GENERATING UNIT MAINTENANCE SCHEDULING USING PROBABILISTIC TECHNIQUES

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PERMISSION TO USE

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DEDICATED TO

MY WIFE

HALA

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LOLE	Loss of load expectation
LOEE	Loss of energy expectation
LOLEw	Weekly LOLE criterion
LOLP	Loss of load probability
MCS	Monte Carlo simulation
HL I	Hierarchical level I
HL II	Hierarchical level II
HL III	Hierarchical level III
RBTS	Roy Billinton test system
IEEE-RTS	IEEE-Reliability test system
FOR	Forced outage rate
MNU	Maximum number of units allowed for maintenance in a single week
COPT	Capacity outage probability table
CPCOPT	Conditional probability COPT approach
CE	Contingency enumeration approach
CLU	Capacity of the largest unit
P(H)	Probability of health
Pw(H)	Weekly P(H) criterion
P(M)	Probability of margin
P(R)	Probability of risk
DPLVC	Daily peak load variation curve
LDC	Load duration curve
PL	Peak load
EUE	Expected unsupplied energy
CRM	Capacity reserve margin

1. INTRODUCTION

1.1. Introduction

The main objective of an electrical power system is to supply its customers with electrical energy as economically as possible and with an acceptable level of reliability. Industrial and commercial utilization of electrical energy is an important factor in economic growth and population wellbeing. It is, however, impossible to have a power system with a hundred percent reliability and therefore, power system planners have always attempted to achieve the highest possible reliability at an affordable cost.

The word reliability has many definitions when it is used in different applications. A simple definition for reliability is " a measure of the overall ability of a system to perform its intended function"[1,2].

A power system can be divided into functional zones in order to focus on specific problem areas and to simplify the analysis. The three basic functional zones are those of generation, transmission, and distribution. These functional zones can be combined .to form Hierarchical Levels (HL) for conducting system reliability analysis [3]. Figure 1.1 shows three hierarchical levels. Reliability assessment at HL I is concerned with the generation facilities. Reliability assessment at HL II considers the generation and transmission as a composite system. The effect of facility additions can be studied and reliability indices can be evaluated for the overall system as well as for the individual buses. All of the three functional zones are involved in an HL III assessment. The main objective of an HL III study is to determine adequacy indices at the consumer load points. The research work described in this thesis deals with HL I assessment.

In an HL I reliability study, the system is represented by a single bus at which the total generation and load are connected. This representation is shown in Figure 1.2. The basic objective in a reliability study at HL I is to assess the capability of the

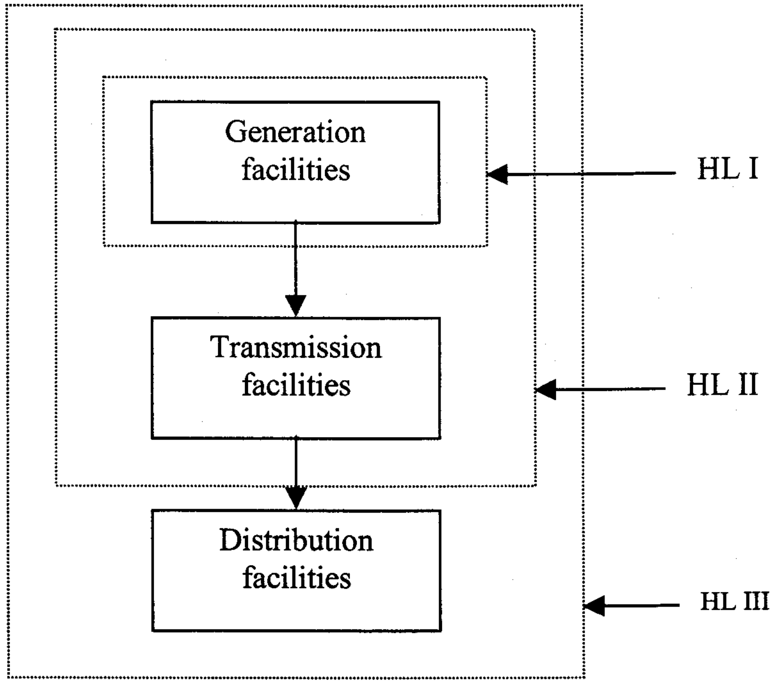

Figure 1.1: Hierarchical levels.

generation facilities to meet the total demand. The ability to deliver the generated energy to the various bulk supply points is not part of the assessment. The main concern is the ability of the generation to satisfy the system demand and to have sufficient excess capacity to conduct the required preventive maintenance on the generating facilities.

Figure 1.2: HL I model.

Adequacy assessment at HL I depends on many factors, such as the installed capacity, unit size and availability, maintenance requirements, load forecast uncertainty, the shape of the load model and other considerations. In order to maintain a desired level of reliability, the system must have a capacity reserve in excess of the actual load demand. The system reliability will increase with higher reserve margin but so will the system capital cost. Many techniques have been developed to determine the required level of capacity reserve in a system. These techniques can be divided into two types; probabilistic and deterministic. The most common deterministic criterion utilizes the capacity of the largest unit in the determination of the required reserve. A number of Canadian surveys have been conducted [14] and some the results of these surveys are presented in Table 1.1 and 1.2. Table 1.1 shows the general approach used by Canadian utilities. It can be seen from the table that Canadian utility practice has moved over time from a deterministic approach to probabilistic analysis.

Table 1.1: Criteria used in reserve capacity planning.

	Criteria	1964	1969	1974	1977	1987
1	Percent Margin	1	4	2	2	1
2	Loss of Largest Unit	4	1	1	1	-
3	Combination of 1 and 2	3	6	6	6	-
4	Probability Methods	1	5	4	4	8
5	Other Methods	2	1	-	-	-

Table 1.1 shows that only one utility used a probabilistic technique in 1964. By 1977, the number of the utilities using probability methods had increased to four. All of these utilities using a probabilistic approach utilized the loss of load expectation technique. Table 1.2 shows the probabilistic criteria used by Canadian utilities in 1987. It can be seen from Table 1.2, that the LOLE method was the most popular technique. This approach has also been used by many utilities around the world.

Table 1.2: Basic criteria and indices

System	Criterion	Index
BC Hydro and Power Authority	LOLE	1 day/10years
Alberta Interconnected System	LOLE	0.2 days/year
Saskatchewan Power Corporation	EUE	200 Units per million (UPM)
Manitoba Hydro	LOLE	0.003 days/year (with connections) 0.1 days/year (without interconnection)
Ontario Hydro	EUE	25 system minutes (SM)
Hydro Quebec	LOLE	2.4 hours/year
New Brunswick Electric Power Commission	CRM*	Largest unit or 20% of the system peak (whichever is larger)
Nova Scotia Power Corporation	LOLE**	0.1 days/year
Newfoundland and Labrador Hydro	LOLE	0.2 days/year

LOLE - Loss of Load Expectation
EUE - Expected Unsupplied Energy
CRM - Capacity Reserve Margin
* With supplementary checks for LOLE
** With supplementary checks for CRM

As mentioned earlier, the system capacity reserve must be sufficient to permit required preventive maintenance on the system generating units. The basic objective of preventive maintenance is to prevent or forestall future random failures of the system facilities, by removing the facilities from service at an appropriate time and conducting diagnostic tests and element replacements.

In any problem that has more than one solution there is an objective function to be either maximized or minimized. Two main objectives in a maintenance scheduling problem are, to minimize the maintenance cost [4,5,6,11] and to maximize the system reliability [7,8,9,10,12,24].

When cost is used as the objective function, it is usual to divide it into the two categories of maintenance costs and production costs. Dopazo [11] discusses the use of the maintenance cost in great length and concluded that the maintenance cost is usually a convex function. In this approach there is an ideal time that generating unit maintenance should be performed if maintenance cost is the only concern. It should be noted that this objective function only minimizes the maintenance cost. The overall objective, however, should be to minimize the total operating costs where the maintenance cost is simply one component of the operating cost.

Using the production cost as an objective function has been considered by other authors [5,6]. Minimizing the production cost requires either many approximations or extensive simulations. Many authors reported results that show the production cost as an insensitive objective. In a discussion of Reference [6], Garver, Happ, Dopazo, and Merrill indicated that the insensitivity of production cost is consistent with their experience in maintenance scheduling.

As noted earlier, the alternate approach is to use reliability maximization as the objective function. The reliability oriented methods fall into one of two categories, deterministic or stochastic.

Deterministic reliability techniques try to levelize the capacity reserve and are relatively easy to apply in practical situations. It has been recognized [8,10,12,24] that this approach does not levelize the system reliability, as it ignores the uncertainties in demand and generating unit availabilities.

Many authors have applied a stochastic approach using a range of techniques [8,9,10,12,13,24]. There are limitations in many of these techniques such as ignoring the load uncertainty or the generating forced outages due to some difficulties involving excessive computations. The research work described in this thesis deals with the application of both probabilistic and deterministic techniques to maintenance scheduling in generating systems.

1.2. Scope and objective of the thesis

In this thesis, four basic techniques are illustrated to conduct maintenance scheduling. Two of these techniques are probabilistic and the other two are based on deterministic criteria. The basic objective in the approach is to create a maintenance schedule that keeps the system reliability in an acceptable predetermined level. As mentioned earlier, the simplest techniques for maintenance scheduling are deterministic. These approaches, however, contain considerable limitations [8,10,12,24].

Probabilistic methods are, in general, much more complicated but have the ability to reflect the nature of the system, which contain many uncertainties related to the generation and the load.

Most of the available probabilistic techniques involve some approximations in building the load model or the generation model which affect the accuracy of the achieved results. Some authors have dealt with the maintenance scheduling problem by adding the capacity on maintenance to the load and using a single capacity outage probability table and others have used a single capacity outage probability table but the total available capacity is reduced by the quantity on maintenance outage. Many studies have been conducted on practical systems that show that this approximation can result in higher calculated risk levels and the error increases with increase in the maintenance capacity [3]. In the research described in this thesis, maintenance scheduling was performed by creating a capacity outage probability table for each week, which includes the available generating units in that period. It is believed that this approach provides a reasonable balance between detailed modeling and practical application.

The basic objective of this research work is to examine the difference between the basic deterministic and probabilistic techniques for maintenance scheduling by application to two test systems. New probabilistic approaches using the concept of wellbeing analysis [22,23] is developed in this research work. Exact calculation procedures were developed to incorporate the probabilistic uncertainties in the evaluation.

1.3. Thesis outline

Following the introduction in Chapter 1, Chapter 2 describes basic generation capacity reliability evaluation concepts. The recursive technique for building a capacity outage probability table is introduced. Wellbeing analysis is introduced in this chapter and a method to include period based wellbeing analysis is described. A brief description of the Roy Billinton Test System (RBTS) [15] is presented together with the basic reliability indices for the RBTS.

The basic approach to preventive maintenance scheduling is illustrated in Chapter 3. The four techniques for maintenance scheduling are introduced in this chapter. A basic study conducted on the RBTS and the IEEE-RTS is described.

Chapter 4 illustrates the effects on the developed maintenance schedules of system factors such as the generating unit forced outage rates, the maximum number of units allowed out for maintenance in a single week and the selected criterion using the four developed techniques. Different combinations of these factors are also examined. Two test systems are used to illustrate these effects. Annual risk analysis is also included.

More sensitivity studies are presented in Chapter 5. The effect of system load characteristic on maintenance scheduling was examined. The effect of system peak load and the load profile were examined using the four techniques. The factors considered in the previous chapter are incorporated and examined with the load characteristic. The RBTS was used in this chapter.

A new scheduling technique using dual probabilistic criteria is illustrated in Chapter 6 and examined by application to the RBTS. Finally, Chapter 7 summarizes the thesis and highlights the conclusions.

2. BASIC GENERATING CAPACITY RELIABILITY EVALUATION

2.1. Introduction

As noted in Chapter 1, generating capacity reliability evaluation is conducted at HL I. The basic objective of studies at this level is the determination of the required generating capacity to satisfy the forecast demand. This area of study can be divided into two different segment designated as static and operating capacity requirements. A static capacity study deals with the long-term evaluation of the required capacity to maintain a desired level of reliability. An operating capacity study is focused on the capacity required to actually operate in the next few hours in order to maintain a desired level of reliability [3]. Considerable effort has been devoted to static capacity assessment [16,17,18,19]. This thesis deals with static capacity assessment. Literature on this subject [16,17,18,19] indicate that the most widely used approach for generating capacity adequacy evaluation are the loss of load probability and expectation methods. The second most popular approach is the loss of energy expectation techniques.

The basic elements needed to conduct generating capacity reliability evaluation are the generation model and the load model. A risk model is then formed by convolving the generation and load models as shown in Figure 2.1.

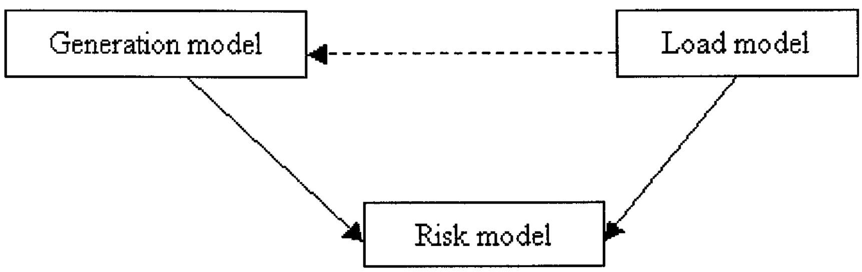

Figure 2.1: Conceptual tasks for HL I evaluation

The basic data generating unit statistic used in static capacity evaluation is the probability of finding the unit on forced outage at some distant time in the future. This probability is known as the unit forced outage rate (FOR) [3]. In more general terms, the FOR is known as the unit unavailability (U) [20]. The unit FOR is obtained using Equation 2.1.

$$\text{FOR} = \frac{\sum[\text{down\_time}]}{\sum[\text{down\_time}] + \sum[\text{up\_time}]}. \tag{2.1}$$

The use of the FOR to create the generation model is illustrated in the next section.

The load model provides a convenient representation of the system load data over a specified period of time, which is usually one year in a planning study. The representation will be different for different evaluation techniques and study requirements. The most popular load models are the daily peak load variation curve (DPLVC), which utilizes the peak loads of each day, and the load duration curve (LDC) which utilizes the hourly load variations. The DPLVC can only be used to evaluate LOLE indices, while the LDC can be used to evaluate both LOLE and the LOEE indices.

2.2. Capacity outage probability table

The generation model is usually in the form of a capacity outage probability table (COPT) which includes the available or unavailable capacity levels and their corresponding probabilities. The COPT can be created in a number of ways. The basic recursive technique [3] is used in this thesis. This technique is very flexible and can be used to add multi state units as well as two state units.

Case 1: No derated state:

In this case, the unit is considered to reside in one of two states. The unit is either fully available or totally out of service. The probability of a capacity outage state of X MW can be calculated using Equation 2.2.

$$P(X) = (1-U)P'(X) + (U)P'(X-C), \tag{2.2}$$

where:

P' (X) & P (X) are the cumulative probabilities of a capacity outage level of X MW before and after the unit of capacity C is added respectively. P'(X) = 1.0 for $X < 0$ and P' (X) = 0 otherwise to initialize Equation 2.2

Case 2 : Derated states included:

In this case, the unit can reside in one or more derated states in addition to the two states described above. Equation 2.3 can be used to add this type of unit to a capacity outage probability table.

$$P(X) = \sum_{i=1}^{n} p_i P'(X - C_i), \tag{2.3}$$

where,

n = the number of unit states,

C_i = the capacity outage state i for the unit being added,

p_i = the probability of existence of the unit state i.

In order to illustrate the recursive technique for unit addition, a small test system, System X, is given in Table 2.1. System X has three generating units described by their output capacities and their corresponding probabilities.

Table 2.1: The generation facilities for System X.

Unit ID #	Output (MW)	Probability
1-2	0	0.03
	50	0.2
	100	0.77
3	0	0.05
	40	0.95

The basic approach to building a COPT is to add the units one at a time using Equation 2.2 or Equation 2.3

Step1: add unit #1

P(0) = 0.03*P'(0-100) + 0.2*P'(0-50) + 0.77*P'(0-0)

= 0.03*1 + 0.2*1 + 0.77*1 = 1

P(50) = 0.03*P'(50-100) + 0.2*P'(50-50) + 0.77*P'(50-0)

= 0.03*1 + 0.2*1 + 0.77*0 = 0.23

P(100) = 0.03*P'(100-100) + 0.2*P'(100-50) + 0.77*P'(100-0)

= 0.03*1 + 0.2*0 + 0.77*0 = 0.03

Step2: add unit #2

P(0) = 0.03*1 + 0.2*1 + 0.77*1 = 1

P(50) = 0.03*1 + 0.2*1 + 0.77*0.23 = 0.4071

P(100) = 0.03*1 + 0.2*0.23 + 0.77*0.03 = 0.0991

P(150) = 0.03*0.23 + 0.2*0.03 + 0.77*0 = 0.0129

P(200) = 0.03*0.03 + 0.2*0 + 0.77*0 = 0.0009

Step3: add unit #3

P(0) = (1-0.05)*1 + 0.05*1 = 1

P(40) = (1-0.05)*0.4071 + 0.05*1 = 0.436745

P(50) = (1-0.05)*0.4071 + 0.05*0.4071 = 0.4071

P(90) = (1-0.05)*0.0991 + 0.05*0.4071 = 0.1145

P(100) = (1-0.05)*0.0991 + 0.05*0.0991 = 0.0991

P(140) = (1-0.05)*0.0129 + 0.05*0991 = 0.01721

P(150) = (1-0.05)*0.0129 + 0.05*0.0129 = 0.0129

P(190) = (1-0.05)*0.0009 + 0.05*0.0129 = 0.0015

P(200) = (1-0.05)*0.0009 + 0.05*0.0009 = 0.0009

P(240) = (1-0.05)*0 + 0.05*0.0009 = 0.000045

The final capacity outage probability table for System X is shown in Table 2.2 and contains both cumulative and individual state probabilities.

Table 2.2: Capacity model of System X

Cap. Out of service	Individual Prob.	Cumulative Prob.
0	0.563255	1.000000
40	0.029645	0.436745
50	0.292600	0.407100
90	0.015400	0.114500
100	0.081890	0.099100
140	0.004310	0.017210
150	0.011400	0.012900
190	0.000600	0.001500
200	0.000855	0.000900
240	0.000045	0.000045

2.3. Recursive technique for unit removal

The recursive technique can also be used to remove a unit from a total system generation model. This procedure avoids the necessity of building a new model every time a unit is removed from service for preventive maintenance. This is an effective alternative way to obtain the required model for each maintenance time period [3].

Case 1: no derated states:

The following equation can be used to remove a two state unit from the original COPT.

$$P'(X) = \frac{P(X) - (U)P'(X - C)}{(1 - U)}. \tag{2.4}$$

Case 2: derated states included:

The following equation can be used to remove a multi-state unit from the original table.

$$P'(X) = \frac{P(X) - \sum_{i=2}^{n} p_i P'(X - C_i)}{p_1}. \tag{2.5}$$

All the capacity outage levels in the original COPT have to be recalculated and the new table will include some dummy capacity outage levels which should not be shown in the new table. These capacity levels will have probabilities equal to those of the next actual capacity outage level and can be discarded.

System X is used to illustrate the recursive technique for unit removal. Assume that units 2 & 3 are removed for maintenance. The new COPT can be created from the original COPT by removing these two units one at a time using Equations 2.4 & 2.5.

Step 1 : remove unit # 2

P'(0) = [P(0) – 0.03*P'(0-100) – 0.2*P'(0-50)] / 0.77

= [1 – 0.03*1 – 0.2*1] / 0.77 = 1

P'(40) = [P(40) – 0.03*P'(40-100) – 0.2*P'(40-50)] / 0.77

= [0.436745 – 0.03*1 – 0.2*1] / 0.77 = 0.2685

P'(50) = [P(50) – 0.03*P'(50-100) – 0.2*P'(50-50)] / 0.77

= [0.4071 – 0.03*1 – 0.2*1] / 0.77 = 0.23

P'(90) = [P(90) – 0.03*P'(90-100) – 0.2*P'(90-50)] / 0.77

= [0.1145 – 0.03*1 – 0.2*0.2685] / 0.77 = 0.04

P'(100) = [P(100) – 0.03*P'(100-100) – 0.2*P'(100-50)] / 0.77

= [0.0991 – 0.03*1 – 0.2*0.23] / 0.77 = 0.03

P'(140) = [P(140) – 0.03*P'(140-100) – 0.2*P'(140-50)] / 0.77

= [0.01721 – 0.03*0.2685 – 0.2*0.04] / 0.77 = 0.0015

P'(150) = [P(150) – 0.03*P'(150-100) – 0.2*P'(150-50)] / 0.77

= [0.0129 – 0.03*0.23 – 0.2*0.03] / 0.77 = 0

P'(190) = [P(190) – 0.03*P'(190-100) – 0.2*P'(190-50)] / 0.77

= [0.0015 – 0.03*0.04 – 0.2*0.0015] / 0.77 = 0

It can be seen from Step 1, that the probabilities of 150 & 190 MW are zero, which should be obvious as these two outage capacity levels exceed the total installed capacity during this period.

Step 2: remove unit # 3

P'(0) = [1 – 0.05*1] / 0.95 = 1

P'(40) = [0.2685 – 0.05*1] / 0.95 = 0.23

P'(50) = [0.23 – 0.05*0.23] / 0.95 = 0.23

P'(90) = [0.04 – 0.05*0.23] / 0.95 = 0.03

P'(100) = [0.03 – 0.05*0.03] / 0.95 = 0.03

There are some dummy capacity outage levels in Step 2 which should not appear in the new COPT. Each of these capacity outage levels have probabilities equal to that of the next capacity outage level. The final COPT after removing the dummy capacity outage levels is as follows:

P(0) = 1

P(50) = 0.23

P(100) = 0.03

In this example, Unit 2 and 3 were removed. The final table shown above is the capacity model for Unit 1.

2.4. Description of the Roy Billinton Test System (RBTS)

The Roy Billinton Test System (RBTS) [15] is an educational test system developed at the University of Saskatchewan. The main purpose in designing the RBTS was to provide the ability to perform a large number of reliability studies on a practical system with relatively low computation time. The system has 11 generating units, ranged from 5 MW to 40 MW. The system peak load is 185 MW and the total installed capacity is 240 MW. Table 2.3 shows the generation data for the RBTS. The full system data set is given in reference [15].

Table 2.3: Generating data for RBTS

Unit ID	Unit size (MW)	Forced outage rate	Scheduled maintenance wk/yr
1	5	0.010	2
2	5	0.010	2
3	10	0.020	2
4	20	0.015	2
5	20	0.015	2
6	20	0.015	2
7	20	0.015	2
8	20	0.025	2
9	40	0.020	2
10	40	0.030	2
11	40	0.030	2

Three state representations for units 10 and 11 are used in this research. Table 2.4 shows the probabilities of these states.

Table 2.4: Three state data for unit 10 and 11

State Capacity (MW)	Probability
0	0.02
20	0.02
40	0.96

2.5. Basic reliability evaluation for the RBTS and the RTS

The concepts described in the previous sections have been applied to the RBTS. The developed programs were used to perform some basic studies on the

RBTS. The loss of load expectation (LOLE) using the DPLVC was found to be 0.092 days/year. The Loss of Energy Expectation (LOEE) cannot be determined using the daily peak loads, and therefore the load duration curve (LDC) was used. The LOEE was found to be 0.006 MWH/year

The chronological daily peak load model shown in Figure 2.2 has been used as the basic load model in the maintenance scheduling studies described in this thesis. An alternative model is introduced later in the thesis for comparison purposes.

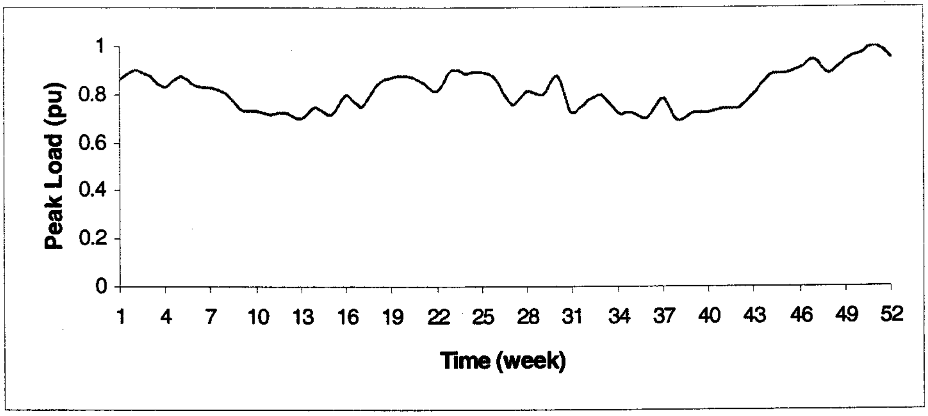

Figure 2.2: The RBTS chronological daily peak load model

It can be seen from Figure 2.2, that the basic load model has two low load periods located in the weeks 7 to 19 and 31 to 43. The system will have the highest reliability level during these two periods as reflected in Figure 2.3 which shows the weekly loss of load expectation for the RBTS.

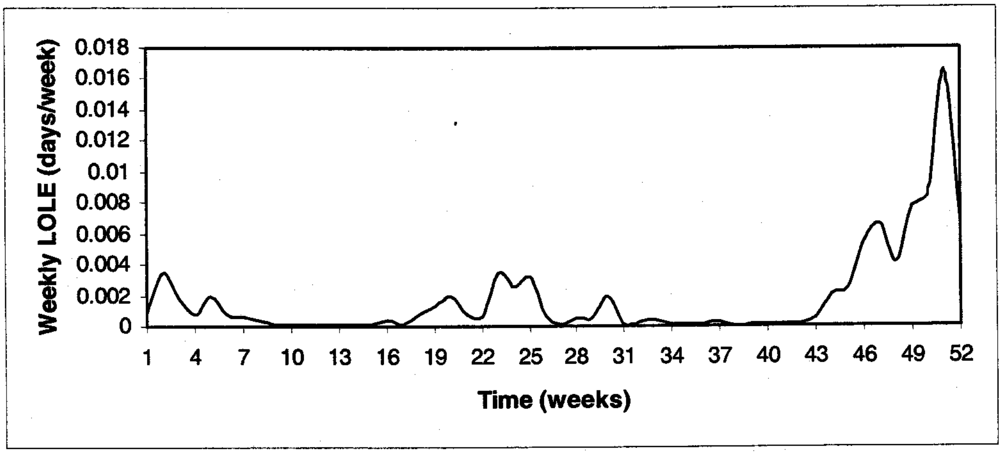

Figure 2.3: Weekly loss of load expectation for the RBTS

As noted above, weeks 7 to 19 and 31 to 43 have the lowest LOLE in the year. The risk is higher for the rest of the year especially in week 51 where the load is at its maximum value. Figure 2.3 provides a basic risk profile reference and can be compared with the results shown later in this thesis when maintenance is included in the analysis.

A full description of the RTS is given in reference [21]. An abbreviated description showing only the generation facilities is given in Appendix A. The chronological load model was used as the load model for the base case study. The loss of load expectation (LOLE) for the RTS is 1.236 days/year.

2.6. Wellbeing indices evaluation

In the past, conventional reliability assessment of a power system was normally done using deterministic techniques. Generating system reliability was provided by having a reserve margin equal to an acceptable fraction of the installed capacity, such as the size of the largest unit or some percentage of the peak load. The actual system behavior and the probability of component failures are not included in the deterministic approaches.

Wellbeing analysis was developed to combine the deterministic and the probabilistic approaches in a single framework Reference [22]. The capacity reserve of the system is evaluated using probabilistic techniques and compared to an accepted deterministic criterion, such as the loss of the largest unit, in order to measure the degree of system comfort. System wellbeing analysis [22] utilizes three wellbeing indices; the probability of health P(H), the probability of margin P(M) and the probability of risk P(R). The probability of risk P(R) is in fact the conventional risk index known as the loss of load probability (LOLP).

These three probabilities reflect the three states that the system can reside in. The probability of health P(H) is the probability of the system being in the healthy state where the available reserve is equal to or greater than the required capacity reserve. In this research , the capacity of the largest unit is used as the required capacity reserve. The probability of margin P(M) is the probability of the system being in the marginal state. In this state, the available reserve is less than the required capacity reserve but greater than zero. The probability of risk P(R) is the probability of the system being in the risk state. In this state, the load exceeds the available generation.

The wellbeing indices can be evaluated using analytical techniques or by Monte Carlo Simulation (MCS) [3,20]. The analytical approach was used in this research work. There are two basic techniques which can be applied. They are the Contingency Enumeration method and the Conditional Probability Capacity Outage Probability Table approach (CPCOPT) [23]. These analytical techniques are illustrated using a small system in the following section.

2.6.1. Contingency enumeration approach

In this approach, a generation model is created which includes all possible combinations of the existing generating unit outages with their corresponding probabilities. The available reserve in each state is compared with the capacity of the largest unit (CLU) in that state. If the available reserve is greater than or equal to the CLU, this state said to be a healthy state. When the available reserve is less than the CLU and greater than zero, this state considered to be a marginal state. When the reserve is negative, the state is considered to be a risk state.

The health probability is the sum of all the probabilities of the healthy states. The margin probability is the sum of the probabilities of the states deemed to be in the margin condition. The probability of risk is the sum of all the state probabilities with a negative reserve margin.

The technique is illustrated in Table 2.5 using System X given in Table 2.1. A constant load model with a peak load of 90 MW is used. Table 2.5 illustrates the application of the contingency enumeration approach to System X. The probabilities of health, margin and risk are, 0.9235, 0.075 and 0.0015 respectively.

It is obvious from this example that it is quite difficult to use this technique for a large system with a non-constant load model. In order to apply this technique to the RBTS using a two state representation for units 10 and 11, there will be 2^{11} or 2048 states. The CPCOPT approach [23] was developed to provide a more practical calculation procedure for large systems. This technique is used in the maintenance scheduling studies described in this thesis.

Table 2.5: Contingency enumeration approach for System X

Units out or derated	Prob.	Avai Cap.	CLU	Res.	H	M	R
None	0.563255	240	100	150	*		
1	0.021945	140	100	50		*	
2	0.021945	140	100	50		*	
3	0.029645	200	100	110	*		
$\underline{1}$	0.146300	190	100	100	*		
$\underline{2}$	0.146300	190	100	100	*		
1,2	0.000855	40	40	-50			*
1,3	0.001155	100	100	10		*	
2,3	0.001155	100	100	10		*	
$\underline{1}$,2	0.005700	90	50	0		*	
$\underline{1}$,3	0.007700	150	100	60		*	
$\underline{2}$,1	0.005700	90	50	0		*	
$\underline{2}$,3	0.007700	150	100	60		*	
$\underline{1}$,$\underline{2}$	0.038000	140	50	50	*		
$\underline{1}$,$\underline{2}$,3	0.002000	100	50	10		*	
$\underline{1}$,2,3	0.000300	50	50	-40			*
1,$\underline{2}$,3	0.000300	50	50	-40			*
1,2,3	0.000045	0	0	-90			*
				Total	P(H)= 0.9235	P(M)= 0.075	P(R)= 0.0015

2.6.2. Conditional probability COPT approach

The CPCOPT approach was developed in [23] to overcome the limitations of the contingency enumeration approach. There are three steps in this technique. The first step is to determine the LOLP, which is the probability of risk, using the well-known LOLP method [3]. The second step is to obtain the probability of health using a similar technique in which several COPT are created and convolved with the load model. In each case, the P(H) is obtained and weighted with the corresponding generating units probabilities. In the final step, the P(H) and the P(R) are subtracted from 1 to evaluate the probability of margin. This technique is illustrated using System X.

Step1: P(R) calculation

In this step the P(R) is evaluated using the basic LOLP method. Table 2.6 shows the required COPT for System X.

Table 2.6: COPT for System X

Available capacity	Margin	Cumulative probability
240	150	1.000000
200	110	0.436745
190	100	0.407100
150	60	0.114500
140	50	0.099100
100	10	0.017210
90	0	0.012900
50	**-40**	**0.001500**
40	-50	0.000900
0	-90	0.000045

The cumulative probability of the first negative margin gives the probability of risk. This value of 0.0015 is highlighted in Table 2.6.

Step 2: P (H) calculation

As previously noted, the second step is to obtain the probability of health using a similar technique in which one of the generating units is selected and assumed to reside in the various states. For each state another unit is selected and considered in the same way. The more units considered, the more accurate the final result. A COPT is constructed for each conditional state and convolved with the load model to calculate the P(H). The P(H) values are weighted by the corresponding generating unit probabilities. The conditional probability approach is explained in detailed in [20].

Selecting Unit 1 and assuming that the unit is out of service:

Table 2.7 shows the calculation of P(H) with unit 1 out. In this table, tk is the time in which the outage capacity level exceeds the reserve. D is the length of the period of the study (i.e. one year) which is 1 p.u. in this case.

Table 2.7: Calculating P(H) with Unit 1 out

		Unit 2 out		Unit 2 derated		Unit 2 in	
		CLU=40 , X=0		CLU=50 , X=50		CLU=100 , X=100	
Cap in	Indv. Prob.(pk)	D-tk	(D-tk)*pk	D-tk	(D-tk)*pk	D-tk	(D-tk)*pk
X+40	0.95	0	0	0	0	0	0
X+0	0.05	0	0	0	0	0	0
		Px(H)=0		Py(H)=0		Pz(H)=0	

Using the conditional probability, the P(H) under this condition in which unit#1 is out, is calculated as follows:

$$P(H)|_{unit1\ out} = Px(H)*P(2\ out) + Py(H)*P(2\ derated) + Pz(H)*P(2\ in)$$

$$P(H)|_{unit1\ out} = 0*0.03 + 0*0.2 + 0*0.77 = 0$$

Assuming Unit 1 is derated:

Table 2.8 shows the calculation of P(H) where unit 1 is derated. Using conditional probability, the P(H) under this condition in which unit#1 is derated is calculated as shown below.

Table 2.8: Calculating P(H) with Unit#1 derated

		Unit 2 out		Unit 2 derated		Unit 2 in	
		CLU=50 , X=50		CLU=50 , X=100		CLU=100 , X=150	
Cap in	Indv. Prob.(pk)	D-tk	(D-tk)*pk	D-tk	(D-tk)*pk	D-tk	(D-tk)*pk
X+40	0.95	0	0	1	0.95	1	0.95
X+0	0.05	0	0	0	0	0	0
		Px(H)=0		Py(H)=0.95		Pz(H)=0.95	

$$P(H)|_{unit1\ derated} = Px(H)*P(2\ out) + Py(H)*P(2\ derated) + Pz(H)*P(2\ in)$$

$$P(H)|_{unit1\ derated} = 0*0.03 + 0.95*0.2 + 0.95*0.77 = 0.9215$$

Assuming Unit 1 is in: CLU=100 , X = 100:

Table 2.9 shows the calculation of P(H) while unit 1 is in service.

Table 2.9: Calculating P(H) for Period#1 for this condition.

Cap in	Indv. Prob.(pk)	D-tk	(D-tk)*pk
X+140	0.7315	1	0.7315
X+100	0.0385	1	0.0385
X+90	0.1900	1	0.1900
X+50	0.0100	0	0
X+40	0.0285	0	0
X+0	0.0015	0	0
			Px=0.96

$$P(H)|_{unit1\ in} = 0.96$$

$$P(H)=P(H)|_{unit1\ out}*\ P(1\ out)+P(H)|_{unit1\ derated}*\ P(1\ derated)+P(H)|_{unit1\ in}*P(1\ in)$$

$$= 0 * 0.03 + 0.9215 * 0.2 + 0.96 * 0.77 = 0.9235$$

Step 3: P (M) calculation

$$P(M) = 1 - P(H) - P(R)$$

$$= 1 - 0.9235 - 0.0015 = 0.075$$

The P(H), P(M), and P(R) values calculated using the CPCOPT method can be compared with those shown in Table 2.5 obtained using the CE method.

The conditional probability COPT approach was applied to the RBTS with the DPLVC load model. The resulting system wellbeing indices are as follows:

P(H) = 0.988539

P(M) = 0.011207

P(R) = 0.000254

Figure 2.4 shows the weekly probability of health and probability of risk. The probability of risk profile is similar to the LOLE profile shown in Figure 2.3 but with a different scale. The first impression from Figure 2.4 is that the two profiles look like mirror images. The P(R) profile is similar to the P(H) profile in that when the health increases, the risk decreases, and when the health decreases, the risk increases.

