CHAPTER-2

THE BASIC MODELLING APPROACH FOR RELIABILITY EVALUATION
The generation system reliability plays an important role in the planning for future system capacity addition. It is a measure of adequacy such that the total generation system capacity is sufficient to give adequate electricity when required.

2.1 Generation System Reliability

The reliability of generation includes adequacy and security. The adequacy of the system refers to availability of sufficient generators to meet the consumer load demand. The system security means the ability of the system to respond to the disturbances occurring within the system. In this work the adequacy of generation system has been taken into account whereas system security has not been considered (Billinton, R. et al. 1984).

In the basic modelling approach for analysis of adequacy of the generating system the generation and load models are convolved to develop the work model. Alternatively, this can be explained as follows:

1. Generation model is developed using the characteristics of generating units.
2. A load model is developed.
3. Convolution of generation model and load model results in the development of risk model.

This is shown in Fig- 2.1
Fig. 2.1: Elements of generation reliability evaluation

Analytical procedures can be used to determine reliability indices. In this method, system is represented by an analytical model and then indices are calculated using mathematical techniques.

Alternatively, Monte-Carlo Simulation can also be used to calculate indices by simulating the actual process and random behaviour of the system (Billinton, R. et al. 1994).

According to Wang and McDonald (1994), the process of evaluation of power system reliability starts by treating a mathematical model of a system and then proceeding with a numerical solution described as follows:

1. Define boundary of the systems and components included
2. Provide reliability data such as Failure Rate, Repair Rate, Repair Time, Scheduled Maintenance Time, etc. for every component.
3. Develop reliability model for every component.
4. Define criteria model for normal and faulty system.
5. Develop mathematical model for system reliability and its basic assumptions.
6. Decide an algorithm to determine the system reliability indices.
Reliability models can be developed and evaluated as per procedure in Fig. 2.2

![Diagram of Reliability models construction process]

**Fig. 2.2** Reliability models construction process

### 2.2 The Load Model

The load in a power system may not be constant in any period of time and hence it is difficult to represent it by mathematical formula. Thus, different load models are created using primary load data and requirement of reliability calculation. Primary load data contains minimum data that is essential to establish hourly chronological load profile (Blintron R et al. 1984). The primary load data contains percentage of maximum monthly load or weekly load in a year, the load in 24 hour in a typical day in each season and maximum load in each day in a week. Thus knowing the annual peak load the hourly load profile can be obtained. In some other situations the daily peak load for 365 days (one year) are sufficient when the modelling requires the daily peaks. However, these daily peaks are assumed to occur entire day (Billinton, R et al. 1996).
The main requirements of determining the reliability of generation system are capacity of individual generating units as well as the probabilities of individual generating units. The probability of the failure of a unit is given by the following relation

\[ U = \frac{\lambda}{\lambda + \mu} \]  

(2.1)

\( U \) = Unit unavailability, \( \lambda \) = unit failure rate, \( \mu \) = unit repair rate

\( U \) = Also known as force outage rate (FOR) which is defined by following relation

\[ FOR = \frac{\text{Forced Outage Rate}}{\text{In Service Hours} + \text{Forced Outage Hours}} \]  

(2.2)

The value of FOR for a period of 365 days (one year) is same as unavailability defined by equation 2.2.

The capacity and availability of individual units are combined to form generation model and available generation in the system can be obtained. The result of this combination in the capacity models in which each generating unit is denoted by its nominal capacity \( C_i \) and its unavailability \( U_i \) (or FOR). The capacity or the outage capacity \( X \) is considered to be random variable in power system reliability analysis.

The probability model of a two state generator model has only two states, in operation or on outage. There are \( 2^n \) possible different capacity states. The individual state probability can be described by the relation

\[ \begin{align*}
P(X=x_i) = & \begin{cases} 
1- q & x_i = c_i \\
q & x_i = 0 
\end{cases} 
\end{align*} \]  

(2.3)

The cumulative state probability is given by the relation

\[ P(X=x_i) = p(x_i) \text{ where } i=0,1,2,... \]  

(2.4)

\[ P(x_k) = P(X \geq x_k) = \sum_{i \geq k} p(x_i) \]  

(2.5)
The Capacity Outage Probability Table (COPT) can be generated using these above relations (Billinton et al. 1996).

