 | 0 | 0 | 1 |

Table 4.8 Best solution decoding

The figures below represent best evaluation function value, generators availability, and capacity constraints respectively.

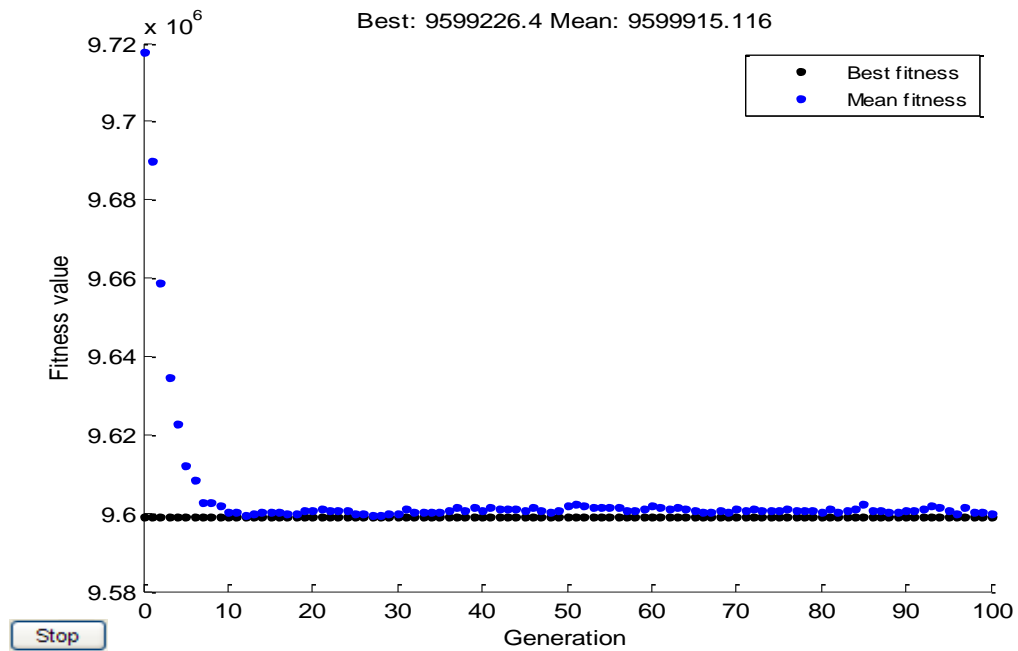


Figure 4.2 Best evaluation function value

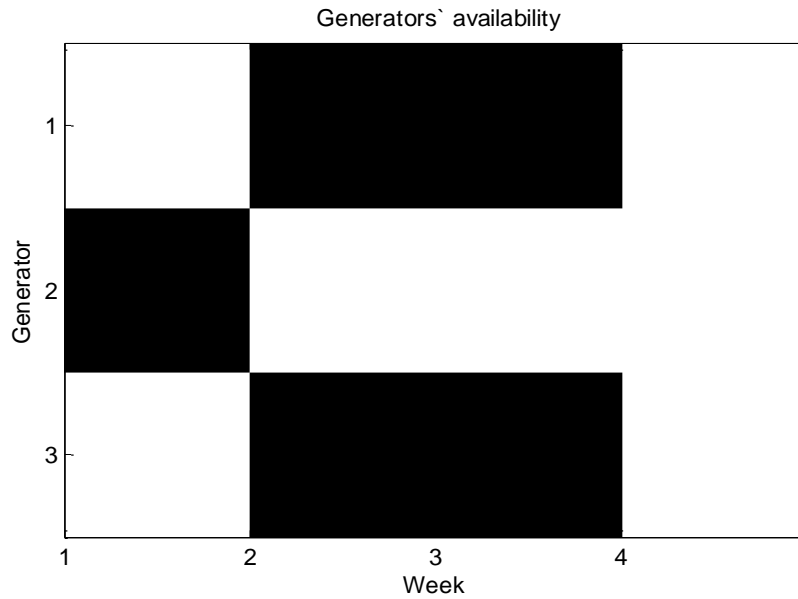


Figure 4.3 Generators availability

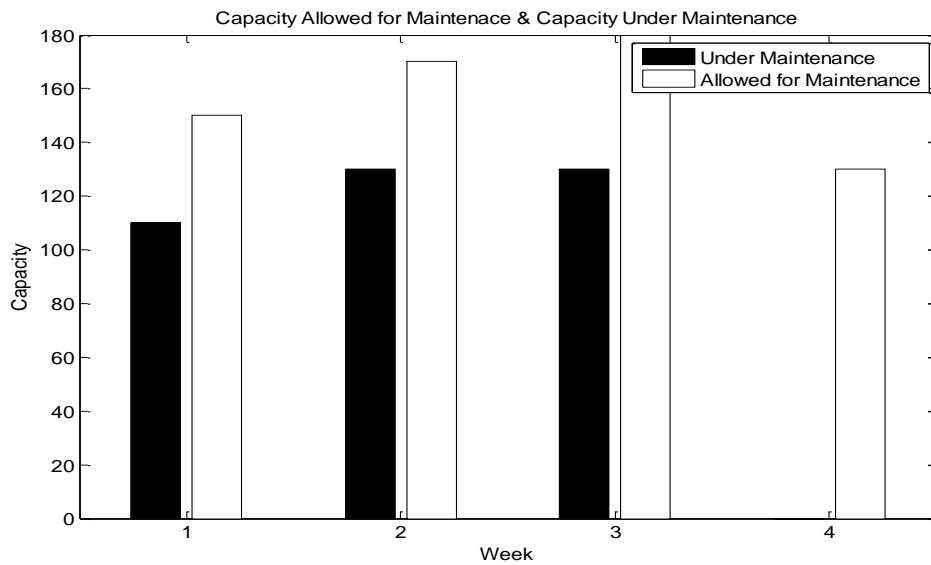


Figure 4.4 Capacity constraints

In this test problem were able to formulate the problem, and to demonstrate the data gathering methodology. The developed cost model which covers nearly all maintenance components was utilized in maintenance planning and scheduling. It has been solved using GA approach with a specific encoding and operators. However, the size of this

problem may not reflect the real situation. Therefore, in the next section we solve a larger problem.

4.3 Problem Design for Twenty One Generator Case Study

In order to reflect real life situation, in this case study we considered a 21 generating units system and 52 time intervals (week) presented in (Dahal and McDonald 1997). The generating units encompass a single GENCO. The main objectives of the study are the following:

- Test the efficiency of the maintenance costs components model on large scale case study close to real life situation.
- Introduce new constraints.
- Establish a robust market oriented maintenance cost model in deregulated power system.
- Test the effect of *MCP* during off-peak periods; also perform some sensitivity analysis on *MCP*.

The constraints for this problem are the following:

- Maintenance window: Each unit must be maintained exactly once and the maintenance for each unit must occupy the required time duration without interruption.
- Load constraint: The system's peak load is 4739 MW.
- Crew constraint: Only 20 people available for the maintenance work weekly.

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Objective: Minimize the sum of total expected market maintenance and production costs.

The system and maintenance data for 21 units in 52 week time are presented in table 4.9.

| Unit | Capacity (MW) | Allowed period | Outage duration in weeks | Manpower required for each week of maintenance |
|------|---------------|----------------|--------------------------|------------------------------------------------|
| 1 | 555 | 1-26 | 7 | 10+10+5+5+5+5+3 |
| 2 | 555 | 27-52 | 5 | 10+10+10+5+5 |
| 3 | 180 | 1-26 | 2 | 15+15 |
| 4 | 180 | 1-26 | 1 | 20 |
| 5 | 640 | 27-52 | 5 | 10+10+10+10+10 |
| 6 | 640 | 1-26 | 3 | 15+15+15 |
| 7 | 640 | 1-26 | 3 | 15+15+15 |
| 8 | 555 | 27-52 | 6 | 10+10+10+5+5+5 |
| 9 | 276 | 1-26 | 10 | 3+2+2+2+2+2+2+2+2+3 |
| 10 | 140 | 1-26 | 4 | 10+10+5+5 |
| 11 | 90 | 1-26 | 1 | 20 |
| 12 | 76 | 27-52 | 3 | 10+15+15 |
| 13 | 76 | 1-26 | 2 | 15+15 |
| 14 | 94 | 1-26 | 4 | 10+10+10+10 |
| 15 | 39 | 1-26 | 2 | 15+15 |
| 16 | 188 | 1-26 | 2 | 15+15 |
| 17 | 58 | 27-52 | 1 | 20 |
| 18 | 48 | 27-52 | 2 | 15+15 |
| 19 | 137 | 27-52 | 1 | 15 |
| 20 | 469 | 27-52 | 4 | 10+10+10+10 |
| 21 | 52 | 1-26 | 3 | 10+10+10 |

Table 4.9 GMS problem with 21 units over a 52 week period (Dahal and McDonald 1997)

4.3.1 Presentation of the Data used in this Experiment

The same direct/indirect labor and material costs per week presented in the previous experiment were used in this experiment. The same methodologies for calculating the MCP , SMP , and generation costs functions will be used in this experiment.

- MCP_t is obtained from historical data
- Spot Market price = $SMP_t = MCP_t(1 + \alpha)$ (4.20)

Where α , as explained in Chapter 3, is a random variable equal to the following:

$$\alpha = \begin{cases} |\beta| & \forall t \in (5,20) \\ \beta & \forall t \in (1,4) \cup ((21,24)) \end{cases} \quad (4.21)$$

- Generation costs functions = $C_{it} = a_i g_{it}^2 + b_i g_{it} + c_i$ (4.22)

Where, a_i , b_i , c_i are the cost coefficient of unit i in interval t .

In this case study a code was designed to obtain MCP , spot market price, and the generation costs functions values and feed them directly to formulas (4.5) and (4.6) in order to obtain opportunity costs for each unit/week. The code for MCP_t is designed so that the MCP_t values will be generated using historical data as explain in previous section. Then the spot market price using formula (4.20) after calculating α using (4.21) will be obtained. Figure 4.5 shows the values for MCP_t and SMP_t for 52 weeks which will be used for this case study.

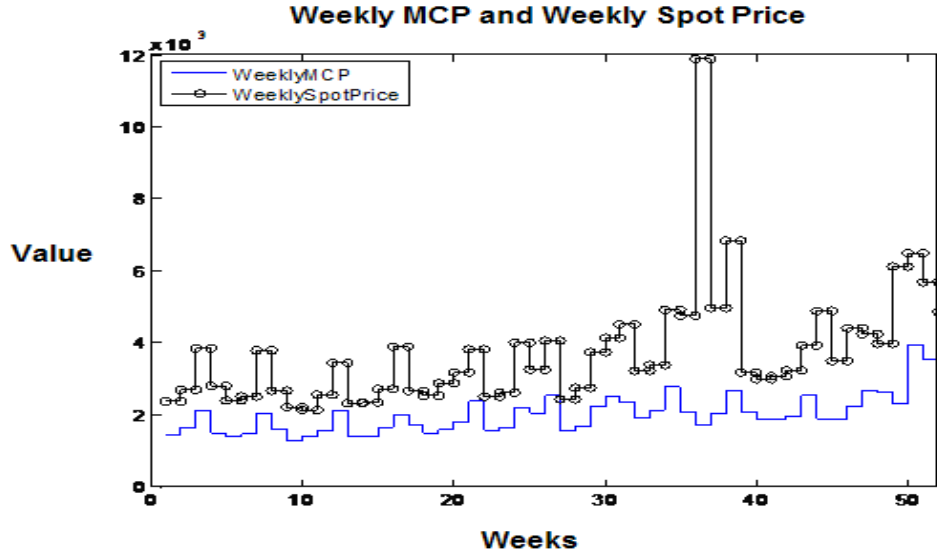


Figure 4.5 MCP and SMP for 52 weeks

In this case study we use the same failure data presented in previous examples (section 4.2.3).

4.3.2 Encoding and Scheduling Formulation

Maintenance window: Maintenance must be done once and only once within the planning period and the unit must be down through its entire maintenance interval. If s_i is the start week of maintenance for unit i , the constraint may be written as shown in (4.23).

$$X_{it} = \begin{cases} 1 & \text{for } s_i \leq t < s_i + d_i, \text{ for } s_i \text{ such that } e_i \leq s_i < l_i, \\ 0 & \text{otherwise.} \end{cases} \quad (4.23)$$

Where,

e_i = earliest week for maintenance of unit i to start,

l_i = latest week for maintenance of unit i to start,

d_i = duration of maintenance for unit i .

Crew constraints: Only a limited number of generators may be serviced at one time because of labor availability. The number and the type of labor for each stage of maintenance of each unit are identified as follows:

$$\sum_{i=1}^N X_{it} L_{ij} \leq AL_{ij} \quad \forall j, \forall t \quad (4.24)$$

Where,

L_{ij} = labor of type j needed by unit i at period t ,

AL_{ij} = available labor of type j at period t ,

$j = 1, 2, \dots, J =$ type of labor.

Load constraint: The sum of the capacity of units in maintenance (Ca) should not exceed the capacity available for maintenance (Ma).

$$\sum_{i=1}^N Ca_{it} X_{it} \leq Ma_t \quad \forall t \quad (4.25)$$

The unknowns for this problem (genes) form a population of candidate solutions and join together to form a string of values (chromosomes). Where each of the genes can take a value of '0' (Maintenance starts) or a '1' (maintenance does not start).

Let Y_{it} is the maintenance status of generator i in week t , such that

$$Y_{it} = \begin{cases} 0, & \text{if unit } i \text{ is off for maintenance at week } t \\ 1, & \text{otherwise} \end{cases} \quad (4.26)$$

In order to reduce the GA search space, the maintenance status unknowns Y_{it} will be replaced by start week of maintenance (Dahal and McDonald 1997) unknowns X_{it} .

Where;

$$X_{it} = \begin{cases} 1, & \text{if week } t \text{ is the start week of maintenance of unit } i \\ 0, & \text{otherwise} \end{cases} \quad (4.27)$$

4.3.3 Objective Functions

As presented in previous case study, the objective function which minimizes total operating cost over the operational planning period, subject to unit maintenance and system constraints will be used here. The operating cost includes two components: the energy production cost and the maintenance cost. Hence the objective function may be written as:

$$\text{Min} \sum_{i=1}^N \sum_{t=1}^T [C_{it}(1 - X_{it}) + c_{it}g_{it}] \quad (4.28)$$

The maintenance cost C_{it} of unit i in interval t includes the costs of failure and opportunity costs. The production (generation) cost c_{it} is mainly the cost of fuel needed for unit i to produce the certain amount of the electrical energy in interval t and can be modelled (Shahidehpour and Marwali 2000). In this research this cost was replaced by MCP_t in order to make the model market oriented. Basically, competitive market environment price of electricity available in the market is considered rather than the production cost. Therefore, the objective function can be written as following:

$$\text{Min} \sum_{i=1}^N \sum_{t=1}^T [\text{Exp}(C)_{it}(1 - Y_{it}) + MCP_t g_{it}] \quad (4.29)$$

4.3.4 Evaluation Function Penalty Function Approach

An evaluation function is required to assign a figure of merit to each coded solution, which should reflect the utility or ability of the individual that the chromosome represents. As in earlier case study, a penalty function approach is used to take care of the various constraints imposed on the system. These take into account not only the constraint violations but also the degree of those violations. The evaluation function presented in (4.19) will be used in this case study.

