

COMPOSITE SYSTEM RELIABILITY EVALUATION

*Thesis submitted in partial fulfillment of the requirements for the award of
degree of*

**Master of Engineering
in
Power Systems & Electric Drives**



Thapar University, Patiala

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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled, "**Composite System Reliability Evaluation**" in partial fulfillment of the requirements for the award of degree of Master of Engineering in Power System & Electric Drives submitted in Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of *Mr. Nitin Narang* and refers other researcher's works which are duly listed in the reference section.

The matter presented in this thesis has not been submitted anywhere for the award of any other degree.

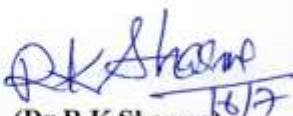

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Dedicated to My Parents

Reliability is old concept and a new discipline. Reliability is, and always has been, one of the major factors in planning, design, operation and maintenance of electric power system. Reliability of an electric supply system has been defined as the probability of providing the user with continuous service of satisfactory quality. Reliability prediction is a method of quantitatively stating what is expected to occur and can be used to indicate the relative merits of alternate design proposals with regard to a predetermined level of performance adequacy.

This thesis deals with reliability evaluation of combined generation and transmission system known as composite system. It describes a technique and a program to calculate composite system reliability and its indices by applying it on a system. Composite system reliability is achieving considerable attention these days as utilities are finding it increasingly necessary to quantitatively evaluate individual busbar and overall system indices. In this research work following reliabilities has been calculated and evaluated for a system:

- Generation system reliability
- Transmission system reliability
- Composite system reliability
- Composite system reliability indices

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INTRODUCTION TO RELIABILITY

1.1 INTRODUCTION

Electricity has been the driving force for economies of the world and provides day-to-day necessity for the population in the world. The generation, transmission and retailing of electricity have existed hundreds of years in providing the much needed electricity. Due to the nature of electricity systems, the variable demand at every moment needs to be met by consistent electricity supply to make sure the continuous availability of the resources. Not meeting the demand in any case will lead to a huge loss of income to the generators as well as to the consumers. The reliability of the generation, transmission and distribution of electricity in this sense is crucial for the continuous supply of electricity to meet the demand.

A modern power system is complex, highly integrated and very large. Fortunately, the system can be divided into appropriate subsystems or functional areas that can be analysed separately [1]. These functional areas are generation, transmission and distribution. The function of the generation system is to make sure that enough capacity is available to meet the load/demand at any time. Transmission and distribution systems need to be reliable in making sure the electricity generated can be delivered to the consumers. System planners have been assigned the role of planning, for forecasting the load into the future and plant capacity addition to meet the load and provide a level of reliability in case some of the plants are out on maintenance or breakdown. Probabilistic method is often used to determine the system reliability and the system reliability can be summed up into a single value.

Reliability studies are conducted for two purposes. Long-term evaluations are performed to assist in system planning and short-term evaluations to assist in day to day operating decisions. In short, these reliability indices (for long-term evaluations) are used by system planners and the authorities to decide on and advice for new investments in building new generation capacities.

1.2 RELIABILITY

The term reliability is broad in meaning. In general, reliability designates the ability of a system to perform its assigned function, where past experience helps to form advance estimates of future performance. A useful definition that illustrates the different dimensions of the concept is the following:

Reliability is the probability of a device or system performing its function adequately, for the period of time intended, under the operating conditions intended [1].

Reliability can be measured through the mathematical concept of probability by identifying the probability of successful performance with the degree of reliability. Generally, a device or system is said to perform satisfactorily if it does not fail during the time of service. On the other hand, a broad range of devices are expected to undergo failures, be repaired and then returned to service during their entire useful life. In this case a more appropriate measure of reliability is the availability of the device, which is defined as follows:

The availability of a repairable device is the proportion of time, during the intended time of service, that the device is in, or ready for service.

The indices used in reliability evaluation are probabilistic and, consequently, they do not provide exact predictions. They state averages of past events and chances of future ones by means of most frequent values and long-run averages. This information should be complemented with other economic and policy considerations for decision making in planning, design and operation.

1.3 POWER SYSTEM RELIABILITY

System reliability is commonly interpreted as the probability of that system staying in the operating state, performing its intended purpose adequately for a period of time without failures under required conditions. The concept of power system reliability is extremely broad and covers all aspects of ability of system to satisfy the customer requirements. The term applied to power system can be subdivided into two domains of adequacy and security assessment [1, 2] as shown in figure 1.1

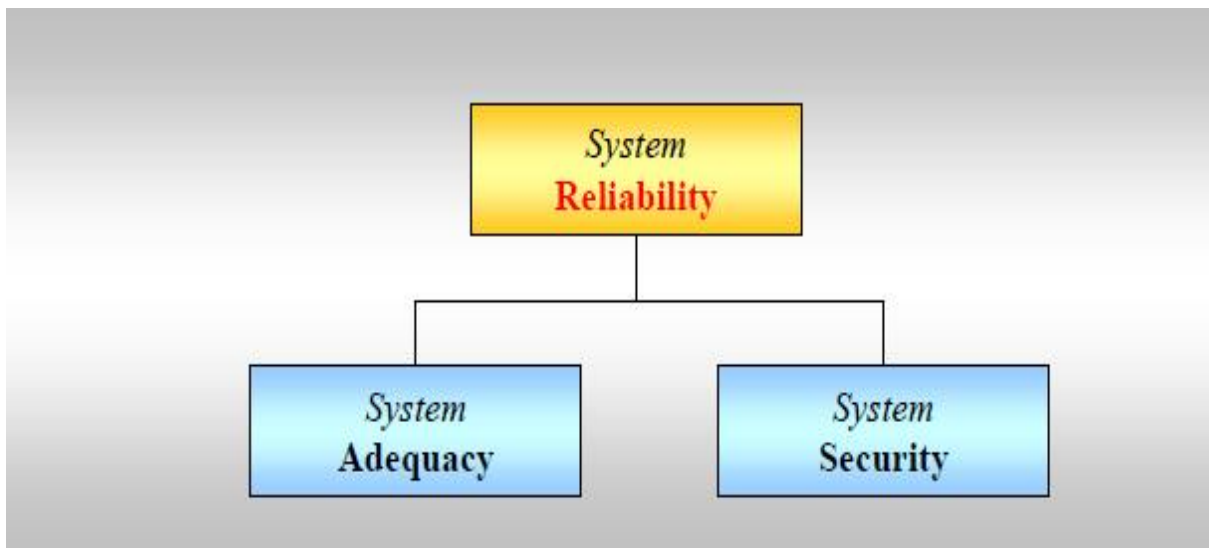


Figure 1.1: Components of system reliability

Adequacy considers the system in static conditions which does not include system disturbances. It relates to the existence of sufficient facilities within the system to satisfy the consumer load demand. This includes necessary facilities to generate sufficient electrical energy and associated transmission and distribution required to transfer energy to actual customer load points. It is the property of having enough capacity to remain secure almost all the time. In terms of generation, an adequate generation system is a matter of installed capacity and ability to meet the annual peak demand with this capacity under normal operating conditions, taking into account scheduled and reasonably forced outages of generators. Adequacy, therefore, involves steady state post outage analysis of power systems.

System Security, on other hand, relates to the ability of the system to withstand sudden perturbations arising within it. This includes the conditions associated with both local and widespread disturbances and loss of major generation and transmission facilities. In terms of generation, generation system security is the capability of the generators in enduring unexpected contingencies involving frequency and voltage any time during system operation. Security is a dynamic measure of response to the unforeseen events. Security, therefore, involves the analysis of both static and dynamic conditions.

Together, adequacy and security provides the overall reliability description of the Power system, which can be broadly described as the ability to supply the quantity and quality of electricity desired by the customer when it is needed.

1.3.1 Functional Zones and Hierarchical Levels

Modern power systems in developed countries are usually very large highly integrated and complex. The numerous numbers of components and the complex interrelations between them makes evaluation of the overall system extremely tricky as it would require very complicated analytical models. These models are not impossible to build but they are extremely difficult to develop and would require excessive computing time. Furthermore, the results obtained are likely to be so vast that meaningful interpretation will be difficult.

Due to these characteristics, power systems are normally divided into three main functional zones, namely generation, transmission and distribution system. Typically, the zones are evaluated separately for better measures of reliability in terms of making appropriate assumptions and flexibility in failure criteria selection. They can then be combined into higher hierarchical levels to convey a more wholesome performance of the system. Power system can be divided into three hierarchical levels [1-3] which are shown in figure 1.2 they are:

- First level (HL I) containing the equipment and units generating electricity;
- Second level (HL II) containing both the units and equipment for generation and transmission of electricity
- Third level (HL III) containing whole system, including distribution.

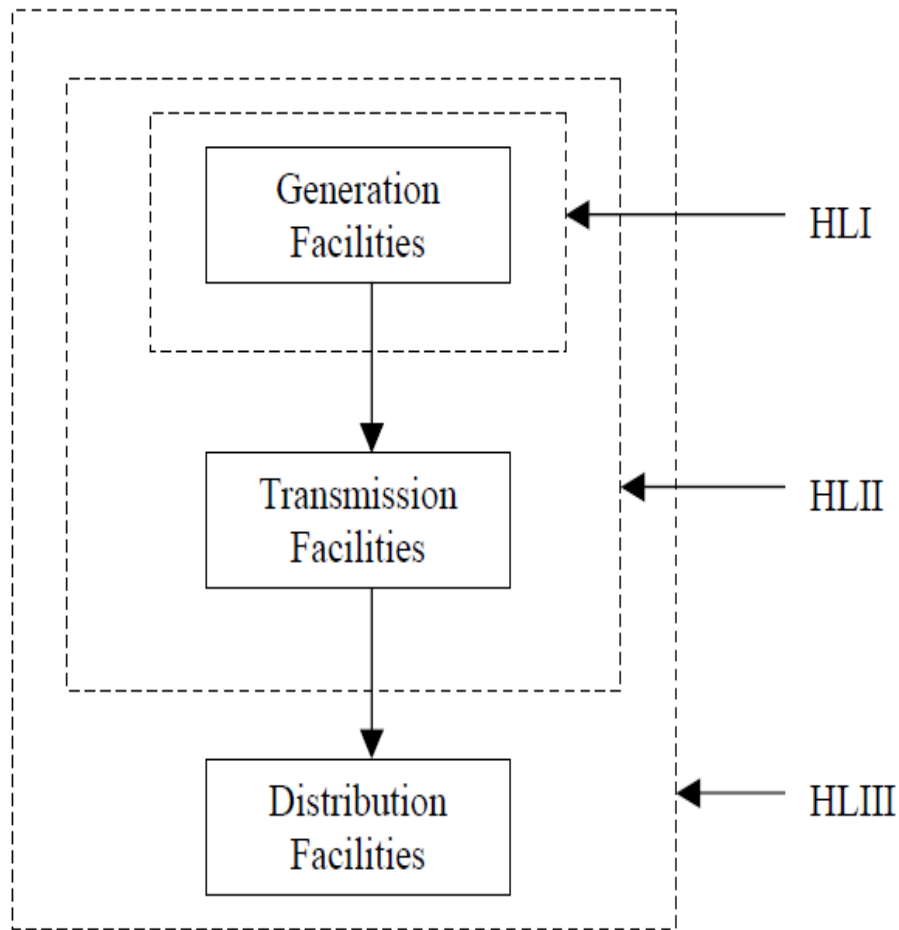


Fig 1.2: Functional zones and Hierarchical level

Adequacy evaluation at HL1 is concerned with only the adequacy of generation to meet the system load requirement and this area of activity is usually termed as generating capacity reliability evaluation. Both generation and associated transmission facilities are considered at HLII adequacy assessment and is sometimes referred to as composite system or bulk system adequacy evaluation. HLIII adequacy assessment involves the consideration of all three functional zones in an attempt to evaluate customer load point adequacies. Therefore, Evaluation of HLIII is therefore termed as overall power system adequacy assessment. The reliability indices calculated at each hierarchical level are physically different. System reliability is usually predicted using one or more indices which quantify expected system reliability performance and

is implemented using criteria based on acceptable value of these indices. The research work described in this thesis is focused on reliability evaluation at HLII.

The following remarks are important when assessing the reliability of the entire power system:

- The actual degree of reliability experienced by a customer will vary from location to location. Different functional areas may offer different degrees of reliability.
- There should be uniformity between the reliability of various parts of the system. It is useless to strongly reinforce a part if weaker areas exist on the supply chain.
- In deregulated systems, efficient pricing mechanisms for transmission and distribution must consider a reliability component.

1.4 RELIABILITY EVALUATION

Electric power networks are good examples of reliable systems. In many power systems the average duration of interruptions experienced by a customer is just a few hours per year, which translates into high availability of power supply. In general, to ensure these levels of supply availability, the probability of load being disconnected for any reason is reduced by introducing redundancy in the system. For decades, satisfactory levels of reliability were achieved through empirical methods and policies. However, as systems grew larger and more complex, formal, more rigorous analytical techniques have been applied.

