

Load Forecasting

- Forecasting refers to the prediction of the load behavior for the future
- It is well understood that both the energy (MWh, kWh) and the power (MW, kW) are the two basic parameters of a load
- By load, we mean the power
- If the load shape is known, the energy can be calculated from its integral

Load Driving Parameters

These driving parameters are:

Time factors such as:

- Hours of the day (day or night)
- Day of the week (weekday or weekend)
- Time of the year (season)

- Weather conditions (temperature and humidity)
- Class of customers (residential, commercial, industrial, agricultural, public, etc.)
- Special events (TV programs, public holidays, etc.)
- Population
- Economic indicators (per capita income, Gross National Product (GNP), Gross Domestic Product (GDP), etc.)
- Trends in using new technologies
- Electricity price

- ❑ we normally classify load forecasting methods into Short-Term Load Forecasting (STLF), Medium-Term Load Forecasting (MTLF), and Long-Term Load Forecasting (LTLF) methods
- ❑ The STLF methods are used for hour-by-hour predictions while LTLF may be used for the peak seasonal predictions. STLF may be used for 1 day to 1 week, while LTLF may be used for several years
- ❑ For instance, GDP may have strong effects on LTLF; while ineffective in STLF. On the other hand, TV programs are effective in STLF but ineffective in LTLF.
- ❑ STLF normally results in an hour-by-hour forecast (for 1 day to 1 week)
- ❑ MTLF normally results in a daily forecast (for several weeks to several months)
- ❑ LTLF focuses on monthly or seasonal forecasts (the peak of the month or the season) for several years from now
- ❑ Due to inaccuracies involved in long-term driving parameters, it is of common practice to perform LTLF for several scenarios (such as various GDPs, weather forecasts, etc.).

Long-Term Load Forecasting Methods

- ❖ Trend analysis,
- ❖ Econometric modeling,
- ❖ End-use analysis and
- ❖ Combined analysis (Econometric modeling + End-use analysis)

Trend Analysis

- The trend extrapolation method uses information of the past to forecast the load of the future

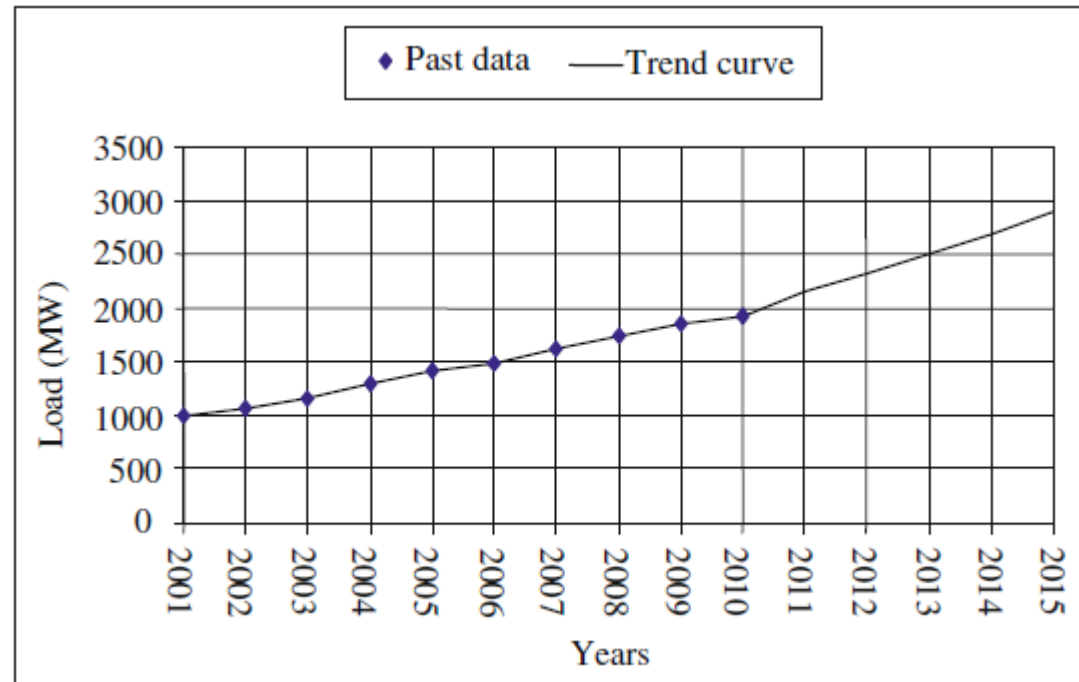


Fig.1 Trend Analysis

- A simple example is shown in Fig.1, in which the load is shown for the last 10 years and predicted to be 2906 MW in 2015.
- A curve-fitting approach may be employed to find the load of the target year. This approach is simple to understand and inexpensive to implement.
- However, it implicitly assumes that the trends in various load-driving parameters remain unchanged during the study period. For instance, if there is a substantial change in economic growth, the approach fails to forecast the future load, accurately.
- In a modified method, more weights may be attached to the loads towards the end of the past period

Econometric Modeling

- In this approach, initially, the relationship between the load and the driving parameters is estimated. The relationship may be nonlinear, linear; additive or in the form of multiplication.
- This relationship is established based on available historical data. Various driving parameters may be checked to find the ones that have the dominant effects.

A typical nonlinear estimation is:

$$D_i = a (\text{per capita income})_i^b (\text{population})_i^c (\text{electricity price})_i^d$$

where i denotes the year and a , b , c and d are the parameters to be determined from the historical data

Once this relationship is established, the future values of the driving variables (i.e. per capita income, population, electricity price, etc.) should be projected. D_i for a future year can then be determined.

- This approach is widely used and may be applied to various customer classes (residential, commercial, etc.) and to the system as a whole.
- The drawback is the assumption of holding the relationship established for the past to be applicable to the future

End-use Analysis

This type of analysis is mostly confined to residential loads but may be applied with some modifications to other load classes, too.

As a simple example refrigerator is concerned, based on the number of households and estimating the percent of households having a refrigerator, the number of refrigerators for a future year may be estimated

Following that and based on the average energy use of such an appliance, the total energy consumption of refrigerators may be estimated.

It is obvious that the average energy use is dependent on the intensity of appliance use, its efficiency, and the thermal efficiency of homes. The same procedure may be applied to other type of appliances and equipment in order to forecast the total energy requirement.

As evident, this approach explicitly predicts energy consumption. If the load is to be estimated, some indirect approaches have to be used to convert the predicted energy to load (power demand).

This approach may lead to accurate results if its extensive accurate data requirements can be provided. Various driving parameters effects may be taken into account.

CHAPTER 6

MARKOV ANALYSIS

6.1 INTRODUCTION

Markov Analysis (MA) is the mathematical abstractions to model simple or complex concepts in quite easily computable form. The MA has also considered powerful modeling and analysis tool in solving reliability tribulations. MA is a tool for modeling complex system designs involving timing, sequencing, repair, redundancy, and fault tolerance. The availability and maintainability of the modern wind turbines are increased considerably, but the failure of the WT depends on many factors such as wind speed, wind direction and location, but they are natural. The natural events do not depend on the past events. The main purpose of determining the system availability is to identify the flaw of the system and enumerate the failure rate (λ), repair rate (μ) and probability of failure of the different components. The reliability is a function of mission time, type of failure and repair characteristics of the system and all its components. The availability of the system depends on the individual component down time, repair time, grid down time and mean active maintenance time. In the modern age, the higher reliability requirement systems are getting complicated because of the control system, computing system multistage interconnection and critical power system. This complexity causes frequent failures. The MA is used to determine such measures as the probability of being in a given state at a given point of time.

Markov chains are random processes in which changes occur only at fixed times. The most common methods currently utilized in practice for

quantifying the reliability of the WTS with sub assemblies having failure rates are based on Fault tree analysis. They are easy to solve and accuracy, dependability and availability and safety of the component at different states cannot be predictable. In this work, MA is accomplished by drawing system state transition diagram for analyzing how undesired state is reached. The main objective of this research is to carry out a MA on the constant speed and constant pitch wind turbines of 250 kW, 225 kW and 400 kW respectively, by considering all the major sub assemblies to quantify the probability and reliability at Muppandal site, India.

6.1.1 Advantage of MA For Reliability Analysis

1. The Markov model allows us to model the system to investigate the system in terms of model parameters.
2. The graphical representation helps us to understand the model and the system behavior.
3. A state diagram is more accurate in certain situations where the system has to be modeled in terms of interdependencies of states and actions.
4. Markov model allows us to model and to assess the probability of decreased performance and its effect on accomplishing the stated mission objectives.
5. Markov allows us to specify different types of states and state groups for observation.

6.2 IMPORTANT TERMINOLOGIES OF MA

6.2.1 Markov Diagram

Markov diagram is a graphical representation of the Markov model. It has states and transitions to model.

6.2.2 State

It represents all possible "conditions" the system can exist in. The system can only ever be in one state at a time. A single state must be set up as the initial starting state. The states are represented in circles. A failed state is represented by a small circle on top of the state. To complete the model, there must be at least one failed state in the system and the initial state of the system must be defined properly. Initial state can be any one state or it might be defined using probability of multiple states being initial states.

6.2.3 Transition

Transition rates represent the rate at which the Markov diagram moves from one state to another. The transition rate from a working state to a failed state is represented by the failure rate (λ) whereas the transition from a failed state to working state is represented by the repair rate (μ). The transitions are represented by the connections linking the circular states, with arrows indicating the transition direction. The λ and μ are in opposite direction.

6.2.4 State Transition Diagram

The reliability behavior of a system is represented using a state-transition diagram, which consists of a set of discrete states that the system

can be in, and defines the speed at which transitions between those states take place.

6.2.5 Phase

Phases define the slices of time in which the total mission time can be divided. There may be circumstances where certain states, or the order of states, will vary for different phases of the system lifetime.

6.2.6 State Group

State group is simply a group of Markov states. It means grouping of states and providing a sub set of analysis results for that group, in addition to the overall system results.

6.3 ASSUMPTIONS

In this research, the following assumptions are made in Markov analysis to compute the availability of WT.

6.3.1 MA Assumptions

1. The probability that an item in the system either will change from one state to another or remain in its current state is a function of the transition probabilities only.
2. Simultaneous component failure events are considered insignificant.
3. The transition probabilities remain constant over time.
4. There are a limited or finite number of possible states.

5. We can predict any future state from the previous state and the matrix of transition probabilities.
6. The size and makeup of the system do not change during the analysis.

6.3.2 Availability Analysis Assumptions

1. Failure of any sub assembly makes the WT shutdown for replacement or repair.
2. After any repair or replacement, a failed component will be restored as good as new.

6.4 WTS AND ITS SUB ASSEMBLIES

The block diagram shown in Figure 6.1 is similar to WTS in Figure 1.3, but the mechanical and hydraulic systems of rotor system are combined to get a state transition. Similarly the hydraulic and mechanical brake systems are also combined together.

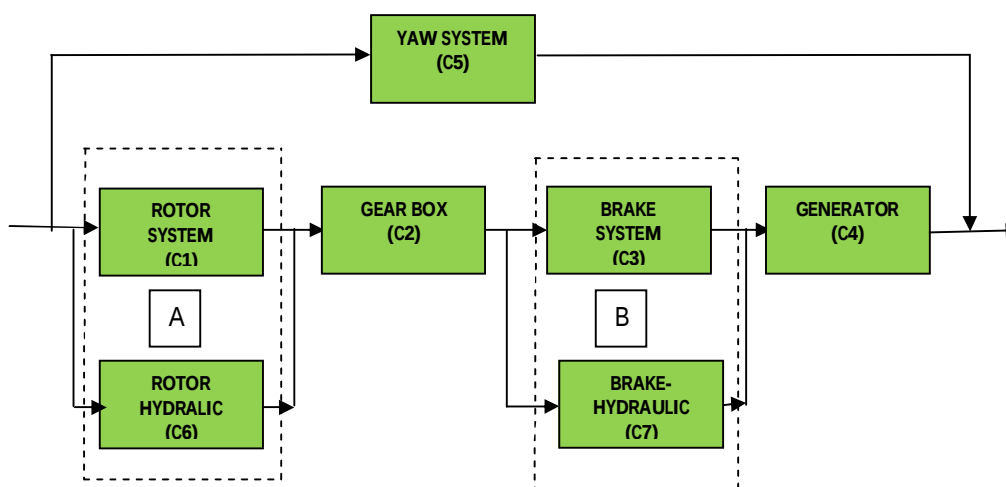


Figure 6.1 Block diagram of WTS and its Sub assemblies

6.5 BLOCK DIAGRAM OF MA FOR WTS

MA is an analysis technique for modeling system transitions and calculating the probability of reaching various system states from the model. MA is a tool for modeling complex system designs involving timing, sequencing, repair, redundancy and fault tolerance. The Figure 6.2 shows the block diagram of MA for WTS and its sub assemblies.

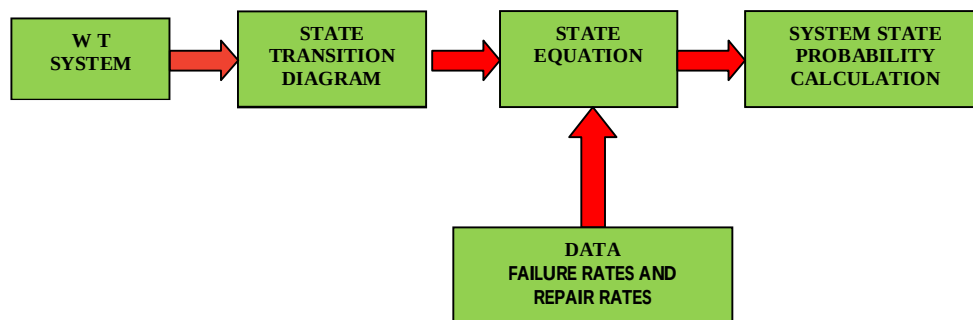


Figure 6.2 Block diagram of MA for WTS and its Sub assemblies

MA accomplished by drawing the system state transition diagram to denote how some undesired states are reached and their relative probability. The Markov process is a random process in which changes occurs continuously over a period time, where the future depends only on the present state and is independent of the past history.