The weighting coefficients have been obtained using the same methodology discussed before. The results are shown in Table 4.10.

| Run No. | Objective | penalty for crew size constraints violations | penalty for capacity constraints violations |
|------------------------|-----------|----------------------------------------------|---------------------------------------------|
| 1 | 1.816E9 | 2,170 | 20,170 |
| 2 | 1.779E9 | 1,390 | 1,220 |
| 3 | 1.819E9 | 23,900 | 3,110 |
| 4 | 1.782E9 | 39,100 | 57,660 |
| 5 | 1.821E9 | 149,600 | 31,810 |
| Average | 1.803E9 | 43,232 | 80,052 |
| Weighting coefficients | 1 | 41,725 | 22,533 |

Table 4.10 Determination of Weighting coefficients

4.3.5 Experiment Design

In this section a set of experiments for 21 generating units over 52 weeks case study will be carried out. A Roulette wheel selection method will be applied. The crossover operator which will be used here is one-point crossover and the crossover and mutation probability equal to 0.8 and 0.01, respectively. The population size is 100.

The design of these experiments is in Table 4.11.

| No. | Parameter | Exp -1 | Exp -2 | Exp 3 |
|-----|-----------------------|-----------|---------|---------|
| 1 | Number of run | 10 | | |
| 2 | GA Operators | | | |
| 2.1 | Population size | 100 | | |
| 2.2 | Crossover probability | 0.8 | | |
| 2.3 | Mutation probability | 0.010 | | |
| 2.4 | Type of selection | Roulette | | |
| 2.5 | Type of Crossover | One-point | | |
| 3 | MCP | MCP | MCP*0.6 | MCP*1.6 |

Table 4.11 Experiments design

In this case study the code covers all modelling aspects, taking into consideration the effect of off-peak time on the of *MCP* and spot market values. The value of *MCP* and *SMP* for the first experiment is equal to the value presented in figure 4.5. For experiments 2 and 3 the *MCP* value have been changed to *MCP**0.6 and *MCP**1.6, respectively.

4.4 Sensitivity Analysis and Result

For the first experiment, out of 10 runs only 2 runs reached a solution which satisfies the constraints. For experiments 2 and 3 the number of runs to obtain feasible solutions was 5, and 3 respectively. The result shows, changing the *MCP* value either by increasing or decreasing will affect both the evaluation function value and the schedule. The evaluation function value depends also on which crew and capacity results are

achieved. Figure 4.6 doesn't show mean variation clearly because of the large scale values on Y-Axis, therefore we plot 15-65 generation with smaller scale values on Y-Axis, in order to see the actual mean variation as shown in figure 4.6.

The best evaluation function value was obtained in the third run of experiment 2 and it is equal to 1.779E9 as shown in figure 4.6 with the following schedule (the start week of maintenance for generators):

13 - 48 - 3 - 1 - 27 - 24 - 21 - 38 - 15 - 13 - 2 - 40 - 19 - 9 - 7 - 5 - 33 - 45 - 34 - 49 - 9

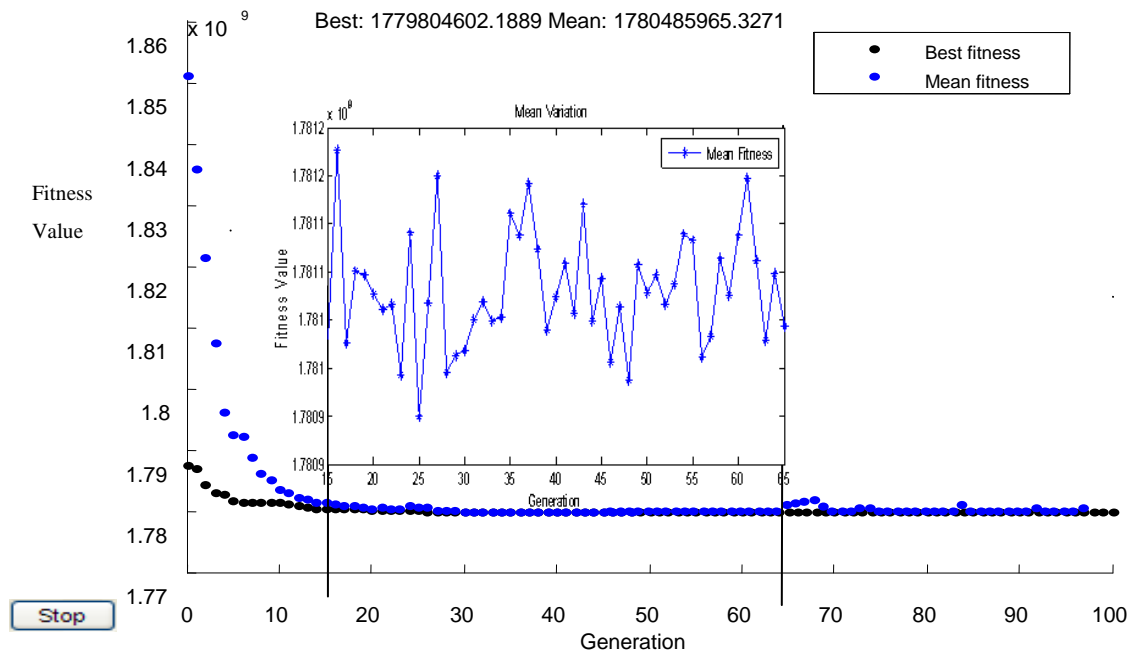


Figure 4.6 Best evaluation function value

Neither capacity nor crew constraints were violated by this schedule. Figure 4.7 shows the required capacity and figure 4.8 shows the required crew size.

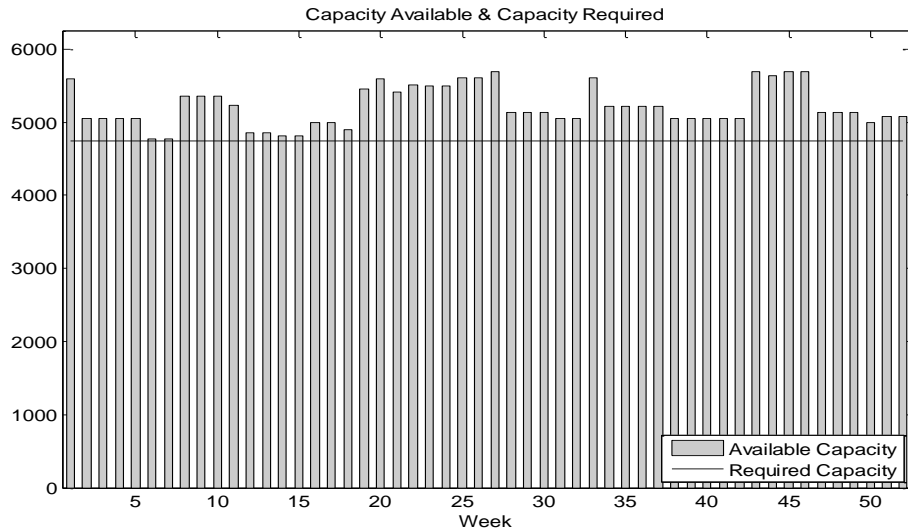


Figure 4.7 Capacity constraints

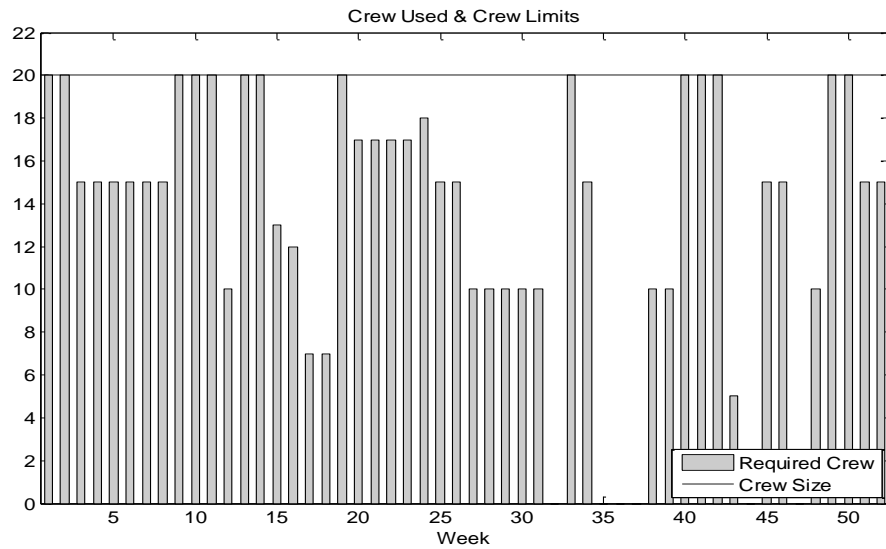


Figure 4.8 Crew constraints

Figure 4.9 shows generator status, where black bars indicate the generator is down for maintenance. For example the first generator will start maintenance at week number 13 and will stay down for 7 weeks (till week 20) since the maintenance duration is 7 weeks. We can see that most of the generators were not put into maintenance during the high value of both MCP and SMP as in weeks 32, 37 and 44, but they were scheduled between weeks 1-30 where both MCP and SMP are considered low.

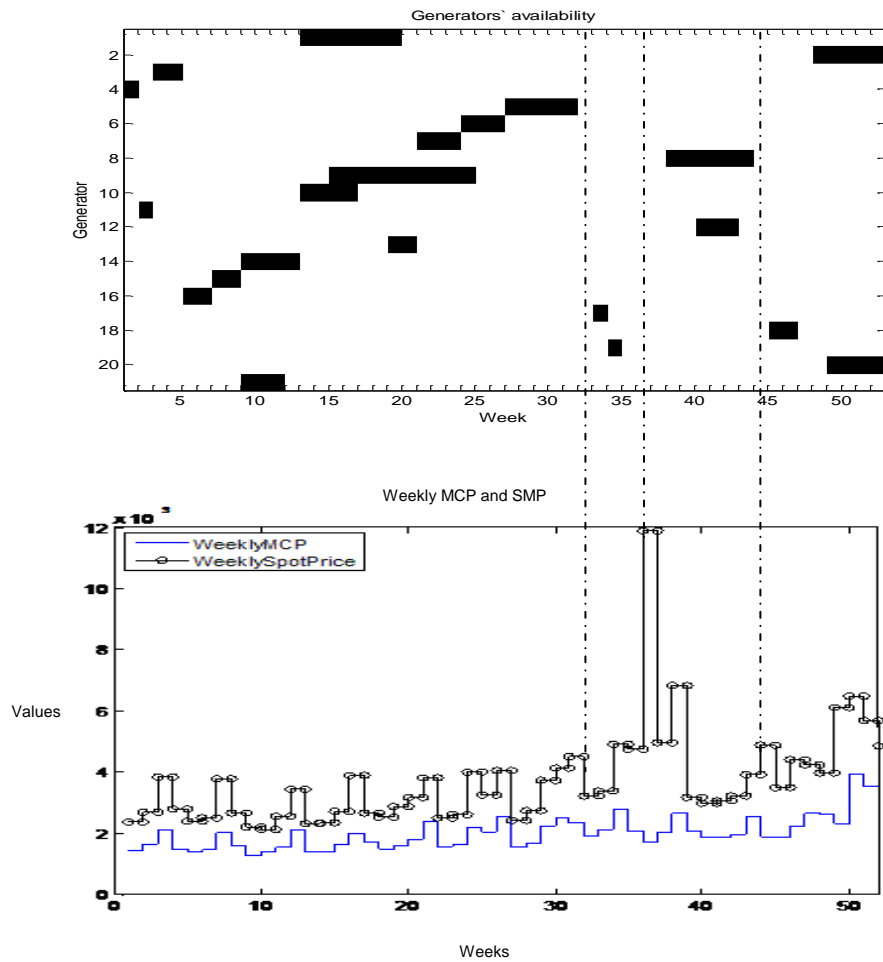


Figure 4.9 *MCP* and generators availability

In the code a *MCP* multiplier was coded in order to perform sensitivity analysis on *MCP*. The result shows, changing the *MCP* value either by increasing or decreasing will affect both the evaluation function value and the schedule. Increasing *MCP* multiplier will result in increasing weekly *MCP*. The variation of *SMP* is a result of Cauchy-Normal distribution which was used in obtaining it. Regardless to *MCP* multiplier value, the random numbers generated from Cauchy-Normal could be large or small and this will affect resulting *SMP*. *MCP* does not depend on those random numbers, because it is calculated simply as an average of *MCP* initial historical data multiplied by *MCP* multiplier over required weeks. As we mention earlier the

evaluation function value depends on crew and capacity constraints. The results and schedule show that the problem is tightly constrained by these constraints. Therefore, in order to check the affect of *MCP* on the final solution we may need to relax the constraints.

4.5 Further Analysis and Result

For a tightly constrained problem, the most of search effort is spent on finding feasible solutions. There could be a small number of feasible solutions, which are not that sensitive to the cost parameters. Therefore, we are going to relaxed the problem constraints and perform sensitivity analysis on *MCP* again. Using the same data and design for the previous experiments, we re-conducted the experiments under relaxation of crew and capacity constraints. For the first experiment, the best value of evaluation function found in the 4th run and it is equal to 1.729E9 with the following schedule (the start week of maintenance for generators):

3-44-22-21-39-16-12-39-2-1-20-34-10-16-24-14-27-32-37-28-24

The reduction of evaluation function value is a result of constraint relaxation. The figure 4.10 represents the *MCP* values and generators availability for the first experiment. In order to evaluate the effect of *MCP* on both evaluation function and the schedule; the other two experiment will be conducted where we decrease and increase *MCP* in experiment number two and three, respectively.

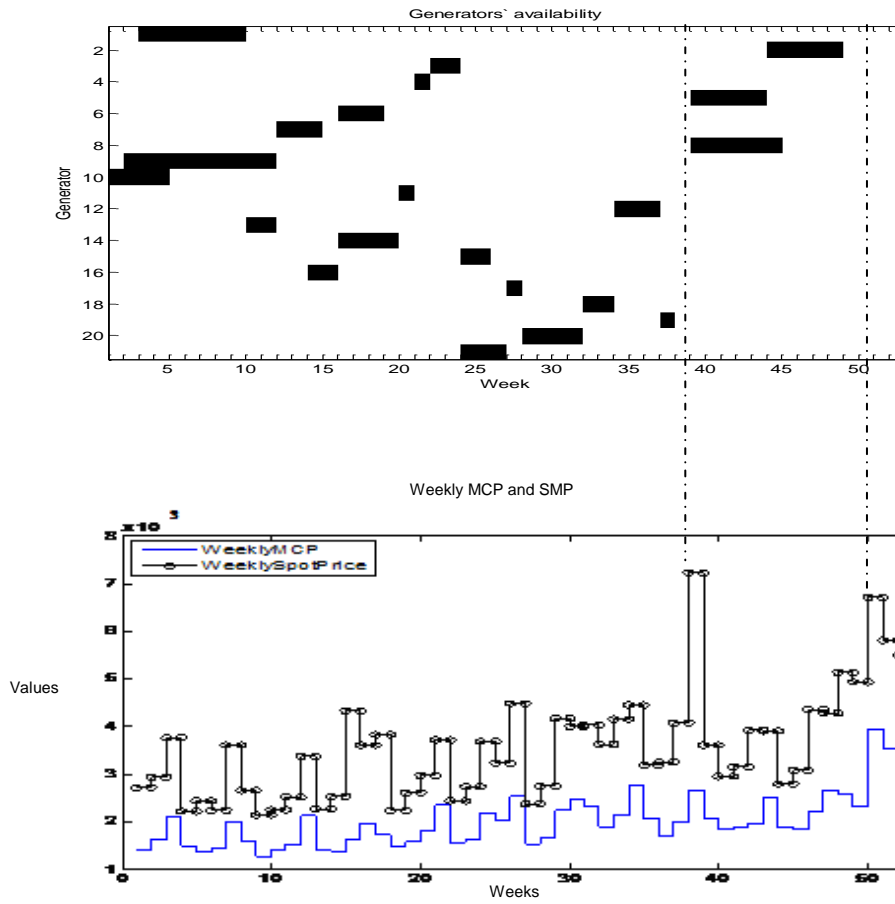


Figure 4.10 *MCP* and generators availability for first experiment

In the second experiment the *MCP* was decreased by 40%, figure 4.11 shows the reduction on the *MCP* for this experiment, where we can see that the maximum *MCP* was around 1500.