The first techniques used were all deterministic. Typical criteria included planning generation margins equal to a fixed percentage of the forecast peak demand and operating generation margins sufficient to cover the most likely contingencies. Additionally, network capacity is usually installed to meet the N-1 or N-2 criteria, which requires the system to operate with one or maximum two elements out of service. An important shortcoming of these methods is that they do not account for the stochastic nature of system behavior. Indeed, randomly occurring or probabilistic events in the system are easy to recognize: forced outages of generating units, failure of overhead lines, and uncertainty in customer demand.

Probabilistic methods can provide more meaningful information to be used in design and resource in planning and allocation. There are two main approaches [5] for probabilistic evaluation of power systems reliability: analytical methods and Monte Carlo simulation. Analytical techniques represent the system by mathematical models and use direct analytical solutions to evaluate a priori reliability indices from the model. Monte Carlo simulation estimates a posteriori reliability indices by simulating the actual random behavior of the system. Whichever approach is used, the predicted indices are as good as the derived models, the relevance of each technique and the quality of the data.

Reliability studies are conducted for two purposes. First, long-term evaluations are performed to assist in system planning. Secondly, short-term evaluations assist in day to day operating decisions.

1.5 LITERATURE SURVEY

It may be surprising to note that the application of probability methods in power system came into prominence only in last three decades. Considering that the industry itself is over one hundred years old and that discussions on probability concepts appeared in Italian manuscripts as early as 1380. Probabilistic reliability assessment different functional zones and hierarchical levels has undergone considerable development since the 1930's. These development can be seen from bibliographies [6-11] published in IEEE transactions, which contain more than 900 papers on probabilistic reliability evaluation of power systems. The first significant paper on power system reliability evaluation appeared in 1947 (Calabrese, 1947; Lyman, 1947; Seelye, 1947; Loane and Watchorn, 1947) [6]. The first book written in English on application of probabilistic methods in power system studies was published in 1970 by Billinton [6]. Since then, several books on power system reliability theory and application has been printed [6-10]. Probability methods are now routinely applied in power system design, planning and operation. The many excellent publications [6-10] clearly indicate the increasing usage and interest in application of probability methods in evaluation of power system reliability.

A considerable number of papers have been published on static generating capacity reliability evaluation and the historical development which led to techniques in use at the present time is very interesting. Although it is rather difficult to determine just when the first published material appeared, it is safe to say that it was at least sixty years ago [6]. Interest in the application of probability to generating capacity requirement become evident about 1933, but it was not until 1947 that the first group of papers was published. This group presents some of basic concepts upon which the methods in use at present time are based. The effect of interconnections were first discussed in 1950 (Waterchorn, 1950; Calabrese, 1951) [6]. several excellent papers appeared each year until in 1958 a second group of papers which extend and modify the 1947 group and also introduced a more sophisticated approach to problem using simulation techniques. The initial approach to calculation of outage frequency and duration indices in generating capacity reliability evaluation was presented in 1947 and was modified in a series of papers by inclusion of recursive algorithm [6]. the load model used in static generating system reliability evaluation was modified to achieve a more realistic representation using daily load curves and a continuously varying factor was introduced in 1972 (Billinton and Singh, 1972) [7]. The PJM method [6] was proposed in 1963 as a means of evaluating the spinning reserve requirement of Pennsylvania-New Jersey-Maryland (PJM) interconnected system. It has been considerably refined and enhanced since then (Billinton and Musick, 1967; Billinton and Bhavaraju, 1968; Patton, 1970-1972; Billinton and Jain, 1971-1973) [6,7] but still remains a basic method for evaluating unit commitment risk.

Several of earlier papers on static generation capacity reliability evaluation included suggestions for numerical reliability criteria for transmission and distribution systems. The development of transmission system reliability evaluation dates from late 1960s in North America and Europe. Prior to this time, the development was mainly focused in the generation area. The initial impetus to the activity in this area can be said to have been provided by two 1964 publications (Todd, 1964; Gaver, Montmeat and Patton, 1964) [6]. The application of Markov process was first implemented in 1968 (Billinton and Bollinger) [6]. The state enumeration approach was first used in 1969 to analyze more complicated systems (Billinton, 1969; Billinton and Bhavaraju, 1970) [6]. The term “composite power system reliability evaluation” was proposed by Billinton in 1969 and an approach for evaluating composite power

system adequacy is described in Reference13. This thesis basically tells us about the various indices which are used for evaluation of HLII which includes both generation and transmission system.

HLIII evaluation, which includes all three functional zones is an overall assessment of customer load point reliability, is not normally done directly due to enormity of problem in practical power system. The overall problem of HLIII reliability evaluation can be quite complex in most systems as it involves starting at generating points and terminating at the individual customer load points. The reliability of distribution system is normally evaluated assuming that bulk system is adequate to provide the required supply. A considerable amount of work has been developed in this area [6-11]. The first attempt to evaluate reliability of distribution systems was in 1954. A series of important selected papers on reliability assessment of electric power systems are presented in reference 1 and 2.

1.6 OBJECTIVE AND SCOPE OF THESIS

From above introduction we can see that there is considerable interest in the application of probability techniques in quantitative evaluation of power system reliability. Reliability evaluation of power systems using probabilistic methods is an important area of concern for system planners and operators. Methods of evaluating the reliability of generating systems have been well established and accepted by the utilities. These techniques do not generally recognize the presence of transmission facilities. So basic Objective and Scope of this thesis is to calculate composite system reliability (HLII). Composite system reliability evaluation refers to assessments that consider both generation and transmission facilities. Reliability evaluation of composite system is concerned with the problem of determining adequacy of combined generation and transmission system in regard to providing a dependable and suitable supply at bulk load points.

The aim of proposed work is to present an overview of method for calculating the reliability of composite generation and transmission system by calculating reliability indices. The primary

objective of this approach is to calculate reliability indices for total system and at every load point in system.

1.7 ORGANIZATION OF THESIS WORK

The work here described is organized in five chapters

Chapter 1 highlights the brief introduction about reliability, its components, its zones and its evaluation. It also presents summary of work carried out by various researchers. Objective and scope of work is also identified and organization of thesis work is also given in this chapter.

Chapter 2 provides a background of generation system reliability and its evaluation methods and gives a description of generating unit reliability modelling process & COPT table. This chapter also presents various types of generation system reliability indices and algorithm for calculating generation system reliability & its indices.

Chapter 3 briefs the concept of composite generation and transmission system reliability and technique for its evaluation. It also describes various composite system reliability indices and algorithm for calculating composite system reliability.

Chapter 4 discusses the results and various types of reliability indices for generation, transmission and composite system. It also discusses the probability and frequency of system failure under different conditions.

Chapter 5 shows the conclusion of this thesis work and discusses the future scope of the work.

GENERATION SYSTEM RELIABILITY

Generation system reliability is an important aspect in the planning for future system capacity expansion. It provides a measurement of reliability or adequacy to make sure that the total generation system capacity is sufficient to provide adequate electricity when needed.

2.1 GENERATION SYSTEM RELIABILITY

Reliability has been and always is one of the major factors in the planning, design, operation, and maintenance of electric power system. Generation system reliability focuses on the reliability of generators in the whole electric power system where electric power is produced from the conversion process of primary energy (fuel) to electricity before transmission. The generation system is an important part of the electricity supply chain and it is crucial that enough electricity is generated at every moment to meet the demand. Generating units will occasionally fail to operate and the system operator has to make sure that enough reserve is available to be operated when this situation happens.

Reliability of the generation system is divided into adequacy and security. System adequacy relates to the existence of sufficient generators within the system to satisfy the consumer load demand or system operational constraints. System adequacy is associated with static conditions of the system and do not include system disturbances. System security on the other hand relates to the ability of the system to respond to disturbances arising within the system. Therefore system security is associated with the response of the system to whatever perturbation it is subjected to. In this study, the reliability evaluations will be focused on the generation system adequacy and will not take into account system security.

In a generation system study, the total system generation is examined to determine its adequacy to meet the total system load requirement. This activity is usually termed “generating system

adequacy assessment”. The transmission system is ignored in generating system adequacy assessment and is treated as a load point. The main idea of the generating system adequacy assessment is to estimate the generating capacity required to meet the system demand and to have excess capacity to cater for planned and forced outage events.

The basic modelling approach for the generating system adequacy assessment consists of three parts as shown in Figure 2.1. The generation and load models are convolved to form an appropriate risk model where the element of interest is the risk of generation capacity less than the load. In short, adequacy evaluation of generation systems consists of three general steps:

- Create a generation capacity model based on the operating characteristics of the generating units.
- Build an appropriate load model.
- Combined the generation capacity model with load model to obtain a risk model.

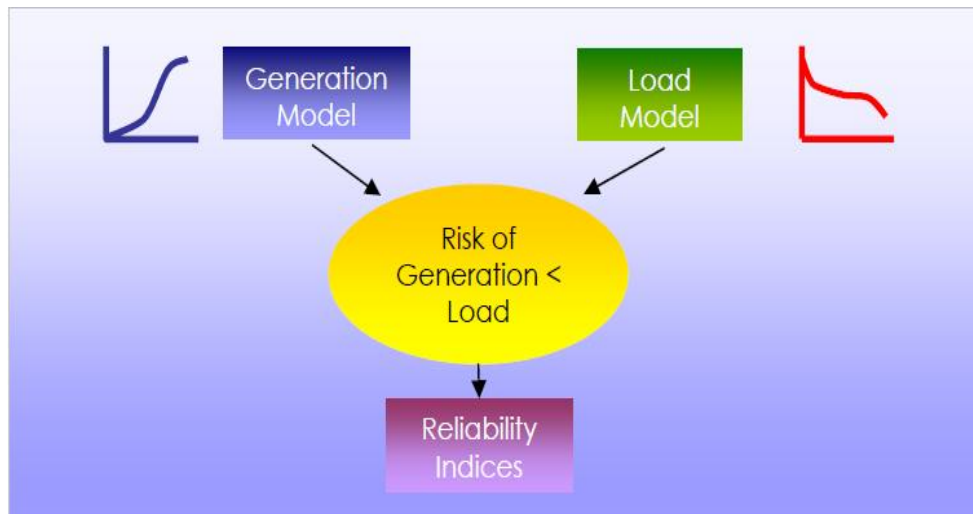


Figure 2.1: Elements of generation system reliability evaluation

Analytical methods or Monte Carlo simulation can be used to calculate the reliability indices. Analytical techniques represent the system by analytical models and evaluate the indices from these models using mathematical solutions. Monte Carlo simulations, on the other hand estimate

the indices by simulating the actual process and random behavior of the system, treating the problem as a series of experiments. The reliability indices obtained indicate the ability of the generating facilities to meet the system demand. In the analytical method, the generating system model used for generation capacity adequacy assessment is a *Capacity Outage Probability Table* (COPT) which can be created using the recursive technique which will be explained later in this chapter. As for the load model, the daily peak load or hourly load for a period of one year is normally used to form the *Load Probability Table* (LPT).

The process of evaluation of power system reliability starts by creating a mathematical model of a system or a subsystem and then proceeding with a numerical solution, summarized in the following general steps [14]:

- Define the boundary of the system and list all the components included.
- Provide reliability data such as failure rate, repair rate, repair time, scheduled maintenance time, etc., for every component.
- Establish reliability models for every component.
- Define the mode of system failure, or define the criterion for normal and faulty systems.
- Establish a mathematical model for the system reliability and its basic assumptions.
- Select an algorithm to calculate the system reliability indices.

