PROBABILISTIC ASSESSMENT OF SPINNING RESERVE IN INTERCONNECTED GENERATION SYSTEMS

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by

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ABSTRACT

Reliability evaluation of a power system is an important aspect of a utility's overall planning and operation process. Most utilities use deterministic techniques for spinning reserve assessment. Deterministic methods do not respond to the stochastic nature of system components. Probabilistic criteria usually respond to the significant factors which affect the reliability of a system.

A probabilistic technique called the 'Expected Energy Assistance' is developed to assess spinning reserve requirements in interconnected generation systems. The expected energy assistance is an energy based approach which incorporates both the magnitude and the duration of assistance in its evaluation process. The expected energy assistance technique provides a consistent way of assessing spinning reserve sharing among interconnected systems. The technique, along with the effect of generating unit sizes, tie-line capacity and lead time on spinning reserve requirements are illustrated in the thesis. Reliability test systems are utilized throughout the thesis in order to provide numerical examples.

Assessment of spinning reserve requirements in interconnected generating systems with export/import agreement is illustrated. Mathematical models have been developed to represent export/import constrained tie capacity and export/import constrained assistance. These developments are illustrated in detail in this thesis.

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List of Symbols and Abbrevations

C_i	Capacity
dt	Discete time step
EEA	Expected Energy Assistance
E_{ij}	Export of System i to System J
F(R)	Risk Function
ISR	Inter Connected System Risk
I_{ij}	Import of System i from System J
L_a	Load in System A
MW	Mega Watt
MWh	Mega Watt-hour
R_s	Specified Risk
SSR	Single System Risk
λ	Failure rate
μ	Repair rate

1. INTRODUCTION

1.1. Review

The economic, social and political climate in which the electric power industry operates has changed considerably during the last few decades. It is now widely recognized that statistical assessment of past performance is an important aspect of planning and operating of power systems [1].

The increasing dependence of modern society on electrical energy puts tremendous pressure on electric utilities with regard to the quality and continuity of electric supply. Due to the diversified nature of customer demand and economic constraints, electric utilities face a tremendous challenge to provide a reliable supply of electric power. Due to random equipment failures it is neither possible nor economical to provide 100% reliable service. Service reliability can greatly improve if equipment is well maintained and investments are made in order to create redundancy. There are many different ways to achieve redundancy in an electric power system. The degree of redundancy depends on the need and associated cost. The consequences of service interruptions vary widely from customer to customer. They range from simple inconvenience to loss of production in a process industry. A reasonable trade off between the cost of increased reliability and the value of increased reliability can be achieved by weighing investment in dollars against the cost of unreliability.

A power system commits a certain number of its available generating units in order to satisfy its load. Unit commitment usually varies from low load periods to peak load periods. The generation capacity synchronized to the bus at any time is usually greater than the load connected to the bus. This additional capacity, defined as spinning reserve, is required to satisfy the unforeseen changes in the load and also to withstand sudden loss of some generating capacity. Different utilities use different techniques to assess their spinning reserve requirements. These techniques can be broadly classified as deterministic and probabilistic.

The emphasis when using a deterministic approach is to minimize operating cost [2,3,4] and in doing so a system faces different degrees of risk throughout the day. The assessment of spinning reserve requirements utilizing a deterministic approach is done using,

i) a fixed capacity margin,

ii) a fixed percentage of system load,

iii) a fixed percentage of operating capacity,

iv) largest contingency, or

v) any combination of the above.

Most Canadian utilities use deterministic methods in order to assess their spinning reserve requirements [5]. Deterministic approaches do not specifically utilize the stochastic nature of system components in its computation in a consistent way.

Probabilistic methods recognize the stochastic nature of system components and incorporate them in the spinning reserve assessment process in a consistent manner. Generation, transmission and other system component failure and repair rates influence the magnitude of the spinning reserve requirement. A probabilistic index known as unit commitment risk [6] has been introduced in order to maintain a desired degree of reliability at the generation level. This index is defined as the probability that the generation system fails to meet the load or just be able to meet the load during the period of time that generation can not be replaced [6]. The actual magnitude and even the type of spinning reserve is therefore determined on the basis of system risk, which can be expressed mathematically as [6],

$$R(t) = \sum_{i=1}^{m} P_i(t)\, Q_i(t) \,,$$

where:

$R(t)$ = system risk at time t,

$P_i(t)$ = probability that the system is in state i at time t in the future,

$Q_i(t)$ = probability that the state i constitutes a breach of security at time t in the future,

m = total number of system states.

System reliability at the generation level can be improved by increasing the magnitude of spinning reserve provided all other factors remain unchanged. An increase in the spinning reserve with a corresponding decrease in the unit commitment risk reduces the expected outage cost but increases operating costs. A decrease in the spinning reserve with a corresponding increase in the unit commitment risk may result in an increase in expected outage cost and a loss of revenue. Therefore, the selection of a suitable risk level is a management decision.

Reliability of a power system, in general, is greatly improved by interconnection with other power systems. Interconnected systems can export/import energy, interchange economic energy and share their spinning reserve. Interconnection also provides a path for emergency assistance. Assistance through an interconnection is limited by the tie-line capacity and governed by the agreement between interconnected areas. Assessment of spinning reserve requirement in an interconnected generating system, therefore, should include not only the generation and the load models of the participating systems, but also the tie-line model and export/import agreement between the interconnected systems.

The basic technique for spinning reserve evaluation utilizing a probabilistic approach was published in 1962 [7]. This technique was used to evaluate the spinning reserve requirement in single area generation systems in order to maintain a uniform level of risk in day-to-day operation. Spinning reserve evaluation in isolated systems using probabilistic method has been published [8]. Reference [9] illustrates a technique to evaluate the benefits of interconnection in terms of spinning reserve. Little work has been reported in the literature to address the issue of spinning reserve assessment in multi-area interconnected systems. A technique designated as the 'Two Risks Concept' [10] has recently been published. The 'Two Risks Concept' utilizes risk evaluation at two different levels in order to assess the spinning reserve requirement in interconnected systems. Reference [10], however, does not address the issue of interconnection between systems of radically different sizes in an adequate manner. A new probabilistic approach called the 'Expected Energy Assistance' is developed to assess the spinning reserve requirements in interconnected systems. An energy based index is proposed to measure/compare expected energy assistance provided by interconnected systems to each other.

1.2. Objective and Structure of the Thesis

This work attempts to further the state of the art and to provide insight into the assessment of spinning reserve requirements in interconnected systems.

The following were the objectives of the work described in this thesis,

1. To develop a technique for equitable sharing of spinning reserve between interconnected generation systems.
2. To develop the essential elements and models in order to implement the technique.
3. To utilize this technique to assess spinning reserve requirements with export/import constraints.

The thesis is structured as follows;

Chapter 2 describes the basic concepts of reliability evaluation of power systems. Application of probabilistic techniques to spinning reserve assessment in a single system is also illustrated in Chapter 2. Concepts of area risk curve has been utilized to illustrate the effect of rapid start and hot reserve units on risk level. The probabilistic technique designated as the 'Two Risks Concept' is illustrated in detail and its drawbacks are discussed in Chapter 2. An improved probabilistic technique is developed for spinning reserve assessment in multi-area interconnected systems and is presented in details in Chapter 3. The technique is designated as the 'Expected Energy Assistance' and is applied to two test systems. A method is proposed to estimate a feasible index for expected energy assistance between interconnected systems. This method along with some results is also illustrated in Chapter 3. The application of this new technique to several reliability test systems is illustrated in Chapter 4. A mathematical model of export/import constrained tie-line has been developed in order to assess the spinning reserve requirement with export/import constraints. The mathematical models with numerical examples of spinning reserve assessment with export/import constraints are illustrated in Chapter 5. Chapter 6 presents the conclusions of this research work.

2. BASIC CONCEPTS OF SPINNING RESERVE ASSESSMENT

2.1. Introduction

One of the primary functions of an electric power system is to supply energy as economically and as reliably as possible. Reliability assessments are usually performed in order to address concerns regarding the ability of a system to provide an adequate supply of electrical energy. Reliability assessments can be utilized to find the weak points in a system. Remedial actions and their costs then can be weighted against the resulting worth in order to find economic solutions.

System reliability assessment can be subdivided into system adequacy assessment and system security assessment. System adequacy relates to the existence of sufficient facilities within the system to satisfy consumer demand or system operational constraints. These includes the facilities necessary to generate sufficient energy and the associated transmission and distribution facilities required to transport the energy to the consumer load points. Adequacy is therefore associated with static conditions which do not include system disturbances.

System security relates to the ability of the system to respond to disturbances arising within the system. Security is, therefore, associated with the response of the system to whatever perturbation it is subjected.

These include the conditions associated with both local and widespread disturbances and the loss of major generation and transmission facilities.

The evaluations usually done in adequacy are loss of load expectation (LOLE) and loss of energy expectation (LOEE). Security assessment involves the evaluation of spinning reserve and transient stability. The work in this thesis is restricted to spinning reserve assessment in interconnected generation systems. The study, however, does not include system dynamics.

Electrical facilities in a power system can be divided into three functional zones [11]. These functional zones are 1) generation, which produces the energy; 2) transmission, which transports the energy at high voltage to bulk supply points in the system and 3) distribution, which supplies the energy to the individual consumers. This complex system structure presents a great difficulty when a power system is analyzed as one entity. Instead, it is divided into hierarchical levels as shown in Figure 2.1. Generation facilities alone form hierarchical level-I (HL I) and together with the transmission facilities constitute hierarchical level-II (HL II). Hierarchical level III is composed of all three functional zones. At HL I, the total system generation is examined to determine its adequacy to meet the total system load requirement as shown in Figure 2.2. The proposed method reported in this thesis is concerned with the assessment of spinning reserve in interconnected systems at HL I.

2.2. Concept for HL I Analysis

In HL I studies, the transmission is considered 100 percent reliable. All constraints regarding the ability of the transmission facilities to move

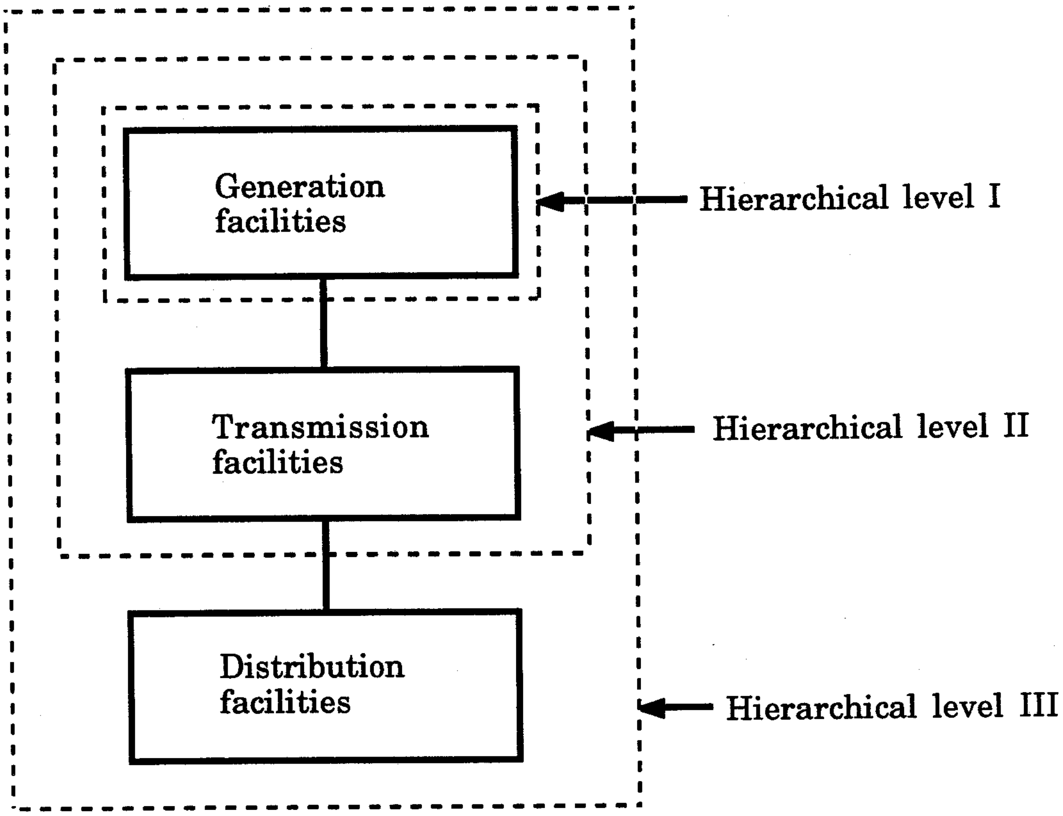

Figure 2.1: Hierarchical Levels.

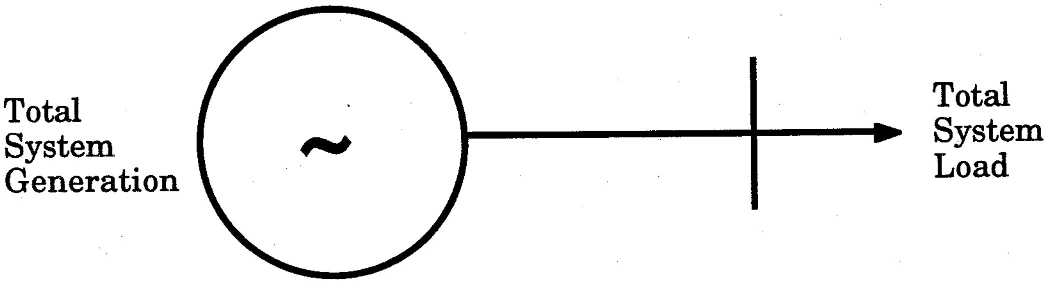

Figure 2.2: Model For Hierarchical Level I.

the generated energy to the consumer load point are ignored. Limited consideration of transmission, however, can be included in HL I studies. These considerations include the modelling of remote generation facilities (Figure 2.3) and interconnected systems (Figure 2.4). In the latter case, only the tie lines connecting the systems are modelled; the internal system connections are ignored. In the case of a remote generation, the capacity model of the remote source is modified by the reliability of the transmission line before being added to the system capacity model. In the case of interconnected systems the available assistance model of the assisting system is modified before adding it to the capacity model of the system under study [11].

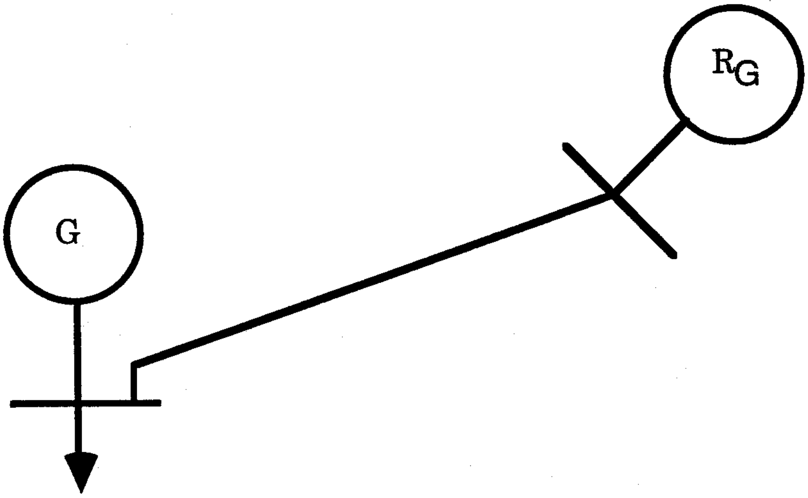

Figure 2.3: Model of Remote Generation in HL I Studies.

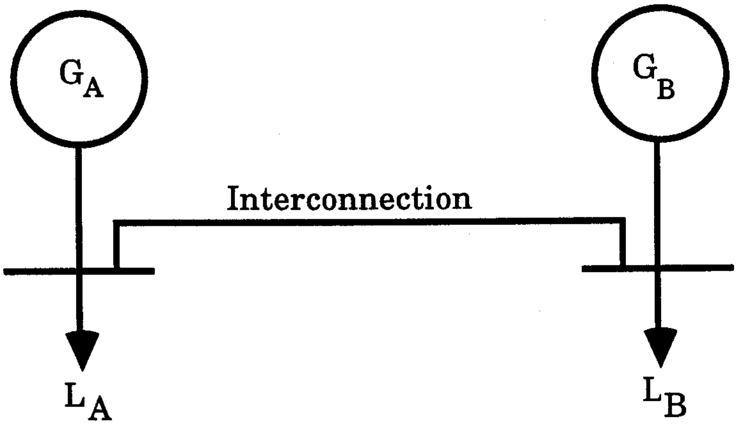

Figure 2.4: Model of Interconnected Systems in HL I Studies.