MA can be used to model system performance, dependability, availability, reliability, and safety. MA describes failed states or partially failed states where some functions are performed. This research deals with the availability analysis by MA for the major components of WT, such as the rotor system, gear system, brake system, generator system, hydraulic system and yaw system at uncertain wind. Uncertain wind means the direction and velocity of the wind changes frequently. The uncertainty of wind occurs in the main pass and hill areas. The main objective of this work is to increase the

efficiency of power generation by improving the life of the component which has premature failure. The system availability is calculated through a study of MA for a twenty numbers of grid connected wind turbines of 250 kW under successfully completing an intended mission for a specified period of a constant three year interval time over a span of 15 years at Muppandal site, India.



Figure 6.3 Markov Analysis Procedure

6.6 STATE TRANSITION DIAGRAM (STD)

6.6.1 STD for Single Component with Two States

This research considers the failure rate of sub assemblies that are highly critical. To illustrate the methodology of this research consider a simple element with two states and two elements with five states as shown in the Figure 6.4 and 6.5. The relevance of single element is shown in Table 6.1. For a two component system, the failure occurs only when 'A' fails

or component 'A' failed before component B and its relevance is shown in Table 6.2.



Figure 6.4 State Transition Diagrams for Single Component with of two states

Table 6.1 Relevance of single component with two states

State	Component A	System State	Probability in state at time t
1	Success	Success	$X_1(t)$
2	Failure	Failure	$X_2(t)$

6.6.2 STD for Two Components with Five States

The gear system, generator system and yaw system are considered as single component with two states. The rotor system and the brake system are considered as two parallel components connected with five states. The rotor hydraulic control system is connected parallel to rotor. If the rotor hydraulic control fails before the rotor then the system will be a success. If the rotor or both fails then the system can be a failure. Similarly for the brake system, the brake hydraulic control is connected parallel to the brake system. If the brake hydraulic control fails before the brake system then the system will be a 'success'. If the brake system or both fails, then the entire brake system can fail. The probability rate is derived as given in Equation (6.1).

$$p(t) = \frac{\lambda}{\lambda + \mu} - \frac{\lambda}{\lambda + \mu} e^{-(\lambda + \mu)t} \quad (6.1)$$

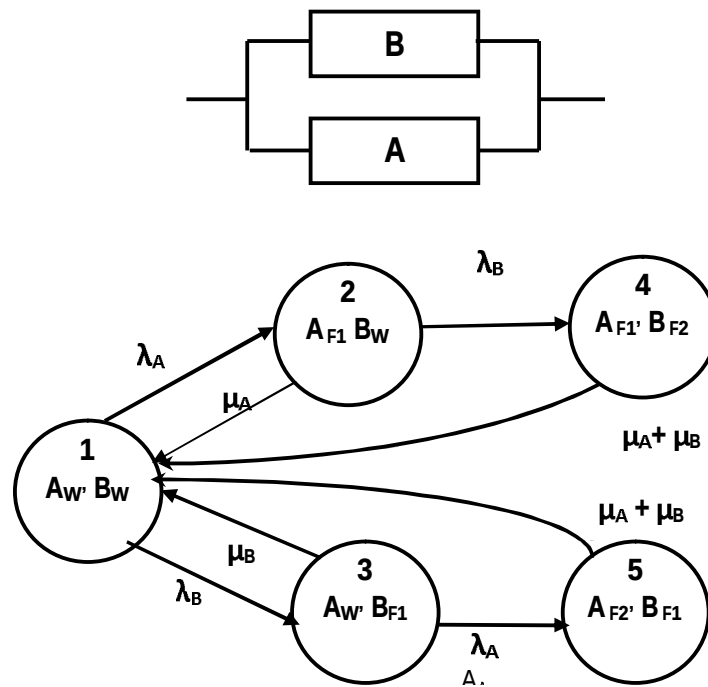


Figure 6.5 State Transition Diagram for Two Parallel Components with five states

Table 6.2 Relevance of Two components with of five states

State	Component A (Rotor)	Component B (Rotor Hydra)	System State	Probability of being in state at time t
1	Success	Success	Success	$X_1(t)$
2	Failure	Success	Failure	$X_2(t)$
3	Success	Failed	Success	$X_3(t)$
4	A Failed before B	Success	Failure	$X_4(t)$
5	Success	B Failed before A	Success	$X_5(t)$

The MA provides the result of the probability that the system will be in a given state as a function of time. For instance, assuming that at $t = 0$ the system is in state 1, making state 1 the 'initial state', computations are performed to determine the probabilities that the system will be in state 1, 2, and 3 at any given time 't'. At each point in time, the sum of probabilities of the states must add up to 1, if the probability that the system is in one state decreases by a certain amount x , that same amount x must be distributed over the other states in the system.

The Figure 6.5 shows a Markov transition diagram for a two component system comprised of component B and A. A_w designates component A is working and A_F points out that the component A is failed. S1, S2, S3, S4 and S5 are the states of the system. The system success requires both must operates successfully at the same time. The system failure occurs only both fail, but if A fails before B.

The Markov differential equations are developed by describing the probability being in each system state $t + \Delta t$ as a function of state of the system at time t . The probability being in first state (S1) at time t not transitioning out during Δt . The equation can be written as

$$P_1(t + \Delta t) = P_1(t) \cdot [1 - (\lambda_A + \lambda_B) \cdot \Delta t] \quad (6.2)$$

The probability being in state S2 at time $t + \Delta t$ is equal to the probability of being in state S2 at time t and not transitioning out during Δt . This equation can be written as

$$P_2(t + \Delta t) = P_1(t) \cdot \lambda_A \cdot \Delta t + P_2(t) \cdot (1 - \lambda_B \cdot \Delta t) \quad (6.3)$$

The remaining state equations are obtained as follows

$$P_3(t + \Delta t) = P_1(t) \cdot \lambda_B \cdot \Delta t + P_3(t) \cdot (1 - \lambda_A \cdot \Delta t) \quad (6.4)$$

$$P_4(t + \Delta t) = P_2(t) \cdot \lambda_B \cdot \Delta t + P_4(t) \quad (6.5)$$

$$P_5(t + \Delta t) = P_3(t) \cdot \lambda_A \cdot \Delta t + P_5(t) \quad (6.6)$$

Rearranging the equations (6.4) (6.5) and (6.6), we get

$$P_1(t + \Delta t) = P_1(t) - P_1(t)(\lambda_A + \lambda_B) \cdot \Delta t \quad (6.7)$$

$$P_1(t + \Delta t) - P_1(t) = -P_1(t)(\lambda_A + \lambda_B) \cdot \Delta t \quad (6.8)$$

$$\frac{P_1(t + \Delta t) - P_1(t)}{\Delta t} = -(\lambda_A + \lambda_B)P_1(t) \quad (6.9)$$

Similarly

$$\frac{P_2(t + \Delta t) - P_2(t)}{\Delta t} = \lambda_A P_1(t) - \lambda_B P_2(t) \quad (6.10)$$

$$\frac{P_3(t + \Delta t) - P_3(t)}{\Delta t} = \lambda_B P_1(t) - \lambda_A P_3(t) \quad (6.11)$$

$$\frac{P_4(t + \Delta t) - P_4(t)}{\Delta t} = \lambda_B P_2(t) \quad (6.12)$$

$$\frac{P_5(t + \Delta t) - P_5(t)}{\Delta t} = \lambda_A P_3(t) \quad (6.13)$$

The matrix form of above Equations (6.9), (6.10), (6.11), (6.12) and (6.13) is

$$\begin{bmatrix} P_1(t + \Delta t) / \Delta t \\ P_2(t + \Delta t) / \Delta t \\ P_3(t + \Delta t) / \Delta t \\ P_4(t + \Delta t) / \Delta t \\ P_5(t + \Delta t) / \Delta t \end{bmatrix} = \begin{bmatrix} -(\lambda_A + \lambda_B) & 0 & 0 & 0 & 0 \\ \lambda_A & -\lambda_B & 0 & 0 & 0 \\ \lambda_B & 0 & -\lambda_A & 0 & 0 \\ 0 & \lambda_B & 0 & 0 & 0 \\ 0 & 0 & \lambda_A & 0 & 0 \end{bmatrix} \quad (6.14)$$

The solution of this Equation (6.14) provides the probability of being in each state.

Similarly by considering repair rate and failure rate

$$\frac{dP_1(t)}{dt} = \mu_A P_2(t) + \mu_B P_3(t) - (\lambda_B + \mu_B) P_1(t) \quad (6.15)$$

$$\frac{dP_2(t)}{dt} = \mu_B P_4(t) + \lambda_A P_1(t) - (\lambda_A + \mu_A) P_2(t) \quad (6.16)$$

$$\frac{dP_3(t)}{dt} = \mu_A P_5(t) + \lambda_B P_1(t) - (\lambda_B + \mu_B) P_3(t) \quad (6.17)$$

$$\frac{dP_4(t)}{dt} = \lambda_B P_2(t) - \mu_B P_4(t) \quad (6.18)$$

$$\frac{dP_5(t)}{dt} = \lambda_A P_3(t) - \mu_A P_5(t) \quad (6.19)$$

$$[P] = \begin{bmatrix} -(\lambda_B + \mu_B) & \mu_A & \mu_B & 0 & 0 \\ \lambda_A & -(\lambda_A + \mu_A) & 0 & \mu_B & 0 \\ \lambda_B & 0 & -(\lambda_B + \mu_B) & 0 & \mu_A \\ 0 & \lambda_B & 0 & -\mu_B & 0 \\ 0 & 0 & \lambda_A & 0 & -\mu_A \end{bmatrix} \quad (6.20)$$

The solution of this Equation (6.20) provides the probability of being in each state by considering failure rate and repair rate.

6.7 MA OF WIND TURBINES

MA is an analysis technique for modeling system transitions and calculating the probability of reaching various system states from the model. MA is a tool for modeling complex system designs involving timing, sequencing, repair, redundancy and fault tolerance. MA accomplished by drawing the system STD to denote how some undesired states are reached and their relative probability. The Markov process is a random process in which changes occurs continuously over a period of time, where the future depends only on the present state and is independent of the past history.

In this work MA is carried out by three types, they are

1. WT as whole system (3 different capacity WT)
2. WT and its sub assembly (3 different capacity WT)
3. WT and its sub assembly(20 numbers of 250 kW Capacity)

6.8 MA FOR WT AS WHOLE SYSTEM WITH THREE DIFFERENT CAPACITY WT

The wind turbines each with a capacity of 225kW, 250 kW and 400 kW are considered for this research. These three wind turbines are constant pitch and constant speed WT with Micon made and they are sited close to each other at Aramboly, Muppandal main pass.

6.8.1 STD for whole WT with 128 States

The State Transition diagram (STD) is used to give an abstract description of the behavior of a WTS. STD is a directed graph representation of system states, transitions between states, and transition rates. These diagrams contain sufficient information for developing the state equations, which are used for probability calculations. There are 128 states obtained for 7 components of WTS as shown in Figure 6.6, and it is listed in the Table 6.3. The states 6, 7, 8, 22, 23, 29 and 54 are successful states of the system and the remaining all are the failure states of the WTS. The failure rates $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6$ and λ_7 are in the forward direction and they denote the failure rates of rotor, gear, brake system, generator, yaw system, hydraulic control of rotor and hydraulic control of brake of the WT states. Similarly, $\mu_1, \mu_2, \mu_3, \mu_4, \mu_5, \mu_6$ and μ_7 are the repair rates and their transition rates are given in the reverse direction. The individual component failure rate and repair rate are calculated by the following formula:

$$\begin{aligned} \text{Failure rate}(\lambda) &= \frac{1}{\text{MTBF}} \\ \text{Repair rate}(\mu) &= \frac{1}{\text{MTTR}} \end{aligned} \tag{6.21}$$