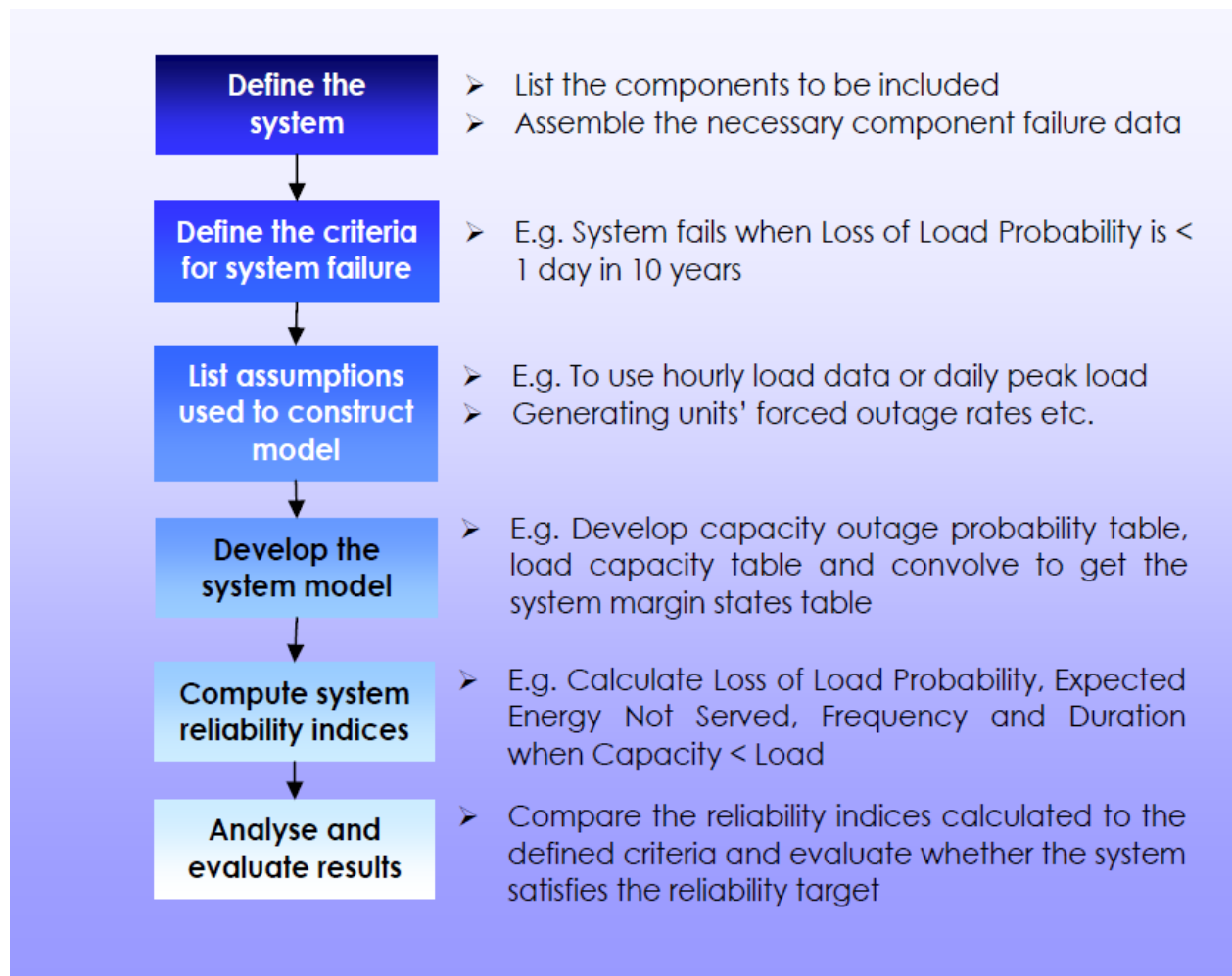


Figure 2.2: Reliability model construction process

2.2 LOAD MODEL AND REPRESENTATION

The load in a power system in any time period is a stochastic process, which is difficult to describe with a simple mathematical formula. Different models are created, starting from primary load data and according to the need to calculate reliability. Primary load data will provide a minimum amount of data that is needed to establish an hourly chronological load profile. Most primary load data consist of the percentage of maximum monthly load or weekly load in a year, the load in 24 hours in a typical day in each season and the maximum load in each day in a week. With the percentages of these data available and the annual peak load known, the hourly chronological load profile can be established.

In other circumstances, daily peak load for a year (365 days) are sufficient when the modelling uses the daily peaks. However, these daily peaks are assumed to occur over the entire duration of the day.

2.2.1 Conventional Generating Unit Reliability Model

The most important input quantities required in generation system reliability analysis are the capacity and the failure probabilities of individual generating units. If a simple two-state model is assumed for the operation of a unit, its failure probability is given by its unavailability U , which can be expressed in terms of the unit failure rate λ and repair rate μ in given equation.

$$U = \frac{\lambda}{\lambda + \mu} \tag{2.1}$$

Where,

λ = unit failure rate

μ = unit repair rate

U = unit unavailability

Unit unavailability is also known conventionally as “forced outage rate” (*FOR*), although the value is not a rate. The *FOR* is defined in Equation 2.2 below

$$FOR = \frac{\text{forced outage hours}}{IN - \text{service hours} + \text{forced outage hours}} \tag{2.2}$$

The *FOR* calculated for a long period of time (e.g. 365 days), is the same index as the unavailability defined in Equation 2.1. The *FOR* is a good approximation for the 2 state approximations.

The next step in building a generation model is to combine the capacity and availability of the individual units to estimate available generation in the system. The result of this combination

will be a capacity model, where each generating unit is represented by its nominal capacity, C_i and its unavailability, U_i (or *FOR*). The capacity or the outage capacity, X is considered to be a random variable in power system reliability analysis. The capacity or outage capacity is discrete and obeys an exponential distribution. The unit model is the probability table of a generator unit's capacity state.

The probability model of a two-state generator model has only two states; in operation or on outage. There are $2n$ possible different capacity states. The individual state probability can be described in Equation 2.3.

$$P(X = x_i) = \begin{cases} 1 - q & x_i = C_i \\ q & x_i = 0 \end{cases} \quad (2.3)$$

The cumulative state probability (the distribution function) can be obtained by summing up the individual state probability for all capacity less than x_i . Equation 2.4 gives the cumulative state probability.

$$P(X = x_i) = \begin{cases} 0, & x_i < 0 \\ q, & 0 \leq x_i \leq C_i \\ 1, & x_i \geq C_i \end{cases} \quad (2.4)$$

There will be a forced outage rate for every capacity C_i , and the individual state probability and cumulative state probability are summarized in Equation 2.5 and 2.6 respectively.

$$P(X = x_i) = P(x_i) \quad \text{Where } i = 0, 1, 2, \dots \quad (2.5)$$

$$P(x_k) = P(X \geq x_k) = \sum_{i \geq k} p(x_i) \quad (2.6)$$

From these equations, the *Capacity Outage Probability Table* (COPT) that represents the probability of different capacity outages of the system can be generated.

We can also use binomial distribution $(U + A)^n$ for calculation of probability of different outage states

$$P(j) = \frac{N!}{j!N-j!} \times A^{N-j} \times U^j \quad (2.7)$$

Where,

- U unit unavailability
- A unit availability
- N no: of units
- j outage state
- P(j) Probability of outage state j

2.3 ALGORITHM FOR COPT

Following steps present the method of calculating COPT (capacity outage probability table) for evaluating reliability of generation system:

- Step 1 : Input N, λ , μ , and capacity of units (C_j) for $j = 1, 2, \dots, N$
- Step 2 : For N units calculate no: of states & Calculate U & A from equation (2.1)
- Step 3 : Set $j = 0$, calculate probability when no generating unit is on outage using equation (2.7)
- Step 4 : Set $O = 0$
- Step 5 : Set $j = j + 1$, calculate probability when 1st unit goes on outage using equation (2.7)
- Step 6 : $O = O + C_j$
- Step 7 : Repeat Step 5 & 6 for $j \leq N+ 1$, otherwise go to Step 8
- Step 8 : Print COPT table.

2.4 GENERATION SYSTEM RELIABILITY INDICES

The quantification of reliability is an important aspect of generation system reliability assessment. The measurement used to quantify reliability of a generation system is given by various reliability indices. These reliability indices are used to assess the reliability performance of a generation system against some predetermined minimum requirements or reliability standards, compare alternative designs, identify weak spots and determine ways for correction in the generation system and to be integrated with costs and performance considerations for decision making. These indices are better understood as estimates of system-wide generation adequacy and not as absolute measures of system reliability.

Basically, system reliability evaluations can be divided into deterministic and probabilistic. The most common deterministic indices are the Reserve Margin and the largest set in the system. An important shortcoming of these methods is that they do not account for the stochastic nature of system behavior. Probabilistic methods can provide more meaningful information to be used in design and resource in planning and allocation.

There are two approaches that use probabilistic evaluation [15]. The analytical methods and Monte Carlo simulation as can be seen from Figure 2.3. The analytical methods represent the system by mathematical models and use direct analytical solutions to evaluate reliability indices from the model. As for the Monte Carlo simulation, reliability indices are estimated by simulating the actual random behavior of the system. So of the commonly used probabilistic reliability indices are Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE), Loss of Energy Expectation (LOEE), and Loss of Load Frequency (LOLF) and Loss of Load Duration (LOLD). Most of these indices are basically expected values of a random variable [16]. Expectation indices provide valid adequacy indicators which reflect various factors such as system component availability and capacity, load characteristics and uncertainty, system configurations and operational conditions, etc.

Typical reliability indices used in power system evaluations and their categorizing is shown in Figure 2.3

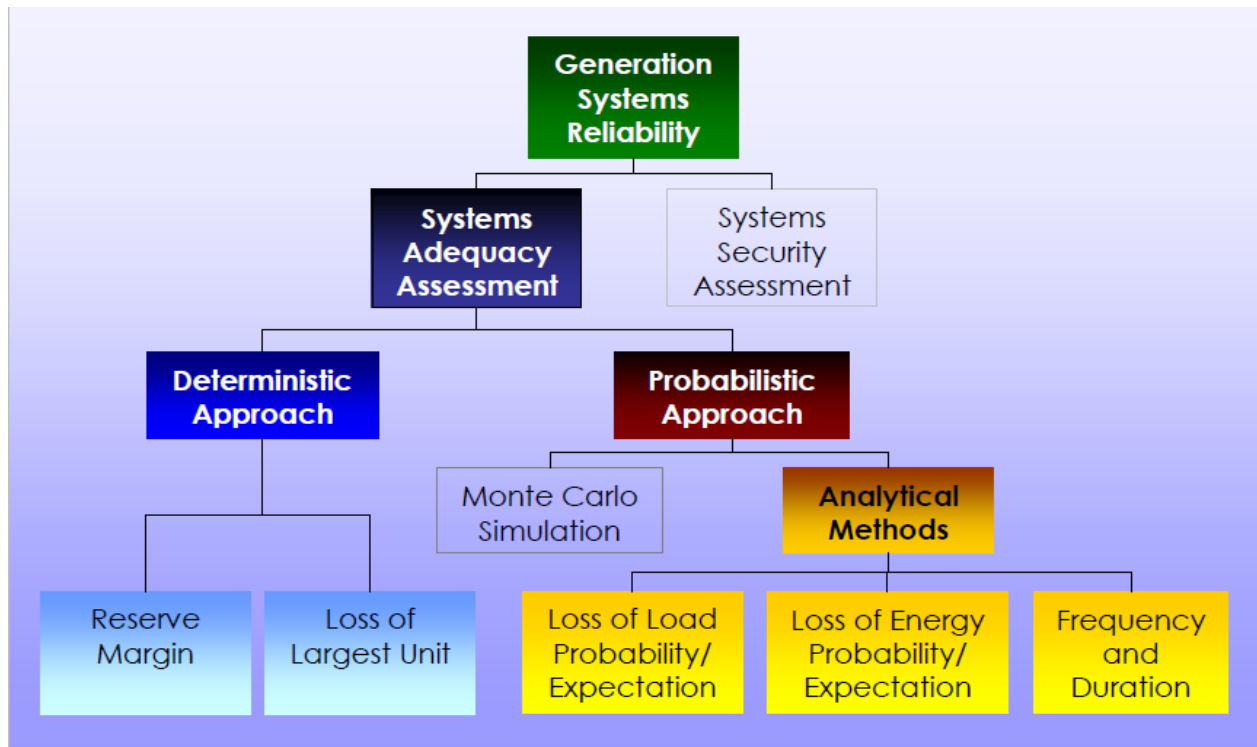


Figure 2.3: Generation system reliability assessment indices category

2.4.1 Reserve Margin

Reserve Margin is the percentage of additional installed capacity over the annual peak demand. It is a deterministic criteria used to evaluate system reliability by defining a target generation margin. The formula to calculate the reserve margin is shown in Equation 2.8.

$$\text{Reserve margin} = \frac{\text{Installed Capacity(MW)} - \text{Peak Demand(MW)}}{\text{Peak Demand}} \times 100\% \quad (2.8)$$

The forecasted peak demand and the expected capacity in planning need to be extracted from planning data to calculate the future system Reserve Margin. The assumptions used in the calculation of Reserve Margin is that Installed Capacity or the Nameplate Capacity is used instead of derated Capacity, and therefore does not give a true representation of the actual available margin the system will operate with. This method compares the adequacy of reserve

requirements in totally different systems on the sole basis of their peak load, mainly used in the past for generation system expansion planning of small and established systems. Based on past experience, a certain percentage of reserve is set to be available to meet the peak demand, usually ranges from 15% to 20%. Plant addition is done when the Reserve Margin goes below the expected level. This method is very easy to use and understand in quantifying reliability and generation system adequacy.

However, as the electricity system grows in sizes and complexities, Reserve Margin alone is not sufficient to provide the reliability assessment. The basic weakness of Reserve Margin is that it does not respond to, nor reflect, the probabilistic or stochastic nature of system behaviour, of customer demands, or of component failure. For example, it does not consider the failure rate of different plant types and sizes. Deterministic analysis using just Reserve Margin calculation could lead to overinvestment in generation expansion or insufficient system reliability. Therefore, most of the utilities and system planner have been using the probabilistic indices rather than the Reserve Margin criteria.