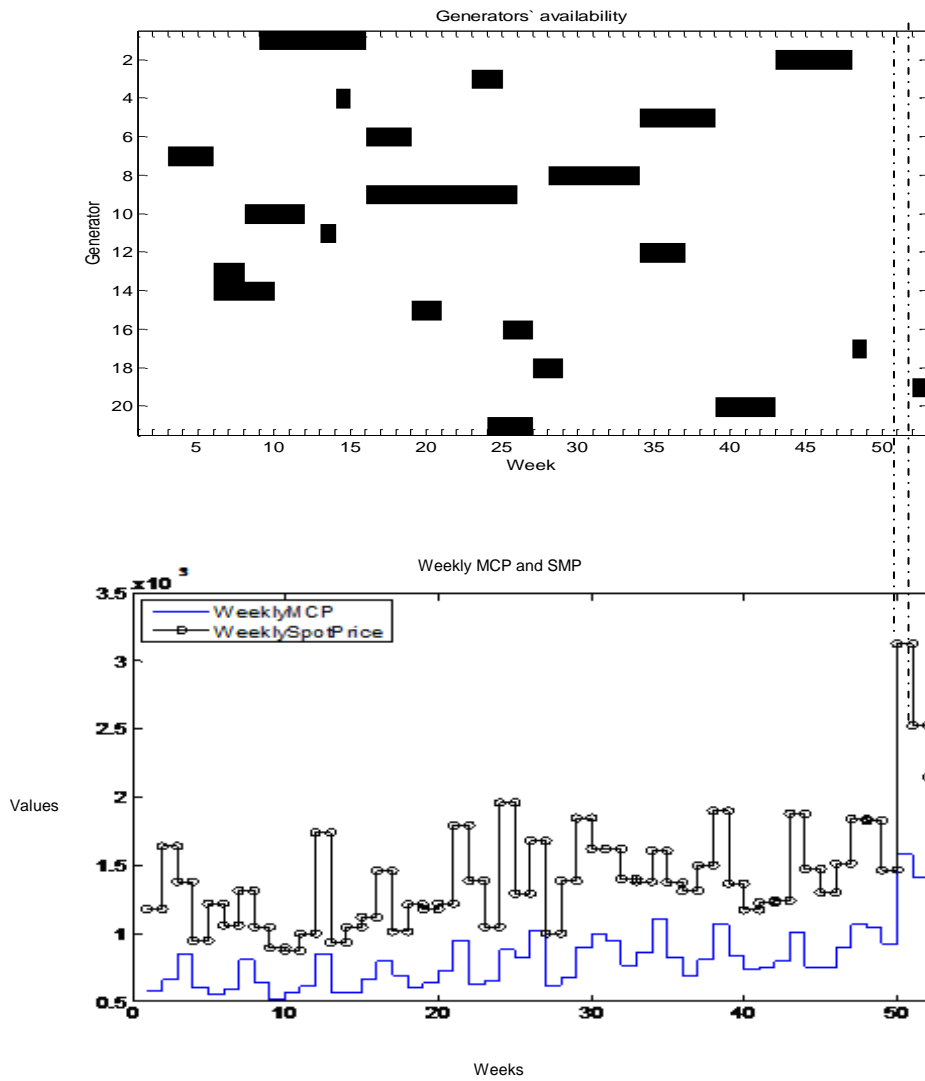


Figure 4.11 *MCP* and generators availability for second experiment

The result shows different values for evaluation function with different schedule. In the 7th run of this experiment the best evaluation function value was found and it is equal to 1.651E9 with the following schedule:

9-43-23-14-34-16-2-28-16 8-13-34 6-6-19-25-48-27-52-39-24

As we can see that the evaluation function value has decreased as a result of the reduction in *MCP*.

Also, we can see that the generators were not put in maintenance when *MCP* and *SMP* reached a high value which can be indicated as a peak time.

In the next experiments (number 3) *MCP* was increased by 60% (Figure 4.12).

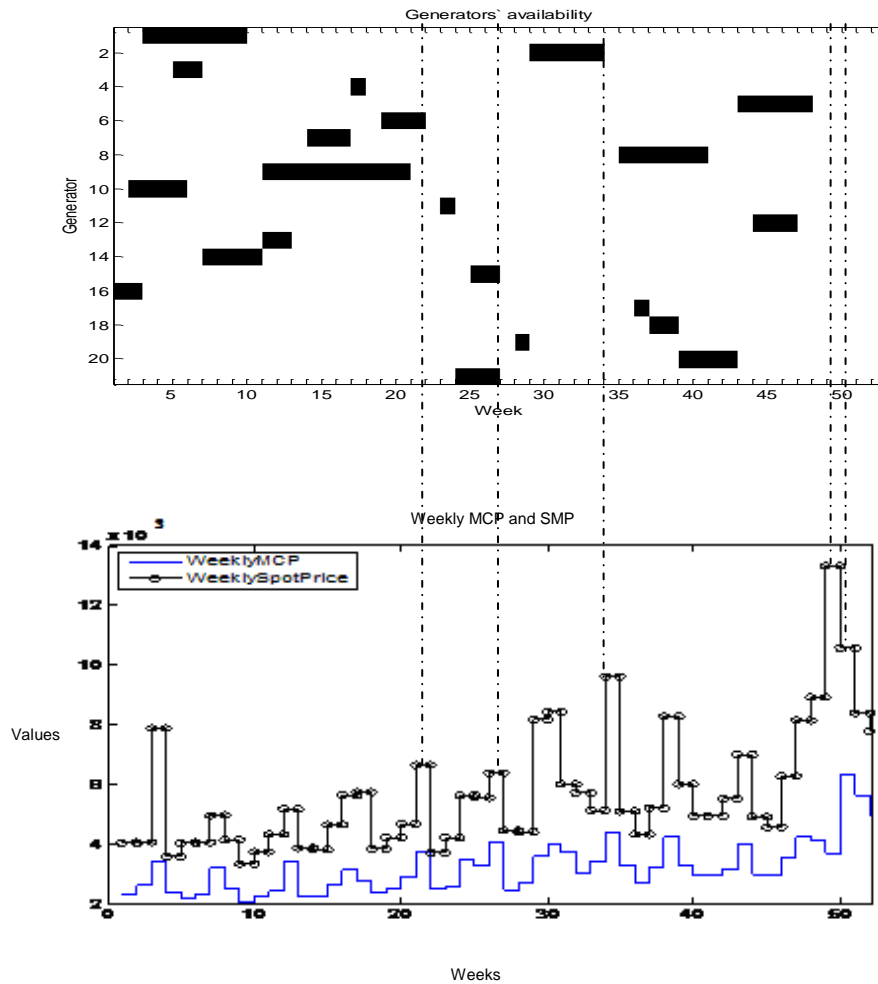


Figure 4.12 *MCP* and generators availability for third experiment

The result shows that increasing *MCP* will result in increasing evaluation function value and a new schedule was obtained. The best evaluation function value was obtained in the 4th run and it is equal to 1.989E9 with the following schedule:

3-29-5-17-43-19-14-35-11-2-23-44-11-7-25 -1-36-37-28-39-24

In conclusion we can say that *MCP* is a factor introduced to the maintenance scheduling in deregulation environment which has an effect on the final solution. Therefore, *MCP* should be carefully modelled in order to reflect more realistic situation for maintenance scheduling for generators in deregulated environment.

4.6 Outcome Analysis of the Case Studies

The main contributions in this research are demonstrations of modelling and data gathering processes, and the application of GA to obtain a maintenance schedule of the GMS problem.

In this chapter, a test problem was constructed to optimize a GMS problem which uses the developed maintenance cost model. As we mentioned earlier, the main objectives of this case study are demonstration of data gathering process, development of GA encoding, evaluation function formulations and implementation of the maintenance scheduling model. The objective function was to minimize the total market maintenance and production costs subject to a set of maintenance and system constraints. All maintenance cost components were modelled to assess their affect on the objective function value and the maintenance schedule. Comparing this problem with the other problems presented in literature (Shahidehpour and Marwali 2000) and (Marwali and Shahidehpour 1998), we can say that the same schedule was obtained; however the value of evaluation function increased in this case study because of the new maintenance cost components.

Since the small case study can't represent the real situation, a large scale case study close to real life situation is considered in this chapter. The main objectives of this study are testing the efficiency of the maintenance costs model on large scale case study close

Chapter 4. GA Based Approach for Generator Maintenance Scheduling

to real life situation with new constraints and testing the effect of *MCP* on the final solution. A 21 unit for 52 weeks case study was solved using GA. A code was developed which covers all modelling aspects including *MCP* values during off-peak time periods. An appropriate representation, evaluation function and GA parameters and operators were selected for the problem in order to reach the optimal solutions of a problem.

The result shows that *MCP* has a significant affect on the final solution, therefore, it should be considered and carefully modelled in maintenance scheduling of generating units in deregulated structure. In this case study opportunity costs were not considered, in chapter five we will use the best solution of this case study in order to compare the results when opportunity costs are considered.

4.7 Chapter Summary

Reducing the maintenance cost is one of the main objectives in power system maintenance scheduling. So, the maintenance scheduling model for deregulated power systems should include various costs especially maintenance cost functions.

The main aim of maintenance scheduling is to ensure the maximum availability of electricity to supply, while at the same time minimizing the overall maintenance costs. A number of objectives for the maintenance optimization program have been employed in the literature; each one employed a number of objectives for a particular power system based on maintenance needs of the system. The general constraints to be satisfied by the GMS are also system specific and independent of the objective function employed. Different sizes of case studies are presented in this chapter, to demonstrate the utilization of the developed maintenance costs model.

Further research in the following directions may improve the performance of the developed model for finding the optimal solution for market oriented GMS problems:

- Consider the cost of losses of customer goodwill.
- Introduce different maintenance strategy.

In the next chapter an analytical hierarchy process technique will be introduced. Then, it will be implemented to price out losses of customer goodwill. The maintenance cost model will be redeveloped to include these changes. The same GMS problems will be resolved considering losses of customer goodwill.

Chapter 5

Opportunity Cost Modelling

Chapter 5: Opportunity Cost Modelling

5.1 Chapter Overview

In the previous chapter, we show that the opportunity cost includes no-bids losses, penalties, goodwill losses, and interruption losses. A loss of goodwill is the inconvenience cost that the user may incur during generator failure or during planned maintenance that may affect its decision in the next electricity supply contract. The goodwill is like customer's loyalty to the supply company due to its good service/reputation. The cost of: lost sales, penalty of lost demand, damaged stock or stock holding and stock out are different representations of loss of customer goodwill in literature (Lim 2001), (Frank et al. 2003), (Tsay 1999), (Milner and Rosenblatt 2001) and (Ng and Bjornsson 2001). 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 a GENCO, each generator may have different cost of loss of customer goodwill depending on the importance they place in supplying electricity to strategic customers and the amount of power they produce. These costs can form the cost of loss of customer goodwill for a specific GENCO. All opportunity cost components except, loss of goodwill and interruption costs were modelled in the previous chapter. This chapter concentrates on modelling loss of customer goodwill for a GENCO in a deregulated power system using Analytical Hierarchy Process (AHP).

The remainder of this chapter is arranged as follows. Section 2 is a review of opportunity costs representations. Sections 3 and 4 present a literature review of Decision Making (DM) and Analytical Hierarchy Process (AHP) techniques, respectively. Section 5 explained the AHP technique. An implementation of AHP case study is illustrated in section 6. Implementations for GMS case studies including losses of goodwill and interruption costs will be presented in section 7. Outcome analysis of case studies is presented in section 8. Section 9 concludes this chapter.

5.2 Review of Opportunity Costs

As the major factor in maintenance scheduling problem formulation, the opportunity cost needs to be carefully modelled to reflect the real-world situations. It must be accurately quantified; otherwise the optimal solution will not reflect the realistic situation. Different maintenance models have been established to consider the decision criteria of when to perform maintenance. In addition to the classical maintenance cost, the maintenance model for deregulated power systems needs to include opportunity costs such as loss of customer goodwill cost.

In literature the cost of loss of customer goodwill has been presented differently. Frank et al. (2003) considered a periodic review inventory system with both deterministic and stochastic priority demand classes. The former demand must be satisfied immediately in each period. However, the goods of later demand that are not met during the period when demand occurs are treated as lost sales. In their developed model, set-up costs are incurred every time an order is placed and loss of goodwill costs are incurred for the

portion of stochastic demand that is not satisfied (lost sale), where losing a sale results in the loss of marginal profit as well as the loss of goodwill. Another form of loss of customer goodwill was presented by Lim (2001) which investigates the contract design problem of a producer when goods are purchased from a supplier, and there is incomplete information regarding the quality of them. The aim was to find the optimal contract that maximizes the expected payoff of the producer. The developed model considered two compensation schemes, a price rebate and a warranty. The supplier of goods has to pay a discount to the producer for found defective goods upon inspection by the latter. Then, a warranty is given to a customer, and a damage cost, which includes the cost resulting from replacement and loss of customer goodwill, among other costs, is shared between the supplier and the producer when a customer has a defective item.

The retailer goodwill loss was studied by Tsay (1999). He considered a supply chain which consists of a supplier that delivers a product to a retailer, which in turn distributes to a market. The retailer submits a forecast of its intended purchase list, without any commitment. Benefiting from over production while not bearing the immediate costs, the customer has incentive to initially over forecast before eventually purchasing a lesser quantity. The author developed a model of the two parties' incentives, identifying causes of inefficiency and suggesting remedies. A Quantity Flexibility (QF) contract, which couples the customer's commitment to purchase no less than a certain percentage below the forecast with the supplier's guarantee to deliver up to a certain percentage above, was considered. The retailer goodwill loss per unit was included in the model

when market demand exceeds available finished goods, where such demand results in lost sales.

The order adjustment costs were defined as a goodwill costs. Milner and Rosenblatt (2001) analyzed a two-period supply contract which allows for order adjustment by the buyer. After observing initial demand, the buyer is then allowed to adjust the second order, paying a per unit order adjustment penalty. The order adjustment costs are explicitly part of a contract or implicitly in the context of a buyer-supplier relationship. The authors have developed a model for such a flexible contract considering the expected revenue from sold units less than the purchasing cost (overage/underage costs), the holding cost and shortage cost that reflects the loss of goodwill. The flexible contract determined the buyer's initial order quantities and optimal second period adjustment policy (Milner and Rosenblatt 2001).

It follows from the above discussion that there are different representation of loss of customer goodwill. Taking some of these idea forward, a model of losses of customer goodwill cost in maintenance scheduling for a deregulated environment, can be developed. If losses of customer goodwill are assigned fixed values, this may restrict their use in optimization models.