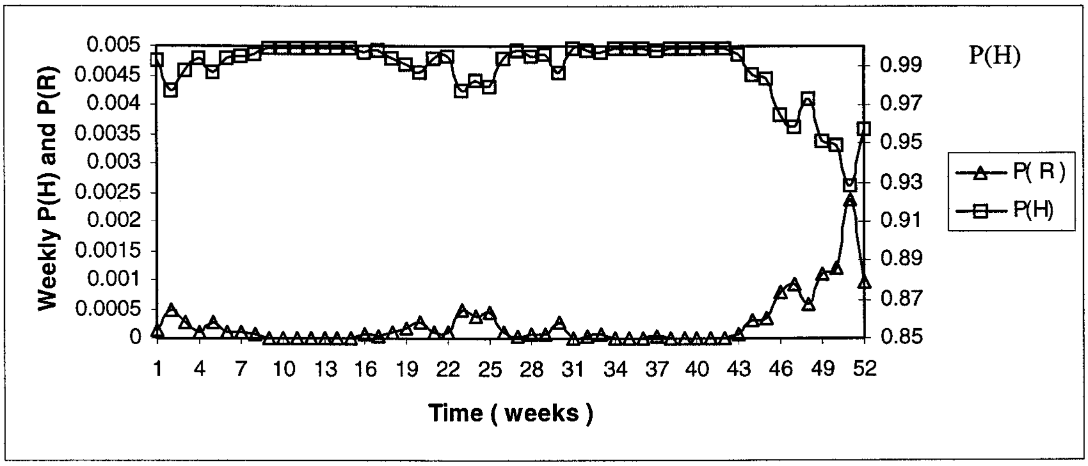

Figure 2.4: Weekly probability of health and risk for the RBTS

The basic wellbeing indices P(H), P(M), P(R) obtained for the RTS using the chronological load model are 0.961891, 0.041505 and 0.003396 respectively. These indices were calculated for the RTS without considering maintenance, using the CPCOPT technique presented in Chapter 2. The weekly P(H) and P(R) for the RTS are shown in Figure 2.5.

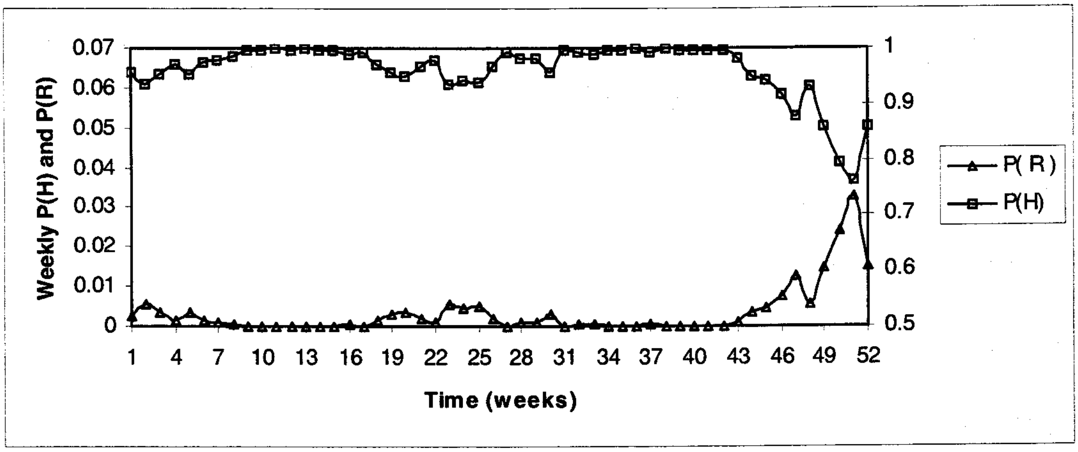

Figure 2.5: The weekly P(H) and P(R) for the RTS

Figure 2.5 can be compared with Figure 2.4, which shows the weekly P(H) and P(R) obtained for the RBTS using the same load model. It can be seen that these two figures are similar. In both figures, the risk is low in the two low load periods and the health is high during these two periods. The risk levels for the RTS are, however, higher than those for the RBTS. In a similar manner, the health is higher in the RBTS than the RTS.

2.7. Wellbeing indices evaluation on a period basis

Wellbeing analysis was illustrated in the previous section using the contingency enumeration approach and the conditional probability capacity outage probability table method. In this illustration, it was assumed that there is one load model and one generation model for the whole period (i.e. one year). This is not valid if preventive maintenance is included in the process. The contingency enumeration approach and the conditional probability COPT approach are used to illustrate the determination of wellbeing indices on a period basis..

2.7.1. Contingency enumeration approach on a period basis

In this approach, a generation model is built for each maintenance period (weeks). As previously noted, all possible combinations of the existing generating unit states are listed in this model with their corresponding probabilities. The available reserve for each state is compared with the CLU of that state. If the available reserve is greater than or equal to the CLU, this state said to be a healthy state. When the available reserve is less than the CLU and greater than zero, this state is considered to be a marginal state. When the reserve is less than zero, this state is considered as a risk state.

The probability of health for this maintenance period is the summation of all the probabilities of the healthy states. The marginal state probability for this period is the summation of all the probabilities of the individual margin states. The probability of risk is the summation of all the probabilities of the individual risk states. The same procedure is applied to all the other maintenance periods. The total P(H), P(M) and P(R) for the whole period (one year) are given by the following equations:

$$P(H) = \sum_{i=1}^{n}\left[P_i(H) * \frac{\text{period}_i}{\text{total\_period}}\right]. \tag{2.6}$$

$$P(M) = \sum_{i=1}^{n}\left[P_i(M) * \frac{\text{period}_i}{\text{total\_period}}\right]. \tag{2.7}$$

$$P(R) = \sum_{i=1}^{n}\left[P_i(R) * \frac{\text{period}_i}{\text{total\_period}}\right]. \tag{2.8}$$

Where :

i : the maintenance period number,

n : the total number of maintenance periods,

period_i : the duration of the i_{th} maintenance period.

This technique is illustrated using System X, for which the generating unit data is given in Table 2.1. A constant load of 90 MW is used. The system maintenance data is given in Table 2.10.

Table 2.10: System X maintenance data

i	Unit out for maintenance	Maintenance period From	Maintenance period To	Duration (months)
1	Nil	Jan1	Apr30	4
2	2	May1	Dec31	8

The probabilities of health, margin and risk are shown in Table 2.11 for the first period considering all the generating units. P(H), P(M), P(R) are, 0.9235, 0.0750 and 0.0015 respectively. These indices are the same as those shown in Table 2.5 and are weighted by the period duration, as shown in Equations 2.6, 2.7 and 2.8.

Table 2.11: The Contingency enumeration approach for System X, maintenance period # 1.

Units out or derated	Prob.	Avail. Cap.	CLU	Res.	H	M	R
None	0.563255	240	100	150	*		
1	0.021945	140	100	50		*	
2	0.021945	140	100	50		*	
3	0.029645	200	100	110	*		
1	0.146300	190	100	100	*		
2	0.146300	190	100	100	*		
1,2	0.000855	40	40	-50			*
1,3	0.001155	100	100	10		*	
2,3	0.001155	100	100	10		*	
1,2	0.005700	90	50	0		*	
1,3	0.007700	150	100	60		*	
2,1	0.005700	90	50	0		*	
2,3	0.007700	150	100	60		*	
1,2	0.038000	140	50	50	*		
1,2,3	0.002000	100	50	10		*	
1,2,3	0.000300	50	50	-40			*
1,2,3	0.000300	50	50	-40			*
1,2,3	0.000045	0	0	-90			*
				Total	P1(H)= 0.9235	P1(M)= 0.075	P1(R)= 0.0015

Table 2.12 shows the probabilities of health, margin and risk for the second period with unit 2 out for maintenance. P(H), P(M) and P(R) are , 0.00, 0.96 and 0.04 respectively.

The system health, margin and risk probabilities for the whole year calculated using Equations 2.6, 2.7, and 2.8 are:

P(H) = 0.92350*4/12 + 0.00*8/12 = 0.307833

P(M) = 0.075*4/12 + 0.96*8/12 = 0.665

P(R) = 0.00150*4/12 + 0.04*8/12 = 0.027167

Table 2.12: The Contingency enumeration approach for System X, maintenance period # 2.

Units out or derated	Prob.	Avail. Cap.	CLU	Res.	H	M	R
None	0.7315	140	100	50		*	
1	0.2850	40	40	-50			*
3	0.0385	100	100	10		*	
1	0.1900	90	50	0		*	
1,3	0.0100	50	50	-40			*
1,3	0.0015	0	0	-90			*
				Total	P2(H)= 0.0	P2(M)= 0.96	P2(R)= 0.04

2.7.2. Conditional probability COPT approach on a period basis

The three step procedure described in Section 2.6.2 is again followed. These steps are repeated for each maintenance period. After evaluating the health and risk probabilities for all the maintenance periods, the total probability of health and risk are evaluated using Equations 2.9 and 2.10 and the probability of margin for the total period is obtained using Equation 2.11.

$$P(H)=\sum_{i=1}^{n} P_i(H) \tag{2.9}$$

$$P(R)=\sum_{i=1}^{n} P_i(R) \tag{2.10}$$

$$P(M)=1-P(H)-P(R) \tag{2.11}$$

This method is applied to System X in the following example.

<u>Maintenance period #1 :</u>

This calculation is similar to that shown in Section 2.6.2 as all three generating units are under consideration in this maintenance period. The P(H) and P(R) values for this period are :

P(H) = 0.9235*4/12 = 0.30783

P(R) = 0.0015*4/12 = 0.00050

Maintenance period #2 :

Step1: P(R) calculation :

The cumulative probability of the first negative margin gives the probability of risk for this period as shown in Table 2.13.

$P_2(R) = 0.04 * 8/12 = 0.0266667$

Table 2.13: System X COPT for period #2

Available capacity	Cumulative probability
140	1.0000
100	0.2685
90	0.2300
50	<u>0.0400</u>
40	0.0300
0	0.0015

Step 2: P (H) calculation :

The calculation is shown in Table 2.14

Table 2.14: Calculating P(H) for period#2 .

		Unit 1 out		Unit 1 derated		Unit 1 in	
		CLU=40 , X=0		CLU=50 , X=50		CLU=100 , X=100	
Cap in	Indv. Prob.(pk)	D-tk	(D-tk)*pk	D-tk	(D-tk)*pk	D-tk	(D-tk)*pk
X+40	0.95	0	0	0	0	0	0
X+0	0.05	0	0	0	0	0	0
		Px(H)=0		Py(H)=0		Pz(H)=0	

From Table 2.14, $P_2(H)$ can be calculated as follows :

$$P_2(H) = Px(H)*P(1\ out) + Py(H)*P(1\ derated) + Pz(H)*P(1\ in)$$

$$= 0*0.03 + 0*0.2 + 0*0.77 = 0$$

The P(H), P(M) and P(R) for the whole year is calculated using Equations 2.9,2.10 and 2.11.

$$P(H) = P_1(H) + P_2(H) =$$

$$= 0.30783 + 0 = 0.30783$$

$$P(R) = P_1(R) + P_2(R) =$$

$$= 0.0005 + 0.0266667 = 0.027167$$

$$P(M) = 1 - P(H) - P(R)$$

$$= 1 - 0.30783 - 0.027167 = 0.665$$

These values can be compared with those obtained using the Contingency Enumeration method.

In order to illustrate the wellbeing calculation procedure using a chronological load model, consider the load profile shown in Figure 2.6. This is a very simple load model in which each day is represented by its daily peak load. The load is assumed to vary as shown.

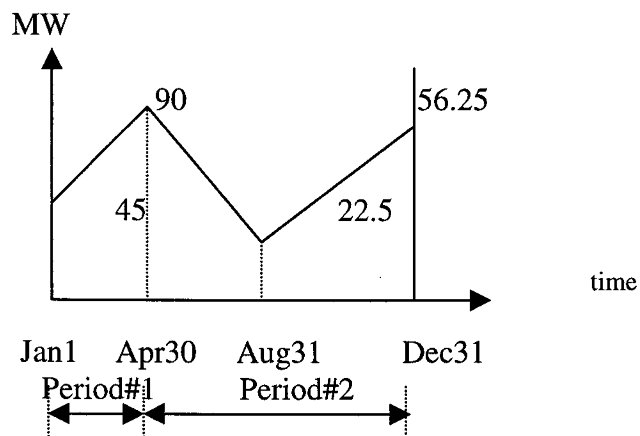

Figure 2.6: Chronological load model for System X

There are two maintenance periods. In order to apply the proposed technique in this case, the chronological loads for each maintenance period are rearranged in a descending order. The wellbeing indices can be evaluated by following the same steps used earlier.

Maintenance period #1 :

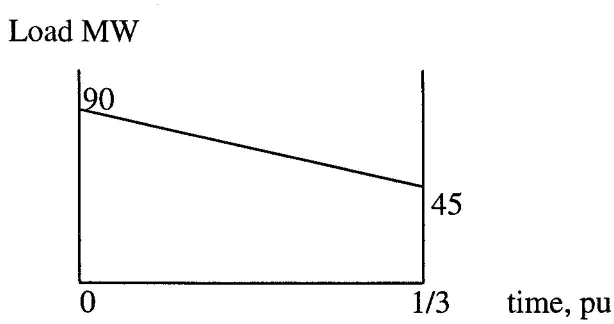

Figure 2.7: DPLVC for maintenance period #1

The calculation of P(H) and P(R) for the first period is as follows.

Step1: P(R) calculation :

Table 2.15 shows the calculation for the P(R) for the first period.

Table 2.15: COPT for System X for the first period

Available capacity	Individual probability	tk	tk*pk
240	0.563255	0	0
200	0.029645	0	0
190	0.292600	0	0
150	0.015400	0	0
140	0.081890	0	0
100	0.004310	0	0
90	0.011400	0	0
50	0.000600	0.2963	0.000178
40	0.000850	1/3	0.000283
0	0.000045	1/3	0.000015
			P(R)=0.000611

The probability of risk for the first maintenance period is 0.000611.

Step 2: P (H) calculation :

Table 2.16 shows the calculation process assuming that Unit 1 is out of service.

Table 2.16: Calculating P(H) for period#1 with unit 1 out.

		Unit 2 out		Unit 2 derated		Unit 2 in	
		CLU=40 , X=0		CLU=50 , X=50		CLU=100 , X=100	
Cap in	Indv. Prob.(pk)	D-tk	(D-tk)*pk	D-tk	(D-tk)*pk	D-tk	(D-tk)*pk
X+40	0.95	0	0	0	0	0	0
X+0	0.05	0	0	0	0	0	0
		Px(H)=0		Py(H)=0		Pz(H)=0	

Using conditional probability, the $P_1(H)$ under the condition that unit#1 is out, is as follows:

$P_1(H)|_{unit1\ out}$ = Px(H)*P(2 out) + Py(H)*P(2 derated) + Pz(H)*P(2 in)

$P_1(H)|_{unit1\ out}$ = 0*0.03 + 0*0.2 + 0*0.77 = 0

Table 2.17 shows the calculation process assuming that Unit 1 is derated.

Table 2.17: Calculating P(H) for period#1 with unit 1 derated.

		Unit 2 out		Unit 2 derated		Unit 2 in	
		CLU=50 , X=50		CLU=50 , X=100		CLU=100 , X=150	
Cap in	Indv Prob (pk)	D-tk	(D-tk)*pk	D-tk	(D-tk)*pk	D-tk	(D-tk)*pk
X+40	0.95	0	0	4/12	0.31667	4/12	0.31667
X+0	0.05	0	0	0.03704	0.001852	0.03704	0.001852
		Px(H)=0		Py(H)=0.31852		Pz(H)=0.31852	

Using conditional probability, the $P_1(H)$ under the condition that unit#1 is derated , is as follows:

$P_1(H)|_{\text{unit1 derated}}$ = Px(H)*P(2 out) + Py(H)*P(2 derated) + Pz(H)*P(2 in)

$P_1(H)|_{\text{unit1 derated}}$ = 0*0.03 + 0.31852*0.2 + 0.31852*0.77 = 0.3089644

Table 2.18 shows the calculation of P1(H) given unit 1 is in service. The capacity of the largest unit is 100 MW.

Table 2.18: Calculating P(H) for period#1 with unit 1 in.

Cap in	Indv. Prob.(pk)	D-tk	(D-tk)*pk
X+140	0.7315	4/12	0.243833
X+100	0.0385	4/12	0.012833
X+90	0.1900	4/12	0.063333
X+50	0.0100	0.03704	0.003704
X+40	0.0285	0	0
X+0	0.0015	0	0
			Px=0.323694

$P_1(H)|_{\text{unit1 in}}$ = 0.323694

The value of $P_1(H)$ for the period is as follows.

$P_1(H)$=$P_1(H)|_{\text{unit1 out}}$* P(1out)+$P_1(H)|_{\text{unit1 derated}}$ * P(1derated)+$P_1(H)|_{\text{unit1 in}}$ *P(1 in)

= 0 * 0.03 + 0.3089644* 0.2 + 0.323694* 0.77 = 0.311037

Maintenance period #2 :

The DPLVC for this period is shown in Figure 2.8.

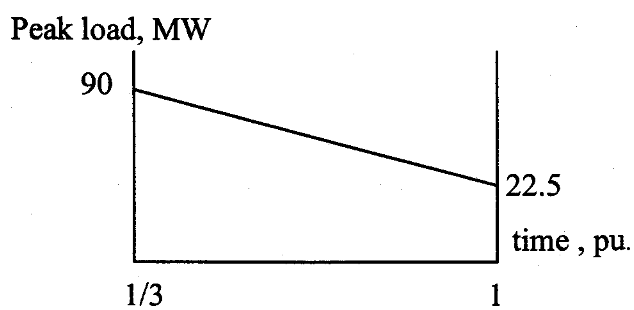

Figure 2.8: DPLVC for maintenance period #2

Step1: P(R) calculation :

The P(R) calculation process is shown in Table 2.19 for period # 2.

Table 2.19: COPT for system X for the second period

Available capacity	Individual probability	tk	tk*pk
140	0.7315	0	0
100	0.0385	0	0
90	0.19	0	0
50	0.01	0.3951	0.003951
40	0.0285	0.4938	0.01407
0	0.0015	2/3	0.001
			P(R)=0.019021

The probability of the first negative margin gives the probability of risk.

$P_2(R) = 0.019021$

Step 2: P (H) calculation :

The P(H) calculation process is shown in Table 2.20 for period #2.

Table 2.20:calculating P(H) for period#2 .

		Unit #1 out		Unit #1 derated		Unit #1 in	
		CLU=40 , X=0		CLU=50 , X=50		CLU=100 , X=100	
Cap in	pk	D-tk	(D-tk)*pk	D-tk	(D-tk)*pk	D-tk	(D-tk)*pk
X+40	0.95	0	0	0.17284	0.164198	0.17284	0.164198
X+0	0.05	0	0	0	0	0	0
		Px(H)=0		Py(H)=0.164198		Pz(H)=0.164198	

Using conditional probability, the P(H) for this period is calculated as follows.

$$P_2(H) = Px(H)*P(1\ out) + Py(H)*P(1\ derated) + Pz(H)*P(1\ in)$$

$$= 0*0.03 + 0.164198*0.2 + 0.164198*0.77 = 0.1592721$$

The total P(H), P(M) and P(R) for the whole year can be calculated using Equations 2.9,2.10 and 2.11.

$$P(H) = P_1(H) + P_2(H) =$$

$$= 0.311037 + 0.1592721 = 0.47031$$

$$P(R) = P_1(R) + P_2(R) =$$

$$= 0.000611 + 0.019021 = 0.019632$$

$$P(M) = 1 - P(H) - P(R)$$

$$= 1 - 0.47031 - 0.019632 = 0.510058$$

In the last example, the actual load model was used in the CPCOPT approach. In order to use this load model with the CE approach, the load must be represented by a number of discrete load levels. A very large number of discrete steps must be used to represent the load model in order to achieve the same accuracy as obtained using the CPCOPT.

2.8. Conclusion

The COPT is the most common representation of the generation model. The basic recursive technique is the best approach to create the COPT. This technique can also be used to remove generating units for maintenance purposes from the COPT. This is much more efficient than creating a new COPT for each maintenance period.

The loss of load expectation (LOLE) and loss of energy expectation (LOEE) are the most widely used risk indices. They are evaluated by convolving the generation model with the load model.

Two techniques are illustrated in this chapter to evaluate the wellbeing indices. These are the contingency enumeration approach and the Conditional Probability COPT method. The wellbeing approach and the resulting indices provide a bridge between the deterministic and probabilistic methodologies.

The basic wellbeing approach is extended in this chapter by using the contingency enumeration approach and the Conditional Probability COPT method to incorporate period base analysis. This extension is used further in the determination of period based indices associated with the scheduling of preventive maintenance. As noted in this chapter, the CE approach is difficult to use in large systems to evaluate the wellbeing indices particularly with variable load models. The CPCOPT approach was used in all the further studies described in this thesis.

3. PREVENTIVE MAINTENANCE SCHEDULING

3.1. Introduction

Preventive maintenance scheduling of generating equipment is a challenging task in a large continuously operating entity such as an electric power system, as removing some generating units for maintenance may create excessive risk to the system. Some of the difficulties encountered in scheduling maintenance are: the system may have generating units with different sizes and different efficiencies, the load is changing all the time and the available maintenance crews may or may not be sufficient to perform the scheduled maintenance.

Chapter 1 noted that Dopazo, Garver, Happ and Merrill concluded in references [6] and [11] that the cost objective function is insensitive to maintenance scheduling. This research work is therefore focused on the utilization of reliability criteria to schedule maintenance. Both probabilistic and deterministic reliability criteria have been utilized in this thesis.

Chapter 2 presents the basic concepts of generating capacity reliability evaluation and the tools required to incorporate reliability criteria in maintenance scheduling. Maintenance scheduling analyses are conducted on a period base due to the changing load and generation models during the year. The period base concepts outlined in Chapter 2 are integral elements in the maintenance scheduling activities described in this chapter.

Four different techniques are illustrated in this chapter to perform preventive maintenance scheduling. The main objective of each of these four techniques is to levelize the reliability over the year at an acceptable level. A fixed capacity reserve and the capacity of the largest unit were used as deterministic criteria. The probability of health and the loss of load expectation (LOLE) were used as probabilistic criteria.

Figure 2.2 shows the IEEE-RTS load model with two low load periods. Maintenance should be performed, if possible, during these two periods because, at these times, the available reserve will be high, the risk will be low and the health high. These conclusions can be observed from Figures 2.3 and 2.4. Scheduling the maintenance during these periods will result in an increase in the period risks. These risk levels should not exceed the desired risk criterion. The probability of health and the available reserve for these two periods will decrease but should remain above the desired health and reserve criteria. In this way, the health and the reserve will be levelized above the desired level and the risk will be levelized below the desired level. In order to accomplish this, some maintenance may have to be scheduled at other times of the year. In order to examine this approach, the four techniques noted above were utilized. The four techniques have been designated as follows:

1- Health Levelization.

2- Risk Levelization.

3- Reserve Levelization.

4- Loss of the Largest Unit.

The first two techniques are probabilistic approaches. In the health levelization technique, the probability of health P(H) is used as the criterion. In the risk levelization technique, the LOLE is used as the criterion. The other two techniques are deterministic approaches in which, the available capacity reserve in MW and the capacity of the largest unit are used as criteria.

3.2. Description of the developed techniques

All four maintenance scheduling techniques follow the same basic procedure in order to make the resultant maintenance schedules comparable. The approach can be summarized in the following steps:

1- Specify the Maximum Number of Units (MNU), which can be taken out for maintenance at the same time in any week during the year.

2- Arrange the generating units in a descending capacity order so that the unit with the largest capacity will be scheduled first, then the next largest unit and so on. The largest units in the system and the units requiring longer times for maintenance are the most difficult units to schedule.

3(a) In order to apply the health levelization technique, sort the weeks in descending order with respect to the weekly probability of health. The week with the largest probability of health will be occupied first followed by the next week with the next largest probability of health and so on. This order is referred to as the criterion order in subsequent discussion.

3(b) In order to apply the risk levelization technique, sort the weeks in ascending order with respect to the weekly probability of risk. The week with the smallest probability of risk will be occupied first followed by the next week with the next smallest probability of risk and so on.

3(c) In order to apply the reserve levelization technique, sort the weeks in descending order with respect to the weekly reserve. The weeks with the largest reserve will be occupied first followed by the next week with the next largest reserve and so on.

3(d) In order to apply the loss of the largest unit technique, sort the weeks as in the reserve levelization technique.

4- Take the first unit in the capacity order and place it into the first week in the criterion order and in the following weeks for a number of weeks equal to the time required to perform the maintenance on this unit.

5- Check the number of units out for maintenance in the weeks mentioned in step 4. In the first instance only one unit will be scheduled. Additional units are scheduled as the process proceeds. If the number of units out for maintenance in any week is less than or equal to the MNU then go to the next step. Otherwise take the unit and place it in the next week in the criterion order and the following weeks for a number of weeks equal to the time required to perform the maintenance for this unit and check the MNU in this step.

6(a) In the case of the health levelization technique, calculate the probability of health for these weeks and go to the next step.

6(b) In the case of the risk levelization technique, calculate the probability of risk for these weeks and go to the next step.

6(c) In the case of the reserve levelization technique, calculate the reserve for these weeks and go to the next step.

6(d) In the case of the loss of the largest unit technique, calculate the reserve for these weeks and go to the next step.

7(a) In the case of the health levelization technique, check the calculated probability of health for these weeks after removing the unit for maintenance. If the calculated health of each week is more than or equal to the health criterion go to the next step. Otherwise take the unit and place it in the next week in the criterion order and the following weeks for a number of weeks equal to the time required to perform the maintenance on this unit and go to step 5.

7(b) In the case of the risk levelization technique, check the calculated probability of risk for these weeks after removing the unit for maintenance. If the calculated risk of each week is less than or equal to the chosen risk criterion then go to the next step. Otherwise take the unit and place it in the next week in the criterion order and the following weeks for a number of weeks equal to the time required to perform the maintenance for this unit and go to step 5.

7(c) In the case of the reserve levelization technique, check the calculated reserve for these weeks after removing the unit for maintenance. If the calculated reserve of each week is more than or equal to the chosen reserve criterion go to the next step. Otherwise take the unit and place it in the next week in the criterion order and the following weeks for a number of weeks equal to the time required to perform the maintenance for this unit and go to step 5.

7(d) In the case of the loss of the largest unit technique, check the calculated reserve for these weeks after removing the unit for maintenance. If the calculated reserve of each week is more than or equal to the capacity of the largest unit available in the corresponding week then go to the next step. Otherwise take the unit and place it in the next week in the order and the following weeks for a number of weeks equal to the time required to perform the maintenance for this unit and go to step 5.

8- At this point, the unit maintenance location is established. Take the next largest unit and go to step 3.

This process is terminated in two ways, either by successfully scheduling all of the generating units or by determining that one of the generating units is impossible to schedule due to constraint violation in every week in the year. In these cases, the desired reliability level is not achievable.

The basic steps presented above were used to perform maintenance scheduling using the four techniques. In this procedure, weekly indices are calculated and checked to make sure that the risk is kept below the desired risk level in every period of the year and the health and the reserve are kept above the desired levels in these periods.

3.3. Base case study of the RBTS and the RTS

The four techniques described earlier were applied to the RBTS and the RTS. The chronological load model shown in Figure 2.2 was used as a load model in these studies. The basic steps and procedures are illustrated using the Health Levelization technique on the RBTS. A peak load of 185 MW was assumed and the maximum number of units allowed out for maintenance in a single week (MNU) was fixed at 3. As noted earlier, any reasonable value can be used as the MNU. The criterion probability of health was chosen to be 0.9.

In order to start, the weeks are sorted according to their P(H) without considering maintenance. Week 38 comes first with the highest probability of health followed by the weeks 13, 36 and so on. The units are then sorted according to their sizes in a descending order so that the largest unit, unit 11, will be scheduled first followed by the next largest unit, unit 10, then the next one, unit 9, and so on. The scheduling of the first four large units is demonstrated in Table 3.1 to show how the technique works. Table 2.3 notes that each maintenance activity requires 2 weeks.

Table 3.1: Maintenance scheduling with the health levelization technique for the RBTS

UNITS	WEEKS	MNU	MNU≤3	P(H)	P(H)≥0.9
11	38	1	yes	0.964	yes
11	39	1	yes	0.961	yes
10	13	1	yes	0.963	yes
10	14	1	yes	0.961	yes
9	36	1	yes	0.943	yes
9	37	1	yes	0.923	yes
8	35	1	yes	0.995	yes
8	36	2	yes	0.887	no
8	11	1	yes	0.995	yes
8	12	1	yes	0.995	yes

Table 3.1 illustrates a small portion of the process used to construct the maintenance plan using the health levelization technique. Unit 11 is scheduled in week 38 where the unit satisfies the MNU and P(H) conditions. The following week is then examined, i.e. week 39. Unit 11 satisfies the constraints for this week as well and therefore the final position for unit 11 is weeks 38 and 39.

The criterion order of the weeks is revised after scheduling Unit 11. Unit 10 is scheduled in week 13, which became the first week in the new criterion order. This satisfies the criterion constraint for this week and the following week, therefore, Unit 10 is allocated to weeks 13 and 14.

The criterion order is reexamined after scheduling Unit 10. Unit 9 is considered for maintenance in week 36 which is the first week in the new criterion order. It is then considered for the following week and as it satisfies the constraints Unit 9 is therefore scheduled in weeks 36 and 37.

The criterion order is again revised after scheduling Unit 9. Unit 8 was considered for maintenance in week 35, and satisfied the constraints. The following week, week 36, was then considered and was not satisfactory. The next week in the criterion order which is week 11 was then considered. Unit 8 was scheduled in this week and the following week and proved to meet the constraints. The same procedure was used to schedule the other generating units.

A similar process to that described above was used to conduct maintenance scheduling using the other three techniques. In the case of the risk levelization technique, the weeks are sorted according to the weekly risk evaluated before conducting maintenance scheduling. In this case, the calculated risk should be less than or equal to the system risk criterion.

The same basic steps are followed when scheduling using the reserve levelization technique but with two small modifications. The first is to sort the weeks based on their weekly reserve and to use the reserve constraint so that the calculated reserve after removing a unit in a certain week is more than or equal to the chosen reserve criterion in order to schedule the unit in this week.

The same basic steps are followed using the loss of the largest unit technique. In this case, the available reserve in a certain week must be more than or equal to the capacity of the largest unit in service during that week.

The following sections illustrate the individual developed techniques. More detailed studies of the RBTS and the RTS are given in Chapter 4.

3.3.1. Health levelization technique

In this basic study, the health levelization technique was applied to the RBTS and the RTS using the chronological load model with a peak load of 185 MW for the RBTS and 2850 MW for the RTS. The selected MNU is 3 for the RBTS and 4 for the RTS. The selected P(H) criterion is 0.9 for the RBTS and 0.85 for the RTS. The selected MNU and reliability criteria are important parameters in the maintenance scheduling process. The sensitivity of the maintenance schedule to these parameters is illustrated in Chapter 4. The resulting maintenance schedules obtained for the RBTS and the RTS are shown in Tables 3.2 and 3.3 respectively.

Table 3.2: Maintenance schedule for the RBTS with a Peak Load of 185 MW and P(H) of 0.9

WEEK	Units on Maints.
1-8	NIL
9	2
10	5,2
11	8,5
12	8
13	10
14	10
15	3
16	3
17-30	NIL
31	6
32	6
33	NIL
34	4
35	4
36	9
37	9
38	11
39	11
40	7
41	7
42	1
43	1
42-52	NIL
P(H)	0.981202

Table 3.2 shows the RBTS maintenance schedule obtained using the health levelization technique. It can be seen from this table that the generating units were scheduled in the two low load periods and that is possible to have all the required maintenance done during the low load periods. It can also be seen from the table that the three large units in the system, units 11, 10, and 9, are scheduled in different periods, which is reasonable. The P(H) for the system without conducting any maintenance , is given in Section 2.6.2 as 0.988539. The P(H) for the system with

the maintenance schedule shown in Table 3.2 is 0.981202. As expected, the system probability of health decreases due to the need to conduct preventive maintenance.

The health levelization technique was applied to the RTS. The maintenance schedule obtained is shown in Table 3.3.

Table 3.3: Maintenance schedules for the RTS with a Peak Load of 2850 MW and P(H) of 0.85

WEEK	Units on Maints.	WEEK	Units on Maints.
1	3	23	20
2	3	24	20
3	NIL	25	NIL
4	16,1	26	9,6
5	16,1	27	27,18,9,6
6	17,16	28	27,18
7	23,17	29	27,18
8	23,17	30	27
9	23,22,13	31	29,24,10
10	28,23,22,13	32	29,24,10
11	31,28,22	33	29,24
12	31,28	34	29,25,24
13	31,28	35	25,15,14
14	31,12,8	36	30,25,15,14
15	31,21,12,8	37	30,25
16	31,21	38	32,30,2
17	26,21,7,4	39	32,30,2
18	26,7,4	40	32,30
19	26	41	32,19,5
20	26	42	32,19,5
21	11	43	32,19
22	20,11	45-52	NIL
		P(H)	0.918893

Table 3.3 shows the maintenance plan obtained for the RTS. In this case, generating unit maintenance is spread over most of the year. Most of the generating units are, however, scheduled during the low load periods. It can be seen from Table 3.3 that the probability of system health dropped significantly from 0.961891 to 0.918893 with the inclusion of preventive maintenance.

3.3.2. Risk levelization technique

The risk levelization technique was applied to the RBTS and the RTS. The risk index used in this study is the LOLE with a criterion value of 1/52 days/week for the RBTS and 0.1 days/week for the RTS. The maintenance plans for the RBTS and the RTS are shown in Tables 3.4 and 3.5.

Table 3.4 shows the maintenance schedule constructed for the RBTS using the risk levelization technique. As in the application of the health levelization technique, the generating units are scheduled during the low load periods and the three large units are scheduled in different periods. The system risk increased due to the need to perform maintenance on the system. The LOLE increases from 0.092 to 0.130 days/year.

Table 3.4: Maintenance schedule for the RBTS with a Peak Load of 185 MW and LOLE of 1/52 days/week

WEEK	Units on Maints.
1-8	NIL
9	2
10	4,2
11	8,4
12	8
13	10
14	10
15	3
16	3
17-30	NIL
31	5
32	5
33	NIL
34	6
35	6
36	9
37	9
38	11
39	11
40	7
41	7
42	1
43	1
44-52	NIL
LOLE(d/y)	0.130389

The maintenance schedule obtained for the RTS is shown in Table 3.5. As in the application of the health levelization technique, most of the generating units are scheduled during the low load periods. The system risk also increases significantly with the maintenance schedule. The two maintenance schedules can be compared by considering Tables 3.3. and 3.5. it can be seen that in this case, there is considerable difference between the two maintenance schedules.

Table 3.5: Maintenance schedule for the RTS with a Peak Load of 2850 MW and LOLE of 0.1 days/week

WEEK	Units on Maints.	WEEK	Units on Maints.
1	3	23	18
2	3	24	18
3	NIL	25	NIL
4	14,6,4	26	7
5	14,6,4	27	25,20,8,7
6	16,1	28	25,20,8
7	17,16,1	29	25,20
8	21,17,16	30	25
9	26,24,21,17	31	27,23,11,2
10	26,24,21	32	27,23,11,2
11	30,26,24	33	27,23
12	30,26,24	34	27,23,12
13	31,30	35	28,19,15,12
14	31,30	36	29,28,19,15
15	31,30	37	29,28,19
16	31	38	32,29,28
17	31,9	39	32,29
18	31,9	40	32,22,13,5
19	NIL	41	32,22,13,5
20	NIL	42	32,22
21	10	43	32
22	18,10	44-52	NIL
		LOLE(d/y)	2.517775

3.3.3. Reserve levelization technique

The maintenance schedules for the RBTS and the RTS obtained using probabilistic criteria are shown in the previous two subsections. In this subsection and the following subsection, the maintenance schedules for these systems are shown using the deterministic criteria. In these techniques, there are no probabilistic quantities involved in the process. The first deterministic technique illustrated is the reserve levelization approach. The reserve criterion used for the RBTS is a 30 MW reserve. A value of 600 MW is used for the RTS. Tables 3.6 and 3.7 show the maintenance schedules created for the RBTS and the RTS respectively.

Table 3.6 shows the maintenance schedule constructed for the RBTS with a reserve criterion of 30 MW. The first thing to notice is that the generating units are scheduled during the low load periods in the year. It can be also seen that none of the weeks contain three generating units, i.e. the MNU. This is due to the high system reserve margin and because the system is relatively small.

Table 3.6: Maintenance schedule for the RBTS with a Peak Load of 185 MW and reserve of 30 MW

WEEK	Units on Maints.
1-8	NIL
9	1
10	2,1
11	8,2
12	8
13	10
14	10
15	7
16	7
17-30	NIL
31	6
32	6
33	NIL
34	3
35	4,3
36	9,4
37	9
38	11
39	11
40	5
41	5
42-52	NIL

Table 3.7 shows the maintenance schedule for the RTS with a reserve criterion of 600 MW. As in the previous case, most of the generating units are scheduled during the low load periods in the year. It can be seen by comparing this schedule with the schedules obtained using the probabilistic techniques, that fewer weeks are occupied during the year in this schedule. This is because more generating units are scheduled in certain weeks. This could result in a decrease in system reliability but this problem is not recognized by the deterministic technique.