The evaluation techniques utilized in HL I analysis can be classified as analytical and Monte Carlo simulation. Analytical techniques represent the system by a mathematical model and evaluate the reliability indices from this model using mathematical solutions. Monte Carlo simulation methods attempt to simulate the actual system events and the corrective actions taken during the disturbances and estimate the reliability indices based on these simulated events. Analytical techniques have been utilized to study the test systems reported in this thesis.

2.3. Modelling of Power System Components

In order to evaluate the probability, frequency and duration of outages, components are usually represented by state transitional diagrams called state space models [12]. It is usually assumed that the state residence times of power system components are exponentially distributed [12]. The behavior of many components in a power system can therefore be modelled as a Markov process. A stochastic process is considered to be Markovian when the future evaluation of the process depends only on the path it took to attain the current state [12]. The basic modelling approach for an HL I study is shown in Figure 2.5. The generation model of a system is convolved with its load model in order to assess system risk. The generation model can be in the form of a capacity outage probability table. This table represents the capacity outage states of an equivalent multi-state unit together with the probability of each state. The load model can either be a daily peak load variation curve (DPLVC) which only includes the peak loads of each day, or a load duration curve (LDC) which represents the hourly variation of the load. The dotted line from the load model to the generation model in Figure 2.5 indicates that the development of the generation model of the system may take its load model into consideration.

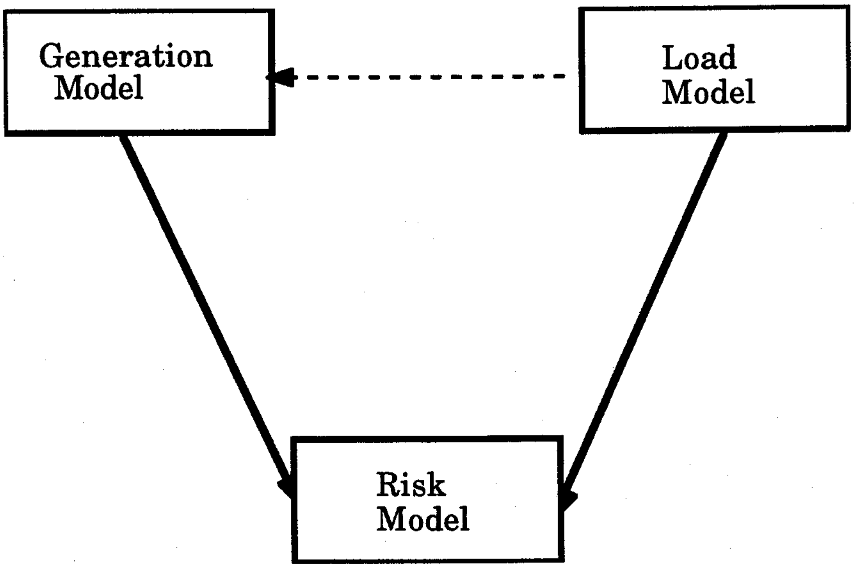

Figure 2.5: Basic Modelling Approach for HL I Evaluation.

2.3.1. Basic two-state model

A two-state Markovian model is the most common representation of a generating unit for probabilistic assessment of static or operating capacity requirements. Figure 2.6 shows a two-state model of a generating unit. The generating unit is considered to be either operating at full capacity or failed. The unit changes its state from the full capacity state to the failed state with a transition rate of λ. The unit can be back to its full capacity state from the failed state with a transition rate of μ.

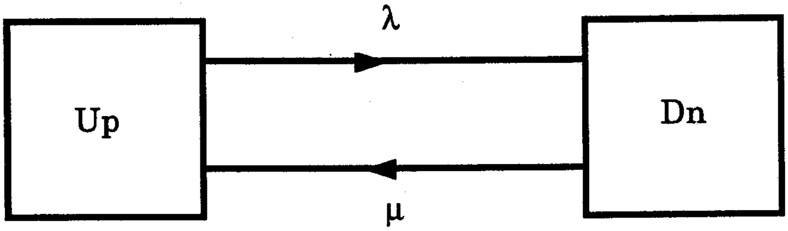

Figure 2.6: Two-state Model of a Generating Unit.

The time dependent state probabilities of a generating unit represented by this model are shown in Equation 2.1, given that unit is in operating state at time t=0,

$$P(Up) = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} e^{-(\lambda + \mu)t}, \qquad (2.1)$$

$$P(Dn) = \frac{\lambda}{\lambda + \mu} - \frac{\lambda}{\lambda + \mu} e^{-(\lambda + \mu)t}. \qquad (2.2)$$

Where

λ = Failure rate of the component,

μ = Repair rate of the component.

Steady state probabilities are used for static capacity evaluation. The steady state probability is the limiting state probability when time (t) is set to infinity. With $t = \infty$, Equations 2.1 and 2.2 become,

$$P(Up) = P_{Up}(t=\infty) = \frac{\mu}{\lambda + \mu}, \qquad (2.3)$$

$$P(Dn) = P_{Dn}(t=\infty) = \frac{\lambda}{\lambda + \mu}. \qquad (2.4)$$

The basic difference between static and operating capacity evaluation is in the time period considered. The evaluation done with static capacity is for long term predictions, while the operating capacity evaluation is done for short term capacity assessment to meet a load demand in the near future. If failures and repairs are exponentially distributed, the probability of finding a two-state unit on outage at time 'T' [6] can be expressed as

$$P(Dn) = \frac{\lambda}{\lambda + \mu} - \frac{\lambda}{\lambda + \mu} e^{-(\lambda + \mu)T}. \qquad (2.5)$$

The time period used in an operating capacity evaluation is generally relatively small and, therefore, the repair process can be neglected. The time T as utilized in an operating capacity evaluation is called the lead time. It is the time period during which additional generation can not be brought into service. Setting $\mu = 0$, Equation 2.5 becomes,

$$P(Dn) = 1 - e^{-\lambda T}. \qquad (2.6)$$

P(Dn) expressed by Equation 2.6 is often called the outage replacement rate (ORR) of an unit. For short times of up to several hours $\lambda T << 1$, Equation 2.6 becomes,

$$ORR = \lambda T. \qquad (2.7)$$

Outage replacement rate [6] represents the probability that a unit fails and is not replaced during the lead time T.

2.3.2. Derated-state model

A typical large thermal unit has many auxiliary ststems. Failure of one of these auxiliaries may force the unit to run at a derated capacity. It is, therefore, important to utilize a multi-state model in order to represent a large thermal unit. The states other than the full capacity and the failed can represent the many possible output deratings of the unit. It is not feasible to consider a model with a large number of derated states because of the computational time and complexity it adds to reliability studies.

In general, a large unit can be represented by a three-state model containing operating, derated and failed states as shown in Figure 2.7(a) [6]. If the repair is neglected during the short lead time then the model shown in Figure 2.7(a) is reduced to that shown in Figure 2.7(b) [6]. If the probability of more than one failure of each unit is negligible during the short lead time, then the three-state model of Figure 2.7(b) is further reduced to that shown in Figure 2.7(c) [6]. The three-state model shown in Figure 2.7(c) can be used for spinning reserve study's.

For short lead time $\lambda_1 T << 1$ and $\lambda_2 T << 1$, where T is the lead time in hours; it follows from Equation (2.7);

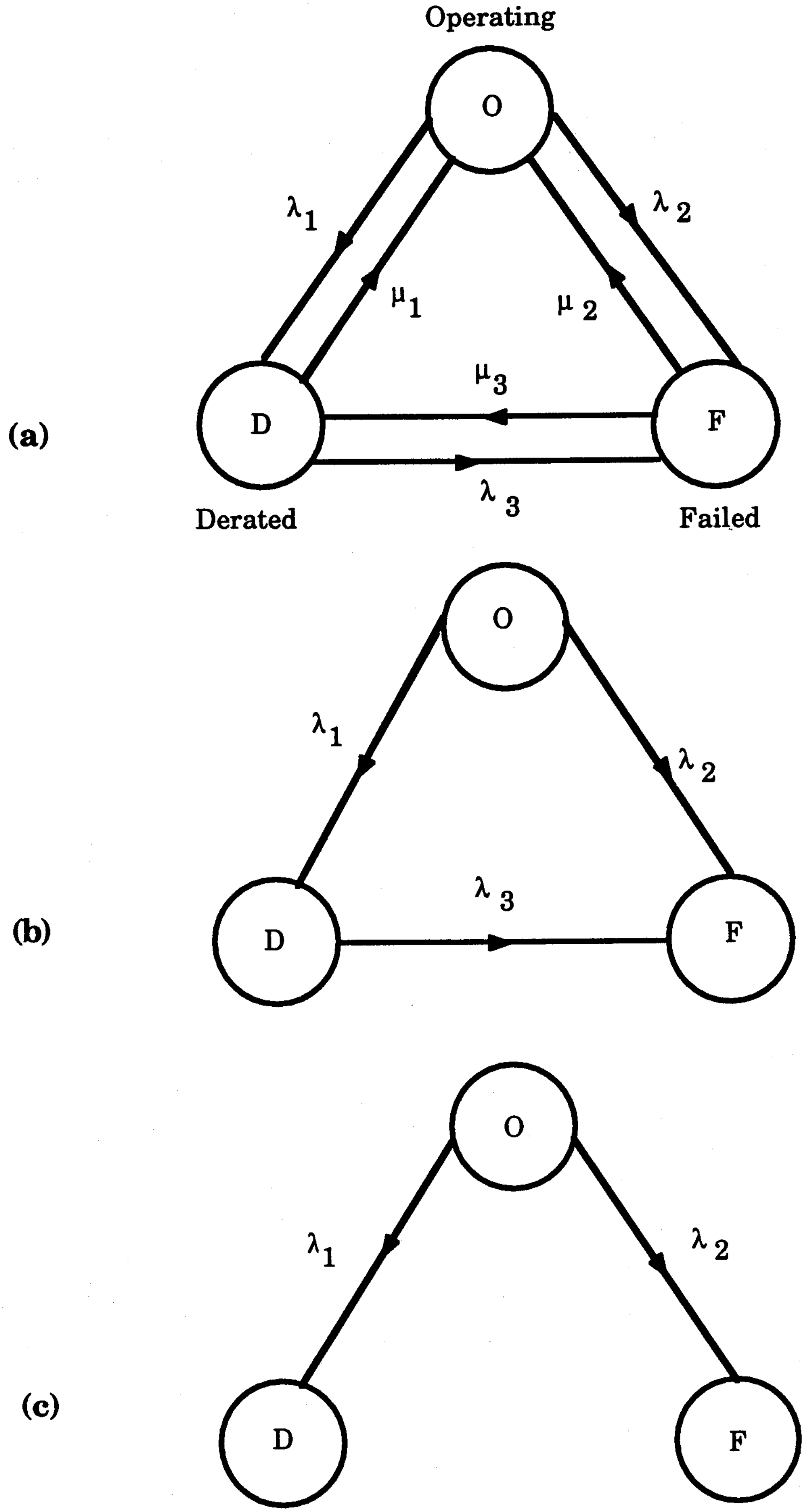

Figure 2.7: Three-State Model of a Generating Unit.

$$P(\text{down}) = \lambda_2 T. \tag{2.8}$$

$$P(\text{derated}) = \lambda_1 T. \tag{2.9}$$

$$P(\text{operating}) = 1 - (\lambda_1 + \lambda_2)T. \tag{2.10}$$

2.4. Spinning Reserve Assessment in a Single System

Probabilistic techniques have been applied to evaluate unit commitment and spinning reserve requirements in a power system [6]. This section illustrates the determination of required spinning reserve for a designated risk level. The selection of an allowable risk level depends on the desired degree of reliability, the corresponding cost and the optimum benefit.

2.4.1. Terms used in spinning reserve studies

A few terms related to spinning reserve study are explained below [6]:

Spinning reserve

It is the generation capacity synchronized at the bus on top of the system load.

Operating reserve

Operating reserve is defined as the reserve that can be brought into the system in a short period of time. Operating reserve includes spinning reserves, rapid start units (gas turbines or hydro units), hot reserve units (thermal units which can be started and loaded in about one hour) and assistance from interconnected systems.

Lead time

Lead time is defined as the time required to start, synchronize and load a generating unit. For a thermal unit, the lead time ranges between 4 to 24 hours depending upon the size of the unit and the length of the time since it last operated. For hydro and gas turbine units, this time is very small and ranges from 5 to 30 minutes.

Unit commitment risk

The probability that the system will fail to meet the load or just be able to meet the load for a given lead time of additional generation in the system.

2.4.2. Unit commitment

The determination of an effective unit commitment schedule is essential for meeting system load, interchange and spinning reserve requirements. A system usually commits a certain number of units based upon forecast load, export/import agreement and other operational constraints. It is not economical to commit all available units throughout the day. Units should be committed in a way that a specified risk is satisfied. The unit commitment risk can be expressed as [6],

$$R(t) = \sum_{i=1}^{N} P_i(t) * Q_i(t), \tag{2.11}$$

where:

$R(t)$ = system risk at time t,

$P_i(t)$ = probability that the system is in state i at time t,

$Q_i(t)$ = probability that the system load will be equal to or greater than the generation in state i at time t,

N = total number of system states .

In spinning reserve evaluations $Q_i(t)$ becomes either zero or unity.

$Q_i(t) = 0$ for load < capacity (C_i)

$Q_i(t) = 1$ for load ≥ capacity (C_i)

Equation(2.11), therefore, can be modified as

$$R(t) = \sum_{i=n}^{N} P_i(t). \qquad (2.12)$$

Where n is an integer such that

$C_{n-1} > \text{load} \geq C_n$

If R_s is the specified unit commitment risk for a period of (0,t) then the unit commitment should be such that

$$R(t) \leq R_s. \qquad (2.13)$$

2.4.3. Rapid start and hot reserve units

There is a time delay associated with additional generation. This time delay, called the lead time, mainly depends on the type of additional generation. Rapid start units such as gas turbine have a very short lead time compared to the thermal units. The lead time of some thermal units can be reduced to one hour by keeping their boilers in a hot state.

Rapid start and hot reserve units can be included in spinning reserve assessment with the help of an area risk curve [6]. Different types of standby generation can be incorporated in the capacity model using this approach. Figure 2.8 shows an area risk curve for a system with no standby units, where F(R) is the risk function. An area risk curve with standby units such as rapid start and hot reserve is shown in Figure 2.9.

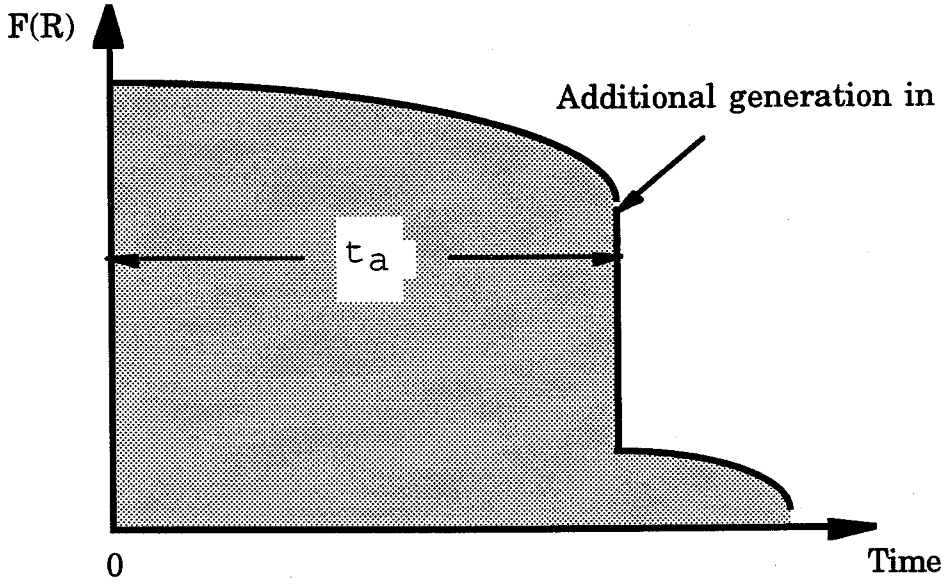

Figure 2.8: Area Risk Curve for a Single System with no Standby Units.