Decision analysis is widely used in different sectors for decision making. An important field for decision analysis applications has been in public utilities, especially electric power generation (Clemen 1995). Some of the problems utilities faces are appropriate for handling with decision analysis technique. Finding best loyalty value that minimizes losses of customer goodwill may involve long time frames and hence a high level of

uncertainty. Making decision for such problems may affect many different stakeholders, therefore multiple objectives must be considered. Individual judgments about uncertainty are important input for decision analysis. Understanding the problems people facing and applying decision technique can lead to better decisions. Therefore, decision making analysis will be used in this thesis to select best customer loyalty value.

5.3 Decision Making Technique

Decision Analysis techniques are logical systematic procedures for applying serious thinking to information, data, and experience in order to make a preferred decision when the choice between alternatives is unclear. The steps of applying decision analysis techniques include clarifying purpose, evaluating alternatives, assessing risks and benefits, and making a decision using a decision matrix. They are adaptable to many situations, as determined by the complexity of the problem, needs of the customer, experience of the decision team/analysts/facilitators, and the time and resources available. No one decision making method is appropriate for all decisions (Baker et al. 2002) and (Harris 1980).

The aim in decision-making analysis is to provide the decision-maker with the ability to look into the future, and to make the best possible decision based on past and present information and future predictions. Understanding decision making models allows us to make intentional choices about which model might be most appropriate for the various decisions that they confront. The theory of decision analysis is designed to help make a choice among a set of pre-specified alternatives. The decision making process relies on

information about the alternatives. This diversity in type and quality of information about a decision problem calls for methods and techniques that can assist in information processing. Ultimately, these methods and techniques may lead to better decisions. Multi-Criteria Decision Making (MCDM) is the study of methods and procedures by which concerns about multiple conflicting criteria can be formally incorporated into the management planning process. There are different MCDM methods such as the Analytic Hierarchy Process (AHP), Multi-Attribute Utility Theory (MAUT) and Cost-benefit analysis (CBA). Decision making methods are used for identifying and choosing alternatives based on the values and preferences of the decision maker. They are based on three items, goal, criterion and alternative. The main aim of MCDM is to select the most acceptable alternative among all feasible alternatives (Edwards 1977).

The goal is often the first step in a formal decision process. The actual decision breaks down to selecting "a good choice" from a number of available choices. Each choice represents a decision alternative. In the MCDM context, the selection is done by evaluating each alternative on the set of criteria. The criteria must be quantitative or qualitative and their outcomes must be measured for every decision alternative. Criterion outcomes provide the basis for comparison of choices and consequently facilitate the selection of one, satisfactory choice (Goodwin and Wright 1998).

5.4 Analytical Hierarchy Process (AHP) Applications

Analytical Hierarchy Process (AHP) is one of the more broadly applied multi-attribute decisions making quantitative comparison techniques. It is a well-known and widely

used in operations research. In the early 1970s, Thomas L. Saaty developed the AHP. It is a multi-criteria technique that can combine qualitative or quantitative criteria for prioritizing, ranking and evaluating alternatives to select the best among them (Saaty 1977), (Saaty 1980) and (Saaty 2000). It involves structuring multiple choice criteria into a hierarchy, then assessing their relative importance and selecting the best alternative for each criterion.

AHP has been applied to different applications in the literature (Saaty 1977), (Saaty 1980) and (Saaty 2000), (Atthirawong and McCarthy 2002) and (Sato and Kataoka 1995) have used AHP for different applications ranging from material selection to telecom services. These applications vary in terms of the nature of the problem being considered. For example, Atthirawong and McCarthy (2002) have proposed a model using the AHP for evaluating overseas site selection for an electronic appliance machine manufacturing company in Thailand, in order to add competitive advantage, as well as providing superior and quicker customer service. The model took into consideration a broad variety of factors counting objective and subjective aspects. They examined all related factors such as time to deliver goods to markets, risks linked with site, quality of labor and quality of products for each location alternative. The number of the AHP levels depends on the difficulty of the problem being analyzed. A six level hierarchy decision method were implemented. Level 1 the goal of this application, is, 'choosing the best or most appropriate country to place a manufacturing plant'. The second level represents performance capabilities of a firm for setting up a new manufacturing plant which are cost, quality, speed, flexibility and dependability. Thirteen key factors and

seventy sub-factors affecting international site decisions are offered at the third and the fourth levels of hierarchy. Five points ranking is used at the fifth level of the hierarchy to decrease the number of pair-wise judgments. The place alternatives are at the last level of the hierarchy. The results prove that the model has the ability to be flexible, to be valid to different types of industries by allowing managers to organize their unique problems into priority weights, which can reflect their own priority considerations. Also, it provides a thoughtful of a set of significant factors influencing international site decisions in a case instance.

In telecommunication services Sato and Kataoka (1995) have introduced a customer satisfaction study and analyzed customer perception. All customers are surveyed regarding service order reception, provisioning, and repairs. Concerning the other items such as: telegrams, directory assistance, telephone directories, network performance, terminal equipment, and public telephones customers, they are surveyed randomly. The inspection results are counted up each month for the first set of items and each quarter for the rest. They projected two methods of assessing the data obtained from these surveys. AHP was used to inspect the customer's perception of the importance of the Quality of Service (QOS), and estimate the overall Customer Satisfaction (CS) measured by importance. In AHP, the importance weight is obtained from data rated by a pair-wise comparison. During the survey, the respondents subjectively rated the comparative importance for every pair of items, by selecting one of nine rankings. The other way measures customer satisfaction by categorizing customer opinions into optimistic and pessimistic comments. A probability model is planned that can forecast

the number of optimistic and pessimistic comments, and which can be used to design CS objectives.

In power systems, AHP was used by Nigim et al. (2003). They have used AHP to investigate the impact of special protection schemes (SPS) miss-operations in a power system due to hidden failures in the SPS at the most significant bus locations. The Western States Coordinating Council (WSCC) 179 bus system was selected as the test bed. Each generator site is supposed to be equipped with a SPS that is capable of tripping generation. Hidden failures, which are failures that are not noticeable during normal operation of a system, but become exposed during a fault, are main contributing factor for a serious system interruption to happen. In AHP structure, the target is avoiding needless power-cuts. The second level is the criteria level which is the line fault and failure of SPS to trip the suitable generator. The alternatives are cured by redundant SPS. The AHP reduces time and effort in locating the most and least susceptible SPS as it integrates an expert's service knowledge in the field with probability tools.

The above review shows the ability of AHP in making decision and solving multi-criteria problems for different applications. Similar to AHP applications in telecommunication services and power system operation discussed earlier, AHP will be used here to model loss of goodwill. We investigate and model GENCO loss of customer goodwill that is affected by maintenance activities of generators using the AHP. We focus on formulating an AHP model to select the best loyalty value which contains the most important criteria that affect loss of customer loyalty. The concepts of

the developed model will be used to mathematically quantify the loss of customer goodwill in maintenance scheduling of deregulated power systems.

5.5 Analytical Hierarchy Process (AHP)

The AHP approach is a subjective methodology where information and the priority weights of criteria may be obtained from a decision-maker using direct questioning or a questionnaire method (Cheng and Li 2001). It is a decision approach designed to solve complex multiple criteria problems in a number of application domains. The first step in AHP is to develop a hierarchical representation of a problem. At the top of the hierarchy level 0 is the goal of the analysis. Level 1 is multi-criteria that must be satisfied. Level 2 is the alternatives. The lines connecting different blocks between levels indicate relationships between criteria, alternatives and goal.

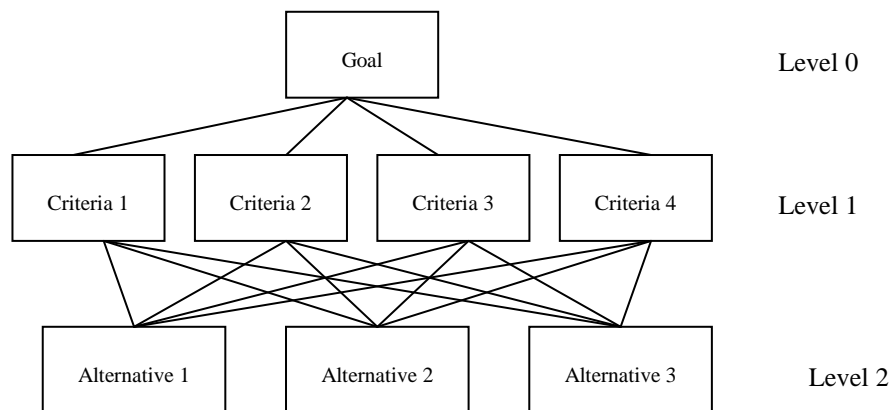


Figure 5.1 Analytical Hierarchy Process (AHP) representations

Once the hierarchy has been structured, the priorities of criteria and alternatives at each level can be determined. Comparison matrices of all criteria and alternatives in each level with respect to criteria and alternatives of the immediately higher level are constructed to prioritize and convert individual comparative judgements into ratio scale measurements.

5.5.1 Analytic Hierarchy Process Steps

There are three steps for considering problems by AHP (Saaty 1980): constructing hierarchies; comparative judgement; and selecting the highest ranking alternative.

Stage I Preparation:

- Set the goal.
- Define qualitative or quantitative criteria.
- State all alternatives.

Stage II Outline of Analytic Hierarchy Process:

- Arrange the information (in Stage I) into a hierarchical model with different levels.
- Use pair-wise assessment to determine the relative importance of each criterion and alternative.
- Mathematically generate relative ratios of measurement, to rank the priorities from the pair-wise assessments.
- Select the highest ranking alternative.

5.5.2 Pair-wise Comparison

The pair-wise is an assessment tool used to determine the relative importance of each criterion and each alternative. It specifies which criterion or alternative is more preferable with respect to the goal or the selected criterion. The weights are quantified by using a nine-point scale (Saaty 2000). The meaning of each scale measurement is explained in Table 5.1.

| weights | Level of importance | Definition Explanation |
|----------------|----------------------------|---------------------------------------------------------------------------------------------------|
| 1 | Equally preferred | Two activities contribute equally to the objective |
| 3 | Moderately preferred | Experience and judgement slightly favour one activity over another |
| 5 | Strongly preferred | Experience and judgement strongly or essentially favour one activity over another |
| 7 | Very strongly preferred | An activity is strongly favoured over another and its dominance demonstrated in practice |
| 9 | Extremely preferred | The evidence favouring one activity over another is of the highest degree possible of affirmation |
| 2,4,6,8 | Intermediates values | Used to represent compromise between the preferences listed above |

Table 5.1 Scales of preference (Crowe et al. 1998) and (Hafeez et al. 2002)

The pair-wise comparison works by judging each criterion as to its relative preference to the goal and judging each alternative as to its relative preference to its parent criterion. Judging can be done using bottom up or top down pair-wise assessment, depending on which is better understood, the criteria or the alternatives. The pair-wise comparisons generate a matrix of relative rankings for each level of the hierarchy. The number of

matrices depends on the number criteria and alternatives at each level. The order of the matrix at each level depends on the number of criteria and alternatives at the lower level that it links to. Then, the relative weights (Eigen-vectors), global weights, and the maximum Eigen-value (λ_{max}) for each matrix are then calculated.

The λ_{max} value is used to validate whether the pair-wise comparison matrix provides a completely consistent evaluation. The consistency ratio (CR) can be obtained using:

$$CR = CI/RI \tag{5.1}$$

Where, the consistency index (CI) for each matrix with an order (n) is obtained using the following formula:

$$CI = (\lambda_{max} - n) / (n - 1) \tag{5.2}$$

Where, (λ_{max}) is the maximum Eigen-value.

The random consistency index (RI) can be randomly obtained from a large number of simulation runs and varies depending upon the order of matrix. Tables 5.2 shows the random average consistency index (RI) obtained by approximating random indices using a sample size of 500 (Saaty 2000).

| | | | | | | | | | | |
|----|---|---|------|------|------|------|------|------|------|------|
| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| RI | 0 | 0 | 0.52 | 0.89 | 1.11 | 1.25 | 1.35 | 1.40 | 1.45 | 1.49 |

Table 5.2 Average random index based on matrix size (Saaty 2000)

The acceptable CR range varies according to the size of matrix, 10% was used as an acceptable CR for small matrices (Saaty 2000). If the value of CR is equal to, or less than the acceptable value, it implies that the evaluation within the matrix is acceptable

or indicates a good level of consistency in the comparative judgements represented in that matrix. And, if CR is more than the acceptable value, then the evaluation process should be improved and repeated (Saaty 2000) and (Atthirawong and McCarthy 2002).

5.6 Applying AHP to Model Goodwill

Now we implement AHP to price out losses of customer goodwill and demonstrate this in a case study. The decision-maker judges the importance of each criterion in pair-wise comparisons. The result of AHP is a prioritized ranking of each alternative. The weight of the alternatives will handle the minimization of loss of customer goodwill in maintenance scheduling of power generators. The hierarchy is constructed by following the AHP steps as below:

- The goal is to determine the best loyalty value that minimizes loss of customer goodwill (level0).
- Criteria are developed and presented in table 5.3 (level1).
- The alternatives are Loyalty Value A, Loyalty Value B, and Loyalty Value C (level2).

These criteria were selected based on direct questions to a decision maker of Electricity Company. Also the deregulation is expected to promote technical support, increase efficiency and improve customer satisfactions (Bajpai and Singh 2004). Therefore, GENCOs are expected to lose customers if they fail to deliver these expectations. The alternatives are classified to reflect the different services which GENCO are expected to perform with a specific cost according to the selected criterion. The cost corresponds to

the quality of loyalty value (i.e. services), assuming that the best loyalty value will have the highest cost. This is like a service level agreement (SLA) between customer and service provider (i.e. electricity supplier or telecomm provider) as explained in table 5.3.

| Criteria | Technical Solution | Reputation | Customer satisfaction | Discount |
|---------------------------------|--------------------|-----------------|-----------------------|-----------------|
| Loyalty Value A High - SLA | High Focusing | Medium Focusing | Low Focusing | High Focusing |
| Loyalty Value B Medium - SLA | Medium Focusing | Medium Focusing | Low Focusing | Medium Focusing |
| Loyalty Value C Low - SLA | Low Focusing | Low Focusing | High Focusing | Medium Focusing |

Table 5.3 Example of relation between alternatives and criterion

The selection of best alternative depends on the criterion, where each alternative has different weights for different criterion. For example, if a Loyalty Value A is chosen to be the best model with respect to criterion, then the GENCO are expected to account for the cost of maintaining those criterion in the total generators maintenance cost in order to avoid loss of customer goodwill. The cost of Value A will be quantified using MCP to reflect the real situation of deregulated environment. Table 5.4 explains the criterion which will be used in the case study.

| No. | Criterion | Explanations |
|-----|-----------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1 | Provide Technical Solution (TS) in case of failure | <ul style="list-style-type: none"> • Provide Uninterrupted power supply (UPS) • Provide Emergency lights • Provide solar system for lights • Provide deployment of portable power generator |
| 2 | Reputation (Rep) | Maintained excellent reputations among other competitors |
| 3 | Customer Satisfaction (CS) | Maintained excellent customer satisfaction by pleasing customer and providing good services |
| 4 | Gives Discount (Dis) during no failure | <ul style="list-style-type: none"> • Gives discount on price of electricity • Gives electricity free of charge for a certain period for customer as compensation |

Table 5.4 Criterion classifications

Now we outline the AHP as explained in Stage II section 5.5.1.

