Power System Generation Reliability

by

Ibrahim Omar Ali Habibullah

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES
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DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

In

ELECTRICAL ENGINEERING

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Power system generation reliability

Habibullah, Ibrahim Omar Ali, M.S.
King Fahd University of Petroleum and Minerals (Saudi Arabia), 1987
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This thesis, written by MR. IBRAHIM OMAR HABIBULLAH under the direction of his Thesis Committee, and approved by all its members, has been presented to and accepted by the Dean, College of Graduate Studies, in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE IN ELECTRICAL ENGINEERING.

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IN THE NAME OF ALLAH, THE MOST MERCIFUL AND THE MOST GRACIOUS

THIS THESIS IS DEDICATED TO MY PARENTS
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ABSTRACT

The reliability analysis of a proposed expansion strategy for an isolated system and two systems interconnected by a tie-line is considered. Two alternative methods namely, recursive convolution and Capacity Outage Probability Tables, are used for the analysis.

A comprehensive computer program based on the recursive convolution method is developed. The method takes into consideration unit availability and their effects on the reliability indices namely: Loss Of Load Probability, Loss Of Load Expectation, Expected Demand Not Served, Expected Energy Not Served, and Energy Index of Reliability.

The effect of uncertainties of demand forecast are included. The Effective Load Carrying Capacity of an added unit as well as the Load Carrying Capability of the total system for a specific Loss Of Load Expectation risk index are incorporated. Load correlation effect for two interconnected systems is also considered.
ملخص البحث

تحليل قدرة الأطراف كفاءة نظام توليد الطاقة الكهربائية

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كما تمت أيضًا حساب قيمة القدرة الفعلية للبولد عند إضافته

للنظام الموجود، بالإضافة إلى حساب مقدرة الحملة على

التحميل لقيمة كفاءة معين
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Chapter I
INTRODUCTION

1.1 POWER GENERATION RELIABILITY

In most of the third-world countries, population growth coupled with industrial development have led to large energy consumptions. More specifically, in the Gulf area energy consumption has increased tremendously over the last twenty-five years.

To serve future demand for energy, more power generators need to be installed and/or interconnected systems of energy exchange must be constructed. To realize both alternatives, economical power system planning must be developed.

The principal aim of power system planning therefore is to guarantee the provision of reliable and inexpensive supply of power to the consumer. System planning necessitates the prediction of future electric energy requirements. The actual planning for the future electric power systems is crucial. Load forecasting provides this as input to various planning decisions.
Obtaining the optimum relationship between power system reliability, which is the ability to provide a continuous energy supply to its customers, and its cost has been a target of power system planners for a number of decades. The application of reliability evaluation technique to power system reliability can be viewed in five-step process [1]. First is the identification of system failure modes which occur when system generation fail to meet the load demand. Next, the events leading to power failure are identified. These might include the simultaneous outage of several units. Third, modeling the reliability of a generation system usually entails the use of a two-state (up/down) unit modeling. The next step is to determine the parameter values of the model, such as the frequency and duration of equipment outages. Lastly, the model may be realistically applied only after all important sources of uncertainty have been included. The above five steps are illustrated in Fig. (1.1).

Uncertainties such as fuel and construction costs must be taken into account by system planners. If not, the electric utility industry could be placed in jeopardy. However, one can determine whether a generation expansion plan satisfies a desired level of reliability defined by reliability indices such as:

1. Loss Of Load Probability (LOLP)
2. Loss Of Load Expectation (LOLE)
3. Expected Demand Not Served (EDNS)
4. Expected Energy Not Served (EENS)
5. Energy Index of Reliability (EIR)
Figure 1.1: Evaluation of the reliability of a power system
The problem for determining the required amount of system generating capacity to ensure an adequate supply of energy, can be divided into two conceptually different areas namely [2]:

1. Static capacity requirements
2. Operating capacity requirements

The static capacity requirement relates to the long-term evaluation of the overall system. It can be considered as the installed capacity that must be planned and constructed in advance of the system requirements. On the other hand, the operating capacity requirement relates to the short-term evaluation. The expected load must be predicted and sufficient generation must be scheduled accordingly. Reserve generation must also be scheduled in order to account for load forecast uncertainties and possible outages of generation plant. Once this is scheduled and spinning, the operator is committed for the period of time it takes to achieve output from other generating plant.

The adequacy of the generating capacity in a power system is normally improved by interconnecting the system to another power system. Each interconnected system can then operate at a given risk level with a lower reserve than would be required without the interconnection.

The actual interconnection benefits depend on the installed capacity in each system, the total tie capacity, the forced outage rates of the tie lines, the load levels and their residual uncertainties in each system and the type of agreement in existence between the systems.
1.2 LITERATURE REVIEW

The field of reliability engineering has developed to an extent where it is beginning to branch out into various specialized sub-fields. The history of the application of probability concepts to electric power generation problems goes back to before World War II. Since then, several papers and books on power system reliability have been published.

A large number of papers which apply probability techniques to generating capacity reliability evaluation have been published in the last 40 years. These publications have been documented in three comprehensive bibliographies published in 1966, 1971, and 1978 which include over 160 individual references [3-5].

The evaluation of generation capacity adequacy to meet the system load demand can be achieved by combining the generation model with the load model as shown in Fig.(1.2). Different papers have been published to build up these models, which mostly depend on the probabilistic techniques. Two alternative techniques will be used namely: Convolution and Capacity Outage Probability Tables.

GENERATION MODEL

This model can be obtained in two different ways:

1. Probability Density Function (PDF)

2. Capacity Outage Probability Tables (COPT).

Although many papers have discussed the former one, it is clearly presented in detail in Sullivan [6]. On the other hand, Billinton and Endrenyi have discussed the COPT method [7-8].
Figure 1.2: Generation capacity adequacy evaluation
Load Model

Two different models can be constructed from the Peak Load Characteristic Curve (PLCC) namely:

1. Load Probability Distribution (LPD)
2. Load Duration Curve (LDC)

The PLCC could be for a week, a month, a season or a year, in which the x-axis is expressed either in days or in hours, and the y-axis in MW. PLCC, LDP, and LDC are illustrated in Figs.(1.3, 1.4, and 1.5) respectively.

Risk Model

The measured risk can be defined by the well known 'Reliability Indices' namely: LOLP, LOLE, EDNS, EENS, and EIR. These indices can be evaluated by two different methods:

1. Convolution method.
2. Obtaining the COPT.

The convolution method, which can be realized by convolving the LPD with the outage probability of each unit, is well discussed in Sullivan book [6]. In 1980, Rau, Toy, and Schenk obtained the convolution technique using the moment approach [9]. Stremel, Jenkins, Babb, and Bayless in the same year, however, published a paper on the same subject but used the cumulant approach to obtain the reliability indices [10].
Figure 1.3: Peak load characteristic
Figure 1.4: Load probability distribution LPD
Figure 1.5: Load duration curve LDC
The COPT method, however, can be used in conjunction with the LDC to obtain the expected number of days or hours in which the peak load will exceed the available capacity. The units, in this method, can be combined using basic probability concepts (or the exact method) [11]. The exact method can be extended to a powerful recursive techniques in which units are added sequentially. These techniques are efficient specially when a large number of units are presented, and they can be achieved by many methods such as:

- Normal Distribution
- Continuous Distribution
- Gram-Charlier Expansion
- Edgeworth Expansion
- Moment method
- Cumulant method
- Fourier Transform
- Fast Fourier Transform

The exact method and normal distribution, Gram-Charlier, and Edgeworth methods are well compared and discussed [12]. Reliability indices evaluation using the continuous distribution method, however, is described in [13]. On the other hand, Rau and Schenk used the Fourier method for calculating the indices [14]. The cumulant method for calculating LOLP is presented in Stremel and Rau paper [15]. The evaluation of LOLP and EENS, using the cumulant method, is also published by Duran and Apdo [16]. The method used allows to include any number of cumulants without additional explicit theoretical development or software implementation effort. Evaluating the EENS using the fast
Fourier transform method is presented and discussed by Allan and Shaalan [17].

The reliability indices can also be improved by interconnected systems. Two different techniques have been used for evaluating these reliability indices, namely: the Equivalent Assisting Unit method and the Probability Array method. The first method models the assisting system as an equivalent assisting unit which can be moved through the tie lines and added into the existing capacity model of the assisted system. The computation of the risk in the assisted system proceeds as in the case of a normal single system study [6]. In the second approach, however, a capacity model is developed for each system and an array of simultaneous capacity outage existance probabilities is then obtained from the individual models [2].

A new method for estimating the reliability of generation supply in a single compact system or in an interconnected system was described by Alton and Damon [18]. Measures of reliability calculated in this paper are:

1. Capacity Deficiency Rate
2. Expected Duration of Capacity Deficient Period
3. Loss Of Load Probability (LOLP)

Pang and Wood [19], presented a technique for the evaluation of the reliability of supplying power in a system with a number of interconnected load-generation areas. Previous techniques using Monte Carlo simulations have been limited to systems with a maximum of three interconnected areas. The method of analysis was based upon the use of a
linear flow network to model the transmission interconnections and makes use of an efficient graph theory algorithm to segregate the failure states by finding critical minimal cuts in the network.

In 1982, a method for the calculation of the LOLP of two interconnected systems incorporating the correlation between demands was proposed [20]. The bivariate Gram-Charlier expansion was used.

The calculation of LOLP of interconnected systems is also presented and discussed by many other authors [2,8].

1.3 **THESIS OBJECTIVES**

The aim of this thesis is directed toward the generating units reliability only, and the rest of the power system is assumed to be perfectly reliable. Evaluation of the reliability indices namely: LOLP, LOLE, EDNS, EENS, and EIR for both isolated and two interconnected areas using the two alternative methods is considered. A computer program based on the recursive convolution method, however, is developed to be used for reliability analysis.

The effective load carrying capacity ELCC of any added unit as well as the load carrying capability LCC of the total system for a specific LOLE level is also considered. Uncertainties of demand forecast effect on the reliability indices are accounted for. The Equivalent Assisting Unit method has been considered for interconnected systems. The effect of load correlation on interconnected systems is also incorporated. Tested samples are used to demonstrate the proposed work.
CHAPTER II
SINGLE AREA RELIABILITY INDICES

2.1 INTRODUCTION

The basic approach to evaluate the adequacy of a particular generation configuration is fundamentally the same for any technique. It consists of the three parts namely: generation model, load model and risk model as indicated in Fig.(1.2). The risk model which can be stated as the reliability indices do not normally include transmission constraints.

The system representation in a conventional study is as shown in Fig(2.1). The calculated indices in this case do not reflect generation at any particular customer load point, but measure the overall adequacy of the generation system.

2.2 PROBABILISTIC GENERATION MODELS

There are many different types of units, all with their own peculiarities, but they can be classified into three major classes, base load units, midrange units and peakers as shown in table (2.1). Although many different types of units are in use today, all units are randomly forced off-line because of technical problems during a normal period of operation.
Figure 2.1: Conventional system model

Figure 2.2: Generating unit state space diagram
TABLE 2.1
Unit Classifications

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<th>Types</th>
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<td>Base Load</td>
<td>90-95 %</td>
<td>1. large fossil-steam units</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. nuclear units</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. hydro units</td>
</tr>
<tr>
<td>Midrange</td>
<td>30-75 %</td>
<td>1. combined-cycle combustion turbines</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. small fossil-steam units</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. hydro units</td>
</tr>
<tr>
<td>Peakers</td>
<td>5-10 %</td>
<td>1. combustion turbines</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. hydro units</td>
</tr>
</tbody>
</table>
The basic generating unit parameter used in static capacity evaluation is the probability of finding the unit on forced outage at some distant time in the future. The probability is defined as the unit unavailability, which is well known as the unit forced outage rate (FOR)

$$\text{FOR} \ (q) = \frac{\lambda}{(\lambda + \mu)} \quad (2.1)$$

$$\text{Availability} \ (r) = \frac{\mu}{(\lambda + \mu)} \quad (2.2)$$

where

- $\lambda$ = expected failure rate.
- $\mu$ = expected repair rate.

The concept of availability and unavailability are associated with the simple two-state model shown in Fig.(2.2). The generation model can be achieved either by probability density function method or by capacity outage probability tables method.

2.2.1 Probability Density Function (PDF)

To account for the random outage or availability of a unit, it is necessary to determine the probability density function which describes the probability that a unit will be forced off-line or will be available during its normal period of operation.
It is more convenient to deal with the forced outage capacity probability density function, \( f_o(L_{oi}) \) of a unit \( i \). For example, if a \( C_i \) MW rated unit has a forced outage rate \( q_i \) and an availability \( p_i \), then its forced outage capacity density function will be as shown as in Fig. (2.3) In the same way the unit available capacity probability density function shown in Fig. (2.4) can be found.

A unit with capacity \( C_i \) that is randomly available may be modeled as a fictitious unit of capacity \( C_i \) that is 100% reliable and a fictitious load of \( C_i \) whose availability is equal to the FOR of the actual unit.

2.2.2 Capacity Outage Probability Tables (COPT)

The development of a COPT for a given set of generating units utilizes the system capacity for each unit, its forced outage rate FOR (q) and its availability (p). The total number of capacity states, however, is equal to \( 2^{NG} \), where NG is the number of generating units in the system.

The COPT for a NG-unit system of different capacities and FOR, is given in table (2.2).
Figure 2.3: Forced outage capacity probability density function

Figure 2.4: Unit available capacity probability density function
TABLE 2.2
COPT for NG Units

<table>
<thead>
<tr>
<th>Number of states</th>
<th>Capacity out of service (MW)</th>
<th>Probability ( p_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>( \prod_{i} p_i )</td>
</tr>
<tr>
<td>2</td>
<td>( C_1 )</td>
<td>( q_1 \prod_{i \neq 1} p_i )</td>
</tr>
<tr>
<td>3</td>
<td>( C_2 )</td>
<td>( q_2 \prod_{i \neq 2} p_i )</td>
</tr>
<tr>
<td>\ldots \ldots \ldots</td>
<td>\ldots \ldots \ldots \ldots</td>
<td>\ldots \ldots \ldots \ldots</td>
</tr>
<tr>
<td>( 2^{NG} )</td>
<td>( \sum_{i} C_i )</td>
<td>( \prod_{i} q_i )</td>
</tr>
</tbody>
</table>

NG = Number of Generating Units

\( p \) = Unit Availability

\( q \) = Unit Forced Outage Rate

\( i = 1, 2, \ldots, NG \)
2.3 PROBABILISTIC LOAD MODELS

Fortunately, the data required to develop load model can be obtained either from the continuous recordings of system demand and energy or from load forecasting. Such data, which is defined as the peak load characteristic (PLC), can be plotted for a particular period of time namely: day, week, month, season or year as illustrated in Fig.(1.3).

2.3.1 LOAD PROBABILITY DISTRIBUTION (LPD)

The probabilistic load model is described or defined as the probability of the load to exceed a certain value, therefore, we are interested in determining the probability of the load to exceed the installed capacity of a particular proposed generation system (i.e. the LOLP). Given the PLC, the load probability distribution shown in Fig(1.4) can be produced, where the y-axis shows the probability of the load to exceed the corresponding x-axis Megawatt value. The load distribution will be denoted generally by \( F(L) \) where \( L \) is the load in Megawatt and \( F \) is the probability.

This model can be used with the convolution method to produce the reliability indices. Furthermore, in this model, if the x-axis is normalised in per-unit load as shown in Fig.(2.5), the load factor of the system can be produced from the area under the curve.
Figure 2.5: Normalised load probability distribution LPD
2.3.2 **Load Duration Curve (LDC)**

From the PLC data, the individual peak loads can be arranged in descending order to form a cumulative load model, which is known as the load duration curve LDC as shown in Fig.(1.5).

This model can be used with the COPT to evaluate the reliability indices. Moreover, when the individual hourly load values are used, the energy required in the given period can be calculated from the area under the curve.

2.4 **Effect of Load Forecast Uncertainties**

Since load forecasting is based on historical load-growth trend, there is an uncertainty associated with it. This uncertainty can be described by a probability distribution whose parameters are determined from historical data of load forecast deviations.

The uncertainty in the load forecasting can be included in the risk calculations by dividing the probability distribution of uncertainty into class intervals such that the area of each class interval below the curve represents the probability of an actual load equal to the class mid value [12]. The mean of the distribution is taken to be the forecast peak load and standard deviation equal to some percentage of the forecast value. The distribution is divided into seven class intervals as shown in Fig.(2.6) in which the probabilities are given.
Figure 2.6: Seven step approximation of the normal distribution for uncertainty in load forecasting
2.5 **EXPECTED VALUE OF DEMAND AND ENERGY**

The expected value of demand EVD can be calculated from the load probability distribution curve either from Fig.(1.4) or Fig.(2.5), as following:

From Fig.(1.4)

\[ \text{EVD} = \int \frac{F(L)}{L} dL \]  

(2.3)

From Fig.(2.5)

\[ \text{LF} = \int \frac{F(L)}{L} dL \]  

(2.4)

\[ \text{EVD} = \lambda \times \text{LF} \]  

(2.5)

where

- \( \lambda \) = maximum peak value in MW
- \( \text{LF} \) = load factor in p.u.