Table 3.7: Maintenance schedules for the RTS with a Peak Load of 2850 MW and reserve of 600 MW

WEEK	Units on Maints.	WEEK	Units on Maints.
1	7,1	23	23
2	7,1	24	23
3	NIL	25	23
4	17,10	26	9
5	17,10	27	25,19,16,9
6	17,4	28	25,19,16
7	18,11,4	29	25,19,16
8	21,18,11	30	25
9	26,24,21,18	31	30,14,6
10	27,26,24,21	32	30,14,6
11	28,27,26,24	33	30
12	28,27,26,24	34	30,13
13	31,28,27	35	30,13
14	31,28	36	29,22,20,15
15	31,8,3	37	29,22,20,15
16	31,8,3	38	32,29,22,20
17	31	39	32,29
18	31	40	32,5,2
19-20	NIL	41	32,5,2
21	12	42	32
22	23,12	43	32
		44-52	NIL

3.3.4. Loss of the largest unit

In the loss of the largest unit (LLU) technique, the reserve must be more than or equal to the capacity of the largest unit in a particular week. Tables 3.8 and 3.9 show the maintenance schedules obtained using this technique for the RBTS and the RTS respectively.

The maintenance schedule obtained for the RBTS with the LLU technique is shown in Table 3.8. As in the previous cases, the generating units are scheduled during the low load periods of the year, which is a reasonable approach. The three large units in the system are also scheduled in different periods, which will enhance the system reliability.

Table 3.8: Maintenance schedules for the RBTS with a Peak Load of 185 MW and the loss of the largest unit criterion

WEEK	Units on Maints.
1-8	NIL
9	1
10	2,1
11	8,2
12	8
13	10
14	10
15	7
16	7
17-30	NIL
31	6
32	6
33	NIL
34	3
35	4,3
36	9,4
37	9
38	11
39	11
40	5
41	5
42-52	NIL

Table 3.9 shows the maintenance plan obtained with the LLU technique for the RTS. Most of the generating units are scheduled during the low load periods. Due to the size of this system, which is relatively large, the generating units require most of the weeks in the year to perform the required maintenance.

Table 3.9: Maintenance schedules for the RTS with a Peak Load of 2850 MW and the loss of the largest unit criterion

WEEK	Units on Maints.	WEEK	Units on Maints.
1	3	23	18,13,7
2	3	24	18
3	NIL	25-26	NIL
4	15,10	27	24,19,14,8
5	15,10	28	24,19,14,8
6	12,5,2	29	24,19
7	16,12,5,2	30	24
8	20,16	31	28,23,11,1
9	25,22,20,16	32	28,23,11,1
10	26,25,22,20	33	28,23

Table 3.9: (Continued)

WEEK	Units on Maints.	WEEK	Units on Maints.
11	29,26,25,22	34	28,23,9
12	29,26,25	35	27,21,17,9
13	31,29,26	36	30,27,21,17
14	31,29	37	30,27,21,17
15	31,4	38	32,30,27
16	31,4	39	32,30
17	31	40	32,30
18	31	41	32
19-20	NIL	42	32
21	6	43	32
22	18,13,7,6	44-52	NIL

Table 3.2, 3.4, 3.6 and 3.8 have been combined to create Table 3.10 in order to provide a simple comparison of the maintenance schedules obtained for the RBTS using the four techniques.

Table 3.10: Maintenance schedules obtained for the RBTS using the four techniques

WEEK	Health	Risk	Reserve	LLU
1-8	NIL	NIL	NIL	NIL
9	2	2	1	1
10	5,2	4,2	2,1	2,1
11	8,5	8,4	8,2	8,2
12	8	8	8	8
13	10	10	10	10
14	10	10	10	10
15	3	3	7	7
16	3	3	7	7
17-30	NIL	NIL	NIL	NIL
31	6	5	6	6
32	6	5	6	6
33	NIL	NIL	NIL	NIL
34	4	6	3	3
35	4	6	4,3	4,3
36	9	9	9,4	9,4
37	9	9	9	9
38	11	11	11	11
39	11	11	11	11
40	7	7	5	5
41	7	7	5	5
42	1	1	NIL	NIL
43	1	1	NIL	NIL
42-52	NIL	NIL	NIL	NIL

It can be seen from Table 3.10 and 3.11 that the maintenance schedules created by the probabilistic techniques are different from the maintenance schedules obtained with the deterministic techniques. The maintenance schedules for the RTS as shown in Table 3.11 are different for each of the four techniques.

Table 3.11: Maintenance schedules obtained for the RTS using the four techniques

WEEK	Health	Risk	Reserve	LLU
1	3	3	7,1	3
2	3	3	7,1	3
3	NIL	NIL	NIL	NIL
4	16,1	14,6,4	17,10	15,10
5	16,1	14,6,4	17,10	15,10
6	17,16	16,1	17,4	12,5,2
7	23,17	17,16,1	18,11,4	16,12,5,2
8	23,17	21,17,16	21,18,11	20,16
9	23,22,13	26,24,21,17	26,24,21,18	25,22,20,16
10	28,23,22,13	26,24,21	27,26,24,21	26,25,22,20
11	31,28,22	30,26,24	28,27,26,24	29,26,25,22
12	31,28	30,26,24	28,27,26,24	29,26,25
13	31,28	31,30	31,28,27	31,29,26
14	31,12,8	31,30	31,28	31,29
15	31,21,12,8	31,30	31,8,3	31,4
16	31,21	31	31,8,3	31,4
17	26,21,7,4	31,9	31	31
18	26,7,4	31,9	31	31
19	26	NIL	NIL	NIL
20	26	NIL	NIL	NIL
21	11	10	12	6
22	20,11	18,10	23,12	18,13,7,6
23	20	18	23	18,13,7
24	20	18	23	18
25	NIL	NIL	23	NIL
26	9,6	7	9	NIL
27	27,18,9,6	25,20,8,7	25,19,16,9	24,19,14,8
28	27,18	25,20,8	25,19,16	24,19,14,8
29	27,18	25,20	25,19,16	24,19
30	27	25	25	24
31	29,24,10	27,23,11,2	30,14,6	28,23,11,1
32	29,24,10	27,23,11,2	30,14,6	28,23,11,1
33	29,24	27,23	30	28,23
34	29,25,24	27,23,12	30,13	28,23,9
35	25,15,14	28,19,15,12	30,13	27,21,17,9
36	30,25,15,14	29,28,19,15	29,22,20,15	30,27,21,17
37	30,25	29,28,19	29,22,20,15	30,27,21,17
38	32,30,2	32,29,28	32,29,22,20	32,30,27
39	32,30,2	32,29	32,29	32,30
40	32,30	32,22,13,5	32,5,2	32,30
41	32,19,5	32,22,13,5	32,5,2	32
42	32,19,5	32,22	32	32
43	32,19	32	32	32
44-52	NIL	NIL	NIL	NIL

3.4. Conclusion

Reliability assessment techniques can be generally divided into deterministic and probabilistic methodologies. The risk levelization technique can be considered as a basic probabilistic approach. The health levelization technique is a hybrid approach which incorporates a deterministic criterion within a probabilistic framework. In the studies described in this thesis, the probability of health is determined using the capacity of the largest unit. The maintenance schedules obtained using the probabilistic techniques are more responsive than the schedules obtained using the deterministic criteria as they have the capability to incorporate many of the uncertainties that exist in the process. The sensitivity of the four techniques to a range of system parameters is considered in Chapter 4. The four techniques are designed to follow the same basic procedure so that the resulting maintenance schedules can be compared.

4. THE IMPACT OF PROBABILISTIC AND DETERMINISTIC FACTORS ON MAINTENANCE SCHEDULING

4.1. Introduction

The techniques under study are presented in Chapter 3 together with base case studies on the RBTS and the RTS. The effect on maintenance scheduling of different probabilistic and deterministic factors, is illustrated in this chapter. The effect on maintenance schedules obtained using the probabilistic techniques due to changes in generating unit forced outage rates (FOR) has been examined for the RBTS and the RTS. The FOR is a probabilistic factor and does not have any effect on the maintenance schedules obtained using the deterministic techniques. The inability to recognize the outage probability of the unscheduled generating facilities is one of the fundamental limitations of deterministic techniques.

The impact changes in the allowable maximum number of units that can be removed for maintenance in a single week is also illustrated in this chapter. This factor is related to the available manpower and ultimately becomes a question of economics. It has an effect on the maintenance schedules obtained using probabilistic and deterministic techniques.

4.2. The effect of unit forced outage rate (FOR) on maintenance scheduling

In the deterministic techniques, a constant reserve or the loss of the largest unit is used as the criterion to construct the maintenance schedule. The generating unit FOR is not utilized in the application of these two techniques. If the FOR of any generating unit is changed it will not influence the maintenance schedule. In the case of the probabilistic techniques, the risk or the health indices are used as criteria to build a maintenance schedule. The generating unit FOR are the main parameters involved in the evaluation of the health and risk indices. As a result, if the FOR of any unit changes then the maintenance schedule could also change.

4.2.1. Health levelization

The effect of FOR variation on the maintenance plan constructed using the health levelization technique has been examined for the RBTS and the RTS. The MNU value was fixed at 3 for the RBTS and 4 for the RTS. A range of situations is considered in the following studies.

Eight maintenance plans for the RBTS are shown in Table 4.1. The FOR of generating unit 9 (40 MW) was varied from 0.005 to 0.04. It can be seen from Table 4.1 that there are four periods in the year in which no maintenance is scheduled in all eight plans. Those periods are, the weeks 1 to 8, 17 to 30, 33 and 44 to 52. These periods are high load periods compared to the other periods, as shown in the load model in Figure 2.2. It is desirable not to perform any maintenance during the high load periods unless it is absolutely necessary.

Table 4.1: Maintenance schedules for the RBTS with a Peak Load of 185 MW and P(H) of 0.9.

Plan FOR	Plan # 1 0.005	Plan # 2 0.01	Plan # 3 0.015	Plan # 4 0.02
WEEK				
1-8	NIL	NIL	NIL	NIL
9	2	2	1	2
10	5,2	5,2	5,1	5,2
11	8,5	8,5	8,5	8,5
12	8	8	8	8
13	10	10	10	10
14	10	10	10	10
15	3	3	4	3
16	3	3	4	3
17-30	NIL	NIL	NIL	NIL
31	6	6	6	6
32	6	6	6	6
33	NIL	NIL	NIL	NIL
34	4	4	2	4
35	4	4	3,2	4
36	9	9	9,3	9
37	9	9	9	9
38	11	11	11	11
39	11	11	11	11
40	7	7	7	7
41	7	7	7	7
42	1	1	NIL	1
43	1	1	NIL	1
44-52	NIL	NIL	NIL	NIL
P(H)	0.985515	0.984078	0.982017	0.981202

Table 4.1: (Continued).

Plan FOR	Plan # 5 0.025	Plan # 6 0.03	Plan # 7 0.035	Plan # 8 0.04
WEEK				
1-8	NIL	NIL	NIL	NIL
9	2	2	2	2
10	5,2	4,2	4,2	5,2
11	8,5	8,4	8,4	8,5
12	8	8	8	8
13	10	10	10	10
14	10	10	10	10
15	3	3	3	3
16	3	3	3	3
17-30	NIL	NIL	NIL	NIL
31	6	6	6	6
32	6	6	6	6
33	NIL	NIL	NIL	NIL
34	4	5	5	4
35	4	5	5	4
36	9	9	9	9
37	9	9	9	9
38	11	11	11	11
39	11	11	11	11
40	7	7	7	7
41	7	7	7	7
42	1	1	1	1
43	1	1	1	1
44-52	NIL	NIL	NIL	NIL
P(H)	0.979764	0.978326	0.976888	0.975450

The three largest units in the system were taken out for maintenance in different periods. Unit 9 is taken out in weeks 36 and 37 in all eight plans. Unit 10 is taken out in weeks 13 and 14 in all plans where unit 11 is taken out in weeks 38 and 39 in all eight plans. These three periods are the lowest load periods with the highest probability of health in the year. It is reasonable to have the largest units out for maintenance during the low load periods. Having the largest units out for maintenance in different periods and not at the same time will also increase the overall system reliability.

Plans 1, 2, 4, 5 and 8 are identical, where Plans 6 and 7 are identical to each other and they are also identical to the previous noted group of plans since Units 4 and 5 are identical. Plan 3 is therefore the only different plan among the constructed plans. The order of the weeks is revised after scheduling each generating unit and that enhances the overall reliability of the constructed plans.

The bottom row in Table 4.1 of the table shows the annual probability of health P(H). The P(H) decreases as the FOR of unit 9 increases as shown in Figure 4.1.

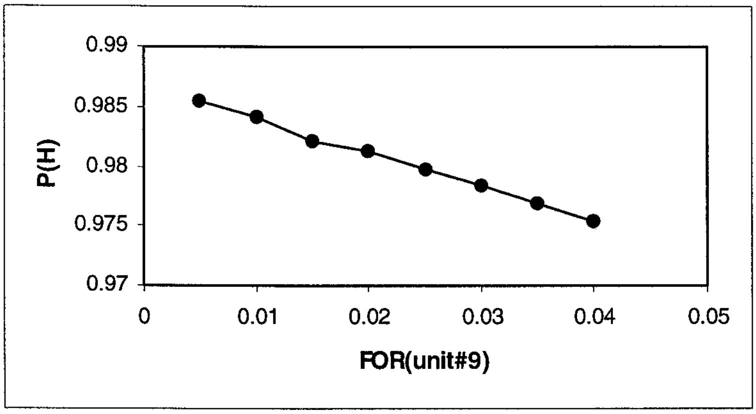

Figure 4.1: Variation in the annual P(H) with FOR variation for a chosen health criterion of 0.9.

The P(H) in this figure ranges from 0.97 to 0.98 while the desired weekly P(H) is 0.9. These high values of the P(H) are achieved because most of the weeks during the year have a P(H) of more than 0.95 because there is sufficient total reserve in this system under these conditions.

Figure 4.2 shows the weekly P(H) for three different FOR values for unit 9. The bulk of the weeks in this figure have a P(H) of more than 0.95. Table 4.1 shows that a few weeks contain no maintenance. The weekly P(H) for these weeks are , however, relatively low and due to the shape of the load model.

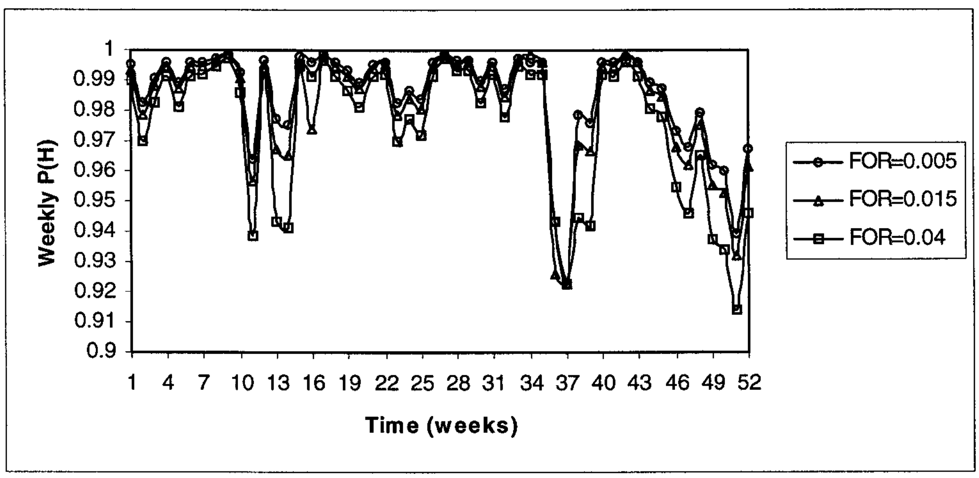

Figure 4.2: The effect of different FOR on the weekly P(H) and the maintenance scheduling with P(H) = 0.9.

Consider the results shown in Figure 4.2, for the FOR = 0.04 case. The load in week 51 is the annual peak. The P(H) for this week is below 0.92 even though there are no units out for maintenance. If this level is selected as the health criterion then the maintenance plan will be constructed such that the P(H) for the weeks with maintenance will be more than or equal to the desired health level and no units will taken out for maintenance during week 51. It should be appreciated that the low level of health during this week does not occur due to the maintenance plan, but because of the system composition, the load and the generating unit FOR.

Table 4.2 shows a comparison of the plans constructed using P(H) values of 0.9 and 0.94 for the same FOR for unit 9. Plan 2 and Plan 4 are identical, although they are constructed with different FOR values. The reason for this is that the criterion order is the same with both FOR values and design criterion is not violated in any week with both FOR values.

Table 4.2: Maintenance schedule for the RBTS with a Peak Load of 185 MW and P(H) of 0.9 & 0.94.

	FOR = 0.005		FOR = 0.015		FOR = 0.04	
	P(H)= 0.9	P(H)= 0.94	P(H)= 0.9	P(H)= 0.94	P(H)= 0.9	P(H)= 0.94
WEEK	Plan # 1	Plan #2	Plan # 3	Plan # 4	Plan #5	Plan # 6
1-8	NIL	NIL	NIL	NIL	NIL	NIL
9	2	1	1	1	2	4
10	5,2	2,1	5,1	2,1	5,2	4
11	8,5	9,2	8,5	9,2	8,5	8
12	8	9	8	9	8	8
13	10	10	10	10	10	10
14	10	10	10	10	10	10
15	3	3	4	3	3	5
16	3	3	4	3	3	5
17-26	NIL	NIL	NIL	NIL	NIL	NIL
27	NIL	NIL	NIL	NIL	NIL	1
28	NIL	NIL	NIL	NIL	NIL	1
29-30	NIL	NIL	NIL	NIL	NIL	NIL
31	6	5	6	5	6	6
32	6	5	6	5	6	6
33	NIL	NIL	NIL	NIL	NIL	NIL
34	4	4	2	4	4	2
35	4	7,4	3,2	7,4	4	9,2
36	9	8,7	9,3	8,7	9	9

Table 4.2: (Continued).

	FOR = 0.005		FOR = 0.015		FOR = 0.04	
	P(H)= 0.9	P(H)= 0.94	P(H)= 0.9	P(H)= 0.94	P(H)= 0.9	P(H)= 0.94
WEEK	Plan # 1	Plan #2	Plan # 3	Plan # 4	Plan #5	Plan # 6
37	9	8	9	8	9	NIL
38	11	11	11	11	11	11
39	11	11	11	11	11	11
40	7	6	7	6	7	7
41	7	6	7	6	7	7
42	1	NIL	NIL	NIL	1	3
43	1	NIL	NIL	NIL	1	3
44-52	NIL	NIL	NIL	NIL	NIL	NIL
P(H)	0.985515	0.985214	0.982017	0.982220	0.975450	0.976210

Figure 4.3 shows the weekly P(H) for the same FOR with two different health criteria, P(H) = 0.9 and 0.94. The profile for P(H) = 0.9 in some weeks goes below the 0.94 health level but it is still above the desired health criterion of 0.9. The profile for P(H) = 0.94 is always above the 0.94 health level except in week 51 where, the load is the annual peak load. The desired criterion is violated in this week even though there is no maintenance in this week. This is due to the shape of the load model and the FOR value. Selecting a higher health criterion will force the profile to move upwards until it get closer to a straight line with some variations, provided that the system is capable of achieving a higher level of health.

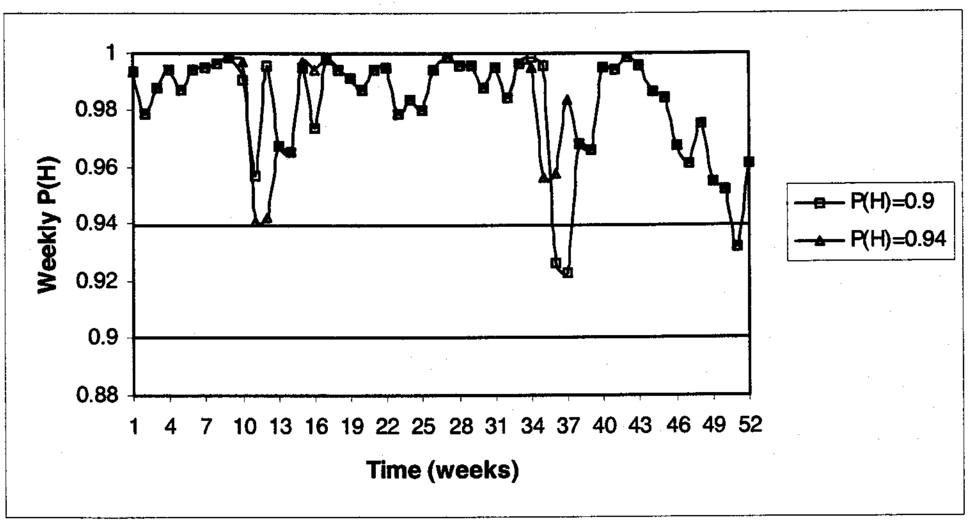

Figure 4.3: Weekly P(H) evaluated with FOR of 0.015 for desired health of 0.9 and 0.94

Figure 4.4 shows that the annual system health did not change much with the higher criterion. This is due to the revising of the weeks after scheduling each generating unit, which will keep the overall probability of health as high as possible with any health criterion, high or low. The health probability should decrease as the unit FOR increases as shown by the two profiles.

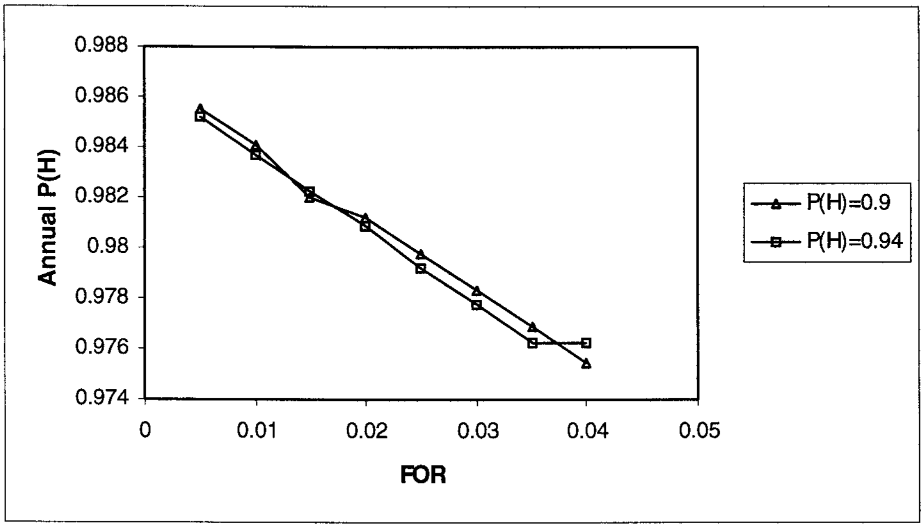

Figure 4.4: Annual probability of health with health criteria of 0.9 and 0.94

A basic study was conducted on the RTS to show that the health levelization technique is also applicable to large systems. The weekly P(H) was set at 0.85 and an MNU of 4 was used in this study. The FOR for unit 30 (350 MW) was varied from 0.02 to 0.14 with a step size of 0.02. The same load model applied to the RBTS was used with a peak load of 2850 MW. The resulting RTS maintenance schedule using the health levelization technique is shown in Table 4.3.

As can be seen from the table that most of the weeks contain generating units on maintenance. This is due to the system size, which is relatively large. It can also be seen that most of the generating units are scheduled during the off peak periods.

The scheduling becomes more difficult with increase in the FOR for unit 30. The system reliability decreases as the unit FOR increases, as shown in the last row in Table 4.3.

Table 4.3: Maintenance schedules for the RTS with a peak load of 2850 MW and a P(H) of 0.85.

Plan FOR	Plan # 1 0.02	Plan # 2 0.04	Plan # 3 0.06	Plan # 4 0.08
WEEK				
1	1	2	3	3
2	1	2	3	3
3	NIL	NIL	NIL	NIL
4	14,6,2	14,6,3	14,6,5	16,1
5	14,6,2	14,6,3	14,6,5	16,1
6	16	16,1	16,2	17,16
7	17,16	17,16,1	17,16,2	23,17
8	20,17,16	20,17,16	20,17,16	23,17
9	26,24,20,17	26,24,20,17	26,24,20,17	23,22,13
10	26,24,20	26,24,20	26,24,20	28,23,22,13
11	30,26,24	30,26,24	30,26,24	31,28,22
12	30,26,24	30,26,24	30,26,24	31,28
13	31,30	31,30	31,30	31,28
14	31,30	31,30	31,30	31,12,8
15	31,30	31,30	31,30	31,21,12,8
16	31	31	31	31,21
17	31,7,3	31,7	31	26,21,7,4
18	31,7,3	31,7	31	26,7,4
19	NIL	NIL	NIL	26
20	NIL	NIL	NIL	26
21	9,5,4	9,5,4	9,7,4	11
22	18,9,5,4	18,9,5,4	18,9,7,4	20,11
23	18	18	18	20
24	18	18	18	20
25	NIL	NIL	NIL	NIL
26	8	8	8	9,6
27	25,19,13,8	25,19,13,8	25,19,13,8	27,18,9,6
28	25,19,13	25,19,13	25,19,13	27,18
29	25,19	25,19	25,19	27,18
30	25	25	25	27
31	27,23,10	27,23,10	27,23,10,1	29,24,10
32	27,23,10	27,23,10	27,23,10,1	29,24,10
33	27,23	27,23	27,23	29,24
34	27,23,12	27,23,12	27,23,12	29,25,24
35	28,22,15,12	28,22,15,12	28,22,15,12	25,15,14
36	29,28,22,15	29,28,22,15	29,28,22,15	30,25,15,14
37	29,28,22	29,28,22	29,28,22	30,25
38	32,29,28	32,29,28	32,29,28	32,30,2
39	32,29	32,29	32,29	32,30,2
40	32,21,11	32,21,11	32,21,11	32,30
41	32,21,11	32,21,11	32,21,11	32,19,5
42	32,21	32,21	32,21	32,19,5
43	32	32	32	32,19
44-52	NIL	NIL	NIL	NIL
P(H)	0.931152	0.926626	0.922052	0.918893

Table 4.3: (Continued).

Plan FOR	Plan # 5 0.1	Plan # 6 0.12	Plan # 7 0.14
WEEK			
1	NIL	NIL	NIL
2	NIL	NIL	NIL
3	NIL	NIL	NIL
4	17	17	18
5	17	17	18
6	18,17	18,17	23,18
7	23,18	23,18	24,23
8	23,18	23,18	24,23
9	23,22,12	23,22,12	24,23,17
10	28,23,22,12	28,23,22,12	28,24,17
11	31,28,22	31,28,22	31,28,17
12	31,28	31,28	31,28
13	31,28	31,28	31,28
14	31,11,7	31,11,3	31,12,5
15	31,21,11,7	31,21,11,3	31,19,12,5
16	31,21	31,21	31,19
17	26,21,5,2	26,21,4,2	25,19,11
18	26,5,2	26,21,4,2	25,11
19	26	26	25
20	26	26	25
21	9,6,1	9,5,1	8,7,2
22	20,9,6,1	20,9,5,1	20,8,7,2
23	20	20	20
24	20	20	20
25	NIL	NIL	NIL
26	8,4	16	16
27	27,19,8,4	27,19,16	26,21,16
28	27,19	27,19,16	26,21,16
29	27,19	27,19	26,21
30	27	27	26
31	29,24,16	29,24,8,6	29,27,4,1
32	29,24,16	29,24,8,6	29,27,4,1
33	29,24,16	29,24	29,27
34	29,25,24	29,25,24	29,27,6
35	25,15,14	25,15,14	22,15,14,6
36	30,25,15,14	30,25,15,14	30,22,15,14
37	30,25	30,25	30,22
38	32,30,3	32,30,7	32,30,10
39	32,30,3	32,30,7	32,30,10
40	32,30	32,30	32,30
41	32,13,10	32,13,10	32,13,9,3
42	32,13,10	32,13,10	32,13,9,3
43	32	32	32
44-52	NIL	NIL	NIL
P(H)	0.913986	0.909656	0.904881

In order to overcome the increase in the FOR and construct a maintenance schedule that will satisfy the desired criterion and constraints, some generating units are moved to other periods in order to improve the system reliability. It can be seen from Table 4.3 that the largest units rarely change their locations due to the difficulties in scheduling these units.

4.2.2. Risk levelization

The effect of the variation in the FOR of unit 9 in the RBTS was examined using the risk levelization approach. The MNU was held at 3 and the FOR varied from 0.005 to 0.04 with a step of 0.005. Table 4.4 shows that in using the risk levelization technique, the weeks, 1 to 8, 17 to 30, 33 and 44 to 52 are not used for scheduled maintenance because they are high load periods.

Table 4.4: Maintenance schedule for the RBTS with a Peak Load of 185 MW and the LOLE = 1/52 days/week

FOR	0.005 - 0.04
WEEK	Units on Maints.
1-8	NIL
9	2
10	4,2
11	8,4
12	8
13	10
14	10
15	3
16	3
17-30	NIL
31	5
32	5
33	NIL
34	6
35	6
36	9
37	9
38	11
39	11
40	7
41	7
42	1
43	1
44-52	NIL
LOLE(d/y)	0.073878 – 0.205740

The maintenance plan shown in Table 4.4 is applicable with all of the FOR values in the given range because it can sustain the increase in FOR and still satisfying the risk level. The last row of the table shows that the risk increases as the FOR increases. This is shown pictorially in Figure 4.5.

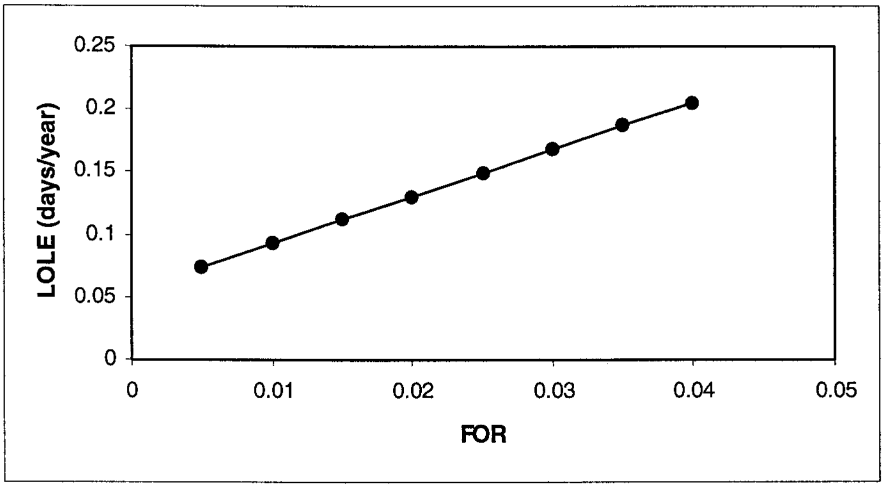

Figure 4.5: Variation in the annual LOLE with FOR variation for a LOLE of 1/52 days/week

Figure 4.6 shows three different profiles of the weekly LOLE for three FOR values. The LOLE of all weeks with units out for maintenance are held below the 1/52 risk level except for week 51 with a FOR of 0.04 where it crosses the risk criterion line. The weekly risk from week 48 to the end of the year steadily increases due to the shape of the load model. No units are scheduled for maintenance in these weeks.

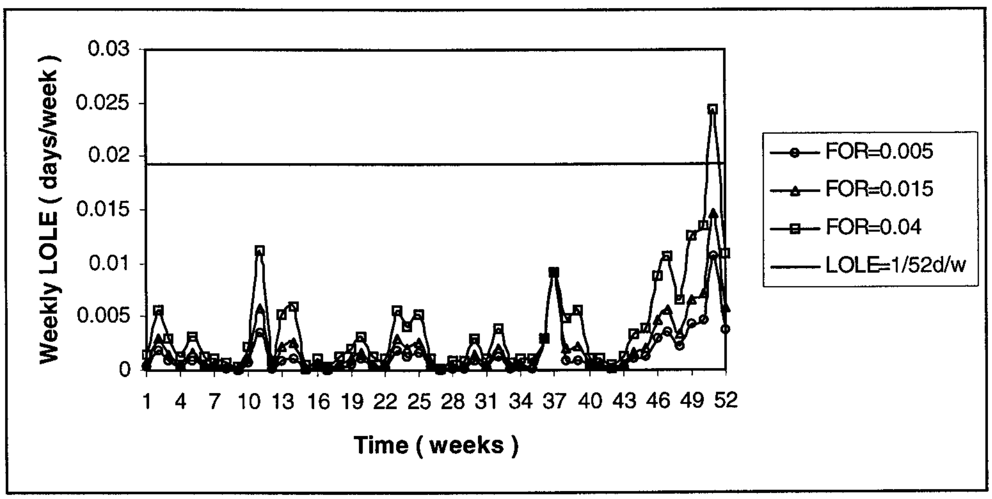

Figure 4.6: The effect of different FOR on the weekly P(H) and the maintenance schedules with LOLE = 1/52 days/week.

Table 4.5 shows a comparison between plans constructed with LOLE = 0.2/52 days/week and LOLE = 1/52 days/week for three different FOR values. There are two common phenomena in the plans created using the two risk criteria.

Table 4.5: Maintenance schedule for the RBTS with a Peak Load of 185 MW and the LOLE = (0.2/52) and (1/52) days/week.

	FOR = 0.005		FOR = 0.025		FOR = 0.04	
	LOLE= 0.2/52	LOLE= 1/52	LOLE= 0.2/52	LOLE= 1/52	LOLE= 0.2/52	LOLE= 1/52
WEEK	Plan # 1	Plan #2	Plan # 3	Plan # 4	Plan #5	Plan # 6
1-8	NIL	NIL	NIL	NIL		NIL
9	1	2	4	2		2
10	2,1	4,2	4	4,2		4,2
11	9,2	8,4	10	8,4		8,4
12	9	8	10	8		8
13	10	10	9	10		10
14	10	10	9	10		10
15	3	3	3	3		3
16	3	3	3	3		3
17-26	NIL	NIL	NIL	NIL		NIL
27	NIL	NIL	1	NIL		NIL
28	NIL	NIL	1	NIL		NIL
29-30	NIL	NIL	NIL	NIL	It was not	NIL
31	4	5	5	5	possible	5
32	4	5	5	5	to create a	5
33	NIL	NIL	NIL	NIL	maintenance	NIL
34	5	6	6	6	schedule	6
35	7,5	6	6	6		6
36	8,7	9	8	9		9
37	8	9	8	9		9
38	11	11	11	11		11
39	11	11	11	11		11
40	6	7	7	7		7
41	6	7	7	7		7
42	NIL	1	2	1		1
43	NIL	1	2	1		1
44-52	NIL	NIL	NIL	NIL		NIL
LOLE (d/y)	0.071842	0.073878	0.138284	0.149227		0.205740

The first common factor is that both criteria create plans that have no maintenance in them during weeks, 1 to 8, 17 to 26, 29 to 30 and 44 to 52. These periods are high load periods and having any units out during these periods will drive the system risk up significantly. The other common element is that unit 11 retains its position in all the maintenance plans. This is not the case with units 9 and 10. Units 9 and 10 stay in one location in the plans constructed with the higher risk criterion. In the plans constructed with the lower risk criterion, units 9 and 10 move to different periods as the FOR increases. The reasons for this are that either, the criterion order of the weeks changed as the FOR increased or that the LOLE evaluated for week 14 violated the risk criterion and therefore the next week in the criterion order was considered. Table 4.5 shows that it was not possible to create an acceptable maintenance schedule with a FOR of 0.04 using the low risk criterion. The last row in Table 4.5 shows that the annual risk is higher in the plans constructed using the higher weekly risk criterion.

Figure 4.7 shows the weekly risk profiles for the maintenance plans constructed using the two weekly risk criteria. The two risk profiles shown in Figure 4.7 are identical for the weeks without maintenance.