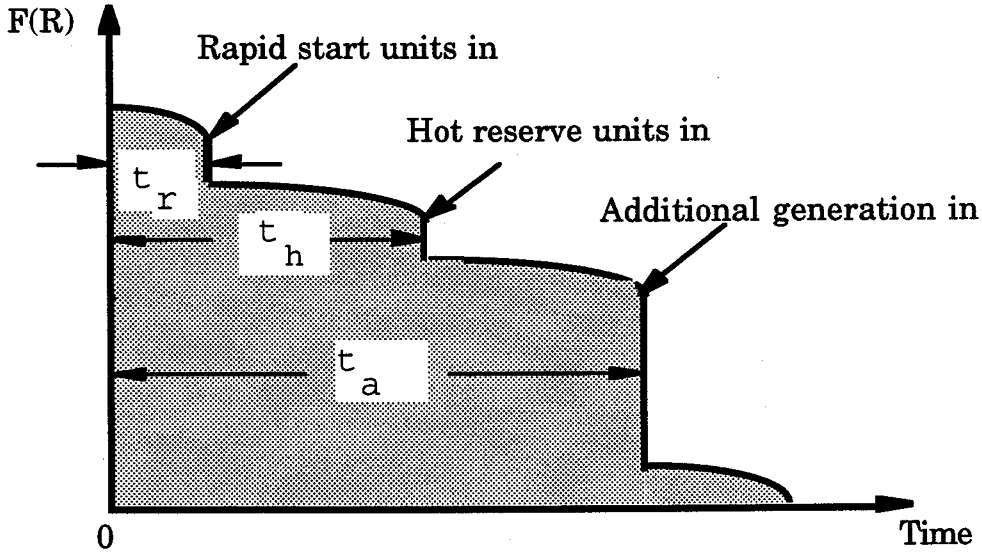

Figure 2.9: Area Risk Curve for a Single System with Standby Units.

Where

F(R) = risk function,

t_r = the time to start rapid start gas turbine units,

t_h = the time to start hot reserve units and

t_a = the lead time for additional thermal units.

A conditional probability approach [13] can be used to evaluate the quantitative effect of these units on unit commitment risk.

Probability of System Failure = (probability of the system generation and the rapid start units just carrying or failing to meet the system load | Rapid start units in) x (probability of the rapid start units in) + (probability of the operating capacity just carrying or failing to meet the system load | rapid start units are not in) x (probability of rapid start unit down) .

The risk level with rapid start and hot reserve units (Figure 2.9) can be expressed as

$$R = \int_0^{t_r} F(R_1)dt + \int_{t_r}^{t_h} F(R_2)dt + \int_{t_h}^{t_a} F(R_3)dt,$$

where:

$\int_0^{t_r} F(R_1)dt$ = risk level calculated for the operating capacity alone for the time interval 0 to t_r,

$\int_{t_r}^{t_h} F(R_2)dt$ = risk level calculated for the operating capacity plus the gas turbine for the time interval t_r to t_h,

$\int_{t_h}^{t_a} F(R_3)dt$ = risk level calculated for the operating capacity plus the gas turbine and hot reserve units for the time interval t_h to t_a.

The area under the curve is calculated directly and the integral equations are not required [6]. The total area under the curve in Figure 2.8 represents the probability that all the present on-line units plus all the back up units in the system will be unable or just be able to meet the system load.

It can be seen from Figure 2.9 that the inclusion of rapid start and hot reserve units reduces the risk function F(R) to a new value depending upon the magnitude of the rapid start capacity.

2.4.3.1. Model of rapid start units

Rapid start units can be started, synchronized and loaded in a relatively short time. Gas turbines, gas engines and some hydro units can pick up load within about five minutes. Figure 2.10 shows a four-state model [6] of a rapid start unit. Transition between different states are also indicated in Figure 2.10.

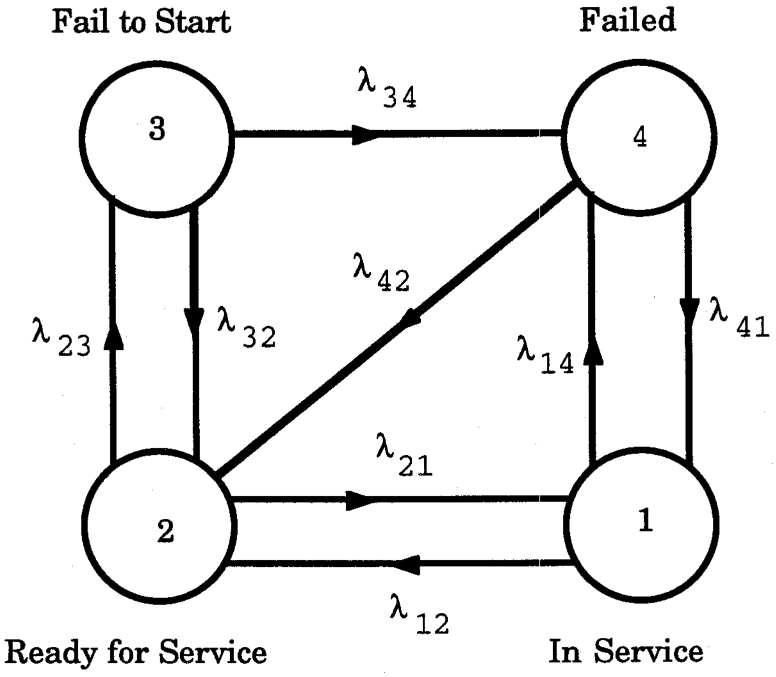

Figure 2.10: Four-state Model for Rapid Start Units.

The probability of residing in any of the states can be evaluated using Markov techniques for any time into the future. The time-dependent probabilities for a continuous Markov process are [6];

$$[\,P(t)\,] = [\,P(0)\,]\,[\,P\,]^{n},$$

where:

$[\,P(t)\,]$ = vector of state probabilities at time t,

$[\,P(0)\,]$ = vector of initial probabilities,

$[\,P\,]$ = stochastic transitional probability matrix,

n = number of time steps used in the discretisation process.

The vector of initial probabilities at the time when the unit may contribute to system generation is

$$[\,P(0)\,] = [P_{10} \;\; 0 \;\; 0 \;\; P_{40}],$$

where:

$$P_{40} = \frac{\text{total number of times unit failed to take up load}}{\text{total number of starts}},$$

$$P_{40} = \frac{\lambda_{23}}{\lambda_{21} + \lambda_{23}},$$

$$P_{10} = 1 - P_{40},$$

$$[P] = \begin{bmatrix} 1-(\lambda_{12}+\lambda_{14})dt & \lambda_{12}dt & 0 & \lambda_{14}dt \\ \lambda_{21}dt & 1-(\lambda_{21}+\lambda_{23})dt & \lambda_{23}dt & 0 \\ 0 & \lambda_{32}dt & 1-(\lambda_{12}+\lambda_{14})dt & \lambda_{34}dt \\ \lambda_{41}dt & \lambda_{42}dt & 0 & 1-(\lambda_{41}+\lambda_{42})dt \end{bmatrix}.$$

The probability of finding the unit on outage given that a demand has occured is given by

$$P(down) = \frac{P_3(t) + P_4(t)}{P_1(t) + P_3(t) + P_4(t)},$$

$$P(up) = 1 - P(down).$$

2.4.3.2. Model of hot reserve units

The model of a hot reserve unit is basically the same as the model of a rapid start unit. A non-operating thermal unit can either be in a hot reserve or in its cold reserve state. A thermal unit can be maintained in a hot reserve state by keeping its boiler(s) operational. In this way a thermal unit can be brought into service in a relatively short time compared to if it were in a cold state. Figure 2.11 shows a five-state model of a hot reserve unit.

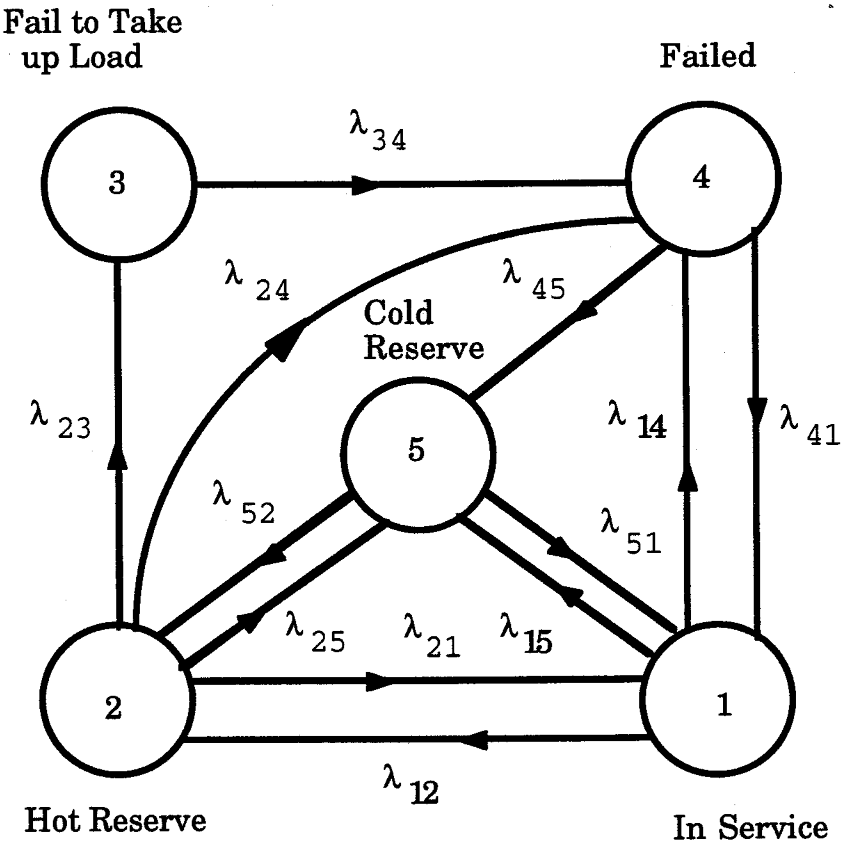

Figure 2.11: Five-state Model for Hot Reserve Units.

The vector of initial probabilities is

$$[P(0)] = [P_{10} \;\; 0 \;\; 0 \;\; P_{40} \;\; 0],$$

$$P_{40} = \frac{\lambda_{23}}{\lambda_{21} + \lambda_{23}},$$

$$P_{10} = 1 - P_{40}.$$

The probability of finding the unit on outage given that a demand has occured is given by

$$P(\text{down}) = \frac{P_3(t) + P_4(t) + P_5(t)}{P_1(t) + P_3(t) + P_4(t) + P_5(t)} ,$$

$$P(\text{up}) = 1 - P(\text{down}) .$$

2.4.4. Application to a hypothetical generation system

The basic spinning reserve evaluation in a single system can be illustrated by utilizing a hypothetical system. Consider a generation system (System-A) with 3 hydro and 13 thermal units. The total installed capacity of the system is 2280 MW. Some of the thermal units in System A are modelled with a derated state. λ_1 is the transition rate from operating to derated state and λ_2 is the transition rate from operating to failed state. Table 2.1 shows the generation data and the corresponding unit failure rates. The unit commitment order is from the top down and the specified single system risk is 0.01. The lead time of additional generation is 4 hours. Units are committed following the loading order until the specified unit commitment risk is satisfied. Each time a unit is added, the previous capacity outage probability table is modified. For a given load, unit commitment risk is evaluated from the modified capacity model.

Table 2.1: Generation Data for the Hypothetical System.

Number of Units	Output Capacity (MW)		Transition Rate (occ/hr)		Unit Type
	Full	Derated	λ_1	λ_2	
1	200			0.0003	Hydro
2	180			0.0003	Hydro
1	200	160	0.0005	0.0003	Thermal
3	150	120	0.0005	0.001	Thermal
3	150	120	0.0002	0.0009	Thermal
2	100			0.0005	Thermal
1	120	100	0.0001	0.0007	Thermal
3	100			0.0006	Thermal

Table 2.2 shows the units that the isolated system must commit in order to meet its risk criteria. Load is varied from 1000 MW to 1800 MW in steps of 100 MW. System A must commit 7 units when the load is 1000 MW. Required unit commitment changes to 8 units when the load changes to 1100 MW. Corresponding spinning reserve is calculated by subtracting the capacity from the load. Although the spinning reserve as a percentage of load varies between 13% to 21%, the required risk criteria is satisfied for all load levels indicated in Table 2.2.

Table 2.2: Unit Commitment in a Single System.

Load (MW)	Number of Units	Capacity (MW)	Spinning Reserve (MW)	Unit Commitment Risk
1000	7	1210	210	0.00014904
1100	8	1360	260	0.00017315
1200	8	1360	160	0.00499031
1300	9	1510	210	0.00028845
1400	10	1660	260	0.00033000
1500	10	1660	160	0.00520423
1600	11	1760	160	0.00524844
1700	12	1860	160	0.00529646
1800	13	1980	180	0.00536881

Assume that System A has one rapid start and one hot reserve unit in addition to those units in Table 2.1. The corresponding transition rates per hour of the rapid start and hot reserve unit are shown in Table 2.3.

Table 2.3: Transition Rates (occ/hr) of the Rapid Start and Hot Reserve Unit.

<table>
<tr><td colspan="5">Rapid Start Unit:
Capacity = 30 MW Lead Time = 10 minutes</td></tr>
<tr><td>λ_{11}= 0.0</td><td>λ_{21}=0.0033</td><td>λ_{31}= 0.0</td><td colspan="2">λ_{41}= 0.015</td></tr>
<tr><td>λ_{12}= 0.005</td><td>λ_{22}= 0.0</td><td>λ_{32}= 0.0</td><td colspan="2">λ_{42}= 0.025</td></tr>
<tr><td>λ_{13}= 0.0</td><td>λ_{23}=0.0008</td><td>λ_{33}= 0.0</td><td colspan="2">λ_{43}= 0.0</td></tr>
<tr><td>λ_{14}= 0.03</td><td>λ_{24}= 0.0</td><td>λ_{34}= 0.025</td><td colspan="2">λ_{44}= 0.0</td></tr>
<tr><td colspan="5">Hot Reserve Unit:
Capacity = 100 MW Lead Time = 60 minutes</td></tr>
<tr><td>λ_{11}= 0.00</td><td>λ_{21}= 0.02</td><td>λ_{31}= 0.02</td><td>λ_{41}= 0.035</td><td>λ_{51}= 0.003</td></tr>
<tr><td>λ_{12}= 0.024</td><td>λ_{22}= 0.0</td><td>λ_{32}= 0.0</td><td>λ_{42}= 0.0</td><td>λ_{52}=0.0025</td></tr>
<tr><td>λ_{13}= 0.0</td><td>λ_{23}=0.0002</td><td>λ_{33}= 0.0</td><td>λ_{43}= 0.0</td><td>λ_{53}= 0.0</td></tr>
<tr><td>λ_{14}= 0.008</td><td>λ_{24}= 0.0</td><td>λ_{34}= 0.03</td><td>λ_{44}= 0.0</td><td>λ_{54}= 0.0</td></tr>
<tr><td>λ_{15}= 0.0</td><td>λ_{25}= 0.0</td><td>λ_{35}= 0.0</td><td>λ_{45}= 0.025</td><td>λ_{55}= 0.0</td></tr>
</table>

A computer program has been developed to include the effect of rapid start and hot reserve units on unit commitment risk. Table 2.4 shows unit commitment in System A with the inclusion of one rapid start and one hot reserve unit as standby. Load is varied from 1000 MW to 1800 MW in steps of 100 MW. In this table, column 5 represents operating reserve which includes spinning reserve and standby capacity. Units are kept in a standby mode in order to reduce the magnitude of required spinning reserve. In the case of an emergency, the standby units can be brought into service in a short period of time. The unit commitment risk with standby units, in general, is reduced in comparison to the unit commitment risk with no standby units for a given set of units and load. The required number of units that System A must commit for the load levels from 1000 MW to 1400 MW are less than the number of units shown in Table 2.2. The unit commitment for load levels from 1500 MW to 1800 MW remains unchanged even with one rapid start and one hot reserve unit. The corresponding unit commitment risk, however, went down due to the availability of the standby units.

Table 2.4: Unit Commitment in a Single System with Rapid Start and Hot Reserve Units.