The expected value of energy EVE, on the other hand, can be calculated directly from the EVD.

\[ \text{EVE} = \text{EVD} \times T \]  

(2.6)

where, \( T \) is the selected period of time in hours.
2.6 COMBINATION OF GENERATION AND LOAD MODEL

2.6.1 Convolution Method

Effective Load

The relation between the system load and generating units is depicted in Fig.(2.7), where actual units have been replaced by fictitious perfectly reliable units and fictitious random loads, whose probability density functions are the outage capacity density function of the units. From Fig.(2.7), the effective load is defined by

\[ L_e = L + \sum_{i=1}^{NG} L_{oi} \]

where NG is number of generators and \( L_{oi} \) is the random outage load of the ith unit. The installed capacity of the system is given by

\[ IC = \sum C_i \]

Effective Load Probability Distribution

In the special case where actual units are 100% reliable, \( L_{oi} = 0 \) and \( L_e = L \). Unfotunaletly, this case never occurs, and hence \( F(L_e) \) must be obtained from \( F(L) \) and \( f_{oi}(L_{oi}) \). Since \( L_e \) is the sum of the independent random variables, \( L \) and \( L_{oi} \), whose distributions are known, we can get \( F(L_e) \) using the recursive convolution equation:

\[ F^i(L_e) = \int F^{i-1}(L_e - L_{oi}) f_{oi}(L_{oi}) \, dL_{oi} \]

(2.9)
Figure 2.7: Fictitious generating units and system load model
where $F^i(L_e)$ is the effective load probability distribution with the outage capacity of the first $i$ units convolved in. It is obvious that

$$F^i(L_e) = \begin{cases} 
F(L) & \text{for } i=0 \\
F(L_e) & \text{for } i=\text{NG}
\end{cases}$$

Since $f_{oi}$ is a discrete density function as depicted in Fig. (2.3), equation 2.9 becomes:

$$F^i(L_e) = \sum_{L_{oi}} F^{i-1}(L_e - L_{oi}) f_{oi} (L_{oi})$$

(2.10)

Because the outage capacity of a unit was defined as a two-state process where

$$f_{oi}(L_{oi}=0) = p_i$$
$$f_{oi}(L_{oi}=C_i) = q_i$$

Eq 2.10 can be simplified even further as:

$$F^i(L_e) = F^{i-1}(L_e) p_i + F^{i-1}(L_e-C_i) q_i$$

(2.11)

$i=1,2,\ldots,\text{NG}$

The effect on $F(L)$ of accounting for random outages of the generating units is to inflate it. This effect tends to increase the probability that the load will exceed a given value, thus reflecting the fact that as units are randomly forced off-line, remaining units see a larger effective load, for they must pick up the load not served by units forced off-line. A typical effective load probability distribution is shown in Fig. (2.8).
Figure 2.8: Typical effective load probability distribution
LOLP AND LOLE EVALUATION FOR SINGLE AREA

From the definition of LOLP, which is the probability that the load will exceed the installed capacity of the system, the evaluation of $F(L_e)$ at the point $L_e=IC$ is only needed to get the LOLP for the particular period of time. Thus,

$$LOLP = F(L_e=IC)$$  \hspace{1cm} (2.12)

$$LOLE = LOLP \times T$$  \hspace{1cm} (2.13)

EDNS, EENS AND EIR EVALUATION FOR SINGLE AREA

The other index of reliability namely EDNS is beginning to see widespread use because of its obvious physical significance, which can be defined as the energy not supplied due to insufficient installed capacity.

Since $F(L_e)$ is known, the extra effort required to calculate the EDNS is minor. In fact it can be expressed as follows:

$$L_e=\theta+IC$$

$$EDNS = \int_{L_e=IC} F(L_e) \, dL_e$$  \hspace{1cm} (2.14)

$$EENS = EDNS \times T$$  \hspace{1cm} (2.15)

The reliability of the system can also be evaluated by the EIR index. This index can be expressed in terms of the probable ratio between the load energy curtailed due to the deficiency in the generating
capacity available (i.e. EENS) and the total load energy required to reserve the requirements of the system (i.e. EVE).

\[
EIR = 1 - \frac{EENS}{EVE}
\]

(2.16)

**Unit Effective Load Carrying Capacity (ELCC)**

The ELCC is an interesting and useful idea that provides system planners with a measure of the relative impact of new units in satisfying system load growth. In essence, ELCC is that part of the capacity of a unit that is available to supply increases in demand in order to maintain system reliability less than some desired level. Typically, where a new unit of capacity \( C_i \) is added to a system, reliability is much improved, but as demand grows, reliability begins to decrease, since both LOLP and EDNS increase. Unfortunaletly, the amount of load growth that can occurs before reliability returns to where it was installed, is less than the capacity \( C_i \) of the new unit. This amount of load growth is the ELCC of the unit. The remainder of the capacity of the unit is required to maintain the desired reliability level as illustrated in Fig.(2.9).

**Load Carrying Capability (LCC)**

The load carrying capability (LCC) of the total system is also essential. It is defined as the amount of load the system can carry for a particular LOLP, as shown in Fig.(2.10).
Figure 2.9: ELCC of a new added unit $C_i$. 
Figure 2.10: LCC for a given LOLPs
2.6.2 COPT Method

LOLP and LOLE Evaluation

The LOLE index can also be obtained using the LDC. Fig. (2.11) shows a typical system load-capacity relationship where the load model is shown as a continuous curve for a particular period of time. A particular capacity will contribute to the system LOLE by an amount equal to the product of the probability of existence of the particular outage and the number of time units in the study interval that loss of load would occur if such a capacity were to exist.

Expressed mathematically, the contribution to the system LOLE made by capacity outage \( O_i \) is \( p_i t_i \). The total LOLE for the study interval is therefore,

\[
LOLE = \sum_{i=1}^{2^{NG}} p_i t_i
\]

where

\( p_i \) = the individual probability of the capacity outage \( O_i \)

\( t_i \) = number of time units in the study interval that an \( O_i \) will result in a loss of load
Figure 2.11: Load-capacity relationship
LOLP = LOLE/T \hspace{1cm} (2.19)

where \( T \) is the selected period of time

**EDNS, EENS AND EIR EVALUATION**

The probabilities of having varying amounts of capacity unavailable are combined with the system load as illustrated in Fig.(2.11). Any outage of generating capacity exceeding the reserve will result in a curtailment of system load energy \( E_i \). This energy curtailment is given by the shaded area in Fig.(2.11).

The probable energy curtailed is \( E_i p_i \). The sum of these products is the total expected energy curtailment which is simply the EENS, where

\[
EENS = \sum_{i=1,2,\ldots,2^{NG}} E_i p_i
\]

\hspace{1cm} (2.20)

\[
EDNS = EENS/T
\]

\hspace{1cm} (2.21)

\[
EIR = 1 - \frac{EENS}{EVE}
\]

\hspace{1cm} (2.22)

where

- \( E_i \) = the energy curtailed associated with \( O_i \)
- \( EVE \) = the expected value of energy = the area under the LDC
CHAPTER III
TWO INTERCONNECTED AREAS RELIABILITY INDICES

3.1 INTRODUCTION

The adequacy of the generating capacity in a power system can be improved by interconnecting a system to another power system. Each interconnected system can then be operated at a given risk level with a lower reserve than would be required without the interconnection.

The rationale for interconnecting system is based primarily on the fact that interconnected utilities can help one another in times of emergency and hence improve system reliability in effect, without investing in additional electric plant.

Typically, the following no-load-loss policy is understood when financially independent utilities share reserves:

1. System A assists B only to the extent that the reserves of A do not become negative, resulting in a loss-of-load condition, and vice versa.
2. System B accepts the emergency reserves of A only when loss of load will result without them, and vice versa.
3. The demand transmitted across the interconnection can not exceed \( C_T \).
There are two different methods in which the reliability indices can be evaluated, namely:

1. Equivalent Assisting Unit method
2. Probability Array method

3.2 **EQUIVALENT ASSISTING UNIT METHOD**

This method depends on the effective load probability distribution ELPD developed for each area. After that, the effect of tie capacity $C_T$ will be encountered to create the interconnected effective load probability distribution of each system.

3.2.1 **INTERCONNECTED EFFECTIVE LOAD**

The effective loads for a sample interconnected system as shown in Fig.(3.1)are:

\[ L_{eAT} = L_{eA} + L_T \]  \hspace{1cm} (3.1)

\[ L_{eBT} = L_{eB} - L_T \]  \hspace{1cm} (3.2)

where

- $L_{eAT}$ = the effective load of system A with interconnection
- $L_{eBT}$ = the effective load of system B with interconnection
- $L_{eA}$ = the effective load of system A
- $L_{eB}$ = the effective load of system B
- $L_T$ = tie-line flow across the interconnection
Figure 3.1: Sample interconnected system
3.2.2 **INTERCONNECTED EFFECTIVE LOAD PROBABILITY DISTRIBUTION**

Utilizing Eqs. 3.1 and 3.2 to obtain the probability distribution $F(L_{eAT})$ and $F(L_{eBT})$, from which the reliability indices can be calculated for a given interconnected capacity, $C_T$. This procedure will require utilizing the joint probability density function $f(L_T, L_{eA}, L_{eB}, C_T)$, which reflects the fact that the values $L_T$ can assume, are dependent on the effective loads in the two interconnected systems and the tie capacity $C_T$.

From Eqs. (3.1, 3.2), it is clear that $L_T$, $L_{eA}$, and $L_{eB}$ are dependent random variables whose joint probability density function $f(L_T, L_{eA}, L_{eB}, C_T)$ can be written as either

$$f(L_{eBT}, L_{eA}, C_T) = f(L_{eBT}/L_{eA}, C_T)f(L_{eA})$$

(3.3)

or

$$f(L_{eAT}, L_{eB}, C_T) = f(L_{eAT}/L_{eB}, C_T)f(L_{eB})$$

(3.4)

depending on which system is to be analyzed. Integrating Eqs 3.3, 3.4 with respect to $L_{eBT}$ and $L_{eAT}$ respectively, the probability that effective load of $B$ exceeds $L_{eBT}$ given $C_T$ and $L_{eA}$ will result:

$$F(L_{eBT}, L_{eA}, C_T) = F(L_{eBT}/L_{eA}, C_T)f(L_{eA})$$

(3.5)

$$F(L_{eAT}, L_{eB}, C_T) = F(L_{eAT}/L_{eB}, C_T)f(L_{eB})$$

(3.6)
For deterministic \( C_T \), \( F(L_{eBT}) \) and \( F(L_{eAT}) \) can be expressed as follows:

\[
F(L_{eBT}) = \int_{C_T} F(L_{eBT}/L_{eA}, C_T) f(L_{eA}) dL_{eA}
\]

\[
F(L_{eAT}) = \int_{C_T} F(L_{eAT}/L_{eB}, C_T) f(L_{eB}) dL_{eB}
\]

(Eq. 3.7 and 3.8)

Eqs. 3.7 and 3.8 can be reexpressed as

\[
F(L_{eBT}) = \int_{-\infty}^{\infty} F(L_{eBT}/L_{eA}, C_T) f(R_{eA}) dR_{eA}
\]

\[
F(L_{eAT}) = \int_{-\infty}^{\infty} F(L_{eAT}/L_{eB}, C_T) f(R_{eB}) dR_{eB}
\]

where

\[
R_{eA} = IC_A - L_{eA}
\]

(Eq. 3.11)

= effective reserve margin of system A

\[
R_{eB} = IC_B - L_{eB}
\]

(Eq. 3.12)

= effective reserve margin of system B

\[
f(R_{eA}) = f(L_{eA} = IC_A - R_{eA})
\]

(Eq. 3.13)

\[
f(R_{eB}) = f(L_{eB} = IC_B - R_{eB})
\]

(Eq. 3.14)
f(L_{eA}) and f(L_{eB}) can be obtained as follows:

\[ f(L_{eA}) = - dF(L_{eA})/dL_{eA} \]  \hspace{1cm} (3.15)

\[ f(L_{eB}) = - dF(L_{eB})/dL_{eB} \]  \hspace{1cm} (3.16)

### 3.2.3 Evaluation of LOLP and LOLE for Two Areas

Assuming that system A will assist B, then Eq. 3.9 can be broken into three separate integrals:

\[ F(L_{eBT}) = \int_{-\infty}^{C_T} F(L_{eBT}/L_{eA}, C_T) f(R_{eA}) dR_{eA} + \int_{0}^{C_T} F(L_{eBT}/L_{eA}, C_T) f(R_{eA}) dR_{eA} + \int_{C_T}^{\infty} F(L_{eBT}/L_{eA}, C_T) f(R_{eA}) dR_{eA} \]  \hspace{1cm} (3.17)

Since each integral has its own characteristics, therefore each one can be considered separately. Let

\[ F_1(L_{eBT}) = \int_{-\infty}^{0} F(L_{eBT}/L_{eA}, C_T) f(R_{eA}) dR_{eA} \]  \hspace{1cm} (3.18)

\[ F_2(L_{eBT}) = \int_{0}^{C_T} F(L_{eBT}/L_{eA}, C_T) f(R_{eA}) dR_{eA} \]  \hspace{1cm} (3.19)

\[ F_3(L_{eBT}) = \int_{C_T}^{\infty} F(L_{eBT}/L_{eA}, C_T) f(R_{eA}) dR_{eA} \]  \hspace{1cm} (3.20)
To determine LOLP\textsubscript{BA}, which is the loss of load probability of system B connected to A, the probability \(F(L_{eBT})\) should be evaluated at \(L_{eBT}=IC_B\). In the first integral, since \(R_{eA}<0\), no flow can occur on the interconnection, indicating that \(L_T=0\). Thus \(L_{eBT}=L_{eB}\), and

\[F(L_{eBT})=F(L_{eB})\] (3.21)

substituting Eq. 3.21 into Eq. 3.18, therefore

\[F^1(L_{eBT}) = F(L_{eB}=L_{eBT}) \int_{-\infty}^{0} f(R_{eA}) dR_{eA}\] (3.22)

and therefore, at \(L_{eBT}=IC_B\),

\[F^1(IC_B) = LOLP_B \int_{-\infty}^{0} f(R_{eA}) dR_{eA}\] (3.23)

The second integral is valid for values of \(0<R_{eA}<C_T\), indicating that \(L_T=R_{eA}\). Thus \(L_{eBT}=L_{eB}-R_{eA}\), and

\[F(L_{eBT})=F(L_{eB}=L_{eBT}+R_{eA})\] (3.24)

substituting Eq. 3.24 into Eq. 3.19, therefore

\[F^2(L_{eBT}) = \int_{0}^{C_T} F(L_{eB}=L_{eBT}+R_{eA}) f(R_{eA}) dR_{eA}\] (3.25)

and therefore, at \(L_{eBT}=IC_B\),

\[F^2(IC_B) = \int_{0}^{C_T} F(L_{eB}=IC_B+R_{eA}) f(R_{eA}) dR_{eA}\] (3.26)
The last integral is valid for values of \( C_T < R_eA \leq \infty \), indicating that \( L_T = C_T \). Thus \( L_{eBT} = L_eB - C_T \), and

\[
F(L_{eBT}) = F(L_eB = L_{eBT} + C_T)
\]

(3.27)

substituting Eq. 3.27 into Eq. 3.20, therefore

\[
F^3(L_{eBT}) = F(L_eB = L_{eBT} + C_T) \int_{C_T}^{\infty} f(R_{eA}) dR_{eA}
\]

(3.28)

and therefore, at \( L_{eBT} = 1C_B \),

\[
F^3(1C_B) = F(L_eB = 1C_B + C_T) \int_{C_T}^{\infty} f(R_{eA}) dR_{eA}
\]

(3.29)

To summarize, the LOLP\(_{BA}\) is defined as:

\[
LOLP_{BA} = F^1(1C_B) + F^2(1C_B) + F^3(1C_B)
\]

(3.30)

substituting for \( F^1, F^2, \) and \( F^3 \), therefore

\[
LOLP_{BA} = \int_{C_T}^{\infty} f(R_{eA}) dR_{eA} + \int_{C_T}^{\infty} F(L_eB = 1C_B + R_{eA}) f(R_{eA}) dR_{eA} + F(L_eB = 1C_B + C_T) \int_{C_T}^{\infty} f(R_{eA}) dR_{eA}
\]