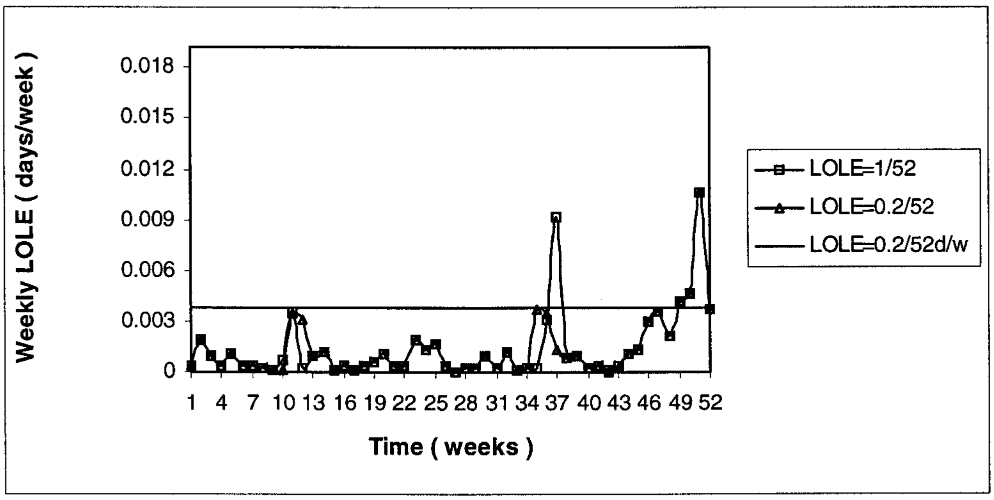

Figure 4.7: The weekly risk variation for LOLE=1/52 and 0.2/52 days/week with FOR = 0.005

Figure 4.8 shows the annual risk for the two different risk criteria with variability in the FOR of unit 9. The two risk values are very close for the low FOR. Reorganizing the weekly criterion list creates two highly reliable maintenance plans with either criterion in this case.

The LOLE = 0.2/52 profile stopped at FOR = 0.25 because it was not possible to construct a maintenance schedule with higher FOR values.

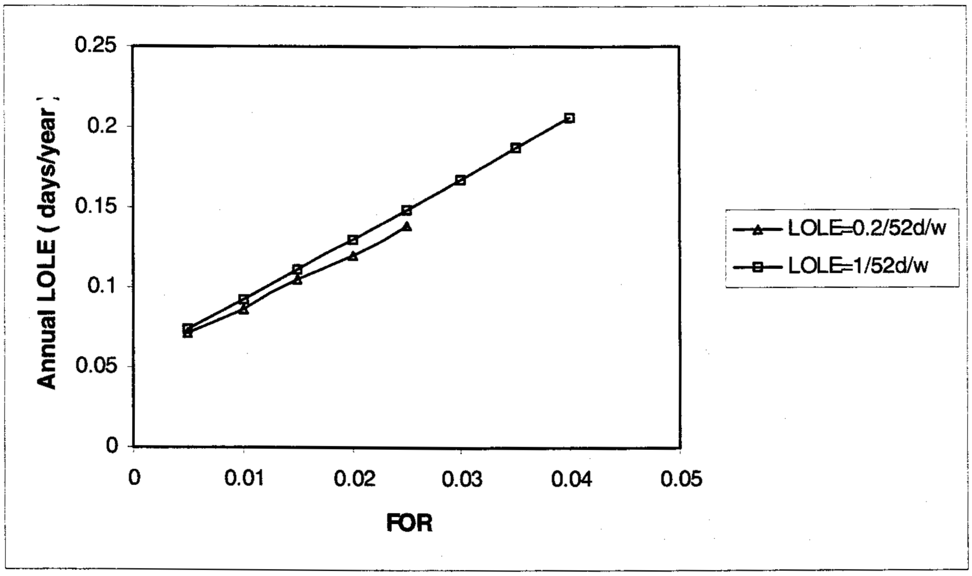

Figure 4.8: The change in the risk with LOLE = 0.2/52 and 1/52 days/week.

A basic maintenance scheduling study was conducted on the RTS using the risk levelization technique. A LOLE of 0.1 days/week was used as the weekly criterion. The MNU was held at 4 and the FOR for Unit 30 was varied from 0.02 to 0.14 with a step of 0.02. The schedules obtained are shown in Table 4.6.

As with the previous plans, most of the units are scheduled during the low load periods. The schedules shown in Table 4.6 can be compared with those shown in Table 4.3. There are a number of general similarities but the two sets of plans are not identical. In order to overcome the increase in FOR, some units move from one period to another period in order to levelize the risk level. Most of the large units in the system do not move due to the difficulty of finding a suitable time during the year for them to be taken out for maintenance. As expected, the annual LOLE increases with the increase in the FOR for unit 30.

Table 4.6: Maintenance Schedules for the RTS with a Peak Load of 2850 MW and a LOLE of 0.1 days/week.

Plan FOR	Plan # 1 0.02	Plan # 2 0.04	Plan # 3 0.06	Plan # 4 0.08
WEEK				
1	NIL	NIL	NIL	3
2	NIL	NIL	NIL	3
3	NIL	NIL	NIL	NIL
4	10,2	13,5,2	13,5,2	14,6,4
5	10,2	13,5,2	13,5,2	14,6,4
6	11	14,4,1	16	16,1
7	14,11	17,14,4,1	17,16	17,16,1
8	19,15,14	20,17	20,17,16	21,17,16
9	26,21,19,15	26,24,20,17	26,24,20,17	26,24,21,17
10	26,22,21,19	26,24,20	26,24,20	26,24,21
11	30,26,22,21	30,26,24	30,26,24	30,26,24
12	30,26,22	30,26,24	30,26,24	30,26,24
13	31,30	31,30	31,30	31,30
14	31,30	31,30	31,30	31,30
15	31,30	31,30	31,30	31,30
16	31	31	31	31
17	31,12	31,10	31,9,7,1	31,9
18	31,12	31,10	31,9,7,1	31,9
19	NIL	NIL	NIL	NIL
20	NIL	NIL	NIL	NIL
21	4,1	7,3	8,4	10
22	17,4,1	18,7,3	18,8,4	18,10
23	17	18	18	18
24	17	18	18	18
25	NIL	NIL	NIL	NIL
26	NIL	6	6	7
27	25,18,8,6	25,19,11,6	25,19,12,6	25,20,8,7
28	25,18,8,6	25,19,11	25,19,12	25,20,8
29	25,18	25,19	25,19	25,20
30	25	25	25	25
31	27,20,16,3	27,23,9,8	27,23,10	27,23,11,2
32	27,20,16,3	27,23,9,8	27,23,10	27,23,11,2
33	27,20,16	27,23	27,23	27,23
34	27,23,9	27,23,12	27,23,11	27,23,12
35	28,23,13,9	28,22,15,12	28,22,15,11	28,19,15,12
36	29,28,23,13	29,28,22,15	29,28,22,15	29,28,19,15
37	29,28,23	29,28,22	29,28,22	29,28,19
38	32,29,28	32,29,28	32,29,28	32,29,28
39	32,29	32,29	32,29	32,29
40	32,24,7,5	32,21,16	32,21,14,3	32,22,13,5
41	32,24,7,5	32,21,16	32,21,14,3	32,22,13,5
42	32,24	32,21,16	32,21	32,22
43	32,24	32	32	32
44-52	NIL	NIL	NIL	NIL
LOLE(d/y)	1.801519	1.996776	2.267925	2.517775

Table 4.6: (Continued).

Plan FOR	Plan # 5 0.1	Plan # 6 0.12	Plan # 7 0.14
WEEK			
1	5	NIL	NIL
2	5	NIL	NIL
3	NIL	NIL	NIL
4	14,7,6	17	17
5	14,7,6	17	17
6	16,2	18,17	18,17
7	17,16,2	19,18	24,18
8	21,17,16	23,19,18	24,18
9	26,24,21,17	23,19,13,10	24,21,12
10	26,24,21	27,23,13,10	27,24,21,12
11	30,26,24	31,27,23	31,27,21
12	30,26,24	31,27	31,27
13	31,30,	31,27	31,27
14	31,30	31,11,6	31,11,5
15	31,30	31,22,11,6	31,20,11,5
16	31	31,22	31,20
17	31	25,22,1	22,20,10,3
18	31	25,1	22,10,3
19	1	25	22
20	1	25	NIL
21	10	7	7,2,1
22	18,10	20,7	19,7,2,1
23	18	20	19
24	18	20	19
25	NIL	NIL	NIL
26	8	2	23
27	25,20,9,8	26,21,16,2	26,23
28	25,20,9	26,21,16	26,23
29	25,20	26,21,16	26,23
30	25	26	26
31	27,23,11,3	28,24,8,5	28,25,8,6
32	27,23,11,3	28,24,8,5	28,25,8,6
33	27,23	28,24	28,25
34	27,23,13	29,28,24	29,28,25
35	28,19,15,13	29,15,14	29,15,14
36	29,28,19,15	30,29,15,14	30,29,15,14
37	29,28,19	30,29	32,29
38	32,29,28	32,30,4	32,30,16
39	32,29	32,30,4	32,30,16
40	32,22,12,4	32,30	32,30,16
41	32,22,12,4	32,12,9,3	32,13,9,4
42	32,22	32,12,9,3	32,13,9,4
43	32	32	32
44-52	NIL	NIL	NIL
LOLE(d/y)	2.783052	3.095484	3.345181

4.3. Effect on the maintenance schedule of the maximum number of units (MNU) out for maintenance in a single week

The initial value for the MNU was chosen to be 3 i.e. the maximum number of units allowed out for maintenance in any single week is three units. This value was used earlier to illustrate the four developed techniques. The MNU depends on the size of the system and maintenance crew availability.

If the system under study is relatively small, the MNU will likely also be a small value. If the system is relatively large, then the MNU should not be too small or it will not be possible to perform the required maintenance.

The availability of maintenance personnel is a major factor in the determination of the MNU. If the number of available people is high then the MNU can be a high value and if there are relatively few qualified people then the MNU will be small.

It may not be possible to achieve the selected reliability criterion because of limitations in the maintenance personnel. Two obvious possibilities arise in this case, either accept a lower level of system reliability or hire more maintenance people, which will cost more. This is an interesting economic decision.

4.3.1. Health levelization

The effect on the RBTS of changing the MNU was examined using the health levelization technique. The MNU was varied from 1 to 5. Table 4.7 shows three maintenance plans using a health criterion of 0.9. The FOR for unit 9 was held at its original value of 0.02 in this study. The maintenance plans constructed with MNU = 4 and 5 are identical to the one with MNU = 3.

In all the plans shown in Table 4.7, there are four common periods in which no maintenance is performed, i.e. weeks, 1 to 8, 17 to 26, 29 to 30 and 44 to 52. As the MNU increases, fewer weeks are required to perform the required maintenance.

The three largest units in the system stay in the same time slot in the all three plans. Each one of the three units is removed for maintenance in different periods and there is no overlapping of their maintenance periods.

Table 4.7: Maintenance Schedules for the RBTS with a peak load of 185 MW and a P(H) of 0.9.

Plan MNU	Plan # 1 1	Plan # 2 2	Plan # 3 3
WEEK			
1-8	NIL	NIL	NIL
9	3	2	2
10	3	5,2	5,2
11	8	8,5	8,5
12	8	8	8
13	10	10	10
14	10	10	10
15	4	3	3
16	4	3	3
17-26	NIL	NIL	NIL
27	1	NIL	NIL
28	1	NIL	NIL
29-30	NIL	NIL	NIL
31	6	6	6
32	6	6	6
33	NIL	NIL	NIL
34	5	4	4
35	5	4	4
36	9	9	9
37	9	9	9
38	11	11	11
39	11	11	11
40	7	7	7
41	7	7	7
42	2	1	1
43	2	1	1
44-52	NIL	NIL	NIL
P(H)	0.981573	0.981202	0.981202

Plans 2 and 3 are identical, even though they involve different values of MNU. A maintenance plan will change as the MNU is increased until it reaches a point at which it remains constant regardless of further increase in the MNU. The last row of Table 4.7 shows that in this example, as the MNU increases, the system health decreases. This is illustrated in Figure 4.9.

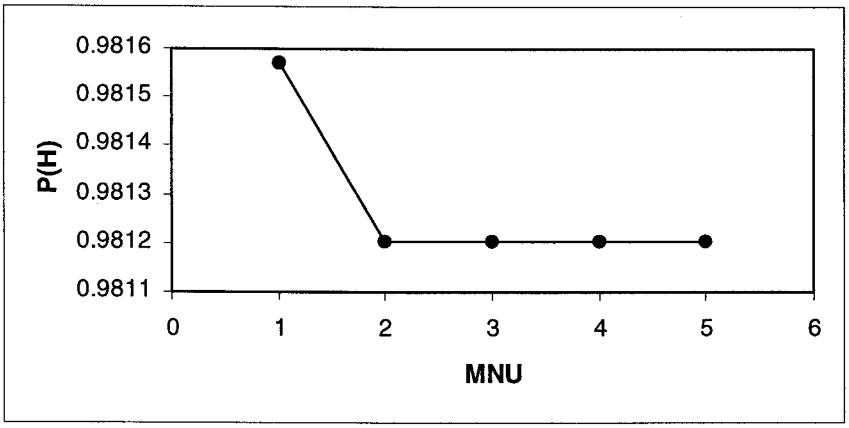

Figure 4.9: Variation in the annual P(H) with respect to MNU variation for a weekly health criterion of 0.9.

Figure 4.10 shows the weekly P(H) for two different values of MNU. The two profiles are above the desired health level of 0.9.

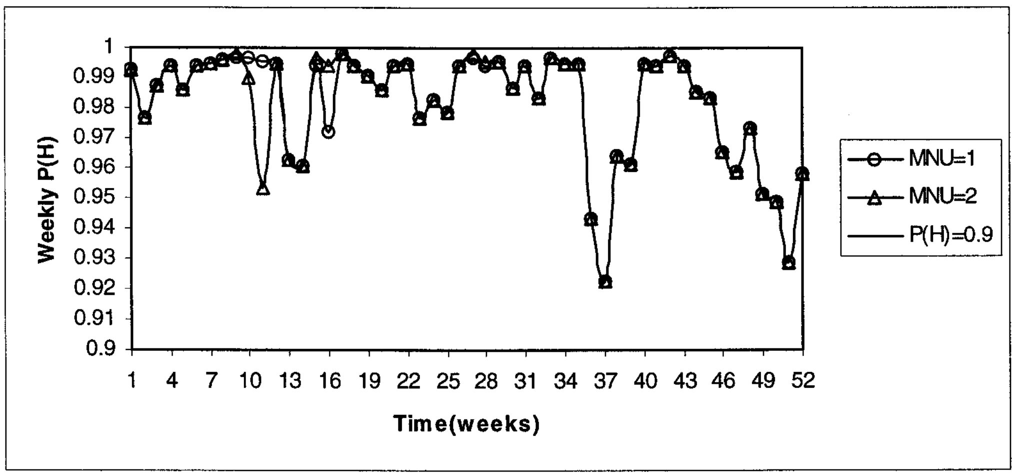

Figure 4.10: The effect of different MNU on the weekly P(H) and the maintenance scheduling with P(H) = 0.9.

The profiles with MNU=1 and 2 are very similar in spite of the fact that the maintenance plans are different. They have obviously the same weekly P(H) for the weeks which do not have any units out for maintenance. The two plans are identical for most of the weeks. The only differences are in the first low load period weeks as shown in Table 4.7.

Table 4.8 shows a series of maintenance schedules for the RBTS using MNU values of 1, 2 and 3 and P(H) values of 0.9 and 0.94. Table 4.8 shows four common periods without maintenance in all the plans, weeks 1 to 8, 19 to 26, 33, and 44 to 52. Units 10 and 11 occupy weeks 13, 14 and 38, 39 respectively in all of the plans. Unit

9 took week 36 as a base point and then fluctuated around it in weeks 35 and 37. These units are the three largest units in the system and should occupy the weeks with the highest health.

Table 4.8: Maintenance schedule for the RBTS with a Peak Load of 185 MW and P(H) of 0.9 & 0.94.

	MNU=1		MNU = 2		MNU = 3	
	P(H)= 0.9	P(H)= 0.94	P(H)= 0.9	P(H)= 0.94	P(H)= 0.9	P(H)= 0.94
WEEK	Plan # 1	Plan #2	Plan # 3	Plan # 4	Plan #5	Plan # 6
1-8	NIL	NIL	NIL	NIL	NIL	NIL
9	3	4	2	3	2	3
10	3	4	5,2	5,3	5,2	5,3
11	8	8	8,5	8,5	8,5	8,5
12	8	8	8	8	8	8
13	10	10	10	10	10	10
14	10	10	10	10	10	10
15	4	5	3	4	3	4
16	4	5	3	4	3	4
17	NIL	1	NIL	NIL	NIL	NIL
18	NIL	1	NIL	NIL	NIL	NIL
19-26	NIL	NIL	NIL	NIL	NIL	NIL
27	1	2	NIL	NIL	NIL	NIL
28	1	2	NIL	NIL	NIL	NIL
29-30	NIL	NIL	NIL	NIL	NIL	NIL
31	6	6	6	6	6	6
32	6	6	6	6	6	6
33	NIL	NIL	NIL	NIL	NIL	NIL
34	5	NIL	4	2	4	2
35	5	9	4	9,2	4	9,2
36	9	9	9	9	9	9
37	9	NIL	9	NIL	9	NIL
38	11	11	11	11	11	11
39	11	11	11	11	11	11
40	7	7	7	7	7	7
41	7	7	7	7	7	7
42	2	3	1	1	1	1
43	2	3	1	1	1	1
44-52	NIL	NIL	NIL	NIL	NIL	NIL
P(H)	0.981573	0.981855	0.981202	0.980908	0.981202	0.980908

The same number of weeks is occupied in Plans 1 and 2 as the weekly criterion does not have much effect on the system health with MNU = 1. Having only one unit out for maintenance at any time will keep the system health at a relatively high level with any value of P(H). Plans 4 and 6 are identical for the different MNU values. This is the same phenomenon discussed earlier with P(H)=0.9.

Figure 4.11 shows the variation in weekly system health. The P(H) = 0.94 profile is always above the 0.94 line except in week 51. In this week, the load is at its annual peak value and there are no units removed for maintenance.

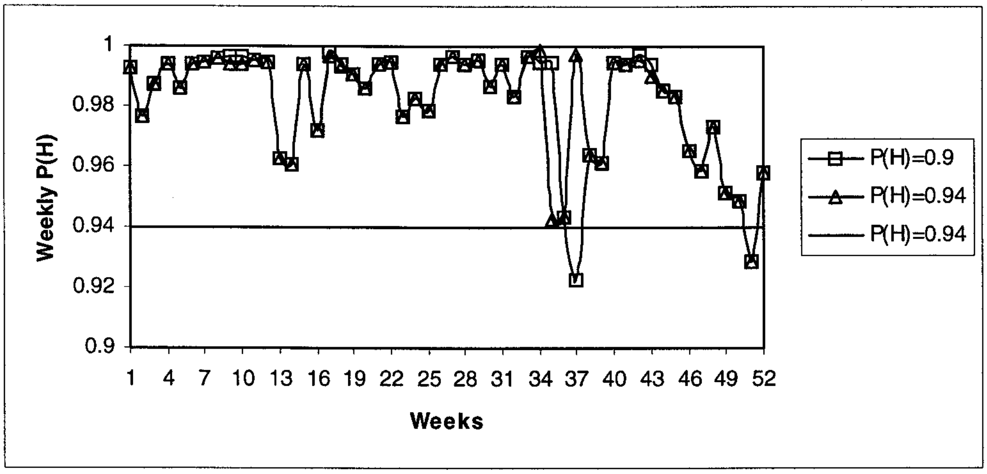

Figure 4.11: The weekly health variation for P(H)=0.9 and 0.94 with MNU = 1.

The P(H) = 0.9 profile is above the desired health level for the whole year even in week 51 as the P(H) in this week is 0.92. Figure 4.11 also shows that the P(H) = 0.94 criterion is violated in week 51.

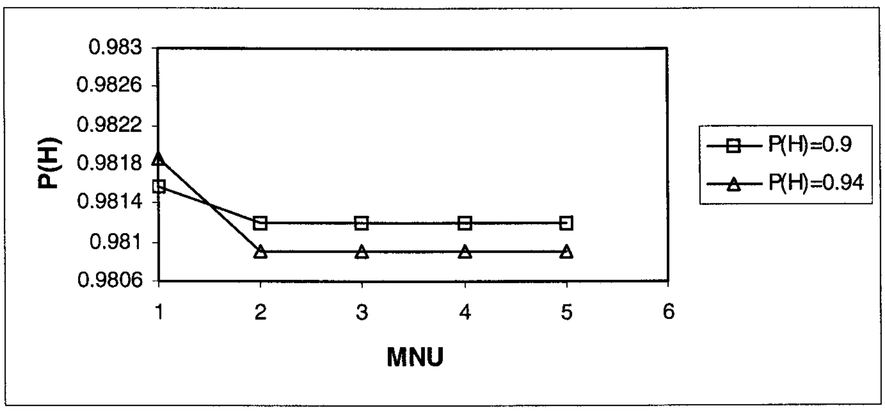

Figure 4.12: The annual health with weekly P(H) = 0.9 and 0.94 with variable MNU.

Figure 4.12 shows that the maintenance schedules created using a weekly P(H) of 0.94 give a higher annual system health than do the maintenance schedules created using a P(H) of 0.9 with MNU = 1. This is reversed as the MNU increases.

The effect of changing the MNU was examined for the RTS. The FOR for unit 30 was held at its original value and the MNU varied from 3 to 6. The maintenance schedules obtained under these conditions are shown in Table 4.9. A probability of health of 0.85 was used as a criterion.

It can be seen from Table 4.9 that most of the generating units are scheduled during the off peak periods as noted earlier. The MNU started at 3, as it is not possible to create a maintenance schedule with a lower MNU that can satisfy the desired criterion. The last row in the table shows the annual probability of health for the constructed plans and it is clear that the differences are very small. The reason is that most of the large units in the system are holding the same positions in all of the plans and only the smaller units move from one period to another. Movement of the small units does not have much effect on the overall reliability of the system.

Table 4.9: Maintenance Schedules for the RTS with a Peak Load of 2850 MW and P(H) of 0.85.

Plan MNU	Plan # 1 3	Plan # 2 4	Plan # 3 5	Plan #4 6
WEEK				
1	8,2,1	3	NIL	NIL
2	8,2,1	3	NIL	NIL
3	4	NIL	NIL	NIL
4	16,6,4	16,1	16	16
5	16,6	16,1	16	16
6	17,16	17,16	17,16	17,16
7	23,17	23,17	23,17	23,17
8	23,17	23,17	23,17	23,17
9	23,22	23,22,13	23,22,12,10	23,22,12,10
10	28,23,22	28,23,22,13	28,23,22,12,10	28,23,22,12,10
11	31,28,22	31,28,22	31,28,22	31,28,22
12	31,28	31,28	31,28	31,28
13	31,28,3	31,28	31,28	31,28
14	31,14,3	31,12,8	31,11,5	31,11,4
15	31,21,14	31,21,12,8	31,21,11,5	31,21,11,4
16	31,21	31,21	31,21	31,21
17	26,21,10	26,21,7,4	26,21,4	26,21,3
18	26,10	26,7,4	26,4	26,3
19	26	26	26	26
20	26	26	26	26
21	13,5	11	9,3	8,2
22	20,13,5	20,11	20,9,3	20,8,2
23	20	20	20	20
24	20	20	20	20

Table 4.9: (Continued).

Plan MNU	Plan # 1 3	Plan # 2 4	Plan # 3 5	Plan #4 6
WEEK				
25	NIL	NIL	NIL	NIL
26	11	9,6	7,2	6,1
27	27,18,11	27,18,9,6	27,18,7,2	27,18,6,1
28	27,18	27,18	27,18	27,18
29	27,18	27,18	27,18	27,18
30	27	27	27	27
31	29,24,12	29,24,10	29,24,8,6,1	29,24,7,5
32	29,24,12	29,24,10	29,24,8,6,1	29,24,7,5
33	29,24	29,24	29,24	29,24
34	29,25,24	29,25,24	29,25,24	29,25,24
35	25,15	25,15,14	25,15,14,13	25,15,14,13,9
36	30,25,15	30,25,15,14	30,25,15,14,13	30,25,15,14,13,9
37	30,25	30,25	30,25	30,25
38	32,30,7	32,30,2	32,30	32,30
39	32,30,7	32,30,2	32,30	32,30
40	32,30	32,30	32,30	32,30
41	32,19,9	32,19,5	32,19	32,19
42	32,19,9	32,19,5	32,19	32,19
43	32,19	32,19	32,19	32,19
44-52	NIL	NIL	NIL	NIL
P(H)	0.918951	0.918893	0.918611	0.918609

4.3.2. Risk levelization

The MNU effect on the maintenance plan for the RBTS was examined using the risk levelization technique. The MNU was varied from 1 to 5 and the FOR of unit 9 was held at 0.02. Table 4.10 shows three maintenance plans constructed with the MNU of 1,2 and 3. The plans constructed with the MNU of 4 and 5 are identical to the plan constructed with MNU=3.

As usual, there are many common periods without maintenance in the three plans shown in Table 4.10. These periods are 1 to 8 , 17 to 26 , 29 to 30 , 33 and 44 to 52. As the MNU increases, more units are scheduled to be taken out in the same week and as a result the number of occupied weeks decreases.

Plans 2 and 3 are identical despite having different MNU values. As the MNU increases, more units will be scheduled in a single week until it reaches a point at which it does not matter what the MNU value is.

Table 4.10: Maintenance Schedules for the RBTS with a Peak Load of 185 MW and a LOLE of 1/52 days/week.

Plan MNU	Plan # 1 1	Plan # 2 2	Plan # 3 3
WEEK			
1-8	NIL	NIL	NIL
9	3	2	2
10	3	4,2	4,2
11	8	8,4	8,4
12	8	8	8
13	10	10	10
14	10	10	10
15	4	3	3
16	4	3	3
17-26	NIL	NIL	NIL
27	1	NIL	NIL
28	1	NIL	NIL
29-30	NIL	NIL	NIL
31	5	5	5
32	5	5	5
33	NIL	NIL	NIL
34	6	6	6
35	6	6	6
36	9	9	9
37	9	9	9
38	11	11	11
39	11	11	11
40	7	7	7
41	7	7	7
42	2	1	1
43	2	1	1
44-52	NIL	NIL	NIL
LOLE(d/y)	0.127461	0.130389	0.130389

In the RBTS studies, as the MNU increases, the overall system risk also increases. This is due to the selection of the criterion risk and the increased flexibility with increasing MNU. The last row of Table 4.10 shows how the system LOLE increases with increased MNU. This is shown pictorially in Figure 4.13.

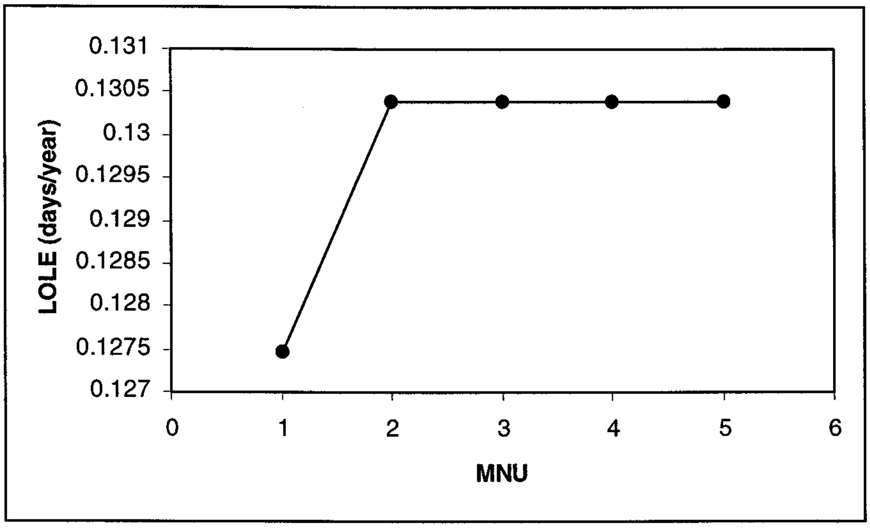

Figure 4.13: Variation in the yearly LOLE with respect to MNU variation for a chosen risk criterion of 1/52 days/week.

Figure 4.14 shows the two weekly risk profiles for MNU values of 1 and 2. The criterion risk is 1/52 days/week. Both profiles are below the 1/52 line for all weeks in the year. The two profiles increase in weeks 41 to 51 due to the load model shape and no units are removed for maintenance during this period. The two profiles become a single profile during the weeks without maintenance.

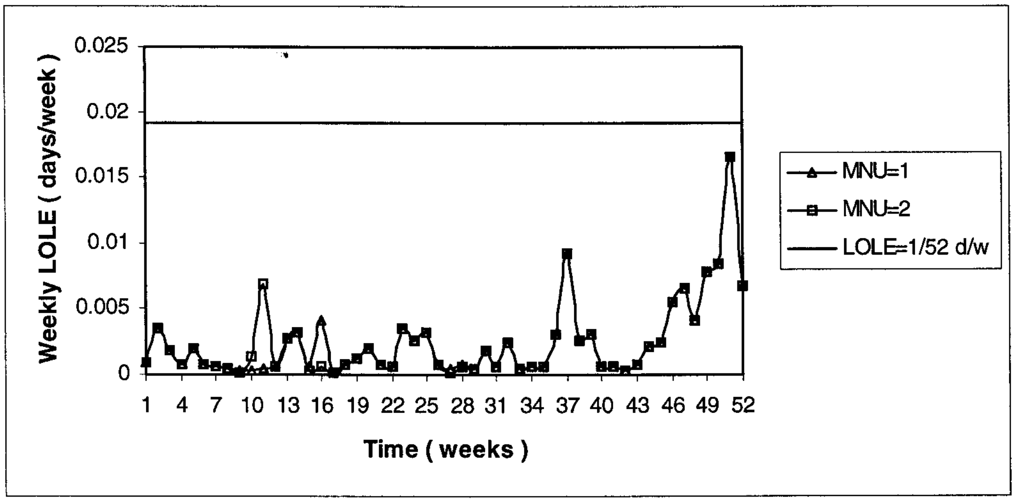

Figure 4.14: The effect of different MNU on the weekly LOLE with LOLE = 1/52 days/week.

Table 4.11 shows the plans constructed with LOLE values of 0.2/52 and 1/52 days/week with variable MNU.

Table 4.11: Maintenance schedule for the RBTS with a Peak Load of 185 MW and LOLE of 0.2/52 and 1/52 days/week.

	MNU=1		MNU = 2		MNU = 3	
	LOLE= 0.2/52	LOLE= 1/52	LOLE= 0.2/52	LOLE= 1/52	LOLE= 0.2/52	LOLE=1/52
WEEK	Plan # 1	Plan #2	Plan # 3	Plan # 4	Plan #5	Plan # 6
1-8	NIL	NIL	NIL	NIL	NIL	NIL
9	4	3	4	2	4	2
10	4	3	4	4,2	4	4,2
11	9	8	9	8,4	9	8,4
12	9	8	9	8	9	8
13	10	10	10	10	10	10
14	10	10	10	10	10	10
15	3	4	3	3	3	3
16	3	4	3	3	3	3
17-26	NIL	NIL	NIL	NIL	NIL	NIL
27	1	1	1	NIL	1	NIL
28	1	1	1	NIL	1	NIL
29-30	NIL	NIL	NIL	NIL	NIL	NIL
31	5	5	5	5	5	5
32	5	5	5	5	5	5
33	NIL	NIL	NIL	NIL	NIL	NIL
34	6	6	6	6	6	6
35	6	6	6	6	6	6
36	8	9	8	9	8	9
37	8	9	8	9	8	9
38	11	11	11	11	11	11
39	11	11	11	11	11	11
40	7	7	7	7	7	7
41	7	7	7	7	7	7
42	2	2	2	1	2	1
43	2	2	2	1	2	1
44-52	NIL	NIL	NIL	NIL	NIL	NIL
LOLE (d/y)	0.120111	0.127461	0.120111	0.130389	0.120111	0.130389

It can be seen from Table 4.11 that the maintenance plans constructed with the lower risk criterion are identical, which is not the case with the higher risk criterion. The selection of a lower risk criterion results in fewer options for the generating units to move around. It also can be observed from Table 4.11 that the plans constructed with the lower risk criterion have lower annual risk than the plans constructed with the higher risk criterion.

Figure 4.15 shows the two risk profiles for the criterion risk levels of 1/52 and 0.2/52 days/week. The two risk profiles are the same for the weeks which have no units out for maintenance. The risk profile using the LOLE = 1/52 days/week for those weeks which have units out for maintenance is higher than the risk profile with the LOLE= 0.2/52 days/week.

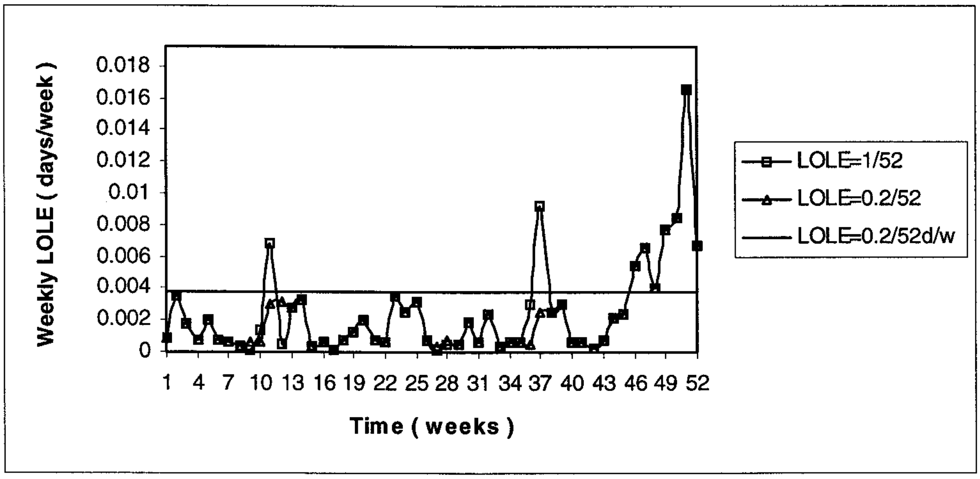

Figure 4.15: Weekly health for LOLE=0.2/52 and 1/52 days/week with the MNU = 2.

The risk in week 51 where no units are taken out for maintenance is very close to the 1/52 risk level. If the selected risk criterion is less than the risk in week 51 then the criterion will be violated in this week, as is the case with the 0.2/52 risk criterion. This criterion is violated not only in week 51 but in all weeks from 47 to 52.

The annual risk shown in Figure 4.16 for the criterion risk of 0.2/52 is constant with increasing MNU. This is not the case with the criterion risk of 1/52. That is due to the tighter constraint created by the lower risk level, which forces the generating units to take the best locations in order to achieve this level, no matter what the value of MNU.

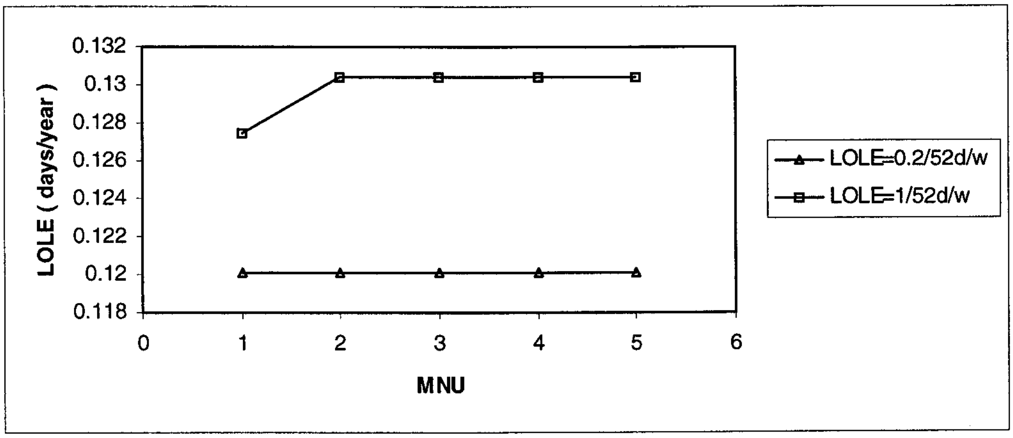

Figure 4.16: Variation in the annual risk with MNU.

The effect on the RTS of the change in the MNU using the risk levelization technique is illustrated using a LOLE of 0.1 days/week as a criterion. The schedules obtained are presented in Table 4.12.

Table 4.12 shows four maintenance plans. The Plan constructed with MNU = 7 is not shown in the table because it is identical to the plan constructed with MNU = 6. The MNU variation in Table 4.12 starts with MNU = 3. There are no maintenance plans which can satisfy the constraints with MNU = 1 and 2. For MNU = 1, it is not possible to construct a maintenance plan because there are only 52 weeks in the year and in order to have only one unit out for maintenance in a single week the schedule will require 96 weeks. It is not possible to satisfy constraints with MNU = 2. The constructed plans stabilize at an MNU value of 6.

Most of the large units or the units that need more weeks for maintenance retain their location with increased MNU due to the difficulty of finding consecutive weeks that satisfy all of the conditions and constraints. The smaller units therefore tend to move from period to period with increase in the MNU.

Most weeks are occupied by generating units because of the size of the system. Another observation seen from the table is that most of the generating units are scheduled for maintenance during the two low load periods.