2.4.2 Loss of Largest Unit

This method simply compares system peak demand with the generation capacity when the largest generation unit is unavailable. In larger system however, more than one generating unit is assumed to be unavailable when carrying out the reliability study. The remaining capacity after the loss of the largest generating unit is then known as the firm capacity and this can be given by Equation 2.9.

$$\text{firm capacity} = \sum_1 c_i - c_l$$

Where,

(2.9)

$$C_l \geq C_i \text{ and } i = 2, \dots, l$$

This method suffers from many drawbacks. Firstly, it does not take into account the probability availability of the generating units. It also takes no account of the actual size of the system as it treats the units in sets depending on their capacity. Last but not least, any new additions of larger unit(s) only mean that the firm capacity increases by the size of the largest set before the capacity

expansion. As a result, the loss of largest unit approach is very inadequate and can be misleading. It is however used in some developing countries. A better indicator of system reliability is can be obtained from indices generated through probabilistic analysis such as loss-of load, loss-of-energy and frequency and duration methods.

2.4.3 Loss of load

Loss of load occurs when the system load exceeds the generating capacity available for use. Loss of Load Probability (LOLP) is a projected value of how much time, in the long run, the load on a power system is expected to be greater than the capacity of the available generating resources. It is defined as the probability of the system load exceeding the available generating capacity under the assumption that the peak load of each day lasts all day [3].

LOLP is based on combining the probability of generation capacity states with the daily peak probability so as to assess the number of days during the year in which the generation system may be unable to meet the daily peak [17].

LOLP can be calculated considering the daily peak loads for 1 year duration or sometimes on each hour's load for a 24 hours day. Therefore, the same system may have two or more values of LOLP depending on how the calculation is being done. The mathematical formula for calculation of LOLP is shown in Equation 2.10.

$$LOLP = \sum_j P[CA = C_j] \cdot P[L > C_j] = \sum_j \frac{P_j \cdot t_j}{100} \quad (2.10)$$

Where,

- L expected load
- C_A available generation capacity
- C_j remaining generation capacity
- P_j probability of capacity outage
- t_j percentage of time when the load exceeds C_j

Alternatively, a load duration curve consists of daily peak loads arranged in descending order can be used to measure LOLP for long term generation capacity evaluation. The assumption used in this case is that the peak load of the day would last all day. The LOLP calculation is illustrated with a daily peak load curve in Figure 2.4.

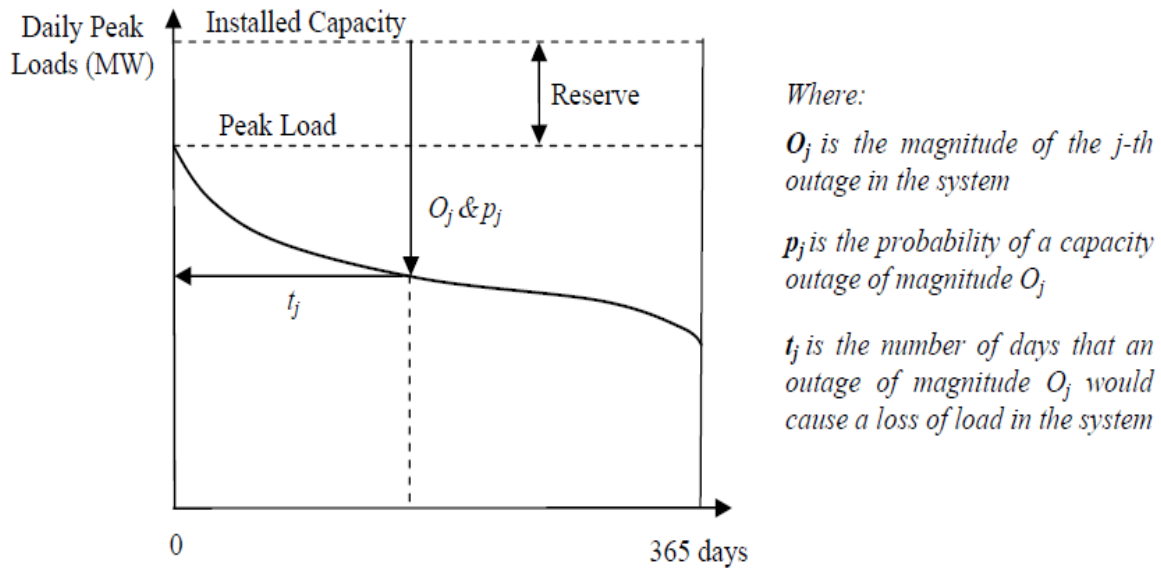


Figure 2.4: LOLP Calculation using Load Duration Curve

Capacity outage less than the amount of reserves will not contribute to a loss of load. When a particular capacity outage is greater than the reserve, the risk in this case will be $p_j \times t_j$.

It must be noted that an LOLE expectation index is more often used than the LOLP probability index in practical applications. The relationship between LOLE and LOLP is shown in Equation 2.11.

$$\text{LOLE} = \text{LOLP} \times T \quad (2.11)$$

Where

$T = 365$ days (if the load model is an annual continuous load curve with day maximum load; the LOLE unit is in days per year).

$T = 8760$ hours (if the load model is an hourly load curve; the LOLE unit is in hours per year).

A level of LOLP is normally set and to be use as a reliability criteria for generation capacity planning. A common practice was to plan the power system to achieve an LOLP of one-day-in-ten-years or less. This does not mean a full day of shortages once every 10 years, but refers to the total accumulated time of shortages that should not exceed one day in 10 years or equivalently 0.0274% of a day. It is expected that a system having an LOLP value lower than the criteria set can withstand expected forced outages, anticipated peak loads and contingencies. A central utility is responsible for planning and making sure the availability of generation, energy purchases, load management and other system balancing mechanisms so as to ensure the resulting system LOLP will be at or below the set criterion. LOLP is used to characterize the adequacy of generation to serve the load on the bulk power system; it does not model the reliability of the power delivery system –transmission and distribution – where the majority of outages actually occur.

The LOLP is like a rule of thumb to give an indication of the reserve margin of 20% or 25%. But it gives a better indication or measure of reliability than the reserve margin index as it takes into account system characteristics such as individual generator reliability, load unpredictability, and unit derations. For example where one utility might function acceptably with 25% reserve margin, another might be having the same LOLP with just a 20% reserve margin. In short, if utilities were planned so that they maintain an appropriate reserve margin, different utilities should have different reserve margins because the same reserve margin in different utilities would result in different levels of reliability [18].

The LOLP index has gained recognition and became a widely used probabilistic index for generation reliability assessment. This is because it provides a probabilistic figure which can be relatively simple to compute and employed in generation capacity planning. It gives a simplified comparison of reliability.

There are several problems with the use of the LOLP for power system reliability evaluations.

- LOLP does not provide any indication of the frequency or duration of shortages and the extent of load shedding in MW or severity of potential shortages which are important

reliability measures. As an expected value, it does not differentiate between one large shortfall and several small, brief ones.

- Different LOLP calculation techniques can result in different indices for the same system. Some utilities calculate LOLP based on the hour of each day's peak load (i.e., 365 computations), while others model every hour's load i.e., 8760 computations [18].
- LOLP does not include additional emergency support that one control area or region may receive from another, or other emergency measures that control area operators can take to maintain system reliability [18].
- Major loss-of-load incidents usually occur as a result of contingencies not modelled by the traditional LOLP calculation. Often, a major bulk power outage event is precipitated by a series of incidents, not necessarily occurring at the time of system peak (when the calculated risk is greatest) [18].
- The LOLP, in days per year, mainly indicates the number of days in the year in which the generation system would not be able to meet the load. The frequency of load shedding may be higher than this figure in case of double peaked daily load curves and in systems which employ units with higher failure rates but short repair duration [17].
- Since the load model used in the loss-of-load method is most often the cumulative curve of daily peak loads, the variations of load within a day are not recognized in it. This makes the LOLP value obtained by that method a rather crude approximation of the true system failure probability, and prevents the calculation of the system failure frequency.
- It is not very useful for comparing the reliabilities of different utilities or national systems, particularly if they have different shapes of the load curve and peak duration.
- It is argued that for the same system the use of the LOLP index would be adequate and correct for investigating different expansion plans and annual maintenance scheduling. This is only correct if the duration peak demand is static over years of the study. This is not the case in many systems with the continuous increase in the middle of the day load being experienced in most cases, particularly in developing countries

2.4.4 Loss of Energy

Loss-of-energy method is another measure for generation reliability assessment. The measure of interest in this case is the ratio of the expected energy not served (EENS) during some long period of observation to the total energy demand during the same period.

A mathematical formula for the Loss of Energy Probability (LOEP) calculation is shown in Equation 2.10.

$$LOEP = \sum_k \frac{E_k \cdot p_k}{E} \quad (2.12)$$

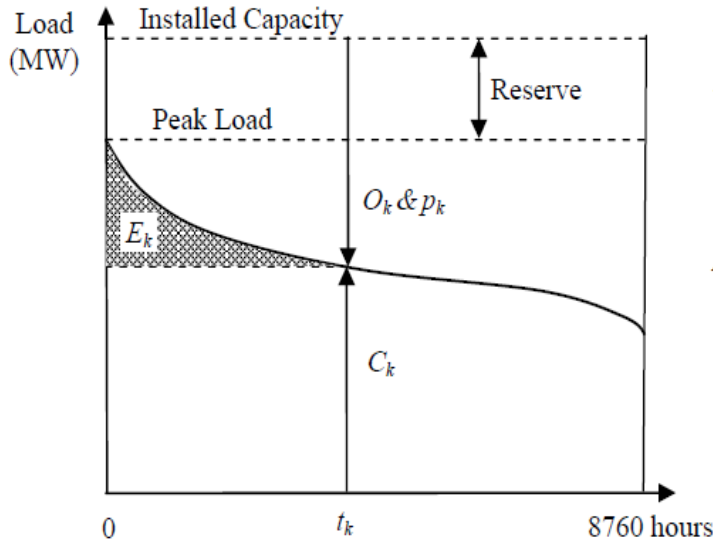
Where

E_k energy not supplied due to a capacity outage O_k

p_k is the probability of the capacity outage O_k

E is the total energy demand during the period of study

The value obtained will have a unit of MWh/year and is also known as the Loss of Energy Expectation (LOEE) since it is an expected value rather than a probability. Similar to the loss-of-load method, a load duration curve can be used to determine the LOEP for installed capacity evaluation.



Where:

E_k is the energy not supplied due to capacity outage O_k

O_k is the magnitude of the k -th outage in the system

p_k is the probability of a capacity outage of magnitude O_k

t_k is the number of hours that an outage of magnitude O_k would cause loss of energy in the system

Figure 2.5: LOEP Calculation using Load Duration Curve

Any capacity outage exceeding the reserve will result in load interruption and energy curtailment. The energy not served, E_k , is the shaded area shown under the load duration curve in Figure 2.5. LOEP can be calculated from Equation 2.12 with E_k and E represented as in Equation 2.13.

$$E_k = \int_0^{t_k} (L - C_k) dt$$

$$E = \int_0^{8760} L dt \quad (2.13)$$

In some ways, the loss of energy index gives a more real representation of the system than the LOLP index [3]. It will show the severity of an event by giving a higher value for more serious events than for marginal failures, even if their probabilities and frequencies are the same. However, the true loss of energy cannot be accurately computed on the basis of the cumulative curve of daily peaks. As a result, the LOEP index is seldom used for reliability evaluations of for generation capacity planning.

2.4.5 Frequency and Duration

The frequency and duration (FAD) method is another set of reliability indices useful when the frequency of power interruption over a certain period of time is of interest. It is a helpful way to evaluate customer point reliability.

The FAD method applies the state-space approach to the set of units present in the system and uses the transition rate parameters λ and μ of generation units. This means that each possible combination of units in up and down states defines a capacity state of the system. The resulting states are characterized by their available capacity, the associated state probabilities and the transition rates. The process of a frequency and duration analysis are as described [15] follows:

- The capacities C_j and the probabilities p_j of each state are calculated for the system capacity outage distribution.
- The frequency of encountering a state j , f_j , is the expected number of stays in (or arrivals into, or departures from) j per unit time, computed over a long period.
- The frequency of state j is $f_j = p_j \times (\lambda_{j+} + \lambda_{j-})$, where λ_{j+} is the transition rate from state j to higher capacity states and the λ_{j-} transition rate to lower capacity states.
- The average state duration T_j is defined by the relation $p_j = f_j \times T_j$.

This representation is combined with a load model to identify marginal states, that is states where a transition to a lower capacity state results in a generation deficit ($C_j < L$). A chronological load curve is needed in this case. Then, cumulative probabilities and frequencies are computed for the marginal states and suitable indices are derived.