(3.31)

where \( f(R_{eA}) \) is defined in Eq. 3.13
Similarly, when system B assist A,

\[
\begin{align*}
\text{LOLP}_{AB} &= \text{LOLP}_A \int_{-\infty}^{\infty} f(R_{eB})dR_{eB} + \\
&= \int_{0}^{C_T} f(L_{eA} = IC_A + R_{eB})f(R_{eB})dR_{eB} + \\
&= \int_{0}^{C_T} f(L_{eA} = IC_A + C_T) f(R_{eB})dR_{eB}
\end{align*}
\]

(3.32)

where \(f(R_{eB})\) is defined in Eq. 3.14

3.2.4 Evaluation of EDNS, EFNS, and EIR for Two Areas

We could use the same idea used in calculating LOLP for two areas to evaluate EDNS as shown in Fig.(3.2), where

\[
L_{eBT} = IC_B + n\Delta
\]

\[n=0,1,2,\ldots\] \hspace{1cm} (3.33)

substitute for each \(n\), and for a given \(\Delta\), in Eq. 3.17

\[
\begin{align*}
F(L_{eBT} = IC_B + n\Delta) &= F(L_{eB} = IC_B + n\Delta) \int_{-\infty}^{\infty} f(R_{eA})dR_{eA} + \\
&= \int_{0}^{C_T} f(L_{eB} = IC_B + n\Delta + R_{eA})f(R_{eA})dR_{eA} + \\
&= \int_{0}^{C_T} f(L_{eB} = IC_B + n\Delta + C_T) f(R_{eA})dR_{eA}
\end{align*}
\]

(3.34)

similarly,

\[
\begin{align*}
F(L_{eAT} = IC_A + n\Delta) &= F(L_{eA} = IC_A + n\Delta) \int_{-\infty}^{\infty} f(R_{eB})dR_{eB} + \\
&= \int_{0}^{C_T} f(L_{eA} = IC_A + n\Delta + R_{eB})f(R_{eB})dR_{eB} + \\
&= \int_{0}^{C_T} f(L_{eA} = IC_A + n\Delta + C_T) f(R_{eB})dR_{eB}
\end{align*}
\]

(3.35)
Figure 3.2: Evaluation of EDNS for two areas
EDNS_{BA} can be, therefore, calculated for \( L_{eBT} = I_{C_B} \) to \( I_{C_B} + \theta_B \) as follows:

\[
EDNS_{BA} = (1/2)[F(L_{eBT} = I_{C_B}) + F(L_{eBT} = I_{C_B} + \theta_B)] + \sum_{n} [F(L_{eBT} = I_{C_B} + \theta_B)]
\]

(3.36)

In the same way, EDNS_{AB} can be expressed as:

\[
EDNS_{AB} = (1/2)[F(L_{eAT} = I_{C_A}) + F(L_{eAT} = I_{C_A} + \theta_A)] + \sum_{n} [F(L_{eAT} = I_{C_A} + \theta_A)]
\]

(3.37)

where \( \theta_A \) = the maximum peak load of system A
and \( \theta_B \) = the maximum peak load of system B

Therefore

\[
EENS_{BA} = EDNS_{BA} \times T
\]

(3.38)

\[
EENS_{AB} = EDNS_{AB} \times T
\]

(3.39)

where \( T \) is the period of the studied system

The system EIR_{BA} and EIR_{AB}, however, can be calculated as follows:

\[
EIR_{BA} = 1 - \left( \frac{EENS_{BA}}{EVE_B} \right)
\]

(3.40)

\[
EIR_{AB} = 1 - \left( \frac{EENS_{AB}}{EVE_A} \right)
\]

(3.41)
3.3 **PROBABILITY ARRAY METHOD**

This method depends on the capacity outage probability tables COPT of each system. The possible states of the two systems can, however, be best illustrated with help of combined-state diagrams.

The diagrams are developed from the arrays of margin states for system A and B. These arrays, in turn, are obtained by merging the generation and load models for each system. The modification of the diagram in Fig.(3.3), however, accounting for the restricted assistance that any of the systems can provide to the other because of the limited tie capacity.

Defining the probability of the i th margin state for system A, with a margin $M_{Ai}$ as $P_{Ai}$, and that of the j th margin state for system B, with a margin $M_{Bi}$ as $P_{Bi}$, therefore, the probability $p_{ij}$ of the corresponding combined state $ij$ is

$$p_{ij} = P_{Ai} P_{Bj}$$

$$i,j=1,2,...,2^{NG} \quad (3.42)$$

Using the load loss matrix table of each system taking into consideration the effect of the tie capacity $C_T$, the corresponding time $t_{ij}$ and energy $E_{ij}$ associated with each load loss state. The expected probability of A failing and B not is
Figure 3.3: Combined states of system A and B with a limited tie capacity $C_T$
LOLE_A &= \sum p_{ij} t_{ij} \\
EENS_A &= \sum p_{ij} E_{ij} \\
i,j=1,2,\ldots,2^{NG} \tag{3.44}

3.4 **EFFECT OF LOAD CORRELATION**

More accurate results can be obtained for the system reliability indices by taking into consideration the effect of load correlation (i.e. including the load diversities between the two systems). The main idea of the load correlation is that, the peak load characteristic of Fig.(1.3), needed to be broken into sub-periods. The selection of each one depends on the behavior of the system.

Once the sub-periods are selected, the reliability indices of the interconnected system must be evaluated for each sub-period separately. After that, the reliability indices of the sub-periods are summed to get the total system indices.
Chapter IV
TESTED SAMPLES

4.1 INTRODUCTION

The concepts presented in chapters 2 and 3, will be applied in this chapter to two different examples. In the first example, a small system will be considered in which a desk calculator can be used to evaluate the system reliability. The convolution method and the capacity outage probability tables COPT will be applied for single area. Moreover, the Equivalent Assisting Unit method and the Probability Array method will be applied for two areas.

In the second example, however, the convolution will be selected for single area and the Equivalent Assisting Unit method for two areas. The effect of load forecast uncertainties as well as the load correlation will be accounted for. Further, the effective load carrying capacity ELCC for an added unit and the load carrying capability LCC of the system for a standard LOLE will be presented.
4.2 A SMALL SYSTEM EXAMPLE

Assume that system A contains two generating units having the following characteristics:

\[ C_1 = 50 \text{ MW} \quad C_2 = 50 \text{ MW} \]
\[ q_1 = 0.02 \quad q_2 = 0.03 \]

The load probability distribution LPD and the load duration curve LDC for the system A are illustrated in Figs.(4.1 and 4.2) respectively. The load duration time assumed is 168 hours for a given week period, and the peak value of the system is 78.034 MW. Moreover, assume that the interconnected tie capacity \( C_T \) is 20 MW.

For simplification, assume that system B has the same generation and load model as system A. Further, ignore the load forecast uncertainties and assume one full period (i.e. no load correlation). Therefore, the evaluation of the system reliability indices for both single area and two areas is as follows:

4.2.1 SINGLE AREA RELIABILITY INDICES

RELIABILITY INDICES OF SYSTEM A

CONVOLUTION METHOD :

Generation Model :

The forced outage capacity probability density function PDF of units 1 and 2 is depicted in Fig.(4.3).
Figure 4.1: Load probability distribution LPD for system A
Figure 4.2: Load duration curve LDC for system A
Figure 4.3: Forcéd outage capacity probability density function for units 1 and 2
Load Model:

The LPD of system A is shown in Fig.(4.1)

Risk Model:

Convolving each unit with the LPD using the convolution equation 2.9, the effective load probability distribution \( F(L_{eA}) \) will be as shown in Fig.(4.4). The installed capacity of system A is

\[
IC_A = 50 + 50 = 100 \text{ MW}
\]

Evaluating LOLP from Fig.(4.4) at \( L_{eA} = IC_A \), thus

\[
\text{LOLP}_A = 0.02981924
\]

Expressing LOLP in hours per week, hence

\[
\text{LOLE}_A = 0.02981924 \times 168 = 5.009632 \text{ hours/week}
\]

Integrating \( F(L_{eA}) \) for \( L_{eA} = IC_A \) to \( IC_A + \text{Peak value} \), the \( \text{EDNS}_A \), which is the shaded area of Fig.(4.4), and the \( \text{EENS}_A \) are therefore,

\[
\text{EDNS}_A = 0.4457919 \text{ MW}
\]

\[
\text{EENS}_A = 0.4457919 \times 168 = 74.89304 \text{ MWH}
\]

From Fig.(4.1), The load factor LF of system A is calculated to be

\[
LF_A = 0.6998
\]

and therefore, the expected value of energy EVE of the system is

\[
\text{EVE}_A = 0.6998 \times 78.034 \times 168 = 9174.172 \text{ MWH}
\]

Therefore, the energy index of reliability EIR of system A is

\[
\text{EIR}_A = 1 - \left( \frac{75.42}{9174.18} \right) = 0.9918365
\]
Figure 4.4: Effective load probability distribution of system A

LOLP_A = 0.02981924

EDNS_A = 0.4457919 MW
COPT Method:

Generation Model:

The COPT for the 2-unit of system A is given in table (4.1).

Load Model:

The LPC of system A is shown in Fig.(4.2)

Risk Model:

Compined the COPT with the LDC of the system, Fig.(4.5) will result. The time $t_i$ and the energy curtailed $E_i$ associated with the capacity outage $O_i$ are tabulated in table (4.2). Applying Eq.2.18, LOLE of the system is found to be

$$\text{LOLE}_A = 5.0096 \text{ hours/week}$$

therefore,

$$\text{LOLP}_A = \frac{5.0096}{168} = 0.0298192$$

The EENS of the system is calculated using Eq.2.20

$$\text{EENS}_A = 74.30774 \text{ MWH}$$

therefore,

$$\text{EDNS}_A = \frac{74.30774}{168} = 0.442308 \text{ MW}$$

But, the expected value of energy EVE of the system is

$$\text{EVE}_A = 9174.18 \text{ MWH}$$

therefore, the energy index of reliability EIR of system A is

$$\text{EIR}_A = 1 - \left(\frac{74.30774}{9174.18}\right) = 0.991900$$
Figure 4.5: Load-capacity relationship for system A
TABLE 4.1
COPT for 2 Units

<table>
<thead>
<tr>
<th>Number of States $= 2^{NG}$</th>
<th>Capacity out of Service (MW) $O_i$</th>
<th>Probability $P_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>$(0.98)(0.97) = 0.9506$</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>$(0.02)(0.97) = 0.0194$</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>$(0.03)(0.98) = 0.0294$</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>$(0.02)(0.03) = 0.0006$</td>
</tr>
</tbody>
</table>
**TABLE 4.2**

Time $t_i$ and Energy Curtained $E_i$ Associated with Capacity Outage $O_i$ and its Probability $p_i$

<table>
<thead>
<tr>
<th>Capacity out of Service (MW) $O_i$</th>
<th>Probability $p_i$</th>
<th>Time in Hours $t_i$</th>
<th>Energy Curtailed (MWH) $E_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.9506</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>50</td>
<td>0.0194</td>
<td>100.59096</td>
<td>8.3927586</td>
</tr>
<tr>
<td>50</td>
<td>0.0294</td>
<td>100.59096</td>
<td>8.3927586</td>
</tr>
<tr>
<td>100</td>
<td>0.0006</td>
<td>168.00</td>
<td>54.6238</td>
</tr>
</tbody>
</table>
RELIABILITY INDICES OF SYSTEM B

Since system B has the same characteristics as system A, the reliability indices of system B will be same as system A.

4.2.2 INTERCONNECTED AREAS RELIABILITY INDICES

EQUIVALENT ASSISTING UNIT METHOD

Assuming that area A is assisting area B. Since these two areas duplicate the single area discussed earlier, we already know that

\[ \text{LOLP}_A = \text{LOLP}_B = 0.02981924 \]

Determining \( f(L_{eA}) \) using Eq. 3.15, we get the result depicted in Fig.(4.6). In addition, utilizing Eq. 3.13, we easily obtained the reserve margin density function \( f(R_{eA}) \) shown in Fig.(4.7).

Therefore, the LOLP\(_{BA}\) of the system using Eq. 3.31 becomes:

\[ \text{LOLP}_{BA} = 0.009823717 \]

and the LOLE\(_{BA}\) of the system becomes:

\[ \text{LOLE}_{BA} = 0.009823717 \times 168 = 1.650384 \text{ hours/week} \]

The EDNS\(_{BA}\) of the system is calculated, using Eq. 3.36, to be:

\[ \text{EDNS}_{BA} = 0.4379897 \text{ MW} \]

therefore, the EENS\(_{BA}\) becomes:

\[ \text{EENS}_{BA} = 0.4379897 \times 168 = 73.58226 \text{ MWH} \]

and the EIR\(_{BA}\), using Eq. 3.40, is

\[ \text{EIR}_{BA} = 1 - (73.58187/9174.18) = 0.9919794 \]
Figure 4.6: Effective load probability density function $f(L_{eA})$
Figure 4.7: Effective reserve probability density function $f(R_{eA})$
**Probability Array Method**

Since the COPT and the load model of the two areas are the same, the probability of simultaneous outages and the load loss in both areas will be the same. Assuming that area B is in shortage, the probability of simultaneous outages in area B is shown in table (4.3). For example, the probability that area B will lose the two units (i.e. 100 MW is out of service), and area A has no loss (i.e. all units are available) is

\[ (0.0006)(0.9506) = 5.7036 \times 10^{-4} \]

Moreover, the load loss in area B is given in table (4.4). For example, when all units of area B are out of service, the load loss is 78.034 MW. At the same time, if area A has all the units available then the reserve in A is \( (100-78.024=21.976 \text{ MW}) \). But since the tie line capacity \( C_T \) is only 20 MW, then area A can feed B with 20 MW, and therefore, the load loss in area B will become 58.034 MW.

Calculate the associated time \( t_{ij} \) and energy curtailed \( E_{ij} \) as given in tables (4.5) and (4.6) respectively. Using Eqs. 3.43 and 3.44, we can calculate the following indices:

- \( \text{LOLE}_{BA} = 1.68058 \text{ hours/week} \)
- \( \text{LOLP}_{BA} = 1.68058/168 = 0.0100 \)
- \( \text{EENS}_{BA} = 12.3606 \text{ MWH} \)
- \( \text{EDNS}_{BA} = 12.3606/168 = 0.073575 \text{ MW} \)
- \( \text{EIR}_{BA} = 0.99865 \)
TABLE 4.3
Probability of Simultaneous Outages in Area B

<table>
<thead>
<tr>
<th>MW out (A)</th>
<th>0</th>
<th>50</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>9.0364 E-01</td>
<td>1.8442 E-02</td>
<td>2.7948 E-02</td>
<td>5.7036 E-04</td>
</tr>
<tr>
<td>50</td>
<td>1.8442 E-02</td>
<td>3.7636 E-04</td>
<td>5.7036 E-04</td>
<td>1.1640 E-05</td>
</tr>
<tr>
<td>50</td>
<td>2.7948 E-02</td>
<td>5.7036 E-04</td>
<td>8.6436 E-04</td>
<td>1.7640 E-05</td>
</tr>
<tr>
<td>100</td>
<td>5.7036 E-04</td>
<td>1.1640 E-05</td>
<td>1.7640 E-05</td>
<td>3.6000 E-07</td>
</tr>
<tr>
<td>MW out (A)</td>
<td>0</td>
<td>50</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>-----------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>MW out (B)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>50</td>
<td>8.034</td>
<td>28.034</td>
<td>28.034</td>
<td>28.034</td>
</tr>
<tr>
<td>50</td>
<td>8.034</td>
<td>28.034</td>
<td>28.034</td>
<td>28.034</td>
</tr>
<tr>
<td>100</td>
<td>58.034</td>
<td>78.034</td>
<td>78.034</td>
<td>78.034</td>
</tr>
</tbody>
</table>

TABLE 4.4
Load Loss in Area B
### Table 4.5

<table>
<thead>
<tr>
<th>MW out (A)</th>
<th>0</th>
<th>50</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>50</td>
<td>28.827</td>
<td>100.591</td>
<td>100.591</td>
<td>100.591</td>
</tr>
<tr>
<td>50</td>
<td>28.827</td>
<td>100.591</td>
<td>100.591</td>
<td>100.591</td>
</tr>
<tr>
<td>100</td>
<td>168.00</td>
<td>168.00</td>
<td>168.00</td>
<td>168.00</td>
</tr>
</tbody>
</table>

Time t in Hours
### Table 4.6
Energy curtailed in MW

<table>
<thead>
<tr>
<th>MW out (A)</th>
<th>0</th>
<th>50</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>50</td>
<td>115.798</td>
<td>1409.98</td>
<td>1409.98</td>
<td>1409.98</td>
</tr>
<tr>
<td>50</td>
<td>115.798</td>
<td>1409.98</td>
<td>1409.98</td>
<td>1409.98</td>
</tr>
<tr>
<td>100</td>
<td>5816.80</td>
<td>9176.80</td>
<td>9176.80</td>
<td>9176.80</td>
</tr>
</tbody>
</table>
4.2.3 Summary

The reliability indices namely: LOLP, LOLE, EDNS, EENS, and EIR for area A using two alternative techniques (Convolution and COPT) were evaluated, and the comparison between them for both single area and two interconnected areas is given in tables (4.7, and 4.8).