Table 4.12: Maintenance schedules for the RTS with a peak load of 2850 MW and the LOLE = 0.1 days/week.

Plan MNU	Plan # 1 3	Plan # 2 4	Plan # 3 5	Plan #4 6
WEEK				
1	8,3	3	NIL	NIL
2	8,3	3	NIL	NIL
3	NIL	NIL	NIL	NIL
4	16,7,2	14,6,4	13,5,3	13,5,2
5	16,7,2	14,6,4	13,5,3	13,5,2
6	17,16	16,1	16	16
7	17,10	17,16,1	17,16	17,16
8	21,17,10	21,17,16	21,17,16	21,17,16
9	26,24,21	26,24,21,17	26,24,21,17	26,24,21,17
10	26,24,21	26,24,21	26,24,21	26,24,21
11	30,26,24	30,26,24	30,26,24	30,26,24
12	30,26,24	30,26,24	30,26,24	30,26,24
13	31,30	31,30	31,30	31,30
14	31,30	31,30	31,30	31,30
15	31,30	31,30	31,30	31,30

Table 4.12: (Continue).

Plan MNU	Plan # 1 3	Plan # 2 4	Plan # 3 5	Plan #4 6
WEEK				
16	31	31	31	31
17	31,9	31,9	31,9	31,9
18	31,9	31,9	31,9	31,9
19	6,1	NIL	NIL	NIL
20	6,1	NIL	NIL	NIL
21	12,5	10	8,4	8,4
22	18,12,5	18,10	18,8,4	18,8,4
23	18	18	18	18
24	18	18	18	18
25	NIL	NIL	NIL	NIL
26	NIL	7	6,2	6,1
27	25,20,11	25,20,8,7	25,20,7,6,2	25,20,7,6,1
28	25,20,11	25,20,8	25,20,7	25,20,7
29	25,20	25,20	25,20	25,20
30	25	25	25	25
31	27,23,13	27,23,11,2	27,23,10	27,23,10
32	27,23,13	27,23,11,2	27,23,10	27,23,10
33	27,23	27,23	27,23	27,23
34	27,23,14	27,23,12	27,23,11	27,23,11,3
35	28,19,14	28,19,15,12	28,19,15,14,11	28,19,15,14,11,3
36	29,28,19	29,28,19,15	29,28,19,15,14	29,28,19,15,14
37	29,28,19	29,28,19	29,28,19	29,28,19
38	32,29,28	32,29,28	32,29,28	32,29,28
39	32,29	32,29	32,29	32,29
40	32,22,15	32,22,13,5	32,22,12,1	32,22,12,
41	32,22,15	32,22,13,5	32,22,12,1	32,22,12
42	32,22,4	32,22	32,22	32,22
43	32,4	32	32	32
44-52	NIL	NIL	NIL	NIL
LOLE(d/y)	2.531245	2.517775	2.520779	2.519502

4.3.3. Reserve levelization

The effect of MNU variation using the reserve levelization technique was examined. Table 4.13 shows three plans with different values of the MNU. Units 9,10 and 11 are located in weeks 36,37,13,14 and 38,39 respectively. Weeks 36,13 and 38 are the three weeks with the largest reserve in the year. The high load periods are avoided in these plans.

Plan 2 in Table 4.13 is able to take advantage of the increase in MNU, as the reserve constraints are satisfied. The increase in MNU from 1 to 2 permits some weeks during the year to hold two units. It can be seen that Plans 2 and 3 are actually one plan achieved with two different values of MNU.

Table 4.13: Maintenance schedules for the RBTS with a peak load of 185 MW and reserve criterion of 30 MW

Plan MUN	Plan # 1 1	Plan # 2 2	Plan # 3 3
WEEK			
1-8	NIL	NIL	NIL
9	3	1	1
10	3	2,1	2,1
11	8	8,2	8,2
12	8	8	8
13	10	10	10
14	10	10	10
15	7	7	7
16	7	7	7
17	1	NIL	NIL
18	1	NIL	NIL
19-30	NIL	NIL	NIL
31	6	6	6
32	6	6	6
33	NIL	NIL	NIL
34	4	3	3
35	4	4,3	4,3
36	9	9,4	9,4
37	9	9	9
38	11	11	11
39	11	11	11
40	5	5	5
41	5	5	5
42	2	NIL	NIL
43	2	NIL	NIL
44-52	NIL	NIL	NIL

Table 4.14 shows the effect of varying the reserve criterion. Plans 1 and 2 are identical for the two criteria. Plan 1 constructed to achieve the reserve criterion of 30 MW is also valid for the reserve criterion of 50 MW with an MNU = 1.

Table 4.14: Maintenance schedule for the RBTS with a peak load of 185 MW and a reserve criterion = 30 & 50 MW.

	MNU=1		MNU = 2		MNU = 3	
	Reserve =30	Reserve =50	Reserve =30	Reserve =50	Reserve =30	Reserve =50
WEEK	Plan # 1	Plan # 2	Plan # 3	Plan # 4	Plan # 5	Plan # 6
1-8	NIL	NIL	NIL	NIL	NIL	NIL
9	3	3	1	2	1	2
10	3	3	2,1	3,2	2,1	3,2
11	8	8	8,2	8,3	8,2	8,3
12	8	8	8	8	8	8
13	10	10	10	10	10	10
14	10	10	10	10	10	10
15	7	7	7	7	7	7
16	7	7	7	7	7	7
17	1	1	NIL	NIL	NIL	NIL
18	1	1	NIL	NIL	NIL	NIL
19-30	NIL	NIL	NIL	NIL	NIL	NIL
31	6	6	6	6	6	6
32	6	6	6	6	6	6
33	NIL	NIL	NIL	NIL	NIL	NIL
34	4	4	3	4	3	4
35	4	4	4,3	4	4,3	4
36	9	9	9,4	9	9,4	9
37	9	9	9	9	9	9
38	11	11	11	11	11	11
39	11	11	11	11	11	11
40	5	5	5	5	5	5
41	5	5	5	5	5	5
42	2	2	NIL	1	NIL	1
43	2	2	NIL	1	NIL	1
44-52	NIL	NIL	NIL	NIL	NIL	NIL

The profile of the weekly reserve for Plan 1 is shown in Figure 4.17. The two straight lines shown in the figure present the 30 and 50 MW reserve criteria. The profile shows that the weekly reserve is not only above the 30 MW level, but it is also above the 50 MW level.

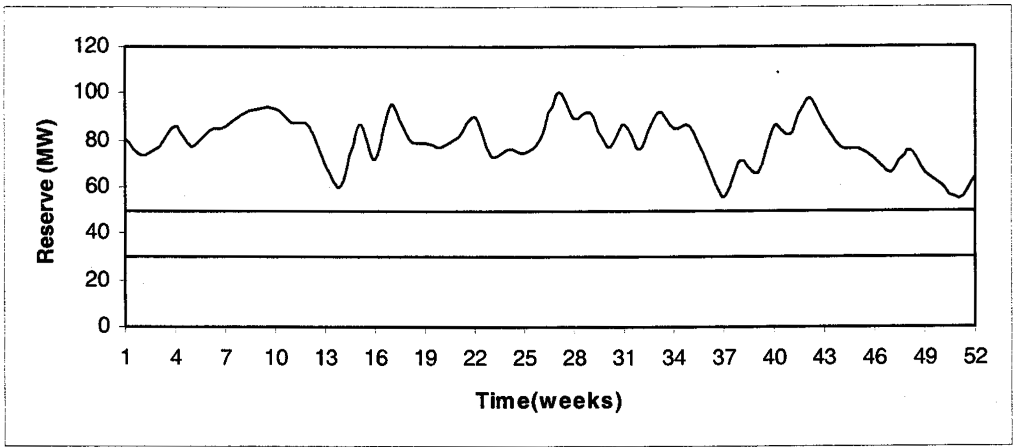

Figure 4.17: The weekly reserve with a reserve criterion of 30MW and MNU = 1.

Figure 4.18 shows the weekly reserve variation for reserve criteria of 30 MW and 50 MW with the MNU = 2. The weekly reserve in both profiles is above the 50 MW level due to the high reliability achieved by sorting the weeks after scheduling each generating unit. The reserve in the last few weeks is descending due to the relatively high load at these times.

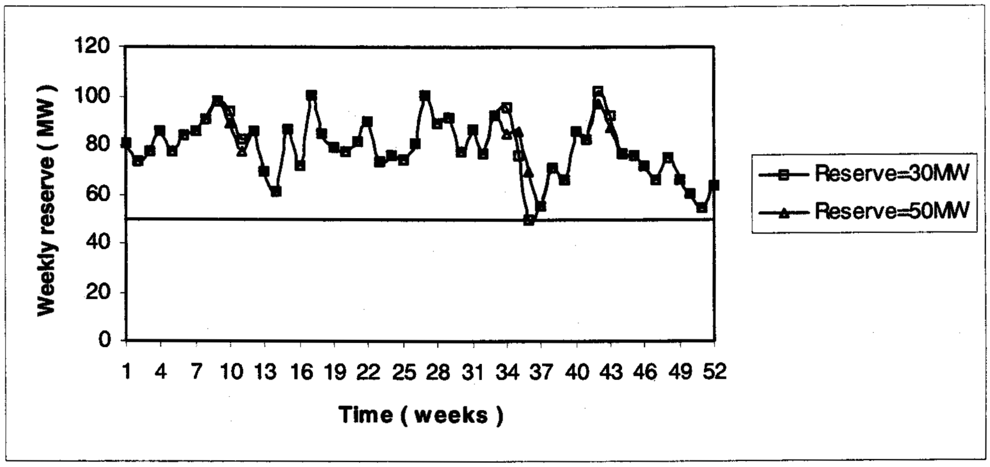

Figure 4.18: The weekly reserve variation for reserve criteria of 30 and 50 MW with MNU = 2.

Figure 4.19 shows a comparison of the weekly P(H) for two schedules created using health and reserve levelization. An MNU of 3 and a weekly P(H) criterion of 0.9 and a 30 MW reserve criterion were used. It can be seen from the figure that the probability of health for week 36 drops significantly in the reserve levelization case but with health levelization the P(H) is constrained at a higher level. Deterministic techniques are basically insensitive to system reliability.

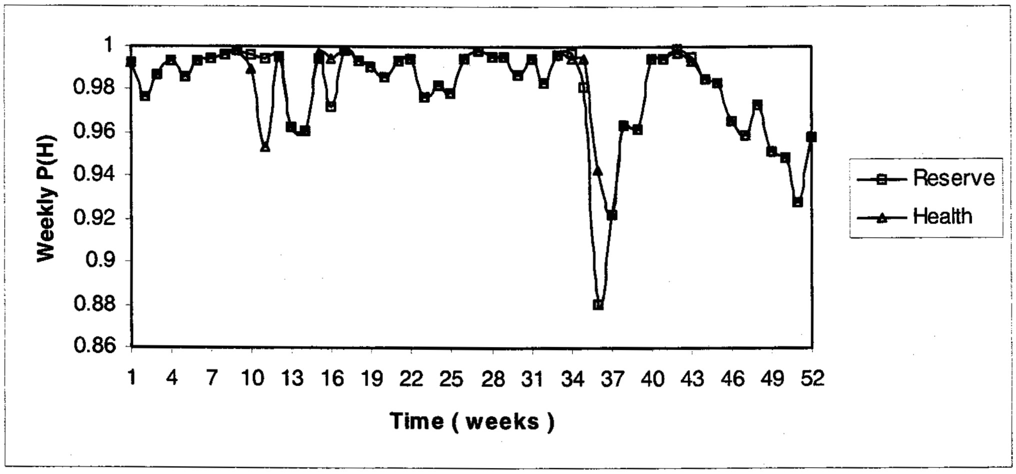

Figure 4.19: The weekly P(H) obtained using the health levelization technique and the reserve levelization technique with MNU = 3.

A similar conclusion based on risk levelization can be observed from Figure 4.20. In this case, the weekly risk is determined using the risk levelization technique with a 1/52 days/week criterion and the reserve levelization technique using a 30 MW criterion.

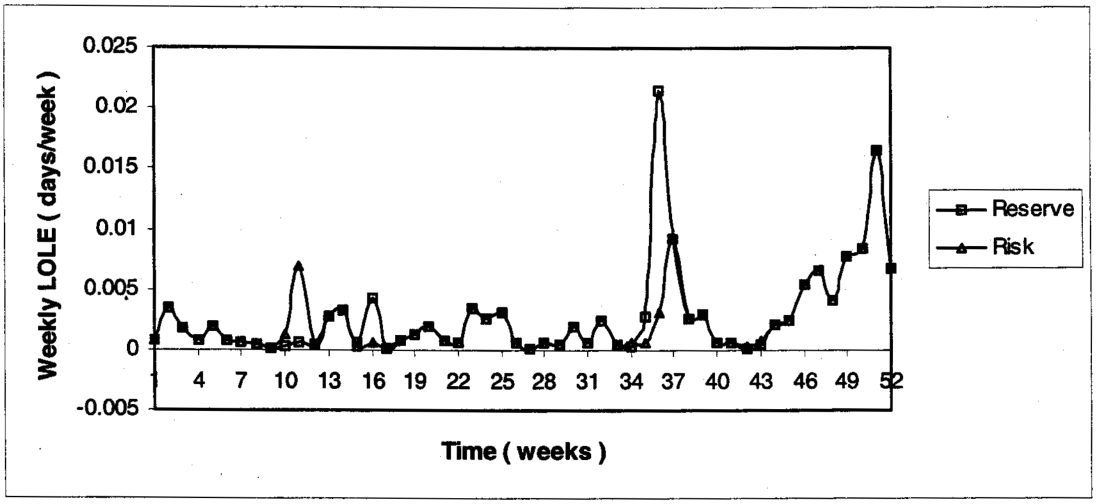

Figure 4.20: The weekly LOLE obtained using the risk levelization technique and the reserve levelization technique with MNU = 3 for the RBTS.

The annual indices were evaluated under the same conditions and it was found that the annual P(H) obtained using health levelization and reserve levelization are 0.981202 and 0.980294 respectively. The annual LOLE using risk levelization and reserve levelization are 0.130389 and 0.1468029 days/year respectively. The annual indices show that the system reliability obtained using the probabilistic techniques are higher than those for the reserve levelization deterministic technique.

The effect on the RTS of the MNU when using the reserve levelization technique has been examined. A reserve criterion of 600 MW was used. The maintenance schedules obtained are illustrated in Table 4.15.

Table 4.15 shows the maintenance plans obtained using the reserve levelization technique for a reserve criterion of 600 MW. It can be seen from the table that at the lower MNU values, the units are spread over most of the weeks during the year. The number of units removed for maintenance in a single week is quite small, which tends to keep the system at an acceptable reliability level. With an increase in the MNU, more units are taken out in a single week and the maintenance activity occupies fewer weeks.

Comparing the plans obtained using the reserve levelization technique with those obtained with a probabilistic technique can reflect that by using a probabilistic approach, the generating units spread into more weeks with fewer units taken out for maintenance in the same week. The reserve levelization approach creates plans with low reliability levels even though they satisfy the desired reserve criterion.

Table 4.15: Maintenance schedules for the RTS with a peak load of 2850 MW and a reserve of 600 MW.

Plan MNU	Plan # 1 3	Plan # 2 4	Plan # 3 5	Plan #5 6
WEEK				
1	12,3	7,1	6	6
2	12,3	7,1	6	6
3	5	NIL	NIL	NIL
4	20,10,5	17,10	17,9,1	17,9,1
5	20,10	17,10	17,9,1	17,9,1
6	20,7	17,4	17,2	17,2
7	23,7	18,11,4	18,10,2	18,10,2
8	23,14	21,18,11	21,18,10	21,18,10
9	26,23,14	26,24,21,18	26,24,21,18	26,24,21,18
10	27,26,23	27,26,24,21	27,26,24,21	27,26,24,21
11	28,27,26	28,27,26,24	28,27,26,24	28,27,26,24
12	28,27,26	28,27,26,24	28,27,26,24	28,27,26,24
13	31,28,27	31,28,27	31,28,27	31,28,27
14	31,28	31,28	31,28	31,28
15	31,13,4	31,8,3	31,7	31,7
16	31,13,4	31,8,3	31,7	31,7
17	31	31	31	31
18	31	31	31	31
19	9,6	NIL	NIL	NIL
20	9,6	NIL	NIL	NIL
21	16	12	11	11
22	24,16	23,12	23,11	23,11
23	24,16	23	23	23

Table 4.15: (Continued).

Plan MNU	Plan # 1 3	Plan # 2 4	Plan # 3 5	Plan #5 6
WEEK				
24	24	23	23	23
25	24	23	23	23
26	NIL	9	8	8
27	25,21,19	25,19,16,9	25,19,16,8	25,19,16,8
28	25,21,19	25,19,16	25,19,16	25,19,16
29	25,21,19	25,19,16	25,19,16	25,19,16
30	25	25	25	25
31	30,18,8	30,14,6	30,14,5,3	30,14,5,3
32	30,18,8	30,14,6	30,14,5,3	30,14,5,3
33	30,18	30	30	30
34	30,15	30,13	30,12	30,12
35	30,17,15	30,13	30,13,12	30,13,12
36	29,22,17	29,22,20,15	29,22,20,15,13	29,22,20,15,13
37	29,22,17	29,22,20,15	29,22,20,15	29,22,20,15
38	32,29,22	32,29,22,20	32,29,22,20	32,29,22,20
39	32,29	32,29	32,29	32,29
40	32,11,1	32,5,2	32,4	32,4
41	32,11,1	32,5,2	32,4	32,4
42	32	32	32	32
43	32	32	32	32
44	2	NIL	NIL	NIL
45	2	NIL	NIL	NIL
46-52	NIL	NIL	NIL	NIL

Figure 4.21 shows the weekly LOLE evaluated using the risk levelization technique and the reserve levelization approach. It can be seen from the figure that the 0.1 risk criterion is violated during some weeks which have scheduled maintenance. Weekly LOLE evaluation is not part of this technique and this results in a relatively high risk in these periods. This is not the case using the risk levelization technique as the weekly risk is held below the desired risk level.

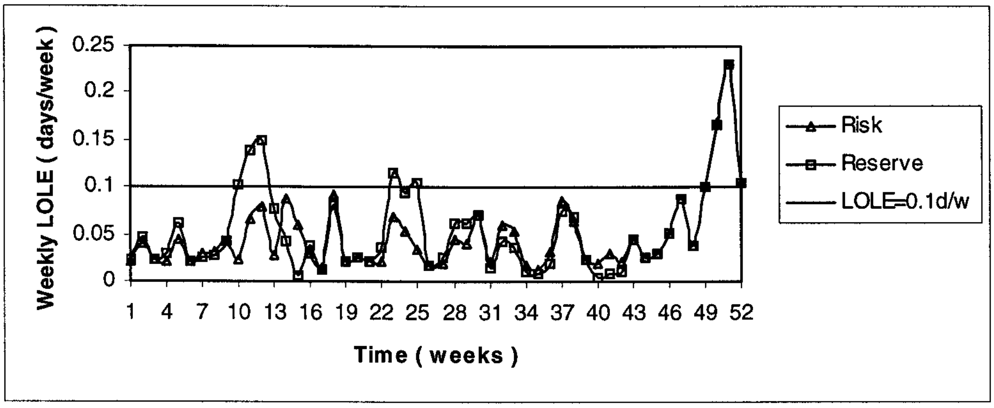

Figure 4.21: The weekly LOLE obtained using the risk levelization technique and the reserve levelization technique with MNU = 4 for the RTS.

Table 4.15 shows that the reserve levelization method assigns high capacity units for maintenance during peak periods such as weeks 23 – 25. This will affect adversely the annual LOLE of the system. The annual LOLE for Plan 2 in Table 4.12 using the risk levelization technique is 2.517539 days/year. Plan 2 in Table 4.15, obtained using the reserve levelization approach gives an annual LOLE of 2.816890. The same phenomenon occurs when using the health levelization technique. The advantage of using a probabilistic technique over the deterministic methods is more visible in large systems.

4.3.4. Loss of the largest unit

The loss of the largest unit approach is a popular deterministic technique. It has been applied to the RBTS with a peak load of 185 MW. In this approach, the objective is to maintain a reserve in each week at least equal to the capacity of the largest unit. Maintenance plans were constructed with MNU = 1, 2, 3,4, and 5. The plans constructed with MNU of 4 and 5 are identical to Plan 3 and therefore are not shown in Table 4.16.

When unit 3 is taken out in weeks 9 and 10, the largest remaining unit is unit 11 with a capacity of 40 MW. The reserve for these two weeks is above the 40 MW line, as shown in Figure 4.22. In weeks 11 and 12, unit 8 is out for maintenance and the largest available unit in that week is unit 11 with 40 MW. Figure 4.22 shows that the reserve is 40 MW for these two weeks. Unit 11, which is the largest unit in the system, is the largest remaining unit in all weeks of the year except for weeks 38 and 39 where it is taken out for maintenance. The largest remaining unit in these two weeks is unit 10, which also has a capacity of 40 MW. The capacity of the largest remaining unit in every week is therefore 40 MW. Figure 4.22 shows a straight line at the 40 MW level representing the capacity of the largest unit for each week of the year. It is not automatic, however, that the capacity of the largest unit will be the same for all of the year. If units 11,10 and 9 are taken out for maintenance in the same week then the capacity of the largest unit for that week will be that of unit 8. i.e. 20 MW.

Plan 1 in Table 4.16 is the same as plans 1 and 2 shown in Table 4.14 constructed using the reserve levelization technique. In plan 1 of Table 4.16, the capacity of the largest remaining unit was 40 MW for the entire year. This level is between the 30 and 50 MW levels used in Plans 1 and 2 in Table 4.10.

Table 4.16: Maintenance schedules for the RBTS with a peak load of 185 MW and a loss of the largest unit criterion.

Plan MUN	Plan # 1 1	Plan # 2 2	Plan # 3 3
WEEK			
1-8	NIL	NIL	NIL
9	3	1	1
10	3	2,1	2,1
11	8	8,2	8,2
12	8	8	8
13	10	10	10
14	10	10	10
15	7	7	7
16	7	7	7
17	1	NIL	NIL
18	1	NIL	NIL
19-30	NIL	NIL	NIL
31	6	6	6
32	6	6	6
33	NIL	NIL	NIL
34	4	3	3
35	4	4,3	4,3
36	9	9,4	9,4
37	9	9	9
38	11	11	11
39	11	11	11
40	5	5	5
41	5	5	5
42	2	NIL	NIL
43	2	NIL	NIL
44-52	NIL	NIL	NIL

The plans shown in Table 4.16 are identical to those shown in Table 4.13 obtained using the reserve levelization technique. The plans constructed with a 30 MW reserve criterion are still valid for a 40 MW reserve criterion. As a result, the discussion associated with Figures 4.19 and 4.20 applies in this case.

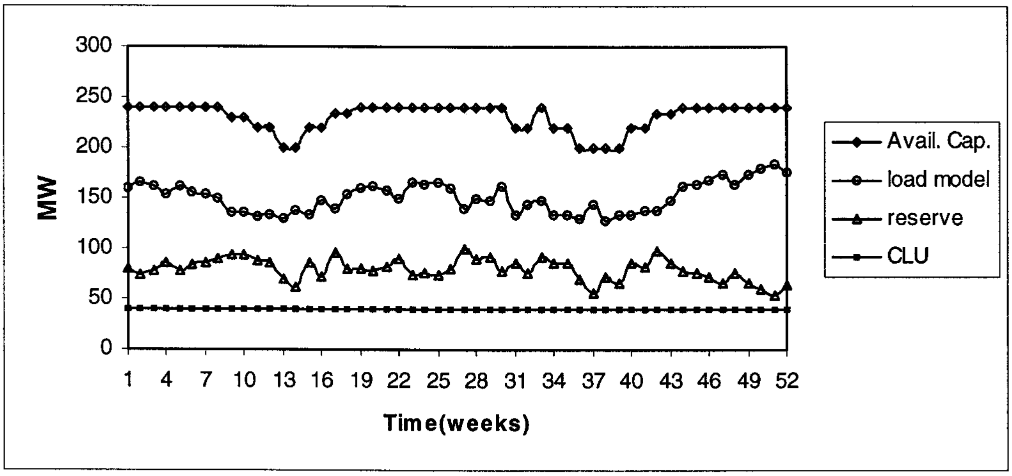

Figure 4.22: Variation in load, reserve, capacity of the largest remaining unit and the available capacity over the year, MNU = 1.

Figure 4.22 shows the available capacity variation during the year. The available capacity for the weeks without maintenance is the total installed capacity, which appears as a straight line during the high load periods. In the low load periods, the available capacity decreases due to the scheduled maintenance.

The loss of the largest unit technique was applied to the RTS to study the effect of changing the MNU. Table 4.17 shows the maintenance schedules obtained for the RTS.

Table 4.17: Maintenance schedules for the RTS with a peak load of 2850 MW and the loss of the largest unit as the criterion.

Plan MNU	Plan # 1 3	Plan # 2 4	Plan # 3 5	Plan #4 6	Plan #5 7
WEEK					
1	8,5,3	3	1	NIL	NIL
2	8,5,3	3	1	NIL	NIL
3	1	NIL	NIL	NIL	NIL
4	17,10,1	15,10	15,10	15,10	15,10
5	17,10	15,10	15,10	15,10	15,10
6	17,7	12,5,2	12,5	12,5	12,5
7	18,11,7	16,12,5,2	16,12,5	16,12,5	16,12,5
8	21,18,11	20,16	20,16	20,16	20,16
9	25,21,18	25,22,20,16	25,22,20,16	25,22,20,16	25,22,20,16
10	26,25,21	26,25,22,20	26,25,22,20	26,25,22,20	26,25,22,20
11	29,26,25	29,26,25,22	29,26,25,22	29,26,25,22	29,26,25,22
12	29,26,25	29,26,25	29,26,25	29,26,25	29,26,25
13	31,29,26	31,29,26	31,29,26	31,29,26	31,29,26
14	31,29	31,29	31,29	31,29	31,29
15	31,9,6	31,4	31,2	31,1	31,1

Table 4.17: (Continue).

Plan MNU	Plan # 1 3	Plan # 2 4	Plan # 3 5	Plan #4 6	Plan #5 7
WEEK					
16	31,9,6	31,4	31,2	31,1	31,1
17	31	31	31	31	31
18	31	31	31	31	31
19	4,2	NIL	NIL	NIL	NIL
20	4,2	NIL	NIL	NIL	NIL
21	12	6	6	6	6
22	19,16,12	18,13,7,6	18,13,7,6	18,13,7,6	18,13,7,6
23	19,16	18,13,7	18,13,7	18,13,7	18,13,7
24	19,16	18	18	18	18
25	NIL	NIL	NIL	NIL	NIL
26	NIL	NIL	NIL	2	2
27	24,20,15	24,19,14,8	24,19,14,8,3	24,19,14,8,3,2	24,19,14,8,3,2
28	24,20,15	24,19,14,8	24,19,14,8,3	24,19,14,8,3	24,19,14,8,3
29	24,20	24,19	24,19	24,19	24,19
30	24	24	24	24	24
31	28,23,14	28,23,11,1	28,23,11	28,23,11	28,23,11
32	28,23,14	28,23,11,1	28,23,11	28,23,11	28,23,11
33	28,23	28,23	28,23	28,23	28,23
34	28,23,13	28,23,9	28,23,9,4	28,23,9,4	28,23,9,4
35	27,22,13	27,21,17,9	27,21,17,9,4	27,21,17,9,4	27,21,17,9,4
36	30,27,22	30,27,21,17	30,27,21,17	30,27,21,17	30,27,21,17
37	30,27,22	30,27,21,17	30,27,21,17	30,27,21,17	30,27,21,17
38	32,30,27	32,30,27	32,30,27	32,30,27	32,30,27
39	32,30	32,30	32,30	32,30	32,30
40	32,30	32,30	32,30	32,30	32,30
41	32	32	32	32	32
42	32	32	32	32	32
43	32	32	32	32	32
44-52	NIL	NIL	NIL	NIL	NIL

It can be seen from the table, that similar conclusions to those obtained using the reserve levelization technique apply to the maintenance plans obtained with the loss of the largest unit technique.

Figure 4.23 shows the weekly P(H) obtained using the health levelization technique with a health criterion of 0.85 and the weekly P(H) using the capacity of the largest unit approach. It can be seen from the figure that the P(H) in some weeks, obtained using the capacity of the largest unit technique at some weeks is less than the P(H) obtained using the health levelization technique especially in week 37 where the P(H) drops significantly for the loss of the largest unit approach.

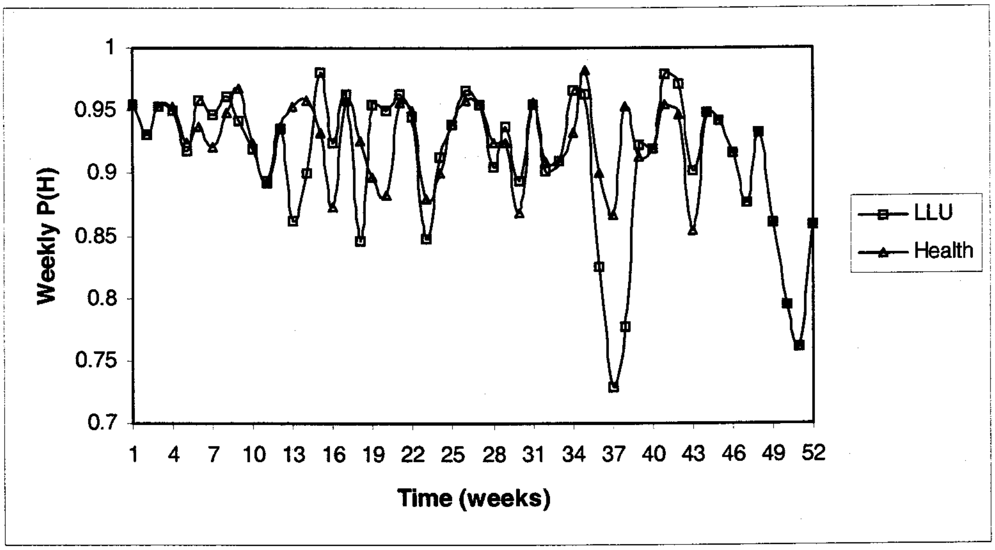

Figure 4.23: The weekly P(H) using health levelization and the capacity of the largest unit, MNU = 4

4.4. Annual risk analysis

The studies presented in this chapter for the RBTS and the RTS are concluded in this section using tables and three dimensional figures. The selected maintenance scheduling criteria can have a wide range of values. In some cases, the selected criterion was violated in some weeks and in other cases the criterion was satisfied for the entire year. There are, therefore, practical limits on the criteria.

Figure 2.4 shows the weekly probability of health and risk for the RBTS without including any maintenance. It can be seen that the desired health criterion must be selected to be less than or equal to the weekly probability of health of week 51 which is 0.928 in order to find a maintenance plan that satisfy this criterion. Table 4.18 shows the maintenance schedule obtained using the health levelization technique with the 0.928 health criterion.

The maintenance plan shown in Table 4.18 has some similarities to the plans obtained for different health criteria presented earlier in this chapter. It is also identical to the plan obtained with the 0.94 health criterion shown in Table 4.8. The last two columns of Table 4.19 reflect the same idea. The annual P(H) for the maintenance schedules obtained with the 0.928 health criterion and the 0.94 health criterion are identical for the corresponding MNU values. Table 4.19 shows the annual P(H) obtained for different health criterion and MNU values.

Table 4.18: Maintenance schedule for the RBTS with a peak load of 185 and P(H) criterion of 0.928.

WEEK	Units on Maints.	WEEK	Units on Maints.
1-8	NIL	33	NIL
9	3	34	2
10	5,3	35	9,2
11	8,5	36	9
12	8	37	NIL
13	10	38	11
14	10	39	11
15	4	40	7
16	4	41	7
17-30	NIL	42	1
31	6	43	1
32	6	44-52	NIL
		P(H)	0.980908

Table 4.19: The annual P(H) for the RBTS with different MNU and health criteria values.

MNU	Pw(H)=0.85	Pw(H)=0.9	Pw(H)=0.928	Pw(H)=0.94
1	0.981573	0.981573	0.981855	0.981855
2	0.980002	0.981202	0.980908	0.980908
3	0.980002	0.981202	0.980908	0.980908
4	0.980002	0.981202	0.980908	0.980908
5	0.980002	0.981202	0.980908	0.980908

Pw(H) : The weekly probability of health criterion

The highest annual probability of health in Table 4.19 is obtained with a MNU of 1. As the MNU increases from 1 to 2, the annual probability of health decreases. The annual P(H) did not change with further increase in the MNU. The constructed plans with MNU of 3 or higher shown in this chapter do not have a single week with three units out in the same week. This means that the most suitable MNU value for the RBTS is either 1 or 2. This provides a valuable indicator of the actual number of the maintenance personnel required for this system. Having the maintenance personnel to satisfy an MNU of 3 or more is not beneficial and will cost the utility more than it will gain.

Table 4.19 can also be considered from a system reliability point of view. The annual P(H) for the maintenance schedules obtained with the health criteria of 0.928 and 0.94 are the same for all MNU values. This provides some insight regarding a suitable health criterion for this system that can be achieved without demanding an unnecessary high health level but gives the same maintenance plan. This is illustrated in Figure 4.24. It can be seen from this figure that it is not automatic that the highest possible annual health probability Pa(H) is achieved by using the highest possible weekly probability of health criterion for MNU of 2 or more.

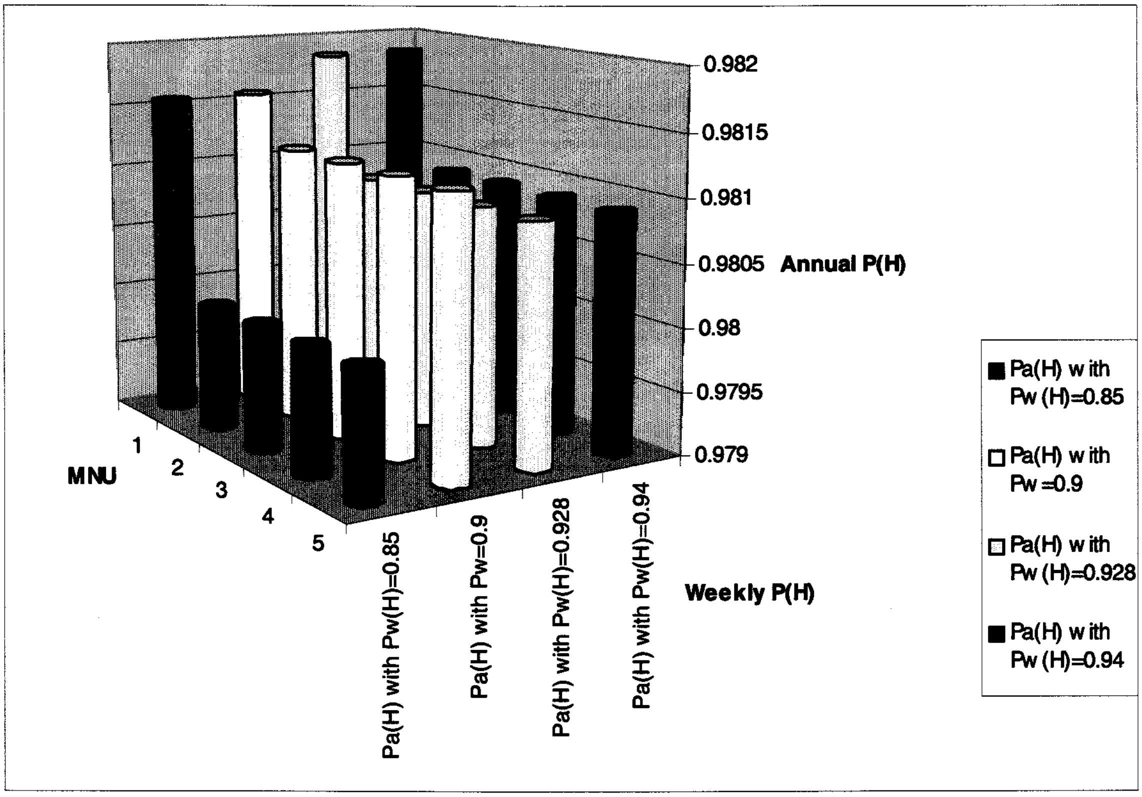

Figure 4.24: The annual P(H) for the RBTS with the change in the MNU for different health criteria values.

The same analysis noted earlier using the health criterion was conducted for the risk criterion. Figure 2.4 shows that the minimum P(R) that can be used as a criterion without violation is 0.00237, which is 0.0166 days/week. Table 4.20 shows the maintenance schedule constructed using the risk levelization approach with a MNU of 3 and a LOLE weekly criterion of 0.0166 days/week.