2.3 Generation System Reliability Indices

In order to analyse the reliability of generation System, the quantification of reliability has to be taken into consideration. The reliability performance of a generation system is determined using reliability indices by comparing with some reliability standards, alternative designs and also identifying weak spots and then finding ways to make corrections in the generation system (Chen H, 2000)

In this work probabilistic techniques are used which are useful in design, resource planning and allocation. The two probability techniques used are the Analytical Method and Monte Carlo Simulation as shown in Fig. 2.3.
The analytical technique utilize mathematical models and direct analytical solutions to determine reliability indices (Billinton. R et al. 1994).

In Monte-Carlo Simulation reliability indices are determined by simulating the random behaviour of the system. The reliability indices which are expected values of a random variable are Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE), Loss of Energy Probability (LOEP), Loss of Energy Expectation (LOEE), Expected
Energy Not Served (EENS), Loss of Load Frequency (LOLF) and Loss of Load Duration (LOLD) (Billinton, R et al. 1994).

2.4 Loss of Load

It occurs when the load on the system is more than its capacity. Loss of Load Probability (LOLP) is the expected value of time for which load on the system remains more than the available capacity. 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 (Endrenyi 1978). Mathematically LOLP is given by:

\[ LOLP = \sum_{j} P[C_A = C_j] \cdot P[L > C_j] = \sum_{j} p_j \cdot t_j \]  

(2.6)

Where,

- \( P \) = The Probability of expected Load
- \( L \) = expected Load
- \( C_A \) = available Generating Capacity
- \( C_j \) = remaining Generating Capacity
- \( p_j \) = probability of Capacity Outage
- \( t_j \) = percentage of time when the load exceeds \( C_j \)

In practice Loss of Load Expectation (LOLE) index is more commonly used than LOLP. However, LOLP may be used to calculate LOLE as per following relation

\[ LOLE = LOLP \times T \]  

(2.7)

where \( T=365 \) days = 8760 hours
The LOLP level is selected and used as index for generation reliability assessment (Endrenyi, 1978).

### 2.4.1 Loss of Energy

It is another measure of generation system reliability assessment. It is defined as the ratio of Expected Energy Not Served (EENS) during some large periods of observation to the total energy demand during the same period. The Loss of Energy Probability (LOEP) is calculated using the relation:

\[
LOEP = \sum_k \frac{E_k p_k}{E}
\]  

(2.8)

Where, \(E_k\) = Energy Not Served due to Outage of Capacity \(O_k\)

\(p_k\) = Probability of Outage Capacity \(O_k\)

\(E\) = Total Energy Demand During the period of study

The unit of LOEP is MWh/year and is also known as Loss of Energy Expectation (LOEE) because it is an expected value and not probability. A load duration curve \(C\) Load vs Time can be used to determine the LOEP (Sinden G, 2005).

### 2.5 Intermittent Generation Reliability Model

The conventional generating units utilize fossil fuels for their operation and are available all the time except the interruption of supply. The renewable generation units on the other hand depend for their operation on natural resources as their fuel. The supply of renewable fuels is fluctuating in nature and it fluctuates all the time and time of the day, season of the year. These fluctuations of renewable energy are uncontrollable and hence known as intermittent in nature. The resources are therefore
known as intermittent generation and reliability modelling of such resources is different from conventional generating units.

The predictability and variability of various renewable energy sources is shown in below Fig: 2.4

![Diagram showing variability and predictability of renewable energy sources]

**Fig. 2.4:** Variability and predictability of RE sources (Source: Sinden, 2005)

Intermittent generators have the advantage of providing energy with zero energy cost and reduce emissions. However they provide small contribution to the reliability than conventional generators.