4.3 G.C.G. System Example

In this example, the two Gulf countries, United Arab Emaret U.A.E., and Oman, are considered. The daily peak load data, for a period of 217 days, for each country is given in Appendix A. Moreover, the unit capacities and the associated forced outage rate q of each unit are also given in Appendix A. The interconnected tie capacity $C_T$ between the two countries is 450 MW.

In this example, however, the convolution technique will be considered for single area and the Equivalent Assisting Unit method for interconnected areas. The effect of load forecast uncertainties for first area will be accounted for. The uncertainty is assumed to be normally distributed using seven-step approximation. Load correlation effect on the interconnected system is also presented. The 217 days period has been broken-out into 8 different period forms. The ELCC for a 160 MW unit to be added to the first country with a forced outage rate of 0.08 is included. Also, the LCC for a standard LOLE of 0.1 day is calculated.
TABLE 4.7
Comparison Between Convolution and COPT Methods for Single Area

<table>
<thead>
<tr>
<th>Reliability Indices</th>
<th>Convolution Method</th>
<th>COPT Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOLP (P.U.)</td>
<td>0.02981924</td>
<td>0.0298182</td>
</tr>
<tr>
<td>LOLE (hours)</td>
<td>5.009632</td>
<td>5.0096</td>
</tr>
<tr>
<td>EDNS (MW)</td>
<td>0.4457919</td>
<td>0.442308</td>
</tr>
<tr>
<td>EENS (MWH)</td>
<td>74.89304</td>
<td>74.30774</td>
</tr>
<tr>
<td>EIR</td>
<td>0.9918365</td>
<td>0.9919</td>
</tr>
</tbody>
</table>
TABLE 4.8
Comparison Between Convolution and COPT Methods for two Interconnected Areas

<table>
<thead>
<tr>
<th>Reliability Indices</th>
<th>Convolution Method</th>
<th>COPT Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOLP (P.U.)</td>
<td>0.00982373</td>
<td>0.0100</td>
</tr>
<tr>
<td>LÖLE (hours)</td>
<td>1.650384</td>
<td>1.68058</td>
</tr>
<tr>
<td>EDNS (MW)</td>
<td>0.07055944</td>
<td>0.073575</td>
</tr>
<tr>
<td>EENS (MWH)</td>
<td>11.85399</td>
<td>12.3606</td>
</tr>
<tr>
<td>EIR</td>
<td>0.9987080</td>
<td>0.99865</td>
</tr>
</tbody>
</table>
4.3.1 Single Area Reliability Indices

The reliability indices can be evaluated for each area (assuming area A for U.A.E. and area B for Oman) following the flow chart illustrated in Fig. (4.8). Using the daily peak load data of each area to develop the daily peak load curve shown in Fig. (4.9). The load probability distribution \( F(L_A) \) and \( F(L_B) \) of each area can be then defined as shown in Figs. (4.10 and 4.11). The load factor LF, expected value of demand EVD, and the expected value of energy EVE of each area are calculated using Eqs. 2.4, 2.5, and 2.6.

Convolving each unit with the LPD curve using Eq. 2.11 to construct the effective load probability distribution \( F(L_{eA}) \) and \( F(L_{eB}) \) as shown in Figs. (4.10 and 4.11). Reliability indices can be, therefore, evaluated using Eqs. 2.12, 2.13, 2.14, 2.15, and 2.16. The results are given in tables (D.1 and D.2).

4.3.2 Interconnected Area Reliability Indices

The flow chart needed for evaluating the reliability indices of two interconnected areas is shown in Fig. (4.12). The tie line capacity \( C_T \) between the two systems is 450 MW, and it is assumed 100% reliable. The effective load probability distribution \( F(L_{eA}) \) and \( F(L_{eB}) \) from the load probability distribution \( F(L_A) \) and \( F(L_B) \) are developed as in the single area case.
Figure 4.8: Single Area Reliability Indices Flow Chart

where

\( ND = \text{Number of Days} \)

\( NG = \text{Number of Generators} \)

\( \text{PEAK}_i = \text{Load Peak Data} , \quad (i=1,2,\ldots, ND) \)

\( \text{CAP}_j = \text{Generation Capacity} \)

\( \text{FOR}_j = \text{Forced Outage Rate} , \quad (j=1,2,\ldots, NG) \)
Figure 4.9: Daily peak load curve for area U.A.E. and Oman
Figure 4.10: Load and effective load probability distribution of area $A$
Figure 4.11: Load and effective load probability distribution of area B
Start

Read : ND, CT

Read : NGA, PEAKA_i, CAPA_j, FORA_j

Call LPD subroutine to find-out $F(L_A)$

Calculate $LF_A$, $EVD_A$, and $EVE_A$

Call ELPD subroutine to find-out $F(L_{eA})$

Calculate $LOLP_A$, $LOLE_A$, $EDNS_A$, $EENS_A$, $EIR_A$

Read : NGB, PEAKB_i, CAPB_j, FORB_j

Call LPD subroutine to find-out $F(L_B)$

Calculate $LF_B$, $EVD_B$, and $EVE_B$

Call ELPD subroutine to find-out $F(L_{eB})$

Calculate $LOLP_B$, $LOLE_B$, $EDNS_B$, $EENS_B$, $EIR_B$
Figure 4.12: Interconnected Areas Reliability Indices Flow Chart

where

\[ C_T = \text{Tie Capacity} \]
Using Eqs. 3.15 and 3.16 to evaluate the effective load probability density function \( f(L_{eA}) \) and \( f(L_{eB}) \). Therefore, the effective load reserve margin \( f(R_{eA}) \) and \( f(R_{eB}) \), can be found using Eqs. 3.13 and 3.14. With these information and using Eqs. 3.23, 3.36, and 3.40, we can evaluate the interconnected reliability indices. The results are given in tables (D.1 and D.2).

4.3.3 **LOAD FORECAST UNCERTAINTIES EFFECT**

The load forecast uncertainty is represented by a seven-step approximation to the normal distribution as shown in Fig.(2.6). The standard deviation of this distribution is chosen to be 0.08 of the forecast peak load. There are therefore seven conditional load shapes, each with a probability of existence. These load shapes are combined together using the interpolation technique to produce a load profile which includes uncertainty. After that, we convolve each unit with the modified load probability distribution using Eq. 2.9. The reliability indices are then evaluated as in the single area case. Following the flow chart of Fig.(4.13), the results are shown in table (D.3).

4.3.4 **LOAD CORRELATIONS EFFECT**

It is more convenient to include the load correlation in evaluating the system reliability indices. This could be done by breaking the full period into sub-periods. To obtain a good enhancement, it is better to divide the study-period as small as possible. However, since the contribution from the peaker periods are the most effective one, they will be considered.
Figure 4.13: Load Forecast Uncertainties Flow Chart
In our example, we have divided the two areas into eight sub-periods as shown in Fig.(4.14). Then each period is treated by itself and at the end we sum up the results. The flow chart is presented in Fig.(4.15). The results of the sub-periods are given in tables (D.4 to D.11) and the summation is in table (D.12).

4.3.5 ELCC

Assuming that the system is existing and we want to know the effective value of a 160 MW unit with a FOR of 0.08 to be added to area A. The flow chart is given in Fig.(4.16). The actual value is given in table (D.13).

4.3.6 LCC

Assuming that the system is existing and we want to know the system carrying capability for a standard LOLE of 0.1 day in area A. The flow chart for calculating the system LCC is given in Fig.(4.17). The system LCC is given in table (D.14).

4.3.7 Summary

The reliability indices namely: LOLP, LOLE, EDNS, EENS, and EIR have been evaluated for both single area and two interconnected areas. The convolution method has been selected for single area, whereas, the Equivalent Assisting Unit method for two interconnected areas. The effect of interconnection on reliability indices is given on table (4.9).
The effect of load forecast uncertainties are shown on table (4.10). The effect of load correlation are, also, considered as given in table (4.11). The contribution from each frame as well as the total frames were calculated. The ELCC of an added unit and the LCC for the system have also been calculated.
Figure 4.14: Daily peak load curve for area A and B including load correlation.
Start

Read: ND, C_T, NLC, LCF_i

Read: NGA, PEAKA_i, CAPA_j, FORA_j

Read: NGB, PEAKB_i, CAPB_j, FORB_j

LL=1

ND=LCF_i

Call LPD subroutine to find-out F(L_A)

Calculate LF_A, EVD_A, and EVE_A

Call ELPD subroutine to find-out F(L_{eA})

Call LPD subroutine to find-out F(L_B)

Calculate LF_B, EVD_B, and EVE_B

Call ELPD subroutine to find-out F(L_{eB})
Figure 4.15: Load Correlations Flow Chart

where

\[ NLC = \text{Number of load correlation} \]
\[ LCF_i = \text{Load correlation forms, } (i=1,2,\ldots,\text{NLC}) \]
Figure 4.16: ELCC Flow Chart

where

UNIT = Unit to be added
QU = The associated forced outage rate
Figure 4.17: LCC Flow Chart

where

LOLEs = The standard LOLE
<table>
<thead>
<tr>
<th>Reliability Indices</th>
<th>Single Area</th>
<th>Two Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOLP (P.U.)</td>
<td>0.1823929 E-01</td>
<td>0.1334408 E-02</td>
</tr>
<tr>
<td>LOLE (Hours)</td>
<td>0.3957926 E 01</td>
<td>0.2895665 E 00</td>
</tr>
<tr>
<td>EDNS (MW)</td>
<td>0.3375051 E 01</td>
<td>0.2172005 E 00</td>
</tr>
<tr>
<td>EENS (MWH)</td>
<td>0.1757726 E 05</td>
<td>0.1131180 E 04</td>
</tr>
<tr>
<td>EIR</td>
<td>0.9993220 E 00</td>
<td>0.9999564 E 00</td>
</tr>
<tr>
<td>Reliability Indices</td>
<td>Without Uncertainty</td>
<td>With Uncertainty</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>LOLP (P.U.)</td>
<td>0.1823929 E-01</td>
<td>0.8186162 E-01</td>
</tr>
<tr>
<td>LOLE (Hours)</td>
<td>0.3957926 E 01</td>
<td>0.1776396 E 02</td>
</tr>
<tr>
<td>EDNS (MW)</td>
<td>0.3375051 E 01</td>
<td>0.2777309 E 02</td>
</tr>
<tr>
<td>EENS (MWH)</td>
<td>0.1757726 E 05</td>
<td>0.1446422 E 06</td>
</tr>
<tr>
<td>EIR</td>
<td>0.9993220 E 00</td>
<td>0.8661098 E 00</td>
</tr>
</tbody>
</table>
### TABLE 4.11
Effect of Load Correlation on System A (U.A.E.)

<table>
<thead>
<tr>
<th>Reliability Indices</th>
<th>Without Correlation</th>
<th>With Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOLP (P.U.)</td>
<td>0.1334408 E-02</td>
<td>0.3719720 E-04</td>
</tr>
<tr>
<td>LOLE (Hours)</td>
<td>0.2895665 E 00</td>
<td>0.8071805 E 00</td>
</tr>
<tr>
<td>EDNS (MW)</td>
<td>0.2172005 E 00</td>
<td>0.5707844 E 00</td>
</tr>
<tr>
<td>EENS (MWH)</td>
<td>0.1131180 E 04</td>
<td>0.2972645 E 04</td>
</tr>
<tr>
<td>EIR</td>
<td>0.9999564 E 00</td>
<td>0.9998853 E 00</td>
</tr>
</tbody>
</table>
CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The reliability indices for single area and two interconnected areas have been evaluated. Two different techniques were illustrated for evaluation, namely: Convolution and Capacity Outage Probability Tables, and two examples were used for simulations.

The system reliability can be improved by either adding more units or by buying energy from surrounding. It has been found from the first example that the reliability indices by the two techniques are nearly the same. Moreover, it can be stated that the convolution technique can be applied to both small system as well as for large system whereas the COPT technique can be applied only for small system. For large system approximate techniques are needed.

The system reliability has been calculated more accurately by including the load forecast uncertainty for single area and the load correlation for two areas. It was noticed that the system reliability has decreased.

From the second example, one can calculate the ELCC for an added unit and the LCC of the overall system for a given LOLEs by using the convolution technique.
5.2 RECOMMENDATIONS

For future work the generating unit can be assumed to exist in more than two derated states. Therefore, the present work can be extended by incorporating the derated states. However, the data for derated states have to be available for this type of study.

The energy index can be developed from the COPT for two interconnected areas but it may need large memory in the computer.

On the same line and as a future work, one can extend the evaluation of the reliability indices for more than two interconnected areas.
APPENDIX A
PROGRAM DESCRIPTION

# THIS PROGRAM HAS BEEN DEVELOPED TO COMPUTE THE FOLLOWING
# FOR SINGLE AND TWO AREAS:
# 1) LOAD PROBABILITY DISTRIBUTION CURVE (LPD)
# 2) EFFECTIVE LOAD PROBABILITY DISTRIBUTION CURVE (ELPD)
  # TO CALCULATE THE RELIABILITY INDICES NAMELY:
  #   A- LOSS OF LOAD PROBABILITY (LOLP)
  #   B- LOSS OF LOAD EXPECTATION (LOLE)
  #   C- EXPECTED DEMAND NOT SERVED (EDNS)
  #   D- EXPECTED ENERGY NOT SERVED (EENS)
  #   E- ENERGY INDEX OF RELIABILITY (EIR)
# 3) EFFECTIVE LOAD CARRYING CAPACITY (ELCC) FOR
   AN UNIT TO BE ADDED.
# 4) LOAD CARRYING CAPABILITY (LCC) FOR A GIVEN STANDARD
   LOLES.
# 5) THE EFFECT OF THE LOAD FORECAST UNCERTAINTIES
# 6) THE EFFECT OF LOAD CORRELATION.
#
REAL MWPUA(101), MWUA(101), LOLPUA, LOLEUA, LOLES, LFA,
+LOLPA, LOLEA, LOLPAB, LOLEAB, LOLPAT, LOLEAT, LOLPAC, LOLEAC
REAL MWPU(101), LFB, LOLPB, LOLEB, LOLPBA, LOLEBA, LOLPBT,
+LOLEBT, LOLPBC, LOLEBC, LOLPO
DIMENSION PEAKA(400), CAPA(140), FORA(140), PRA(101), EPRA(350)
DIMENSION PEAKB(400), CAPB(140), FORB(140), PRB(101), EPRB(350)
DIMENSION EPR(140, 350), ILC(10), PRUA(101)
COMMON/COM1A/PEAKA/COM2A/MWPUA/COM3A/PRA/COM4A/CAPA, FORA
COMMON/COM1B/PEAKB/COM2B/MWPUB/COM3B/PRB/COM4B/CAPB, FORB
COMMON/COM1/ MWUA/MWUB/PRUA/COM3/EPR/COM5A/EPRA/COM5B/EPRB
READING THE INPUT DATA:

NA = NUMBER OF AREAS
ND = NUMBER OF DAYS
IU = INCLUDING LOAD FRECAST UNCERTAINTIES
CT = INTERCONNECTING TIE CAPACITY
PEAK = PEAK VALUES IN MW
CAP = UNIT CAPACITY IN MW
FOR = UNIT FORCED OUTAGE RATE (F.O.R.)
UNIT = ANY UNIT TO BE ADDED FOR CALCULATING ELCC
QU = F.O.R. OF THE UNIT TO BE ADDED FOR CALCULATING ELCC
LOLES = THE STANDARD LOLE TO CALCULATE THE SYSTEM LCC

READ(5,*)NA,ND,IU,CT,LC
READ(5,200)(PEAKA(I),I=1,ND)
READ(5,*)NGA
READ(5,210)(CAPA(I),FORA(I),I=1,NGA)
READ(5,*)NU,UNIT,QU
READ(5,*)LOLES
10 IF(NA-1)15,15,10
READ(5,200)(PEAKB(I),I=1,ND)
READ(5,*)NGB
READ(5,210)(CAPB(I),FORB(I),I=1,NGB)
IF(LC.EQ.0) GOTO 15
READ(5,220)(ILC(I),I=1,LC)

CALCULATING THE LOAD PROBABILITY DISTRIBUTION (LPD)

15 CALL LPD(PEAKA,ND,MWPUA,PRA,LFA,BASEA,NDMA,EVDA,EVEA)

CALCULATING THE EFFECTIVE LOAD CARRYING CAPACITY (ELCC) FOR A UNIT

20 IF(NU)25,25,20
CALL ADDU(BASEA,NGA,UNIT,QU)
GOTO 100

CALCULATING THE EFFECTIVE LOAD PROBABILITY DISTRIBUTION (ELPD)