Load (MW)	Number of Units	Capacity (MW)	Spinning Reserve (MW)	Operating Reserve (MW)	Unit Commitment Risk
1000	6	1060	60	190	0.00576904
1100	7	1210	110	240	0.00469593
1200	8	1360	160	290	0.00105077
1300	8	1360	60	190	0.00795002
1400	9	1510	110	240	0.00677467
1500	10	1660	160	290	0.00120886
1600	11	1760	160	290	0.00121862
1700	12	1860	160	290	0.00122880
1800	13	1980	180	220	0.00066477

2.5. Spinning Reserve Assessment in Interconnected Systems

Most utilities operate in an interconnected fashion. Interconnected utilities can export/import energy, exchange energy and share spinning reserve. Most utilities utilize deterministic techniques to assess spinning reserve requirements. Deterministic techniques do not use the stochastic behavior of system components in a consistent manner. A system whose generating units fail more frequently than its neighbour may not be maintaining its share of spinning reserve and may not be aware of this due to the very nature of the deterministic technique used. A probabilistic technique can be utilized to assess the spinning reserve requirement in interconnected systems. Probabilistic techniques usually include the component failure rates and other stochastic component behavior in a consistent manner. Application of probabilistic techniques in interconnected systems can be illustrated by a numerical example. Consider a hypothetical system (System X) with the generating units and failure rates given in Table 2.5. A capacity model of System X in the form of a capacity outage probability table is shown in Table 2.6. All seven units have been incorporated in the capacity model. The lead time of System X is considered to be 2 hours. For a given load, all capacity states above the load indicate positive margin states and all the states with capacity less then the load indicate negative margin states. A system has the potential to assist its neighbour if it resides in one of the positive margin states. The positive margin states, therefore, can be grouped to form an equivalent assistance model.

Table 2.5: Generating Unit Data for System X.

Unit Size (MW)	Number of Units	Failure Rate (occ/yr)
60	2	3
30	3	5
10	2	2

Table 2.6: Capacity Outage Probability Table.

Capacity Out (MW)	Capacity In (MW)	Individual Probability	Cumulative Probability
0	230	0.99430757	1.0
10	220	0.00090722	0.00569236
20	210	0.00000021	0.00478514
30	200	0.00341039	0.00478494
40	190	0.00000311	0.00137454
60	170	0.00136504	0.00137143
70	160	0.00000124	0.00000639

Table 2.7 shows the equivalent assistance model of System X for a load of 190 MW. The equivalent assistance model of System X can be viewed as a multi-state unit which can be added to the capacity model of a neighbouring system (System Y). The neighbouring system will view the equivalent assistance model of System X as an extra unit in addition to the units that are already committed (in System Y). The addition of the extra unit will lower the unit commitment risk in System Y.

Table 2.7: Equivalent Assistance Model of System X.

Capacity Out (MW)	Capacity In (MW)	Probability
0	40	0.99430757
10	30	0.00090722
20	20	0.00000021
30	10	0.00341039
40	0	0.00137454

2.5.1. Two risks concept

A probabilistic technique called the 'Two Risks Concept' [10] can be utilized to assess spinning reserve requirements in interconnected systems. The 'Two Risks Concept' deals with the assessment and verification of probabilistic risk at two different levels. An interconnected system must meet a unit commitment risk designated as single system risk (SSR) at isolated level. In addition, an interconnected system must meet another risk criteria at interconnection level designated as interconnected system risk (ISR). The units are committed in each individual system such that it meets the SSR criterion without considering any assistance from the neighbour and then the assistance to each other are considered to determine the ISR. The system more removed from meeting its ISR criteria is responsible for adding additional unit(s). The process continues until all systems concerned meet their ISR criteria. The applications of the 'Two Risks Concept' can be illustrated with a numerical examples. Consider two identical systems connected through two tie lines. The data for generating units in each system is given in Table 2.1. The tie-line data are shown in Table 2.8. The lead time in both systems is considered to be 4 hours.

Table 2.8: Tie-Line Data.

Number of Tie-Lines	Capacity of Each Line (MW)	Failure Rate (occ/yr)
2	100	0.00011415

Table 2.9 shows the number of units that must be committed in both systems for a specified SSR of 0.01 and for a specified ISR of 0.0001. The load in System A is varied from 1000 MW to 1800 MW, while the load in System B

Table 2.9: Unit Commitment in Interconnected Hypothetical Systems.

Load (MW)		· Single System				Interconnected system			
		Number of Units		Capacity (MW)		Number of Units		Capacity (MW)	
A	B	A	B	A	B	A	B	A	B
1000	1600	7	11	1210	1760	7	11	1210	1760
1100	1600	8	11	1360	1760	8	11	1360	1760
1200	1600	8	11	1360	1760	8	12	1360	1860
1300	1600	9	11	1510	1760	9	11	1510	1760
1400	1600	10	11	1660	1760	10	11	1660	1760
1500	1600	10	11	1660	1760	10	12	1660	1860
1600	1600	11	11	1760	1760	11	11	1760	1760
1700	1600	12	11	1860	1760	13	11	1980	1760
1800	1600	13	11	1980	1760	14	11	2080	1760

SSR = 0.01, ISR = 0.0001
A = System-A(Lead Time = 4 hours)
B = System-B(Lead Time = 4 hours)

is kept constant at 1600 MW. System A's commitment varies from 7 to 14 units for a corresponding load variation of 1000 MW to 1800 MW. Although System B's load is fixed at 1600 MW, the unit commitment in System B varies between 11 and 12 units. This is due to fact that the actual ISR in System B depends on the magnitude of assistance received from its neighbour (System A). The magnitude of assistance provided by System A, among other factors, depends on the load and unit commitment in System A. The 'Two risks concept' does not take into account the system size and lead time in a direct manner. For a wide range of unit commitment risk (SSR) and load levels, the magnitude of spinning reserve is dominated by the capacity of the largest unit. A system with unit sizes larger than its neighbour can provide larger capacity assistance to its neighbour than the assistance provided by the neighbour with smaller units. The assistance from a large system, therefore, can modify the ISR of a small system to a great extent. This assistance may bring the ISR of the smaller system below the specified level. The assistance from a small system usually do not have a significant effect on the ISR of a large system. The large system may have to add additional unit(s) to meet its ISR criteria. This can be illustrated by considering RBTS (Roy Billinton Test System) [14] and a hypothetical system from Table 2.1 as a System A. The RBTS is connected to System A through two tie lines. The RBTS is a small test system, the details of which will be discused later. The generating unit data for RBTS is given in Table 2.10. The data for tie-line is given in Table 2.8. The lead time for both systems is considered as 4 hours.

Table 2.10: RBTS Generating Unit Data.

Unit Type	Unit Size (MW)	Priority Loading Order	Failure Rate (f/Yr)
Hydro	40	1	3
Hydro	20	2	2.4
Hydro	20	3	2.4
Thermal	40	4	6
Thermal	40	5	6
Thermal	20	6	5
Thermal	10	7	4
Hydro	20	8	2.4
Hydro	20	9	2.4
Hydro	5	10	2
Hydro	5	11	2

It can be noticed from Table 2.11 that the RBTS can meet its ISR with the units committed to satisfy its SSR. System A in most cases, however, requires to add an extra unit on top of those committed to meet its SSR criterion in order to satisfy its ISR. This is due to the fact that the unit sizes in the RBTS are smaller than those in System A and, therefore, the RBTS provides a smaller assistance to System A as compared to the assistance provided by System A to the RBTS. A system can not bring its additional generation within the lead time. In the event of an emergency, a system, therefore, becomes dependent upon the assistance of its neighbour for a period at least equal to the lead time of the system. A system with a lead time greater than that of its neighbour would likely be dependent on its neighbour for a longer period of time than that of its neighbour. A technique, such as the 'Two Risks Concept', solely dependent upon the

Table 2.11: Unit Commitment in Interconnected RBTS and System A.

Load (MW)		Single System				Interconnected system			
		Number of Units		Capacity (MW)		Number of Units		Capacity (MW)	
1	2	1	2	1	2	1	2	1	2
100	1000	4	7	120	1210	4	8	120	1360
110	1100	4	8	120	1360	4	9	120	1510
120	1200	5	8	160	1360	5	9	160	1510
130	1300	5	9	160	1510	5	10	160	1660
140	1400	5	10	160	1660	5	11	160	1760
150	1500	5	10	160	1660	5	12	160	1860
160	1600	7	11	190	1760	7	13	190	1980
170	1700	8	12	210	1860	8	14	210	2080
180	1800	8	13	210	1980	8	15	210	2180

SSR = 0.01, ISR = 0.0001
1 = RBTS(Lead Time = 4 hours)
2 = System-A(Lead Time = 4 hours)

verification of the unit commitment risk can not address this issue in a consistent manner.

A new probabilistic approach for equitable sharing of spinning reserve requirement in interconnected systems has been developed. This technique overcomes the disadvantages of the 'Two Risks Concept' discussed in this section. This new technique is called the 'Expected Energy Assistance'. The technique and its application to test systems are described in the next chapter.

2.6. Summary

The definitions and basic terms associated with the reliability evaluation at HL I level are introduced in this chapter. The component models and their applications to unit commitment are discussed. Spinning reserve assessment in a single system is discussed with the inclusion of rapid and hot reserve units. Spinning reserve in interconnected systems is introduced and applications of the 'Two Risks Concept' are illustrated using numerical examples. The drawbacks of the 'Two risks concept' are discussed.

3. EXPECTED ENERGY ASSISTANCE IN INTERCONNECTED SYSTEMS

3.1. Introduction

Adequate spinning reserve is required in a power system in order to maintain a desired level of reliability at the generation level. The magnitude of the spinning reserve requirement can be determined either by a deterministic or a probabilistic approach. Probabilistic approaches take into account random outages of system components and other stochastic component behavior in a consistent manner and can provide quantitative measures of system reliability. System reliability at the generation level can be improved by increasing the magnitude of spinning reserve (provided all other factors remain same). For a given load and set of generating units, an increase in the spinning reserve will result in an increase in the system operating cost. Interconnection between systems is an effective way of reducing the magnitude of spinning reserve requirement yet maintaining the desired level of reliability at the generation level. If required, a system can assist its neighbour with the help of its excess capacity held as spinning/operating reserve for an expected duration of time. The magnitude of the assistance that a system is able to provide depends, among other things, on the size of the operating units and the load level. A system's assistance to its neighbour also depends on the tie-line capacity between the interconnected systems. The maximum power received by the assisted system is limited to the tie-line capacity.

A system with unit sizes larger than its neighbour can provide larger capacity assistance to its neighbour than can be provided by the neighbour to it. This assistance is expected to continue for a time period equal to the lead time of additional units in the assisted system. An interconnected system with a lead time greater than its neighbour is likely to be dependent on its neighbour during a contingency for the transfered energy for a period greater than that of its neighbour. A method like the 'Two Risks Concept', based on capacity assistance, can not take this factor into account in a consistent manner. The magnitude of the expected capacity assistance can be convolved with the lead time to form an energy based index. This energy based index will remove the main disadvantages of the 'Two Risks Concept' discussed earlier.

3.2. Expected Energy Assistance

Expected energy assistance (EEA) is the energy that can be transfered from a system to the troubled system if required. Once initiated this assistance is expected to continue until additional units are brought into service in the troubled system.

An interconnected system can assist its neighbour if its generation capacity resides in one of many positive margin states. The positive margin states can be combined to form a multi-state unit designated as an equivalent assistance unit. The neighbouring system will view the equivalent assistance unit as an additional unit. The equivalent assistance unit, however, will be constrained to the capacity and unavailability of the tie lines. The expected energy assistance of one interconnected system to the other can be determined once the states of the tie constrained equivalent assistance unit are evaluated for a given time delay. Two radially connected hypothetical systems (Figure 3.1) are utilized to illustrate the concepts of expected energy assistance. The hypothetical systems are connected through the tie line T_{ab}.

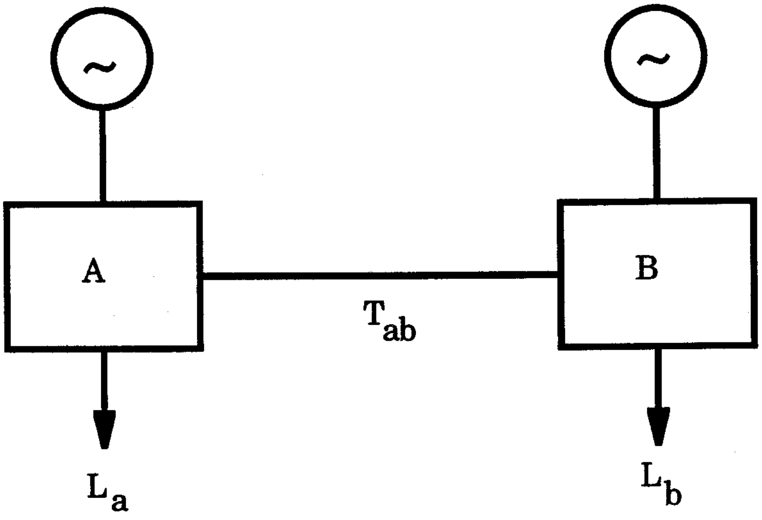

FIGURE 3.1: Interconnected Systems.

Equivalent assistance unit of System A to System B can be found by subtracting System A's load from its capacity model.

$$C_{ab} \rightarrow A - L_a ,$$

where:

C_{ab} is the equivalent assistance unit model of System A to System B, A is the capacity model in the form of a capacity outage probability table for System A,

and

L_a is the load in system A .

Expected energy assistance of System A to System B can be expressed as

$$EEA_{ab} = \sum_{i=1}^{n} C'_{ab}(i) * P_{ab}(i) * t_b , \qquad (3.1)$$

where:

EEA_{ab} is the Expected Energy Assistance from System A to System B,

$C'_{ab}(i)$ is the i^{th} capacity state of the tie constrained equivalent assistance unit of System A to System B,

$P_{ab}(i)$ is the exact probability of the i^{th} state of the tie constrained equivalent assistance unit of System A to System B,

t_b is the lead time of additional thermal generation in System B,

and

n is the total number of capacity states of the tie constrained equivalent assistance unit.

Equivalent assistance unit of System B to System A is

$$C_{ba} \rightarrow B - L_b ,$$

where:

C_{ba} is the equivalent assistance unit model of System B to System A,

B is the capacity model in the form of a capacity outage probability table for System B,

and

L_b is the load in system B.

Expected energy assistance of System B to System A can be expressed as

$$EEA_{ba} = \sum_{i=1}^{n} C'_{ba}(i) * P_{ba}(i) * t_a , \qquad (3.2)$$

where:

EEA_{ba} is the Expected Energy Assistance from System B to System A,

$C'_{ba}(i)$ is the i^{th} capacity state of the tie constrained equivalent assistance unit of System B to System A,

$P_{ba}(i)$ is the exact probability of the i^{th} state of the tie constrained equivalent assistance unit of System B to System A,

t_a is the lead time of additional thermal generation in System A,

and

n is the total number of capacity states of the tie constrained equivalent assistance unit.

A computer program has been developed to evaluate the expected energy assistance for interconnected generating systems.

3.3. Test Systems

The generating units in a large system are usually larger than the units in a small system. A large system, therefore, is more likely to provide a greater level of assistance than its neighbour if it is connected to a comparatively smaller system. In order to demonstrate the expected energy assistance and its dependence on unit size and system lead time two test systems are utilized. These systems are, the 6 bus Roy Billinton Test System [14] (RBTS) and a hypothetical system [15]. The RBTS is smaller than the hypothetical system.

3.3.1. Expected energy assistance in interconnected Roy Billinton Test System

The Roy Billinton Test System (RBTS) is an educational test system developed at the University of Saskatchewan [14]. It is sufficiently small to conduct a large number of reliability studies with a little computational effort but detailed enough to reflect the complexities involved in a practical system.

The single line diagram of the test system is shown in Figure 3.2. The system has two generator buses, four load buses, nine transmission lines and eleven generating units. The system peak load is 185 MW and the total generating capacity is 240 MW. The generating unit data for the RBTS are given in Table 2.10. The tie-line data are shown in Table 3.1. Two identical RBTS are considered as RBTS A and RBTS B with a specified SSR of 0.01. Table 3.2 shows the unit commitment and corresponding expected energy assistance of the two RBTS's with identical lead times of 2 hours. The units are committed such that the specified SSR is met. The load in RBTS A is varied from 100 MW to 160 MW while the load in RBTS B is constant at 110 MW. The tie capacity is varied from 2x15 MW to 2x50 MW and for each tie capacity the EEA at each load level is evaluated. Spinning reserve can be found by subtracting system load from the corresponding spinning capacity. The expected energy assistance of each RBTS remain basically unchanged when the tie capacity is varied from 2x15 MW to 2x50 MW with the exception of EEA at a load level of 120 MW in RBTS A. This is due to the fact that the spinning reserves at all load levels are consistently lower than the available tie capacity except at the load level of 120 MW in RBTS A. EEA at the load level of 120 MW increases from 59.8 MWh to 79.7 MWh when the tie capacity is increased from 2x15 MW to 2x30 MW. At 120 MW load in RBTS A the spinning reserve is 40 MW.