The frequency and duration indices can be calculated using the Equation 2.14 and 2.15 respectively.

$$\text{Loss of Load Frequency, LOLF(occ/year)} = \sum_{i \in S} (F_j - f_j) \quad (2.14)$$

Where,

F_j is the frequency of departing system state j

f_j is the portion of F_j which corresponds to not going through the boundary wall between the loss-of-load state set and the no-loss-of-load state set.

$$\text{Loss of Load Duration, LOLD(hr/disturbance)} = \frac{LOLE}{LOLF} \quad (2.15)$$

Frequency and duration are a basic extension of the LOLE index in that they identify the expected frequency of encountering a deficiency and the expected duration of load deficiencies. Both indices contain additional physical characteristics which make them sensitive to additional generation system parameters. However, the criterion has not been used very widely in generation system reliability analysis.

2.5 ALGORITHM FOR GENERATION SYSTEM RELIABILITY EVALUATION

Following steps present the method of calculating reliability indices of generation system:

- Step 1 : Input N , λ , μ , and capacity of units (C_j) for $j = 1$ to N , Max load
- Step 2 : Calculate the COPT table from section 2.3 & Read max load for year and load duration curve to develop appropriate load model
- Step 3 : Calculate the different values of T_j for diff: values of O_j
- Step 4 : Calculate LOLP & LOLE using equation (2.10) & (2.11)
- Step 5 : Calculate the expected energy lost for each capacity outage from load Model
- Step 6 : Calculate LOEE using equation (2.12)
- Step 7 : Stop

2.6 COMPARISON OF RELIABILITY INDICES

We have reviewed basic concepts and techniques used to evaluate generation reliability in power systems. The results are expressed as a series of reliability indices that measure the risk of supply shortages for a given configuration. However, in practice there is no uniformity in the interpretation and application of the different risk measures.

Deterministic Criteria: The probabilistic methods are far superior to the percentage reserve and other rules of thumb often used. They provide analytical basis to consistently define system risk for different configurations. Deterministic criteria are insensitive to factors that significantly influence system reliability, such as unit size, failure rates or load characteristics. In fact, the reliability of two systems with same percentage reserve but different unit composition may be quite different. Moreover, the percentage reserve conveys the misleading idea that all the risk can be removed keeping a fixed amount of reserves.

LOLP/LOLE: This is the probability of system failure (to serve the load) based on a load duration curve or daily peak load curve. Depending on which load model is used the LOLP have different meanings. This index is often expressed as the expected fraction of time, LOLE, on which the system will be observed undergoing an outage event that leads to load of loss. All loss-of-load events count for its time contribution and not for the magnitude of the loss. LOLP/LOLE is easy to calculate and understand but it does not differentiate small capacity outages from large ones.

FAD: The frequency of system failure measures the average number of failure occurrences per unit time. The corresponding duration indicates the average residence time on the failure states. This information is not provided by LOLP, but FAD does not either give information about the size of the outages when they occur. The frequency and duration of capacity outages have a greater physical significance than LOLP, but the FAD models require more detailed information about each generating unit and more computational effort.

LOEP: It measures the expected fraction of system energy not served due to capacity outage events. The loss-of-energy approach has much greater physical relevance than the other approaches and takes into account the magnitude of the different outage events.

2.7 THE COMMON PRACTICE AND APPLICATION OF RELIABILITY INDICES

Different countries and utilities employ different reliability standards for their specific and unique electricity system. This is because all systems are different from one another and therefore, the reliability criteria are also different.

The last security standard employed in the UK by the Central Electricity Generating Board (CEGB) proposed capacity margin of about 24%, where the capacity margin is defined as the percentage difference between total system generation capacity and peak system load.

As for the adequacy standard in Ireland, the authority proposes that an expectation of failure should not be larger than 8 hours per year LOLP. For France, the level of supply deficits accepted as stated in the Generation Adequacy Reports a mathematical expectation of less than three hours per year (LOLP < 3 hours) [19].

In India, a reliability target planning criterion of 5 per cent (i.e., 18.25 days a year) was adopted in the First National Power Plan (NPP, 1983) and in the Second NPP (1987). Such a very high level of LOLP target was justified in view of the inability, in terms of funds, to bring in a very large quantum of new capacity additions required for a desirably low target. Later on the general improvement in the technical performance of the generating plants, as also the introduction of new vintage larger size plants with higher efficiency lent sufficient force to decide, during the exercises for evolving the Third NPP (1991), on an LOLP target of 2 per cent (i.e., 7.3 days a year). The same level was proposed to be retained during the 9th Five Year Plan (FYP) period in the Fourth NPP (1997) also, in view of the unexpected wide gap between the target and the achievement in capacity addition. At the same time, substantial capacity addition in the near future through independent power producers (IPP) has also been expected. It is hence proposed

to improve the reliability target planning criterion further to 1 per cent (i.e., 3.65 days a year) LOLP by the end of the 10th FYP [20] .

It has been a common practice in some of the advanced countries to adopt in electricity supply an arbitrary reliability target, such as one-day-in-ten-years LOLP .This does not mean full day of shortages once every ten years; rather, it refers to the total accumulated time of shortages that should not exceed one day in 10 years, or, equivalently, 0.03 per cent of a day.

In some of the Asian and African countries (e.g., Korea, Hong Kong, Thailand, and Zimbabwe), LOLP criteria are found to vary from 12 to 24 hours per year, equivalent to five to ten days in ten years.

COMPOSITE SYSTEM RELIABILITY

3.1 INTRODUCTION

The basic function of a composite generation and transmission system is to generate the required electricity and deliver it to the major load points. The major objective of composite system adequacy assessment (HLII) is to evaluate the ability of the system to perform this basic function.

The reliability assessment of composite generation and transmission systems has been receiving considerable attention during the past few years. The main reason is that, as utilities are finding it increasingly necessary to quantitatively evaluate individual busbar and overall system reliability indices. Although these systems cause customer interruptions or loss of service quality very infrequently, they can have a major and widespread effect on society and the environment when problems arise. There is therefore a significant need to assess the reliability, or more commonly the adequacy, of these systems, the effect outages have on the system and its consumers, and the relative merits and costs of alternative expansion plans and operation scenarios.

Reliability evaluation of a composite generation and transmission system is concerned with the problem of determining the adequacy of the combined generation and transmission system in regard to providing a dependable and suitable supply at the bulk load points. Composite system adequacy assessment is very complex since it involves not only system analyses but also many practical considerations [21]. The system analyses involved in the assessment include load flow studies, contingency assessment, generation rescheduling, transmission overload alleviation, load curtailment, etc. A complete investigation involves the analysis of each possible outage condition in the system. The performance of the system under each outage condition can be examined by conducting an appropriate load flow study. A single or first order outage evaluation examines the outage of one element in the system at a time. The double or second order outage appraisal involves the outage combination of two elements. The third and higher order outage situations can similarly be defined: In this thesis, the term 'element' refers to a generating unit, transformer or transmission line, and the term 'composite system' refers to a composite generation and transmission system.

The available publications on composite generation and transmission system reliability evaluation basically assume that the simultaneous or overlapping outages constituting a contingency situation are independent. This assumption is not true for all outage situations. The outage of two or more circuits on the same transmission tower can occur from a single cause. Such outages can be classified as common-cause or common-mode outages, since a single event results in an outage of two or more elements. Recent investigations, however, have indicated that common-cause outages of transmission configurations can appreciably affect the predicted reliability. So this thesis work also includes the effect of some major outages on reliability of composite system. This thesis presents an small overview of a method for evaluating the reliability of composite generation and transmission systems.

3.2 TECHNIQUE FOR EVALUATING RELIABILITY OF COMPOSITE SYSTEM

The primary objective of this approach is to evaluate reliability indices for the total system and at every load point in the system. The failure of service at any busbar in the system is considered due to failure of the system to supply the total load connected to that busbar due to line overloads. Inadequacy of the available generation to meet system load requirements is also considered as a failure at each busbar. The evaluation of a composite system, in a complete sense, involves the analysis of all possible contingency states. Many outage combinations of lines and generating units can exist in a practical power system, and each outage condition has a probability of existence and a frequency of occurrence. In its simplest form, each element of the power system can be assumed to be either available or under forced outage, and that the element outages are independent random events. These assumptions are used in this thesis for applying this approach [21].

The approach described considers the situations arising owing to the outage of generating units and lines individually and in combination with other generating units and lines. The generation schedules at appropriate generating busbars can be modified for each generating unit outage case to compensate for the loss of generation by using reliability study of composite system. Violation

of a specified service quality criterion can be determined for each outage condition by conducting an a.c. load flow analysis. The computation involved therefore varies with

- the size of the system;
- the order of overlapping (or simultaneous) independent outages considered, and
- the load flow technique adopted for analysing each outage case.

The computational time of this technique varies nonlinearly with the total number of busbars, generating units and transmission lines in the system.

The bulk of the computational time is utilised in the load flow analysis of each outage condition. Since the purpose of each load flow solution is to identify line overloads etc. This approach has been used in the work described in this thesis. when problem regarding overload of transmission lines is encountered. The simplest solution to this problem is to allow these elements to operate in the overloaded condition. This assumption results in optimistic reliability indices especially when the line overload is heavy and persists for a long duration. An alternative solution is to remove the overloaded component and continue to analyse the remaining system until no other element is overloaded, or until the total system has failed. This approach results in pessimistic reliability indices which may suggest expensive and unnecessary investment in system improvement.

3.3 CONCEPTS OF COMPOSITE SYSTEM ANALYSIS

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

The quantitative assessment of each of the functional zones of an electric power system is widely conducted using existing techniques. Application of these techniques in planning of generation systems and distribution networks is fairly well advanced and is widely used. The development of a suitable transmission network to convey energy to the major load points is an important part

of planning process and is termed as composite or bulk power system expansion planning. The application of quantitative reliability assessment techniques to composite generation and transmission systems is in infancy and relatively little use is made in practical decision making. The need, however is widely recognized and interest is expanding rapidly [2].

The procedures used for adequacy assessment at HLII can be broadly classified into two general areas:

- Analytical methods
- Monte Carlo simulation techniques.

Analytical techniques represent the system by a mathematical model and evaluate the reliability indices from this model using mathematical solutions. Monte Carlo simulation methods, however, estimate the reliability indices by simulating the actual process and random behavior of system. There are merits and demerits of both the methods. Generally Monte Carlo simulation requires a large amount of computing time compared to analytical methods. However, it can include any system effect or system process which may have to be approximated in an analytical approach.

There are two basic techniques utilized when Monte Carlo methods are applied to power system reliability evaluation. These methods are known as the sequential and non sequential techniques. The research work conducted in this thesis is based on analytical methods of calculating composite system reliability and its indices. There are wide range of indices which can be calculated at each major load point and of overall system. These indices convey meaningful information regarding the performance of system and are also well suited to making system design/alternate decisions.

Individual load point indices are necessary to identify weak points in system and to help establish the optimum response to system investment. Overall system adequacy indices provide an appreciation of global adequacy which proves more appealing to management and is useful in comparison of one system with another.

3.3.1 Conditional Probability Approach

Many probability applications in reliability evaluation assume that component failures within fixed environment are independent events. This may or may not be true. It is, however, entirely possible that component failure can result in system failure in a conditional sense. This can occur in parallel facilities that are not completely redundant. If the load can be considered as random variable and described by probability distribution, then failure at any terminal station due to component failure is conditional upon the load exceeding the defined carrying capability of the remaining facilities. Load point failure in this case may be defined as inadequate voltage or available energy at customer bus.

If occurrence of event A is dependent upon a number of events B_i which are mutually exclusive, then

$$P(A) = \sum_{i=1}^n P(A/B_i)P(B_i) \quad (3.1)$$

if occurrence of A is dependent upon only two mutually exclusive events for component B, success and failure, designated B_s and B_f respectively, then

$$P(A) = P(A/B_s)P(B_s) + P(A/B_f)P(B_f) \quad (3.2)$$

If the event A is system failure, then

$$P(\text{system failure}) = P(\text{system failure} / B \text{ is good}) P(B_s) + P(\text{system failure} / B \text{ is bad}) P(B_f) \quad (3.3)$$

This approach can be applied to simple radial configuration as shown in figure 3.1

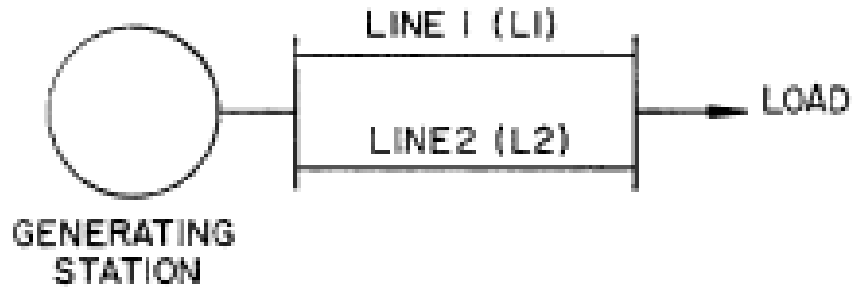


Figure 3.1: Simple radial generation transmission system [22]

Here,

P_g probability of generation inadequacy

P_c probability of transmission inadequacy i.e., $P_c(1), P_c(2)$ are the probabilities that the load will exceed the carrying capabilities of lines 1 and 2, respectively and $P_c(1, 2)$ is the probability that the load will exceed the combined carrying capability of lines 1 and 2.