25 CALL ELPD(PRA,BASEA,ND,CAPA,FORA,NGA,EPRA,TOTA,SUMA)

CALCULATING THE SYSTEM LOAD CARRYING CAPABILITY (LCC)

30 IF(LOLES)35,35,30
CALL INTERR(EPRA,TOTA,LOLPO)
CALL SLCC(BASEA,ND,NGA,LOLES,LOLPO)
GOTO 100
RELIABILITY INDICES EVALUATION

35 CALL RIE(EVEA, BASEA, ND, EPRA, TOTA, SUMA, LOLPA, LOLEA, EDNSA,
  +EENSA, EIRA)

INCLUDING THE LOAD FORECAST UNCERTAINTIES (LPDIU)

40 IF(IU)45, 45, 40
45 CALL LPDIU(ND, BASEA, EVEUA, BASEUA)
CALL ELPD(PRUA, BASEUA, ND, CAPA, FORA, NGA, EPRA, TOTUA, SUMUA)
CALL RIE(EVEUA, BASEUA, ND, EPRA, TOTUA, SUMUA, LOLPUA, LOLEUA,
  +EDNSUA, EENSUA, EIRUA)

RELIABILITY INDICES EVALUATION FOR INTERCONNECTED SYSTEMS

50 IF(NA-1)70, 70, 50
55 CALL LPD(PEAKB, ND, MWPUB, PRB, LFB, BASEB, NDMB, EVDB, EVEB)
CALL ELPD(PRBB, BASEB, ND, CAPEB, FORB, NGB, EPRB, TOTB, SUMB)
CALL RIE(EVEB, BASEB, ND, EPRB, TOTB, SUMB, LOLPB, LOLEB,
  +EDNSB, EENSB, EIRB)

RELIABILITY INDICES EVALUATION

60 CALL RIEIS(ND, CT, BASEA, SUMA, TOTA, EPRA, LOLPA, BASEB, SUMB, TOTB,
  +EPRB, EVEB, LOLPBA, LOLEBA, EDNSBA, EENSBA, EIRBA)
CALL RIEIS(ND, CT, BASEB, SUMB, TOTB, EPRB, LOLPB, BASEA, SUMA, TOTA,
  +EPRA, EVEA, LOLPAB, LOLEAB, EDNSAB, EENSAB, EIRAB)
GOTO 85

INCLUDING THE EFFECT OF LOAD CORRELATION (ELC)

65 LL=0
KK=0
LOLEAT=0.0
EENSAT=0.0
LOLEBT=0.0
EENSBT=0.0
IF(LC)100, 100, 60
60 LL=LL+1
NDC=ILC(LL)
DO 65 I=1, NDC
PEAKA(I)=PEAKA(I+KK)
PEAKB(I)=PEAKB(I+KK)
CALL ELC(NDC, CT, LL, NGA, NGB, LOLEBC, EENSBC, LOLEAC, EENSAC)
LOLEAT=LOLEAT+LOLEAC
EENSAT=EENSAT+EENSAC
LOLEBT=LOLEBT+LOLEBC
EENSBT=EENSBT+EENSBC
KK=KK+NDC
IF(LL-LC) 60, 90, 90
C
C # OUTPUT SUBROUTINES NAMELY :
C # SOUT = SYSTEM OUTPUT FOR SINGLE AREA
C # RIO = RELIABILITY INDICES OUTPUT FOR SINGLE AREA
C # RIOIU= R.I. OUTPUT INCLUDING UNCERTAINTIES FOR SINGLE AREA
C # ISOUT= INTERCONNECTED SYSTEMS OUTPUT
C # ISOLC= I. S. OUTPUT INCLUDING LOAD-CORRELATION
C

70 CALL SOUT(ND, NGA, BASEA, TOTA, LFA, EVDA, EVEA)
   IF(IU)75,75,80
75 CALL RIO(LOLPA, LOLEA, EDNSA, EENS, EIRA)
   GOTO 100
80 CALL RIOIU(LOLPA, LOLEA, EDNSA, EENS, EIRA,
+LOLPBA, LOLEBA, EDNSBA, EENSBA, EIRBA)
   GOTO 100
85 CALL ISOUT(ND, CT, NGA, BASEA, TOTA, LFA, EVDA, EVEA, LOLPA, LOLEA, EDNSA,
+LFA, EIRA, LOPABA, LOLEAB, EDNSAB, EENSAB, EIRAB,
+NGB, BASEB, TOTB, LFB, EVDB, EVEB, LOPB, LOLEB, EDNSB,
+EENS, EIRB, LOPBBA, LOLEBBA, EDNSBBA, EENSBB, EIRBBA)
   GOTO 55
90 CALL ISOLC(ND, EVEA, LOLEAT, EENSAT, LOLPAB, LOLEAB, EDNSAB, EENSAB, EIRAB
+, EVEB, LOLEBT, EENSBT, LOPBA, LOLEBA, EDNSBA, EENSBA, EIRBA)
200 FORMAT(7(F8.3))
210 FORMAT(2F10.5)
220 FORMAT(10(I3))
100 STOP
END
SUBROUTINE LPD(PEAK, ND, MWPU, PR, LF, BASE, NDM, EVD, EVE)

* THIS SUBROUTINE IS Used TO CALCULATE THE LOAD PROBABILITY *
* DISTRIBUTION CURVE (LPD), GIVEN THE LOAD PEAK DATA OF *
* A SYSTEM. MOREOVER, IT CALCULATE THE FOLLOWING: *
* BASE = THE MAXIMUM PEAK VALUE *
* NDM = THE DAY IN WHICH THE MAXIMUM PEAK OCCURE *
* LF = LOAD FACTOR *
* EVD = THE EXPECTED VALUE OF DEMAND *
* EVE = THE EXPECTED VALUE OF ENERGY *

REAL MWPU(101), LF, MAX
DIMENSION PEAK(ND), PR(101)

FINDING THE MAXIMUM PEAK VALUE

MAX=PEAK(1)
DO 10 I=2, ND
   IF(PEAK(I).GT.MAX) THEN
      MAX=PEAK(I)
      NDM=I
   ENDIF
10 CONTINUE
BASE=MAX

NORMALIZING THE PEAK VALUES

DO 20 I=1, ND
   20 PEAK(I)=PEAK(I)/BASE

FORMULATING THE PROBABILITY-AXIS (PR) AND THE MW-AXIS
IN PER-UNIT (MWPU) TO BERFORM THE PLD.

DO 30 I=1, 101
   30 MWPU(I)=(I-1)/100.0
DO 50 J=1, 101
   SUM=0.
   DO 40 I=1, ND
   40 IF(PEAK(I).GE.MWPU(J)) THEN
      SUM=SUM+1.
      NDM=I
   ENDIF
   CONTINUE
   PR(J)=SUM/ND
50 CONTINUE
THE PEAK VALUES IN THEIR ACTUAL VALUES

DO 60 I=1,ND

60 PEAK(I)=PEAK(I)*BASE

CALCULATION OF THE LOAD FACTOR (LF)

DELT=MWPU(2)-MWPU(1)
AREA=(PR(1)+PR(101))/2
DO 70 I=2,100
70 AREA=AREA+PR(I)
LF=AREA*DELT

CALCULATING THE EXPECTED VALUE OF DEMAND (EVD)
AND THE EXPECTED VALUE OF ENERGY (EVE)

EVD=LF*BASE
EVE=EVD*ND*24.0
RETURN
END

SUBROUTINE RIOIU(LOLP, LOLE, EDNS, EENS, EIR,
+LOLPIU, LOLEIU, EDNSIU, EENSIU, EIRIU)

REAL LOLP, LOLE, LOLPIU, LOLEIU

WRITE(6,100)

100 FORMAT(//8X,'RELIABILITY INDICES',20X,'RELIABILITY INDICES'/
+,'45X,'INCLUDING UNCERTAINTIES')
WRITE(6,200)LOLP,LOLPIU

200 FORMAT(//5X,'LOLP =',E14.7,2X,'P.U.',13X,'LOLP =',E14.7,2X,'P.U.')
WRITE(6,300)LOLE,LOLEIU

300 FORMAT(//5X,'LOLE =',E14.7,2X,'MW',15X,'LOLE =',E14.7,2X,'MW')
WRITE(6,400)EDNS,EDNSIU

400 FORMAT(//5X,'EDNS =',E14.7,2X,'MW',15X,'EDNS =',E14.7,2X,'MW')
WRITE(6,500)EENS,EENSIU

500 FORMAT(//5X,'EENS =',E14.7,2X,'MWH',14X,'EENS =',E14.7,2X,'MWH')
WRITE(6,600)EIR,EIRIU

600 FORMAT(//5X,'EIR =',E14.7,19X,'EIR =',E14.7//)
RETURN
END
**SUBROUTINE SOUT(ND, NG, BASE, TOT, LF, EVD, EVE)**

C

**********
C * THIS SUBROUTINE PRINT GENERAL INFORMATIONS *
C * ABOUT THE SYSTEM *
C **********

REAL LF, IC
WRITE(6, 100)
100 FORMAT('0'/'15X,'SINGLE AREA RELIABILITY INDICES'/14X,33('*'))
WRITE(6, 200) ND
200 FORMAT(/5X,'DURATION TIME = ',I4,2X,'DAYS')
WRITE(6, 300) BASE
300 FORMAT(/5X,'MAXIMUM PEAK VALUE = ',F10.2,2X,'MW')
IC=TOT*BASE/100.
WRITE(6, 400) NG
400 FORMAT(/5X,'NUMBER OF GENERATION UNITS =',I5,2X,'UNITS')
WRITE(6, 500) IC
500 FORMAT(/5X,'SYSTEM INSTALLED CAPACITY = ',F9.2,2X,'MW')
WRITE(6, 600) LF
600 FORMAT(/5X,'LOAD FACTOR = ',E14.7)
WRITE(6, 700) EVD
700 FORMAT(/5X,'EXPECTED VALUE OF DEMAND = ',E14.7,2X,'MW')
WRITE(6, 800) EVE
800 FORMAT(/5X,'EXPECTED VALUE OF ENERGY = ',E14.7,2X,'MWH')
RETURN
END

**SUBROUTINE RIIOL(LOLP, LOLE, EDNS, EENS, EIR)**

C

**********
C * THIS SUBROUTINE PRINT THE RELIABILITY INDICES *
C * NAMELY: LOLP, LOLE, EDNS, EENS, EIR *
C **********

REAL LOLP, LOLE
WRITE(6, 100)
100 FORMAT(///10X,'RELIABILITY INDICES')
WRITE(6, 200) LOLP
200 FORMAT(/5X,'LOLP = ',E14.7,2X,'P.U.')
WRITE(6, 300) LOLE
300 FORMAT(/5X,'LOLE = ',E14.7,2X,'MW')
WRITE(6, 400) EDNS
400 FORMAT(/5X,'EDNS = ',E14.7,2X,'MW')
WRITE(6, 500) EENS
500 FORMAT(/5X,'EENS = ',E14.7,2X,'MWH')
WRITE(6, 600) EIR
600 FORMAT(/5X,'EIR = ',E14.7/)
RETURN
END
SUBROUTINE ISOUT(ND, CT, NGA, BASEA, TOTA, LFA, EVDA, EVEA, LOLPA, LOLEA,
+EDNSA, ENSA, EIRA, LOLPAB, LOLEAB, EDNSAB, EENSAB, EIRAB,
+NGB, BASEB, TOTB, LFB, EVDB, EWEB, LOLPB, LOLEB, EDNSB,
+EENSB, EIRB, LOLPBA, LOLEBA, EDNSBA, EENSBA, EIRBA)
REAL IC, LFA, LFB, LOLPA, LOLPB, LOLEA, LOLEB
+, LOLPAB, LOLPBA, LOLEAB, LOLEBA
WRITE(6,100)
100 FORMAT('0',//I5X,'INTERCONNECTED AREAS RELIABILITY INDICES'/
+I4X,42('*'))
WRITE(6,200)ND, CT
200 FORMAT('/5X,'SYSTEM DURATION TIME = ',I4,2X,'DAYS'
+/5X,'SYSTEM TIE CAPACITY = ',F7.2,2X,'MW'
+/25X,'SYSTEM A'/25X,7('('')
WRITE(6,300)BASEA
300 FORMAT('/5X,'MAXIMUM PEAK VALUE = ',F10.2,2X,'MW')
WRITE(6,350)NGA
350 FORMAT('/5X,'NUMBER OF GENERATION UNITS = ',I5,2X,'UNITS')
IC=TOTA*BASEA/100.
WRITE(6,400)IC
400 FORMAT('/5X,'SYSTEM INSTALLED CAPACITY = ',F9.2,2X,'MW')
WRITE(6,500)LFA
500 FORMAT('/5X,'LOAD FACTOR = ',E14.7)
WRITE(6,600)EVDA
600 FORMAT('/5X,'EXPECTED VALUE OF DEMAND = ',E14.7,2X,'MW')
WRITE(6,700)EVEA
700 FORMAT('/5X,'EXPECTED VALUE OF ENERGY = ',E14.7,2X,'MWH')
WRITE(6,800)
800 FORMAT('/8X,'RELIABILITY INDICES',21X,'RELIABILITY INDICES'/
+6X,'WITHOUT INTERCONNECTION',18X,'WITH INTERCONNECTION')
WRITE(6,900)LOLP, LOLP
900 FORMAT('/5X,'LOLP = ',E14.7,2X,'P.U.',14X,'LOLP = ',E14.7,2X,'P.U.')
WRITE(6,1000)LOLEA, LOLEAB
1000 FORMAT('/5X,'LOLE = ',E14.7,2X,'MW',16X,'LOLE = ',E14.7,2X,'MW')
WRITE(6,1100)EDNSA, EDNSAB
1100 FORMAT('/5X,'EDNS = ',E14.7,2X,'MW',16X,'EDNS = ',E14.7,2X,'MW')
WRITE(6,1200)EENS, EENSAB
1200 FORMAT('/5X,'EENS = ',E14.7,2X,'MWH',15X,'EENS = ',E14.7,2X,'MWH')
WRITE(6,1300)EIRA, EIRAB
1300 FORMAT('/5X,'EIR = ',E14.7,20X,'EIR = ',E14.7,
+'0'/25X,'SYSTM B'/25X,7('(''))
WRITE(6,1400) BASEB
1400 FORMAT('/5X,'MAXIMUM PEAK VALUE = ',F10.2,2X,'MW')
WRITE(6,1450)NGB
1450 FORMAT('/5X,'NUMBER OF GENERATION UNITS =',I5,2X,'UNITS')
IC=TOTB*BASEB/100.
WRITE(6,1500) IC
1500 FORMAT('/5X,'SYSTEM INSTALLED CAPACITY =',F9.2,2X,'MW')
WRITE(6,1600) LFB
1600 FORMAT('/5X,'LOAD FACTOR = ',E14.7)
WRITE(6,1700) EVDB
1700 FORMAT('/5X,'EXPECTED VALUE OF DEMAND = ',E14.7,2X,'MW')
WRITE(6,1800) EVEB
1800 FORMAT('/5X,'EXPECTED VALUE OF ENERGY = ',E14.7,2X,'MWH')
WRITE(6,1900)
1900 FORMAT('/8X,'RELIABILITY INDICES',2X,\'RELIABILITY INDICES\'/ +6X,'WITHOUT INTERCONNECTION',18X,'WITH INTERCONNECTION')
WRITE(6,2000) LOLPB,LOLPBA
2000 FORMAT('/5X,'LOLP =',E14.7,2X,'P.U.',14X,'LOLP =',E14.7,2X,'P.U.')
WRITE(6,2100) LOLEB,LOLEBA
2100 FORMAT('/5X,'LOLE =',E14.7,2X,'MW',16X,'EDNS =',E14.7,2X,'MW')
WRITE(6,2200) EDNSB,EDNSBA
2200 FORMAT('/5X,'EDNS =',E14.7,2X,'MW',16X,'EENS =',E14.7,2X,'MWH')
WRITE(6,2300) EENSB,EENSB
2300 FORMAT('/5X,'EENS =',E14.7,2X,'MWH',15X,'EIR =',E14.7,2X,'MWH')
WRITE(6,2400) EIRB,EIRBA
2400 FORMAT('/5X,'EIR =',E14.7,2X,'EIR =',E14.7)
RETURN
END