Table 3.1: Tie- Line Data.

Number of Tie-Lines	Capacity of Each Line (MW)	Failure Rate (occ/yr)
2	15	0.00011415

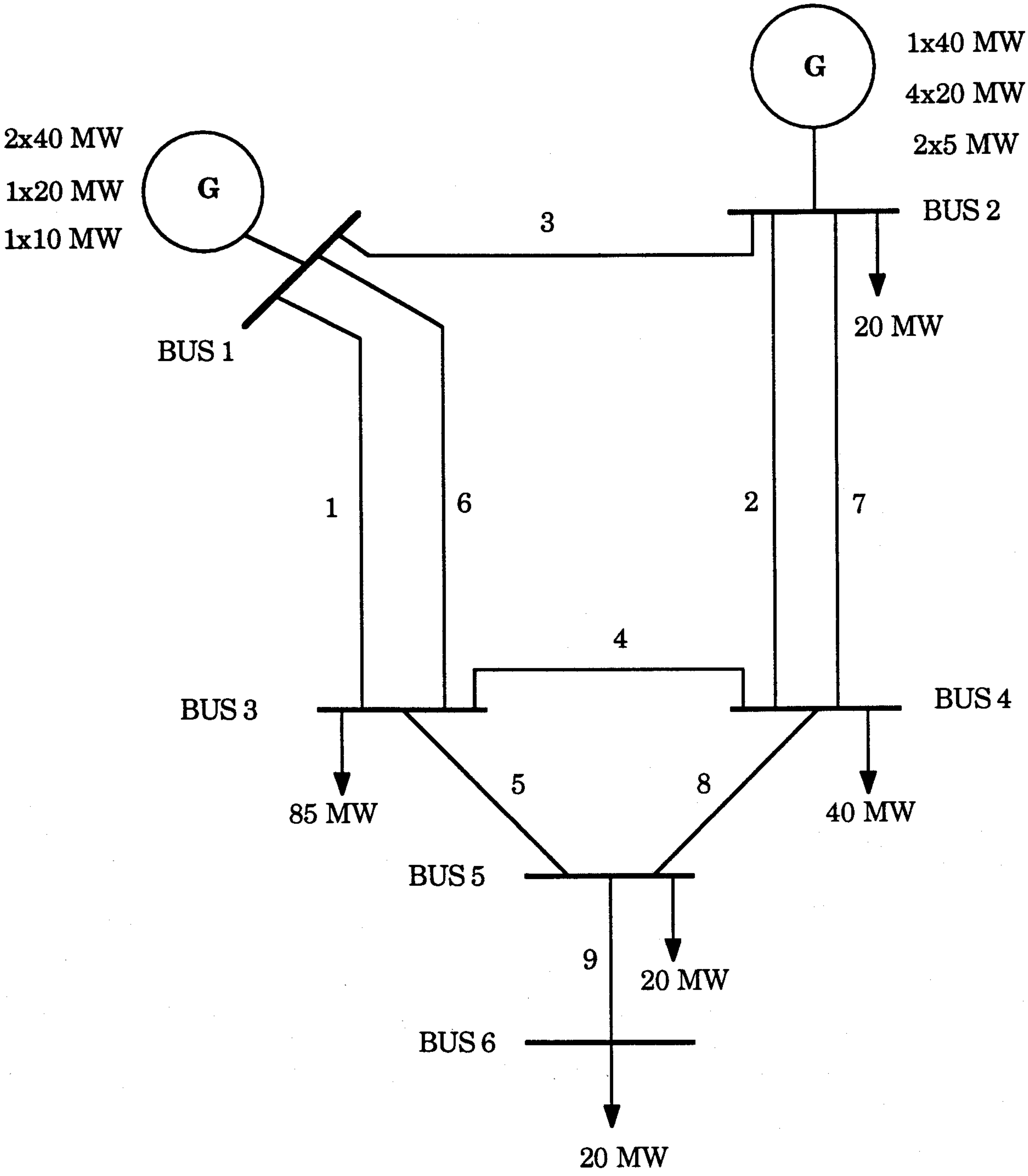

Figure 3.2: Single Line Diagram of the RBTS.

Table 3.2: Unit commitment and EEA in the RBTS (identical lead time).

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)							
						Tie-Cap. =							
						2X15 MW		2X30 MW		2X40 MW		2X50 MW	
A	B	A	B	A	B	A	B	A	B	A	B	A	B
100	110	4	4	120	120	39.9	19.9	39.9	19.9	39.9	19.9	39.9	19.9
110	110	4	4	120	120	19.9	19.9	19.9	19.9	19.9	19.9	19.9	19.9
120	110	5	4	160	120	59.8	19.9	79.7	19.9	79.7	19.9	79.7	19.9
130	110	5	4	160	120	59.7	19.9	59.7	19.9	59.7	19.9	59.7	19.9
140	110	5	4	160	120	39.8	19.9	39.8	19.9	39.8	19.9	39.8	19.9
150	110	5	4	160	120	19.9	19.9	19.9	19.9	19.9	19.9	19.9	19.9
160	110	6	4	180	120	39.8	19.9	39.8	19.9	39.8	19.9	39.8	19.9

SSR = 0.01
A = RBTS A(Lead Time = 2 hours)
B = RBTS B(Lead Time = 2 hours)

In the event of a loss of capacity, a system is expected to receive assistance from its neighbour for a period equal to its lead time of additional units. Consider that the lead time in RBTS A is 2 hours and the lead time in RBTS B is 4 hours. It will take longer for RBTS B compared to RBTS A to start its additional units in the case of an emergency. During the lead time of RBTS B, RBTS A can assist RBTS B. Table 3.3 shows the unit commitment and the corresponding EEA in the two RBTS. Load in both RBTS is kept equal and varied from 100 MW to 160 MW. The tie capacity is varied from 2x15 MW to 2x50 MW and the EEA for each load level is evaluated. The EEA of RBTS A is higher than that of RBTS B. This is due to the fact that RBTS A is expected to assist RBTS B for a longer period of time. The EEA of both the RBTS have increased for a load level of 120 MW when the tie capacity is increased from 2x15 MW to 2x30 MW, and remain unchanged for other tie capacities beyond 2x40 MW. This is due to the fact that at 120 MW load in both the RBTS, the spinning reserve is 40 MW which is greater compared to the spinning reserves at other load levels.

3.3.2. Expected energy assistance in interconnected RBTS and a Hypothetical System

Consider two systems of different sizes, one is the RBTS and the other is a hypothetical system. The generating unit data for the hypothetical (System A) system is shown in Table 2.1 in Section 2.4.4. The RBTS is smaller than System A. The largest unit in the RBTS is of 40 MW capacity, while, the largest unit in System A is of 200 MW capacity. The peak load in the RBTS is 185 MW and the peak load in System A is 1900 MW. Consider that the RBTS and System A are radially connected. The tie-line data is given in Table 3.1. The lead time of additional units is 2 hours in both

Table 3.3: Unit commitment and EEA in the RBTS (different lead time).

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)							
						Tie-Cap. =							
						2X15 MW		2X30 MW		2X40 MW		2X50 MW	
A	B	A	B	A	B	A	B	A	B	A	B	A	B
100	100	4	4	120	120	79.7	39.9	79.7	39.9	79.7	39.9	79.7	39.9
110	110	4	4	120	120	39.9	19.9	39.9	19.9	39.9	19.9	39.9	19.9
120	120	5	4	160	160	119.5	59.8	159.4	79.7	159.3	79.7	159.3	79.7
130	130	5	4	160	160	119.5	59.7	119.5	59.7	119.5	59.7	119.5	59.7
140	140	5	4	160	160	79.6	39.8	79.6	39.8	79.6	39.8	79.6	39.8
150	150	5	4	160	160	39.8	19.9	39.8	19.9	39.8	19.9	39.8	19.9
160	160	6	4	180	180	79.5	39.8	79.5	39.8	79.5	39.8	79.5	39.8

SSR = 0.01
A = RBTS A(Lead Time = 2 hours)
B = RBTS B(Lead Time = 4 hours)

systems. Table 3.4 shows the unit commitment and the corresponding EEA in the RBTS and System A. Load in the RBTS is kept constant at 120 MW while the load in System A is varied from 1400 MW to 2000 MW in steps of 100 MW. The EEAs are evaluated for the tie-line capacities ranging from 2x15 MW to 2x160 MW. The EEA of the RBTS and System A remain basically same for the tie capacity of 2x15 MW. The EEA of the RBTS increases when the tie capacity increases from 2x15 MW to 2x40 MW and remain unchanged at a level of 79.7 MWh for other tie capacities beyond 2x40 MW. In System A, the EEA increases at all load levels when the tie capacity is increased from 2x15 MW to 2x80 MW. The EEA of System A increases at the load levels of 1400, 1800, 1900 and 2000 MW, when the tie capacity is increased from 2x80 MW to 2x100 MW. The EEA of System A at all load levels remains basically unchanged for the tie capacity variations from 2x120 MW to 2x160 MW except at the load level of 1400 MW. At 1400 MW load, the spinning reserve in System A is 260 MW which is greater than that of the spinning reserves at other load levels in System A. In general, the EEA of System A, is greater than the EEA of the RBTS.

Consider the lead time for RBTS to be 2 hours and for System A to be 4 hours. The tie line capacity is varied from 2x15 MW to 2x160 MW in discrete steps. It can be seen from Table 3.5 that the EEA of the RBTS at the tie capacity of 2x15 MW is higher than that of System A. This is due to the fact that RBTS is expected to assist System A for a longer period of time. The EEA of the RBTS increases with the increase in tie capacity from 2x15 MW to 2x40 MW and remains unchanged for tie capacities beyond 2x40 MW. This is due to the fact that the spinning reserve in the RBTS is well below the tie capacity of 2x60 MW. The EEA of System A is larger than that of the

Table 3.4: Unit commitment and EEA in the RBTS and System A (identical lead time).

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)							
						Tie-Cap. =							
						2X15 MW		2X40 MW		2X60 MW		2X80 MW	
1	2	1	2	1	2	1	2	1	2	1	2	1	2
120	1400	5	10	160	1660	59.8	60.0	79.7	159.9	79.7	239.5	79.7	318.4
120	1500	5	10	160	1660	59.8	59.4	79.7	158.0	79.7	236.9	79.7	315.5
120	1600	5	11	160	1760	59.8	59.4	79.7	158.0	79.7	236.8	79.7	315.3
120	1700	5	12	160	1860	59.8	59.4	79.7	157.9	79.7	236.7	79.7	315.1
120	1800	5	13	160	1980	59.8	59.8	79.7	158.4	79.7	237.0	79.7	315.5
120	1900	5	14	160	2080	59.8	59.8	79.7	158.4	79.7	236.9	79.7	315.3
120	2000	5	15	160	2180	59.8	59.8	79.7	158.4	79.7	236.8	79.7	315.1

SSR = 0.01

1 = RBTS(Lead Time = 2 hours)

2 = System A(Lead Time = 2 hours)

Cont. Table 3.4: Unit commitment and EEA in the RBTS and System A.

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)							
						Tie-Cap. =							
						2X100 MW		2X120 MW		2X140 MW		2X160 MW	
1	2	1	2	1	2	1	2	1	2	1	2	1	2
120	1400	5	10	160	1660	79.7	397.3	79.7	476.0	79.7	515.3	79.7	515.3
120	1500	5	10	160	1660	79.7	315.5	79.7	315.5	79.7	315.5	79.7	315.4
120	1600	5	11	160	1760	79.7	315.3	79.7	315.3	79.7	315.3	79.7	315.2
120	1700	5	12	160	1860	79.7	315.1	79.7	315.1	79.7	315.1	79.7	315.0
120	1800	5	13	160	1980	79.7	354.6	79.7	354.6	79.7	354.7	79.7	354.7
120	1900	5	14	160	2080	79.7	354.4	79.7	354.4	79.7	354.4	79.7	354.4
120	2000	5	15	160	2180	79.7	354.2	79.7	354.2	79.7	354.2	79.7	354.2

SSR = 0.01
1 = RBTS(Lead Time = 2 hours)
2 = System A(Lead Time = 2 hours)

RBTS beyond the tie capacity of 2x15 MW. This is due to the fact that System A is a comparatively large system than the RBTS and has larger spinning reserves at each load level than the RBTS. The spinning reserve in System A corresponding to the unit commitments shown in Table 3.5 varies between 160 MW to 260 MW. System A, therefore, can utilize the tie capacity in a better way compared to that of the RBTS up to the tie capacity of 2x140 MW. Beyond the tie capacity of 2x140 MW the EEA of System A becomes saturated.

Table 3.6 shows the unit commitment and EEA in the hypothetical system if it is connected to another system identical to its size and set of generating units. The load in one of the hypothetical systems (System A) is held constant at 1800 MW and the load in the other hypothetical system (System B) is varied from 1400 MW to 2000 MW. The EEA provided by each system to the other is in the same order. This is due to the fact that the two systems are identical to each other with respect to their generating units. This fact was not obvious from the EEA results of two interconnected RBTS due to the fact that the RBTS is a very small system, and like most small systems the capacity model of the RBTS has many discrete jumps. The capacity model of a large system has fewer such jumps and tend to be continuous with respect to capacity states.

It can be noticed that the systems of the same size with identical lead time can provide energy assistance of the same order. The expected energy assistances between systems of distinctly different sizes are of different order. A small system, in general, can provide small energy assistance with respect to that provided by a large system. In order to overcome the disparity of assistance, an index can be utilized to measure/compare

Table 3.5: Unit commitment and EEA in the RBTS and System A (differnet lead time).

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)							
						Tie-Cap. =							
						2X15 MW		2X40 MW		2X60 MW		2X80 MW	
1	2	1	2	1	2	1	2	1	2	1	2	1	2
120	1400	5	10	160	1660	119.5	60.0	159.3	159.8	159.3	239.0	159.3	316.8
120	1500	5	10	160	1660	119.5	58.8	159.3	156.1	159.3	233.9	159.3	311.0
120	1600	5	11	160	1760	119.5	58.8	159.3	156.0	159.3	233.6	159.3	310.6
120	1700	5	12	160	1860	119.5	58.8	159.3	155.9	159.3	233.4	159.3	310.3
120	1800	5	13	160	1980	119.5	59.7	159.3	156.8	159.3	234.1	159.3	310.1
120	1900	5	14	160	2080	119.5	59.7	159.3	156.8	159.3	233.9	159.3	310.8
120	2000	5	15	160	2180	119.5	59.7	159.3	156.8	159.3	233.7	159.3	310.4

SSR = 0.01
1 = RBTS(Lead Time = 2 hours)
2 = System A(Lead Time = 4 hours)

Cont. Table 3.5: Unit commitment and EEA in the RBTS and System A.

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)							
						Tie-Cap. =							
						2X100 MW		2X120 MW		2X140 MW		2X160 MW	
1	2	1	2	1	2	1	2	1	2	1	2	1	2
120	1400	5	10	160	1660	159.3	394.6	159.3	472.2	159.3	510.7	159.3	510.7
120	1500	5	10	160	1660	159.3	311.0	159.3	311.1	159.3	311.1	159.3	311.0
120	1600	5	11	160	1760	159.3	310.7	159.3	310.7	159.3	310.7	159.3	310.6
120	1700	5	12	160	1860	159.3	310.3	159.3	310.3	159.3	310.3	159.3	310.2
120	1800	5	13	160	1980	159.3	349.4	159.3	349.4	159.3	349.4	159.3	349.4
120	1900	5	14	160	2080	159.3	348.9	159.3	348.9	159.3	348.9	159.3	348.9
120	2000	5	15	160	2180	159.3	348.4	159.3	348.4	159.3	348.4	159.3	348.5

SSR = 0.01
1 = RBTS(Lead Time = 2 hours)
2 = System A(Lead Time = 4 hours)

Table 3.6: Unit commitment and EEA in the Hypothetical System (identical lead time).

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)							
						Tie-Cap. =							
						2X15 MW		2X40 MW		2X60 MW		2X80 MW	
A	B	A	B	A	B	A	B	A	B	A	B	A	B
1800	1400	13	10	1980	1660	59.8	60.0	158.4	159.9	237.0	239.5	315.5	318.4
1800	1500	13	10	1980	1660	59.8	59.4	158.4	158.0	237.0	236.9	315.5	315.5
1800	1600	13	11	1980	1760	59.8	59.4	158.4	158.0	237.0	236.8	315.5	315.3
1800	1700	13	12	1980	1860	59.8	59.4	158.4	157.9	237.0	236.7	315.5	315.1
1800	1800	13	13	1980	1980	59.8	59.8	158.4	158.4	237.0	237.0	315.5	315.5
1800	1900	13	14	1980	2080	59.8	59.8	158.4	158.4	237.0	236.9	315.5	315.3
1800	2000	13	15	1980	2180	59.8	59.8	158.4	158.4	237.0	236.8	315.5	315.1

SSR = 0.01

A = System A(Lead Time = 2 hours)

B = System B(Lead Time = 2 hours)

Cont. Table 3.6: Unit commitment and EEA in the Hypothetical System.