Q_s probability of system failure

A_1, U_1 line 1 availability and unavailability respectively

A_2, U_2 line 2 availability and unavailability respectively

From equation (3.3)

$$Q_s = Q_s(L1 \text{ in})A_1 + Q_s(L1 \text{ out})U_1$$

For L1 in,

$$Q_s = Q_s(L2 \text{ in})A_2 + Q_s(L2 \text{ out})U_2$$

For L1 and L2 in,

$$Q_s = P_g + P_c(1,2) - P_g P_c(1,2)$$

It has been assumed that the probabilities of capacity deficiencies and transmission inadequacies are independent.

For L1 in and L2 out,

$$Q_s = P_g + P_c(1) - P_g P_c(1)$$

Therefore for L1 in,

$$Q_s = A^2(P_g + P_c(1,2) - P_g P_c(1,2)) + U^2(P_g + P_c(1) - P_g P_c(1))$$

For L1 out,

$$\begin{aligned} Q_s &= Q_s(L2 \text{ in})A^2 + Q_s(L2 \text{ out})U^2 \\ &= A^2(P_g + P_c(2) - P_g P_c(2)) + U^2 \end{aligned}$$

For complete system,

$$Q_s = A^1[A^2(P_g + P_c(1,2) - P_g P_c(1,2)) + U^2(P_g + P_c(1) - P_g P_c(1))] + U^1[A^2(P_g + P_c(2) - P_g P_c(2)) + U^2] \quad (3.4)$$

If two lines are identical this reduces to

$$Q_s = A^2[P_g + P_c(1,2) - P_g P_c(1,2)] + 2UA[P_g + P_c(1) - P_g P_c(1)] + U^2 \quad (3.5)$$

The solution of this simple system could have been obtained directly by using the terms of binomial expansion of $(A + U)^2$, each term being weighted by relevant probability of generation and line inadequacy. A set of general equations can be written to give the same result as that shown in equation (3.5)

The probability of failure Q_k at bus K in a network can be expressed as

$$Q_k = \sum_j [P(B_j)(P_{gj} + P_{1j} - P_{gj}P_{1j})] \quad (3.6)$$

Where,

- B_j an outage condition in transmission network (including zero outage)
- P_{gj} probability of generating capacity outage exceeding the reserve capacity
- P_{1j} probability of load at bus K exceeding the maximum load that can be supplied at that bus without failure

If the generating unit outages and load variations are considered in terms of probability only and not in terms of frequency of occurrence, then an estimate of expected frequency of failure F_k at bus K is given by

$$F_k = \sum_j [F(B_j)(P_{gj} + P_{1j} - P_{gj}P_{1j})] \quad (3.7)$$

Where,

- $F(B_j)$ = frequency of occurrence of outage B_j

Equation (3.6) & (3.7) consider the generating facility as single entity. This may be acceptable in radial configuration but may not be in cases where the generation is dispersed throughout the system. A more general set of equations can be obtained directly from

$$Q_k = \sum_j [P(B_j)P_{1j}] \quad (3.8)$$

$$F_k = \sum_j [F(B_j)P_{1j}] \quad (3.9)$$

In this case, generation outages are treated individually, as are the transmission outage events, and the generation schedule and resulting load flow are modified accordingly. It should be noted, however, that equation (3.9) does not include a frequency component due to load assumptions that all system loads transit from high to low level loads at the same time. Equation (3.7) & (3.9) also include possible frequency components due to transition between states each of which represent a failure condition.

When above equations are applied to some composite network having both generation system and transmission system then the actual carrying capability of transmission line will depend upon criterion of success at load point. If it is assumed that an adequate voltage level is required in addition to required load demand, then the characteristics of line, associated VAR support and sending end voltage constraints must be considered. For different type of outage configuration on system, the probability of inadequate transmission capability in each of these configuration can be found after performing a load flow study on each configuration using appropriate load model. The state selection process is illustrated by considering first and second order generating unit and transmission line outages. The unavailability associated with a transmission is normally much lower than that of a generating unit and therefore, higher order contingency level should be used when generating units are considered [22].

Equation (3.9) includes possible transition between failure states and will therefore give an expected failure frequency at the load point which is slightly higher than that determined by creating a complete set of Markov model and evaluating the frequency of transition across a specified capacity boundary wall. In this case transitions between failure states would not be included. The probability and frequency component for each state is weighted by probability that the load will exceed the capability of that state to give the failure probability and frequency. By adding all states failure probability and frequency we get load point failure probability and frequency for a given peak load at different line –carrying capability levels. If the load level is considered constant for a year then given load point failures can be termed as annualized values and system failure probability and frequencies can be calculated, and from this further load point indices and system indices can be calculated.

3.4 RELIABILITY INDICES IN COMPOSITE SYSTEM ADEQUACY ASSESSMENT

Reliability indices are an important outcome of quantitative adequacy assessment of a composite system. Both load point and system indices can be used to measure composite system adequacy. Load point indices indicate the reliability at the individual load buses while system indices provide an overall evaluation of total system reliability and reliability worth. The two sets of indices have different functions but complement each other.

Load point indices are usually used when the focus of the adequacy assessment is to find and strengthen unreliable buses in the system. System indices are used when the purpose of the adequacy assessment is to provide a global assessment of the system and to compare one system with another. These indices are calculated on assumption that system has fixed load level. These indices when expressed on yearly basis are therefore referred as Annualized indices. Annualized indices calculated at system peak load level are usually much higher than the actual annual indices [23-25].

The effect of variable load level can be included in order to produce a more representative annual index but at the expense of considerable computer time. The increase in cost depends on the degree to which the load variation is modelled. Annualized indices can be used to compare alternate expansion plans and to assess the sensitivity of system adequacy to configuration changes[24-27].

3.4.1 Annualized Load Point Indices

Table 3.1: Annualized load point indices

(I) Basic values
<ul style="list-style-type: none"> • Probability of failure • Expected frequency of failure • Expected no: of voltage violations • Expected no: of load curtailments • Expected load curtailed • Expected energy not supplied • Expected duration of load curtailment
(II) Maximum values
<ul style="list-style-type: none"> • Maximum load curtailed • Maximum energy curtailed • Maximum duration of load curtailment
(III) Average values
<ul style="list-style-type: none"> • Average load curtailed • Average energy not supplied • Average duration of curtailment
(IV) Bus isolation values
<ul style="list-style-type: none"> • Expected no: of curtailments • Expected load curtailed • Expected energy not supplied • Expected duration of load curtailed

- Probability of failure $Q_k = \sum P_j P_{kj}$

- Frequency of failure $F_k = \sum F_j P_{kj}$

Where,

- j outage condition in network
- P_j probability of existence of outage j
- F_j frequency of occurrence of outage j
- P_{kj} probability of load at bus K exceeding the maximum load that can be supplied at that bus during outage j.

- Expected no: of voltage violations =

$$\sum_{j \in V} F_j$$

Where,

j ∈ V includes all contingencies which cause voltage violation at bus K

- Expected no: of Load curtailments =

$$\sum_{j \in X,y} F_j$$

Where,

j ∈ X includes all contingencies resulting in line overloads which are alleviated by load curtailment at bus K

j ∈ y includes all contingencies which result in isolation of bus K

- Expected energy not supplied (EENS)

$$\begin{aligned} &= \sum_{j \in X,y} L_{kj} D_{kj} F_j \text{ MWh} \\ &= \sum_{j \in X,y} L_{kj} P_i \times 8760 \text{ MWh} \end{aligned}$$

Where,

D_{kj} is the duration in hours of load curtailment arising due to the outage j

L_{kj} is load curtailment at bus K to alleviate line overloads arising from contingency j

Expected duration of load curtailment (EDLC)

$$= \sum_{j \in \mathcal{E}_{x,y}} D_{kj} F_j \text{ hours}$$

$$= \sum_{j \in \mathcal{E}_{x,y}} P_j \times 8760 \text{ hours}$$

- Maximum load curtailed = $\text{Max}\{L_{k1}, L_{k2}, \dots, L_{kj}, \dots\}$
- Maximum energy curtailed = $\text{Max}\{L_{k1}D_{k1}, L_{k2}D_{k2}, \dots, L_{kj}D_{kj}, \dots\}$
- Maximum duration of load curtailment = $\text{Max}\{D_{k1}, D_{k2}, \dots, D_{kj}, \dots\}$

- Average load curtailed

$$= \frac{\sum_{j \in \mathcal{E}_{x,y}} L_{kj} F_j}{\sum_{j \in \mathcal{E}_{x,y}} F_j} \text{ MW/curtailment}$$

- Average energy not supplied

$$= \frac{\sum_{j \in \mathcal{E}_{x,y}} L_{kj} D_{kj} F_j}{\sum_{j \in \mathcal{E}_{x,y}} F_j} \text{ MWh/curtailment}$$

- Average duration of curtailment

$$= \frac{\sum_{j \in \mathcal{E}_{x,y}} D_{kj} F_j}{\sum_{j \in \mathcal{E}_{x,y}} F_j} \text{ h/curtailment}$$

- Expected no: of curtailment due to isolation of bus K

$$= \sum_{j \in \mathcal{E}_y} F_j$$

- Expected load curtailed due to isolation of bus K

$$= \sum_{j \in \mathcal{E}_y} L_{kj} F_j \text{ MW}$$

- Expected energy not supplied due to isolation of bus K

$$= \sum_{j \in \mathcal{E}_y} L_{kj} D_{kj} F_j \text{ MWh}$$

$$= \sum_{j \in \mathcal{E}_y} L_{kj} P_j \times 8760 \text{ MWh}$$

- Expected duration of load curtailment due to isolation of bus K

$$= \sum_{j \in \mathcal{E}_y} D_{kj} F_j \text{ hours}$$

$$= \sum_{j \in \mathcal{E}_y} P_j \times 8760 \text{ hours}$$

3.4.2 Annualized System Indices

Table 3.2: Annualized system indices

(I) Basic values
<ul style="list-style-type: none"> • Bulk power interruption index • Bulk power supply average MW curtailment / disturbance • Bulk power energy curtailment index • Modified bulk power energy curtailment index
(II) Average values
<ul style="list-style-type: none"> • Average no: of curtailments / load point • Average load curtailed / load point • Average energy curtailed / load point • Average duration of load curtailment / load point
(III) Maximum values
<ul style="list-style-type: none"> • Maximum system load curtailed under any contingency condition • Maximum system energy not supplied under any contingency condition

- Bulk power interruption index

$$= \frac{\sum_K \sum_{j \in \mathcal{E}_{x,y}} L_{kj} F_j}{L_S} \text{ MW/MWyr}$$

Where,

L_S = total system load

- Bulk power supply average MW curtailment/disturbance

$$= \frac{\sum_K \sum_{j \in \mathcal{E}_{x,y}} L_{kj} F_j}{\sum_{j \in \mathcal{E}_{x,y}} F_j} \text{ MW/disturbance}$$

- Bulk power energy curtailment index

$$= \frac{\sum_K \sum_{j \in x,y} 60L_{kj}D_{kj}F_j}{L_s} \text{ MWmin/MWyr}$$

Bulk power energy curtailment index has also been designated as Severity index. The severity associated with each outage event is defined as the total unsupplied energy because of that event, expressed in megawatt minutes, divided by the peak system load in megawatts. Severity is therefore expressed in 'system minutes'. One system minute is equivalent to an interruption of the total system load for one minute at the time of system peak. It does not represent a real system outage time because interruption need not occur at time of system peak [2, 21]. The severity index for expressing the total unavailability of the system can thus be defined as follows:

Severity index

$$= \frac{\sum_K \sum_{j \in x,y} 60L_{kj}D_{kj}F_j}{L_s} \text{ system minutes}$$

The system severity index is equivalent to the bulk power energy curtailment index defined by the IEEE working group. A useful modification of the bulk power energy curtailment index, in MWh/yr., is possible by dividing this index by a factor of 8760. The modified index is the probable ratio of the load energy curtailed due to deficiencies in the composite generation and transmission system to the total load energy required to serve the requirements of the system.