SUBROUTINE EXTER (F,K,Y,RES)
C
C  **********************************************************************************************************************
C * THIS SUBROUTINE EVALUATE THE LOAD POINT (RES) GIVEN
C * THE LOAD POINT (K) AND ITS ASSOCIATED PROBABILITY F(K) .
C  **********************************************************************************************************************
C
DIMENSION F(350)
RES=K-(Y-F(K))/(F(K-1)-F(K))
RETURN
END
SUBROUTINE ISOLC (ND, EVEA, LOLEAT, EENSAT, LOLPAB, LOLEAB, EDNSAB, EENSAB +, EIRAB, EWEB, LOLEBT, EENSBT, LOLPBA, LOLEBA, EDNSBA, EENSBA, EIRBA)

* THIS SUBROUTINE PRINT THE RELIABILITY INDICES FOR *
* INTERCONNECTED SYSTEMS INCLUDING LOAD CORRELATION *

REAL IC, LOLPAT, LOLEAT, LOLPAB, LOLEAB
REAL LOLPBT, LOLEBT, LOLPBA, LOLEBA

LOLPAT = LOLEAT / ND
EDNSAT = EENSAT / (ND * 24.0)
EIRAT = 1 - (EENSAT/EVEA)
LOLPBT = LOLEBT / ND
EDNSBT = EENSBT / (ND * 24.0)
EIRBT = 1 - (EENSBT/EWEB)

WRITE (6,100)
100  FORMAT (' 0'//25X,'SYTEM A'/25X,7(''-'))
WRITE (6,200)
200  FORMAT ('//8X,'RELIABILITY INDICES',21X,'RELIABILITY INDICES'/
+5X,'WITHOUT LOAD-CORRELATION',18X,'WITH LOAD CORRELATION')
WRITE (6,300) LOLPAT, LOLPBT
300  FORMAT ('//5X,'LOLP =','E14.7,2X,'P.U.' ,14X,'LOLP =','E14.7,2X,'P.U.')
WRITE (6,400) LOLEAB, LOLEAT
400  FORMAT ('//5X,'LOLE =','E14.7,2X,'MW',16X,'LOLE =','E14.7,2X,'MW')
WRITE (6,500) EDNSAB, EDNSAT
500  FORMAT ('//5X,'EDNS =','E14.7,2X,'MW',16X,'EDNS =','E14.7,2X,'MW')
WRITE (6,600) EENSAB, EENSAT
600  FORMAT ('//5X,'EENS =','E14.7,2X,'MWH',15X,'EENS =','E14.7,2X,'MWH')
WRITE (6,700) EIRAB, EIRBT
700  FORMAT ('//5X,'EIR =','E14.7,20X,'EIR =','E14.7')

WRITE (6,110)
110  FORMAT (' 0'//25X,'SYTEM B'/25X,7(''-'))
WRITE (6,210)
210  FORMAT ('//8X,'RELIABILITY INDICES',21X,'RELIABILITY INDICES'/
+5X,'WITHOUT LOAD-CORRELATION',18X,'WITH LOAD CORRELATION')
WRITE (6,310) LOLPBA, LOLPBT
310  FORMAT ('//5X,'LOLP =','E14.7,2X,'P.U.' ,14X,'LOLP =','E14.7,2X,'P.U.')
WRITE (6,410) LOLEBA, LOLEBT
410  FORMAT ('//5X,'LOLE =','E14.7,2X,'MW',16X,'LOLE =','E14.7,2X,'MW')
WRITE (6,510) EDNSBA, EDNSBT
510  FORMAT ('//5X,'EDNS =','E14.7,2X,'MW',16X,'EDNS =','E14.7,2X,'MW')
WRITE (6,610) EENSBA, EENSBT
610  FORMAT ('//5X,'EENS =','E14.7,2X,'MWH',15X,'EENS =','E14.7,2X,'MWH')
WRITE (6,710) EIRBA, EIRBT
710  FORMAT ('//5X,'EIR =','E14.7,20X,'EIR =','E14.7')

RETURN
END
SUBROUTINE LPDIU(ND, BASE, EVEIU, BASEIU)

******************************************************************************
* THIS SUBROUTINE IS USED TO CALCULATE THE LOAD PROBABILITY          *
* DISTRIBUTION CURVE INCLUDE THE LOAD FORECAST UNCERTAINTIES          *
* (LPDIU). MOREOVER, IT CALCULATE THE FOLLOWING:                        *
*    BASEIU = THE MAXIMUM FORECASTED PEAK VALUE                        *
*    EVEIU = THE EXPECTED VALUE OF ENERGY FORECASTED                    *
******************************************************************************

REAL MWPU(101), PR(101), MWF(10), PRF(10), MWIU(101), PRIU(101)
REAL MWI(101), PRI(101), PRI1(101)
COMMON/COM2A/MWPU/COM3A/PR/COM1/MWIU/COM2/PRIU

THE NUMBER OF THE FORECASTED STEPS

NF=7

THE FRECASTED PEAK VALUES

STEP=0.08
MWF(1)=BASE-3*STEP*BASE
MWF(2)=BASE-2*STEP*BASE
MWF(3)=BASE-STEP*BASE
MWF(4)=BASE
MWF(5)=BASE+STEP*BASE
MWF(6)=BASE+2*STEP*BASE
MWF(7)=BASE+3*STEP*BASE

THE STANDERED FORECASTED PROBABILITY VALUES

PRF(1)=0.0062
PRF(2)=0.0606
PRF(3)=0.2418
PRF(4)=0.3829
PRF(5)=0.2418
PRF(6)=0.0606
PRF(7)=0.0062

THE NEW FORECASTED MAXIMUM PEAK VALUE

BASEIU=MWF(NF)
NL=101
NL1=NL-1
DO 30 I =1,NL1
   J=I+1
30 MWIU(J) = I*MWF(NF)/NL1
MWIU(1)=0.
C
MULTIPLY FORCAST VALUES WITH THE LPD DATA
C
DO 40 I =1,NL
   PRIU(I) =0.
   DO 50 I =1,NF
   DO 60 J =1,NL
      MWI(J)=MWF(I)*MWPU(J)
      PRI(J)=PRF(I)*PR(J)
   60 CONTINUE
C
DO INTERPOLATION, NOTING THAT REFERENCE NOT NEED INTERPLOATION
C
   IF(I .EQ. NF) GO TO 110
   DO 70 M =1,NL
   DO 80 N =1,NL
      IF(M .EQ. 1)GO TO 1000
      GO TO 1110
   1000 PRI1(M)=PRI1(1)
      GO TO 70
   1110 IF(MWIU(M) .GE. MWF(I)) GO TO 100
       IF(MW(i(N)) .GT. MWIU(M)) GO TO 90
   80 CONTINUE
   90 NN=N-1
      PRI1(M)=PRI1(N)-(MWI(N)-MWIU(M))*(PRI(N)-PRI(NN))/(MWI(N)-MWI(NN))
      GO TO 70
   100 PRI1(M)=0.
   70 CONTINUE
   GO TO 130
   110 CONTINUE
   DO 120 K =1,NL
   120 PRI1(K)=PRI(K)
   130 CONTINUE
   DO 140 L =1,NL
   140 PRIU(L)=PRIU(L)+PRI1(L)
   50 CONTINUE
C
EXPECTED VALUE OF ENERGY INCLUDING UNCERTAINTY (EVEIU)
C
   DEL=MWIU(2)-MWIU(1)
   AREA=(PRIU(1)+PRIU(NL))/2
   NN=NL-1
   DO 99 I=2,NN
   99 AREA=AREA+PRIU(I)
   EVEIU=AREA*DEL*ND*24.0
   RETURN
   END
SUBROUTINE ADDU(BASE, ND, NGO, UNIT, QU)
C *********************************************************
C * THIS SUBROUTINE CALCULATE THE EFFECTIVE LOAD CARRYING  *
C * CAPACITY (ELCC) FOR ANY ADDED UNIT                       *
C *********************************************************
REAL ICO, LOLPO, LOLPN
DIMENSION PR(101), EPR(140, 350), CAP(140), FOR(140), EPRA(350)
COMMON/COM3A/PR/COM4A/CAP, FOR/COM3/EPR
NG=NGO+1
CAP(NG)=UNIT
FOR(NG)=QU
CALL ELPD(PR, BASE, ND, CAP, FOR, NG, EPRA, TOT, SUM)
C CALCULATING THE EFFECTIVE LOAD CARRYING CABABILITY (ELCC)
C
NG1=NG+1
TOTO=TOT-CAP(NG)*100.0/BASE
CALL INTER (EPR, NG, TOTO, LOLPO)
ICO=TOTO*BASE/100.
BASEN-BASE
DUNIT=UNIT
10 DELTA=DUNIT/3.0
30 BASEN=BASEN+DELA
CALL ELPD(PR, BASEN, ND, CAP, FOR, NG, EPRA, TOT, SUM)
CALL INTER (EPR, NG1, TOT, LOLPN)
IF (LOLPN.GE.LOLPO) THEN
AUNIT=BASEN-DELA
GOTO 50
ENDIF
GOTO 30
50 IF((LOLPN-LOLPO).LE.1.0 E-06) THEN
ELCC=AUNIT-BASE
GOTO 90
ENDIF
DUNIT=DELA
BASEN=AUNIT
GOTO 10
90 WRITE(6,100) ICO
100 FORMAT ('0'//'5X,'SYSTEM INSTALLED CAPACITY =',F9.2,2X,'MW')
WRITE(6,200) BASE
200 FORMAT('/5X,'SYSTEM MAXIMUM PEAK VALUE =',F9.2,2X,'MW')
WRITE(6,300) LOLPO
300 FORMAT('/5X,'SYSTEM LOLP =',E16.7,2X,'P.U.')
WRITE(6,400) UNIT
400 FORMAT('/5X,'THE ADDED UNIT CAPACITY =',F9.2,2X,'MW')
WRITE(6,500) ELCC
500 FORMAT('/5X,'THE ELCC OF THE ADDED UNIT =',F9.2,2X,'MW')
RETURN
END
SUBROUTINE RIE(EVE, BASE, ND, EPR, TOT, SUM, LOLP, LOLE, EDNS, EENS, EIR)

REAL LOLP, LOLE
DIMENSION EPR(350)

CALCULATION OF LOSS OF LOAD PROBABILITY LOLP

CALL INTERR (EPR, TOT, LOLP)

CALCULATION OF LOSS OF LOAD EXPECTATION LOLE

LOLE=LOLP*ND

CALCULATION OF EXPECTED DEMAND NOT SERVE EDNS

IX=SUM
K=TOT+1
CALL INTERR (EPR, SUM, X)
AREA=0.5*(LOLP+X)
DO 120 I=K, IX

120 AREA=AREA+EPR(I)
EDNS=AREA*BASE/100.

CALCULATION OF EXPECTED ENERGY NOT SERVE EENS

EENS=EDNS*ND*24.0

CALCULATION OF ENERGY INDEX OF RELIABILITY EIR

EIR=1.0-EENS/EVE
RETURN
END
SUBROUTINE ELPD(PR, BASE, ND, CAP, FOR, NG, EPRA, TOT, SUM)

********************************************************************
* THIS SUBROUTINE CALCULATE THE EFFECTIVE LOAD PROBABILITY    *
* DISTRIBUTION CURVE (ELPD)                                   *
********************************************************************

LD  = A VECTOR OF MW
PR  = THE PROBABILITY VECTOR
EPR = THE EFFECTIVE PROBABILITY AND IT IS A MATRIX (I,J), WHERE
      I REPRESENTS THE NORMALIZED MW, AND J IS THE PROBABILITY
NG  = NUMBER OF GENERATORS
ND  = NUMBER OF DAYS

DIMENSION LD(350), PR(101), EPR(140, 350), CAP(140), P(140),
       +FOR(140), C(140), EPRA(350)
COMMON/COM3/EPR

30   DO 40 I=1, 250
40   LD(I)=I

INITIALIZE F3 TO BE 0.0

DO 50 I=1, 140
   DO 50 J=1, 350
      50   EPR(I, J)=0.0

DO 60 I=2, 101
   EPR(1, I-1)=PR(I)

TOTAL INSTALLED CAPACITY=TOT.

   TOT=0.0
   DO 70 I=1, NG
      TOT=TOT+CAP(I)

GENERATOR AVALABILITY P(I)

   P(I)=1.0-FOR(I)

NORMALIZED GEN. CAP. AND TOT.

   70   C(I)=100.0*CAP(I)/BASE
       TOT=100.0*TOT/BASE
TO FIND EPR

SUM=100.0
DO 110 I=1,NG
SUM=SUM+C(I)
DO 100 J=1,350
Y=J-C(I)
IF(J .GT. SUM) THEN
  Y=SUM-C(I)
ENDIF
IF(Y .LE. 2.0) GO TO 80
CALL INTER (EPR,I,Y,RES)
VAL=RES
GO TO 90
80
VAL=1.0
90
CAL=EPR(I,J)*P(I) + VAL*FOR(I)
EPR(I+1,J)=CAL
IF(J .GT. SUM) GO TO 110
IF(CAL.LE.1.0 E-15) THEN
  SUM=J
GOTO 110
ENDIF
100 CONTINUE
110 CONTINUE
NG1=NG+1
DO 120 I=1,350
120 EPR(A(I)=EPR(NG1,I)
RETURN
END
SUBROUTINE SLCC(BASE, ND, NG, LOLES, LOLPO)

** THIS SUBROUTINE CALCULATE THE SYSTEM LOAD CARRYING **
** CAPABILITY (LCC) FOR A STANDARD LOLES **

REAL LOLPS, LOLES, LCC, IC, LOLPN, LOLPO, LOLEN, LOLEO
DIMENSION PR(101), EPR(140, 350), CAP(140), FOR(140), EPR(350)
COMMON/COM3A/PR/COM4A/CAP, FOR/COM3/EPR
LOLEO=LOLPO*ND
LOLPS=LOLES/ND
BASEN=BASE
DELTA=BASEN

IF(LOLES-LOLEO) 10, 10, 40
10 DELTA=DELTA/4.0
20 BASEN=BASEN-DELTA
CALL ELPD(PR, BASEN, ND, CAP, FOR, NG, EPR, TOT, SUM)
CALL INTERR(EPR, TOT, LOLPN)
IF(LOLPN.LT.LOLPS) THEN
GOTO 25
ENDIF
GOTO 20
25 IF((LOLPS-LOLPN).LE.1.0E-05) THEN
LCC=BASEN
GOTO 90
ENDIF
DELTA=DELTA
BASEN=BASEN+DELTA
GOTO 10
40 DELTA=DELTA/4.0
50 BASEN=BASEN+DELTA
CALL ELPD(PR, BASEN, ND, CAP, FOR, NG, EPR, TOT, SUM)
CALL INTERR(EPR, TOT, LOLPN)
IF(LOLPN.GT.LOLPS) THEN
GOTO 55
ENDIF
GOTO 50
55 IF((LOLPN-LOLPS).LE.1.0E-05) THEN
LCC=BASEN
GOTO 90
ENDIF
DELTA=DELTA
BASEN=BASEN-DELTA
GOTO 40
IC=TOT*BASEN/100.
LOLEN=LOLPN*ND
DELTA=BASEN-BASE
WRITE(6,100) IC
100 FORMAT('0'//,5X,'SYSTEM INSTALLED CAPACITY =',F9.2,2X,'MW')
WRITE(6,200) BASE
200 FORMAT(/,5X,'SYSTEM MAXIMUM PEAK VALUE =',F9.2,2X,'MW')
WRITE(6,310) LOLEO
310 FORMAT(/,5X,'THE SYSTEM LOLP =',E16.7,2X,'MW')
WRITE(6,300) LOLES
300 FORMAT(/,5X,'THE STANDARD LOLES =',E16.7,2X,'MW')
WRITE(6,400) LCC
400 FORMAT(/,5X,'THE SYSTEM LCC =',F9.2,2X,'MW')
IF(Delta)31,41,51
31 WRITE(6,500)ABS(Delta)
500 FORMAT(/,5X,'THE SYSTEM SHORTAGE CAPACITY =',F9.2,2X,'MW')
GOTO 61
41 WRITE(6,600)ABS(Delta)
600 FORMAT(/,5X,'THE SYSTEM SAVED CAPACITY =',F9.2,2X,'MW')
GOTO 61
51 WRITE(6,700)ABS(Delta)
700 FORMAT(/,5X,'THE SYSTEM SAVED CAPACITY =',F9.2,2X,'MW')
61 RETURN
END

SUBROUTINE INTER(F,I,Y,RES)

************************************************************************************************
* THIS SUBROUTINE EVALUATE THE PROBABILITY POINT (RES) GIVEN
* THE PROBABILITY POINTS F(I,K) AND F(I,K-1).
************************************************************************************************

DIMENSION F(140,350)
K=Y+1
RES=F(I,K)+(F(I,K-1)-F(I,K))*(K-Y)
RETURN
END
SUBROUTINE RIEIS(ND, CT, BASEA, SUMA, TOTA, FA, LOLPA, BASEB, SUMB, TOTB,
+FB, EWEB, LOPB, LOLEA, EDNSBA, EENSBA, EIRBA)

***********************************************************************
* THIS SUBROUTINE EVALUATE THE RELIABILITY INDICES (LOLP, LOLE, *
* EDNS, EENS, EIR), FOR INTERCONNECTED SYSTEMS *
***********************************************************************

DIMENSION FA(350), FB(350), FNEW(350), FII(350), AB2(350),
+FS(350), FR(350), FI(350), FBR(350), FIR(350), FIB(350, 350), FII(350)
REAL LOLPA, LOLPBA, LOLEA

TOW AREA , ASSUMING SHORTAGE IN SYSTEM B

CTA=CT*100./BASEA
CTB=CT*100./BASEB
IXA=SUMA+l
KA=TOTA+l
KAN=TOTA
IXB=SUMB+l
KB=TOTB+l
KBN=TOTB
DO 550 I=1,250
FS(I)=O.
FR(I)=O.
FI(I)=O.
FII(I)=O.
FII(I)=O.
550 FNEW(I)=O.