The maintenance schedule shown in Table 4.20 is identical to the ones obtained with other weekly risk criteria. The annual LOLE obtained for the maintenance schedules constructed with different weekly risk criteria and MNU are shown in Table 4.21.

Table 4.20: Maintenance schedule for the RBTS with a peak load of 185 and LOLE criterion of 0.0166 days/week.

WEEK	Units on Maints.	WEEK	Units on Maints.
1-8	NIL	33	NIL
9	2	34	6
10	4,2	35	6
11	8,4	36	9
12	8	37	9
13	10	38	11
14	10	39	11
15	3	40	7
16	3	41	7
17-30	NIL	42	1
31	5	43	1
32	5	44-52	NIL
		LOLE(d/y)	0.130389

The lowest annual risk occurs with a MNU of 1. This MNU value forces the maintenance to be spread in more weeks. If this is not desirable then a higher MNU value is required. This will result in a higher annual risk as shown in the table. The annual risk did not increase with further increase in the MNU which indicates that there is no benefit in hiring more maintenance people.

Table 4.21: The annual LOLE for the RBTS with different values of MNU and risk criteria.

MNU	LOLEw=0.0038	LOLEw=0.01	LOLEw=0.0166	LOLEw=0.0192	LOLEw=0.1
1	0.120111	0.127461	0.127461	0.127461	0.127461
2	0.120111	0.130389	0.130389	0.130389	0.148689
3	0.120111	0.130389	0.130389	0.130389	0.148689
4	0.120111	0.130389	0.130389	0.130389	0.148689
5	0.120111	0.130389	0.130389	0.130389	0.148689

The annual LOLE evaluated with 0.0166 days/week is the same as that obtained using 0.0192 and 0.01 days/week. Therefore, there is no point in utilizing a low risk criterion if the same reliability level can be achieved with a higher risk criterion. However, demanding a lower risk criterion may result in an lower annual risk as is the case with the 0.0038 days/year. As previously noted, however the minimum period risk is 0.0166 days/week, which is attained the peak load periods during which there is no scheduled maintenance. One alternative is to accept this risk during these peak load periods, and to institute some form of load shedding policy if action is required. These conditions are displayed in the three dimensional representation shown in Figure 4.25.

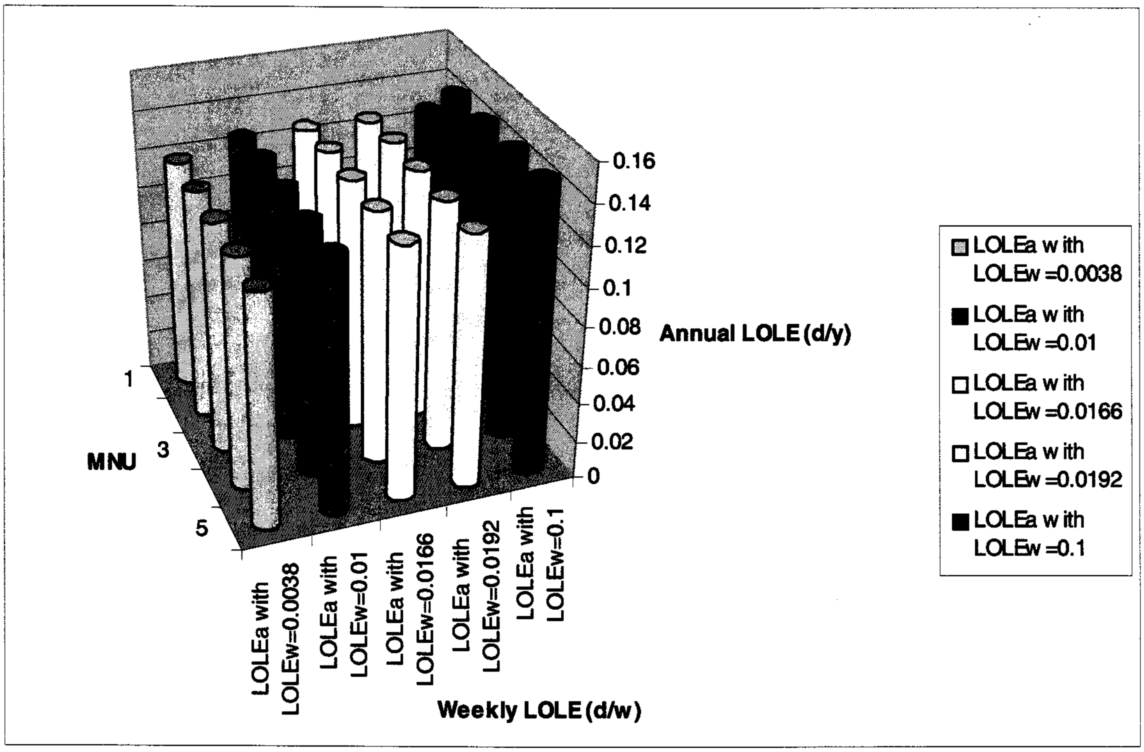

Figure 4.25: The annual LOLE for the RBTS with changes in the MNU for different risk criteria.

Similar phenomenon can be seen for the RTS. Figure 2.5 shows the weekly P(H) and P(R) evaluated for the RTS without considering maintenance. Minimum P(H) occurs in week 51 with a value of 0.761. This is the highest value that can be considered as a health criterion in order to construct maintenance plans that do not violate this criterion for the entire year. Table 4.22 shows the maintenance plan constructed with this criterion.

Table 4.22: Maintenance schedule for the RTS with a peak load of 2850 and a P(H) criterion of 0.761.

WEEK	Units on Maints.	WEEK	Units on Maints.
1-3	NIL	24	16
4	12,3	25	NIL
5	12,3	26	6
6	13,1	27	23,18,11,6
7	14,13,1	28	23,18,11
8	19,15,14	29	23,18
9	24,21,19,15	30	23
10	25,24,21,19	31	26,22,17,10
11	30,25,24,21	32	26,22,17,10
12	30,25,24	33	26,22,17
13	31,30,25	34	27,26,9,5
14	31,30	35	28,27,9,5
15	31,30	36	29,28,27
16	31	37	29,28,27
17	31,2	38	32,29,28
18	31,2	39	32,29
19	NIL	40	32,20,7
20	NIL	41	32,20,7
21	8,4	42	32,20
22	16,8,4	43	32
23	16	44-52	NIL
		P(H)	0.913847

This maintenance schedule has an annual P(H) of 0.913847. This value is lower than the P(H) values obtained with the 0.85 health criterion shown in Table 4.9. Table 4.23 shows the annual P(H) for the maintenance schedules constructed with different MNU and health criterion values.

Table 4.23: The annual P(H) for the RTS with different values of MNU and health criteria.

MNU	Pw(H)=0.7	Pw(H)=0.761	Pw(H)=0.8	Pw(H)=0.85
3	0.914152	0.914152	0.916649	0.918951
4	0.913847	0.913847	0.916493	0.918893
5	0.913854	0.913854	0.916499	0.918611
6	0.913854	0.913854.	0.916499	0.918609
7	0.913854	0.913854	0.916499	0.918609

It can be seen from Table 4.23 that the highest annual P(H) is achieved with the lowest MNU. Higher MNU values could be considered if fewer number of weeks are available for maintenance, even though this might result in lower health. The benefit of having higher MNU disappears at the point where the annual P(H) is not affected by further MNU increase. The MNU values indicates the number of people required for maintenance activities and can be used to assess the maintenance cost from this point of view.

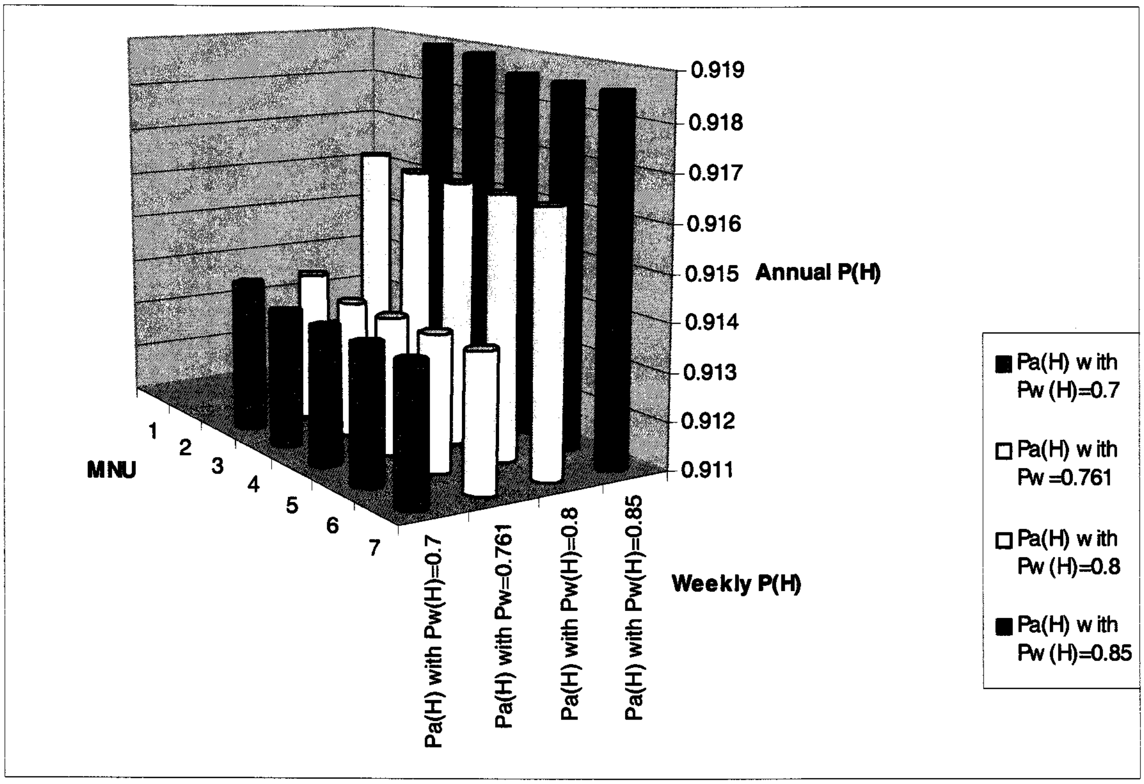

Figure 4.26: The annual P(H) for the RTS with changes in the MNU for different health criteria.

The annual P(H) increases with increase in the weekly P(H) criterion. At some point the planner must make a decision, either to accept a lower annual P(H) without violating the desired health criterion or have a higher annual P(H) and violate the desired health criterion at the peak load times. Figure 4.26 provides a pictorial representation of the results in Table 4.23.

Table 4.24 shows the maintenance schedule constructed for the RTS using the risk levelization technique with the 0.231 days/week risk criterion. This maintenance schedule is similar to the other schedules obtained with different risk criteria and shown in Table 4.12. The annual LOLE for this plan is higher than the annual LOLE for the plans in Table 4.12 constructed with a lower risk criterion.

Table 4.24: Maintenance schedule for the RTS with a peak load of 2850 and a LOLE criterion of 0.231 days/week.

WEEK	Units on Maints.	WEEK	Units on Maints.
1-3	NIL	24	16
4	12,2	25	NIL
5	12,2	26	4
6	13,1	27	23,18,10,4
7	14,13,1	28	23,18,10
8	19,15,14	29	23,18
9	24,21,19,15	30	23
10	25,24,21,19	31	26,22,17,8
11	30,25,24,21	32	26,22,17,8
12	30,25,24	33	26,22,17
13	31,30,25	34	27,26,9,7
14	31,30	35	28,27,9,7
15	31,30	36	29,28,27
16	31	37	29,28,27
17	31,6	38	32,29,28
18	31,6	39	32,29
19	NIL	40	32,20,11
20	NIL	41	32,20,11
21	5,3	42	32,20
22	16,5,3	43	32
23	16	44-52	NIL
		LOLE (d/y)	2.678765

Table 4.25 shows the annual LOLE for the maintenance schedules constructed with different MNU and risk criteria.

Table 4.25: The annual LOLE for the RTS with different MNU and risk criteria

MNU	LOLEw=0.1	LOLEw=0.231	LOLEw=0.3	LOLEw=0.5
3	2.531245	2.668513	2.668513	2.668513
4	2.517775	2.678765	2.678765	2.678765
5	2.520779	2.678408	2.678408	2.678408
6	2.519502	2.679258	2.679258	2.679258
7	2.519502	2.679258	2.679258	2.679258

It can be seen from the table that there is a limiting MNU value, where the annual LOLE is not affected by increase in the MNU. As a result, there is no reason to hire more people to perform maintenance with an MNU of 7 if the same result can be achieved with a lower MNU value i.e. fewer maintenance people.

It can also be seen also from the table that the same annual LOLE can be achieved using a wide range of risk criteria. Utilizing a lower risk criterion could result in a lower annual risk if the planner is prepared to accept violating the weekly risk criterion for some weeks. These conclusions are illustrated in Figure 4.27.

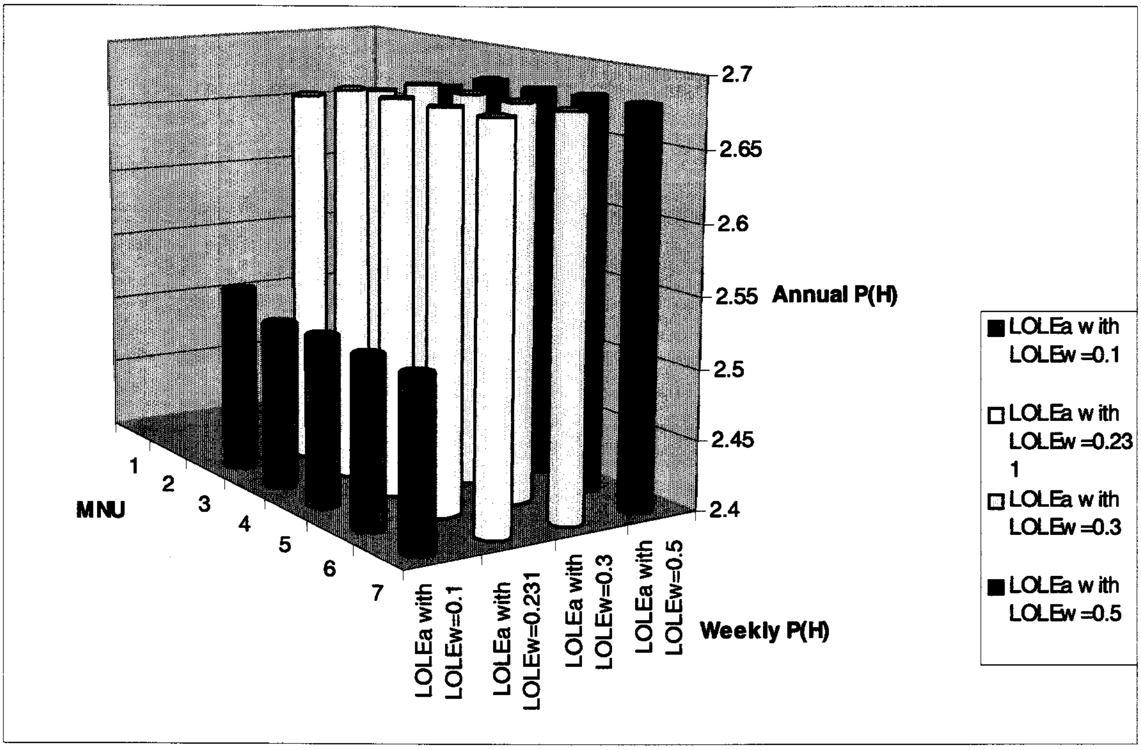

Figure 4.27: The annual LOLE for the RTS with the change in the MNU with different risk criteria values

4.5. Conclusion

The studies described in this chapter indicate that there is no significant effect on a derived maintenance plan due to reasonable variation in a unit FOR for the RBTS. The annual reliability associated with the constructed plans, however, decreases as the FOR increases. This does not mean that there is absolutely no affect due to this factor. This phenomenon resulted due to the size of the system and the stability of the criterion order, which is largely affected by the nature of the load model. In addition the constructed plans were able to sustain the increased FOR without violating the desired criterion.

It can be concluded from the studies conducted in this chapter that demanding a higher reliability criterion may require having only a few generating units out for maintenance in a single week in order to satisfy this criterion. The selection of a very high reliability criterion may result in criterion violation in the high load periods without any maintenance or it may not be possible to create a maintenance schedule using this criterion.

It is not always true that increasing the MNU results in a lower annual reliability. The annual reliability can be lower in certain cases with a decrease in the MNU. A low MNU value may force the units to not follow the criterion order and it could result in creating some weeks with lower reliability levels which could decrease the annual reliability.

Deterministic techniques can create maintenance plans that satisfy the approved deterministic criterion. They can also create situations in some weeks in which there is excessive system risk due to the fact that the deterministic techniques do not involve any consideration of the actual risk.

5. THE EFFECT OF SYSTEM LOAD CHARACTERISTICS ON MAINTENANCE SCHEDULING

5.1. Introduction

The factors studied in Chapter 4 are directly related to the generation facilities. The effect on maintenance scheduling of factors related to system load is examined in this chapter. Two aspects are considered. First, the system load is assumed to increase and secondly, a different load shape is considered. These modifications were examined by applying the four maintenance scheduling techniques to the RBTS.

5.2. The effect of system peak load on maintenance scheduling

In this section, the effect of a 195 MW peak load in the RBTS is examined using the four techniques. In each case, the effect of the change in the system peak load is considered in conjunction with changes in the FOR and MNU.

The FOR effect is examined by changing the FOR of unit 9. The MNU value is fixed in this study at 3. Comparison tables and figures are presented to illustrate the effect of increasing the system peak load from 185 to 195 MW. The effect of changing the MNU is examined while keeping the generating unit FOR at their original values.

5.2.1. Health levelization

The effect on the maintenance schedule of changing the MNU and the FOR for unit 9 using the health levelization technique was examined earlier using a system peak load of 185MW. A similar study is described in this section in which the system peak load is increased to 195MW.

Table 5.1 shows two sets of maintenance plans constructed for the peak loads of 185 and 195 MW with different FOR values. The criterion order of the weeks changes with the increase in the system peak. This can be seen from the location of unit 9 which moves from weeks 36 and 37 to weeks 11 and 12. The system health decreases as the system peak load increases as indicated by the last row in the table.

Table 5.1: Maintenance schedule for the RBTS with a P(H) of 0.9 and peak loads of 185 and 195 MW.

	FOR = 0.005		FOR = 0.04	
	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW
WEEK	Plan # 1	Plan #2	Plan #3	Plan # 4
1-8	NIL	NIL	NIL	NIL
9	2	1	2	1
10	5,2	2,1	5,2	2,1
11	8,5	9,2	8,5	9,2
12	8	9	8	9
13	10	10	10	10
14	10	10	10	10
15	3	4	3	4
16	3	4	3	4
17-30	NIL	NIL	NIL	NIL
31	6	3	6	3
32	6	3	6	3
33	NIL	NIL	NIL	NIL
34	4	5	4	5
35	4	6,5	4	6,5
36	9	8,6	9	8,6
37	9	8	9	8
38	11	11	11	11
39	11	11	11	11
40	7	7	7	7
41	7	7	7	7
42	1	NIL	1	NIL
43	1	NIL	1	NIL
44-52	NIL	NIL	NIL	NIL
P(H)	0.985515	0.972062	0.975450	0.956331

Figure 5.1 shows the variation in the weekly probability of health. In general, the health profile with a peak load of 195MW is below the 185 MW profile except for week 37. Unit 8 was scheduled in week 37 with the 195 MW peak load. Unit 8 is a smaller unit than unit 9, which was scheduled in week 37 with the 185 MW peak load. This is why the probability of health in week 37 is higher at the 195 MW peak load level than at the 185 MW peak load level. The FOR of unit 9 in this study is the base value of 0.02.

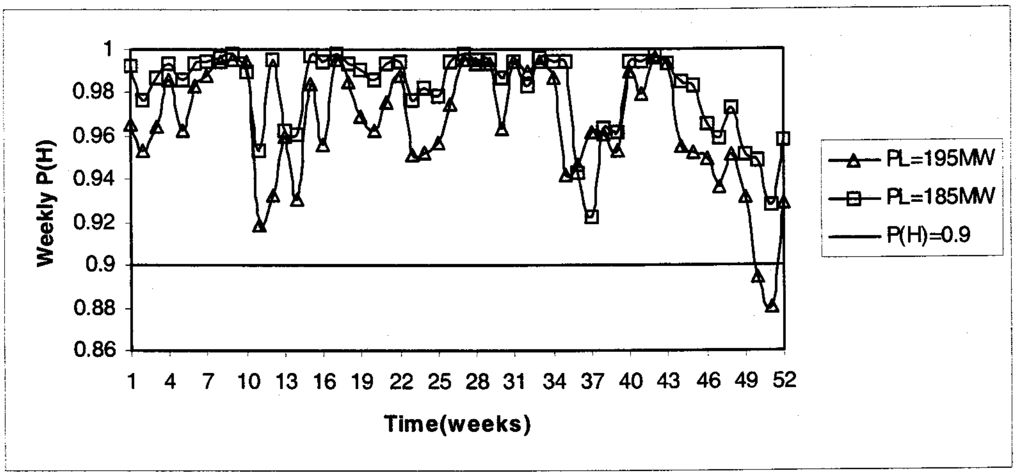

Figure 5.1: The weekly P(H) for system peak loads of 185 and 195 MW.

The weekly criterion is violated with the higher peak load in weeks 50 and 51 due to the shape of the load model and the increase in the peak load.

The two profiles shown in Figure 5.2 represent the annual system probability of health for the system peak loads of 185 and 195 MW.

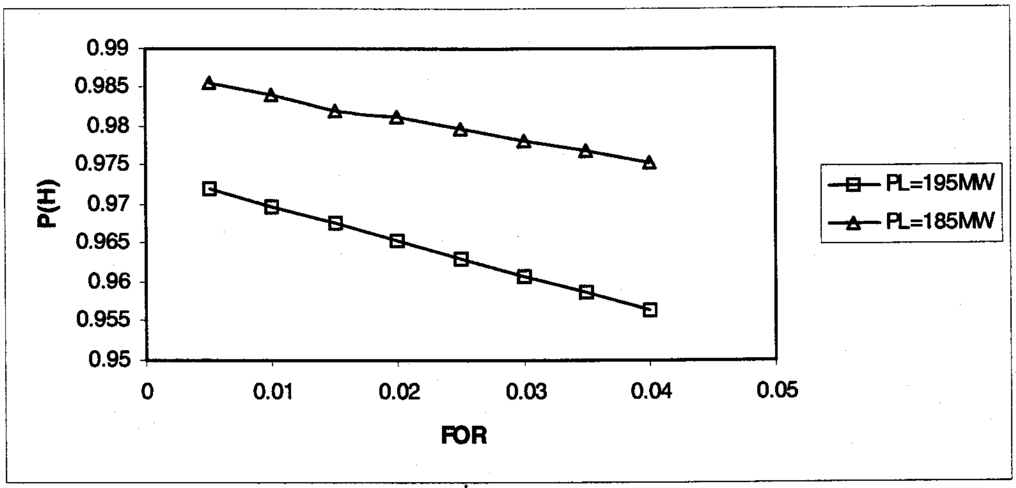

Figure 5.2: The system probability of health with a desired health criterion of 0.9 with system peak loads of 185 and 195 MW.

The effect of changing the FOR of unit 9 with the increase in system peak load is shown in Figure 5.2. It can be seen that the effect on system health of increased FOR is more pronounced as the load level increases. The impact of changing the MNU is illustrated in the next example using a health criterion of 0.9. Table 5.2 shows a comparison between the plans developed for a 185 MW system peak load with those obtained with the 195 MW peak load.

Table 5.2 shows three plans1,3 and 5, constructed for a 185 MW system peak load and three plans 2,4 and 6, constructed for a 195 MW peak load. The plans obtained with the 195 MW peak load have lower probability of health than those with the 185 MW peak load. Increasing the system peak load, decreases the general reserve margin and drives the system health down.

Table 5.2: Maintenance schedule for the RBTS with a P(H) of 0.9 and peak loads of 185 & 195 MW.

	MNU =1		MNU =2		MNU =3	
	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW
WEEK	Plan # 1	Plan #2	Plan # 3	Plan # 4	Plan #5	Plan # 6
1-8	NIL	NIL	NIL	NIL	NIL	NIL
9	3	3	2	1	2	1
10	3	3	5,2	2,1	5,2	2,1
11	8	9	8,5	9,2	8,5	9,2
12	8	9	8	9	8	9
13	10	10	10	10	10	10
14	10	10	10	10	10	10
15	4	5	3	4	3	4
16	4	5	3	4	3	4
17-26	NIL	NIL	NIL	NIL	NIL	NIL
27	1	1	NIL	NIL	NIL	NIL
28	1	1	NIL	NIL	NIL	NIL
29-30	NIL	NIL	NIL	NIL	NIL	NIL
31	6	4	6	3	6	3
32	6	4	6	3	6	3
33	NIL	NIL	NIL	NIL	NIL	NIL
34	5	6	4	5	4	5
35	5	6	4	6,5	4	6,5
36	9	8	9	8,6	9	8,6
37	9	8	9	8	9	8
38	11	11	11	11	11	11
39	11	11	11	11	11	11
40	7	7	7	7	7	7
41	7	7	7	7	7	7
42	2	2	1	NIL	1	NIL
43	2	2	1	NIL	1	NIL
44-52	NIL	NIL	NIL	NIL	NIL	NIL
P(H)	0.981573	0.966042	0.981202	0.965320	0.981202	0.965320

Figure 5.3 shows the weekly probability of health profiles for the two load levels. The probability of health with a peak load of 195 MW is lower than the probability of health with a peak load of 185 MW for most weeks.

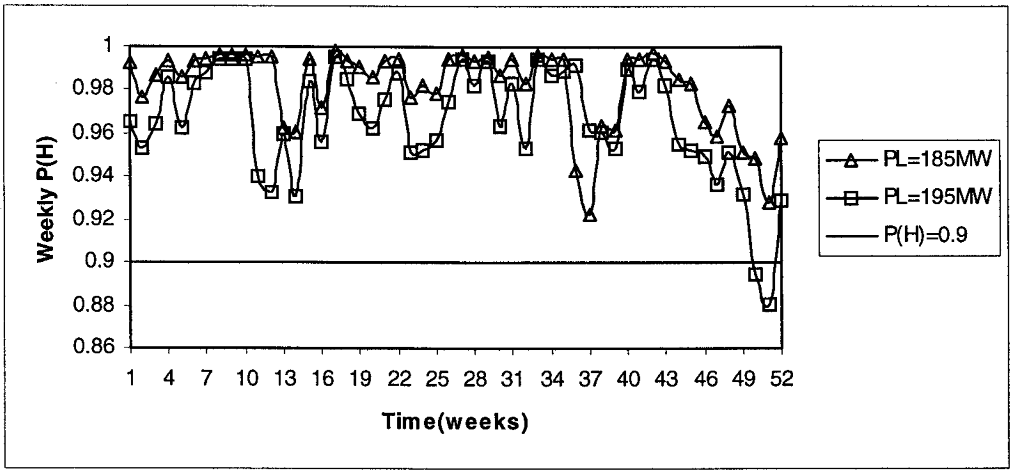

Figure 5.3: Weekly probability of health variation with a health criterion of 0.9 and peak loads of 195MW and 185 MW, MNU = 1.

The probability of health drops below the desired level in weeks 50 and 51 where no maintenance is performed due to the system peak load.

Figure 5.4 shows the probability of health with the system peak loads of 185 and 195 MW. Both profiles have constant values after the MNU reaches a value of 2 as the plans do not change after this point.

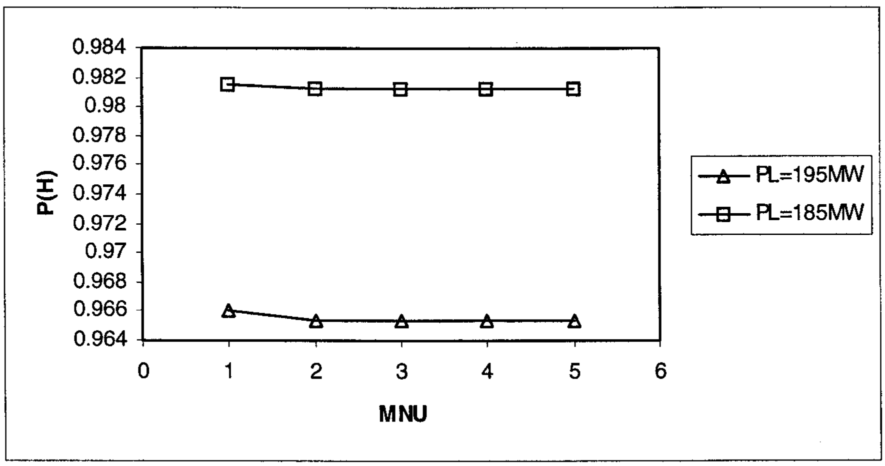

Figure 5.4: The annual probability of health with the change in MNU and a criterion P(H) of 0.9.

5.2.2. Risk levelization

As done in Section 5.2.1, the effect on the RBTS of the MNU and the FOR is examined for a 195 MW peak load. The selected risk criterion is 1/52 days/week. The MNU was held at 3 in order to examine the effect of the FOR. The base case FOR were used to examine the effect of the MNU.

Table 5.3 shows the maintenance schedules constructed with the 185 and 195 MW peak loads. Plans 1 and 3 and Plans 2 and 4 are identical. This means that the maintenance schedule is not affected by this change in the FOR at this risk criterion and with the different peak loads. This does not mean that it would not be affected under other similar circumstances. The increase in the peak load caused the annual risk to increase as shown in the last row of the table.

Table 5.3: Maintenance schedule for RBTS with LOLE of 1/52 days/weekand Peak Load of 185 and 195 MW.

	FOR = 0.005		FOR = 0.04	
	PL=185MW	PL=195MW	PL=185MW	PL=195MW
WEEK	Plan # 1	Plan #2	Plan #3	Plan # 4
1-8	NIL	NIL	NIL	NIL
9	2	1	2	1
10	4,2	2,1	4,2	2,1
11	8,4	9,2	8,4	9,2
12	8	9	8	9
13	10	10	10	10
14	10	10	10	10
15	3	4	3	4
16	3	4	3	4
17-30	NIL	NIL	NIL	NIL
31	5	3	5	3
32	5	3	5	3
33	NIL	NIL	NIL	NIL
34	6	5	6	5
35	6	6,5	6	6,5
36	9	8,6	9	8,6
37	9	8	9	8
38	11	11	11	11
39	11	11	11	11
40	7	7	7	7
41	7	7	7	7
42	1	NIL	1	NIL
43	1	NIL	1	NIL
44-52	NIL	NIL	NIL	NIL
LOLE(d/y)	0.073878	0.186439	0.205740	0.472889

The weekly risk with the higher system peak load is in general higher than the risk with the lower peak load as shown in Figure 5.5.

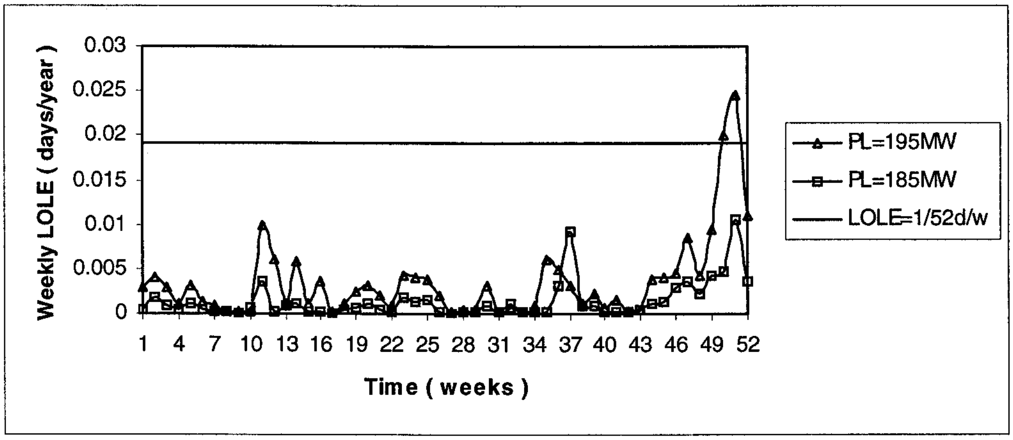

Figure 5.5: Weekly LOLE with FOR=0.005 for peak loads of 185 and 195 MW with the desired LOLE = 1/52 days/week.

The risk level was kept below the 1/52 days/week level for the 185MW peak load. In the case of the 195MW peak load, the risk crosses the desired level in weeks 50 and 51 where the highest weekly peak load occurs. This is uncontrollable because there is no maintenance performed during these weeks. The risk increases due to the load and not due to the maintenance plan. If the desired criterion is mandatory then some load shedding must be conducted at these times to reduce the risk to the acceptable level.

Figure 5.6 shows the annual LOLE for the 185 and 195 MW peak loads. The risk increases for both load levels as the FOR of unit 9 increases. The increase is more severe for the 195 MW load condition.

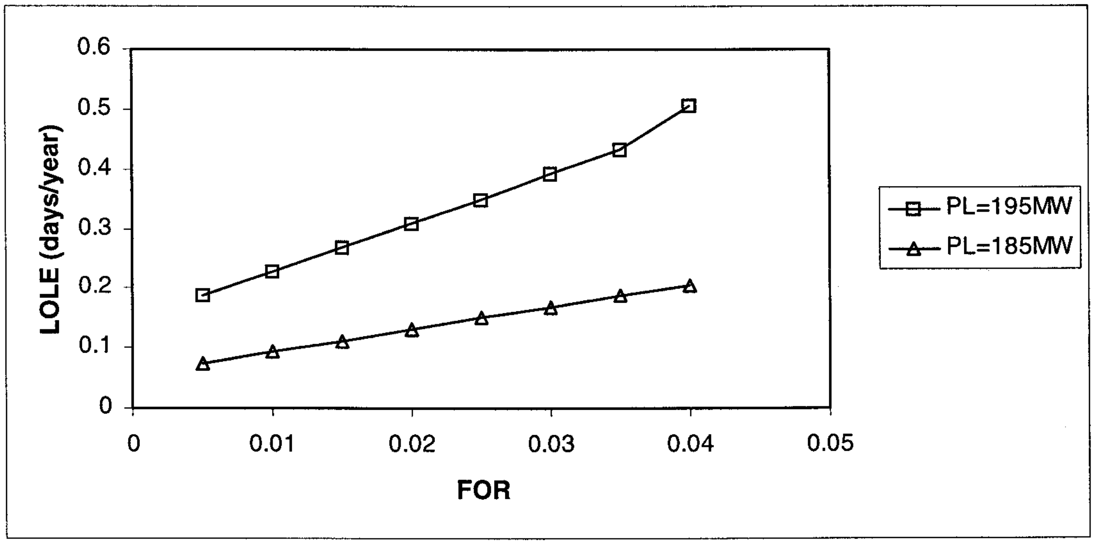

Figure 5.6: Risk variation with forced outage rate for a desired risk level of LOLE=1/52 day/week and 185 and 195 MW peak loads.

The effect of changing the MNU was examined at a peak load of 195 MW. The FOR for unit 9 was held at its original value of 0.02.

Maintenance plans, 1,3 and 5 shown in Table 5.4 were built for a peak load of 185 MW. Plans 2,4 and 6 were built for a 195 MW peak load. In plans 1 and 2 with MNU = 1, the only difference is that unit 9 is switched with unit 8. This occurs due to a change in the criterion order of the weeks.

Table 5.4: Maintenance schedule for the RBTS with a LOLE of 1/52 days/week and peak loads of 185 and 195 MW.

	MNU =1		MNU =2		MNU =3	
	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW
WEEK	Plan # 1	Plan #2	Plan # 3	Plan # 4	Plan #5	Plan # 6
1-8	NIL	NIL	NIL	NIL	NIL	NIL
9	3	3	2	1	2	1
10	3	3	4,2	2,1	4,2	2,1
11	8	9	8,4	9,2	8,4	9,2
12	8	9	8	9	8	9
13	10	10	10	10	10	10
14	10	10	10	10	10	10
15	4	5	3	4	3	4
16	4	5	3	4	3	4
17-26	NIL	NIL	NIL	NIL	NIL	NIL
27	1	1	NIL	NIL	NIL	NIL
28	1	1	NIL	NIL	NIL	NIL
29-30	NIL	NIL	NIL	NIL	NIL	NIL
31	5	4	5	3	5	3
32	5	4	5	3	5	3
33	NIL	NIL	NIL	NIL	NIL	NIL
34	6	6	6	5	6	5
35	6	6	6	6,5	6	6,5
36	9	8	9	8,6	9	8,6
37	9	8	9	8	9	8
38	11	11	11	11	11	11
39	11	11	11	11	11	11
40	7	7	7	7	7	7
41	7	7	7	7	7	7
42	2	2	1	NIL	1	NIL
43	2	2	1	NIL	1	NIL
44-52	NIL	NIL	NIL	NIL	NIL	NIL
LOLE(d/y)	0.127461	0.297974	0.130389	0.309202	0.130389	0.309202

Fewer weeks are occupied by the generation units in Plans 3 and 4 which take advantage of the increase in the MNU. The plans constructed with a MNU of 2 and 3 are identical with both peak loads. One reason is that the generating units were not required to exceed the value of MNU of 2 when Plans 5 and 6 were constructed. Another reason is that the criterion order did not change with the change in the MNU.