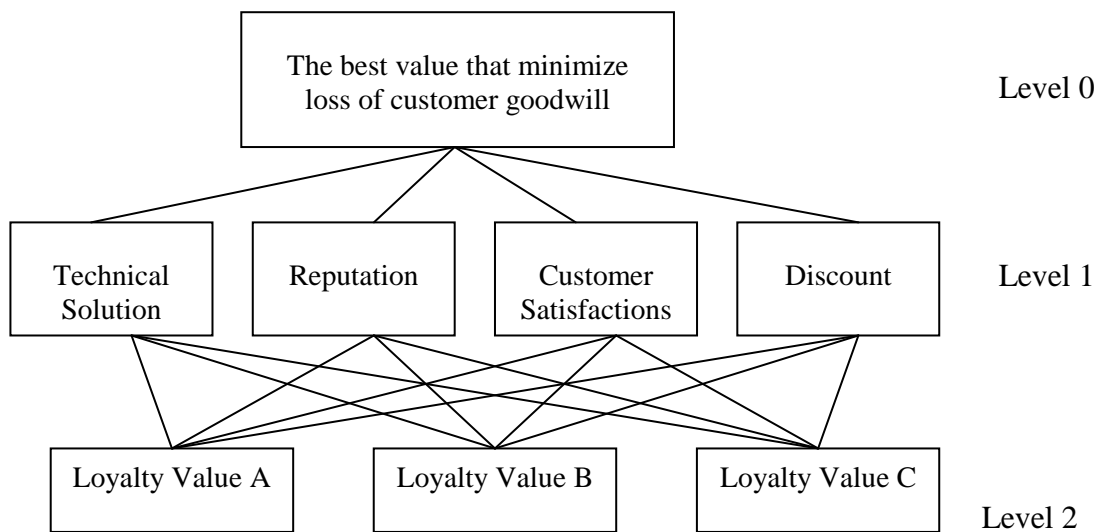


Figure 5.2 AHP structure

In Figure 5.2, the goal is in level 0. Level 1 represents four criteria, and the three alternatives are in level 2. There will be a 4 by 4 matrix corresponding to pair-wise

comparisons between 4 criteria with respect to the goal for level 1. As each alternative is connected to each criterion, there will be 4 comparison matrices at level 2. Each of these has a 3 by 3 matrix.

Four criteria are placed in Table 5.5 forming the first matrix using the scale of preference presented in Table 5.1. We set the diagonal *equal* to one ($a_{ii} = 1$). Furthermore, we set $a_{ij} = k$, and we set $a_{ji} = 1/k$. where the value of k is subjectively determined by a decision maker choosing from a preference scale in Table 5.1

| Criteria | Technical Solution | Reputation | Customer satisfaction | Discount |
|-----------------------|--------------------|------------|-----------------------|----------|
| Technical Solution | 1 | 3 | 7 | 9 |
| Reputation | 0.33 | 1 | 5 | 5 |
| Customer Satisfaction | 0.14 | 0.20 | 1 | 3 |
| Discount | 0.11 | 0.20 | 0.33 | 1 |
| Sum | 1.58 | 4.40 | 13.33 | 18.00 |

Table 5.5 Paired comparison matrix with respect to the goal

The overall weight assigned to each criterion is between 0 and 1, and the total weights will add to 1. We do that by taking each entry and dividing by the sum of the column it appears in. The weights for each criterion are presented in Table 5.6.

| Criteria | Technical Solution | Reputation | Customer Satisfaction | Discount | Sum | Priority Vector |
|--------------------|--------------------|------------|-----------------------|----------|-------|-----------------|
| Technical Solution | 0.630 | 0.682 | 0.525 | 0.500 | 2.337 | 58.42% |
| Reputation | 0.210 | 0.228 | 0.375 | 0.278 | 1.090 | 27.25% |
| Customer | 0.090 | 0.045 | 0.075 | 0.167 | 0.377 | 9.43% |
| Discount | 0.070 | 0.045 | 0.025 | 0.055 | 0.196 | 4.90% |
| Sum | 1.000 | 1.000 | 1.000 | 1.000 | 4.000 | 100.0% |

Table 5.6 The overall weight that is assigned to each criterion

The priority vector is obtained from a normalized Eigen λ_{\max} vector of the matrix. The priority vector for each criteria is equal to the average, for example it is equal to $2.237/4 = 0.5842$ for Technical Solution, 0.2725, 0.0943, 0.0490 for Reputation, Customer Satisfaction and Discount respectively.

Then, the maximum Eigen-value (λ_{\max}) is calculated as follows:

$$\lambda_{\max} = (0.5842)(1.58) + (0.2725)(4.40) + (0.0943)(13.33) + (0.0490)(18.00) = 4.2611$$

The λ_{\max} value is used to validate whether the pair-wise comparison matrix provides a completely consistent evaluation. The consistency ratio (CR) can be obtained using: CI/RI ; Where, the consistency index (CI) for each matrix = $CI = (\lambda_{\max} - n)/n-1 = (4.2611 - 4)/3 = 0.087$

Using Table 5.2 the random consistency is equal to 0.89 and the acceptable consistency is assumed to be 10% or less (Saaty 2000).

$$CR = CI/RI = 0.087/0.89 = 9.78\%, \text{ acceptable.}$$

Since the value of Consistency Ratio is less than 10%, the inconsistency is acceptable. The same analysis is performed for level 2. The comparison matrices are made for each alternative, with respect to each other.

| Alternative | Loyalty Value A | Loyalty Value B | Loyalty Value C |
|---------------|-----------------|-----------------|-----------------|
| Loyalty Value | 1 | 3 | 7 |
| Loyalty Value | 0.33 | 1 | 5 |
| Loyalty Value | 0.14 | 0.20 | 1 |
| sum | 1.47 | 4.20 | 13.00 |

Table 5.7 Paired comparison matrix level 2 with respect to (TS)

| Alternative | Loyalty Value A | Loyalty Value B | Loyalty Value C | Sum | Priority Vector |
|-----------------|-----------------|-----------------|-----------------|-------|-----------------|
| Loyalty Value A | 0.677 | 0.714 | 0.538 | 1.929 | 64.30% |
| Loyalty Value B | 0.226 | 0.238 | 0.385 | 0.849 | 28.30% |
| Loyalty Value C | 0.097 | 0.048 | 0.077 | 0.222 | 7.40% |
| Sum | 1.00 | 1.00 | 1.00 | 3.000 | 100.0% |

Table 5.8 Priority vector from the normalized Eigen vector

We have use the same methodology presented above in obtaining λ_{\max} , CI , and CR for level 2, and the result as follows:

$$\lambda_{\max} = 3.097, \text{ CI} = 0.0484, \text{ CR} = 9.30\% < 10\% \text{ (acceptable)}$$

| Alternative | Loyalty Value A | Loyalty Value B | Loyalty Value C |
|-----------------|-----------------|-----------------|-----------------|
| Loyalty Value A | 1 | 3 | 5 |
| Loyalty Value B | 0.33 | 1 | 3 |
| Loyalty Value C | 0.20 | 0.33 | 1 |
| sum | 1.53 | 4.33 | 9.00 |

Table 5.9 Paired comparison matrix level 2 with respect to (Rep)

| Alternative | Loyalty Value A | Loyalty Value B | Loyalty Value C | Sum | Priority Vector |
|-----------------|-----------------|-----------------|-----------------|-------|-----------------|
| Loyalty Value A | 0.654 | 0.693 | 0.556 | 1.903 | 63.43% |
| Loyalty Value B | 0.217 | 0.231 | 0.333 | 0.781 | 26.03% |
| Loyalty Value C | 0.131 | 0.076 | 0.111 | 0.318 | 10.602% |
| sum | 1.000 | 1.000 | 1.000 | 3.000 | 100.0% |

Table 5.10 Priority vector from normalized Eigen vector

We have use the same methodology presented above in obtaining λ_{\max} , CI , and CR for level 2, and the result as follows:

$$\lambda_{\max} = 3.055, CI = 0.0277, CR = 5.32\% < 10\% \text{ (acceptable)}$$

However, in this particular example, we see that some weights of level 2 matrices are negligible, too small to contribute to the overall decision, thus we ignore them.

We do not use the paired comparison matrix level 2 for Customer Satisfaction and Discount, as their weights are negligible. Therefore we can assume that their weights are zero. Thus, the weights of Technical Solution and Reputation in Table 5.6 must be adjusted so that the sum is still 100%.

$$\text{Adjusted weight for Technical Solution} = 0.5842 / (0.5842 + 0.2725) = 0.6819$$

$$\text{Adjusted weight for Reputation} = 0.2725 / (0.5842 + 0.2725) = 0.3181$$

Then we compute the overall composite weight of each alternative based on the weight of level 1 and level 2. The overall weight is just normalization of linear combination of multiplication between weight and priority vector.

| | Technical Solution | Reputation | Composite Weight |
|-------------------|--------------------|------------|------------------|
| (Adjusted) Weight | 0.6819 | 0.3181 | |
| Loyalty Value A | 64.30% | 63.43% | 64.02% |
| Loyalty Value B | 28.30% | 26.03% | 27.57% |
| Loyalty Value C | 7.40% | 10.60% | 8.41% |

Table 5.11 Overall composite weight of the alternatives

Overall consistency of the hierarchy is given by: $\bar{\bar{C}R} = \sum_i w_i CI_i / \sum_i w_i RI_i$ (5.3)

$$\begin{aligned} \bar{\bar{C}R} &= [0.0885(1) + 0.0484(0.6819) + 0.0277(0.3181)] / [0.89(1) + 0.52(0.6819) \\ &\quad + 0.52(0.3181)] = 9.2 \% < 10\%, \text{ acceptable} \end{aligned}$$

The final result shows that two criteria, Technical Solution and Reputation are better than the others as they have higher weights. Loyalty Value A is the best model; Loyalty

Value B becomes second best and Loyalty Value C is third. Loyalty Value A is the best model with a weight of 0.64 with respect to both criterion Technical Solution and Reputation.

Value A should be implemented for very important (high priority) customers. Any supply interruption will cause a high loss of goodwill value. Value B can be implemented for the second category of customers and so on.

Now, the composite weight of the loyalty values can be used to quantify loss of customer goodwill. The GENCO can set a value of the loss of customer goodwill by multiplying the cost of the market production cost, which is equal to MCP multiplied by the power scheduled to be generated by generator i at time t , by the composite weight of the loyalty values. If we use Loyalty Value A, then the loss of customer goodwill cost for generator i at time t is equal to:

$$\text{Composite weight of the Loyalty Value A} * g_{i,sched}^t MCP^t \quad (5.4)$$

This value together with other maintenance costs will be added to the maintenance cost model to represent the opportunity costs in maintenance scheduling of a deregulated power system.

5.7 Design and Implementation of GA to GMS Problem Including Opportunity Costs

5.7.1 Problem Design for Three Generator Units Case Study

In Chapter 4, GA was used to solve GMS problems. We didn't include goodwill or interruption costs in the maintenance cost models. The main objectives of this case study are the following:

1. Quantifying loss of customer goodwill cost using AHP.
2. Introducing loss of customer goodwill and interruption costs to the maintenance scheduling model.
3. Solving GMS problem using GA with the updated model.

In order to demonstrate the solution methodology using the Genetic Algorithm technique for solving GMS problems, a test system with three generating units maintained over a 4 week planning horizon is described in detail here. The system and relevant data were presented in Chapter 4.

Using the data presented in Chapter 4 the interruption cost is assumed to be equal 74,835 \$/week. The cost of loss of customer goodwill in the case is modelled using AHP. Value A will be used to quantify loss of customer goodwill in this case study for the first experiment, while Models B or C will be used for the other experiments. For example, the cost of loss of customer goodwill for generator one at week one is equal to the following:

$$\begin{aligned}\text{Loss of customer goodwill} &= \text{Weight of the Loyalty Value A} * g_{1,sched}^1 MCP^1 \\ &= 0.6402 * 80 * 6,120 = 313,442 \text{ \$/week}\end{aligned}$$

The costs of loss of customer goodwill for the other generator units will be calculated similarly. Now, we can calculate the two maintenance cost models, by adding both losses of customer goodwill and interruption costs to the previous maintenance cost models explained in Chapter 4.

Similarly, as in table 4.4 (Chapter 4, section 4.2.3), table 5.12 represents the estimated values for maintenance cost components for the three generating units for four weeks, but in table 5.12 we include loss of customer goodwill and interruption costs .

| W E E I K T | U N I T | Other Maintenance Costs/Unit (\$) | | | | | | | Indirect/ Direct Main. costs \$ | Main. cost under no failure (Cost A) \$ | Main. cost under failure (Cost B) \$ |
|----------------------------|------------------|-----------------------------------|--------------------|--------------------|-------------------|--------------------|-----------------|--------------------|------------------------------------------|-----------------------------------------------------|--------------------------------------------------|
| | | Because of Maintenance | | Because of Failure | | | | | | | |
| | | No bids losses | goodwill losses | Cost of failure | No bids losses | goodwill losses | Interr. cost | Penalty to pool | | | |
| 1 | 1 | 401,440 | 313,442 | 142,900 | 401,440 | 313,442 | 74,835 | 204,000 | 215,226 | 930,108 | 2,066,725 |
| | 2 | 552,024 | 430,983 | 142,900 | 552,024 | 430,983 | 74,835 | 231,360 | 215,226 | 1,198,233 | 2,630,335 |
| | 3 | 250,920 | 195,901 | 142,900 | 250,920 | 195,901 | 74,835 | 146,400 | 215,226 | 662,047 | 1,473,003 |
| 2 | 1 | 448,704 | 350,317 | 142,900 | 448,704 | 350,317 | 74,835 | 261,600 | 215,226 | 1,014,247 | 2,292,603 |
| | 2 | 310,560 | 481,686 | 142,900 | 310,560 | 481,686 | 74,835 | 310,560 | 215,226 | 1,007,472 | 2,328,013 |
| | 3 | 280,440 | 218,948 | 142,900 | 280,440 | 218,948 | 74,835 | 182,400 | 215,226 | 714,614 | 1,614,137 |
| 3 | 1 | 477,043 | 372,443 | 142,900 | 477,043 | 372,443 | 74,835 | 296,160 | 215,226 | 1,064,712 | 2,428,093 |
| | 2 | 655,934 | 512,109 | 142,900 | 655,934 | 512,109 | 74,835 | 358,080 | 215,226 | 1,383,269 | 3,127,127 |
| | 3 | 298,152 | 232,777 | 142,900 | 298,152 | 232,777 | 74,835 | 204,000 | 215,226 | 746,155 | 1,698,819 |
| 4 | 1 | 415,642 | 324,505 | 142,900 | 415,642 | 324,505 | 74,835 | 221,280 | 215,226 | 955,373 | 2,134,535 |
| | 2 | 571,507 | 446,194 | 142,900 | 571,507 | 446,194 | 74,835 | 255,120 | 215,226 | 1,232,927 | 2,723,483 |
| | 3 | 259,776 | 202,815 | 142,900 | 259,776 | 202,815 | 74,835 | 157,200 | 215,226 | 677,817 | 1,515,343 |

Table 5.12 Maintenance cost components

Table 5.13 illustrates the expected total maintenance costs including loss of customer goodwill and interruption costs for all units/week assuming that the probability of failure is 5%.

| Week | Unit | \$ Cost A * 0.95 | \$ Cost B * 0.05 | Total expected maintenance costs (\$) |
|------|------|------------------|------------------|---------------------------------------|
| 1 | 1 | 883,603 | 103,336 | 986,939 |
| | 2 | 1,138,321 | 131,517 | 1,269,838 |
| | 3 | 628,945 | 73,650 | 702,595 |
| 2 | 1 | 963,535 | 114,630 | 1,078,165 |
| | 2 | 957,098 | 116,401 | 1,073,499 |
| | 3 | 678,883 | 80,707 | 759,590 |
| 3 | 1 | 1,011,476 | 121,405 | 1,132,881 |
| | 2 | 1,314,106 | 156,356 | 1,470,462 |
| | 3 | 708,847 | 84,941 | 793,788 |
| 4 | 1 | 907,604 | 106,727 | 1,014,331 |
| | 2 | 1,171,281 | 136,174 | 1,307,455 |
| | 3 | 643,926 | 75,767 | 719,693 |

Table 5.13 Total expected maintenance costs for 3 generating unit

5.7.2 Experiment Design

In this section a set of experiments for the 3 generator unit test problem was carried out. Table 5.14 shows the design of the experiments. Each experiment consisted of 5 runs and based on our experiments in Chapter 4. The probability for both crossover and mutation are equal to 0.8 and 0.01, respectively. Loyalty Value A will be used to model loss of customer goodwill for first experiment. Loyalty Values B and C will be used to model loss of customer goodwill for experiments 2 and 3, respectively. The experiments were run using GA tool box version (7.5.0.324 (R2007b)).