CALCULATING THE FIRST INTEGRAL

DO 500 I=2, IXA
DLT=0.1
X1=(I+DLT)
CALL INTERR (FA, X1, XX)
X2=(I-DLT)
CALL INTERR (FA, X2, YY)
IF((XX-YY).LT.0.1E-21) THEN
FS(I)=0.0
GOTO 500
ENDIF
FS(I)=-(XX-YY)*100/(2*DLT*BASEA)
500 CONTINUE

DO 505 J=1, KA
505 FR(KA-J+1)=FS(J)
DO 510 I=KBN, IXB
510 FI(I)=FB(I)*LOLPA
CALCULATING THE SECOND INTEGRAL

INC=100
INCT=INC+1
DO 10 J=KBN,IXB
   DO 10 I=1,INCT
      II=I-1
      X=J+CTB*II/INC
      CALL INTERR (FB,X,XX)
   10   FIB(J,I)=XX
      DO 20 I=1,INCT
         II=I-1
         X=1+CTA*II/INC
         IF(X.EQ.1.) THEN
            XX=FR(1)
            GOTO 19
         ENDIF
      CALL INTERR (FR,X,XX)
   19   FIR(I)=XX
   20   CONTINUE
      DO 534 J=KBN,IXB
      DO 533 I=1,INCT
      IF(FIB(J,I).LT.0.1 E-10 .OR. FIR(I).LT.0.1 E-10) THEN
         AB2(I)=0.0
      GOTO 533
      ENDIF
      AB2(I)=FIB(J,I)*FIR(I)
   533   CONTINUE
      XX=AB2(I)
      YY=AB2(INCT)
      A2=(XX+YY)/2
      DO 531 I=2,INC
      A2=A2+AB2(I)
   531   AII(J)=A2+CTA/INC

CALCULATING THE THIRD INTEGRAL

CALL INTERR (FR,CTA,XX)
CALL INTERR (FR,TOTA,YY)
A3=(XX+YY)/2.0
ICTA=CTA+1
DO 530 I=ICTA,KAN
   A3=A3+FR(I)
   A3=A3*BASEA/100
   DO 535 I=KBN,IXB
   XCTB=I+CTB
   CALL INTERR (FB,XCTB,XX)
   IF(XCTB.GT.SUMB) GOTO 540
   535   FIII(I)=XX*A3
   540   DO 545 I=KBN,IXB
   545   FNEW(I)=FI(I)+FII(I)+FIII(I)
CALCULATION OF LOLP AND LOLE

CALL INTERR (FNEW,TOTB,LOLPBA)
LOLEBA=LOLPBA*ND

CALCULATION OF EDNS AND EENS

CALL INTERR (FNEW,SEMB,X)
AREA=0.5*(LOLPBA+X)
IX=SEMB
DO 120 I=KB,IX
120 AREA=AREA+FNEW(I)
EDNSBA=AREA*BASEB/100.
EENSBA=EDNSBA*ND*24.0

CALCULATION OF EIR

EIRBA=1.0-EENSBA/EVEB
RETURN
END

SUBROUTINE INTERR(F,Y,RES)

**********************************************************************
* THIS SUBROUTINE EVALUATE THE PROBABILITY POINT (RES) GIVEN      *
* THE PROBABILITY POINTS F(K) AND F(K-1)                          *
**********************************************************************

DIMENSION  F(350)
K=Y+1
RES=F(K)+(F(K-1)-F(K))*(K-Y)
RETURN
END
SUBROUTINE ELC(ND, CT, LL, NGA, NGB, LOLEBA, EENSBA, LOLEAB, EENSAB)

*****************************************************************************
* THIS SUBROUTINE EVALUATE THE RELIABILITY INDICES (LOLP, LOLE, *
* EDNS, EENS, EIR), FOR TWO INTERCONNECTED SYSTEMS TAKING INTO *
* CONSIDERATION THE EFFECT OF LOAD CORRELATIONS.                      *
*****************************************************************************

REAL MWPUA(101), LFA, LOLPA, LOLEA, LOLPAB, LOLEAB
REAL MWPUB(101), LFB, LOLFB, LOLEB, LOLPBA, LOLEBA
DIMENSION PEAKA(400), CAPA(140), FORA(140), PRA(101),
+EPRA(350), EPR(140, 350)
DIMENSION PEAKB(400), CAPB(140), FORB(140), PRB(101), EPRB(350)
COMMON/COM1A/PEAKA/COM2A/MWPUA/COM3A/PRA/COM4A/CAPA, FORA
COMMON/COM1B/PEAKB/COM2B/MWPUB/COM3B/PRB/COM4B/CAPB, FORB
COMMON/COM5C/EPRB/COM6A/EPRA/COM7B/EPRB

CALL LPD(PEAKA, ND, MWPUA, PRA, LFA, BASEA, NDM, EVDA, EVEA)
CALL ELPD(PRA, BASEA, ND, CAPA, FORA, NGA, EPRA, TOTA, SUMA)
CALL RIE(EVEA, BASEA, ND, EPRA, TOTA, SUMA, LOLPA, LOLEA, EDNSA
+, EENSA, EIRA)
CALL LPD(PEAKB, ND, MWPUB, PRB, LFB, BASEB, NDMB, EVDB, EVEB)
CALL ELPD(PR, BASEB, ND, CAPB, FORB, NGB, EPRB, TOTB, SUMB)
CALL RIE(EVEB, BASEB, ND, EPRB, TOTB, SUMB, LOLPB, LOLEB, EDNSB
+, EENS, EIRB)
CALL RIEIS(ND, CT, BASEA, SUMA, TOTA, EPRA, LOLPA, BASEB, SUMB, TOTB,
+EPRB, EVEB, LOLPBA, LOLEBA, EDNSBA, EENSBA, EIRBA)
CALL RIEIS(ND, CT, BASEB, SUMB, TOTB, EPRB, LOLPB, BASEA, SUMA, TOTA,
+EFPRA, EVEA, LOLPAB, LOLEAB, EDNSAB, EENSAB, EIRAB)
RETURN
END
APPENDIX B

GENERATION DATA

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CAP = Generation Rating

FOR = Forced Outage Rating
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**CAP** = Generation Rating

**FOR** = Forced Outage Rating
## APPENDIX C

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APPENDIX D
OUTPUT SAMPLES

TABLE D.1
Reliability Indices for Area A

INTERCONNECTED AREAS RELIABILITY INDICES

SYSTEM DURATION TIME = 217 DAYS  
SYSTEM TIE CAPACITY = 450.00 MW

SYSTEM A (U.A.E.)

MAXIMUM PEAK VALUE = 6313.00 MW
NUMBER OF GENERATION UNITS = 134 UNITS
SYSTEM INSTALLED CAPACITY = 6685.00 MW
LOAD FACTOR = 0.7885203E 00
EXPECTED VALUE OF DEMAND = 0.4977926E 04 MW
EXPECTED VALUE OF ENERGY = 0.2592501E 08 MWH

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<td>EDNS = 0.3375051E 01 MW</td>
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**TABLE D.2**

Reliability Indices for Area B

INTERCONNECTED AREAS RELIABILITY INDICES

SYSTEM DURATION TIME = 217 DAYS
SYSTEM TIE CAPACITY = 450.00 MW

SYSTEM B (Oman)

MAXIMUM PEAK VALUE = 2037.00 MW
NUMBER OF GENERATION UNITS = 37 UNITS
SYSTEM INSTALLED CAPACITY = 2247.00 MW
LOAD FACTOR = 0.7426206E 00
EXPECTED VALUE OF DEMAND = 0.1512718E 04 MW
EXPECTED VALUE OF ENERGY = 0.7878234E 07 MWH

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**Effect of Load Forecast Uncertainties**

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</tr>
<tr>
<td>Expected Value of Energy</td>
<td>0.2592501E 08 MWH</td>
</tr>
</tbody>
</table>

**Reliability Indices**

<table>
<thead>
<tr>
<th>Index</th>
<th>Value</th>
<th>Index</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOLP</td>
<td>0.1823929E-01 P.U.</td>
<td>LOLP</td>
<td>0.8186162E-01 P.U.</td>
</tr>
<tr>
<td>LOLE</td>
<td>0.3957926E 01 Days</td>
<td>LOLE</td>
<td>0.1776396E 02 Days</td>
</tr>
<tr>
<td>EDNS</td>
<td>0.3375051E 01 MW</td>
<td>EDNS</td>
<td>0.2777309E 02 MW</td>
</tr>
<tr>
<td>EENS</td>
<td>0.1757726E 05 MWH</td>
<td>EENS</td>
<td>0.1446422E 06 MWH</td>
</tr>
<tr>
<td>EIR</td>
<td>0.9993220E 00</td>
<td>EIR</td>
<td>0.8661098E 00</td>
</tr>
</tbody>
</table>
TABLE D.4
Reliability Indices for Area A and B, Form 1

SYSTEM DURATION TIME = 50 DAYS

SYSTEM A (U.A.E.)

MAXIMUM PEAK VALUE = 5546.00 MW
LOAD FACTOR = 0.7210963E 00
EXPECTED VALUE OF DEMAND = 0.3999197E 04 MW
EXPECTED VALUE OF ENERGY = 0.4799035E 07 MWH

<table>
<thead>
<tr>
<th>RELIABILITY INDICES</th>
<th>RELIABILITY INDICES</th>
</tr>
</thead>
<tbody>
<tr>
<td>WITHOUT INTERCONNECTION</td>
<td>WITH INTERCONNECTION</td>
</tr>
</tbody>
</table>

| LOLP | 0.1577350E-04 P.U. | LOLP | 0.2576852E-07 P.U. |
| LOLE | 0.7886752E-03 DAYS | LOLE | 0.1288426E-05 DAYS |
| EDNS | 0.1490749E-02 MW | EDNS | 0.1054065E-02 MW |
| EENS | 0.1788898E 01 MWH | EENS | 0.1264877E 01 MWH |
| EIR  | 0.9999996E 00     | EIR  | 0.9999998E 00     |

SYSTEM B (Oman)

MAXIMUM PEAK VALUE = 1722.00 MW
LOAD FACTOR = 0.6510953E 00
EXPECTED VALUE OF DEMAND = 0.1121186E 04 MW
EXPECTED VALUE OF ENERGY = 0.1345422E 07 MWH

<table>
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<tr>
<th>RELIABILITY INDICES</th>
<th>RELIABILITY INDICES</th>
</tr>
</thead>
<tbody>
<tr>
<td>WITHOUT INTERCONNECTION</td>
<td>WITH INTERCONNECTION</td>
</tr>
</tbody>
</table>

<p>| LOLP | 0.4571944E-04 P.U. | LOLP | 0.1593231E-08 P.U. |
| LOLE | 0.2285972E-02 DAYS | LOLE | 0.7966156E-07 DAYS |
| EDNS | 0.2375119E-02 MW | EDNS | 0.1981488E-02 MW |
| EENS | 0.2850141E 01 MWH | EENS | 0.2377785E 01 MWH |
| EIR  | 0.9999979E 00     | EIR  | 0.9999983E 00     |</p>
<table>
<thead>
<tr>
<th>TABLE D.5</th>
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<tbody>
<tr>
<td>Reliability Indices for Area A and B, Form 2</td>
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<tr>
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<tr>
<td>SYSTEM DURATION TIME = 50 DAYS</td>
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<tr>
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</tr>
<tr>
<td>SYSTEM A (U.A.E.)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>MAXIMUM PEAK VALUE = 5927.00 MW</td>
</tr>
<tr>
<td>LOAD FACTOR = 0.9340986E 00</td>
</tr>
<tr>
<td>EXPECTED VALUE OF DEMAND = 0.5536398E 04 MW</td>
</tr>
<tr>
<td>EXPECTED VALUE OF ENERGY = 0.6643677E 07 MWH</td>
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<tr>
<td>LOLP = 0.3194455E-02 P.U.</td>
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<td>LOLE = 0.1597227E 00 DAYS</td>
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<tr>
<td>EDNS = 0.4254910E 00 MW</td>
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<tr>
<td>EENS = 0.5105889E 03 MWH</td>
</tr>
<tr>
<td>EIR = 0.9999232E 00</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>RELIABILITY INDICES</td>
</tr>
<tr>
<td>WITH INTERCONNECTION</td>
</tr>
<tr>
<td>LOLP = 0.9377820E-04 P.U.</td>
</tr>
<tr>
<td>LOLE = 0.4688907E-02 DAYS</td>
</tr>
<tr>
<td>EDNS = 0.3336025E 00 MW</td>
</tr>
<tr>
<td>EENS = 0.4003228E 03 MWH</td>
</tr>
<tr>
<td>EIR = 0.9999398E 00</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>SYSTEM B (Oman)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>MAXIMUM PEAK VALUE = 1877.00 MW</td>
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<tr>
<td>LOAD FACTOR = 0.9176983E 00</td>
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<tr>
<td>EXPECTED VALUE OF DEMAND = 0.1722519E 04 MW</td>
</tr>
<tr>
<td>EXPECTED VALUE OF ENERGY = 0.2067022E 07 MWH</td>
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<tr>
<td></td>
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<tr>
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</tr>
<tr>
<td>WITHOUT INTERCONNECTION</td>
</tr>
<tr>
<td>LOLP = 0.2588192E-02 P.U.</td>
</tr>
<tr>
<td>LOLE = 0.1294096E 00 DAYS</td>
</tr>
<tr>
<td>EDNS = 0.1660728E 00 MW</td>
</tr>
<tr>
<td>EENS = 0.1992874E 03 MWH</td>
</tr>
<tr>
<td>EIR = 0.9999036E 00</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>RELIABILITY INDICES</td>
</tr>
<tr>
<td>WITH INTERCONNECTION</td>
</tr>
<tr>
<td>LOLP = 0.1534272E-04 P.U.</td>
</tr>
<tr>
<td>LOLE = 0.7671362E-03 DAYS</td>
</tr>
<tr>
<td>EDNS = 0.1419266E 00 MW</td>
</tr>
<tr>
<td>EENS = 0.1703120E 03 MWH</td>
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<tr>
<td>EIR = 0.9999176E 00</td>
</tr>
</tbody>
</table>
## TABLE D.6
Reliability Indices for Area A and B, Form 3

**SYSTEM DURATION TIME = 10 DAYS**

**SYSTEM A (U.A.E.)**

- **MAXIMUM PEAK VALUE = 6161.00 MW**
- **LOAD FACTOR = 0.9604993E 00**
- **EXPECTED VALUE OF DEMAND = 0.5917629E 04 MW**
- **EXPECTED VALUE OF ENERGY = 0.1420230E 07 MWH**

<table>
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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>LOLP</strong> = 0.7179922E-01 P.U.</td>
<td><strong>LOLP</strong> = 0.1149588E-01 P.U.</td>
</tr>
<tr>
<td><strong>LOLE</strong> = 0.7179922E 00 DAYS</td>
<td><strong>LOLE</strong> = 0.1149588E 00 DAYS</td>
</tr>
<tr>
<td><strong>EDNS</strong> = 0.1076793E 02 MW</td>
<td><strong>EDNS</strong> = 0.8910295E 01 MW</td>
</tr>
<tr>
<td><strong>EENS</strong> = 0.2584304E 04 MWH</td>
<td><strong>EENS</strong> = 0.2138470E 04 MWH</td>
</tr>
<tr>
<td><strong>EIR</strong> = 0.9981804E 00</td>
<td><strong>EIR</strong> = 0.9984943E 00</td>
</tr>
</tbody>
</table>

**SYSTEM B (Oman)**

- **MAXIMUM PEAK VALUE = 1971.00 MW**
- **LOAD FACTOR = 0.9494991E 00**
- **EXPECTED VALUE OF DEMAND = 0.1871462E 04 MW**
- **EXPECTED VALUE OF ENERGY = 0.4491509E 06 MWH**