Figure 5.7 shows that the risk with the higher peak load is more than the risk with the lower peak load for most weeks and exceeds the desired risk level of 1/52 days/week in weeks 50 and 51 due to the shape of the load model.

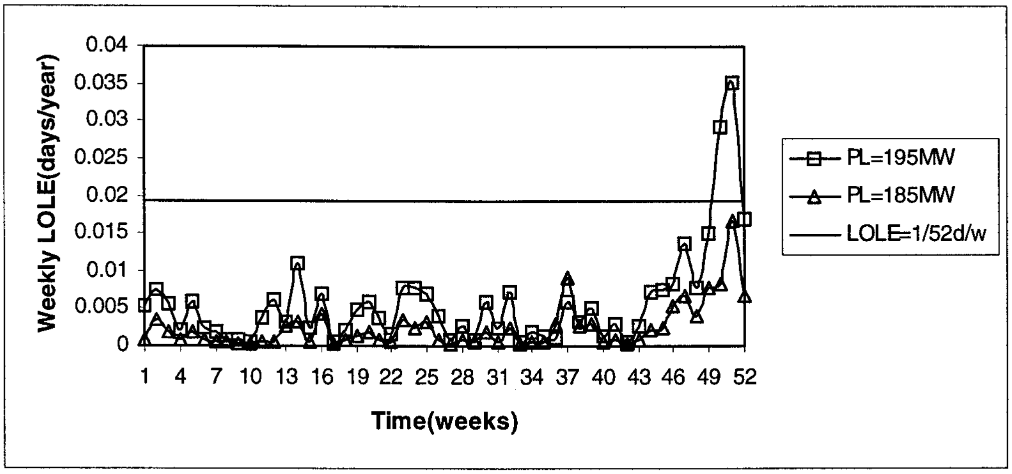

Figure 5.7: The weekly LOLE with a desired criterion of 1/52 days/week for system peak loads of 195MW and 185 MW with MNU = 1.

Figure 5.8 shows that the system risk increases as the system peak load increases. Both profiles however are basically level and not affected by the MNU value.

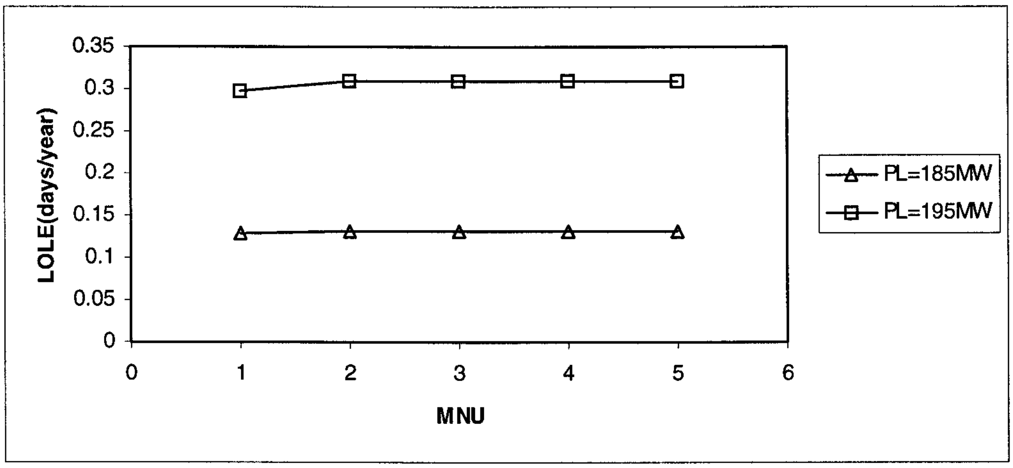

Figure 5.8: The annual LOLE with variable MNU and system peak loads of 185 and 195 MW.

As the peak load increases, the LOLE profile will increase to the point at which that the system cannot handle the increase in the peak load.

5.2.3. Reserve levelization

The reserve levelization technique is a deterministic approach and there are no probabilistic quantities involved in the process. There is therefore no effect on maintenance scheduling due to changing the FOR with this technique. In this section, the effect of changing the system peak load is examined with changes in the MNU. A 195 MW system peak load is used and Table 5.5 shows the resulted plans.

Table 5.5: Maintenance schedule for the RBTS with a reserve criterion of 30 MW and peak loads of 185 and 195 MW.

	MNU =1		MNU =2		MNU =3	
	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW
WEEK	Plan # 1	Plan #2	Plan # 3	Plan # 4	Plan #5	Plan # 6
1-8	NIL	NIL	NIL	NIL	NIL	NIL
9	3	3	1	1	1	1
10	3	3	2,1	2,1	2,1	2,1
11	8	8	8,2	8,2	8,2	8,2
12	8	8	8	8	8	8
13	10	10	10	10	10	10
14	10	10	10	10	10	10
15	7	7	7	7	7	7
16	7	7	7	7	7	7
17	1	1	NIL	NIL	NIL	NIL
18	1	1	NIL	NIL	NIL	NIL
19-30	NIL	NIL	NIL	NIL	NIL	NIL
31	6	6	6	6	6	6
32	6	6	6	6	6	6
33	NIL	NIL	NIL	NIL	NIL	NIL
34	4	4	3	3	3	3
35	4	4	4,3	4,3	4,3	4,3
36	9	9	9,4	9,4	9,4	9,4
37	9	9	9	9	9	9
38	11	11	11	11	11	11
39	11	11	11	11	11	11
40	5	5	5	5	5	5
41	5	5	5	5	5	5
42	2	2	NIL	NIL	NIL	NIL
43	2	2	NIL	NIL	NIL	NIL
44-52	NIL	NIL	NIL	NIL	NIL	NIL

Table 5.5 shows that all the plans constructed for the 185 MW peak load are identical to the corresponding ones built for the 195 MW peak load. The plans built for a peak load of 185 MW are still valid for the 195 MW load level.

These plans remain valid with increase in the system peak load until the system reaches a point where it cannot take further increase in the peak load. The system then changes to other plans, which can cope with the increase in the peak load. At some point the system peak load increases to a level at which no maintenance plan can be constructed.

Figure 5.9 shows the weekly reserve for Plans 3 and 4 from Table 5.5. The weekly reserve obtained for the 195 MW peak load is always lower than that for the 185 MW peak load. This is to be expected since the two plans are identical.

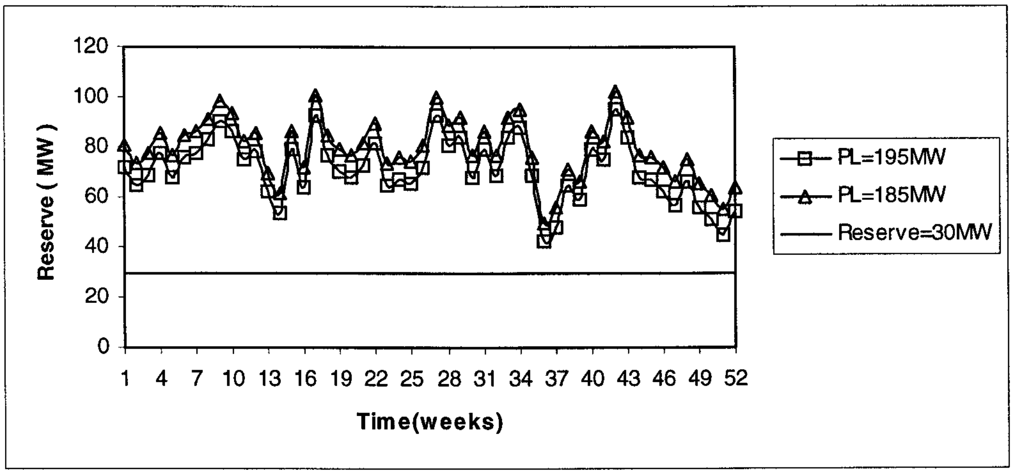

Figure 5.9: The weekly reserve with MNU = 2 for system peak loads of 185 and 195 MW using a criterion reserve of 30 MW.

5.2.4. Loss of the largest unit

The loss of the largest unit technique is also a deterministic approach, and therefore, does not respond to changes in the FOR. The change in the system peak load with changes in the MNU is examined in this section. A peak load of 195 MW is used and the resulting maintenance schedules are compared with the other plans obtained at the 185 MW load level.

The RBTS has three generating units with a capacity of 40 MW. Although two of these three units have derated states, the deterministic techniques do not distinguish between these units. The three 40 MW units are considered to be identical in the deterministic applications. The three units are scheduled in different periods in the plans shown in Table 4.16. As a result, the capacity of the largest unit is fixed at 40 MW for the entire year. The same results can be achieved using the reserve levelization technique if a reserve criterion of 40 MW is selected. In fact, the results found with the reserve criterion of 30 MW are identical to the ones obtained with the loss of the largest unit technique as shown in Tables 4.13 and 4.16.

The results presented in Table 5.5 obtained using the reserve levelization technique are identical to the results obtained using the loss of the largest unit technique.

5.3. The effect of the load model on maintenance scheduling

The maintenance schedules obtained using probabilistic and deterministic criteria are obviously highly related to the annual load model used in the analysis. The load model used in both the RBTS and the RTS studies is shown in Figure 2.2. This model was initially developed as part of the RTS. The daily loads in the original model were utilized to create a new load model with a distinctly different chronological profile. The new model, shown in Figure 5.10, represents a winter peaking system with relatively low loads in the in the summer period. A range of maintenance scheduling studies was conducted using the new load model to examine the effect of load profile changes on the resulting plans.

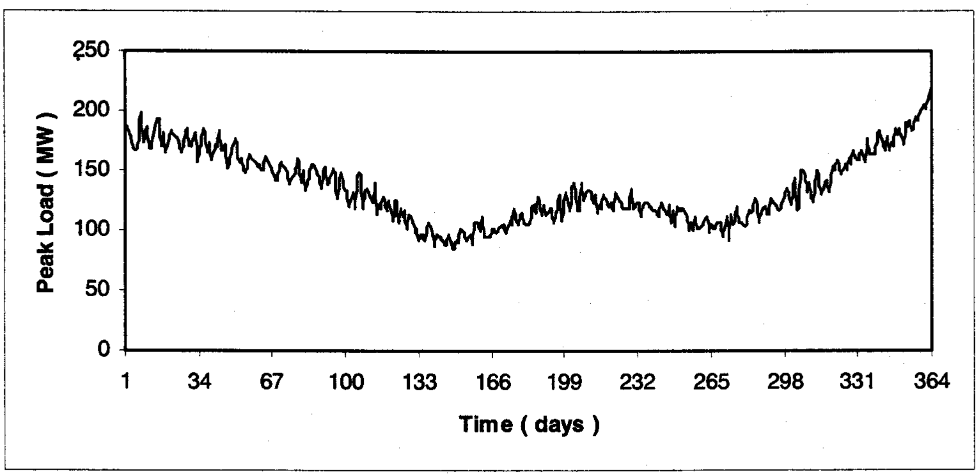

Figure 5.10: The new load model.

The criteria applied with the new load model are the same as those used with the original load model in order to easily see the effect of the load model change.

5.3.1. The effect of unit FOR on maintenance scheduling

This section presents the effects on the maintenance schedule of changes in the forced outage rate of unit 9 with the new load model. The FOR of unit 9 is changed from 0.005 to 0.04 with a step of 0.005. The MNU is held at 3. The deterministic techniques are not affected by changes in the FOR.

The maintenance schedules obtained with the health levelization technique were first examined with the new load model. A desired health criterion of 0.9 was selected.

Table 5.6 shows the maintenance plans constructed using the health levelization technique. The generating units are basically scheduled for maintenance during the off peak periods.

Table 5.6: Maintenance schedules for the RBTS with a peak load of 185 MW and a P(H) of 0.9.

Plan FOR	Plan # 1 0.005	Plan # 2 0.01	Plan # 3 0.015	Plan # 4 0.02
WEEK				
1-18	NIL	NIL	NIL	NIL
19	7	5	5	5
20	7	11,5	9,5	6,5
21	2,1	11	9	7,6
22	9,2,1	6	10	7
23	9	8,6	10	9
24	6	10,8	4	9
25	6	10	7,4	3
26	5	9	7	8,3
27	5	9	NIL	8
28	10	1	3	2
29	10	1	3	2
30-34	NIL	NIL	NIL	NIL
35	NIL	NIL	NIL	NIL
36	3	2	1	NIL
37	4,3	3,2	6,1	4
38	11,4	4,3	8,6	10,4
39	11	7,4	11,8	11,10
40	8	7	11	11
41	8	NIL	2	1
42	NIL	NIL	2	1
43-52	NIL	NIL	NIL	NIL
P(H)	0.994972	0.994264	0.993551	0.993524

Table 5.6: (Continued).

Plan FOR	Plan # 5 0.025	Plan # 6 0.03	Plan # 7 0.035	Plan # 8 0.04
WEEK				
1-18	NIL	NIL	NIL	NIL
19	4	4	5	6
20	9,4	11,4	11,5	9,6
21	9	11	11	9
22	10	8	8	11
23	10	10,8	8	11
24	11	10	9	8
25	11	6	9	8
26	5	9,6	7	7
27	5	9	7	7
28	3	2	3	3
29	3	2	3	3
30-34	NIL	NIL	NIL	NIL
35	1	NIL	1	1
36	2,1	1	2,1	2,1
37	7,2	3,1	4,2	4,2
38	8,7	7,3	10,4	10,4
39	8	7	10	10
40	6	5	6	5
41	6	5	6	5
42	NIL	NIL	NIL	NIL
43-52	NIL	NIL	NIL	NIL
P(H)	0.992168	0.991437	0.990745	0.990043

It can be seen from Table 5.6 that the three largest units change their positions as the FOR changes. This is due to the criterion order which is affected by changes in the FOR. This was not the case with the original load model.

The new load model was examined using the risk levelization technique. A risk criterion of 1/52 days/week was chosen. The FOR for unit 9 again ranged from 0.005 to 0.04 with a step of 0.005.

Table 5.7 shows the maintenance plan constructed for the RBTS using the risk levelization technique. Plan 2 was built to satisfy the selected risk criterion with a FOR of 0.01 for unit 9. A new plan was created when the FOR was increased to 0.015 due to the creation of a different criterion order. Plans 4,5,6 and 7 are identical to Plan 2 due to the creation of a similar criterion order. The high system reliability created by the available system reserve makes it relatively easy to achieve the selected criterion. Plan 8 is quite different due to the new criterion order.

Table 5.7: Maintenance schedules for the RBTS with a peak load of 185 MW and a LOLE of 1/52 days/week.

Plan FOR	Plan # 1 0.005	Plan # 2 0.01	Plan # 3 0.015	Plan # 4 0.02	Plan # 5 0.025	Plan # 6 0.03	Plan # 7 0.035	Plan # 8 0.04
WEEK								
1-18	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL
19	7	6	6	6	6	6	6	5
20	10,7	10,6	10,6	10,6	10,6	10,6	10,6	10,5
21	10	11,10	11,10	11,10	11,10	11,10	11,10	11,10
22	11	11	11	11	11	11	11	11
23	11	8	9	8	8	8	8	9
24	8	9,8	9	9,8	9,8	9,8	9,8	9
25	8	9	7	9	9	9	9	7
26	5	4	7	4	4	4	4	7
27	5	4	NIL	4	4	4	4	NIL
28	3	2	3	2	2	2	2	3
29	3	2	3	2	2	2	2	3
30-34	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL
35	1	NIL	1	NIL	NIL	NIL	NIL	NIL
36	2,1	1	2,1	1	1	1	1	2
37	6,2	5,1	5,2	5,1	5,1	5,1	5,1	4,2
38	9,6	7,5	8,5	7,5	7,5	7,5	7,5	6,4
39	9	7	8	7	7	7	7	8,6
40	4	3	4	3	3	3	3	8
41	4	3	4	3	3	3	3	1
42	NIL	NIL	NIL	NIL	NIL	NIL	NIL	1
43-52	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL
LOLE	0.019664	0.024687	0.029616	0.034804	0.039863	0.044921	0.049980	0.055005

5.3.2. The effect of the MNU on maintenance scheduling

The effect of the maximum number of units allowed on maintenance in a single week with the new load model is studied in this section. The four developed techniques are examined in this case. The MNU was varied from 1 to 5. The forced outage rate of unit 9 is the original value of 0.02 in this study.

The health levelization technique using a weekly health criterion of P(H) = 0.9 was applied to the new load model. The plans constructed using the health levelization technique with MNU of 4 and 5 are not shown in Table 5.8 because they are identical to Plan 3.

Table 5.8: Maintenance schedules for the RBTS with a peak load of 185 MW and a P(H) of 0.9.

Plan MUN	Plan # 1 1	Plan # 2 2	Plan # 3 3
WEEK			
1-16	NIL	NIL	NIL
17	1	NIL	NIL
18	1	NIL	NIL
19	7	5	5
20	7	6,5	6,5
21	9	7,6	7,6
22	9	7	7
23	10	9	9
24	10	9	9
25	NIL	3	3
26	8	8,3	8,3
27	8	8	8
28	5	2	2
29	5	2	2
30-32	NIL	NIL	NIL
33	2	NIL	NIL
34	2	NIL	NIL
35	3	NIL	NIL
36	3	NIL	NIL
37	6	4	4
38	6	10,4	10,4
39	11	11,10	11,10
40	11	11	11
41	4	1	1
42	4	1	1
43	NIL	NIL	NIL
44-52	NIL	NIL	NIL
P(H)	0.992810	0.993524	0.993524

It can be seen from Table 5.8 that units 10 and 11 in Plan 2 overlap in week 39. That occurs because after scheduling unit 11, the criterion order is revised and week 38 comes first so that unit 10 is scheduled in this week and the following one. It is clear from the last row in Table 5.8 that the annual health increased when the MNU increased from 1 to 2. The reason for this is that with a MNU of 2, there is more flexibility for the generating units to follow the criterion order. With a MNU of 1, the units are forcibly scheduled in weeks which are relatively low down in the criterion order because a unit has already been scheduled in the weeks higher up in the order.

The effect of the change in the MNU was examined using the risk levelization technique and the new load model. A criterion risk level of 1/52 days/week was used. The FOR for unit 9 was held at 0.02. The constructed plans are shown in Table 5.9.

Table 5.9: Maintenance Schedules for the RBTS with a peak load of 185 MW and a LOLE of 1/52 days/week.

Plan MUN	Plan # 1 1	Plan # 2 2	Plan # 3 3
WEEK			
1-16	NIL	NIL	NIL
17	1	NIL	NIL
18	1	NIL	NIL
19	8	6	6
20	8	10,6	10,6
21	11	11,10	11,10
22	11	11	11
23	NIL	8	8
24	10	9,8	9,8
25	10	9	9
26	7	4	4
27	7	4	4
28	5	2	2
29	5	2	2
30-32	NIL	NIL	NIL
33	2	NIL	NIL
34	2	NIL	NIL
35	NIL	NIL	NIL
36	4	1	1
37	4	5,1	5,1
38	9	7,5	7,5
39	9	7	7
40	6	3	3
41	6	3	3
42	3	NIL	NIL
43	3	NIL	NIL
44-52	NIL	NIL	NIL
LOLE (d/y)	0.034491	0.034804	0.034804

Table 5.9 shows that the generating units are again scheduled during the off peak periods. It can also be seen from the table that the annual risk increases slightly with the increase in the MNU as the reliability of the system is negatively affected by having more units out for maintenance at the same time.

The effect of the allowable maximum number of units on maintenance in a single week was examined using the deterministic techniques. Table 5.10 shows the maintenance plans constructed using the reserve levelization technique and a reserve criterion of 30 MW.

Table 5.10: Maintenance schedules for the RBTS with a peak load of 185 MW and a reserve criterion of 30 MW.

Plan MUN	Plan # 1 1	Plan # 2 2	Plan # 3 3
WEEK			
1-18	NIL	NIL	NIL
19	7	5	5
20	7	10,5	10,5
21	11	11,10	11,10
22	11	11	11
23	10	9	9
24	10	9	9
25	9	8	8
26	9	8	8
27	NIL	NIL	NIL
28	4	3	3
29	4	3	3
30-31	NIL	NIL	NIL
32	1	NIL	NIL
33	1	NIL	NIL
34	3	NIL	NIL
35	3	1	1
36	5	2,1	2,1
37	5	4,2	4,2
38	8	6,4	6,4
39	8	7,6	7,6
40	6	7	7
41	6	NIL	NIL
42	2	NIL	NIL
43	2	NIL	NIL
44	NIL	NIL	NIL
45-52	NIL	NIL	NIL

Table 5.10 shows that as the MNU increases, more generating units are taken out in some periods which results in fewer weeks being needed for maintenance.

The effect of changing the MNU was also examined using the loss of the largest unit technique and the new load model. Table 5.11 shows the maintenance plans built using the loss of the largest unit approach with a system peak load of 185 MW.

Table 5.11: Maintenance schedules for the RBTS with a peak load of 185 MW and the loss of the largest unit as the criterion.

Plan MUN	Plan # 1 1	Plan # 2 2	Plan # 3 3
WEEK			
1-18	NIL	NIL	NIL
19	7	5	5
20	7	10,5	10,5
21	11	11,10	11,10
22	11	11	11
23	10	9	9
24	10	9	9
25	9	8	8
26	9	8	8
27	NIL	NIL	NIL
28	4	3	3
29	4	3	3
30-31	NIL	NIL	NIL
32	1	NIL	NIL
33	1	NIL	NIL
34	3	NIL	NIL
35	3	1	1
36	5	2,1	2,1
37	5	4,2	4,2
38	8	6,4	6,4
39	8	7,6	7,6
40	6	7	7
41	6	NIL	NIL
42	2	NIL	NIL
43	2	NIL	NIL
44	NIL	NIL	NIL
45-52	NIL	NIL	NIL

The plans shown in Table 5.11 are identical to the corresponding plans shown in Table 5.10. The three largest units with 40 MW capacity are not scheduled at the same time and therefore, the capacity of the largest unit is 40 MW for the entire year. This is equivalent to using the reserve levelization technique with a reserve criterion of 40 MW. These two sets of maintenance plans are identical because the criterion order is the same for the two criteria.

5.3.3. The effect of system peak load on maintenance scheduling

The effect of increasing the system peak load using the new load model was studied with respect to variation in the FOR of unit 9 and the MNU.

A comparison of the resulting maintenance schedules obtained with the health levelization technique for the new load model with the two peak loads is shown in Table 5.12. A MNU of 3 was used.

Table 5.12: Maintenance schedule for the RBTS with a P(H) of 0.9 and peak loads of 185 and 195 MW

	FOR = 0.005		FOR = 0.02		FOR = 0.04	
	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW
WEEK	Plan # 1	Plan #2	Plan # 3	Plan # 4	Plan #5	Plan # 6
1-17	NIL	NIL	NIL	NIL	NIL	NIL
18	NIL	1	NIL	NIL	NIL	3
19	7	6,1	5	5	6	6,3
20	7	8,6	6,5	9,5	9,6	10,6
21	2,1	8,3	7,6	9	9	10
22	9,2,1	9,3	7	8,3	11	11
23	9	9	9	11,8,3	11	11
24	6	10	9	11	8	8,1
25	6	10	3	6	8	8,1
26	5	4	8,3	6	7	4
27	5	4	8	NIL	7	4
28	10	NIL	2	NIL	3	NIL
29	10	NIL	2	NIL	3	NIL
30-34	NIL	NIL	NIL	NIL	NIL	NIL
35	NIL	NIL	NIL	NIL	1	NIL
36	3	2	NIL	1	2,1	2
37	4,3	5,2	4	4,1	4,2	5,2
38	11,4	11,5	10,4	7,4	10,4	9,5
39	11	11	11,10	10,7	10	9
40	8	7	11	10	5	7
41	8	7	1	2	5	7
42	NIL	NIL	1	2	NIL	NIL
43-52	NIL	NIL	NIL	NIL	NIL	NIL
P(H)	0.994972	0.991629	0.993524	0.988595	0.990043	0.984961

It can be seen from the table that the reliability constraints are more relaxed at the 185MW peak load level and the schedule expands. With the 195 MW peak load, the generating units are squeezed into the off peak periods in order to avoid the high load periods which have lower health.

The new load model revealed a weakness in the procedure used to schedule maintenance. The original load model has two off peak periods. These periods are generally wider than the off peak periods in the new load model. This difference results in some overlapping between the generating unit maintenance periods for the new load model. This can be seen in Table 5.12 with units 8 and 11 in Plan 4 and units 10 and 11 in Plan 3.

The developed technique schedules the generating units in the corresponding week and in the next week. A better way is to examine the next week and also the previous week and then select the best weeks.

The risk levelization technique was used with the new load model to create maintenance plans for the RBTS with a desired criterion of 1/52 days/week and the 195 MW peak load. Table 5.13 shows a comparison between the maintenance plans created with the 185 and 195 MW peak loads.

Table 5.13: Maintenance schedule for the RBTS with a LOLE of 1/52 days/week and peak loads of 185 and 195 MW.

	FOR = 0.005		FOR = 0.02		FOR = 0.04	
	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW
WEEK	Plan # 1	Plan #2	Plan # 3	Plan # 4	Plan #5	Plan # 6
1-17	NIL	NIL	NIL	NIL	NIL	NIL
18	NIL	2	NIL	NIL	NIL	NIL
19	7	6,2	6	5	5	5
20	10,7	10,6	10,6	10,5	10,5	9,5
21	10	10	11,10	11,10	11,10	10,9
22	11	11	11	11	11	11,10
23	11	11	8	8,1	9	11
24	8	9	9,8	9,8,1	9	8
25	8	9	9	9	7	8
26	5	4	4	3	7	3
27	5	4	4	3	NIL	3
28	3	1	2	NIL	3	NIL
29	3	1	2	NIL	3	NIL
30-34	NIL	NIL	NIL	NIL	NIL	NIL
35	1	NIL	NIL	NIL	NIL	NIL
36	2,1	3	1	NIL	2	1
37	6,2	5,3	5,1	4	4,2	4,1
38	9,6	8,5	7,5	6,4	6,4	6,4
39	9	8	7	7,6	8,6	7,6
40	4	7	3	7	8	7
41	4	7	3	2	1	2
42	NIL	NIL	NIL	2	1	2
43-52	NIL	NIL	NIL	NIL	NIL	NIL
LOLE	0.019664	0.046533	0.034804	0.078969	0.055005	0.121384

The generating units are generally scheduled in the same way in Plans 1 and 2. In the other plans developed for the 195 MW peak load, the units are grouped in the off peak periods in a narrower range. The FOR in Plan 2 is low, therefore, the risk is relatively low and provides more flexibility for the schedule to expand. The last row in Table5.13 shows that the annual risk increases with increase in the peak load.

The effect of changing the system peak load in the new load model was also examined with respect to the MNU using the four techniques. Table 5.14 shows a comparison between the maintenance plans constructed with the health levelization technique for the 185 and 195 MW peak loads.

Table 5.14: Maintenance schedule for the RBTS with peak loads of 185 and 195 MW and a P(H) of 0.9.

	MNU=1		MNU = 2		MNU = 3	
	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW
WEEK	Plan # 1	Plan #2	Plan # 3	Plan # 4	Plan #5	Plan # 6
1-16	NIL	NIL	NIL	NIL	NIL	NIL
17	1	NIL	NIL	NIL	NIL	NIL
18	1	5	NIL	1	NIL	NIL
19	7	5	5	5,1	5	5
20	7	9	6,5	9,5	6,5	9,5
21	9	9	7,6	9	7,6	9
22	9	NIL	7	8	7	8,3
23	10	11	9	11,8	9	11,8,3
24	10	11	9	11	9	11
25	NIL	8	3	6	3	6
26	8	8	8,3	6	8,3	6
27	8	4	8	NIL	8	NIL
28	5	4	2	NIL	2	NIL
29	5	NIL	2	NIL	2	NIL
30	NIL	NIL	NIL	NIL	NIL	NIL
31	NIL	1	NIL	NIL	NIL	NIL
32	NIL	1	NIL	NIL	NIL	NIL
33	2	2	NIL	NIL	NIL	NIL
34	2	2	NIL	NIL	NIL	NIL
35	3	3	NIL	NIL	NIL	NIL
36	3	3	NIL	2	NIL	1
37	6	7	4	4,2	4	4,1
38	6	7	10,4	7,4	10,4	7,4
39	11	10	11,10	10,7	11,10	10,7
40	11	10	11	10	11	10
41	4	6	1	3	1	2
42	4	6	1	3	1	2
43-52	NIL	NIL	NIL	NIL	NIL	NIL
P(H)	0.992810	0.988783	0.993524	0.988742	0.993524	0.988595

It can be seen from Table 5.14 that the schedules constructed with the lower peak load have higher annual P(H). The schedules stabilize with respect to the MNU sooner with the lower peak load. The reason is that at the higher peak load, the generating units are constrained by the MNU where, with the lower peak load, the generating units are comfortable with a MNU of 2.

The risk levelization technique was used to obtain maintenance plans for the new load model and a peak load of 195 MW. The same risk criterion was used as in the original load model case. A comparison between the plans created for the 185 and 195 MW peak loads is shown in Table 5.15.

Table 5.15: Maintenance schedule for the RBTS with peak loads of 185 and 195 MW and a LOLE of 1/52 days/week.

	MNU=1		MNU = 2		MNU = 3	
	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW
WEEK	Plan # 1	Plan #2	Plan # 3	Plan # 4	Plan #5	Plan # 6
1-16	NIL	NIL	NIL	NIL	NIL	NIL
17	1	NIL	NIL	NIL	NIL	NIL
18	1	NIL	NIL	NIL	NIL	NIL
19	8	8	6	5	6	5
20	8	8	10,6	10,5	10,6	10,5
21	11	11	11,10	11,10	11,10	11,10
22	11	11	11	11	11	11
23	NIL	NIL	8	8	8	8,1
24	10	10	9,8	9,8	9,8	9,8,1
25	10	10	9	9	9	9
26	7	6	4	3	4	3
27	7	6	4	3	4	3
28	5	4	2	NIL	2	NIL
29	5	4	2	NIL	2	NIL
30	NIL	NIL	NIL	NIL	NIL	NIL
31	NIL	1	NIL	NIL	NIL	NIL
32	NIL	1	NIL	NIL	NIL	NIL
33	2	2	NIL	NIL	NIL	NIL
34	2	2	NIL	NIL	NIL	NIL
35	NIL	3	NIL	NIL	NIL	NIL
36	4	3	1	1	1	NIL
37	4	7	5,1	4,1	5,1	4
38	9	7	7,5	6,4	7,5	6,4
39	9	9	7	7,6	7	7,6
40	6	9	3	7	3	7
41	6	5	3	2	3	2
42	3	5	NIL	2	NIL	2
43	3	NIL	NIL	NIL	NIL	NIL
44-52	NIL	NIL	NIL	NIL	NIL	NIL
LOLE	0.034491	0.078385	0.034804	0.078773	0.034804	0.078969

It can be seen from Table 5.15 that the maintenance plans created with the 185 MW peak load settle down sooner than the plans created with the higher peak load. Plans 3 and 5 are identical. This is not the case with Plans 4 and 6. As the MNU reaches 2 for the lower peak load, the generating units follow the criterion order without skipping some weeks in the order as in the case of a lower MNU value. This is not the case with the higher peak load where the generating units are constrained by the MNU value while trying to follow the criterion order without skipping any weeks in the order.

The maintenance schedules obtained with the reserve levelization technique are shown in Table 5.16.

Table 5.16: Maintenance schedules for the RBTS with peak loads of 185 and 195 MW and a reserve criterion of 30 MW.

	MNU=1		MNU = 2		MNU = 3	
	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW
WEEK	Plan # 1	Plan #2	Plan # 3	Plan # 4	Plan #5	Plan # 6
1-18	NIL	NIL	NIL	NIL	NIL	NIL
19	7	7	5	5	5	5
20	7	7	10,5	10,5	10,5	10,5
21	11	11	11,10	11,10	11,10	11,10
22	11	11	11	11	11	11
23	10	10	9	9	9	9
24	10	10	9	9	9	9
25	9	9	8	8	8	8
26	9	9	8	8	8	8
27	NIL	NIL	NIL	NIL	NIL	NIL
28	4	4	3	3	3	3
29	4	4	3	3	3	3
30-31	NIL	NIL	NIL	NIL	NIL	NIL
32	1	1	NIL	NIL	NIL	NIL
33	1	1	NIL	NIL	NIL	NIL
34	3	3	NIL	NIL	NIL	NIL
35	3	3	1	1	1	1
36	5	5	2,1	2,1	2,1	2,1
37	5	5	4,2	4,2	4,2	4,2
38	8	8	6,4	6,4	6,4	6,4
39	8	8	7,6	7,6	7,6	7,6
40	6	6	7	7	7	7
41	6	6	NIL	NIL	NIL	NIL
42	2	2	NIL	NIL	NIL	NIL
43	2	2	NIL	NIL	NIL	NIL
44	NIL	NIL	NIL	NIL	NIL	NIL
45-52	NIL	NIL	NIL	NIL	NIL	NIL

As can be seen from the table, the maintenance plans created for the 195 MW peak load are identical to the plans constructed for the 185 MW peak load. This indicates that the weekly reserve criterion was not violated by the increase in the system peak load in the plans that were constructed at the lower peak load.

The loss of the largest unit technique was used to create the maintenance schedules for the new load model. These plans are the same as those shown in Table 5.16.

5.4. Conclusion

Increases in the system peak load affects the criterion order obtained using the probabilistic techniques and results in changes in the maintenance schedules. The deterministic techniques do not respond to this increase in the system peak load. These conclusions apply to both the original load model and the new profile used in this chapter.

This further reflects the insensitivity of the deterministic techniques with regard to system factors. The probabilistic techniques incorporate factors such as peak load levels and load profiles in the determination of risk and weekly criterion order and therefore respond to these factors.

Maintenance activities, as expected, are focused in the off peak periods for both the original load model and the new load model. Having the maintenance done during the low load periods results in enhanced system reliability. One of the main differences between the two load models is that the criterion order shows more response to FOR increases with the new load model than with the original load model.

Another phenomenon highlighted by the new load model is the increased overlapping in the generating unit maintenance periods. This was caused by the shape of the new load model, which has narrower off peak periods than the original load model. As a result, the maintenance activity has a higher response to increasing the MNU in the new load model.

6. UTILIZATION OF HEALTH AND RISK LEVELIZATION AS A DUAL CRITERION FOR MAINTENANCE SCHEDULING

6.1. Introduction

Four techniques for maintenance scheduling are presented in this thesis. Two of these are deterministic approaches and the other two incorporate probabilistic parameters. The research conducted indicates that probabilistic techniques provide a more valid assessment of the impact on the system of removing units for maintenance as they can incorporate the inherent uncertainties associated with generating facilities. These factors cannot be incorporated in the deterministic approaches. A new probabilistic technique is presented in this chapter which monitors both the risk and the health of the constructed maintenance schedules and attempts to levelize the probability of health and the loss of load expectation at the same time. In this way, the reliability of the resultant maintenance schedules is improved. This technique is designated as the health and risk levelization technique or the dual criteria technique. It is important to note that the use of dual probabilistic criteria for maintenance scheduling has, to the author's knowledge, not been previously reported.

Different scenarios have been considered with the new technique. This chapter illustrates the effect on the maintenance schedule of FOR variation, changes in the MNU and variable load levels using the dual criteria technique.

In the risk levelization technique, the weeks are sorted based on the LOLE and the generating units are scheduled starting from the week with the lowest risk. In the health levelization technique, the weeks are sorted based on the probability of health and the units are scheduled starting from the week with the highest probability of health. In the dual criteria technique, either sorting order can be used. If the probability of health is considered to be the important index then health sorting should be used. If the system risk is of greater concern then risk sorting should be used. In either case, both criteria are utilized as constraints in the scheduling process described in Section 3.2.

6.2. The effect of FOR on maintenance scheduling

The effect on the maintenance schedule of forced outage rate changes using the health and risk levelization technique was examined by changing the FOR for unit 9 in the RBTS from 0.005 to 0.04 with a step of 0.005.

Table 6.1 shows the maintenance plans constructed with a health criterion of 0.9 and a LOLE of 1/52 days/week. These parameters are the individual criteria used with the health levelization and the risk levelization techniques presented in Chapters 3 and 4. The plans shown in Table 6.1 are constructed using health ordering.