The result of each experiment consists of the best value of the evaluation function and maintenance schedule that shows start week of maintenance.

| No. | Parameter | Exp -1 | Exp -2 | Exp -3 |
|-----|--------------------------------|-----------------|-----------------|-----------------|
| 1 | Number of runs | 5 | | |
| 2 | GA Operators | | | |
| 2.1 | Population size | 100 | | |
| 2.2 | Crossover probability | 0.8 | | |
| 2.3 | Mutation probability | 0.010 | | |
| 2.4 | Type of selection | Roulette wheel | | |
| 2.5 | Type of crossover | Single-point | | |
| 4 | Loss of customer goodwill cost | Loyalty Value A | Loyalty Value B | Loyalty Value C |

Table 5.14 Maintenance status per week

5.7.3 Analysis and Result

Each GA run started from a different initial population pool. In the first experiment, a total of 3 out of 5 runs yield an optimum solution that satisfies all constraints. A solution that satisfies all constraints was found in 2 out of 5 runs for the second experiment. For the third experiment a total of 3 out of 5 runs yield to an optimum solution. The best value for evaluation function was found in experiment 3, where Loyalty Value C was used to quantify loss of customer goodwill during no failure. The same schedule obtained in the previous problem (Chapter 4) was obtained in the 3rd run of experiment 3 which is 2-1-2 with an evaluation function equal to \$9,829,033.

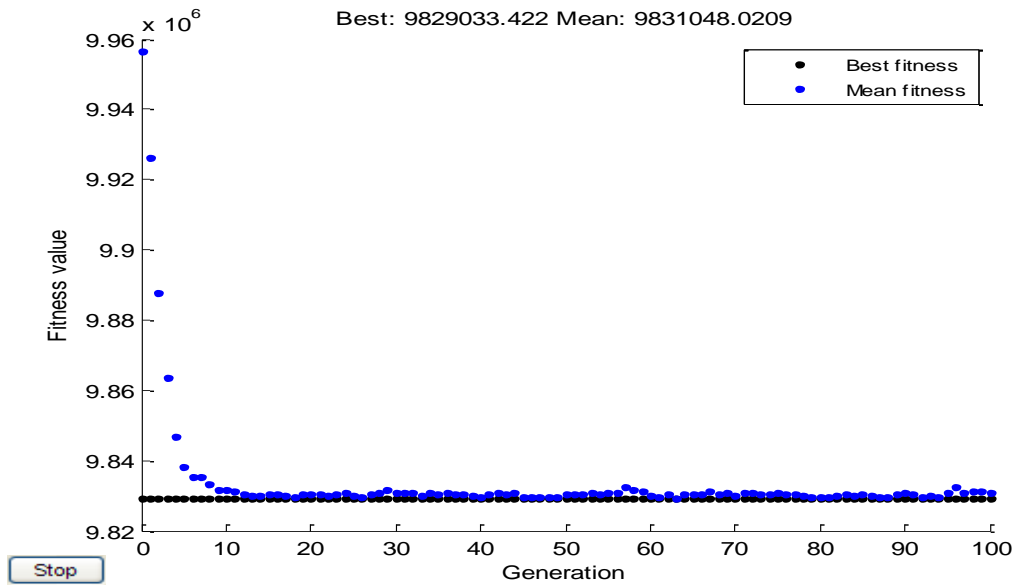


Figure 5.3 Best evaluation function value

We can see that the increase in the evaluation function value compared to the previous result of the same problem in Chapter 4, is as a result of considering the customer related costs mainly loss of customer goodwill and interruption. The results are summarized in Table 5.15.

| Unit | Evaluation Function Value | Best maintenance start weeks schedule | Maintenance status per week | | | |
|------|---------------------------|---------------------------------------|-----------------------------|-------|-------|-------|
| | | | Week1 | Week2 | Week3 | Week4 |
| 1 | \$9,829,033 | 2 | 1 | 0 | 0 | 1 |
| 2 | | 1 | 0 | 1 | 1 | 1 |
| 3 | | 2 | 1 | 0 | 0 | 1 |

Table 5.15 Best solution decoding

Test problem demonstrates the effect of customer related costs mainly losses of goodwill and interruption costs, which were included in the developed model, in the maintenance

planning and scheduling. The highest cost value is obtained in experiments number 1 where we use the best loyalty value (Value A) for quantifying loss of customer goodwill. However, the lowest evaluation function value was obtained in experiment number 3, where we use the poor loyalty value (Value C). The result shows that customer related costs are critical factors impacting the overall maintenance costs value; therefore they must be considered and carefully modelled in order to obtain optimum solutions. We may conclude that Loyalty Value A can be used for pricing out loss of customer goodwill for strategic customers and Loyalty Values B and C for other customers. In the next section we solve a larger problem close to real situation in order to see the affect of customer related costs on the schedule and in overall costs.

5.7.4 Problem Design for Twenty One Generator Units Case Study

In this case study we considered the same 21 generating units system and 52 weeks which were presented in (Dahal and McDonald 1997). The main objective of this study is to test the efficiency of the maintenance costs components model on a large scale case study close to a real life situation where all cost components are mathematically quantified including loss of customer goodwill and interruption costs.

5.7.5 Experiment Design

In this case study three experiments with 10 runs each, were carried out. Value A will be used to model loss of customer goodwill for first experiment. Models B and C will be used to model loss of customer goodwill for experiments 2 and 3, respectively. As discussed in section 4.5 the constraints for this problem will be relaxed and we are

going to use the same *MCP* values presented in that section. The population size was fixed to 100 and the crossover and mutation probability equal to 0.8 and 0.01, respectively. Roulette selection and single-point and crossover types were used here.

5.7.6 Analysis and Result

For the first experiment, out of 10 runs, 5 runs reached the feasible solution. For the second and the third experiments the best solutions were obtained in the 4th and 7th run, respectively. Table 5.16 shows the result of each experiment.

| No. | Solution | Exp-1' | Exp-1 | Exp-2 | Exp-3 |
|-----|-----------------------------------------------------------|--------------------------------------------------------------------------|----------------------------------------------------------------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------|
| 1 | No. of runs out of 10 that reach a final solution | Only one run is conducted | 5 | 4 | 7 |
| 2 | The best value of evaluation function for each experiment | 1.7857E9 | 1.7788E9 | 1.7786E9 | 1.7709E9 |
| 3 | Final schedule (start week of maintenance for generators) | 13-48-3-1-27 24-21-38-15- 13-2-40-19-9- 7-5-33-45-34- 49 – 9 | 1-44-9-17-32- 10-18-39-17- 6-14-29-22- 11-21-4-33- 47-49-27-24 | 12-37-19-6- 46-6-9-27-11- 3-5-31-23-20- 16-20-51-39- 43-42-24 | 10-48-8-6-29- 5-22-40-10- 17-23-35-1- 12-4-25-34- 39-46-35-24 |

Table 5.16 Best solution

We can see that the loss of goodwill cost has an affect on both schedule and evaluation function value. The evaluation function value decreases when we use the poor Loyalty Value C, and vice versa. Also, different schedule were obtained with each solution. As we discussed earlier in Chapter 4 the *MCP* has an affect on the final schedule and we see that clearly after relaxations of constraints. For this case study, we can demonstrate that by looking to figure 5.4 which contain *MCP* values and the schedule obtained in

experiment number one, it is clearly shown that generators were not in maintenance when *MCP* is high. Also, since goodwill cost is time dependent and driven by the *MCP*, therefore the generator shouldn't be put in maintenance in case where goodwill cost is high. We can demonstrate that by plotting the values of goodwill costs for some randomly selected units in the same experiment.

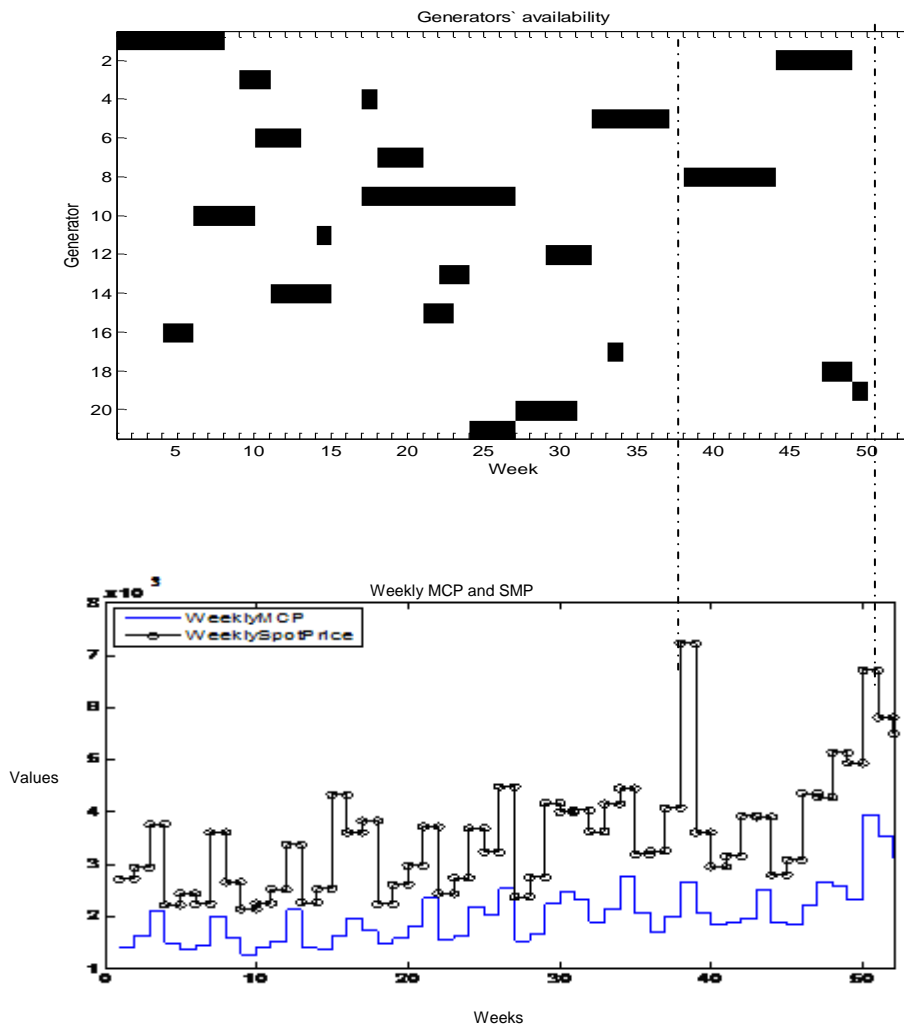


Figure 5.4 Relation between *MCP* and schedule for the first experiment

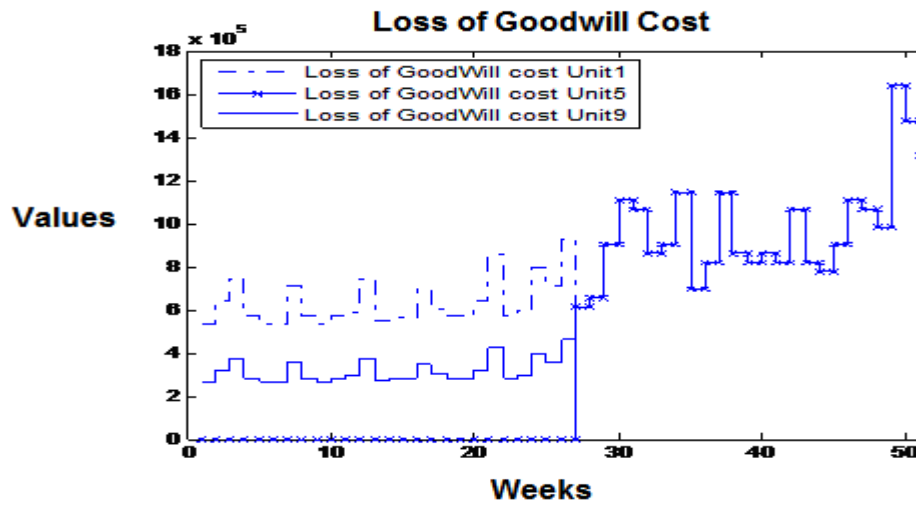


Figure 5.5 Loss of goodwill costs for units 1, 5 and 9

Figure 5.5 shows different values for goodwill costs for different generating units. For example for unit number five we can see clearly that the start week of maintenance is 32 (during the allowed period of maintenance (27-52)) where the value of goodwill is low. The same case can be seen for unit number one.

5.8 Outcome Analysis of the Case Studies

In this chapter, a small case study is developed in order to, demonstrate the quantification process of loss of customer goodwill cost using AHP and introducing opportunity costs (mainly loss of customer goodwill and interruption costs) to the integrated maintenance scheduling model.

By using the same data for both *MCP* and *SMP*, we can see that the evaluation function value increased compared to the previous result of the same problem in Chapter 4, as a

result of considering opportunity costs. The result shows that customer related costs are vital factors impacting total maintenance cost; therefore they must be considered and carefully modelled in order to obtain optimum solutions.

We considered a larger problem (the same 21 generating units system and 52 weeks) in order to see the affect of customer related costs on the schedule and in total costs. The main objective of this study is to test the efficiency of the maintenance costs components model including loss of customer goodwill and interruption costs on a large scale case study close to a real life situation. The result shows that the evaluation function value decreases when we use the poor Loyalty Value C, and vice versa. Also, it is clearly shown that the generator shouldn't be put in maintenance in case where goodwill cost is high.

In order to compare results of this case study with the one in the previous chapter, an experiment (Exp-1') is conducted. We have implemented the best schedule which was obtained in the third run of Exp-2 in chapter 4 section 4.4 (where opportunity costs where not included) to the first experiment in this case study (Exp-1) keeping the same parameters. The result shows that the previous optimum schedule becomes no more optimal and the evaluation function increased significantly because of considering opportunity costs.

5.9 Chapter Summary

There are many cost sensitive components that can be considered in the maintenance scheduling model in a deregulated environment. In this chapter, we have concentrated on pricing-out the loss of customer goodwill cost using AHP to include it in a maintenance scheduling model.

In the case of maintenance or failure the generator companies must minimize the loss of customer goodwill and in either case that is equal to keeping the customer's loyalty, which is a cost on the supplier that should be added to total maintenance cost. We presented the application of AHP to identify the suitable loyalty value for a GENCO to select in order to price out loss of customer goodwill in a deregulated power system, which is considered with in the total maintenance cost. This model reflects the current situation in a deregulated environment. In this chapter we have demonstrated the uses of these loyalty values in pricing out loss of customer goodwill and reflect that in maintenance scheduling of generating units problems.