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)							
						Tie-Cap. =							
						2X100 MW		2X120 MW		2X140 MW		2X160 MW	
A	B	A	B	A	B	A	B	A	B	A	B	A	B
1800	1400	13	10	1980	1660	354.6	397.3	354.6	476.0	354.7	515.3	354.7	515.3
1800	1500	13	10	1980	1660	354.6	315.5	354.6	315.5	354.7	315.5	354.7	315.4
1800	1600	13	11	1980	1760	354.6	315.3	354.6	315.3	354.7	315.3	354.7	315.2
1800	1700	13	12	1980	1860	354.6	315.1	354.6	315.1	354.7	315.1	354.7	315.0
1800	1800	13	13	1980	1980	354.6	354.6	354.6	354.6	354.7	354.7	354.7	354.7
1800	1900	13	14	1980	2080	354.6	354.4	354.6	354.4	354.7	354.4	354.7	354.4
1800	2000	13	15	1980	2180	354.6	354.2	354.6	354.2	354.7	354.2	354.7	354.2

SSR = 0.01

A = System A(Lead Time = 2 hours)

B = System B(Lead Time = 2 hours)

expected energy assistance provided by interconnected systems to each other. Interconnected systems must satisfy an expected energy assistance (EEA) criterion. Interconnected systems should find a suitable EEA criterion based upon their sizes, tie capacity, lead time etc..

3.4. Expected Energy Assistance Index

Each interconnected system must satisfy a risk criterion at isolated level. In addition, the expected energy assistance provided by each system to its neighbour must be equal to or greater than a prespecified level termed as expected energy assistance (EEA) index. The units are committed in each system such that the single system risk (SSR) criterion is satisfied. Once the SSR criterion is satisfied by the interconnected systems, the expected energy assistance of all systems to their neighbour are evaluated. Systems removed from meeting their EEA criterion must commit additional unit(s). The unit addition is done to satisfy the EEA index. If the EEA_{ab} and EEA_{ba} are greater than or equal to the EEA index then the number of generating units committed in both systems are considered to be adequate. Otherwise, if $EEA_{ab} <$ EEA index then System A has to add another generating unit or, if $EEA_{ba} <$ EEA index then System B has to add another generating unit. The evaluation process would continue until all interconnected systems satisfy their EEA indices.

The assistance provided by one interconnected system to another is influenced by the tie capacity between the systems. If the size of the assistance equivalent unit is smaller than the tie capacity then the assistance model is constrained only by the failure rate of the tie line(s). If the size of the assistance equivalent unit, on the other hand, is greater than the tie capacity then the assistance model is constrained by the tie line failures as well as the tie capacity. A tie capacity between two systems, one of which is larger than the other, can influence the assistance model in one of the following ways.

1. The tie capacity is such that the assistance model of both systems are constrained by the tie line failure and capacity,
2. The tie capacity is such that the assistance model of the large system is constrained by the tie line failure and the capacity. The assistance model of the small system is constrained by the tie line failure only,
3. The tie capacity is such that the assistance model of both systems are constrained only by the tie line failure.

Expected energy assistance between interconnected systems for different load conditions have to be assessed in order to arrive at a suitable EEA index.

3.4.1. EEA index for the systems of similar sizes

The EEA index in systems of similar sizes can be illustrated by utilizing two identical hypothetical systems, System A and System B. The lead times for both systems are 2 hours. Load in System B is kept constant at 1400 MW and in System A is varied from 1400 MW to 2000 MW. Table 3.7.1 shows the unit commitment and EEA for a specified value of EEA index of 300 MWh. The tie line capacity is fixed at 2x100 MW. In order to satisfy the specified EEA index, System B must commit 10 units and System

A must commit 10 to 15 units. The EEA of System A varies between 315.1 MWh to 397.3 MWh and EEA of System B is fixed at 397.3 MWh.

Table 3.7.1: Unit Commitment and EEA in Interconnected Hypothetical Systems.

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)	
A	B	A	B	A	B	A	B
1400	1400	10	10	1660	1660	397.274	397.274
1500	1400	10	10	1660	1660	315.480	397.274
1600	1400	11	10	1760	1660	315.282	397.274
1700	1400	12	10	1860	1660	315.085	397.274
1800	1400	13	10	1980	1660	354.635	397.274
1900	1400	14	10	2080	1660	354.397	397.274
2000	1400	15	10	2180	1660	354.160	397.274

SSR = 0.01, EEA Index = 300 MWh, Tie-Cap. = 2x100 MW

A = System A(Lead Time = 2 hours)

B = System B(Lead Time = 2 hours)

Table 3.7.2 shows the unit commitment and the corresponding EEA for a specified EEA index of 360 MWh. The load variations and the tie capacity are the same as that used in Table 3.7.1. System B must commit 10 units and System A must commit 10 to 16 units in order to meet the specified EEA index. The EEA of both systems are basically the same. At an EEA index of 400 MWh, both systems are unable to meet the EEA criterion.

Table 3.7.2: Unit Commitment and EEA in Interconnected Hypothetical Systems.

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)	
A	B	A	B	A	B	A	B
1400	1400	10	10	1660	1660	397.274	397.274
1500	1400	11	10	1760	1660	397.192	397.274
1600	1400	12	10	1860	1660	397.11	397.274
1700	1400	13	10	1980	1660	397.618	397.274
1800	1400	14	10	2080	1660	397.567	397.274
1900	1400	15	10	2180	1660	397.515	397.274
2000	1400	16	10	2280	1660	397.463	397.274

SSR = 0.01, EEA Index = 360 MWh, Tie-Cap. = 2x100 MW

A = System A(Lead Time = 2 hours)

B = System B(Lead Time = 2 hours)

The maximum level of the EEA indices that systems of similar sizes can satisfy will be of the same order. A range of studies should be performed with different load profiles and unit maintenance schedules in order to find the maximum value of the EEA index that both interconnected systems can satisfy without having any difficulty. The specified EEA index that a system should agree upon will be at a value lower than the maximum level.

3.4.2. EEA index for the systems of dissimilar sizes

Consider two systems of different sizes, one is the RBTS and the other one is the hypothetical system (System A) mentioned in Section 3.3.2. The lead times for both systems are 2 hours. The load in the RBTS is 100 MW.

The load in System A is varied from 1400 MW to 2000 MW in steps of 100 MW. The tie capacity is 2x60 MW. Table 3.8.1 shows that the RBTS must commit 8 units and System A must commit 10 to 15 units for a specified EEA index of 200 MWh. The EEA of System A varies from 236.6 MWh to 239.5 MWh and that of the RBTS remain fixed at 219.5 MWh.

Table 3.8.1: Unit Commitment and EEA in Interconnected RBTS and System A.

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)	
1	2	1	2	1	2	1	2
100	1400	8	10	210	1660	219.574	239.487
100	1500	8	10	210	1660	219.574	236.905
100	1600	8	11	210	1760	219.574	236.786
100	1700	8	12	210	1860	219.574	236.667
100	1800	8	13	210	1980	219.574	237.027
100	1900	8	14	210	2080	219.574	236.93
100	2000	8	15	210	2180	219.574	236.834

SSR = 0.01, EEA Index = 200 MWh, Tie-Cap. = 2x60 MW

1 = RBTS(Lead Time = 2 hours)

2 = System A(Lead Time = 2 hours)

Consider that the specified EEA index is changed from 200 MWh to 225 MWh keeping all other factors same. The unit commitment and the EEA in both systems are shown in Table 3.8.2. In order to meet the EEA criterion, the RBTS must commit 9 units and System A must commit 10 to 15 units. The EEA of System A varies between 236.834 MWh to 239.487 MWh and the EEA of the RBTS is unchanged at 239.7 MWh. At the tie capacity of 2x60 MW, the EEA of the RBTS and System A are basically in the same order. At a specified EEA index of 240 MWh both systems are unable to meet the EEA criterion. The EEA of these two systems will vary in different magnitudes with a variation in the tie capacity. This is explained in the next section.

Table 3.8.2: Unit Commitment and EEA in Interconnected RBTS and System A.

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)	
1	2	1	2	1	2	1	2
100	1400	9	10	210	1660	239.7	239.487
100	1500	9	10	210	1660	239.7	236.905
100	1600	9	11	210	1760	239.7	236.786
100	1700	9	12	210	1860	239.7	236.667
100	1800	9	13	210	1980	239.7	237.027
100	1900	9	14	210	2080	239.7	236.93
100	2000	9	15	210	2180	239.7	236.834

SSR = 0.01, EEA Index = 225 MWh, Tie-Cap. = 2x60 MW

1 = RBTS(Lead Time = 2 hours)

2 = System A(Lead Time = 2 hours)

3.4.3. Effect of tie capacity

The energy assistance of interconnected systems depends on the tie capacity and its failure rate. If two systems are very similar in terms of their generating units and load profiles then the EEA of the two systems are influenced by the tie capacity in the same manner. The effect of tie capacity on the EEA would be different in systems radically different in terms of their size and load.

3.4.4. Effect of tie capacity on systems of similar sizes

Consider the two identical hypothetical systems, System A and System B. The lead time for both systems is considered to be 2 hours. Load in System A is varied from 1400 MW to 2000 MW and while the load in System B is fixed at 1400 MW. Table 3.9 shows the unit commitment and EEA for a specified EEA index of 50 MWh. Three discrete tie capacity of 2x15 MW, 2x60 MW and 2x140 MW are considered. Unit commitment for System B is 10 units and for System A varies from 10 to 15 units in order to meet the EEA criterion. The EEA of both systems are basically the same for tie capacity of 2x15 MW and 2x60 MW. The unit commitment in both systems for three tie capacity levels remained the same because of a small EEA index of 50 MWh. It is apparent from Table 3.9 that both systems can satisfy an EEA index of 59 MWh with a 2x15 MW tie capacity. These systems can also satisfy an EEA index of 236 MWh without changing their unit commitments when the tie capacity is increased from 2x60 MW to 2x140 MW.

3.4.5. Effect of tie capacity on systems of dissimilar sizes

Consider two systems of different sizes, the RBTS and the hypothetical system (System A). The lead time for both systems is 2 hours. Load in the RBTS is kept constant at 100 MW and in System A is varied from 1400 MW to 2000 MW. Table 3.10 shows the unit commitment and EEA for a specified EEA index of 50 MWh. Three discrete tie capacity levels of 2x15 MW, 2x60 MW and 2x140 MW are considered. The RBTS must commit 5 units and System A must commit between 10 to 15 units in order to satisfy the specified EEA criterion. The EEA of the RBTS and System A are

Table 3.9: Unit Commitment and EEA in Interconnected Hypothetical Systems.

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh) Tie-Cap. = 2X15 MW		2X60 MW		2X140 MW	
A	B	A	B	A	B	A	B	A	B	A	B
1400	1400	10	10	1660	1660	59.988	59.988	239.487	239.487	515.291	515.291
1500	1400	10	10	1660	1660	59.395	59.988	236.905	239.487	315.498	515.291
1600	1400	11	10	1760	1660	59.394	59.988	236.786	239.487	315.300	515.291
1700	1400	12	10	1860	1660	59.394	59.988	236.667	239.487	315.103	515.291
1800	1400	13	10	1980	1660	59.840	59.988	237.027	239.487	354.653	515.291
1900	1400	14	10	2080	1660	59.839	59.988	236.930	239.487	354.415	515.291
2000	1400	15	10	2180	1660	59.838	59.988	236.834	239.487	354.178	515.291

SSR = 0.01, EEA Index = 50 MWh
A = System A(Lead Time = 2 hours)
B = System B(Lead Time = 2 hours)

identical at a tie capacity of 2x15 MW. This is due to the fact that even though System A is larger than the RBTS its assistance is constrained by the tie capacity. The EEA of the RBTS and System A increase when the tie capacity is increased from 2x15 MW to 2x60 MW. The EEA of the RBTS is 119.655 MWh and that of System A is 239.487 MWh at a tie capacity of 2x60 MW. The EEA in the two systems are of different order. This is due to the fact that the RBTS is a small system with unit sizes smaller than those of System A. The EEA of the RBTS becomes saturated even though the tie lines have more room to transfer assistance. The RBTS can satisfy a specified EEA index of up to 119.615 MWh with the unit commitments shown in Table 3.10 if the tie capacity is 2x60 MW. System A with the unit commitments shown in the Table 3.10 and with a tie capacity of 2x60 MW, on the other hand, can satisfy an EEA index of up to 239.487 MWh. The RBTS can, however satisfy an EEA index higher then 119.655 MWh by commiting more units. The EEA of the RBTS can go upto a level of 239.70 MWh with the addition of 4 more units if the tie capacity remain unchanged at 2x60 MW (Table 3.8.2., page 64). The EEA of the RBTS remain unchanged and the EEA of System A increases when the tie capacity is increased from 2x60 MW to 2x140 MW. At a tie capacity of 2x140 MW, the EEA of System A varies from 315.103 MWh to 515.291 MWh while that of the RBTS remains fixed at 119.655 MWh. This is due to the fact that System A's units are much larger than those of the RBTS and, therefore, System A can better utilize the increased tie capacity resulting in an increased EEA without having to commit additional unit(s).

Table 3.10: Unit Commitment and EEA in Interconnected RBTS and System A.

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance(MWh)					
						Tie-Cap. =					
						2X15 MW		2X60 MW		2X140 MW	
1	2	1	2	1	2	1	2	1	2	1	2
100	1400	5	10	160	1660	59.924	59.988	119.655	239.487	119.655	515.291
100	1500	5	10	160	1660	59.924	59.988	119.655	239.487	119.655	315.498
100	1600	5	11	160	1660	59.924	59.988	119.655	239.487	119.655	315.300
100	1700	5	12	160	1660	59.924	59.988	119.655	239.487	119.655	315.103
100	1800	5	13	160	1660	59.924	59.988	119.655	239.487	119.655	354.653
100	1900	5	14	160	1660	59.924	59.988	119.655	239.487	119.655	354.415
100	2000	5	15	160	1660	59.924	59.988	119.655	239.487	119.655	354.178

SSR = 0.01, EEA Index = 50 MWh
1 = RBTS(Lead Time = 2 hours)
2 = System A(Lead Time = 2 hours)

3.5. Summary

The development of a technique called 'Expected Energy Assistance (EEA)' is illustrated in this chapter. The technique can be utilized to assess spinning reserve requirements in interconnected generating systems. An energy based index is appropriate for an equitable sharing of spinning reserve between interconnected systems. The unit commitment and EEA are evaluated for the interconnected RBTS and a hypothetical system with and without the EEA criterion and results are presented. Effect of tie capacity variation on the proposed technique is discussed and results are presented.

4. APPLICATION TO TEST SYSTEMS

4.1. Introduction

Reliability test systems provide useful references for testing and comparing alternate techniques for power system reliability evaluation. Numerical examples of spinning reserve assessment utilizing the expected energy assistance technique are provided in this chapter. Two reliability test systems, the IEEE-RTS and the RBTS are utilized to provide numerical results. The IEEE-RTS contains a reasonably large power network which is valuable in highlighting and comparing the capabilities of computer programs used in reliability studies. The RBTS is a small system compared to the IEEE-RTS and is mentioned in Section 3.3.1.

4.2. Application to The Identical IEEE-RTS

The IEEE-RTS was developed in 1979 by the IEEE Task Force [16]. The single line diagram of the 24 bus IEEE-RTS is shown in Figure 4.1. The system has 10 generator buses, 10 load buses, 33 transmission lines, 5 transformers and 32 generating units. The unit sizes range between 12 MW and 400 MW. The system peak load is 2850 MW and the total generation is 3405 MW. The generation data for the IEEE-RTS are given in Table 4.1.