- Modified bulk power energy curtailment index

$$= \frac{\sum_K \sum_{j \in x,y} 60L_{kj}D_{kj}F_j}{8760 \times L_s}$$

- Average no: of curtailments / load point

$$= \frac{\sum_K \sum_{j \in x,y} F_j}{C}$$

Where,

C = no: of load points

- Average load curtailed / load point

$$= \frac{\sum_K \sum_{j \in x,y} L_{kj} F_j}{C} \text{ MW/yr}$$

- Average energy curtailed / load point

$$= \frac{\sum_K \sum_{j \in x,y} L_{kj} D_{kj} F_j}{C} \text{ MWh/yr}$$

- Average duration of load curtailed / load point

$$= \frac{\sum_K \sum_{j \in x,y} D_{kj}}{C} \text{ h/yr}$$

- Maximum system load curtailed under any contingency condition

$$= \text{Max} \{ \sum L_{k1}, \sum L_{k2}, \dots, \sum L_{kj}, \dots \}$$

- Maximum system energy not supplied under any contingency condition

$$= \text{Max} \{ \sum L_{k1} D_{k1}, \sum L_{k2} D_{k2}, \dots, \sum L_{kj} D_{kj}, \dots \}$$

3.5 ALGORITHM

Following steps present the method of evaluating reliability of composite generation and transmission system:

- Step 1 : Input the no: of plants (N), their units, their FOR, & their capacity, Max load, load duration curve, R_i , X_i , λ , μ , susceptance.
- Step 2 : Determine the COPT table for all plants i.e COPT1, COPT2...COPTn using algorithm given in section 2.3
- Step 3 : Combine COPT table for different plants and Calculate the COPT table for total system
- Step 4 : Read the max load for year and load duration curve to develop appropriate load model
- Step 5 : Using Step 3 & 4 and using algorithm 2.5 calculate the generation system indices LOLP, LOLE & LOEE
- Step 6 : Repeat Step 4– 5, for different load duration curve and compare the result
- Step 7 : Read the various transmission line data i.e R_i , X_i , λ , μ , susceptance etc.and calculate A_1 , A_2 , A_3 , U_1 , U_2 , U_3 etc
- Step 8 : Set $L_1=0$, conduct study when L_1 is out of case and calculate corresponding probability of outage
- Step 9 : Calculate value of P_{1j} for $L_1=0$ by applying load flow study when no overloading constraint is considered on transmission line
- Step 10 : Calculate value of P_{gj} for $L_1=0$ from Step 3
- Step 11 : $L_2 = L_1+1$, conduct study for L_2 out of case
- Step 12 : Repeat Step 9 & 10 to calculate P_{1j} & P_{gj}
- Step 13 : Repeat Step 11 & 12 for all transmission lines
- Step 14 : Conduct study for different combination of line outages i.e. L_1L_2 , L_1L_3 , L_2L_3 etc. and calculate their corresponding probabilities
- Step 15 : Calculate corresponding P_{1j} and P_{gj} for Step 14 using step 9 & 10
- Step 16 : Calculate the departure rate for different outages using λ & μ
- Step 17 : For different type of line outages & its combinations calculate probability

- of load point failure (individual) using equation (3.9)
- Step 18 : For different type of line outages & its combinations using dept rate calculated in Step 16, calculate frequency of load point failure (individual) using equation (3.9)
- Step 19 : Calculate the Qs & Fs of failure of system considering transmission system only (without constraints of overloading)
- Step 20 : Again calculate the values of P1j for different type of line outages & its combinations when overloading constraint is considered on t/m line
- Step 21 : Repeat Step 16 – 19 for calculating Qs & Fs of failure of system considering transmission system only (with constraints of overloading)
- Step 22 : Combining both generation system and transmission system, calculate no: of outage states for both t/m and gen system by considering first and second order outages only i.e. G1G2, G1L1,G2L3, L1L2 etc
- Step 23 : Calculate corresponding probability of diff: states in Step 22 for both gen and t/m system
- Step 24 : Calculate dept rate for diff: states in Step 25 using λ & μ for both gen and t/m system and calculate corresponding Frequency of occurrence.
- Step 25 : Calculate value of P1j for diff: states with no overloading constraint considered on transmission line
- Step 26 : Using Step 23-25, calculate load point failure probability and frequency calculate table & Qs & Fs of failure of composite system (without constraints of overloading)
- Step 27 : Again calculate value of P1j for diff: states with overloading constraint considered on transmission line
- Step 28 : Repeat Step 26, to calculate Qs & Fs of failure of composite system (with constraints of overloading)
- Step 29 : From table obtained in Step 28, calculate the values of Pkj,Lkj & Dkj.
- Step 30 : Using step 28 & 29, calculate the value of ELC,NLC,EENS, EDLC for diff: outage states & Print Load Point Indices Table
- Step 31 : Calculate annualized load point indices table using section 3.4.1
- Step 32 : Calculate annualized system indices table using section 3.4.2

RESULTS AND DISCUSSION

This chapter presents the results for the system shown in Appendix A. It includes result for reliability evaluation of generation system and transmission system when taken individually and also of composite system. The program is implemented in C++ to give an overview of the method (conditional probability approach) developed in university of Saskatchewan to calculate composite system reliability by calculating annualized load point indices and annualized system indices.

Results shown in this chapter include the following cases:

A. Generation System Reliability

- COPT table for different generating plants
- COPT table for Generation system
- Calculation of Generation Reliability Indices for different Load Model

B. Transmission System Reliability

- Calculation of Qs & Fs without overloading constraints taken on T/m line
- Calculation of Qs & Fs with overloading constraints taken on T/m line

C. Composite System Reliability

- Calculation of Qs & Fs without overloading constraints taken on T/m line
- Calculation of Qs & Fs with overloading constraints taken on T/m line
- Calculation of Annualized Load Point Indices
- Calculation of Annualized System Indices

4.1 GENERATION SYSTEM RELIABILITY

This section includes the COPT table for all generating plants, COPT table for total generation system, reliability indices for different load duration curves and their comparison.

Table 4.1: COPT for Generation Plant 1

State	Capacity outage	Probability
1	0	0.960596
2	20	0.038812
3	40	0.000588
4	60	0.000004
5	80	0.000000

Table 4.2: COPT for Generation Plant 2

State	Capacity outage	Probability
1	0	0.902500
2	30	0.095000
3	60	0.002500

Table 4.3: COPT for Total Generation System

State	Capacity outage	Probability
1	0	0.866938
2	20	0.035028
3	30	0.091257
4	40	0.000531
5	50	0.003687
6	60	0.002405
7	70	0.000056
8	80	0.000097
9	90	0.000000
10	100	0.000001
11	110	0.000000
12	120	0.000000
13	140	0.000000

Table 4.4 & 4.5 gives the various values of time period, expected load loss and expected loss energy with the help of load duration curve 1 (Appendix A) which is straight line from 100% to 60% having a peak load which is assumed to be constant when period of study is taken as 365 days. From this table generation system reliability indices LOLP, LOLE & LOEE are calculated.

Table 4.4: LOLP using individual probabilities for load duration curve 1

State	Capacity out	Probability	Time	Expected Load Loss
1	0	0.866938	0.000000	0.000000
2	20	0.035028	0.000000	0.000000
3	30	0.091257	0.000000	0.000000
4	40	0.000531	22.727272	0.012062
5	50	0.003687	45.454544	0.167597
6	60	0.002405	68.181816	0.163982
7	70	0.000056	90.909088	0.005079
8	80	0.000097	100.000000	0.009704
9	90	0.000000	100.000000	0.000038
10	100	0.000001	100.000000	0.000147
11	110	0.000000	100.000000	0.000000
12	120	0.000000	100.000000	0.000001
13	140	0.000000	100.000000	0.000000

Table 4.5: LOEE using individual probabilities for load duration curve 1

State	Capacity out	Probability	Time	Capacity out > Reserve	Expected Loss Energy
1	0	0.866938	0.000000	0.000000	0.000000
2	20	0.035028	0.000000	0.000000	0.000000
3	30	0.091257	0.000000	0.000000	0.000000
4	40	0.000531	22.727272	10.000000	5.283117
5	50	0.003687	45.454544	20.000000	146.815048
6	60	0.002405	68.181816	30.000000	215.471848
7	70	0.000056	90.909088	40.000000	8.897882
8	80	0.000097	100.000000	50.000000	42.503048
9	90	0.000000	100.000000	60.000000	0.197731
10	100	0.000001	100.000000	70.000000	0.901496
11	110	0.000000	100.000000	80.000000	0.000666
12	120	0.000000	100.000000	90.000000	0.007805
13	140	0.000000	100.000000	110.000000	0.000048

So,

$$\text{LOLP} = 0.003586$$

$$\text{LOLE} = 1.308923 \text{ days/year}$$

$$\text{LOEE} = 420.078705 \text{ Mw-hr}$$

Similarly, Table 4.6 & 4.7 gives the various values of time period, expected load loss and expected loss energy with the help of load duration curve 2 (Appendix A) which is straight line from 100% to 40% having a peak load which is assumed to be constant when period of study is taken as 365 days. From this table generation system reliability indices LOLP, LOLE & LOEE are calculated.

Table 4.6: LOLP using individual probabilities for load duration curve 2

State	Capacity out	Probability	Time	Expected Load Loss
1	0	0.866938	0.000000	0.000000
2	20	0.035028	0.000000	0.000000
3	30	0.091257	0.000000	0.000000
4	40	0.000531	15.151515	0.008041
5	50	0.003687	30.303030	0.111731
6	60	0.002405	45.454544	0.109321
7	70	0.000056	60.606060	0.003386
8	80	0.000097	75.757576	0.007351
9	90	0.000000	90.909088	0.000034
10	100	0.000001	100.000000	0.000147
11	110	0.000000	100.000000	0.000000
12	120	0.000000	100.000000	0.000001
13	140	0.000000	100.000000	0.000000

Table 4.7: LOEE using individual probabilities for load duration curve 2

State	Capacity out	Probability	Time	Capacity Out > Reserve	Expected Loss Energy
1	0	0.866938	0.000000	0.000000	0.000000
2	20	0.035028	0.000000	0.000000	0.000000
3	30	0.091257	0.000000	0.000000	0.000000
4	40	0.000531	15.151515	10.000000	0.008041
5	50	0.003687	30.303030	20.000000	0.111731
6	60	0.002405	45.454544	30.000000	0.109321
7	70	0.000056	60.606060	40.000000	0.003386
8	80	0.000097	75.757576	50.000000	0.007351
9	90	0.000000	90.909088	60.000000	0.000034
10	100	0.000001	100.000000	70.000000	0.000147
11	110	0.000000	100.000000	80.000000	0.000000
12	120	0.000000	100.000000	90.000000	0.000001
13	140	0.000000	100.000000	110.000000	0.000000

So,

$$\text{LOLP} = 0.002400$$

$$\text{LOLE} = 0.876049 \text{ days/year}$$

$$\text{LOEE} = 268.078156 \text{ Mw-hr}$$

When we compare the reliability indices obtained from load duration curve 1 and load duration curve 2, we see that on decreasing the minimum load of the system, reliability of system increases. Similarly, when we increase the maximum load of load duration curve then reliability of system decreases. In above cases, we observe that in second case loss of load and loss of energy during same period of time is less so, reliability of generation system with load duration curve 2 is more than that with load duration curve 1.

4.2 TRANSMISSION SYSTEM RELIABILITY

Results of transmission system reliability evaluation includes state probability table, state frequency table from which probability and frequency of system failure is calculated. We calculate Qs and Fs of transmission system for two case:

- Without overloading condition
- With overloading condition

4.2.1 Without Overloading Condition

Table 4.8: State probabilities without overloading condition

Line out	P(B _j)	P _{g_j}	P _{l_j}	P(system fail individual)
0	0.988446	0.098034	0.000000	0.096901
L1	0.003611	0.098034	0.000000	0.000354
L2	0.004513	0.098034	0.000000	0.000442
L3	0.003385	0.098034	0.000000	0.000332
L1,L2	0.000016	1.000000	0.000000	0.000016
L1,L3	0.000012	1.000000	0.000000	0.000012
L2,L3	0.000015	1.000000	1.000000	0.000015
L1,L2,L3	0.000000	1.000000	1.000000	0.000000

Table 4.9: State frequencies without overloading condition

Line out	Departure rate	F(Bj)	F(system fail individual)
0	12	11.861356	1.162816
L1	1103	3.982671	0.390437
L2	1102	4.973825	0.487604
L3	885	2.995805	0.293691
L1,L2	2193	0.036157	0.036157
L1,L3	1976	0.024434	0.024434
L2,L3	1975	0.030528	0.030528
L1,L2,L3	3066	0.000173	0.000173

Probability of total system failure $Q_s = 0.098074$

Frequency of total system failure $F_s = 2.425840$ f/yr

4.2.2 With Overloading Condition

Table 4.10: State probabilities with overloading condition

Line out	P(Bj)	Pgj	P1j	P(system fail individual)
0	0.988446	0.098034	0.000000	0.096901
L1	0.003611	0.098034	0.000000	0.000354
L2	0.004513	0.098034	1.000000	0.004513
L3	0.003385	0.098034	1.000000	0.003385
L1,L2	0.000016	1.000000	1.000000	0.000016
L1,L3	0.000012	1.000000	1.000000	0.000012
L2,L3	0.000015	1.000000	1.000000	0.000015
L1,L2,L3	0.000000	1.000000	1.000000	0.000000

Table 4.11: State frequencies with overloading condition

Line out	Departure rate	F(Bj)	F(system fail individual)
0	12	11.861356	1.162816
L1	1103	3.982671	0.390437
L2	1102	4.973825	4.973825
L3	885	2.995805	2.995805
L1,L2	2193	0.036157	0.036157
L1,L3	1976	0.024434	0.024434
L2,L3	1975	0.030528	0.030528
L1,L2,L3	3066	0.000173	0.000173

Probability of total system failure $Q_s = 0.105198$

Frequency of total system failure $F_s = 9.614176$ f/yr

By comparing results obtained from section 4.2.1 and 4.2.2, we see that, probability and frequency of failure of transmission system with overloading conditions is more than that of transmission system without overloading conditions.