Table 6.1: Maintenance schedules for the RBTS with a peak load of 185 MW and dual criteria of LOLE = 1/52 days/week and P(H) = 0.9.

Plan FOR	Plan # 1 0.005	Plan # 2 0.01	Plan # 3 0.015	Plan # 4 0.02
WEEK				
1-8	NIL	NIL	NIL	NIL
9	2	2	1	2
10	5,2	5,2	5,1	5,2
11	8,5	8,5	8,5	8,5
12	8	8	8	8
13	10	10	10	10
14	10	10	10	10
15	3	3	4	3
16	3	3	4	3
17-30	NIL	NIL	NIL	NIL
31	6	6	6	6
32	6	6	6	6
33	NIL	NIL	NIL	NIL
34	4	4	2	4
35	4	4	3,2	4
36	9	9	9,3	9
37	9	9	9	9
38	11	11	11	11
39	11	11	11	11
40	7	7	7	7
41	7	7	7	7
42	1	1	NIL	1
43	1	1	NIL	1
44-52	NIL	NIL	NIL	NIL
P(H)	0.985515	0.984078	0.982017	0.981202
LOLE(d/y)	0.073878	0.092716	0.118867	0.130389

Table 6.1: (Continued).

Plan FOR	Plan # 5 0.025	Plan # 6 0.03	Plan # 7 0.035	Plan # 8 0.04
WEEK				
1-8	NIL	NIL	NIL	NIL
9	2	2	2	2
10	5,2	4,2	4,2	5,2
11	8,5	8,4	8,4	8,5
12	8	8	8	8
13	10	10	10	10
14	10	10	10	10
15	3	3	3	3
16	3	3	3	3
17-30	NIL	NIL	NIL	NIL
31	6	6	6	6
32	6	6	6	6
33	NIL	NIL	NIL	NIL
34	4	5	5	4
35	4	5	5	4
36	9	9	9	9
37	9	9	9	9
38	11	11	11	11
39	11	11	11	11
40	7	7	7	7
41	7	7	7	7
42	1	1	1	1
43	1	1	1	1
44-52	NIL	NIL	NIL	NIL
P(H)	0.979764	0.978326	0.976888	0.975450
LOLE(d/y)	0.149227	0.168064	0.186902	0.205740

Constructed plans can be driven either by the health criterion or by the risk criterion. It can be seen by comparing the plans shown in Table 6.1 with those obtained using the single criterion techniques and shown in Tables 4.1 and 4.4, that the plans in Table 6.1 are identical to the plans in Table 4.1. This means that in these cases the plans constructed using the dual criteria technique are mainly driven by the health criterion. The plans constructed using the risk levelization method are identical to those obtained with the health levelization approach except for Plan 3 in Table 4.1. The plans shown in Table 6.1 are driven by both the health and risk criteria.

Risk ordering was also considered and Figures 6.1 and 6.2 show the annual probability of health and LOLE respectively using both health and risk ordering. The figures also show the annual indices obtained using the single criterion techniques.

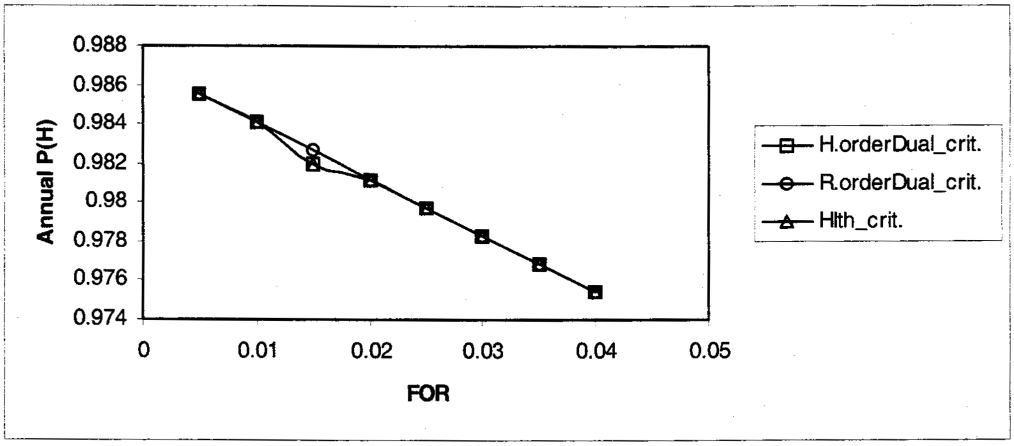

Figure 6.1: The annual probability of health with increase in the FOR using the health levelization technique and the dual criteria technique and health and risk ordering.

Figure 6.1 shows that the annual probability of health obtained using the health levelization technique and the dual criteria approach with health ordering are the same. The annual probability of health obtained using the dual criteria with risk ordering is quite different at a FOR of 0.015. This difference arises due to the change in the criterion order.

It can be concluded that the annual probability of health is improved using the dual criteria approach with risk ordering at a FOR of 0.015.

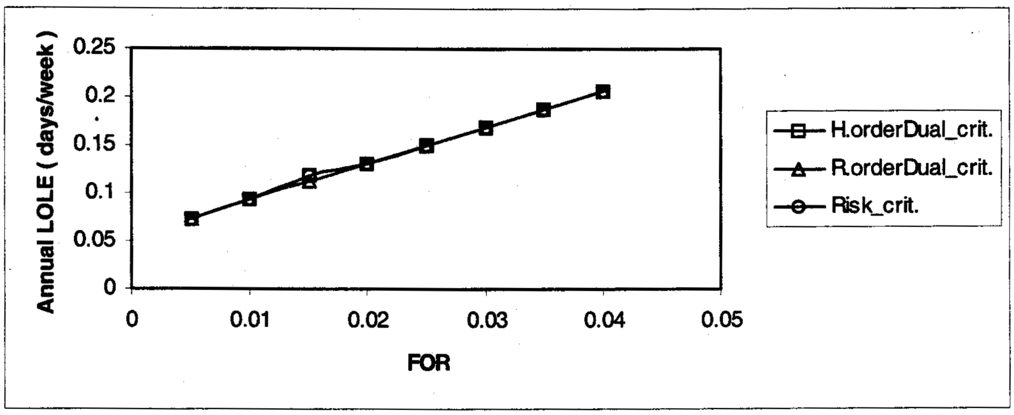

Figure 6.2: The annual LOLE with increase in the FOR using the risk levelization technique and the dual criteria technique and health and risk ordering.

The characteristic shown in Figure 6.2 indicates that the annual LOLE obtained using the single criterion technique and the dual criteria technique with health ordering are the same. The annual LOLE obtained using the dual criteria technique with risk ordering is different at a FOR = 0.015 for the reasons noted earlier. It can also be concluded that the annual risk is decreased using the dual criteria technique at a FOR = 0.015 (i.e. the constructed plan is improved).

Figure 6.3 shows the weekly health and risk for the maintenance plan constructed with FOR = 0.02 using the health and risk levelization approach.

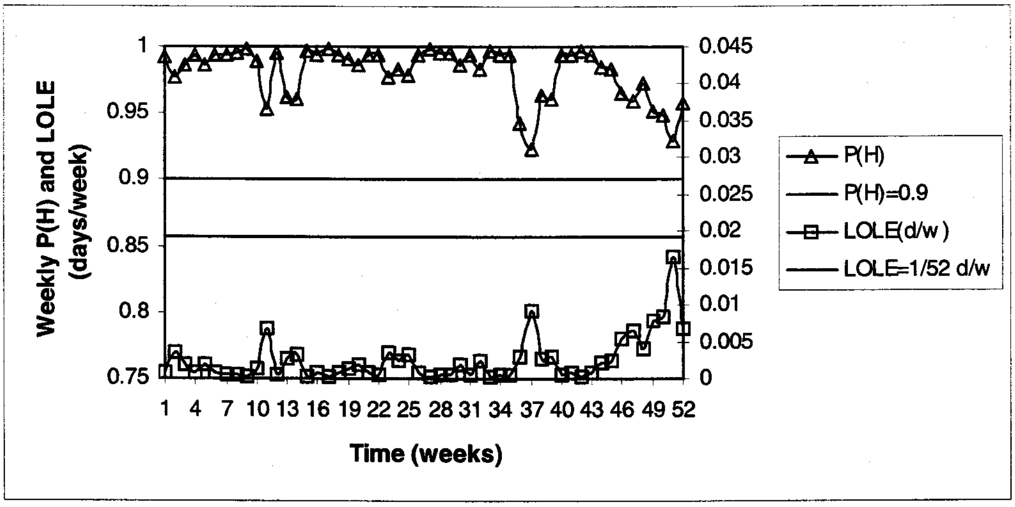

Figure 6.3: The weekly health and risk for the maintenance plan obtained using the dual criteria technique with FOR = 0.02.

The probability of health was held above the selected health level and the system risk was held below the selected risk level. Monitoring the health and risk of the constructed plan at the same time tends to enhance the system reliability associated with the constructed plans compared to those obtained using a single criterion technique. This is further illustrated later in this chapter.

6.3. The effect of the MNU on maintenance scheduling

The effect on the plans constructed with the dual criteria technique of changing the MNU was examined. The RBTS was used in this study and the forced outage rate for unit 9 held at 0.02. The MNU ranged from 1 to 5.

Table 6.2 shows the maintenance plans obtained with the dual criteria technique using health ordering. The plans constructed with MNU of 4 and 5 are identical to Plan 3 and are not shown in the table. The maintenance activity is again done during the low load periods.

Table 6.2: Maintenance schedules for the RBTS with a peak load of 185 MW a LOLE of 1/52 days/week and a P(H) of 0.9.

Plan MNU	Plan # 1 1	Plan # 2 2	Plan # 3 3
WEEK			
1-8	NIL	NIL	NIL
9	3	2	2
10	3	5,2	5,2
11	8	8,5	8,5
12	8	8	8
13	10	10	10
14	10	10	10
15	4	3	3
16	4	3	3
17-26	NIL	NIL	NIL
27	1	NIL	NIL
28	1	NIL	NIL
29-30	NIL	NIL	NIL
31	6	6	6
32	6	6	6
33	NIL	NIL	NIL
34	5	4	4
35	5	4	4
36	9	9	9
37	9	9	9
38	11	11	11
39	11	11	11
40	7	7	7
41	7	7	7
42	2	1	1
43	2	1	1
44-52	NIL	NIL	NIL
P(H)	0.981573	0.981202	0.981202
LOLE(d/y)	0.127461	0.130389	0.130389

The plans shown in Table 6.2 are identical to those shown in Tables 4.7 and 4.10. The plans presented in the latter two tables were created using the single criterion techniques. The same basic criteria are used in the single criteria and dual criteria techniques. The plans shown in Table 6.2 were constructed using health ordering. These plans are identical to those obtained with the single criterion techniques. The last two rows of the table show that the reliability of the constructed plans decreases as the MNU increases.

The annual probability of health and the annual risk obtained using the single risk techniques and the dual risk technique are identical as the derived maintenance schedules are the same in this case.

6.4. The effect on maintenance scheduling of the FOR with the increase in the system peak load

The effect on the maintenance schedule of changing the FOR for unit 9 was examined using the dual criteria technique in Section 6.2. Increasing the system peak load together with changing the FOR is illustrated in this section. The system peak load is increased to 195 MW and the forced outage rate for unit 9 varied from 0.005 to 0.04 with a step of 0.005.

Table 6.3 shows the maintenance plans constructed with the health and risk levelization technique. These plans were constructed using health ordering.

Table 6.3: Maintenance schedule for the RBTS with a LOLE of 1/52 days/week and a P(H) of 0.9 and peak loads of 185 and 195 MW.

	FOR = 0.005		FOR = 0.04	
	PL=185MW	PL=195MW	PL=185MW	PL=195MW
WEEK	Plan # 1	Plan #2	Plan #3	Plan # 4
1-8	NIL	NIL	NIL	NIL
9	2	1	2	1
10	5,2	2,1	5,2	2,1
11	8,5	9,2	8,5	9,2
12	8	9	8	9
13	10	10	10	10
14	10	10	10	10
15	3	4	3	4
16	3	4	3	4
17-30	NIL	NIL	NIL	NIL
31	6	3	6	3
32	6	3	6	3
33	NIL	NIL	NIL	NIL
34	4	5	4	5
35	4	6,5	4	6,5
36	9	8,6	9	8,6
37	9	8	9	8
38	11	11	11	11
39	11	11	11	11
40	7	7	7	7
41	7	7	7	7
42	1	NIL	1	NIL
43	1	NIL	1	NIL
44-52	NIL	NIL	NIL	NIL
P(H)	0.985515	0.972062	0.975450	0.956331
LOLE(d/y)	0.073878	0.186439	0.205740	0.472889

The plans are identical to those obtained with the single criterion technique shown in Tables 5.1 and 5.3.

The risk order was considered and the same results were found. The resulting plans are identical using the single criterion techniques and the dual criteria technique with both health and risk ordering. The reason for this is the selected criteria are satisfied for all the approaches for all weeks. This may not be true if the selected criteria are changed.

6.5. The effect of the MNU on maintenance scheduling with increase in the system peak load

The effect of changing the MNU was examined for the original system peak load of 185 MW in Section 6.3. In this section, the same condition is examined with a peak load of 195 MW. The forced outage rate is held at 0.02 for unit 9. Table 6.4 shows a comparison between the maintenance plans constructed with the 185 MW peak load and 195 MW peak load using the dual criteria technique.

Table 6.4 shows the same maintenance plans as those in Tables 5.2 and 5.4 constructed with the single criterion techniques. These plans are may not always be identical. If the calculated index in one or more weeks violate one of the selected criteria then the resulting schedule will be different.

The plans created with health ordering shown in Table 6.4 are identical to the plans created with risk ordering and results in the same annual indices for the plans constructed with both orders.

Table 6.4: Maintenance schedule for the RBTS with a LOLE of 1/52 days/week and a P(H) of 0.9 and peak loads of 185 and 195 MW.

	MNU=1		MNU = 2		MNU = 3	
	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW	PL= 185MW	PL= 195MW
WEEK	Plan # 1	Plan #2	Plan # 3	Plan # 4	Plan #5	Plan # 6
1-8	NIL	NIL	NIL	NIL	NIL	NIL
9	3	3	2	1	2	1
10	3	3	5,2	2,1	5,2	2,1
11	8	9	8,5	9,2	8,5	9,2
12	8	9	8	9	8	9
13	10	10	10	10	10	10
14	10	10	10	10	10	10
15	4	5	3	4	3	4
16	4	5	3	4	3	4
17-26	NIL	NIL	NIL	NIL	NIL	NIL
27	1	1	NIL	NIL	NIL	NIL
28	1	1	NIL	NIL	NIL	NIL
29-30	NIL	NIL	NIL	NIL	NIL	NIL
31	6	4	6	3	6	3
32	6	4	6	3	6	3
33	NIL	NIL	NIL	NIL	NIL	NIL
34	5	6	4	5	4	5
35	5	6	4	6,5	4	6,5
36	9	8	9	8,6	9	8,6
37	9	8	9	8	9	8
38	11	11	11	11	11	11
39	11	11	11	11	11	11
40	7	7	7	7	7	7
41	7	7	7	7	7	7
42	2	2	1	NIL	1	NIL
43	2	2	1	NIL	1	NIL
44-52	NIL	NIL	NIL	NIL	NIL	NIL
P(H)	0.981573	0.966042	0.981202	0.965320	0.981202	0.965320
LOLE(d/y)	0.127461	0.297974	0.130389	0.309202	0.130389	0.309202

6.6. Annual risk analysis

The results shown in this chapter were obtained considering a health criterion of 0.9 and a risk criterion of 1/52 days/week as the selected dual criteria. Using only one set of criteria may not reflect the utilization of the dual criteria technique, as the results presented in this chapter are identical to those presented in the previous chapters. In this section, more cases and scenarios are considered. The same group of health and risk criteria considered with the single criterion techniques is used to make the results obtained using the dual criteria technique comparable to those obtained using the single criterion techniques.

Table 6.5 shows the annual P(H) and LOLE obtained using the dual criteria technique with the weekly LOLE fixed at 0.0038 days/week and the weekly P(H) ranging from 0.85 to 0.94. The risk is used to create the criterion order in this case. The annual P(H) obtained using the health levelization approach is also shown in the table for the same range of weekly P(H). The annual LOLE obtained using the risk levelization approach is also shown with a weekly LOLE criterion of 0.0038 days/week. The same weekly criteria are used with all techniques for comparison purposes.

Table 6.5: The annual P(H) and LOLE using the dual criteria technique and the single criterion techniques.

	Dual crit.	Health levelization technique			Risk level. technique
MNU	Pw(H) = 0.85 – 0.94	Pw(H)=0.85	Pw(H)=0.9	Pw(H)=0.94	LOLEw=0.0038
1	0.982095 0.120111	0.981573	0.981573	0.981855	0.120111
2	0.982095 0.120111	0.980002	0.981202	0.980908	0.120111
3	0.982095 0.120111	0.980002	0.981202	0.980908	0.120111

It can be seen from Table 6.5 that the annual LOLE obtained using the dual criteria for all weekly P(H) values and all MNU values are the same as the corresponding values obtained using the risk levelization technique. The selected weekly LOLE criterion is sufficiently small that the same maintenance schedules result with the different weekly P(H) criteria. The maintenance schedules are driven by the risk criterion in this case. It also can be seen that the annual P(H) obtained with the dual criteria technique are higher than those evaluated using the health levelization approach. Utilizing the dual criteria technique improved the reliability of the resulting maintenance schedules in this case.

A LOLE weekly criterion, of 0.01 days/week was also considered. The weekly P(H) criterion was varied from 0.85 to 0.94. The resulting annual indices are shown in Figures 6.4 and 6.5. Figure 6.4 shows the annual LOLE obtained using the risk criterion technique and the dual criteria technique. The results obtained for the weekly LOLE criterion of 0.01 days/week are identical to those obtained earlier using 0.0166 and 0.0192 days/week.

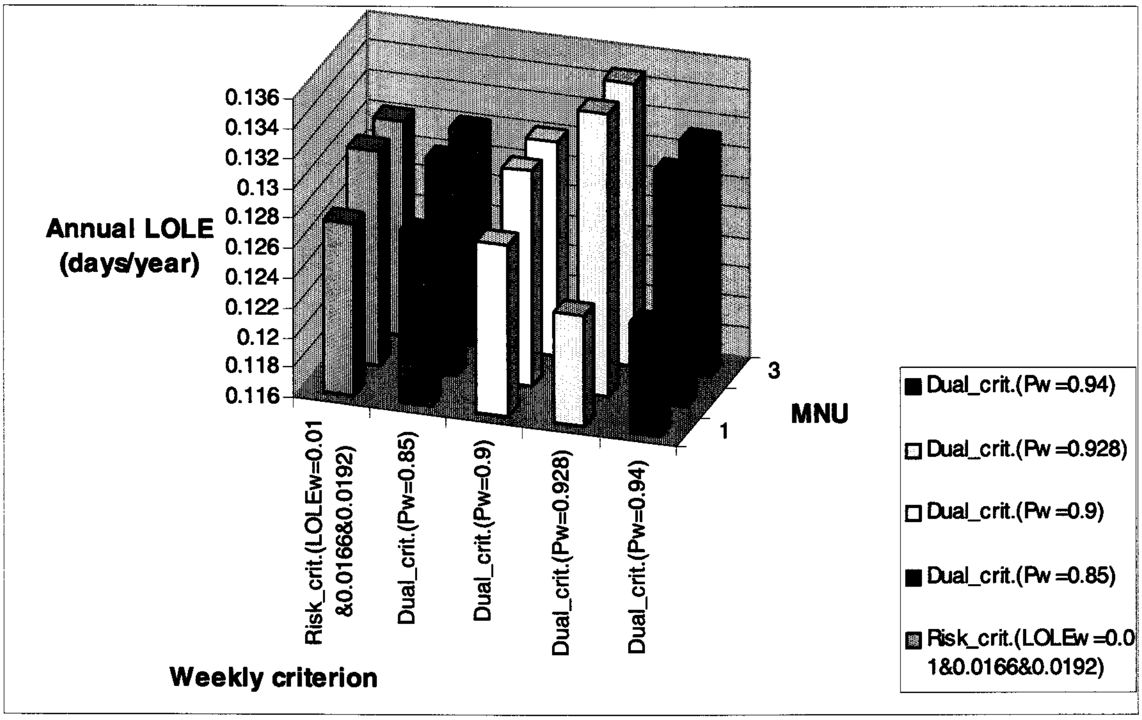

Figure 6.4: The annual LOLE obtained using the risk levelization technique and the dual criteria technique with risk ordering.

It can be seen from Figure 6.4 that the annual LOLE obtained using the risk criterion technique is the same as that obtained using the dual criteria technique with weekly P(H) of 0.85 and 0.9. The annual LOLE improves using the dual criteria technique as the weekly P(H) increases with a MNU of 1. A higher risk is obtained using the dual criteria technique with increase in the MNU. This is caused by the criterion order, which is risk oriented in this case. The 0.928 and 0.94 criteria, which are relatively high, are the driving criteria. If the health oriented order is utilized then the situation would be reversed. Figure 6.5 shows a similar figure but in this case the health order is used.

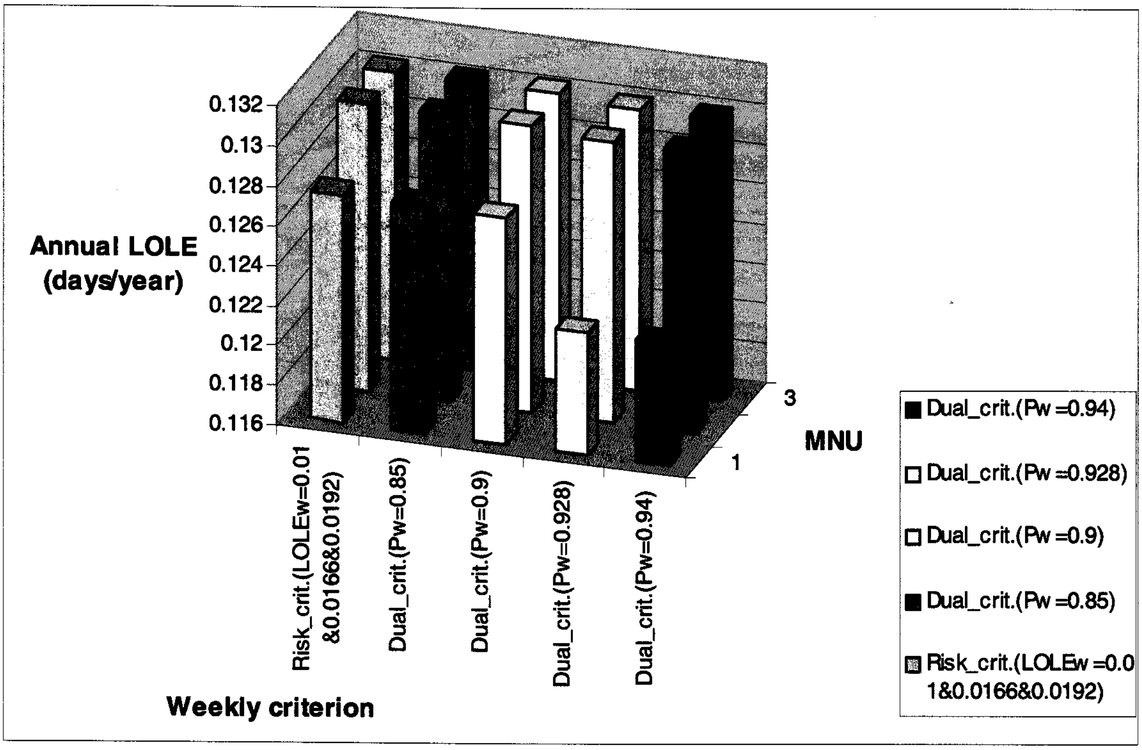

Figure 6.5: The annual LOLE obtained using the risk levelization technique and the dual criteria technique with health ordering.

As it can be seen from Figure 6.5, the annual LOLE either did not change or decreased when the dual criteria technique was used with all MNU values. This reflects the improvement in the resulted maintenance schedules obtained with the dual criteria technique. The same conclusion occurs if the annual P(H) is considered.

A higher weekly LOLE criterion of 0.1 days/week was considered. Table 6.6 shows a comparison table that compares the annual P(H) obtained using the single criteria technique and the dual criteria technique using health and risk ordering. The weekly P(H) criterion ranged from 0.85 to 0.94.

It can be seen from Table 6.6 that the annual P(H) obtained using the dual criteria technique with risk ordering is generally lower than that obtained using the health levelization technique and the dual criteria technique with health ordering. The selected risk criterion does not have any effect on the scheduling in this case due to its high value, which is easy to achieve, and therefore, the weekly health criterion drives the scheduling. This can be concluded from the annual P(H) obtained using the health levelization technique and the dual criteria technique with health sorting.

Table 6.6: The annual P(H) obtained using the health levelization technique and the dual criteria technique with the health and risk ordering.

MNU		Pw(H)=0.85	Pw(H)=0.9	Pw(H)=0.928	Pw(H)=0.94
1	A	0.981573	0.981573	0.981713	0.981713
	B	0.981573	0.981573	0.981855	0.981855
	C	0.981573	0.981573	0.981855	0.981855
2	A	0.980049	0.981202	0.980506	0.980723
	B	0.980002	0.981202	0.980908	0.980908
	C	0.980002	0.981202	0.980908	0.980908
3	A	0.980049	0.981202	0.980506	0.980723
	B	0.980002	0.981202	0.980908	0.980908
	C	0.980002	0.981202	0.980908	0.980908

A : Dual criteria with risk ordering
B : Dual criteria with health ordering
C : Health levelization technique

It also can be seen from Table 6.6 that with the health criterion controlling the scheduling, the annual P(H) obtained with the health order is higher than that obtained with the risk order. Table 6.7 shows that under those conditions, the annual LOLE is also improved. A LOLE weekly criterion of 0.1day/week was used in this table.

Table 6.7: The annual LOLE obtained using the risk levelization technique and the dual criteria technique with health and risk ordering

MNU		Pw(H)= 0.85	Pw(H)= 0.9	Pw(H)= 0.928	Pw(H)= 0.94	Risk level. technique
1	A	0.127461	0.127461	0.123343	0.123343	0.127461
	B	0.127461	0.127461	0.122184	0.122184	
2	A	0.148689	0.130389	0.134944	0.131541	0.148689
	B	0.148083	0.130389	0.130137	0.130137	
3	A	0.148689	0.130389	0.134944	0.131541	0.148689
	B	0.148083	0.130389	0.130137	0.130137	

A : Dual criterion with risk ordering
B : Dual criterion with health ordering

The risk criterion in Table 6.7 is relatively high and therefore the health drives the scheduling as noted earlier. The annual LOLE obtained using health ordering is in general lower than that obtained using risk ordering. The first column of the table shows that the annual LOLE obtained using the risk criterion technique is the same as the annual LOLE obtained using the dual criteria technique with risk criterion ordering because the health criterion in this case is relatively low and therefore does not drive the scheduling in this case.

Applying the dual criteria technique to the RBTS did not show a big difference between the maintenance schedules obtained using the single criterion approaches and the dual criteria technique. This is mainly due to the size and composition of the system, which has a number of generating units with identical capacities. In the following example, two generating units of 40 MW and 10 MW capacity are replaced by a single 50 MW unit. A risk criterion of 0.01 days/week and a health criterion of 0.92 are used. Table 6.8 shows three maintenance schedules obtained using the risk levelization approach, the health levelization technique and the dual criteria technique respectively.

It can be seen from Table 6.8 that the three maintenance schedules are each different. Unit 8, which has a 50 MW capacity, is scheduled in weeks 38 and 39 in all plans and no other units are scheduled at the same time because of the size of this unit and the criterion order. The plan constructed with the dual criteria technique has some similarities to the plan obtained with the health levelization technique, i.e. maintenance in weeks 9 and 10, 13 and 14, and 40 and 41. It has also some similarities with the plan obtained using the risk levelization technique in weeks 31 and 32, and 34 and 35. The rest of the maintenance activities are common in the three plans. As a result of this mixing, both the annual risk and the annual health decrease in the dual criteria approach. This technique is a new approach which requires further investigation regarding the benefit of using it on system of different size.

Table 6.8: Maintenance schedules using the single criterion and the dual criteria techniques.

WEEK	Risk	Health	Dual
1-8	NIL	NIL	NIL
9	NIL	1	1
10	1	1	1
11	10,1	10	10
12	10	10	10
13	9	7	7
14	9	7	7
15	4	3	4
16	4	3	4
17-30	NIL	NIL	NIL
31	3	2	3
32	3	2	3
33	NIL	NIL	NIL
34	2	4	2
35	5,2	5,4	5,2
36	7,5	6,5	6,5
37	7	6	6
38	8	8	8
39	8	8	8
40	6	9	9
41	6	9	9
42-52	NIL	NIL	NIL
P(H)		0.9614658	0.9612147
LOLE(d/y)	0.2462108		0.2439414

6.7. Conclusion

It was found that in general the maintenance schedules constructed with the dual criteria technique utilizing both health and risk constraints provide higher system reliability than the schedules obtained with a single criterion technique. Monitoring the health and the risk of the system at the same time and keeping them at acceptable levels improves the reliability of the constructed maintenance plan.

The conclusions found with the single criteria techniques with respect to the effect of the FOR, MNU and the system peak load are applicable to the dual criteria technique.

If the selected reliability dual criteria are relatively low then using the dual criteria technique will give the same results as the single criterion techniques. If the criterion order is selected to be health oriented then the results will be the same as those obtained using the health levelization technique. If the risk criterion order is used then the results will be identical to those obtained using the risk levelization approach.

It was found that if health was the more restrictive criterion then it would be the driving criterion. Under these conditions then the annual reliability will be better with health criterion ordering than with risk criterion ordering and vice versa. The reliability of the system will, however, improve by using the dual criteria technique regardless the criterion order.

The dual criteria technique is a new technique created in this research work. It has the potential to be a very useful approach to maintenance scheduling. The studies conducted using the RBTS did not indicate significant improvement in the system reliability by using the dual criteria technique. This technique may prove to give better maintenance schedules if applied to larger systems or to systems with different compositions than the RBTS. This is an area for further research.

7. SUMMARY AND CONCLUSION

Preventive maintenance scheduling of generating facilities is an important requirement in generating system planning. Not conducting maintenance may enhance the ability to provide the available reserve in the short run but will lead to higher generating unit failure rates which could create serious reserve shortages and decreased system reliability. The basic concepts and the residual uncertainties associated with the problem of generating unit maintenance scheduling are introduced in Chapter 1.

The recursive technique for building a generation model is used and illustrated in Chapter 2. In this approach, the generation model is developed recursively by adding generating units one at a time to an existing capacity outage probability table. In a maintenance scheduling application, a new COPT is required for the available generating units in each corresponding period. The new COPT can be obtained by using the recursive technique to remove the units which are out for maintenance from the existing COPT. This technique is illustrated in Chapter 2.

The contingency enumeration approach to power system wellbeing evaluation is illustrated in Chapter 2. This approach provides a basic framework for wellbeing analysis. Chapter 2 shows that it becomes difficult to use this technique efficiently for a large system with a variable load model and becomes even more difficult if period base analysis is considered. The conditional probability COPT technique is a practical alternative and was used in this research work. The inclusion of the period base analysis using the CPCOPT approach is presented in Chapter 2.

The conventional technique for preventive maintenance scheduling is the reserve levelization deterministic approach. The reserve is levelized in this technique using a selected reserve margin. The main weakness of deterministic approaches is that they do not assess the actual system risk and ignore the probabilistic nature of system behavior and component failures. These effects can be incorporated in a probabilistic approach to maintenance scheduling. The utilization of the wellbeing framework to develop new probabilistic techniques for generating unit preventive maintenance scheduling is presented in Chapter 3.

The maintenance scheduling approaches illustrated in this chapter are divided into deterministic and probabilistic methodologies. The risk levelization technique can be considered as a basic probabilistic approach. A new technique assigned as the health levelization technique is presented. This technique is a hybrid approach, which incorporates a deterministic criterion within a probabilistic framework. In the studies described in this thesis, the probability of health is determined using the capacity of the largest unit. The maintenance schedules obtained using probabilistic techniques are more responsive than the schedules obtained using the deterministic criteria as they have the capability to incorporate many of the uncertainties that exist in the process.

A range of sensitivity studies are presented in Chapter 4 in which different factors are considered. It was found that there is no significant effect on a derived maintenance plan due to reasonable variation in a unit FOR in a small system such as the RBTS. This does not mean that there is absolutely no effect due to FOR variation. This phenomenon resulted due to the size of the RBTS and the stability of the criterion order, which is largely affected by the nature of the load model. In this case, the constructed plans were able to sustain the increased FOR without violating the desired criterion. The effect of increasing FOR was more visible with a higher reliability criterion and with a larger system such as the IEEE-RTS. It is shown in the studies presented in this chapter that demanding a higher reliability criterion may require having only a few generating units out for maintenance in a single week in order to satisfy the criterion. The selection of a very high reliability criterion may result in criterion violation in the high load periods which contain no maintenance or it may not be possible to create a maintenance schedule using this criterion. It is also shown that it is not always true that increasing the MNU results in a lower annual reliability. The annual reliability can be higher in certain cases with an increase in the MNU. A low MNU value may force the units to not follow the criterion order and could result in creating some weeks with lower reliability levels, which could decrease the annual reliability.

Deterministic techniques can create maintenance plans that satisfy the approved deterministic criteria. They can also create situations in some weeks in which there is excessive system risk due to the fact that the deterministic techniques do not involve any consideration of the actual risk.

The effect on maintenance scheduling caused by the load characteristic is illustrated in Chapter 5. Increases in the system peak load affect the criterion order obtained using the probabilistic techniques and result in changes in the maintenance schedules. The maintenance schedules created using the deterministic techniques do not respond to this increase in the system peak load. These conclusions apply to both the original load model and the new profile used in Chapter 5. This further reflects the insensitivity of the deterministic techniques with regard to system factors. The probabilistic techniques incorporate factors such as peak load levels and load profiles in the determination of risk and weekly criterion order and therefore respond to these factors.

Maintenance activities, as expected, are focused in the off peak periods for both the original load model and the new load model. Having the maintenance done during the low load periods results in enhanced system reliability. One of the main differences between the two load models is that the criterion order shows more response to FOR increases with the new load model than with the original load model.

Another phenomenon highlighted by the new load model is the increased overlapping in the generating unit maintenance periods. This was caused by the shape of the new load model, which has narrower off peak periods than the original load model. As a result, the maintenance activity has a higher response to increasing the MNU in the new load model.

A new probabilistic approach designated as the health and risk levelization technique or the dual criteria technique is presented in Chapter 6. Using only one of the two criteria, the health or the risk, may violate the other criterion. Using both indices as dual criteria will insure that the system is reliable from both aspects. It was found that in general, the constructed maintenance schedules obtained with the dual criteria technique provide higher system reliability than the schedules obtained with the single criterion techniques. Monitoring the health and the risk of the system at the same time and keeping them at acceptable levels improves the reliability of the constructed maintenance plan.

The conclusions found with the single criteria techniques with respect to the effect of the FOR, MNU and the system peak load on maintenance scheduling are applicable to the dual criteria technique.

If the selected reliability dual criteria are relatively low then using the dual criteria technique will give the same results as the single criterion techniques. If the criterion order is health oriented then the results will be the same as those obtained using the health levelization technique. If risk ordering is used then the result will be identical to that obtained using the risk levelization approach.

It was found that if the health is the more restrictive criterion then it becomes the driving criterion. In this case, the annual reliability will be better with health ordering than with risk ordering and vice versa. The reliability of the system will improve with the dual criteria technique regardless of the criterion order.

The dual criteria technique is a new technique created in this research work. It has the potential to be a very useful approach to maintenance scheduling. The studies conducted using the RBTS did not indicate significant improvement in the system reliability by using the dual criteria technique. This technique may prove to give better maintenance schedules if applied to larger systems or to systems with different compositions than the RBTS. This is an area for further research.

There is still considerable research required in the area of generating unit maintenance scheduling. This includes consideration of reliability worth and maintenance cost concepts. There are other system factors which can be incorporated in the approaches developed in this thesis, such as load forecast uncertainty, generating unit deratings, and long term planning. The foundation created by the health levelization technique and the dual criteria method developed in this research work has the potential to provide optimum maintenance schedules at acceptable levels of system reliability.

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APPENDIX A. BASIC IEEE-RTS DATA

Table A.1: Generating unit reliability data

ID number	Unit size (MW)	Number of units	Unit FOR	Scheduled maintenance (weeks/year)
1-5	12	5	0.02	2
6-9	20	4	0.10	2
10-15	50	6	0.01	2
16-19	76	4	0.02	3
20-22	100	3	0.04	3
23-26	155	4	0.04	4
27-29	197	3	0.05	4
30	350	1	0.08	5
31-32	400	2	0.12	6