### 2.6 Capacity Credit

Capacity Credit (CC) is a measure of contribution that intermittent generation can make to reliability i.e. as % of installed capacity of intermittent generation. It is the fraction of installed capacity by which the conventional power generation capacity can be reduced without affecting the Loss of Load Probability (LOLP) (Milborrow, 1996).
According to (Ford et al. 2005). Capacity Credit here is defined as the Ratio of Capacity of thermal plant to rated output of wind plant

2.6.1 Retrospective Analysis

It is the modelling approach used to evaluate Capacity Credit of wind plants. In this approach wind plants are modelled as local modifier. The hourly wind generation capacity is deducted from the expected demand, according to Milligan and Porter (2005). This approach can be established by taking hourly wind generation data and actual load data in the reliability model. This approach can then be conducted to determine the LOLP by applying this net equivalent load to hourly load probability table. Milligan and Porter (2005) also suggested that as additional wind production data becomes available over time, a multiyear analysis that pairs actual wind and load data is possible and it can be significant insights into inner annual variability and ELCC over time. The advantage of this approach is that it takes into consideration the detailed chronological variation of wind plant output. But the drawback of this approach according to Milligan (1996) is that it does not allow the variance of Wind plant output to be captured and quantified into LOLP calculation. There are two techniques to represent the Capacity Credit of wind generator using this method. They are firm capacity method and equivalent capacity method (Milligan et al. 2005).

2.6.2 Firm Capacity Method/ Effective Load Carrying Capability (ELCC) Method

These techniques are based on LOLP measure of system reliability and utilize LOLP calculations in such a manner that the addition of a new generator becomes a benchmark against an ideal perfect reliable unit with 100% availability (Milligan, et al.
Many studies that incorporate the use of electric utility reliability and production cost models characterize wind plants by load modification technique and measure capacity as measured with effective load carrying capability (ELCC) (Milligan, 1996). ELCC can differentiate among generators with differing level of reliability, size and on peak vs off-peak delivery. It also gives information about the plants that are able to supply during periods of peak demand it also marks less reliable unit by calculating a lower Capacity Credit. The following data is required for the calculation of ELCC

- Hourly Load Demand
- Rated Capacity, FOR and maintenance schedule of conventional generators
- Intermittent wind power output data of more than one year
  - According to Milligan and Porter (2005). ELCC can be evaluated as per the steps given below
- The system is modelled without the intermittent generator of interest.
- The loads are adjusted to achieve a given level of reliability i.e. LOLE of 1 day/10 years.
- Once the desired LOLE is achieved the renewable generator is added to the system and the model is re-run.
- The new, lower LOLE is noted and the generator is removed from the system.
- The benchmark unit is added to the system in small incremental capacities until the LOLE with benchmark unit matches the LOLE that was achieved with renewable generator.
The Capacity of benchmark unit is then noted and that become the ELCC of this renewable generator.

2.6.3 Equivalent practical or operable

This method is more practical or operable than ELCC method as it provides more practical value of Capacity Credit then using the ideal perfect reliable unit in Firm Capacity or ELCC method. In this method alternative unit is substituted instead of and ideal unit which is sized so that the LOLP calculation is same as that calculated with wind plant instead of gas plant (Miligan et al. 2005)

2.6.4 Prospective Analysis

According to Milligan and Porter (2005), prospective analysis gives the information of how the wind affects future system reliability, may involve modelling wind in probabilistic way. The approach modelled wind plants with capacity level and effective FOR that takes into consideration both mechanical and fuel (i.e., wind) availability. According to Milligan and Porter (2005), this approach generally involves modelling wind as multi block conventional generator. Several levels of wind output can be calculated and matched with the probability of obtaining that output. These values are then converted into the form that is acceptable by the reliability model so that these capacities and probabilities look like forced outage rates at different output levels (Milligan et al. 2005).
2.7 Reliability Curves

Using similar techniques as retrospective approach the reliability indices (LOLE) can be obtained by varying the annual peak load. The LOLE vs System Load curves can be plotted as shown:

The LOLE can be plotted against the system load for two cases; without wind generation and with wind generation. The two curves can be plotted as shown in an example in Figure 2.5 and this curves show the relationship between a risk index (LOLE) and the annual peak load before and after adding the wind generator. For a predetermined level of reliability, 0.1 days per year in this case, the ELCC for the wind plant can be evaluated by taking the difference between load values at the reliability level for the two curves.