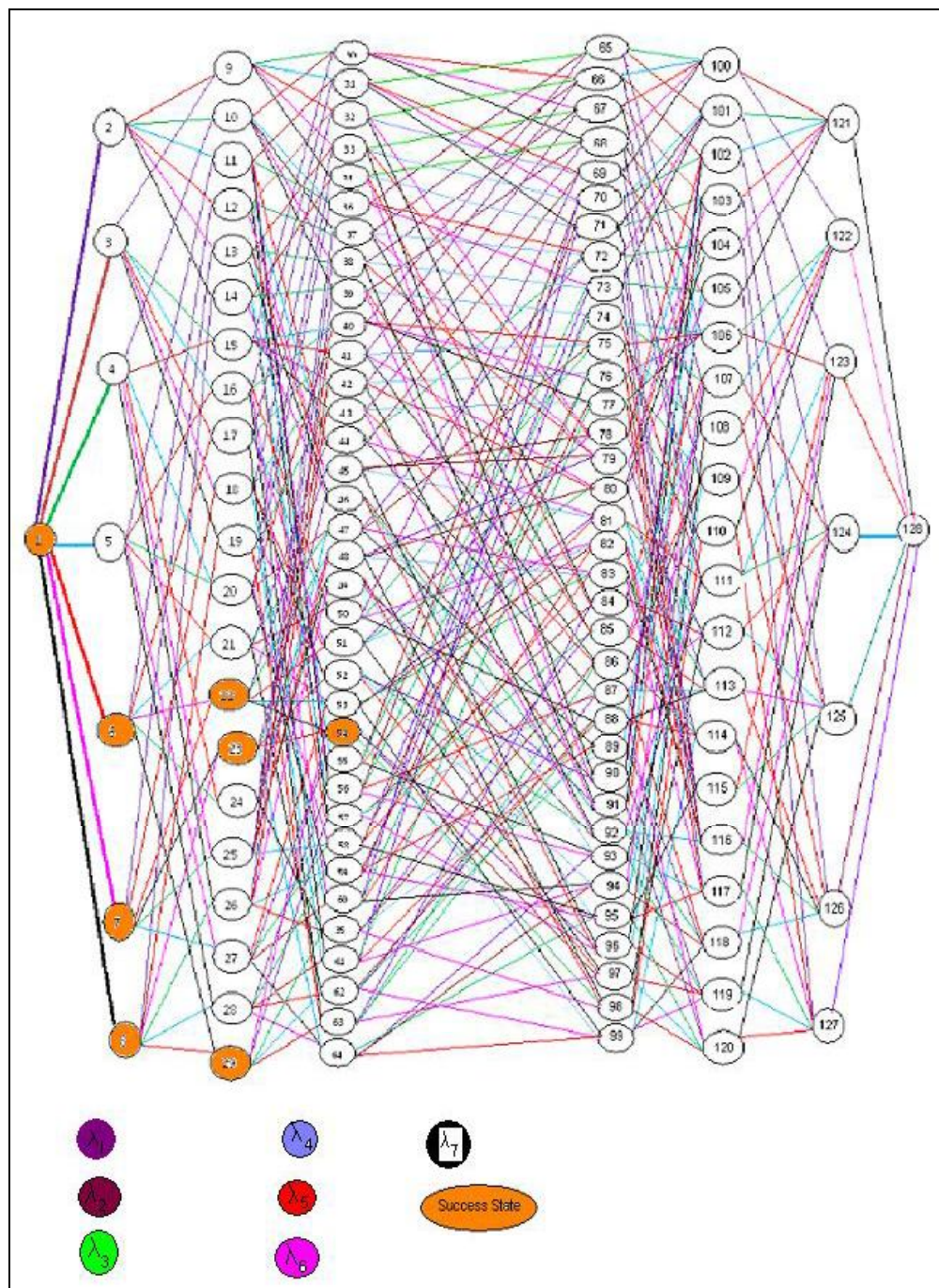


Figure 6.6 STD of WTS

Table 6.3 Relevance of WTS

Sl No	Component							State
	C1	C2	C3	C4	C5	C6	C7	
1	S	S	S	S	S	S	S	S
2	F	S	S	S	S	S	S	F
3	S	F	S	S	S	S	S	F
4	S	S	F	S	S	S	S	F
5	S	S	S	F	S	S	S	F
6	S	S	S	S	F	S	S	S
7	S	S	S	S	S	F	S	S
8	S	S	S	S	S	S	F	S
9	F	F	S	S	S	S	S	F
10	F	S	F	S	S	S	S	F
11	F	S	S	F	S	S	S	F
12	F	S	S	S	F	S	S	F
13	F	S	S	S	S	F	S	F
14	F	S	S	S	S	S	F	F
15	S	F	F	S	S	S	S	F
16	S	F	S	F	S	S	S	F
17	S	F	S	S	F	S	S	F
18	S	F	S	S	S	F	S	F
19	S	F	S	S	S	S	F	F
20	S	S	F	F	S	S	S	F
21	S	S	S	F	F	S	S	F
22	S	S	S	S	F	F	S	S
23	S	S	S	S	S	F	F	S
24	S	S	F	S	F	S	S	F
25	S	S	F	S	S	F	S	F
26	S	S	F	S	S	S	F	F
27	S	S	S	F	S	F	S	F
28	S	S	S	F	S	S	F	F
29	S	S	S	S	F	S	F	S
30	F	F	F	S	S	S	S	F
31	F	F	S	F	S	S	S	F
2	F	F	S	S	F	S	S	F
33	F	F	S	S	S	F	S	F
34	F	F	S	S	S	S	F	F
35	S	S	F	S	F	S	F	F
36	F	S	F	F	S	S	S	F
37	F	S	F	S	F	S	S	F
38	F	S	F	S	S	F	S	F
39	F	S	F	S	S	S	F	F
40	S	F	F	F	S	S	S	F
46	F	S	S	S	S	F	F	F
47	S	S	F	F	F	S	S	F
48	S	S	F	S	F	F	S	F
49	S	S	F	S	S	F	F	F
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55	F	S	S	F	S	F	S	F
56	F	S	S	F	S	S	F	F
57	F	S	S	S	F	S	F	F
58	S	S	F	F	S	F	S	F
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77	S	F	F	F	S	S	F	F
78	F	F	S	S	F	F	S	F
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80	S	F	F	S	F	F	S	F
81	F	S	S	F	F	F	S	F
82	S	F	S	F	F	F	S	F
83	S	S	F	F	F	F	S	F
84	F	F	S	S	F	S	F	F
85	F	S	F	S	F	S	F	F

Table 6.3 (Continued)

41	S	F	F	S	F	S	S	F		86	S	F	F	S	F	S	F	F
42	S	F	F	S	S	F	S	F		87	F	S	S	F	F	S	F	F
43	S	F	F	S	S	S	F	F		88	S	F	S	F	F	S	F	F
44	F	S	S	F	F	S	S	F		89	S	S	F	F	F	S	F	F
45	F	S	S	S	F	F	S	F		90	F	F	S	S	S	F	F	F
91	F	S	F	S	S	F	F	F		110	S	F	F	F	F	S	F	F
92	S	F	F	S	S	F	F	F		111	F	F	F	S	S	F	F	F
93	F	S	S	F	S	F	F	F		112	F	F	S	F	S	F	F	F
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98	S	S	F	S	F	F	F	F		117	S	F	F	S	F	F	F	F
99	S	S	S	F	F	F	F	F		118	F	S	S	F	F	F	F	F
100	F	F	F	F	F	S	S	F		119	S	F	S	F	F	F	F	F
101	F	F	F	F	S	F	S	F		120	S	S	F	F	F	F	F	F
102	F	F	F	S	F	F	S	F		121	F	F	F	F	F	F	S	F
103	F	F	S	F	F	F	S	F		122	F	F	F	F	F	S	F	F
104	F	S	F	F	F	F	S	F		123	F	F	F	F	S	F	F	F
105	S	F	F	F	F	F	S	F		124	F	F	F	S	F	F	F	F
106	F	F	F	F	S	S	F	F		125	F	F	S	F	F	F	F	F
107	F	F	F	S	F	S	F	F		126	F	S	F	F	F	F	F	F
108	F	F	S	F	F	S	F	F		127	S	F	F	F	F	F	F	F
109	F	S	F	F	F	S	F	F		128	F	F	F	F	F	F	F	F

6.8.2 Relevance of WTS

The relevance of 128 states is shown in Table 6.3, For 128 states on seven states are success and the left over 121 states are failure states.

The common approach for representing the failure cause information is as shown in Table 6.4. The MTBF of the 225 kW varies from 24,162 to 25,380 hours. In the years 1995 – 1997, the larger failure has occurred in the gear box which is 254 hours and the next is rotor. In the years 2001-2003 and 2007 – 2010, the highest failure has occurred in the rotor. The Markov analysis for revised transition is shown in Figure 6.7.

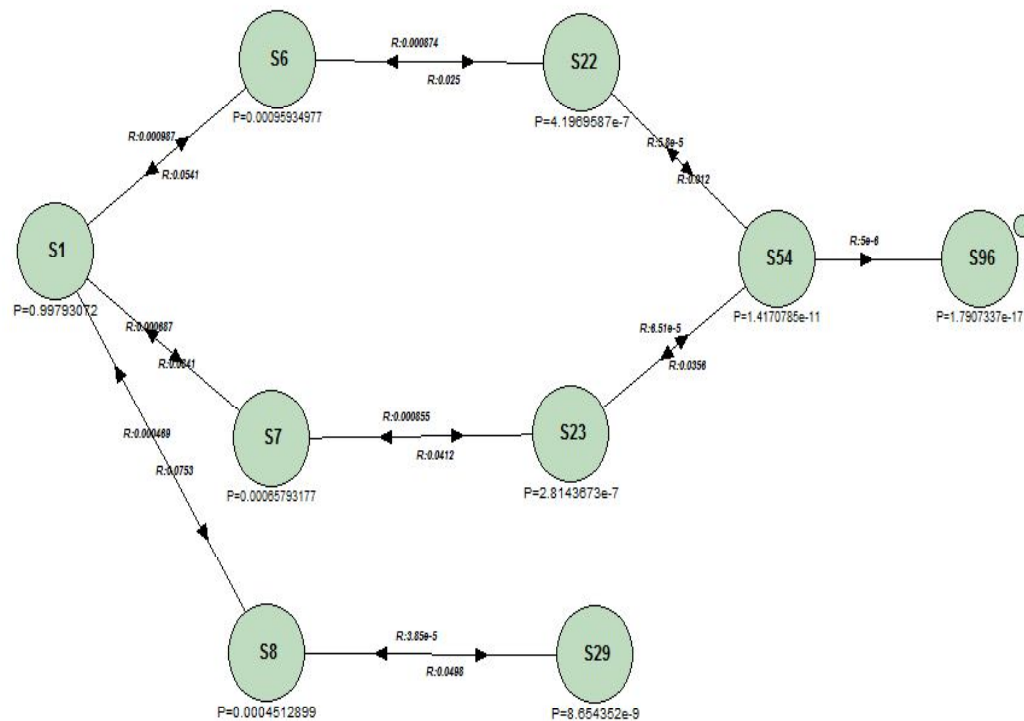


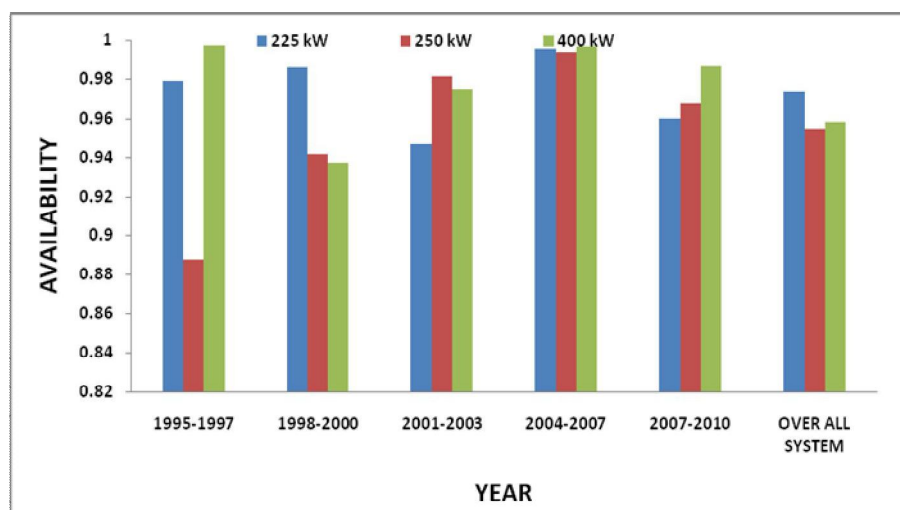
Figure 6.7 MA with revised transition for WTS

6.8.3 Failure data of WTS

The total MTTR of 250 kW WT varies from 130 to 2003 hours, for 225 kW WT the total MTTR varies from 9 to 123 hours and 400 kW WT has 4 to 842 hours of MTTR. The highest failure in the rotor is obtained as 1466 hours in the years 1995-1998. In 1998-2000, 2001-2003 and 2007-2010, the gear box has a considerable failure of 821 hours, 248 hours and 258 hours. The generator has a failure of 826 hours and 248 hours in the years 1998-2000 and 2001-2003 respectively. From 1998 to 2000, the 400 kW WT had more failures in the rotor, gear and generator which are 1338, 821 and 848 hours respectively.

Table 6.4 Failure data of WTS

Loc No	Year	Total time (Hours)	MTTR (Hours)						GDT (Hours)	MTBF (Hours)
			Yaw	Rotor	Brake	Gear	Generator	Total		
PK1/ 225 kW	1995-1997	26304	19	121	7	254	9	410	1306	24588
	1998-2000	26304	9	60	36	24	123	252	672	25380
	2001-2003	26280	34	258	56	432	12	792	556	24932
	2004-2007	26304	12	14	23	4	21	74	1531	24699
	2007-2010	26304	26	454	15	19	18	532	1610	24162
SPA1/ 250 kW	1995-1997	26304	12	1466	7	5	13	1503	1306	23495
	1998-2000	26304	18	327	11	821	826	2003	672	23629
	2001-2003	26280	12	78	10	292	248	640	556	25084
	2004-2007	26304	16	48	13	49	4	130	1531	24643
	2007-2010	26304	12	256	8	258	21	555	1610	24139
SPA 2/ 400 kW	1995-1997	26304	14	12	7	5	13	51	1306	24947
	1998-2000	26304	107	1338	14	821	842	3122	672	22510
	2001-2003	26280	15	288	42	12	11	368	556	25356
	2004-2007	26304	31	13	25	6	4	79	1531	24694
	2007-2010	26304	10	139	8	7	14	178	1610	24516

**Figure 6.8 Availability of WTS**

6.8.4 Availability of Whole WTS

The calculated results of availability from ITEM Toolkit version 8.0.2 for wind turbines with three years interval and system availability are plotted in a graph as shown in Figure 6.8. The system availability of the 225 kW WT for three years interval is varying from 94.657% to 99.551 % and over all availability is obtained as 97.3444%, the availability of the 250 kW WTS is between 88.761 and 99.364 and the overall system availability is 95.441. For 400 kW WT, the range of the availability for three years interval is obtained from 83.691 to 99.731% and the overall system availability for fifteen years is attained as 95.7289%.

The MA analysis is carried out in this research to compute the availability and performance of the wind turbines with capacities 225 kW, 250 kW, and 400 kW at high uncertain wind. An effort is made in the present study to estimate the availability of a WT using ITEM Toolkit version 8.0.2 as a measure of performance. The WTS behavior is analyzed and represented in 128 possible states. The results for the years 1998-2000 and 2001-2003 show that the failure rates are major in the rotor, gear box and generator and it is exposed that if they are eliminated then the availability could be improved to an extent of 99 percent throughout the life of the WT. The availability of the WT is highly affected during high wind season. It reduces the overall power generation considerably. During low wind period and known Grid Down Time (GDT), the Preventive Maintenance (PM) has to be carried out by trained employees to reduce the failures and increase the availability of the wind turbines. The repair time must be reduced by efficient spare parts management, good logistics at nearby sites from the WT manufacturers or Annual Maintenance Contactors and providing Standby support for the critical components.

6.9 MA FOR WT AND ITS SUB ASSEMBLY WITH THREE DIFFERENT CAPACITY

ITEM Tool kit version 8.0.2 software is used for MA and the input data fed for the analysis are the probability of failure of a particular state as state property, mission time in hours, number of intermediate points and failure rate and repair rate as transient properties. The inspection and failure analysis is carried out in every three year interval for a total span of 15 years. The Markov model is constructed in three major steps for a WTS. They are the system specification based on probability of failure, specification of transition rate between the states and analysis of model.