AHP is a probabilistic approach which takes a short time to formulate once the data are available. It is shown that AHP is an effective prediction tool for use for pricing out goodwill. The criteria we used in this model may differ from one GENCO to another. Technical solution *and* Reputations were the most influential criteria in pricing out customer loyalty. The other criteria Customer Satisfaction and Discount have minimal affect on pricing out goodwill. This study illustrates how decision modelling can help GENCO decision makers select the best choice to minimize loss of customer goodwill. The result shows that the final schedule can be affected by the loss of goodwill cost.

Chapter 6

Maintenance Strategies Modelling

Chapter 6: Maintenance strategies modelling

6.1 Chapter Overview

Maintenance is defined as a combination of activities performed to restore a system, or to renew it, to a satisfactory condition in which the system can perform its intended functions. The main types of maintenance are PM, CM, and PdM. Inspections, Replacements, Repairs and Overhauling are possible preventive maintenance actions (Kececioglu 1995). CM is the maintenance actions that occur after system failure. PdM is carried out when it is deemed necessary, based on periodic inspections, diagnostic tests or other means of condition monitoring to predict equipment failure.

In previous chapters we developed maintenance model using the PM strategy with minimum repair. The maintenance strategy is the PM policy, which minimizes the total maintenance cost. In this chapter we investigate and develop a maintenance cost model using PdM policy. The PdM routines contain a set of programs named Reliability Centred Maintenance (RCM). RCM focuses on preserving system function where the main parts for system reliability are prioritized for PM. RCM approaches are gaining importance in industries. It encompasses systematically monitoring for system's conditions and performance. It has been used by different researchers to provide a framework that handles the complexity of maintenance of different systems. It compares different alternatives of maintenance policies, and then selects the most cost-effective strategy for sustaining system reliability (Endrenyi et al. 2001).

RCM merges the different maintenance strategies and adapts these strategies where each is applicable, based on the consequence and frequency of serious failures. This integration of strategies develops a maintenance program which optimizes both

reliability and cost effectiveness. The traditional RCM process involves identifying the systems to be studied, failure modes and causes, and maintenance tasks. In utilities RCM aims to determine the minimum set of preventive maintenance tasks necessary to properly address the risk of severe equipment failures without compromising service reliability (Asgarpoor and Doghman 1999).

In section 2 of this chapter we introduce in detail the RCM strategy methodology and reflect that in generators maintenance scheduling problems. Section 3 discusses RCM in power systems. Next, the maintenance cost model including RCM is developed. Finally, the 3 unit case study for the developed model is presented to demonstrate the data gathering process as well as to analyze the maintenance schedule.

6.2 Reliability Centred Maintenance (RCM)

6.2.1 RCM Review

RCM is the maintenance technique of choice for many industries including power industries. Its main advantage is the effective integration of maintenance practices and resources into a logical and cohesive whole. RCM is a highly adaptable analytic tool and can support conceptual or rigorous analysis (Goodfellow 2000)

RCM definitions in different publications are:

Gurumeta (2007): *“Process used to determine the most effective maintenance”*

Endrenyi et al. (2001): *“Predictive maintenance routines include a group of programme”*

Asgarpoor and Doghman (1999): *“Condition-based maintenance programme that focuses on preventing failures that are likely to be the most serious”*

Goodfellow (2000): *“organized common sense”*

Bertling (2002): “*qualitative systematic approach to organizing maintenance*”

RCM is not a "quick fix" solution, time and effort must be invested on training, awareness, and implementation. RCM is a process for determining maintenance policies based on reliability techniques and using analysis methods for example Failure Mode Effects and Criticality Analysis (FMECA). It begins with a failure mode and effects analysis which identifies structurally the significant failure modes. The process then requires the assessment of each critical failure mode to find out the optimum preventive maintenance policy to shrink the effect of each failure. The selected preventive maintenance policy must consider cost, safety, environmental and operational consequences. Also, the effects of redundancy, spares costs, maintenance crew costs, equipment ageing and repair times must be taken into account. Once optimal maintenance policies have been identified the RCM method provides system performance predictions and costs, expected spares needs and maintenance crew limits.

The main advantages of RCM maintenance strategies are:

1. Reduce major corrective actions.
2. Eliminates unnecessary overhauls.
3. Increases the use of predictive technology.
4. Improves cost-effectiveness.

6.2.2 RCM Methodology

Traditional RCM are time consuming and maintenance task decisions are made subjectively based on RCM team opinions. These opinions are biased toward recent failures, which can be costly over a lifetime, in some cases. The simulation capability of RCM overcomes these problems by allowing for actual failure performance over a lifetime, and provides an evaluation of each task of different policies. Gurumeta (2007)

has proposed a general RCM methodology. The methodology can be described by the following four basic points:

1. Preserve system functions.
2. Identify common failure style.
3. Prioritize function needs.
4. Chose the applicable and effective maintenance activities.

6.2.3 RCM Strategy and Preventive Maintenance Policies

With RCM, the objective of a successful PM program is to avoid or reduce the consequences of failures, not to prevent the failures themselves. However, the consequences of failure vary depending on where and how equipment are installed and operated. We can't assume that all failures can be avoided by PM. Therefore, RCM uses these ideas to determine applicable and effective maintenance for each potential failure.

RCM can identify optimum maintenance tasks; however it does not provide the appropriate interval to perform these tasks. Hauge (2002) suggests using a family of mathematical tools and techniques to determine an appropriate interval for specific maintenance activities, and named it RCM Toolbox. It can identify the best maintenance interval for tasks such as inspection, preventive maintenance, age exploration and failure finding tasks, based on the probability of failure, expected success of the task and historical operating data. The key to using the tool is having collected the appropriate operational data to be used in calculating the intervals. A variety of mathematical tools and techniques can be applied to determine optimal intervals such as statistical analyzes, risk analysis using expected values, age exploration, and Monte

Carlo simulation methods. Common mathematical factors between these methods are cost-benefit considerations and risk. The author has collected the mathematical tools into single software suite, RCM Toolbox.

6.3 RCM Strategy in Maintenance Scheduling of Power Systems

This section will concentrate on RCM in maintenance scheduling of deregulated power systems. Maintenance optimization models can be defined as those mathematical models whose objective is to find the optimum balance between the costs and benefits of maintenance (e.g. less failure costs), while taking into consideration all kinds of constraints. Scheduling outages of electric power systems for maintenance is left out of consideration, unless typical maintenance aspects (such as deterioration) are modelled explicitly (Dekker 1996).

RCM methods have been successfully applied to analysis of maintenance of the utility industry, including power production and transmission distribution substations. It has proven useful in applications that share some common characteristics such as electric utilities where reliability is vital and where quantitative data regarding failure is limited. Deregulation and competition create uncertainty which places an increasing demand for distribution system performance, while at the same time, limiting the availability of maintenance recourses. RCM is a useful approach in bringing renewed attention to the reliable operation of distribution infrastructure (Goodfellow 2000).

In a deregulated market, many companies have started to change their maintenance strategies from time-based preventative strategies to more sophisticated maintenance strategies like RCM. Modelling the reliability of power system equipment is difficult due to the lack of failure data because of high reliability equipment and the high cost of life tests. The goal of modelling the reliability of power system equipment is to be able

to predict failures and prevent or delay them, by applying maintenance. These models are probabilistic and likely future behaviour of the system can be predicted. Examples of reliability measures are hazard function, availability, Mean Time To Repair (MTTR), Mean Time Between Failures (MTBF), etc. The reliability models for power systems require either failure data or other forms of operational information that are not usually stored and can therefore not easily be used for new systems. Because the failure times are not available it may be picked at random from a probability distribution (i.e. Weibull distribution). The Weibull distribution is used due its flexible nature and the possibility to represent a large number of failure characteristics of equipment (Lindquist et al. 2005).

The relationship between reliability and maintenance has been established by analysing the effect of PM to the causes of failure for the component being assessed using two approaches. The former approach assumes a constant reduction ratio between failure rates and the effect of PM, while the latter approach assumes this ratio to be dependent on time. The basic premise is the cost for any PM strategy should be less than taking no action at all. There are several costs that can be related to the effect of system failures such as; *cost of failure*, *cost of the PM actions*, and *interruption cost*. The optimal maintenance strategy is the solution that minimizes the sum of these three costs (Bertling et al. 2005). Reliability Centred Maintenance strategy was implemented on a power distribution system. Bertling et al. (2005) have proposed a methodology for assessing the impact of a Reliability-Centred Asset Maintenance (RCAM) strategy in a power distribution system. The method consists of following steps:

- 1) Define reliability model and required input data.
- 2) Identify critical voltage levels and components for the system reliability.
- 3) Identify failure and define a failure rate model.

- 4) Model effect of PM methods on reliability for each failure cause.
- 5) Define and implement different strategies for PM.
- 6) Estimate the resulting composite failure rate.
- 7) Compare system reliability when applying different maintenance.
- 8) Identify cost effective PM strategy.

A computer code RADPOW (Reliability Assessment of Electrical Distribution Systems), based on the analytical approach has been developed. RADPOW evaluates the load point indices (expected failure rate, annual outage time, etc.) and the overall system indices (i.e. System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI)). The RCAM method has been implemented in MATLAB where output from RADPOW is used as input (Bertling 2002).

Also, the available literature is focused on applying RCM strategy for generating units maintenance scheduling. Abdulwhab and Billinton (2002) have applied a health levelization (well-being) approach for short-term generator maintenance scheduling. The maintenance schedule obtained using the well-being approach is developed in a way to maintain an acceptable reliability level measured by probability of health, and this is how RCM performed. Also, Bier and Glycer (2002) uses the RCM from the viewpoint of the importance of reliability of power system equipment on the profitability of the company.

In this chapter we use PM and other maintenance strategies to formulate RCM cost for generators in power system. Also, we study the relation between RCM and failure rate for generating units. Then, we explain the affect of RCM on the maintenance schedule.

6.4 Maintenance Cost Model Including RCM Strategy

In a previous chapter a maintenance cost model which incorporates different maintenance cost components was developed and evaluated. The company uses a particular type of maintenance strategy, which affects in the maintenance schedule and consequently in the total maintenance cost. It is important to account for other types of maintenance strategies to see their effect on the maintenance schedule. Therefore, the model needs to be redeveloped to incorporate different maintenance strategies. As we stated before the optimal maintenance strategy is the solution that minimizes the sum of the *failure*, *PM actions*, and *interruption costs*. The maintenance cost model was formulated in Chapter 3. For any type of maintenance strategy there are different values for failure rates. Also, the cost of maintenance action and the cost of failure depend on the maintenance strategy being implemented. The developed maintenance cost model considers:

$$Cma_{it}(s) = [L_{it} + M_{it} + IM_{it} + IL_{it}](s) \quad (6.1)$$

$$Cf_{it}(s) = [\lambda_{it}(s) \cdot Cr_{it}(s)] \quad (6.2)$$

$$ICf_{it}(s) = [VLP_{it} + ORC_{it} - ORS_{it}](s) \quad (6.3)$$

The maintenance cost under RCM strategy can be represented as follows:

$$Cma_{it}(RCM) = (L_{it} + M_{it} + IL_{it} + M_{it} + VLP_{it} + ORC_{it} - ORS_{it} + \lambda_{it} \cdot Cr_{it})(RCM) \quad (6.4)$$

The maintenance cost function under RCM strategy 6.4 will replace the maintenance cost in (3.1) (Chapter 3, section 3.7.1). The optimal maintenance strategy under RCM is the solution that minimizes the sum of these three costs. In Bertling (2002) PhD thesis

titled “Reliability Centred Maintenance for Electrical power system” a base line for RCM in power distribution system was developed. Similarly, an RCM for power generation system can be developed. In this chapter we focus on the maintenance cost function under RCM and perform sensitivity analysis to demonstrate its effect on the final maintenance schedule of generators.

6.5 Design and Implementation of GA to GMS Problems Including RCM Strategy

The objective of this case study is to show the affect of RCM strategy on the maintenance schedule of generating units by modifying the maintenance cost function. In order to demonstrate the solution methodology using genetic algorithm technique for solving GMS problems, a test system with three generating units which must be maintained over a 4 week planning horizon is described. The system and relevant data were presented in Chapter 4. The main purpose here is to demonstrate the data collection proposes and to show the steps of including the maintenance cost under RCM within the previously developed maintenance cost model, therefore only 3 units case study will be considered here.

6.5.1 Data Collection

The data gathering process for all cost components was explained in Chapter 4. However, in this test problem we modify the maintenance cost to include maintenance cost function under RCM in each experiment. Table 6.1 represents the estimated values for maintenance cost components for the 3 generating units for four weeks period.

| W E E K | U N I T | Other Maintenance Costs/Unit (\$) | | | | | | Direct/In direct Main. costs \$ | Main. costs \$ With RCM | Main. cost under no failure (Cost A) \$ | Main. cost under failure (Cost B) \$ | |
|------------------|------------------|-----------------------------------|--------------------|--------------------|-------------------|--------------------|-----------------|------------------------------------------|--------------------------------------|---------------------------------------------------------|------------------------------------------------------|--------------------|
| | | Because of Maintenance | | | | | | | | | | |
| | | No bids losses | goodwill losses | Cost of failure | No bids losses | goodwill losses | Interr. cost | | | | | Penalty to pool |
| 1 | 1 | 401,440 | 313,442 | 142,900 | 401,440 | 313,442 | 74,835 | 204,000 | 215,226 | 432,961 | 1,147,843 | 2,284,460 |
| | 2 | 552,024 | 430,983 | 142,900 | 552,024 | 430,983 | 74,835 | 231,360 | 215,226 | 432,961 | 1,415,968 | 2,848,070 |
| | 3 | 250,920 | 195,901 | 142,900 | 250,920 | 195,901 | 74,835 | 146,400 | 215,226 | 432,961 | 879,782 | 1,690,738 |
| 2 | 1 | 448,704 | 350,317 | 142,900 | 448,704 | 350,317 | 74,835 | 261,600 | 215,226 | 432,961 | 1,231,982 | 2,510,338 |
| | 2 | 310,560 | 481,686 | 142,900 | 310,560 | 481,686 | 74,835 | 310,560 | 215,226 | 432,961 | 1,225,207 | 2,545,748 |
| | 3 | 280,440 | 218,948 | 142,900 | 280,440 | 218,948 | 74,835 | 182,400 | 215,226 | 432,961 | 932,349 | 1,831,872 |
| 3 | 1 | 477,043 | 372,443 | 142,900 | 477,043 | 372,443 | 74,835 | 296,160 | 215,226 | 432,961 | 1,282,447 | 2,645,828 |
| | 2 | 655,934 | 512,109 | 142,900 | 655,934 | 512,109 | 74,835 | 358,080 | 215,226 | 432,961 | 1,601,004 | 3,344,862 |
| | 3 | 298,152 | 232,777 | 142,900 | 298,152 | 232,777 | 74,835 | 204,000 | 215,226 | 432,961 | 963,890 | 1,916,554 |
| 4 | 1 | 415,642 | 324,505 | 142,900 | 415,642 | 324,505 | 74,835 | 221,280 | 215,226 | 432,961 | 1,173,108 | 2,352,270 |
| | 2 | 571,507 | 446,194 | 142,900 | 571,507 | 446,194 | 74,835 | 255,120 | 215,226 | 432,961 | 1,450,662 | 2,941,218 |
| | 3 | 259,776 | 202,815 | 142,900 | 259,776 | 202,815 | 74,835 | 157,200 | 215,226 | 432,961 | 895,552 | 1,733,078 |

Table 6.1 Maintenance cost components

Comparing the data on table 6.1 with the data presented in table 5.12 (Chapter 5, section 5.7.1), we can see that the maintenance cost under RCM is included. This cost is obtained by summing cost of failure, interruption cost and direct/indirect maintenance cost.