4.3 COMPOSITE SYSTEM RELIABILITY

Results of composite system reliability includes system state probability and frequency table, load point indices table, annualized load point indices and annualized system indices. System state probability and frequency table includes second order outage condition of both generating units and transmission line to calculate total system failure probability and frequency. It also includes two cases for which we calculate total system failure probability and frequency

- Without overloading condition
- With overloading condition

4.3.1 Without Overloading Condition

Table 4.12: State frequencies & probability table without overloading condition

Element out	P(B _j)	F(B _j)	P1 _j	Prob syst fail (individual)	Freq syst fail (individual)
0	0.856922	18.852274	0.000000	0.000000	0.000000
G1	0.034623	4.154771	0.000000	0.000000	0.000000
G1,G1	0.000525	0.114361	1.000000	0.000525	0.114361
G1,G2	0.003645	0.634149	1.000000	0.003645	0.634149
G1,L1	0.000126	0.153164	0.000000	0.000000	0.000000
G2,L2	0.000158	1.191297	0.000000	0.000000	0.000000
G1,L3	0.000119	0.117742	0.000000	0.000000	0.000000
G2	0.090202	6.855373	1.000000	0.090202	6.855373
G2,G2	0.002374	0.308587	1.000000	0.002374	0.308587
G2,L1	0.000330	0.384534	1.000000	0.000330	0.384534
G2,L2	0.000412	0.480255	1.000000	0.000412	0.480255
G2,L3	0.000309	0.293157	1.000000	0.000309	0.293157
L1	0.003130	3.484032	0.000000	0.000000	0.000000
L1,L2	0.000014	0.031489	1.000000	0.000014	0.031489
L1,L3	0.000011	0.021290	1.000000	0.000011	0.021290
L2	0.003913	4.351127	0.000000	0.000000	0.000000
L2,L3	0.000013	0.026600	1.000000	0.000013	0.026600
L3	0.002935	2.626523	0.000000	0.000000	0.000000

Probability of total system failure $Q_s=0.097834$

Frequency of total system failure $FS=9.149794$

4.3.2 With Overloading Condition

Table 4.13: State frequencies & probability table with overloading condition

Element out	P(B _j)	F(B _j)	P1 _j	Prob syst fail (individual)	Freq syst fail (individual)
0	0.856922	18.852274	0.000000	0.000000	0.000000
G1	0.034623	4.154771	0.000000	0.000000	0.000000
G1,G1	0.000525	0.114361	1.000000	0.000525	0.114361
G1,G2	0.003645	0.634149	1.000000	0.003645	0.634149
G1,L1	0.000126	0.153164	0.000000	0.000000	0.000000
G2,L2	0.000158	1.191297	1.000000	0.000158	0.191297
G1,L3	0.000119	0.117742	1.000000	0.000119	0.117742
G2	0.090202	6.855373	1.000000	0.090202	6.855373
G2,G2	0.002374	0.308587	1.000000	0.002374	0.308587
G2,L1	0.000330	0.384534	1.000000	0.000330	0.384534
G2,L2	0.000412	0.480255	1.000000	0.000412	0.480255
G2,L3	0.000309	0.293157	1.000000	0.000309	0.293157
L1	0.003130	3.484032	0.000000	0.000000	0.000000
L1,L2	0.000014	0.031489	1.000000	0.000014	0.031489
L1,L3	0.000011	0.021290	1.000000	0.000011	0.021290
L2	0.003913	4.351127	1.000000	0.003913	4.351127
L2,L3	0.000013	0.026600	1.000000	0.000013	0.026600
L3	0.002935	2.626523	1.000000	0.002935	2.626523

Probability of total system failure $Q_s=0.104958$

Frequency of total system failure $FS=16.436483$

By comparing results obtained from section 4.3.1 and 4.3.2, we see that, probability and frequency of failure of composite system with overloading conditions is more than that of composite system without overloading conditions.

Table 4.14: Load Point Indices

Element out	P(Bj)	F(Bj)	Cap available	Pkj	Dkj	Lkj	ELC	NLC	EENS	EDLC
0	0.856922	18.852274	140	0.0	398.181818	0.0	0.000000	0.000000	0.000000	0.000000
G1	0.034623	4.154771	120	0.0	73.000000	0.0	0.000000	0.000000	0.000000	0.000000
G1,G1	0.000525	0.114361	100	1.0	40.183486	15.0	1.715417	0.114361	68.931428	4.595429
G1,G2	0.003645	0.634149	90	1.0	50.344828	25.0	15.853732	0.634149	798.153404	31.926136
G1,L1	0.000126	0.153164	120	0.0	7.233691	0.0	0.000000	0.000000	0.000000	0.000000
G2,L2	0.000158	1.191297	86	1.0	7.239669	29.0	5.547599	0.191297	40.162786	1.384924
G1,L3	0.000119	0.117742	95	1.0	8.821752	20.0	2.354845	0.117742	20.773855	1.038693
G2	0.090202	6.855373	110	1.0	115.263158	5.0	34.276863	6.855373	3950.859437	790.171887
G2,G2	0.002374	0.308587	80	1.0	67.384615	35.0	10.800535	0.308587	727.789908	20.793997
G2,L1	0.000330	0.384534	110	1.0	7.506427	5.0	1.922668	0.384534	14.432363	2.886473
G2,L2	0.000412	0.480255	86	1.0	7.512864	29.0	13.927395	0.480255	104.634629	3.608091
G2,L3	0.000309	0.293157	95	1.0	9.230769	20.0	5.863148	0.293157	54.121362	2.706068
L1	0.003130	3.484032	140	0.0	7.870620	0.0	0.000000	0.000000	0.000000	0.000000
L1,L2	0.000014	0.031489	60	1.0	3.976396	55.0	1.731889	0.031489	6.886676	0.125212
L1,L3	0.000011	0.021290	95	1.0	4.410876	20.0	0.425808	0.021290	1.878184	0.093909
L2	0.003913	4.351127	86	1.0	7.877698	29.0	126.182672	4.351127	994.028964	34.276861
L2,L3	0.000013	0.026600	0	1.0	4.413098	115.0	3.058950	0.026600	13.499449	0.117387
L3	0.002935	2.626523	95	1.0	9.787709	20.0	52.530465	2.626523	514.152930	25.707646

4.4 ANNUALIZED LOAD POINT INDICES

(I) Basic Values

- Probability of Failure=0.104958
- Frequency of Failure=16.436483
- Expected no of load curtailment=16.436483
- Expected load curtailment=276.191984
- Expected energy Not Supplied=7310.305374
- Expected Duration of load curtailment=919.432713

(II) Max values

- Max Load Curtailed
 - L2,L3 out, prob = 0.000013, load = 115
- Max Energy Curtailed
 - G2 out, prob = 0.090202, energy curtail = 3950.859375
- Max Duration of load Curtailed
 - G2 out, prob = 0.090202, max duration = 790.171875

(III) Average values

- Average Load Curtailed=16.803594
- Average Energy not Supplied=444.760924
- Average Duration of Curtailment=55.938531

(IV) Bus isolation values

- Expected No of curtailment=0.026600
- Expected Load curtailed=3.058950
- Expected Energy no Supplied=13.499449
- Expected Duration of load Curtailed=0.117387

4.5 ANNUALIZED SYSTEM INDICES

(I) Basic Values

- Bulk power Interruption index = 2.510836 mw/mw-yr
- Bulk power Supply average MW curtailment/disturbance = 16.803594 mw/dis
- Bulk power Energy curtailment Index = 66.457322 mw-hr/mw-yr
- Modified Bulk Power Energy curtailment index = 0.376045

(II) Average values

- Average no of curtailment/load point=16.436483
- Average load curtailed/load point=276.191984 mw/yr
- Average energy curtailed/load point=7310.305374 mw-hr/yr
- Average Duration of load curtailed/load point=919.432713 hr/yr

(III) Max values

- Max System load curtailed Under any contingency condition
 - 115 Mw, L2,L3 out, prob = 0.000013
- Max System Energy not supplied under any contingency condition
 - 3950.859375 Mwhr, G2 out, prob = 0.090202

CONCLUSION & FUTURE SCOPE OF WORK

5.1 CONCLUSIONS

In this thesis work, method has been presented to calculate reliability of composite system by calculating probability and frequency of failure of system under different conditions. The research work done also shows method to calculate various generation system indices and compares them for different load curves. The research work also describes set of indices known as load point indices and system indices to evaluate the performance of composite system. Two set of indices do not replace each other; they complement each other and serve two entirely different functions. Load indices are used for system design, comparing alternative configurations and system additions whereas system indices are useful to management and system planners.

This area of composite power system reliability evaluation is least developed and also one of the most complicated but in view of environmental, ecological, societal and economic constraints faced by most of power utilities, this area is developing and getting attention in international market.

5.2 FUTURE SCOPE OF WORK

After carrying thesis work in composite system reliability evaluation, the presented work can be extended in following area:

- Reliability of complete system which includes generation, transmission and distribution
- Well being analysis of composite power system
- Security analysis of composite power system
- Reliability evaluation of power system for transient conditions

APPENDIX A

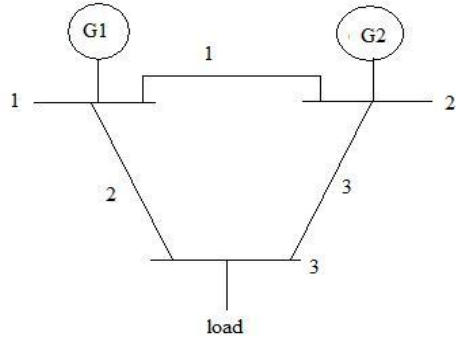


Figure A.1: system configuration

Table A.1: Generation system data

lant	No: of units	Capacity(MW)	Unavailability	λ (f/year)	μ (r/year)
1	4	20	0.01	1	99
2	2	30	0.05	3	57

Table A.2: transmission line data

line	Connected to		λ (f/year)	r (hours)	R (ohms)	X (ohms)	B/2 (mhos)	Rating on 100 MVA base	
	Bus	Bus						(MVA)	(P.U)
1	1	2	4	8	0.0912	0.4800	0.0282	80	0.8
2	1	3	5	8	0.0800	0.5000	0.0212	100	1.0
3	2	3	3	10	0.0798	0.4200	0.0275	90	0.9

Peak load of system is 110 MW

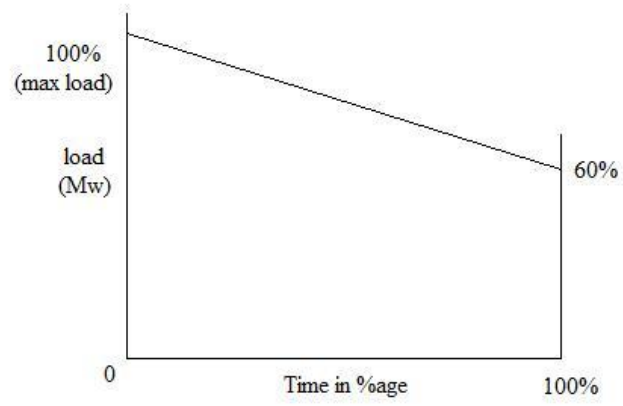


Figure A.2: Load duration curve 1

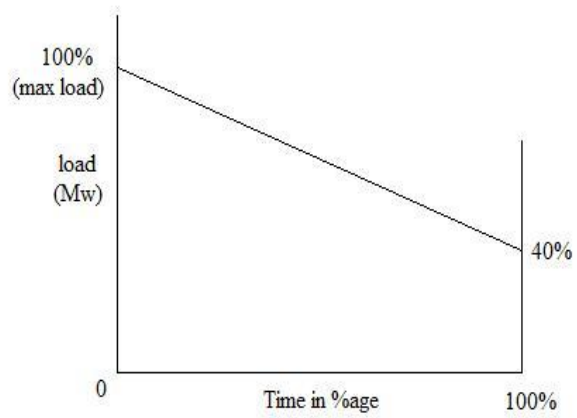


Figure A.3: Load duration curve 2

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