6.9.1 MA model for Single Element

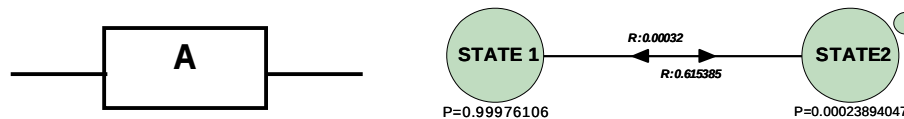


Figure 6.9 Single Element and two state MA

The Figure 6.9 shows a two state system, the success of the system could be achieved only when it operates successfully and failure occurs if it fails.

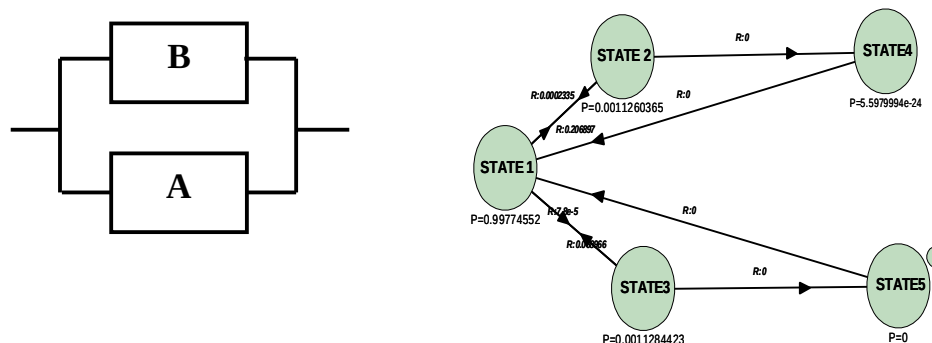


Figure 6.10 Two component system and Two component with five states MA

The Figure 6.10 illustrate the system comprising of two components B and A. λ_A and λ_B are the failure rates. The system success requires that both must operate successfully at the same time, but the system failure occurs if both fail or even if A fails before B. If B fails before A, then also the system operates successfully. The equation for probability of survival of each state is shown in Equation (6.22).

$$P = \frac{\lambda_A (1 - e^{-\lambda_B T}) - \lambda_B (e^{-\lambda_B T} - e^{-(\lambda_A + \lambda_B)T})}{\lambda_A + \lambda_B} \quad (6.22)$$

6.9.2 MA for WT

The MA is carried out in this research to compute the availability and performance of wind turbines with different capacities at high uncertain wind. An effort is made in the present study to estimate the availability of a WT using ITEM Toolkit version 8.0.2 as a measure of performance.

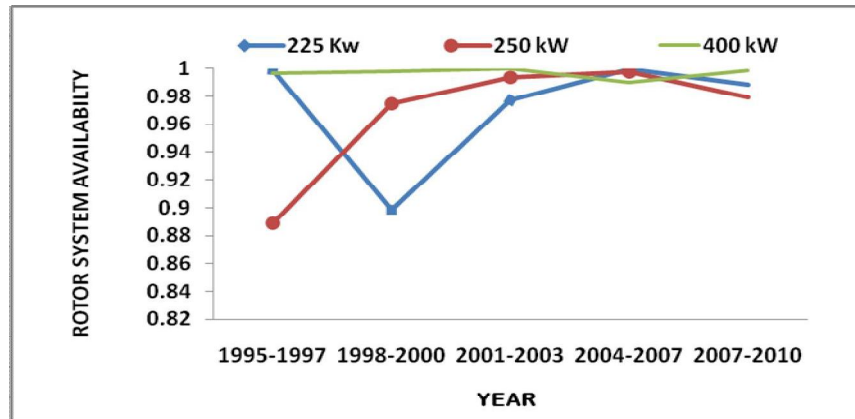


Figure 6.11 Rotor System Availability

The failure rate for three years (26,304 hours) for the WT components varies from a lower value of 0.00004 to 0.0005. The Figure 6.11 compares the availability of rotor systems in different capacity wind turbines

over a period of fifteen years. It can be seen that the curve representing 400 kW wind turbines is reasonably flat and nearly 99.9%, which means that the rotor system of 400 kW wind turbines is more consistent than other wind turbines. But, the availability becomes very low in the year 1999, because of the frequent occurrence of failure of rotor system, followed by the occurrence of gear box and generator failures. The larger repair times make the MTTR very larger at that time.

The rotor systems failures are high in stall controlled WT because of the frequent opening of tip open mechanism, in sufficient rigidity of blade, lightning and hydraulic control failure. For 225 kW WT, the availability is varying from 0.89865 to 0.999, for 250 kW WT. The availability is varying from 0.8891 to 0.991 and for 400kW WT, the availability is varying from 0.996 to 0.9991 shown in Figure 6.11. It clearly illustrates that the failure of rotor reduces the overall power generation up to 10.22 percent.

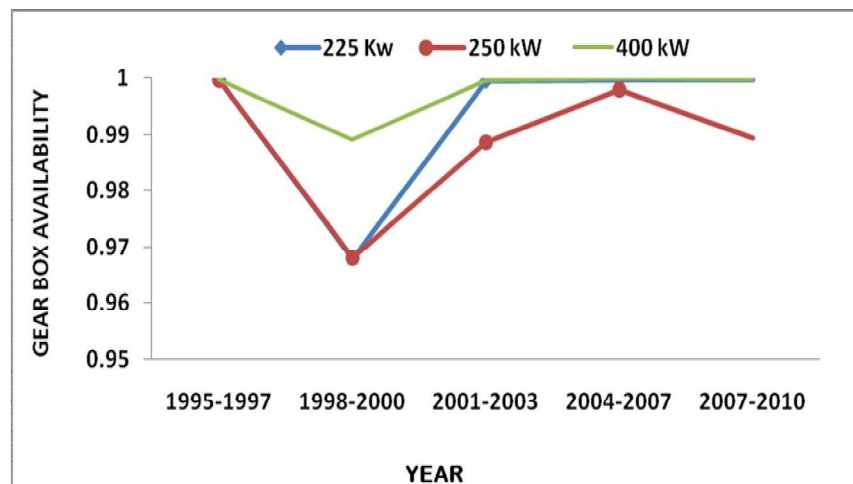


Figure 6.12 Gear box System Availability

The gear box availability for a WT is shown in Figure 6.12. The failure of WT gear box is provoked due to many reasons such as vibration, long-standing fatigue and stress, inevitable impact load and increased shaft

speed. The vibration is amplified in gear box due to machine imbalance. The gear box of 250 kW and 225 kW got heavy failure during the year 1998-2000 because of high fluctuation in wind and frequent grid failure.

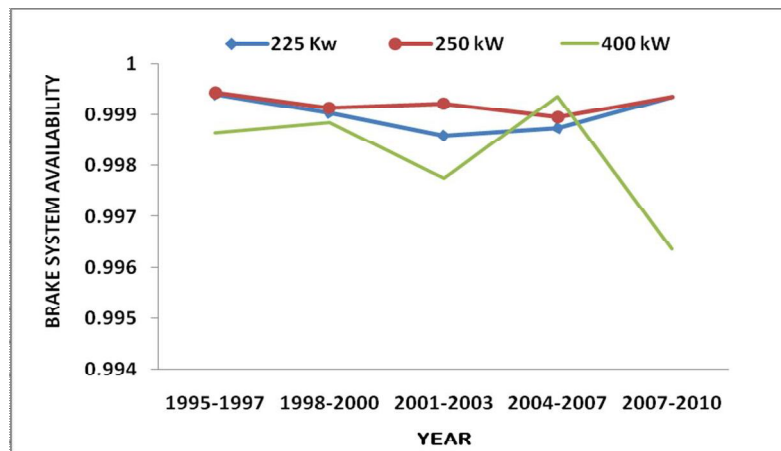


Figure 6.13 Brake System Availability

However, as far as the brake system is concerned, nothing can be concluded about the consistency of different capacity wind turbines, and all capacities show reasonable variations. Comparatively, brake systems used in 250 kW wind turbines are more reliable than their counter parts in other capacities.

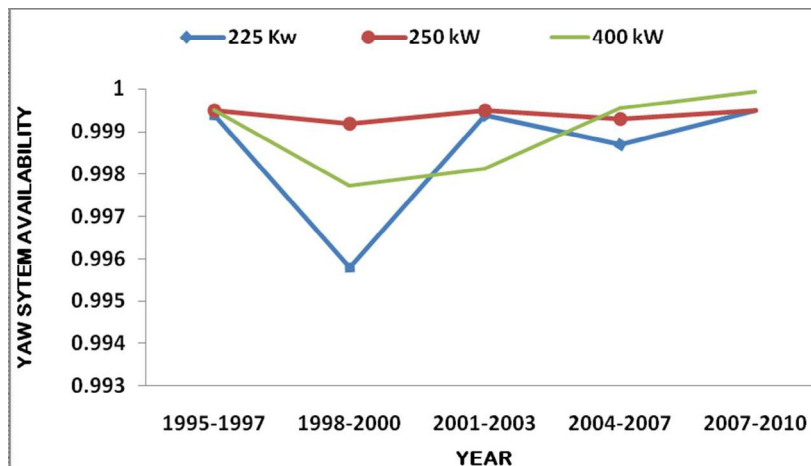


Figure 6.14 Yaw System Availability

For all wind turbines, the major failures occur in the yaw system. The most affected yaw system components are yaw brake, yaw motor, yaw magnetic coil, yaw gear and planetary wheel. The failure rate of yaw system for 225 kW WT varies from 0.000233 to 0.0.0004. Similarly, the failure rates for 250 kW WT with three intervals are 0.0004, 0.000273, 0.00042, 0.000364 and 0.0003241.

The Figure 6.14 reveals that the failures are independent in the yaw system. The larger spare availability and quick repair results lower MTTR as 12, 18, 12, 16, 12 hours and it reduces the repair rate. It is similar for 400 kW WT also. If the yaw system is considered, the availability of 250 kW wind turbines is well above other capacities. More fluctuations can be seen in 225 kW WT followed by 400 kW. This is due to uncertainty in the particular location. But, again in recent years almost all capacities' yaw systems perform well in view of less number of failures

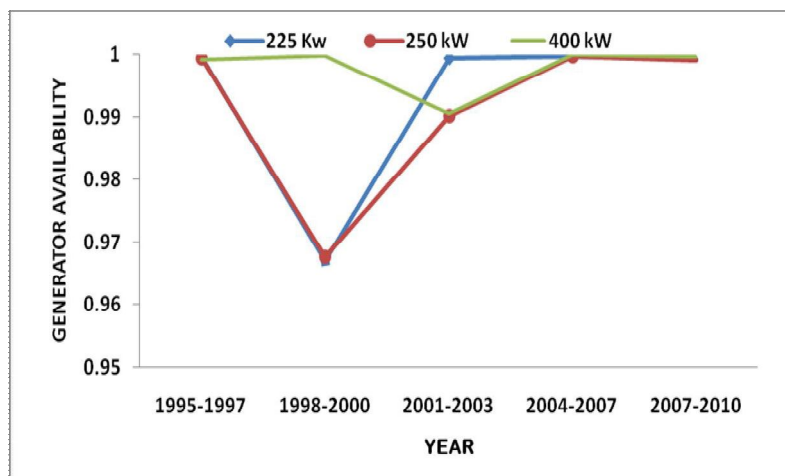


Figure 6.15 Generator System Availability

The generator failures for the different capacity wind turbines from 1995 to 2010 are shown in Figure 6.15. The variations are steep and sudden. But, 400 kW wind turbines show slightly better performance than others.

However, it can be clearly stated that in the recent years, all capacities wind turbines have availabilities is well above 95 percent. But it is necessary to improve the availability to 99.999 percent.

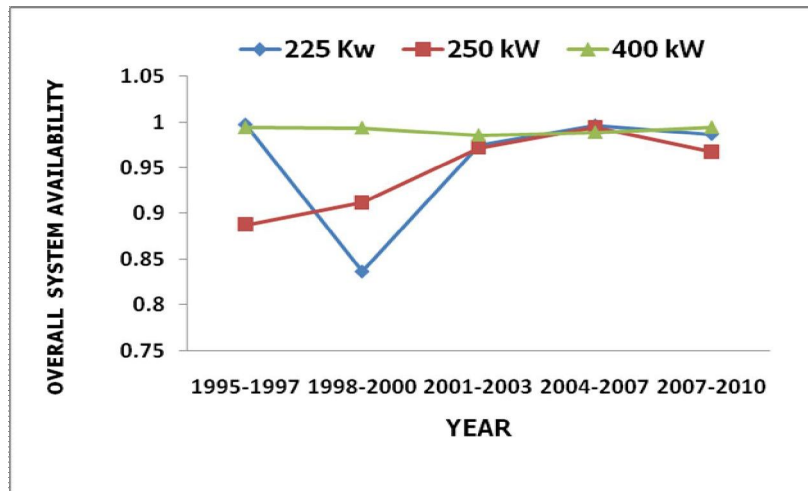


Figure 6.16 Overall System Availability

The Figure 6.16 show that, it can be concluded that 400 kW WT considered here is less problematic, more reliable than others' throughout the span under consideration. Other two capacities show equally oscillating performance over different years. It shows that the failures are independent.

6.10 MA FOR WT AND ITS SUB ASSEMBLY WITH 20 NUMBERS OF 250 kW CAPACITY

The overall system availability of the 225 kW WT is varying from 84.0449 to 99.77, 250 kW WT is varying from 88.803 to 99.48 and 400 kW WT from 98.7 to 99.75. The failures of the rotor, gear box and generator revealed that if they are eliminated, the availability will be improved to an extent of 99.999 percent throughout the life of the WT. It clearly illustrates that the overall power generation will be reduced due to the failure of rotor up

to 10.32 percent, the failure of gear box is up to 3.25 percent and the failure of generator is up to 3 percent.