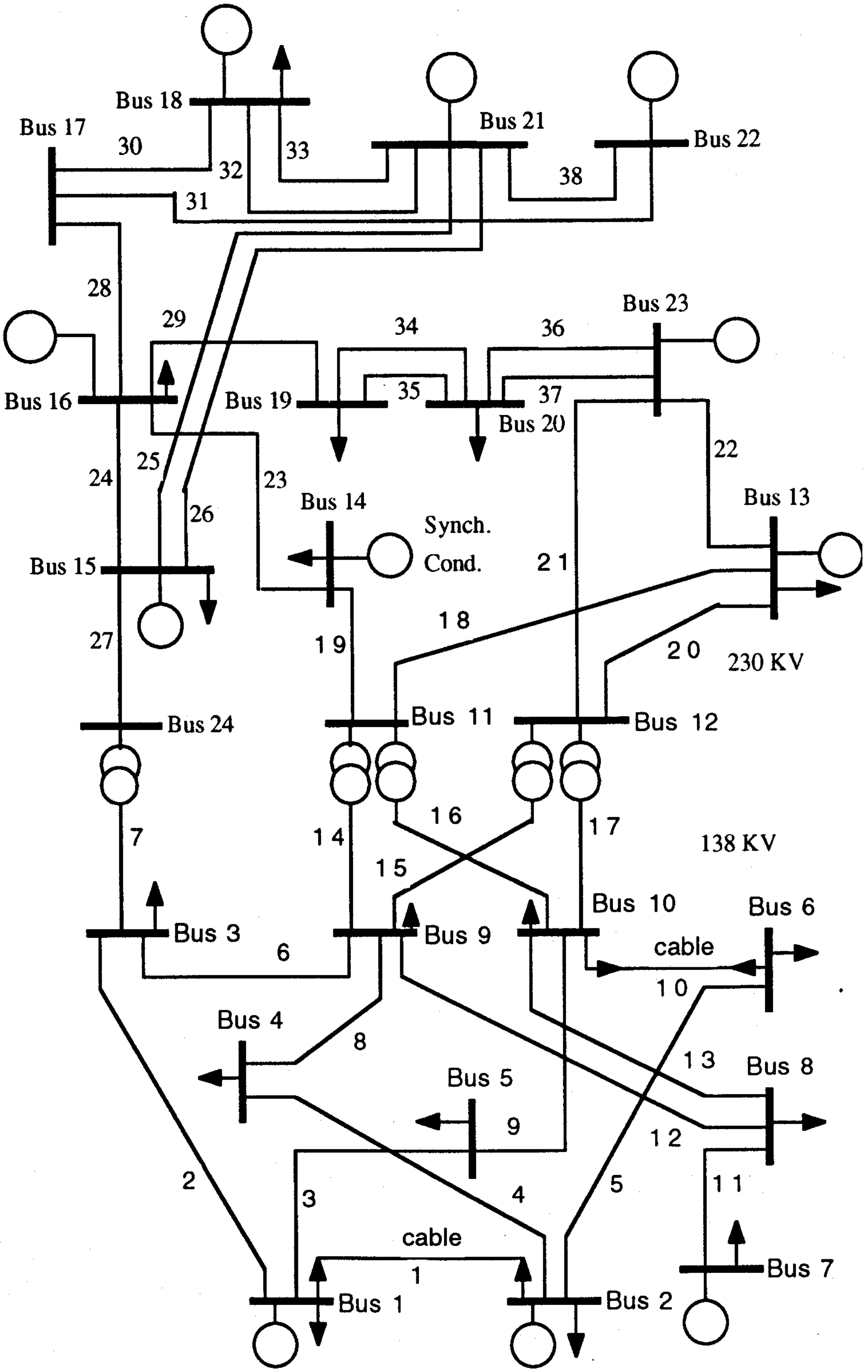

Figure 4.1: Single Line Diagram of the IEEE-RTS.

Table 4.1: Generation Data for the IEEE-RTS.

Unit Type	Unit Size (MW)	Number of Units	Priority Loading Order	Failure Rate (f/Yr)
Hydro	50	4	1-4	4.42
Nuclear	400	2	5-6	7.96
Thermal	350	1	7	7.62
Thermal	197	3	8-10	9.22
Thermal	155	4	11-14	9.13
Thermal	100	3	15-17	7.3
Thermal	76	4	18-21	4.47
Thermal	12	5	22-26	2.98
Thermal	20	4	27-30	19.47
Hydro	50	2	31-32	4.42

Consider two systems IEEE-RTS A and IEEE-RTS B, identical to the IEEE-RTS. IEEE-RTS A and IEEE-RTS B are interconnected through two tie lines. The tie capacity is 2x100 MW and the failure rate of each tie line is one failure per year. The lead times for both IEEE-RTS are 2 hours. The load in IEEE-RTS A is varied from 2000 MW to 2600 MW in steps of 100 MW. The load in IEEE-RTS B is held constant at 2000 MW. Table 4.2 shows the unit commitment and EEA for a specified EEA index of 350 MWh. In order to meet the EEA criterion, IEEE-RTS A must commit 12 to 17 units and IEEE-RTS B must commit 12 units. The EEA of IEEE-RTS A varies between 393.051 MWh to 396.051 MWh and the EEA of IEEE-RTS B is fixed at 395.120

Table 4.2: Unit Commitment and EEA in Interconnected IEEE-RTS.

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)	
A	B	A	B	A	B	A	B
2000	2000	12	12	2251	2251	395.120	395.12
2100	2000	13	12	2406	2251	396.051	395.12
2200	2000	13	12	2406	2251	393.051	395.12
2300	2000	14	12	2561	2251	394.548	395.12
2400	2000	15	12	2661	2251	394.416	395.12
2500	2000	16	12	2761	2251	394.283	395.12
2600	2000	17	12	2861	2251	394.151	395.12

SSR = 0.01, EEA Index = 350 MWh, Tie-Cap. = 2x100 MW

A = IEEE-RTS A(Lead Time = 2 hours)

B = IEEE-RTS B(Lead Time = 2 hours)

Table 4.3 shows the unit commitment and the corresponding EEA for the identical IEEE-RTS keeping all the factors unchanged except the tie capacity. The tie capacity is increased to 3x100 MW. The unit commitments in both the IEEE-RTS remain unchanged from those shown in Table 4.2 while the EEA of both the IEEE-RTS increases with the increase in tie capacity from 2x100 MW to 3x100 MW. It is apparent from Table 4.3 that both systems can satisfy an EEA index of 404 MWh for the given conditions.

Table 4.3: Unit Commitment and EEA in Interconnected IEEE-RTS.

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)	
A	B	A	B	A	B	A	B
2000	2000	12	12	2251	2251	495.063	495.063
2100	2000	13	12	2406	2251	592.124	495.063
2200	2000	13	12	2406	2251	404.944	495.063
2300	2000	14	12	2561	2251	513.670	495.063
2400	2000	15	12	2661	2251	513.340	495.063
2500	2000	16	12	2761	2251	513.009	495.063
2600	2000	17	12	2861	2251	512.678	495.063

SSR = 0.01, EEA Index = 350 MWh, Tie-Cap. = 3x100 MW

A = IEEE-RTS A(Lead Time = 2 hours)

B = IEEE-RTS B(Lead Time = 2 hours)

4.3. Application to The Interconnected RBTS and IEEE-RTS

Consider that two systems of different sizes, the RBTS and the IEEE-RTS, are interconnected through two tie lines. The lead times for both systems are 2 hours. The capacity of each tie line is 2x60 MW with a failure rate of one failure per year. Table 4.4 shows the unit commitments and EEA in both systems. The load in the RBTS is varied from 100 MW to 160 MW in steps of 10 MW. The load in the IEEE-RTS is kept constant at 2000 MW. The RBTS must commit 5 to 9 units and the IEEE-RTS must commit 12 units in order to satisfy the specified EEA index of 100 MWh. The EEA of the RBTS varies from 119.569 MWh to 139.632 MWh and that of the IEEE-RTS remain fixed at 237.656 MWh.

Table 4.4: Unit Commitment and EEA in Interconnected RBTS and IEEE-RTS.

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)	
1	2	1	2	1	2	1	2
100	2000	5	12	160	2251	119.655	237.656
110	2000	6	12	180	2251	139.632	237.656
120	2000	6	12	180	2251	119.609	237.656
130	2000	7	12	190	2251	119.591	237.656
140	2000	8	12	210	2251	139.592	237.656
150	2000	8	12	210	2251	119.569	237.656
160	2000	9	12	230	2251	139.570	237.656

SSR = 0.01, EEA Index = 100 MWh, Tie-Cap. = 2x60 MW

1 = RBTS A(Lead Time = 2 hours)

2 = IEEE-RTS(Lead Time = 2 hours)

Consider that the tie capacity is increased from 2x60 MW to 2x80 MW keeping all other factors same. Table 4.5 shows the unit commitments and the EEAs of both systems. The unit commitments in both systems remain unchanged from those shown in Table 4.5. The EEA of the RBTS basically remains the same and that of the IEEE-RTS increases from 237.656 MWh to 316.388 MWh. This is due to the fact that the IEEE-RTS is a large system and can utilize the increased tie capacity without having to commit additional unit(s).

Table 4.5: Unit Commitment and EEA in Interconnected RBTS and IEEE-RTS.

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)	
1	2	1	2	1	2	1	2
100	2000	5	12	160	2251	119.655	316.388
110	2000	6	12	180	2251	139.605	316.388
120	2000	6	12	180	2251	119.609	316.388
130	2000	7	12	190	2251	119.591	316.388
140	2000	8	12	210	2251	139.564	316.388
150	2000	8	12	210	2251	119.569	316.388
160	2000	9	12	230	2251	139.543	316.388

SSR = 0.01, EEA Index = 100 MWh, Tie-Cap. = 2x80 MW

1 = RBTS A(Lead Time = 2 hours)

2 = IEEE-RTS(Lead Time = 2 hours)

Tables 4.6 and Table 4.7 show the results of unit commitments and the EEAs when the load in the RBTS is kept constant at 100 MW and the load in the IEEE-RTS is varied from 2000 MW to 2600 MW. A tie capacity of 2x60 MW is utilized to provide the numerical results shown in Table 4.6. Table 4.7 shows the unit commitments in the RBTS and IEEE-RTS when the tie capacity is increased to 2x80 MW. In both cases, the RBTS must commit 5 units and IEEE-RTS must commit 12 to 17 units in order to satisfy the EEA criterion. Table 4.6 shows that the EEA of the RBTS is constant at 119.655 MWh and the EEA of IEEE-RTS varies between 236.442 MWh to 237.738 MWh. The EEA of IEEE-RTS increases with the increase in tie capacity to 2x80 MW as shown in Table 4.7. The EEA of IEEE-RTS varies between 314.979 MWh to 317.482 MWh and that of the RBTS remain unchanged at 119.655 MWh.

Table 4.6: Unit Commitment and EEA in Interconnected RBTS and IEEE-RTS.

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)	
1	2	1	2	1	2	1	2
100	2000	5	12	160	2251	119.655	237.656
100	2100	5	13	160	2406	119.655	238.534
100	2200	5	13	160	2406	119.655	236.442
100	2300	5	14	160	2561	119.655	237.738
100	2400	5	15	160	2661	119.655	237.734
100	2500	5	16	160	2761	119.655	237.730
100	2600	5	17	160	2861	119.655	237.725

SSR = 0.01, EEA Index = 100 MWh, Tie-Cap. = 2x60 MW

1 = RBTS A(Lead Time = 2 hours)

2 = IEEE-RTS(Lead Time = 2 hours)

Table 4.7: Unit Commitment and EEA in Interconnected RBTS and IEEE-RTS.

Load (MW)		Number of Units		Spinning Capacity (MW)		Expected Energy Assistance (MWh)	
1	2	1	2	1	2	1	2
100	2000	5	12	160	2251	119.655	316.388
100	2100	5	13	160	2406	119.655	317.482
100	2200	5	13	160	2406	119.655	314.979
100	2300	5	14	160	2561	119.655	316.143
100	2400	5	15	160	2661	119.655	316.138
100	2500	5	16	160	2761	119.655	316.133
100	2600	5	17	160	2861	119.655	316.127

SSR = 0.01, EEA Index = 100 MWh, Tie-Cap. = 2x80 MW

1 = RBTS A(Lead Time = 2 hours)

2 = IEEE-RTS(Lead Time = 2 hours)

4.4. Summary

This chapter has presented the application of the EEA technique to the RBTS and the IEEE-RTS. The EEA criterion has been used to assess the sharing of spinning reserve between two identical IEEE-RTS. Results have also been presented for interconnected systems of different sizes by utilizing the RBTS as a small system and the IEEE-RTS as a large system. The results of interconnected RBTS and IEEE-RTS have been discussed.

5. SPINNING RESERVE WITH EXPORT/IMPORT

5.1. Introduction

Energy transfer and spinning reserve sharing between interconnected utilities are governed by some sort of agreements. Interconnection agreements usually, among other things, specify the minimum spinning reserve requirements and outline mutual standby conditions. In the event of a scheduled energy transfer, the effective tie capacity for spinning reserve assistance is reduced. The tie capacity, left after the scheduled export/import, can be utilized to transfer spinning reserve in the case of a sudden generation loss or a capacity deficiency. The EEA technique can be utilized to assess the spinning reserve requirements in interconnected systems with export/import constraints. Export/import agreement between interconnected utilities may take one of the following forms.

1. Firm purchase backed up by the entire system.

2. Firm purchase is tied to a specific unit in the exporting system.

3. Emergency power contracts.

Many other forms of agreements between different utilities exist and it is not possible to consider all of these exhaustively. In this thesis, it is assumed that the export/import between interconnected systems is backed up by the entire system.

5.2. Export/Import With Firm Purchase Backed Up by The Entire System

In this type of contract, the exporting system will meet its commitment to the importing system essentially as if it were part of its system load. The exporting system will not only supply the power under normal conditions, but will also maintain adequate reserve to assure a continuous supply of energy to the importing system under adverse conditions. The export can be modelled as an additional load as far as the exporting system is concerned, and in the importing system the import can be modelled as an equivalent generating unit with an effective zero forced outage rate [17].

An equivalent load can be utilized in order to take export/import into consideration. Assume that

L_i = load of System i,

I_{ij} = import of System i from System j,

E_{ij} = export of System i to System j,

T_{ij} = tie-line capacity between System i and System j and

L_{ei} = effective load in System i .

The load in the exporting system is modified by its export commitments and the load in the importing system is effectively reduced by its import. The effective load can be expressed as,

$$L_{ei} = L_i + \sum_{j=1}^{n} E_{ij} - \sum_{j=1}^{n} I_{ij} \ ,(j \neq i) . \qquad (5.1)$$

For the sake of simplicity, a two interconnected system case is presented in this thesis. For two interconnected systems, Equation 5.1 can be written as

$$L_{ei} = L_i + E_{ij} - I_{ij} . \qquad (5.2)$$

$L_{ei} = L_i + E_{ij}$, if System i is the exporting system.

$L_{ej} = L_j - I_{ji}$, if System j is the importing system.

Once the effective load is found, required number of units are committed in each system such that the specified SSR criterion is satisfied. Assistance model is formed by subtracting the effective load from the capacity model of the system. If the import of System j is completely backed up by System i (exporter) and the tie lines are 100% reliable, the generation model of System j will be modified by the additional generating unit of capacity equal to the import from System i with a forced outage rate of zero.

The following sections present mathematical details of models utilized to assess spinning reserve requirements in interconnected generation systems with export/import constrains.

5.2.1. Assistance model

The number of units required to satisfy the single system risk criterion in an interconnected system is determined for a given load and export/import commitment(s). The committed units are added to form an equivalent multi-state unit in the form of a capacity outage probability table. An assistance model is obtained by subtracting the effective load from the capacity outage probability table. The assistance model is a two dimensional array representing the magnitude of assistance and the corresponding probability of assistance.

Assume that

$X_i^k(t)$ = K^{th} generation capacity state at time t in System i,

$P_i^k(t)$ = probability that the K^{th} generation capacity exists in System i at time t,

$C_i^k(t)$ = cumulative probability of $X_i^k(t)$.

The capacity outage probability table is arranged in such a way that,

$X_i^{k-1}(t) > X_i^k(t)$, k= 1,2,.....,n

n = total no. of capacity states in the capacity outage probability table.

$G_i^k(t)$ = K^{th} capacity state of the unconstrained model of System i

Assistance

at time t,

$PR_i^k(t)$ = probability that the Kth capacity state of the unconstrained assistance model of System i exists at time t,

m_u = total no. of capacity states in the unconstrained assistance model.

The unconstrained assistance model is obtained in such a way that,

if $L_{ei} \le X_i^k(t)$ then

$$\left.\begin{aligned} G_i^k(t) &= X_i^k(t) - L_{ei} \\ PR_i^k(t) &= P_i^k(t) \end{aligned}\right\} k= 1,2,.....,\alpha$$

where a is an integer such that $X^{\alpha}(t) > L_{ei} \ge X^{\alpha+1}(t)$,

$$G_i^{\alpha+1}(t) = 0$$

$$PR_i^{\alpha+1}(t) = C_i^{\alpha+1}(t) .$$

If $L_{ei} \ge X_i^k(t)$, no assistance from System i is possible.