<table>
<thead>
<tr>
<th>WITHOUT INTERCONNECTION</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>LOLP</strong> = 0.2447205E-01 P.U.</td>
<td><strong>LOLP</strong> = 0.2645517E-02 P.U.</td>
</tr>
<tr>
<td><strong>LOLE</strong> = 0.2447205E 00 DAYS</td>
<td><strong>LOLE</strong> = 0.2645517E-01 DAYS</td>
</tr>
<tr>
<td><strong>EDNS</strong> = 0.1508512E 01 MW</td>
<td><strong>EDNS</strong> = 0.1293414E 01 MW</td>
</tr>
<tr>
<td><strong>EENS</strong> = 0.3620430E 03 MWH</td>
<td><strong>EENS</strong> = 0.3104192E 03 MWH</td>
</tr>
<tr>
<td><strong>EIR</strong> = 0.9991940E 00</td>
<td><strong>EIR</strong> = 0.9993089E 00</td>
</tr>
</tbody>
</table>
### TABLE D.7
Reliability Indices for Area A and B, Form 4

**SYSTEM DURATION TIME = 10 DAYS**

**SYSTEM A (U.A.E.)**

<table>
<thead>
<tr>
<th>Maximum Peak Value</th>
<th>6297.00 MW</th>
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</thead>
<tbody>
<tr>
<td>Load Factor</td>
<td>0.9384986E00</td>
</tr>
<tr>
<td>Expected Value of Demand</td>
<td>0.5909719E04 MW</td>
</tr>
<tr>
<td>Expected Value of Energy</td>
<td>0.1418332E07 MWH</td>
</tr>
</tbody>
</table>

**RELIABILITY INDICES**

**WITHOUT INTERCONNECTION**

<table>
<thead>
<tr>
<th>LOLP</th>
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</tr>
</thead>
<tbody>
<tr>
<td>LOLE</td>
<td>0.1157208E01 DAYS</td>
</tr>
<tr>
<td>EDNS</td>
<td>0.1805109E02 MW</td>
</tr>
<tr>
<td>EENS</td>
<td>0.4332258E04 MWH</td>
</tr>
<tr>
<td>EIR</td>
<td>0.9969456E00</td>
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</table>

**RELIABILITY INDICES**

**WITH INTERCONNECTION**

<table>
<thead>
<tr>
<th>LOLP</th>
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</tr>
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<tbody>
<tr>
<td>LOLE</td>
<td>0.2862341E00 DAYS</td>
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<tr>
<td>EDNS</td>
<td>0.1530883E02 MW</td>
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<tr>
<td>EENS</td>
<td>0.3674118E04 MWH</td>
</tr>
<tr>
<td>EIR</td>
<td>0.9974096E00</td>
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</tbody>
</table>

**SYSTEM B (Oman)**

<table>
<thead>
<tr>
<th>Maximum Peak Value</th>
<th>2026.00 MW</th>
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<tbody>
<tr>
<td>Load Factor</td>
<td>0.9254984E00</td>
</tr>
<tr>
<td>Expected Value of Demand</td>
<td>0.1875060E04 MW</td>
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<tr>
<td>Expected Value of Energy</td>
<td>0.4500143E06 MWH</td>
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</tbody>
</table>

**RELIABILITY INDICES**

**WITHOUT INTERCONNECTION**

<table>
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<th>LOLP</th>
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</tr>
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<tr>
<td>LOLE</td>
<td>0.3648978E00 DAYS</td>
</tr>
<tr>
<td>EDNS</td>
<td>0.3221132E01 MW</td>
</tr>
<tr>
<td>EENS</td>
<td>0.7730715E03 MWH</td>
</tr>
<tr>
<td>EIR</td>
<td>0.9982821E00</td>
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</tbody>
</table>

**RELIABILITY INDICES**

**WITH INTERCONNECTION**

<table>
<thead>
<tr>
<th>LOLP</th>
<th>0.5921137E-02 P.U.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOLE</td>
<td>0.5921137E-01 DAYS</td>
</tr>
<tr>
<td>EDNS</td>
<td>0.2911474E01 MW</td>
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<tr>
<td>EENS</td>
<td>0.6987534E03 MWH</td>
</tr>
<tr>
<td>EIR</td>
<td>0.9984473E00</td>
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</tbody>
</table>
TABLE D.8
Reliability Indices for Area A and B, Form 5

SYSTEM DURATION TIME = 10 DAYS
SYSTEM A (U.A.E.)

MAXIMUM PEAK VALUE = 6019.00 MW
LOAD FACTOR = 0.9574986E 00
EXPECTED VALUE OF DEMAND = 0.5763180E 04 MW
EXPECTED VALUE OF ENERGY = 0.1383163E 07 MWH

<table>
<thead>
<tr>
<th>RELIABILITY INDICES</th>
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<th>RELIABILITY INDICES</th>
<th>WITH INTERCONNECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOLP</td>
<td>0.2438078E-01 P.U.</td>
<td>LOLP</td>
<td>0.2167455E-02 P.U.</td>
</tr>
<tr>
<td>LOLE</td>
<td>0.2438078E 00 DAYS</td>
<td>LOLE</td>
<td>0.2167455E-01 DAYS</td>
</tr>
<tr>
<td>EDNS</td>
<td>0.2653684E 01 MW</td>
<td>EDNS</td>
<td>0.1985174E 01 MW</td>
</tr>
<tr>
<td>EENS</td>
<td>0.6368840E 03 MWH</td>
<td>EENS</td>
<td>0.4764414E 03 MWH</td>
</tr>
<tr>
<td>EIR</td>
<td>0.9995396E 00</td>
<td>EIR</td>
<td>0.9996555E 00</td>
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SYSTEM B (Oman)

MAXIMUM PEAK VALUE = 1919.00 MW
LOAD FACTOR = 0.9484985E 00
EXPECTED VALUE OF DEMAND = 0.1820168E 04 MW
EXPECTED VALUE OF ENERGY = 0.4368403E 06 MWH

<table>
<thead>
<tr>
<th>RELIABILITY INDICES</th>
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<th>RELIABILITY INDICES</th>
<th>WITH INTERCONNECTION</th>
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<tbody>
<tr>
<td>LOLP</td>
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<td>LOLP</td>
<td>0.4806739E-03 P.U.</td>
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<tr>
<td>LOLE</td>
<td>0.1267412E 00 DAYS</td>
<td>LOLE</td>
<td>0.4806737E-02 DAYS</td>
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<tr>
<td>EDNS</td>
<td>0.7730256E 00 MW</td>
<td>EDNS</td>
<td>0.6560324E 00 MW</td>
</tr>
<tr>
<td>EENS</td>
<td>0.1855261E 03 MWH</td>
<td>EENS</td>
<td>0.1574478E 03 MWH</td>
</tr>
<tr>
<td>EIR</td>
<td>0.9995753E 00</td>
<td>EIR</td>
<td>0.9996396E 00</td>
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</table>
### TABLE D.9
Reliability Indices for Area A and B, Form 6

**SYSTEM DURATION TIME = 10 DAYS**

**SYSTEM A (U.A.E.)**

MAXIMUM PEAK VALUE = 6313.00 MW
LOAD FACTOR = 0.9444985E 00
EXPECTED VALUE OF DEMAND = 0.5962617E 04 MW
EXPECTED VALUE OF ENERGY = 0.1431028E 07 MWH

<table>
<thead>
<tr>
<th>RELIABILITY INDICES</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>LOP = 0.1304908E 00 P.U.</td>
<td>LOP = 0.3516943E-01 P.U.</td>
</tr>
<tr>
<td>LOLE = 0.1304908E 01 DAYS</td>
<td>LOLE = 0.3516943E 00 DAYS</td>
</tr>
<tr>
<td>EDNS = 0.2618073E 02 MW</td>
<td>EDNS = 0.2317191E 02 MW</td>
</tr>
<tr>
<td>EENS = 0.6283371E 04 MWH</td>
<td>EENS = 0.5561254E 04 MWH</td>
</tr>
<tr>
<td>EIR = 0.9956092E 00</td>
<td>EIR = 0.9961138E 00</td>
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</table>

**SYSTEM B (Oman)**

MAXIMUM PEAK VALUE = 2037.00 MW
LOAD FACTOR = 0.9324983E 00
EXPECTED VALUE OF DEMAND = 0.1899499E 04 MW
EXPECTED VALUE OF ENERGY = 0.4558796E 06 MWH

<table>
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<tr>
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<th>RELIABILITY INDICES</th>
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<tbody>
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<tr>
<td>LOP = 0.4690787E-01 P.U.</td>
<td>LOP = 0.9089597E-02 P.U.</td>
</tr>
<tr>
<td>LOLE = 0.4690787E 00 DAYS</td>
<td>LOLE = 0.9089595E-01 DAYS</td>
</tr>
<tr>
<td>EDNS = 0.3476862E 01 MW</td>
<td>EDNS = 0.3091684E 01 MW</td>
</tr>
<tr>
<td>EENS = 0.8344468E 03 MWH</td>
<td>EENS = 0.7420042E 03 MWH</td>
</tr>
<tr>
<td>EIR = 0.9981696E 00</td>
<td>EIR = 0.9983724E 00</td>
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TABLE D.10
Reliability Indices for Area A and B, Form 7

SYSTEM DURATION TIME = 10 DAYS

SYstem A (U.A.E.)

MAXIMUM PEAK VALUE = 5930.00 MW
LOAD FACTOR = 0.9764993E 00
EXPECTED VALUE OF DEMAND = 0.5790637E 04 MW
EXPECTED VALUE OF ENERGY = 0.1389752E 07 MWH

<table>
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<tr>
<th>RELIABILITY INDICES</th>
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<tbody>
<tr>
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<tr>
<td>LOP = 0.1900176E-01 P.U.</td>
<td>LOP = 0.1629495E-02 P.U.</td>
</tr>
<tr>
<td>LOLE = 0.1900176E 00 DAYS</td>
<td>LOLE = 0.1629495E-01 DAYS</td>
</tr>
<tr>
<td>EDNS = 0.2577936E 01 MW</td>
<td>EDNS = 0.262849E 01 MW</td>
</tr>
<tr>
<td>EENS = 0.6187046E 03 MWH</td>
<td>EENS = 0.4950835E 03 MWH</td>
</tr>
<tr>
<td>EIR = 0.9995548E 00</td>
<td>EIR = 0.9996438E 00</td>
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SYstem B (Oman)

MAXIMUM PEAK VALUE = 1889.00 MW
LOAD FACTOR = 0.9694990E 00
EXPECTED VALUE OF DEMAND = 0.1831383E 04 MW
EXPECTED VALUE OF ENERGY = 0.4395319E 06 MWH

<table>
<thead>
<tr>
<th>RELIABILITY INDICES</th>
<th>RELIABILITY INDICES</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>LOP = 0.1135364E-01 P.U.</td>
<td>LOP = 0.3804604E-03 P.U.</td>
</tr>
<tr>
<td>LOLE = 0.1135364E 00 DAYS</td>
<td>LOLE = 0.3804604E-02 DAYS</td>
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<tr>
<td>EDNS = 0.8327638E 00 MW</td>
<td>EDNS = 0.7291222E 00 MW</td>
</tr>
<tr>
<td>EENS = 0.1998633E 03 MWH</td>
<td>EENS = 0.1749893E 03 MWH</td>
</tr>
<tr>
<td>EIR = 0.9995453E 00</td>
<td>EIR = 0.9996019E 00</td>
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</table>
TABLE D.11
Reliability Indices for Area A and B, Form 8

SYSTEM DURATION TIME = 67 DAYS

SYSTEM A (U.A.E.)

MAXIMUM PEAK VALUE = 6092.00 MW
LOAD FACTOR = 0.7605932E 00
EXPECTED VALUE OF DEMAND = 0.4633527E 04 MW
EXPECTED VALUE OF ENERGY = 0.7450711E 07 MWH

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<thead>
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</tr>
</thead>
<tbody>
<tr>
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</tbody>
</table>

| LOLP = 0.5281713E-02 P.U. | LOLP = 0.1736390E-03 P.U. |
| LOLE = 0.3538747E 00 DAYS | LOLE = 0.1163381E-01 DAYS |
| EDNS = 0.8032154E 00 MW | EDNS = 0.6476235E 00 MW |
| EENS = 0.1291570E 04 MWH | EENS = 0.1041378E 04 MWH |
| EIR = 0.9998267E 00 | EIR = 0.9998603E 00 |

SYSTEM B (Oman)

MAXIMUM PEAK VALUE = 1954.00 MW
LOAD FACTOR = 0.7107416E 00
EXPECTED VALUE OF DEMAND = 0.1388789E 04 MW
EXPECTED VALUE OF ENERGY = 0.2233171E 07 MWH

<table>
<thead>
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<th>RELIABILITY INDICES</th>
<th>RELIABILITY INDICES</th>
</tr>
</thead>
<tbody>
<tr>
<td>WITHOUT INTERCONNECTION</td>
<td>WITH INTERCONNECTION</td>
</tr>
</tbody>
</table>

| LOLP = 0.2753678E-02 P.U. | LOLP = 0.2422846E-04 P.U. |
| LOLE = 0.1844964E 00 DAYS | LOLE = 0.1623307E-02 DAYS |
| EDNS = 0.2170984E 00 MW | EDNS = 0.1904317E 00 MW |
| EENS = 0.3409940E 03 MWH | EENS = 0.3062139E 03 MWH |
| EIR = 0.9998437E 00 | EIR = 0.9998629E 00 |
TABLE D.12
Reliability Indices for Area A and B, the Total Forms

SYSTEM DURATION TIME = 217 DAYS
SYSTEM A (U.A.E.)

MAXIMUM PEAK VALUE = 6313.00 MW
LOAD FACTOR = 0.7888505E 00
EXPECTED VALUE OF DEMAND = 0.4980012E 04 MW
EXPECTED VALUE OF ENERGY = 0.2593590E 08 MWH

<table>
<thead>
<tr>
<th>RELIABILITY INDICES WITHOUT INTERCONNECTION</th>
<th>RELIABILITY INDICES WITH INTERCONNECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOP = 0.1902450E-01  P.U.</td>
<td>LOP = 0.3719720E-04  P.U.</td>
</tr>
<tr>
<td>LOLE = 0.4128318E 01 DAYS</td>
<td>LOLE = 0.8071805E 00 DAYS</td>
</tr>
<tr>
<td>EDNS = 0.3122017E 01 MW</td>
<td>EDNS = 0.2647527E 01 MW</td>
</tr>
<tr>
<td>EENS = 0.1625946E 05 MWH</td>
<td>EENS = 0.1378832E 05 MWH</td>
</tr>
<tr>
<td>EIR  = 0.9993731E 00</td>
<td>EIR  = 0.9994684E 00</td>
</tr>
</tbody>
</table>

SYSTEM B (Oman)

MAXIMUM PEAK VALUE = 2037.00 MW
LOAD FACTOR = 0.7425068E 00
EXPECTED VALUE OF DEMAND = 0.1512486E 04 MW
EXPECTED VALUE OF ENERGY = 0.7877029E 07 MWH

<table>
<thead>
<tr>
<th>RELIABILITY INDICES WITHOUT INTERCONNECTION</th>
<th>RELIABILITY INDICES WITH INTERCONNECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOP = 0.7535320E-04  P.U.</td>
<td>LOP = 0.8643640E-05  P.U.</td>
</tr>
<tr>
<td>LOLE = 0.1635165E 01 DAYS</td>
<td>LOLE = 0.1875672E 00 DAYS</td>
</tr>
<tr>
<td>EDNS = 0.5580227E 00 MW</td>
<td>EDNS = 0.4920348E 00 MW</td>
</tr>
<tr>
<td>EENS = 0.2906182E 04 MWH</td>
<td>EENS = 0.2562517E 04 MWH</td>
</tr>
<tr>
<td>EIR  = 0.9996311E 00</td>
<td>EIR  = 0.9996747E 00</td>
</tr>
</tbody>
</table>
TABLE D.13
Effective Load Carrying Capacity

SYSTEM INSTALLED CAPACITY = 6685.00 MW
SYSTEM MAXIMUM PEAK VALUE = 6313.00 MW
SYSTEM LOLP = 0.1823929E-01 P.U.
SYSTEM LOLE = 0.3957926E 01 DAYS
THE ADDED UNIT CAPACITY = 160.00 MW
THE ELCC OF THE ADDED UNIT = 146.66 MW
TABLE D.14

Load Carrying Capability

SYSTEM INSTALLED CAPACITY = 6685.00 MW
SYSTEM MAXIMUM PEAK VALUE = 6313.00 MW
THE STANDARD LÖLES = 0.1000000E 00 MW
THE SYSTEM LCC = 5879.89 MW
THE SYSTEM SHORTAGE CAPACITY = 433.11 MW
REFERENCES


17. R. N. Allan, and A. M. Shaalan, "Probabilistic Production Costing Model" IEE to be published.