The low wind at Muppandal is varying from 1262 to 1637 hours per year. During this period, the preventive maintenance has to be carried out by trained employees to reduce the failures and increase the availability and reliability of the wind turbines. The repair time must be reduced by efficient spare parts management, good logistics at nearby sites from the WT manufacturers or Annual Maintenance Contactors and providing standby support for the critical components. This work will be helpful in planning timely and cost-effective maintenance of wind turbines.

The individual system availability is calculated by ITEM Toolkit version 8.0.2 software, by considering the relevance of the state. The system availability is calculated by multiplying the individual availability of the WT components.

6.11 MA FOR WT AND ITS SUB ASSEMBLY 20 NUMBERS OF 250 kW CAPACITY

The goal of MA is the determination of availability and maintainability matrices of a complete system, by using probability of failure, failure rate MA and repair rate with time. The grid down time of the WT in three years interval varies from 556 to 1306 hours. The availabilities of different sub systems over a period of time have been analyzed and presented in Figures 6.16 to 6.20.

The Mean Time Between Failure (MTBF) of the rotor varies from 24,294 to 25,721 hours out of 26,304 hours and the Mean Time To Repair (MTTR) varies from 3 to 1338 hours. The failure rate per hour of the rotor is in between 0.00004 to 0.00058. The availability of the rotor is reduced

considerably in four locations in the year 1998-2000 as shown in Figure 6.17. The rotor availability is achieved to a minimum of 0.88918 in location number 9 in the year 1995-1997 and a maximum of 0.9998 in many locations. The range of repair rate per hour is 0.0014 to 0.5. The technical availability of the rotor is in between 0.88918 to 0.99989.

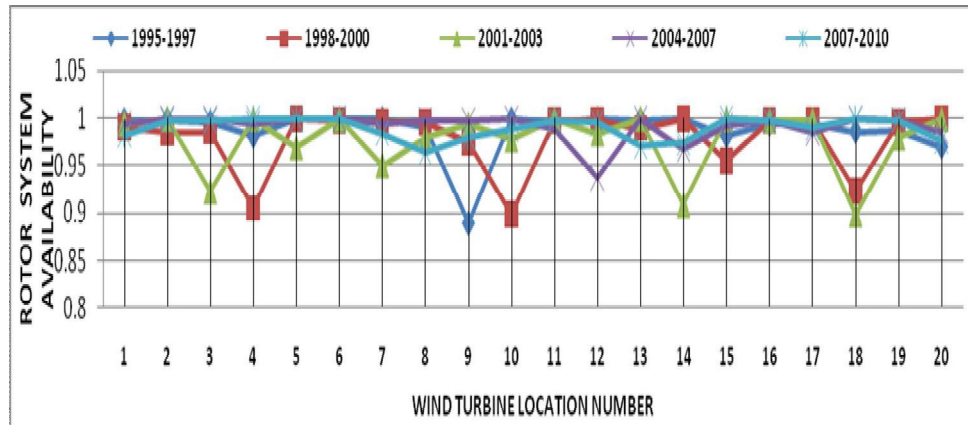


Figure 6.17 Availability of Rotor System of WT

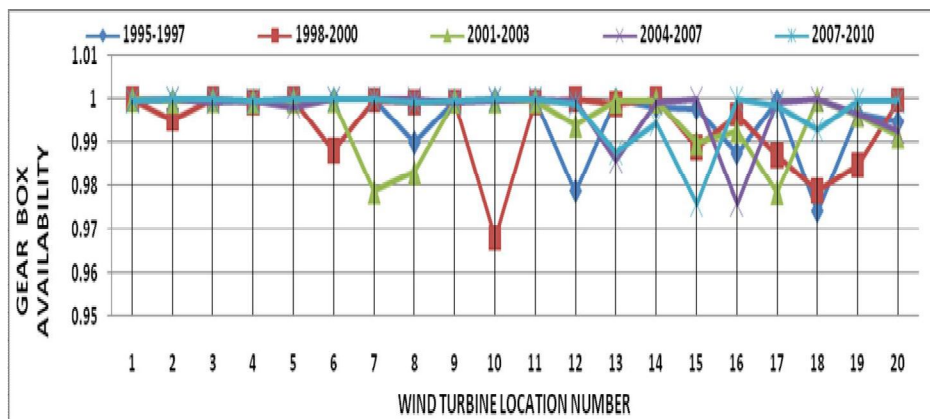


Figure 6.18 Availability of Gear Box of WT

For the gear system, the MTBF is in between 24,724 and 25,627. The failure rate per hour is in between 0.0000403 and 0.000467. The MTTR of the gear system lies between 5 to 870 hours. The larger gear box failure

occurred in the gear oil cooling system and the low speed gear. The technical availability of the rotor is in between 0.96799 and 0.9989 as shown in Figure 6.18.

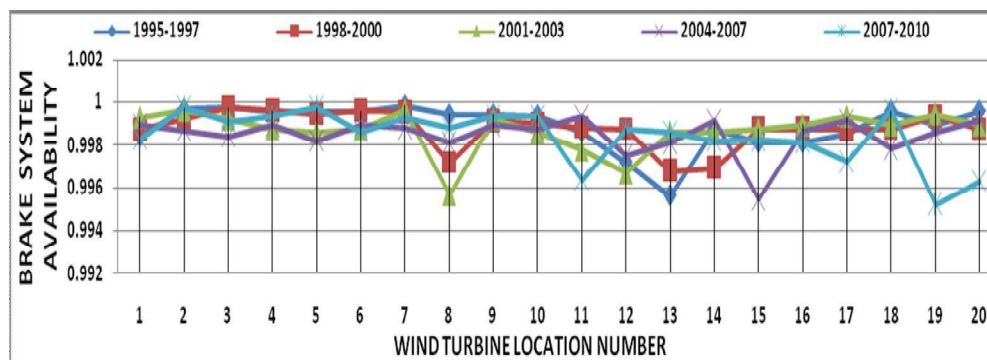


Figure 6.19 Availability of Brake System of WT

The brake system has mechanical brake, electronically actuated brake and hydraulic brake. All are actuated simultaneously. The hydraulic brake has a separate control mechanism which is connected parallel to the mechanical and electronic brake. The maximum failures occurred in the brake system for three years period is 21 numbers in location number 3. The MTTR of brake system falls to a minimum of 3 and a maximum of 42. The brake system failures are higher in locations 8, 11, 12, 13, 15 and 19 is shown in Figure 6.19. The failure rate per hour of brake system is in between 0.000122 and 0.000818.

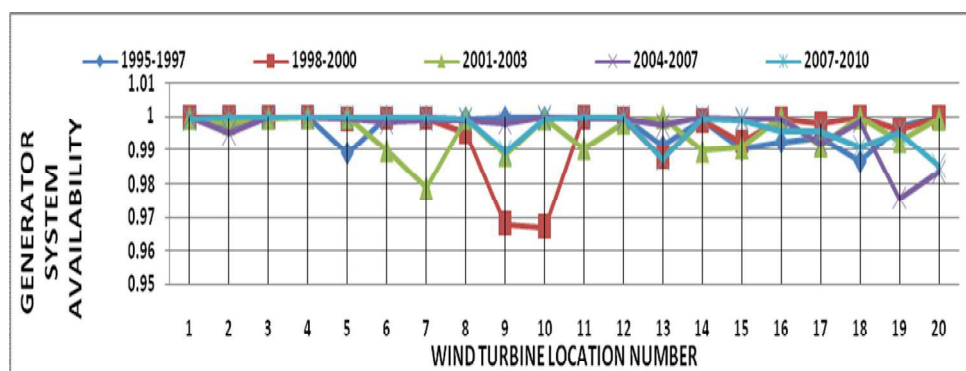


Figure 6.20 Availability of Generator System of WT

The availabilities of WT generator for different locations are shown in Figure 6.20. The MTBF for the generators are from 24,687 to 25,712 hours and MTTR are in the range of 3 to 831 hours. The high failure rate per hour in the generator is obtained as 0.000443. The highest frequency of failure occurred in yaw system. In location number 8, it has a frequency of 20 and a failure rate of 0.0008081 per hour, but the availability of the WT is 98.71%. The availability of the WT is affected less than other components and it is shown in Figure 6.21. The availability is not only reduced for the components with high down time, but also it depends on the components that fail frequently.

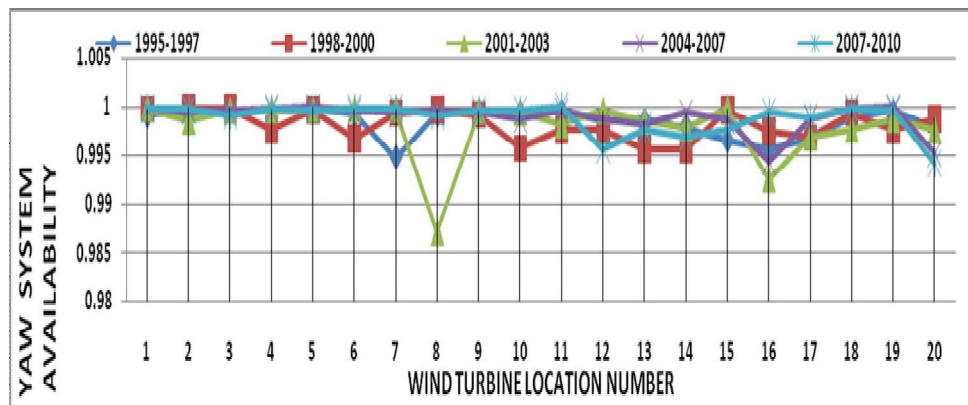


Figure 6.21 Availability of Yaw System of WT

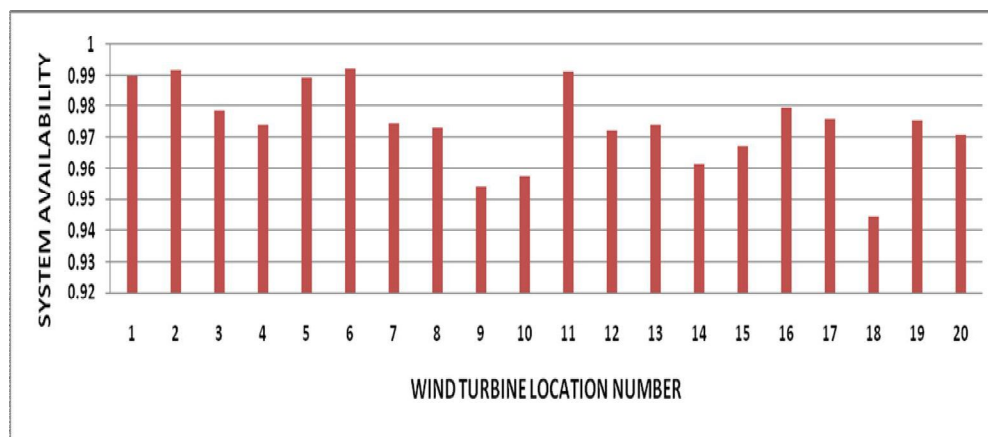


Figure 6.22 System Availability of the WTS

The overall system availability of the twenty wind turbines is shown in Figure 6.22. The results also show that the system availability for the locations 10 and 18 are pulled down rapidly because of the severe reduction in the rotor, gear system and generator availability. For the location number 7 and 9, the system availability is reduced rigorously because of low availability of rotor and generator. The location numbers 4, 12 and 14 has a considerable reduction in availability because of rotor and gear system. This reduction in availability is due to larger MTTR, because of the insufficient spares at site and lack of logistic support. It is not possible to provide a redundant system for the rotor, gear box and generator. If there is any major failure occurred in a system, then it has to be dismantled and then once again it could be erected. But for yaw system and brake system, the redundant system can use. These failures mostly occurred in the high wind period and it considerably reduces the overall power generation.

The MA is carried out in this work to compute the availability and performance of wind turbines with capacity of 250 kW at high uncertain wind. An effort is made in the present study to estimate the availability of a WT using ITEM Toolkit version 8.0.2 as a measure of performance of 20 wind turbines with a capacity of 250 kW exactly placed in the main wind pass. The overall system availability of the WT is varying from 94.45 to 99%. The failures of the rotor and gear box revealed that if they are eliminated, then availability will be improved to an extent of 99.9 percent throughout the life of the WT. The low wind at Muppandal is varying from 1262 to 1637 hours per year. During this period preventive maintenance has to be carried out by trained employees to reduce the failures and increase the availability and reliability of the wind turbines. The repair time must be reduced by efficient spare parts management, good logistics at nearby sites from the WT

manufacturers or Annual Maintenance Contactors and providing standby support for the critical components. This work will be helpful in planning timely and cost-effective maintenance of wind turbines.

6.12 SUMMARY

A new approach, Markov analysis is developed in this chapter where the failure rate and repair rate are explicitly considered in the availability and reliability computation. The objective of this analysis is to discover the impact of restoration time on availability of critical components. The framework provides inherent availability of wind turbines and its sub assemblies.

Network Expansion Planning

The Network Expansion Planning (NEP) process tries to find the optimum routes between the generation buses (determined in the GEP phase) and the load centers (determined from the load forecasting) via substations (determined in the SEP phase), in such a way that:

- Loads are completely supplied during both
 - Normal conditions
 - Once some types of contingencies occur on some system element
- The least costs are incurred

In fact, NEP is an optimization process in which the allocation (the sending and the receiving ends) and class (voltage level, number of conductors, conductor type) of new transmission elements, together with their required availability times are specified.

Problem Definition:

Generally speaking, in NEP, the problem is to determine the transmission paths between substations (both existing and new) as well as their characteristics (voltage level, number of circuits, conductor type, and so on).

In doing so

- The investment cost should be minimized
- The operational cost should be minimized
- Various constraints should be met during
 - Normal conditions
 - Contingency conditions

The contingency is, in fact, an outage occurring on a single element (such as a line, a transformer, a power generation unit) or some elements. The single element case is commonly referred to N-1 conditions

Simultaneous contingencies on two elements (for instance one line and one transformer, two lines, etc.) are referred to N-2 conditions and so on.

By contingency conditions (say N-1), we mean that the network should be so planned that with every single element, out, the load is completely satisfied and no violation happens.