5.2.2. Export/Import constrained tie-line model

Let

$B_{ij}^k(t)$ = Kth capacity state of the tie line between System i and System j at time t,

$D_{ij}^{k}(t)$ = probability that the K^{th} state of the tie-line between System i and System j exists at time t,

n_t = total no.of capacity states in the tie-line model and

$$B_{ij}^{k-1}(t) > B_{ij}^{k}(t),\ k= 1,2,\ldots\ldots,n_t .$$

Also assume that

$R_{ij}^{k}(t)$ = K^{th} capacity state of the export/import constrained tie line between System i and System j at time t,

$S_{ij}^{k}(t)$ = probability that the K^{th} capacity state of the export/import constrained tie line between System i and System j exists at time t,

m_t = total no. of capacity states in the export/import constrained tie line model and

$$R_{ij}^{k-1}(t) > R_{ij}^{k}(t),\ k= 1,2,\ldots\ldots,m_t .$$

Then

$$\left.\begin{aligned} R_{ij}^{k}(t) &= B_{ij}^{k}(t) - E_{ij} - I_{ji} \\ S_{ij}^{k}(t) &= D_{ij}^{k}(t) \end{aligned}\right\} k= 1,2,\ldots\ldots,\gamma$$

where γ is an integer such that $B_{ij}^{\gamma}(t) > I_{ji} \geq B_{ij}^{\gamma+1}(t)$ or

$$B_{ij}^{\gamma}(t) > E_{ij} \geq B_{ij}^{\gamma+1}(t).$$

$$R_{ij}^{\gamma+1}(t) = 0$$

$$S_{ij}^{\gamma+1}(t) = \sum_{k=\gamma+1}^{n_t} D_{ij}^{k}(t)$$

$$m_t = \gamma + 1$$

5.2.3. Tie-Line and export/import constrained assistance Model

Assistance between System i and System j is influenced by the unavailability of the tie line. The assistance model can be modified by the tie line unavailability after the export/import is considered. There are two distinct cases,

a) when the tie capacity is less than or equal to the assistance equivalent unit and

b) when the tie capacity is greater than the assistance equivalent unit.

Assume that

$U_{ij}^{k}(t) = K^{th}$ capacity state of the tie line and export/import constrained assistance from System i to System j at time t,

$V_{ij}^{k}(t)$ = probability that the K^{th} capacity state of the tie line and export/import constrained assistance exists at time t,

l_t = total no. of capacity states in the tie line and export/import constrained assistance model and

$$U_{ij}^{k-1}(t) > U_{ij}^{k}(t),\ k= 1,2,.....,l_t\ .$$

Case a): $G_i^{1}(t) \le R_{ij}^{1}(t)$

$$U_{ij}^{\beta}(t) = G_i^{k}(t), \quad G_i^{k}(t) \le R_{ij}^{k_1}(t)$$

$$= R_{ij}^{k_1}(t), \quad G_i^{k}(t) > R_{ij}^{k_1}(t)$$

$$V_{ij}^{\beta}(t) \ = \ PR_i^{k}(t) * S_{ij}^{k_1}(t)$$

Where $k = 1,2,.....,m_u$

$k_1 = 1,2,.....,m_t$

$\beta = 1,2,.....,m_u * m_t$

Capacity states of the tie line constrained assistance model are rearranged in an ascending order and the probabilities of identical capacity states are added together.

Case b): $G_i^1(t) > R_{ij}^1(t)$

$$U_{ij}^1(t) = R_{ij}^1(t)$$

$$V_{ij}^1(t) = \sum PR_i^m(t) * S_{ij}^k(t)$$

where m is an integer such that $G_i^m(t) \geq R_{ij}^1(t) > G_i^{m+1}(t)$

$$\left.\begin{aligned} U_{ij}^{m+1}(t) &= G_i^{m+1}(t) \\ V_{ij}^{m+1}(t) &= PR_i^{m+1}(t) * S_{ij}^k(t) \end{aligned}\right\} k = 1,2,\ldots\ldots,m_t$$

5.3. Unit Commitment in the interconnected RBTS With Export/Import

Two identical RBTS namely RBTS A and RBTS B are considered as interconnected by two lines. The generation data of the RBTS are given in Table 2.10 (Section 2.5.1). The tie line data are shown in Table 5.1. The lead times for both the RBTS are considered to be 2 hours. The units are committed in both RBTS with a specified SSR of 0.01 and a specified EEA index of 50 MWh. The effective load viewed by a system is modified by the export/import.

Table 5.1: Tie-Line Data.

Number of Tie-Lines	Capacity of Each Line (MW)	Failure Rate (occ/~~y~~hr)
2	60	0.00011415

hr

Assume that the load in the RBTS A is 185 MW and that in the RBTS B is 170 MW.

$L_a = 185$ MW, $E_{ab} = 20$ MW, $I_{ab} = 0$.

The effective load in the RBTS A is

$L_{ea} = L_a + E_{ab} - I_{ab} = 195$ MW .

In order to meet the specified SSR, the RBTS A must commit 8 units. The assistance model for the RBTS A is shown in Table 5.2.

Table 5.2: Assistance Model of the RBTS A.

Capacity Out (MW)	Capacity In (MW)	Probability
0	30	0.9919009
5	25	0.0004525
10	20	0.0009074
15	15	0.0000004
20	10	0.0033095
25	5	0.0000015
30	0	0.0034275

The tie line model for a period of 120 minutes is shown in Table 5.3.

Table 5.3: Tie-Line Model.

Capacity Out (MW)	Capacity In (MW)	Probability
0	120	0.9995435
60	60	0.0004565
120	0	0

The export/import constrained tie-line model is shown in Table 5.4.

Table 5.4: Export/Import Constrained Tie-Line Model.

Capacity Out (MW)	Capacity In (MW)	Probability
0	100	0.9995435
60	40	0.0004565
100	0	0

The EEA of the RBTS A to the RBTS B is evaluated by utilizing the tie-line and export/import constrained assistance model shown in Table 5.5. The EEA of the RBTS A is 49.655 MWh. The RBTS A must commit 10 units in order to satisfy the EEA criterion. The EEA of the RBTS A to the RBTS B with 10 committed units is 59.612 MWh.

Table 5.5: Tie-Line and Export/Import Constrained Assistance Model of the RBTS A.

Capacity Out (MW)	Capacity In (MW)	Probability
0	25	0.9919004
10	15	0.0009074
20	5	0.0033095
25	0	0.0038825

Expected Energy Assistance (EEA) = 49.655 MWh

The RBTS B is importing 20 MW from the RBTS A. The load of the RBTS B is modified by its import.

$L_b = 170$ MW, $E_{ba} = 0$, $I_{ba} = 20$ MW.

The effective load of the RBTS B is

$L_{eb} = L_b + E_{ba} - I_{ba} = 150$ MW.

In order to meet the specified SSR, the RBTS B must commit 5 units. The assistance model for the RBTS B is shown in Table 5.6.

Table 5.6: Assistance Model of the RBTS B.

Capacity Out (MW)	Capacity In (MW)	Probability
0	30	0.9943508
20	10	0.0022272
30	0	0.0034218

Table 5.7 shows the tie line model for a period of 120 minutes and Table 5.8 shows the export/import constrained tie-line model.

Table 5.7: Tie-Line Model.

Capacity Out (MW)	Capacity In (MW)	Probability
0	120	0.9995435
60	60	0.0004565
120	0	0

Table 5.8: Export/Import Constrained Tie-Line Model.

Capacity Out (MW)	Capacity In (MW)	Probability
0	100	0.9995435
60	40	0.0004565
100	0	0

The EEA of the RBTS B to the RBTS A is evaluated by utilizing the tie-line and export/import constrained assistance model shown in Table 5.9. The EEA of the RBTS B is 19.901 MWh. The RBTS B must commit 6 units in order to satisfy the EEA criterion. The EEA of the RBTS B to the RBTS A with 6 committed units is 59.678 MWh.

Table 5.9: Tie-Line and Export/Import Constrained Assistance Model of the RBTS B.

Capacity Out (MW)	Capacity In (MW)	Probability
0	10	0.9950333
10	0	0.0049667

Expected Energy Assistance (EEA) = 19.901 MWh

5.4. Unit Commitment in the interconnected IEEE-RTS and the RBTS With Export/Import

Consider two systems of different sizes, the IEEE-RTS mentioned in Section 4.2 and the RBTS. The data for the tie lines between the IEEE-RTS and the RBTS are given in Table 5.1. The lead times for both systems are 2 hours. Units in both systems are committed in such a way that both systems satisfy a specified SSR of 0.01 and an EEA index of 60 MWh.

Assume that the load in the IEEE-RTS is 2500 MW and that in the RBTS is 160 MW.

$L_a = 2500$ MW, $E_{ab} = 60$ MW, $I_{ab} = 0$.

The effective load in the IEEE-RTS is

$L_{ea} = L_a + E_{ab} - I_{ab} = 2560$ MW.

In order to meet the specified SSR, the IEEE-RTS must commit 16 units. The assistance model for the IEEE-RTS is shown in Table 5.10.

Table 5.10: Assistance Model of the IEEE-RTS.

Capacity Out (MW)	Capacity In (MW)	Probability
0	201	0.9729770
50	151	0.0039270
100	101	0.0032533
150	51	0.0000131
155	46	0.0081277
197	4	0.0061544
200	1	0.0000027
201	0	0.0055450

The tie line model for a period of 120 minutes is shown in Table 5.11.

Table 5.11: Tie-Line Model.

Capacity Out (MW)	Capacity In (MW)	Probability
0	120	0.9995435
60	60	0.0004565
120	0	0

The export/import constrained tie-line model is shown in Table 5.12 and the Export/Import constrained assistance model is shown in Table 5.13.

Table 5.12: Export/Import Constrained Tie-Line Model.

Capacity Out (MW)	Capacity In (MW)	Probability
0	60	0.9995435
60	0	0.0004565

Table 5.13: Tie-Line and Export/Import Constrained Assistance Model of the IEEE-RTS.

Capacity Out (MW)	Capacity In (MW)	Probability
0	60	0.9797098
9	51	0.0000131
14	46	0.0081277
56	4	0.0061544
59	1	0.0000027
60	0	0.0059924

Expected Energy Assistance (EEA) = 118.363 MWh

The RBTS is importing 60 MW from the IEEE-RTS. The load of the RBTS is modified by its import.

$L_b = 160$ MW, $E_{ba} = 0$, $I_{ba} = 60$.

The effective load in the RBTS is

$L_{eb} = L_b + E_{ba} - I_{ba} = 100$ MW.

In order to meet the specified SSR, the RBTS must commit 4 units. The assistance model for the RBTS is shown in Table 5.14.

Table 5.14: Assistance Model of the RBTS.

Capacity Out (MW)	Capacity In (MW)	Probability
0	60	0.9954877
20	40	0.0010916
40	20	0.0034130
60	0	0.0000075

Table 5.15 shows the tie line model for a period of 120 minutes and Table 5.6 shows the export/import constrained tie-line model.

Table 5.15: Tie-Line Model.

Capacity Out (MW)	Capacity In (MW)	Probability
0	120	0.9995435
60	60	0.0004565
120	0	0

Table 5.16: Export/Import Constrained Tie-Line Model.

Capacity Out (MW)	Capacity In (MW)	Probability
0	60	0.9995435
60	0	0.0004565

The EEA is evaluated after the tie-line and export/import constraints are considered. The unit commitment in the IEEE-RTS remain unchanged at 16 units in order to satisfy the specified EEA index of 50 MWh. The EEA of the IEEE-RTS to the RBTS is 118.363 MWh. Table 5.17 shows the tie-line and Export/Import constrained assistance model of the RBTS. The EEA of the RBTS is 39.856 MWh. The RBTS must add its 5th unit in order to satisfy the EEA criterion. The EEA of the RBTS to the IEEE-RTS with 5 committed units is 119.628 MWh.

Table 5.17: Tie-Line and Export/Import Constrained Assistance Model of the RBTS.

Capacity Out (MW)	Capacity In (MW)	Probability
0	20	0.9963983
20	0	0.0036016

Expected Energy Assistance (EEA) = 39.856 MWh

Table 5.18 shows the unit commitment and the corresponding EEA in the IEEE-RTS and the RBTS. The tie capacity is 2x60 MW. The lead times for both systems are considered to be 2 hours. Load in the RBTS is 160 MW and the load in the IEEE-RTS 2200 MW. The export from the IEEE-RTS is varied from 20 MW to 80 MW in steps of 20 MW. The IEEE-RTS must commit 14 units for all the export conditions. The RBTS with an import of 20 MW must commit 6 units in order to satisfy the EEA criterion. The unit commitment in the RBTS, however, decreases with a corresponding increase in its import from the IEEE-RTS. The RBTS with an import of 80 MW must commit 4 units in order to satisfy its EEA criterion.

Table 5.18: Unit Commitment and EEA with Export.

Export E_{21} (MW)	Interconnected System			
	Number of Units		Expected Energy Assistance (MWh)	
	1	2	1	2
20	6	14	79.601	198.86
40	5	14	79.646	159.075
60	5	14	119.628	119.292
80	4	14	79.756	79.528

SSR = 0.01, Tie-Cap. = 2X60 MW, EEA index = 50 MWh
1 = RBTS(Lead Time = 2 hours, Load = 160 MW)
2 = IEEE-RTS(Lead Time = 2 hours, Load = 2200 MW)

5.6. Summary

Spinning reserve assessments in interconnected generating systems with export/import constrains are illustrated in this chapter. Required mathematical models for assistances, export/import constrained tie-line and tie-line and export/import constrained assistances are developed utilizing known probabilistic approaches and are discussed in detail. Numerical examples are presented utilizing two reliability test systems.

6. CONCLUSIONS

An increasing number of utilities in North America are becoming interested in incorporating reliability assessment as an important part of their overall planning and operating process. Most utilities use deterministic methods in order to assess spinning reserve requirement; the most frequently used method being a reserve equal to the size of the largest unit. Deterministic techniques can not ensure an equitable sharing of spinning reserve between interconnected systems. Deterministic techniques do not respond to the essential system parameters like forced outage rate, unit size and load in a consistent manner. A probabilistic technique called the 'Two Risks Concept' is utilized to assess spinning reserve requirement in interconnected systems. The 'Two Risks Concept' is a dominantly capacity based technique. The disadvantages of the 'Two Risks Concept' are;

1. it is solely dependent on the verification of the unit commitment risk,
2. it can not take into account the lead time of the system in a consistent manner.

In this thesis, a new probabilistic method has been presented for the determination of spinning reserve requirements in interconnected generating systems. This method, designated as the 'Expected Energy

Assistance', evaluates the spinning reserve requirements in interconnected generating systems. The expected energy assistance technique is an energy based approach which incorporates the magnitude and the duration of assistance in its evaluation process. Each interconnected system must satisfy a risk criterion at isolated level. In addition, the expected energy provided by each system to its neighbour must satisfy an EEA criterion at interconnection level. The concepts and application of EEA technique have been discussed in detail in Chapter 3. Expected energy assistance technique handles the unit size and lead time in a direct and consistent manner.

The expected energy assistance increases with an increase in the tie capacity depending upon the size of a system. The tie capacity at which the energy assistance benefit will tend to saturate depends on the set of generating units and the load in the interconnected systems. In systems of dissimilar sizes, the EEA of a relatively smaller system is more likely to become saturated after a certain increase in the tie capacity.

The basic agreement for export/import known as firm purchase backed up by the entire system is considered in this thesis. Export/import of spinning reserve in interconnected generating systems using the expected energy assistance technique has been illustrated. The EEA technique, however, can also be applicable to various export/import agreements.

The development of a new technique for spinning reserve assessment based upon energy assistance is illustrated in this thesis. Although examples of two interconnected systems have been provided in the thesis, the expected energy assistance technique can be applied to multi-area interconnected systems with higher order configuration with little difficulty.

6.1. Future Studies

The expected energy assistance technique presented in the thesis will have considerable impact on spinning reserve policy in interconnected generation systems. It is possible to use an energy based index as a basis for the evaluation of the worth associated with the operating capacity reliability level.

The expected energy assistance technique can be expanded further to include the following.

i) standby units such as rapid start and hot reserve,

ii) effect of load forecast uncertainty and

iii) interruptible loads.

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