Assuming the probability of failure is 5%, table 6.2 illustrate the expected total maintenance costs for all units/weeks in first experiment. We can see that the total expected maintenance costs are higher than the total expected maintenance costs presented in table 5.13 (Chapter 5, section 5.7.1) as a result of including RCM strategy.

| Week | Unit | \$ Cost A * 0.95 | \$ Cost B * 0.05 | Total expected maintenance costs (\$) with RCM |
|------|------|------------------|------------------|------------------------------------------------|
| 1 | 1 | 1,090,451 | 114,223 | 1,204,674 |
| | 2 | 1,345,170 | 142,404 | 1,487,573 |
| | 3 | 835,793 | 84,537 | 920,330 |
| 2 | 1 | 1,170,383 | 125,517 | 1,295,900 |
| | 2 | 1,163,947 | 127,287 | 1,291,234 |
| | 3 | 885,732 | 91,594 | 977,325 |
| 3 | 1 | 1,218,325 | 132,291 | 1,350,616 |
| | 2 | 1,520,954 | 167,243 | 1,688,197 |
| | 3 | 915,696 | 95,828 | 1,011,523 |
| 4 | 1 | 1,114,453 | 117,614 | 1,232,066 |
| | 2 | 1,378,129 | 147,061 | 1,525,190 |
| | 3 | 850,774 | 86,654 | 937,428 |

Table 6.2 Total expected maintenance costs for 3 generating unit

6.5.2 Experiment Design

In this section a set of experiments for the 3 generator units test problem are carried out. Table 6.1 shows the data for experiment number one, and other experiments data are obtained the same way. Table 6.4 illustrates the design of the experiments. Each experiment consists of 5 runs and has different value for failure rate and probability of failure. The GA operators and parameters used before are used here.

| No. | Parameter | Exp -1 | Exp -2 | Exp -3 |
|-----|-----------------------------------------|----------------|--------|--------|
| 1 | Number of run | 5 | | |
| 2 | GA Operators | | | |
| 2.1 | Population size | 100 | | |
| 2.2 | Crossover probability | 0.8 | | |
| 2.3 | Mutation probability | 0.010 | | |
| 2.4 | Type of selection | Roulette wheel | | |
| 2.5 | Type of crossover | Single-point | | |
| 3 | MCP | MCP | | |
| 4 | Losses of goodwill cost (Loyalty Value) | Value A | | |
| | RCM cost Multiplier | 1 | 1.25 | 1.5 |
| | Probability of failure | 0.05 | 0.025 | 0.0125 |
| 5 | Failure rate | 0.1429 | 0.0714 | 0.0357 |

Table 6.3 Maintenance status per week

6.5.3 Analysis and Result

The evaluation function value has increased comparing to the results obtained in previous chapter, as a result of applying RCM strategy. The optimum generator maintenance schedule 2-1-2 was obtained in different runs. The value of evaluation function in the first experiment is equal to \$1.233E7, while it is equal to \$1.157E7 in the last experiment as a result of the reduction of both the probability of failure and failure rate (Bertling et al. 2005). Figure 6.1 shows the relation between evaluation

function and both the probability of failure and failure rate for the best solution of each experiment.

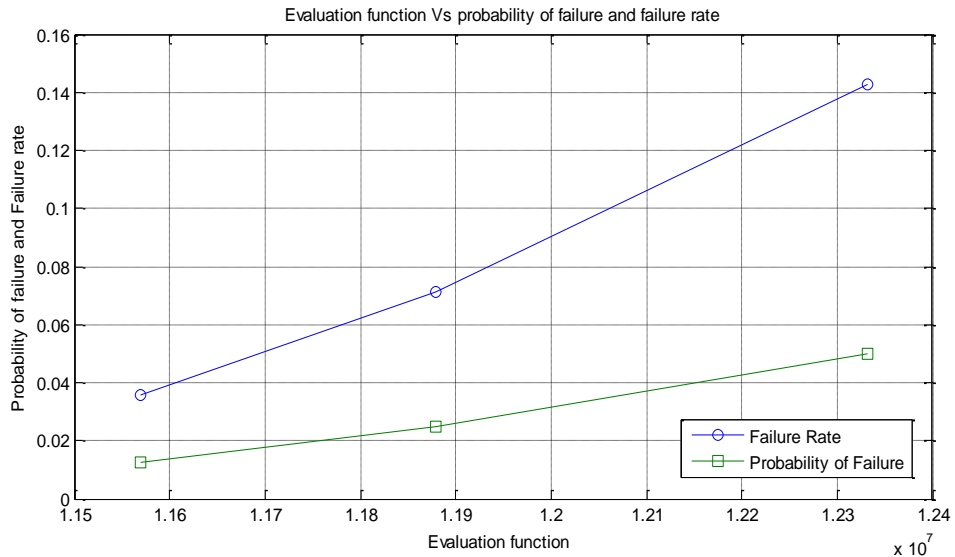


Figure 6.1 Evaluation function Vs probability of failure & failure rate

In order to see the affect of RCM on the generator maintenance schedule we need to have data for the generator conditions. A special computer code need to be developed to gather such information, as presented in (Bertling 2002) RADPOW code has been developed to evaluates the expected failure rate and other indices. Since data is not available we can show the methodology on how to use RCM to improve the maintenance schedule. Let us assume that a generator with a specific failure rate needs to be maintained after a certain period of time when reaching a threshold point. With condition monitoring (RCM strategy) of the generator, we can predict the needed time of maintenance activity. Figure 6.2 illustrates the behaviour of a generator under condition monitoring. The initial value of failure rate is small, and then it will reach the threshold point. The causes of failure can be dominated by condition monitoring, which will result in a reduction in the weeks for the next maintenance activity. However, the failure rate at the start of the next maintenance interval is increased, since the generator

not as new as the first maintenance period. The reduction of weeks of maintenance activity will affect the maintenance schedule. Also, the increase in the failure rate will result in an increase in that maintenance cost. Therefore, the final solution of GMS problem may change following the result of the condition monitoring.

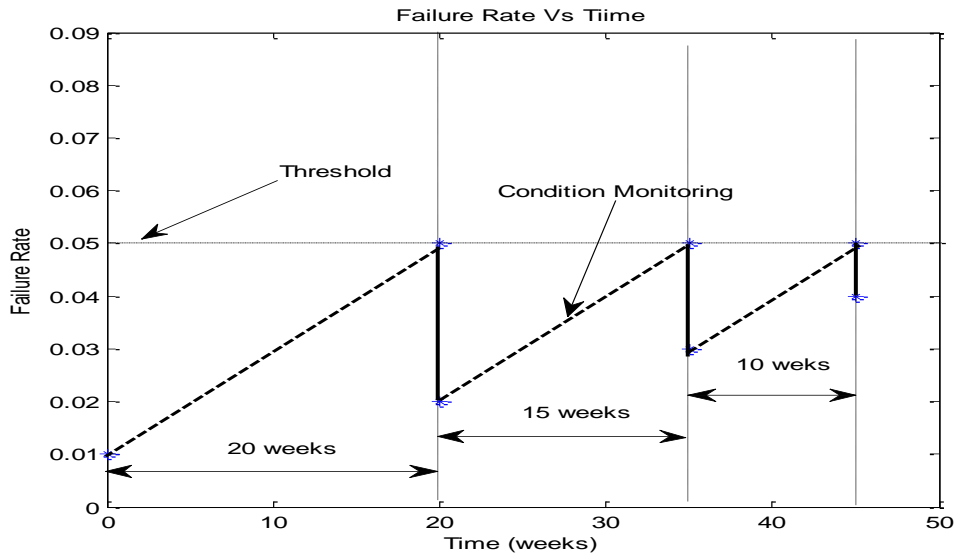


Figure 6.2 The affect of RCM on maintenance interval

In this test problem we were able to demonstrate the effect the new RCM strategy on the final solution. The evaluation function value decreases in experiments because of the reduction in the maintenance, failure, and interruption costs. The result shows that these costs were critical factors on the evaluation function value and the maintenance schedule; therefore they must be considered and carefully modelled in order to obtain optimum solutions.

6.6 Chapter Summary

All operating, repair, and maintenance costs vary depending on maintenance strategy. RCM forms the core of any effective maintenance policy. Different industries, including power system use the RCM techniques in establishing and improving system maintenance. In this chapter a maintenance scheduling model under RCM strategy was developed. The RCM cost function which includes maintenance, failure, and interruption costs, was introduced to the model. A test problem was introduced to implement the model using GA. The previous results obtained in both Chapter 4 and 5 were also used here. The result of the 3 unit's problem is illustrated to show the relation between RCM cost and both probability of failure and failure rate. Also, it shows that condition monitoring may affect the maintenance schedule of generating units. With RCM failure rate will be decreased and failures may be detected before happening which will result in a reduction of total maintenance cost. Also, with condition monitoring direct maintenance cost may be reduce and that may compensate the set-up cost of RCM. Therefore, introducing RCM to maintenance scheduling of generators in power system can be cost effective. Research shows that, RCM programs have been found to pay for themselves in a short term, despite the initial costs associated with their implementation (Gurumeta 2007).

Chapter 7

Conclusions and Future Research

Chapter 7: Conclusions and Future Research

7.1 Summary and Conclusions

Reducing the maintenance cost is one of the main objectives in power system maintenance scheduling. Therefore, the maintenance scheduling model for deregulated power systems should include various cost (especially maintenance cost) functions.

A wide range of maintenance modelling and scheduling for generator units with different scenarios (minimizing direct cost, or maximizing profit) based on the nature of the GMS problem being considered, are reported in the literature. A range of cost components are proposed in the literature to be used in maintenance scheduling. However, to the best of my knowledge a single model which incorporates most of the cost components to analyze the effect of different maintenance strategies for GENCOs is not available.

The research described in this thesis investigates and models many cost factors that affect the maintenance activities of the deregulated GENCOs, and demonstrates the utilization of the developed cost models in maintenance planning and scheduling. A major objective of the research is to develop a single maintenance cost model, which covers almost all maintenance components. Direct/Indirect maintenance costs have been quantified. Failure costs associated with different maintenance strategies have been modelled. Opportunity costs during planned maintenance or during failure have been developed. These costs represent GENCOs losses or customer inconvenience. These maintenance cost components were mathematically calculated using market oriented

prices and costs for deregulated power systems. The research presented in this thesis uses the GA approach to solve maintenance scheduling problem and show the effect of the new maintenance cost components on the objective function value and the maintenance schedule.

In conclusion we can say that, in order to capture the real situation picture, generators maintenance costs should cover two different scenario, maintenance costs under generators failure and maintenance costs under no failure. Also, these costs representations should not be limited to direct/indirect maintenance costs, but it should includes other related maintenance costs such as failure and opportunity costs mainly generators losses and penalties, interruption and inconvenient costs. The interruption cost should cover any economic losses that the customer may incur during generator failure, and the inconvenient cost should represent loss of customer goodwill.

It is very important to incorporate the new maintenance cost components on modelling maintenance for generating units as they may lead to different solutions. The thesis presents an inclusive maintenance cost model for the deregulated environment, which can replace the generator maintenance costs used previously in literature in order to reflect real situation. Also, it is recommended to use the data gathering process illustrated here to find the actual maintenance cost.

The new maintenance cost model includes some components which are market oriented. These components are MCPs and SMPs. Both of them indirectly affect the final schedule. The results obtained from the studies presented in Chapter 4 shows that generators were not in maintenance when MCPs and SMPs are high. Therefore, when

MCPs are high, it is not recommended for maintenance scheduling of generators in deregulated power system.

For the objective functions of the type of minimizing the total maintenance and production costs, subject to a set of maintenance and system constraints, it is recommended to replace the maintenance and production costs by both market maintenance and production costs as presented in Chapter 4.

The analysis conducted in Chapter 5 shows that AHP is an effective prediction tool for use for pricing out the cost of the loss of customer goodwill. The result shows also that Technical solution *and* Reputations were the most influential criteria in pricing out the cost of the loss of customer loyalty.

We have proposed three loyalty value that can be used for pricing out loss of customer goodwill. The selection of which loyalty value to be used is based on the importance of the customer. For example, the analysis in this thesis shows that the best loyalty value (Value A) to be chosen in order to price out loss of goodwill for a critical customer considering minimizing total maintenance cost. This model reflects the current situation in a deregulated environment.

The analysis of maintenance cost models in the early part of this thesis used preventive maintenance as the maintenance strategy. Chapter 6 demonstrated the maintenance models for reliability centred maintenance (RCM) strategy. We have proposed a data gathering process for RCM cost. In power systems it was proven that the RCM techniques improve system maintenance. The results obtained in Chapter 6 supports this argument. The case study shows a reduction in the total maintenance cost by

considering RCM, since both failure rate and probability of failure decreases as result of using RCM.

The research work illustrated in this thesis is focused on modelling maintenance costs and scheduling maintenance activity using the application of GA techniques in the newly deregulated electric power industry. The research work clearly illustrates the utilization of a market oriented maintenance model in the decisions for scheduling maintenance for generating units.

7.2 Future Research

Several open research extensions to the research presented in thesis may be worthy of further consideration. In the following bullet points, we explain some of these extensions and suggest some possible answers.

- The real data used in this thesis was gathered from different sources assuming that geographical location has no affect on data gathering. The data were difficult to obtain from a single source in this research. The data gathering can be from one source which will add more accuracy to the implementation of the case study.
- The generators cost functions used here are assumed to be quadratic with the same coefficients for all generators. It would be more appropriate to use different cost functions for each generator.
- The objective functions for the problems considered in the thesis have been weighted and summed to obtain a single value. The weighting coefficients for the evaluation value were determined empirically. An attractive research would

be to make use of a multi-objective scheduling technique treating individual objectives separately for the problems considered in this thesis.

- Researchers have proposed a number of alternative ways for the solving GMS problems. The GA technique was considered in this thesis to overcome the computational time of other deterministic approaches. Many authors have tackled GMS problems using the deterministic approach such as the Benders decomposition approach. It would be an interesting research area for future work to use the Benders decomposition approach for the problems considered in this thesis and compare the results obtained.
- Researchers have proposed a number of alternative ways for evaluating uncertainty. In this thesis AHP Multi-Criteria Decision Making technique was employed to evaluate loss of customer goodwill. Different criteria were developed subjectively. These criteria may be altered to reflect other customer's concerns; also weights on a criterion may fluctuate from one decision maker to another. This may be one direction for future research. It would be interesting also to use other alternative approaches such as fuzzy logic approach, rather than AHP and compare results.
- In literature a Reliability assessment of electrical distribution (RADPOW) based on the analytical approach has been developed to perform reliability analysis (Bertling et al. 2005). In this thesis the methodology of incorporating RCM in the final maintenance cost model was introduced. One direction for future research may be developing a similar reliability assessment model for generation system for reliability analysis.

- In this thesis we have considered traditional systems and maintenance constraints in the formulation of the GSM problems. It would be interesting to take into account market constraints, such as contractual commitments, electricity market rules and market switch and fuel switch capabilities in maintenance scheduling.
- The objective of GMS problem presented here is to minimize maintenance and production costs subject to maintenance and system constraints. An interesting research direction for future research would be considering other objectives such as minimize the loss of revenue over the operational planning period by minimizing the maintenance cost of generators and transmission line and the energy production cost subject to generation and transmission maintenance and operation constraints.

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