Problem Description

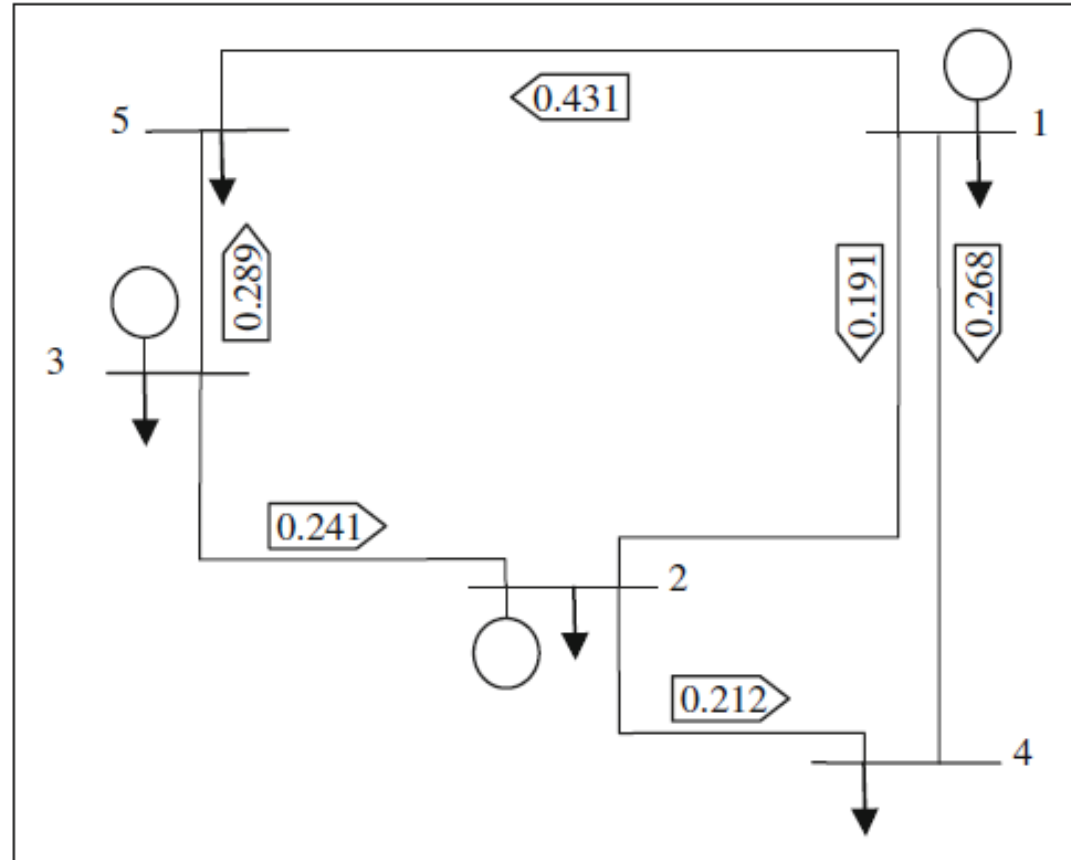


Fig. 1. Flow condition for the Garver test system

A normal load flow solution procedure may be used to determine the power transfer of each line. However, a simplified type of load flow, the so-called DCLF, is normally used in power system planning problems, by which the power transfers may be calculated very fast.

Whatever the calculation procedure is, the normal flow conditions are shown in Fig. 1, in which the numbers within the arrows show the per-unit power transfers of lines

Now assume that a single contingency occurs on each line. In other words, assuming each line to be out, one-by-one, we are going to find out how the powers are distributed throughout the network

Table: N-1 results base case

Contingency on line	Flow on line (p.u.)					
	1-2	1-4	1-5	2-3	2-4	3-5
1-2	0.000	0.340	0.550	-0.360	0.140	0.170
1-4	0.352	0.000	0.538	-0.348	0.480	0.182
1-5	0.499	0.391	0.000	0.190	0.089	0.720
2-3	0.363	0.337	0.190	0.000	0.143	0.530
2-4	0.064	0.480	0.346	-0.156	0.000	0.374
3-5	-0.016	0.186	0.720	-0.530	0.294	0.000

Problem Formulation

- In NEP, the problem is to determine the transmission paths between substations (buses); both existing and new
- The problem may be, generally, viewed as an optimization problem as shown below

Minimize (Objective function)

s.t. (Constraints)

In its simplest form, the objective function consists of the investment cost for new transmission lines, while the constraint terms consist of load-generation balance and transmission limits.

Objective function:

The aim is to minimize total cost, consisting of the investment cost for the new transmission line

$$C_{total} = C_{new-line}$$

$$C_{new-line} = \sum_{i \in Lc} C_L(x_i) L_i$$

where L_i is the transmission length (km) of the candidate, Lc is the set of candidates, x_i is the transmission type of the candidate (set of various types such as number of bundles, conductor types and number of circuits) and $C_L(x_i)$ is the investment cost per km for type x_i .

Constraints:

The load-generation balance should be observed during the optimization process. Moreover, the capacities of transmission lines should not be violated, too.

Load Flow Equations:

The DCLF equations are in the form of:

$$\sum_{j=1}^N B_{ij}(\theta_i - \theta_j) = P_{Gi} - P_{Di} \quad \forall i \in n$$

$$\sum_{j=1}^N B_{ij}^m(\theta_i^m - \theta_j^m) = P_{Gi}^m - P_{Di} \quad \forall i \in n \cap m \in C$$

where θ_i and θ_j are the voltage phase angles of buses i and j , respectively; B_{ij} is the imaginary part of the element ij of the admittance matrix, P_{Gi} is the power generation at bus i , P_{Di} is the power demand at bus i , and n is the set of system buses. The index m shows the contingency parameters and variables. C is the set of contingencies. N is the system number of buses.

Transmission Limits:

For each of the transmission lines, the power transfer should not violate its rating during both normal and contingency conditions (N-1)

$$b_k(\theta_i - \theta_j) \leq \bar{P}_k^{No} \quad \forall k \in (Lc + Le)$$
$$b_k^m(\theta_i^m - \theta_j^m) \leq \bar{P}_k^{Co} \quad \forall k \in (Lc + Le) \cap m \in C$$

where $\bar{P}_k^{No}$ and $\bar{P}_k^{Co}$ are the line k ratings during normal and contingency conditions, respectively; θ_i and θ_j are the voltage phase angles of line k during normal conditions; θ_i^m and θ_j^m are the voltage phase angles of line k following contingency m ; and Le is the set of existing lines. Lc is defined earlier. b_k and b_k^m represent the line k admittances in normal and contingency conditions, respectively.

The problem formulated above may be solved by available optimization techniques. Both mathematical based options and heuristic types may be tried, each with its own capabilities and drawbacks.

Power System Planning

BY: Dr. Omkar Yadav
Assistant Professor
Electrical Engineering Department
National Institute of Technology Durgapur
Durgapur-713209, (W.B.)

Power System Planning:

- Word operation is the normal power system term used for running the current situation
- Referring to the future, the power system experts use the term planning to denote the action required for the future
- Past experiences are always used for efficient operation and planning of the system
- The word planning stems of the transitive verb to plan, meant as to arrange a method or scheme beforehand for any work, enterprise, or proceeding.¹ The aim here is to discuss the meanings of method or scheme, beforehand and work, enterprise or proceeding for a physical power system.

Power System Elements:

- A typical power system is comprised of an enormous number of elements. The elements may vary from a small lamp switch to a giant generator. However, the main elements of interest are:
 - Generation facilities
 - Transmission facilities
 - Substations
 - Network (lines, cables)
 - Loads
- As a matter of fact, in power system planning, the details of each element design are not of main interest. For instance, for a generation facility, the type (steam turbine, gas turbine, etc.), the capacity, and its location are only determined.

Power System Structure:

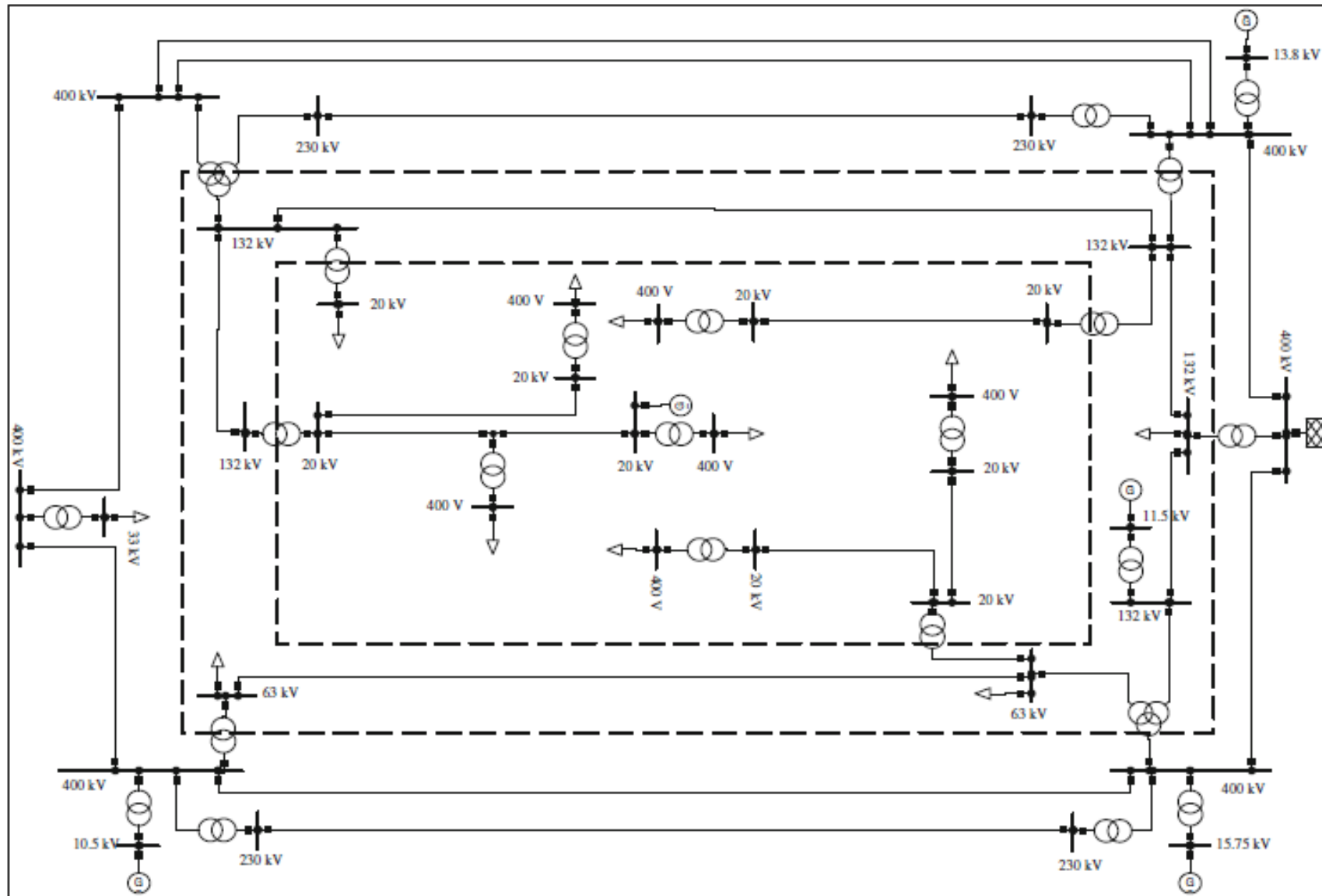
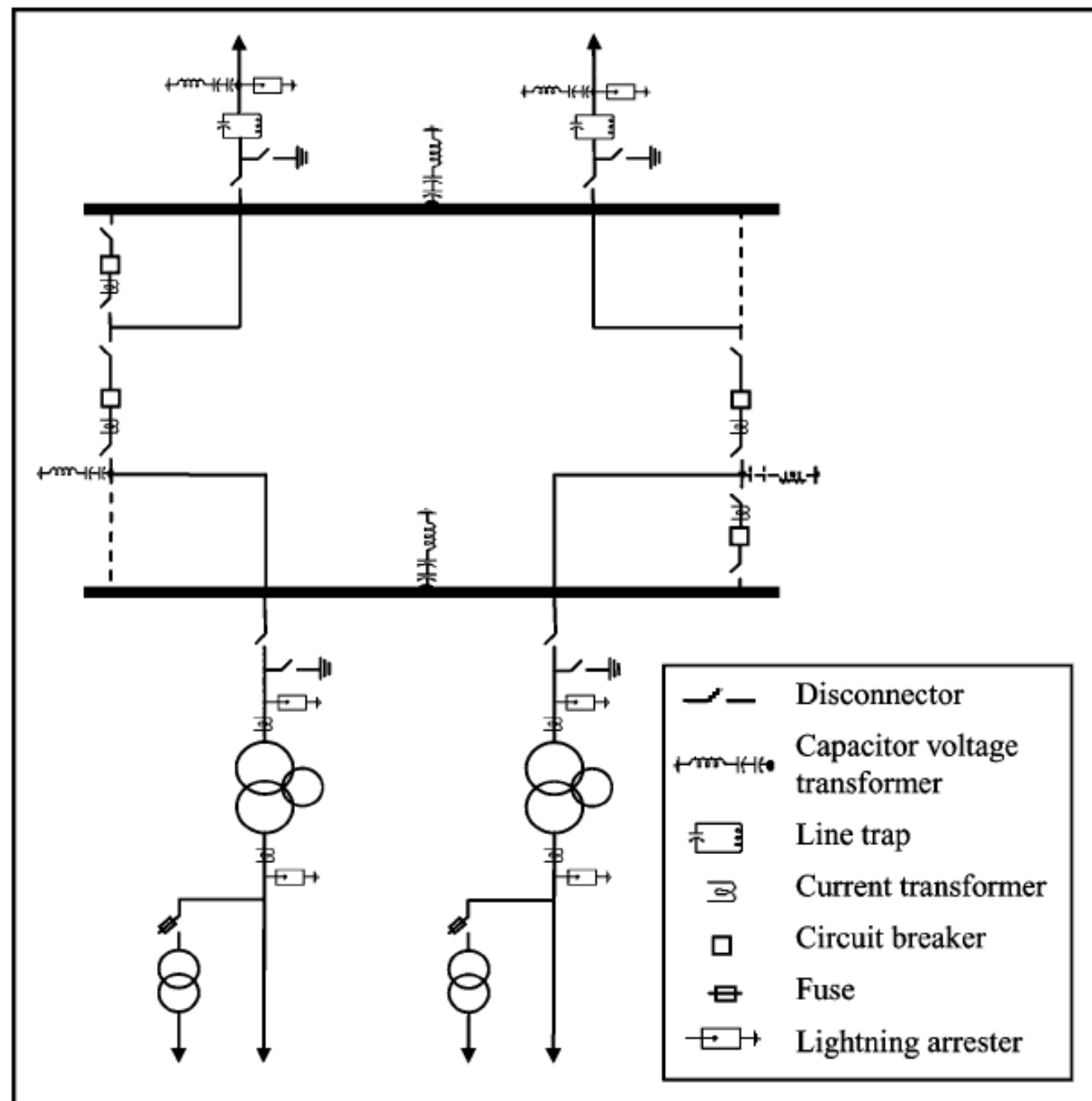


Fig.1. A typical power system

- A typical power system, comprising of the generation, the interface, and the load.
- The generations and the loads are distributed throughout the system. As a result, some interfaces should be provided to transfer the generated powers to the loads.
- The generations may be in the form of a small solar cell or a diesel generator to a very giant nuclear power plant.
- The loads start, also, from a small shop/home to a large industrial complex. Due to both the technical and the economical viewpoints, the generation voltages may be as high as 33 kV or so, while the load voltages may be much lower.
- Due to both the technical and the economical viewpoints, the generation voltages may be as high as 33 kV or so, while the load voltages may be much lower. Moreover, the generation resources may be far away from load centers. To reduce the losses and to make the transmission possible, we have to convert the generation voltages to much higher values and to reconvert them to lower ones at the receiving ends.