![Figure 2.5: Reliability curves for calculating ELCC of a wind plant](image)

This curve shows the relationship between LOLE and annual peak load. The two curves plotted without wind generation and with wind generation respectively. The ELCC for a wind plant can be calculated by taking the difference between the load values at predetermined reliability value for two curves (Awerbuch Shimon, 2003).
2.8 Approximation Methods (Milligan and Porter, 2005) Capacity Factor

The capacity factor of a wind plant can be used to approximate the capacity credit. According to Milligan (2001) from system planner’s point of view the capacity factor is defined as the ratio of statistically expected output divided by annual energy output, is the first stage approximation to overall Capacity Credit (Milligan et al. 2005).

2.8.1 Effects of Intermittent Generation on System Reliability

Intermittent and variable output must be taken into account while considering the generation source. According to Butler (2001) the intermittent and variable generation source may not be suitable as base-load plant but these contribute more to ancillary services, peak demand and seasonal variations. Butler (2001) also suggested that right mix and location of intermittent renewable generation with appropriate aggregation may provide opportunities for provision of base-load output. Grubb (1997) suggested that by using combination of different variable sources, hydro, storage and/or trade there seems no technical reason why large systems should not derive well over half their power from variable source. The effects of intermittency are more noticeable at higher levels. Anderson and Leach (2002) suggest that back-up facilities or electricity storage have been highlighted as potential technologically and economically necessary responses to such effects (Anderson, et al. 2001).

2.9 SOURCES OF DATA

The data used in this work is taken from the Institute of Electrical and Electronics Engineer’s Reliability Test System 1996 (IEEE RTS). This Reliability Test System is
developed by Reliability Test System Task Force for use in bulk power system reliability evaluation studies. According to IEEE RTS Task Force of APM sub-committee 1999, the value of test system is that it will permit comparative and benchmark studies to be performed on new and existing reliability evaluation techniques (IEEE, RTS (1999)). In fact, this test system is an updated version of original IEEE RTS developed in 1979. It was designed and used as reference system that contains the core data and system parameters necessary for composite reliability evaluation methods.

According to the IEEE RTS Task Force of APM sub-committee (1999), in 1986 a second version of the RTS was developed (RTS-86) and published with the objective of making the RTS more useful in assessing different reliability modelling and evaluation methodologies. The advantage of the RTS-86 is that it presented the system reliability indices derived through the use of rigorous solution technique without any approximation in evaluation process. These exact indices can then be used to compare with results obtained from other methods.

The parameters of RTS-96 can be used as references for testing the impact of different evaluation techniques on wide application and technologies.

The load and data of generating units of IEEE RTS 96 is summarized in Appendix A. Table A-1 in Appendix A shows the weekly peak loads in percent of annual peak. Table A-2 in Appendix A shows the assumed daily peak load in percent of weekly peak while table A-3 shows the hourly load in percent of daily peak. The peak demand of load profile is assumed 2850 MW for India. The weekly peak loads of 52 weeks, daily peak loads for 7 day and 24 hourly peak loads in combination with annual peak load results in Hourly load model for a year of 8736 hours.
Table A-4 in Appendix A shows the generating units data with unit unavailability due to maintenance work.

Three sets of hourly data for year 2001 and 2002 wind power output are obtained from three different wind forms located in Scotland. The three set of actual data collected from the site are used in this work for modelling of wind reliability system. Further, 2012 England and Wales Electricity Demand Profile (2002 Great Britain demand profile) is also used in this study.