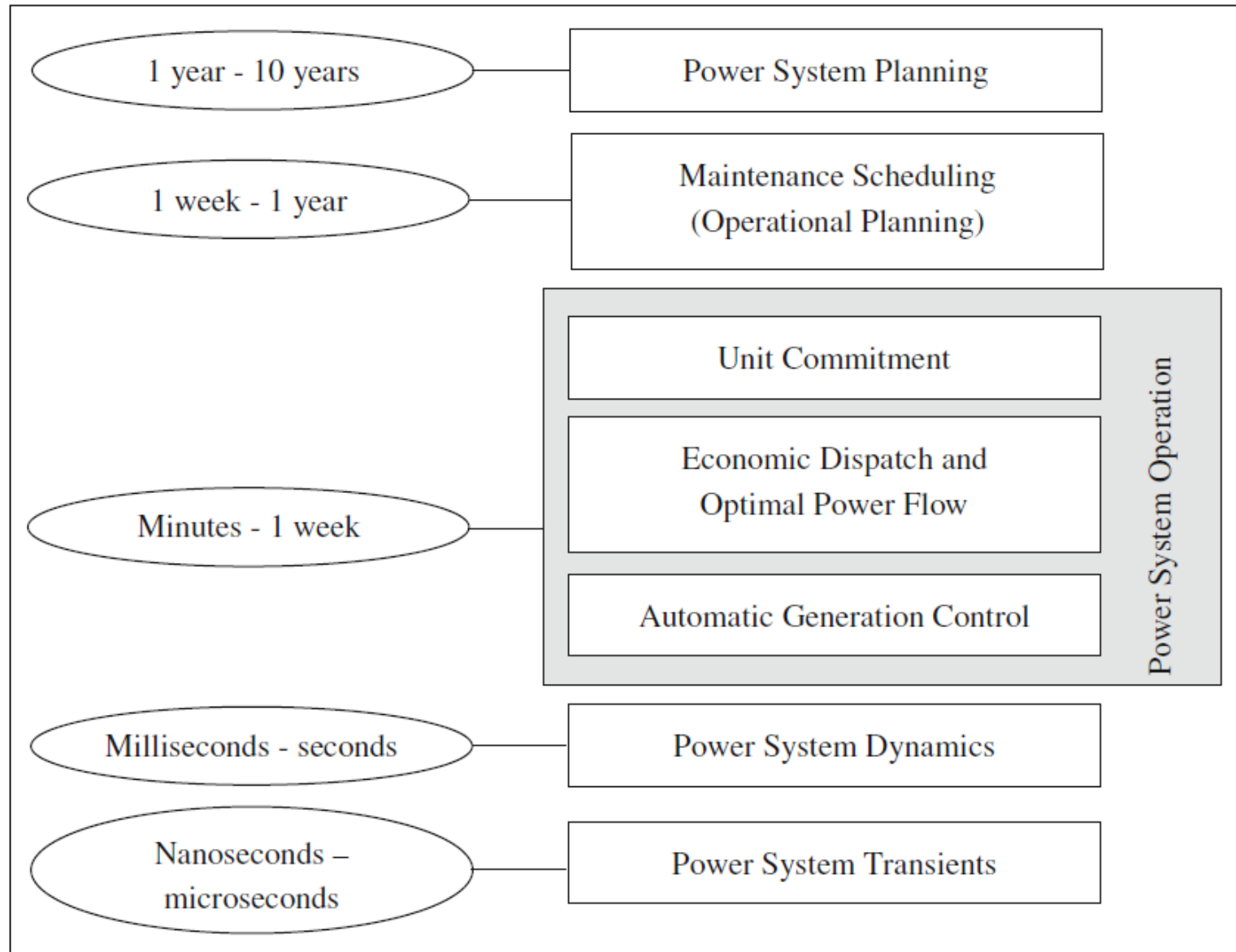
- As a result, the interfaces between the generations and the loads may comprise of several voltages, such as 20, 63, 132, 230, 400, 500 kV or even higher
 - However, regardless of what the available voltages are, it is of normal industrial practice to classify these voltages to:
 - Transmission (for example, 230 kV and higher)
 - Sub-transmission (for example, 63, 132 kV, and similar)
 - Distribution⁴ (for example, 20 kV and 400 V).
- Due to these various voltages, transformers are allocated throughout the network in the so called substations

Fig.2. A typical layout of substation



Power System Studies, a Time Horizon Perspective:

Fig. 3. Power system studies, a time horizon perspective



Power System Planning Issues:

Power system planning is a process in which the aim is to decide on new as well as upgrading existing system elements, to adequately satisfy the loads for a foreseen future.

The elements may be

- Generation facilities
- Substations
- Transmission lines and/or cables
- Capacitors/Reactors

The decision should be

- Where to allocate the element (for instance, the sending and receiving end of a line),
- When to install the element (for instance, 2015),
- What to select, in terms of the element specifications (for instance, number of bundles and conductor type).

Obviously, the loads should be adequately satisfied.

Static versus Dynamic Planning:

Let us assume that our task is to predict the load for 2015–2020. If the peak loading conditions are to be investigated, the studies involve six loading conditions. One way is to, study each year separately irrespective of the other years. This type of study is referred to as static planning which focuses on planning for a single stage.

The other is to focus on all six stages, simultaneously, so that the solution is found for all six stages at the same time. This type of study is named as dynamic planning.

Obviously, although the static planning for a specific year provides some useful information for that year, the process as given above leads to impractical results for the period as the solutions for a year cannot be independent from the solution from the preceding years. One way to solve the problem is to include the results of each year in the studies for the following year. This may be referred to as semi static, semi-dynamic, quasi-static or quasi-dynamic planning.

Transmission versus Distribution Planning

The planning at the transmission level is known as transmission planning and the planning at the distribution level is known as distribution planning

- Transmission and sub-transmission levels are included in transmission level planning except otherwise specified
- Distribution level is often planned; or at least operated, radially.
- As seen, both transmission and distribution networks comprise lines/cables, substations and generations. However, due to specific characteristics of a distribution system (such as its radial characteristics), its planning is normally separated from a transmission system,

Note that switches A and B are normally open and may be closed if required.
Switches C and D are normally closed and may be opened if required.

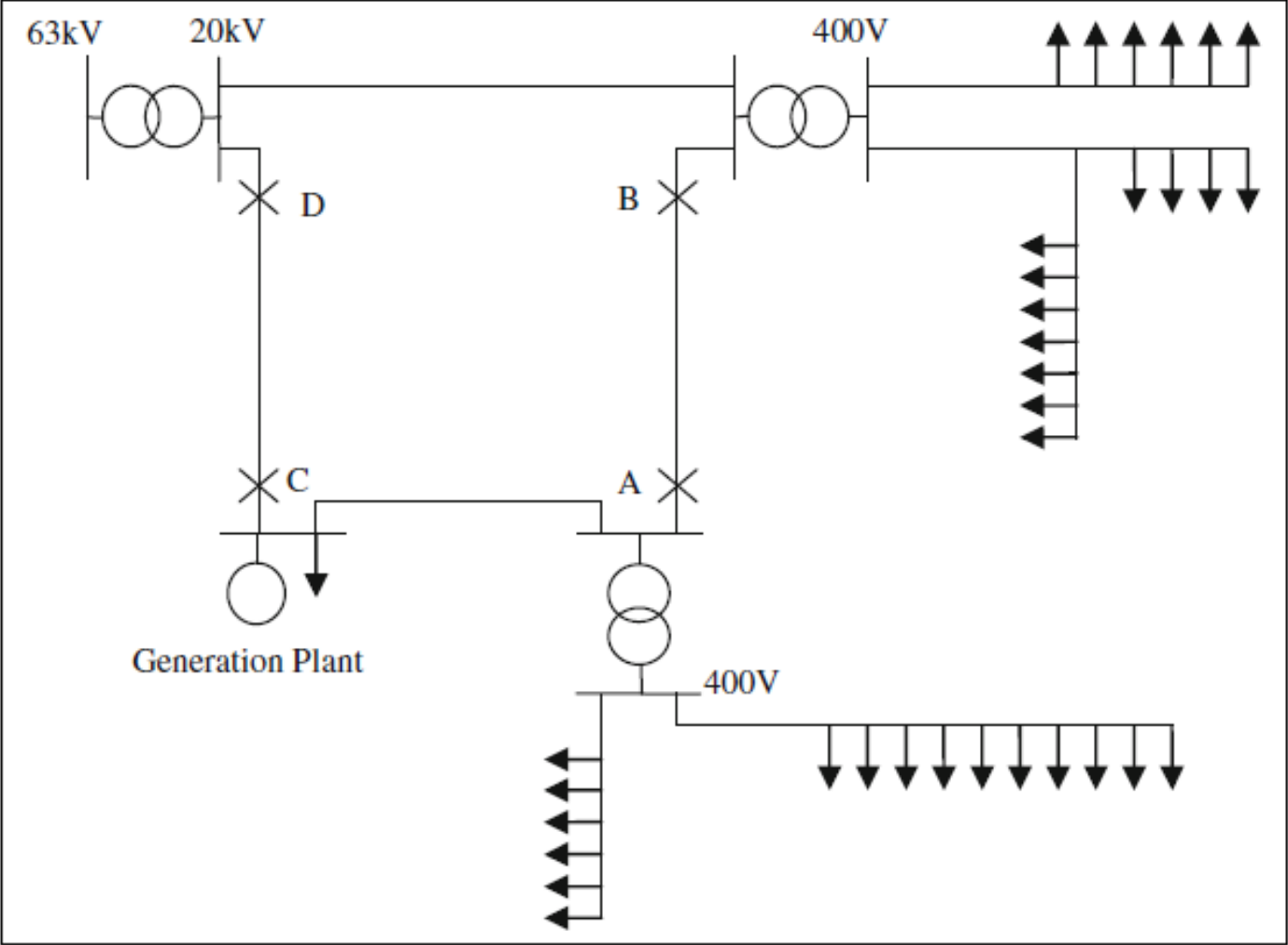


Fig. 4. A typical distribution system

Long-term versus short-term planning

There is no golden rule in specifying short-term or long-term planning issues. Normally, less than 1 year falls into the operational planning and operational issues in which the aim is typically to manage and operate available resources in an efficient manner. More than that falls into the planning stages.

If installing new equipment and predicting system behavior are possible in a shorter time (for instance, for distribution systems, 1–3 years), the term of short-term planning may be used. More than that (3–10 years and even higher) is called long-term planning (typically transmission planning) in which predicting the system behavior is possible for these longer periods. Moreover, installing a new element (such as a 765 kV UHV line or a nuclear power plant) should be decided well in advance so that it would be available in due course.

Basic Issues in Transmission Planning

With due attention to all points mentioned in previous sections, we come now to our main interest in transmission planning. The term commonly used in literature is Transmission Expansion Planning (TEP), to show that we focus on long-term issues.

Load Forecasting

- The first crucial step for any planning study is to predict the consumption for the study period (say 2015–2020), as all subsequent studies will be based on that. This is referred to as load forecasting.
- Short-term load forecasting, used for operational studies, is significantly different from the long-term one used in planning studies.
- short-term load forecasting, for predicting the load for instance, of the next week, we come across predicting the load for each hour of the coming week.
- It is obvious that the determining factors may be weather conditions, special TV programs, and similar.
- In long-term load forecasting, we normally wish to predict the peak loading conditions of the coming years. The determining factors are different here. Population rate increase, GDP) etc. have dominant effects.

Generation Expansion Planning

- After predicting the load, the next step is to determine the generation requirements to satisfy the load. An obvious simple solution is to assume a generation increase equal to a load increase
- If, for instance, in the year 2015, the peak load would be 40,000 MW and at that time, the available generation is 35,000 MW, an extra generation of 5,000 MW would be required.
- Unfortunately, the solution is not so simple at all. Some obvious reasons are
 - What types of power plants do we have to install
 - Where do we have to install the plants
 - What capacity do we have to install
 - As there may be an outage on a power plant (either existing or new), should we install extra generations to account for these situations? If yes, what, where, and how?

Substation Expansion Planning

Once the load is predicted and the generation requirements are known, the next step is to determine the substation requirements, both, in terms of

- Expanding the existing ones,
 - Installing some new ones.
-
- This is referred to as Substation Expansion Planning (SEP)
 - ❖ SEP is a difficult task as many factors are involved such as
 - Those constraints due to the upward grid, feeding the substations,
 - Those constraints due to the downward grid, through which the substation supplies the loads,
 - Those constraints due to the factors to be observed for the substation itself.

Network Expansion Planning

- Network Expansion Planning (NEP) is a process in which the network (transmission lines, cables, etc.) specifications are determined.
- The network is a media for transmitting the power, efficiently and in a reliable manner from generation resources to the load centers.

Single-bus Generation Expansion Planning

Generation Expansion Planning (GEP) is the first crucial step in long-term planning issues after the load is properly forecasted for a specified future period. GEP is, in fact, the problem of determining when, what and where the generation plants are required so that the loads are adequately supplied for a foreseen future.

Note: we first ignore the transmission system to make the problem easy to handle.

Problem Definition

- Generally speaking, GEP, is an optimization problem in which the aim is to determine the new generation plants in terms of when to be available, what type and capacity they should be, and where to allocate so that an objective function is optimized and various constraints are met.
- It may be of static type in which the solution is found only for a specified stage (typically, year), or a dynamic type, in which, the solution is found for several stages in a specified period.
- The objective function consists, generally, of

Objective function=Capital costs + Operation costs

Power System Reliability

BY: Dr. Omkar Yadav
Assistant Professor
Electrical Engineering Department
National Institute of Technology
Durgapur
Durgapur-713209, (W.B.)

About the course

Course Name: Power System Reliability

Course Code: EEE812

Total No. of Contact Hours: L(3)

Credit: 03

Course Assessment Methods: Continuous Assessment (CA), Mid Term (MT), and End Term Assessment (EA)

Marks Distribution: Continuous Assessment (CA): 15 Marks, Mid Term (MT): 25 Marks, and End Term Assessment (EA): 60 Marks

Topics Covered

- Basic Reliability Concepts: The general reliability function. The exponential distribution, Definition of different reliability indices, Mean time to failures, series and parallel systems, Recursive techniques, Simple series and parallel system models. (8)
- Generating Capacity – Basic Probability Methods: The generation system model, Loss of load indices, Capacity expansion analysis, and scheduled outages. Load forecast uncertainty Loss of energy indices. The frequency and duration method. (8)
- Transmission Systems Reliability Evaluation: Radial configuration, Conditional probability approach, Network configurations, State selection, System and load point Indices. (8)
- Distribution Systems Reliability Evaluation: Evaluation Techniques, Additional interruption indices, Effect of lateral distribution protection, Effect of disconnects. (6)
- Introduction to Power System Planning: Basic Principles, Power System Elements, Power System Structure, Power System Studies, Power System Planning Issues, Static Versus Dynamic Planning, Transmission Versus Distribution Planning, Long-term Versus Short-term Planning, Basic Issues in Transmission Planning. (6)
- Single-bus Generation Expansion Planning: Problem Definition, Problem Description, Mathematical Development (2)

- Multi-bus Generation Expansion Planning: Problem Description, Mathematical Formulation (2)
- Network Expansion Planning: Problem Definition, Problem Description, Problem Formulation (2)

Pre-requisites: Power System I, Power System II, and Advanced Power System

Course Outcomes

Upon successful completion of this course, the student should be able to:

CO1: Understand the importance of maintaining reliability of power system components

CO2: Assess the different models of system components used in reliability studies.

CO3: Apply expressions for Reliability analysis of series-parallel and Non-series parallel systems in practical power systems.

CO4: Evaluate reliability of generation, transmission and distribution systems using different reliability indices.

CO5: Analyse required for generation, transmission and distribution systems expansion.

CO6: Design reliable power system considering generation, transmission & distribution together.

Reliability Engineering: Production organizations deploy reliability engineering for highly reliable components and systems.

- Reliability is the probability of a device or system performing its function adequately, for a specified period, under specified conditions.

Reliability Indices

- Several indices have been introduced in reliability theory to facilitate reliability predictions, and others to fit various applications. Quite generally, all of these indices can be classified into the following categories:
 - Probabilities, such as the reliability or the availability
 - Frequencies, such as the average number of failures per unit time
 - Mean durations, such as:
 - the meantime to the first failure;
 - the mean time between the failures;
 - the meantime between the failures
 - Expectations, such as:
 - the average curtailment of energy per unit of time owing to failures in power systems,
 - the expected number of days in a year when a system failure occurs

- The reliability of an electric supply system has been defined as the probability of providing users with continuous service of satisfactory quality
- Quality constraints refer to the requirements that the frequency and voltage of the power supply should remain within prescribed tolerances
- The actual degree of reliability experienced by a customer will, of course, vary from location to location
- Different parts of the power network such as generation, transmission, and distribution systems will exhibit different reliabilities

Typical indices employed for power system applications are:

- **Loss-of-load probability (LOLP)**- the probability of the system load exceeding the available generating capacity under the assumption that the peak load of each day lasts all day.
- **The probability of not meeting the annual peak load**
- **The load interruption index**- the average MW load interrupted per unit time per unit of load served
- **Customer interruption frequency index**- the average number of interruptions experienced per customer affected, per unit of time
- **Customer interruption duration index**- the average duration of customer interruptions during a specific time period
- **Customer curtailment index**- the MW minutes of interrupted load per affected customer per year.

SOME IMPORTANT MEASURES RELATED TO RELIABILITY ANALYSIS

- Reliability measures quantify the effectiveness of the system

RELIABILITY FUNCTION:

The probability that the system fails between 0 and t is given by cumulative distribution function

$$F(t) = P [T \leq t] \quad (1)$$

where, T is non-negative random variable which is the time to failure of a component.

The Reliability function of a system at time t , $t \geq 0$ is

$$\begin{aligned} R(t) &= P[T > t] \\ &= 1 - F(t) \end{aligned} \quad (2)$$

MEAN TIME BETWEEN FAILURES (MTBF):

- Mean time between failures is the expected value of time to failure of the components or system, i.e., it is the average time taken by any two failures of the system.
- Mean Time Between Failure (MTBF) is also known as Mean Time to Failure (MTTF) when the components in the system are not repaired as well.
- Mean Time Between Failure is usually the mathematical expected value of time to failure of the system, which is given by:

$$MTTF = E(T) = \int_0^{\infty} t f(t) dt = \int_0^{\infty} R(t) dt \quad (3)$$

Single-bus Generation Expansion Planning

Problem Definition:

- Generally speaking, GEP, is an optimization problem in which the aim is to determine the new generation plants in terms of when to be available, what type and capacity they should be, and where to allocate so that an objective function is optimized and various constraints are met.
- May be of static type in which the solution is found only for a specified stage (typically, year) or a dynamic type, in which, the solution is found for several stages in a specified period.

The objective function consists generally of:

$$\text{Objective function} = \text{Capital costs} + \text{Operation costs}$$

The first term is, mainly due to:

- Investment costs (C_{inv})
- Salvation value of investment costs (C_{salv})
- Fuel inventory costs (C_{finv})

The second term, consists, mainly, of

- Fuel costs (C_{fuel})
- Non-fuel operation and maintenance costs (CO&M)
- Cost of energy not served (CENS)

- Besides the objective function, some constraints should also be met. A simple constraint is one which describes the available generating capacity to be greater than the load.
- If a reserve margin is required, the difference should also take the reserve into account

Mathematical Development

- The problem is to determine from a list of available options, the number, type and capacity of each unit needed, in each year of the study period.

Objective Functions:

The total cost C_{total} may be described as:

$$C_{total} = C_{inv} + C_{fuel} + C_{O\&M} + C_{ENS}$$

where

C_{inv}	The investment cost
C_{fuel}	The fuel cost
$C_{O\&M}$	The operation and maintenance cost
C_{ENS}	The cost of energy not served

Multi-bus Generation Expansion Planning

- In single bus generation expansion, we ignored the transmission system and found out the total generation requirements based on an optimization model.
- In a practical life, we are, however, confronted with determining the nodal generation requirements. In other words, we should, somehow, allocate the total generation requirements among system buses.
- The solution may be simple if the transmission system strength was infinite, the fuel costs were the same for all buses, the cost of land was also similar and there were no other practical limitations.
- In that case, we can arbitrarily allocate the total generation requirements among the buses according to our wishes.

- If we are going to consider all details, the problem ends up with a model which may be impossible or very difficult to solve.
- To simplify the analysis following assumptions are considered:
 - ✓ The total generation requirements as well as the types and capacities of the generation units are known
 - ✓ Some practical limitations and data are available for system buses. For instance, some types of generations (for example, steam generations) may be allocated in some specific buses or the maximum generation that can be installed in a specific bus is known.
 - ✓ The aim is to allocate the generations among the buses in such a way that transmission enhancement requirements are minimized

Problem Description

The problem is more readily described through one simple example as detailed below.

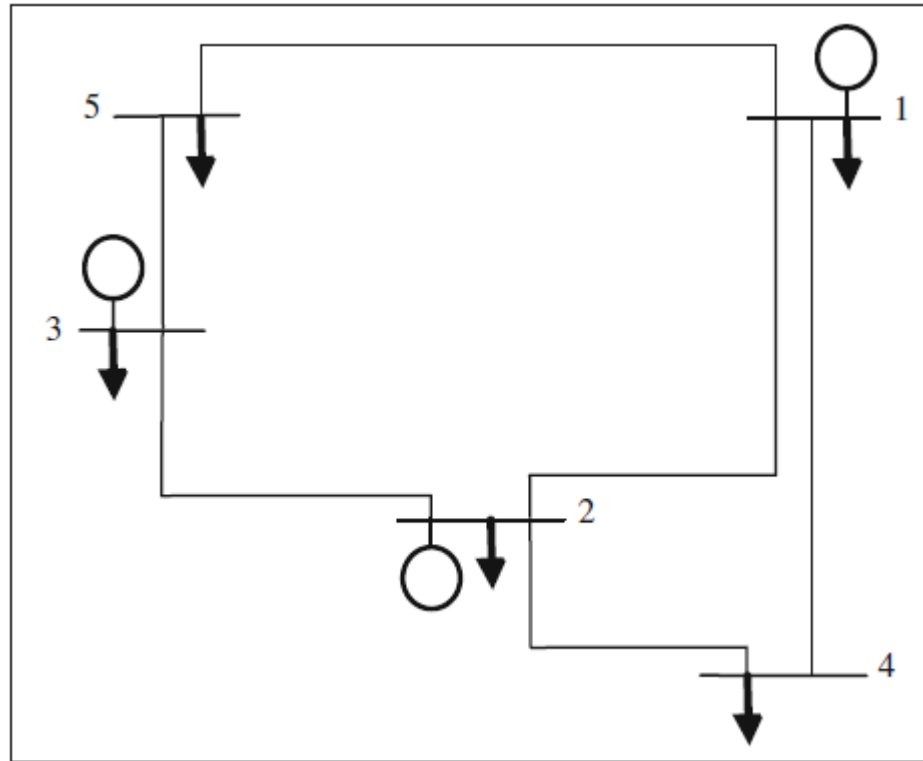


Fig. 2. Garver test system

- Assume that the total generation requirement of a system is known to be 500 MW (1 X 150, 1 X 250, and 1 X 100 MW units)
- assume that the loads of the buses are increased each by 100 MW (total 500 MW) so that 500 MW new generation is required
- In terms of the new generation, the following three cases are assumed
 - ❑ Case 1: All generations are to be installed at bus 1.
 - ❑ Case 2: 250 MW, 150 MW, and 100 MW are to be installed at buses 1, 3, and 4, respectively.
 - ❑ Case 3: 400 MW (1 X 250 and 1 X 150) and 100 MW are to be installed at buses 2 and 4, respectively.

A summary of some load flow results is shown in the Table below:

For our purposes, we have included a sum of lines over loadings (in normal conditions) both in absolute values and multiplied by respective line lengths

Table 1: A summary of load flow results

Scenario	Overloading	
	Sum (absolute values)	Sum (multiplied by lengths)
1	2.089	652.2
2	0.253	50.6
3	0.404	80.6

- From the above load flow result it is clear that case 2 is the best choice.
- However, as in case 3, only two locations are justified for new generations, this may be more attractive in comparison with the scenario 2.

If the system is small and the number of alternatives (scenarios) is limited, the approach presented above may suffice. In practical life, in which the system and the number of alternatives are large, some advanced algorithms should be followed.

A Linear Programming (LP) Based GEP

Basic Principles:

If Direct Current Load Flow (DCLF) is used to model the system behavior, the line flow would be a linear function of the loads and the generations

In that case, an optimization problem may be formulated as follows in which the aim is to allocate the total generation requirements among the buses.

For an N-bus, M-line network, DCLF equations are:

$$\mathbf{P}_G - \mathbf{P}_D = \mathbf{B}\theta \quad (1)$$

where

- $\mathbf{P}_G$ A vector of generations ($N \times 1$)
- $\mathbf{P}_D$ A vector of loads (or demands) ($N \times 1$)
- θ A vector of bus angles ($N \times 1$)
- $\mathbf{B}$ The admittance matrix with $R = 0$ ($N \times N$)

The line flows are calculated as follows:

$$\mathbf{P}_L = \mathbf{b} \mathbf{A} \theta \quad (2)$$

where

- $\mathbf{P}_L$ A vector of line flows ($M \times 1$)
- $\mathbf{b}$ A matrix ($M \times M$) in which b_{ii} is the admittance of line i and non-diagonal elements are zero
- $\mathbf{A}$ The connection matrix ($M \times N$) in which a_{ij} is 1, if a line exists from bus i to bus j ; otherwise zero. Moreover, for the starting and the ending buses, the elements are 1 and -1 , respectively

From (1) and (2), we have:

$$\mathbf{P}_L = \mathbf{bAB}^{-1}(\mathbf{P}_G - \mathbf{P}_D) \quad (3)$$

For a specific line i , the line flow (P_{Li}) is

$$P_{Li} = \sum_{j=1}^N s_{ij}(P_{Gj} - P_{Dj}) \quad (4)$$

where P_{Gj} and P_{Dj} are the generation and the demand (load) of bus j , respectively. s_{ij} is, in fact, the ij th element of $\mathbf{bAB}^{-1}$ matrix, describing the i th line flow sensitivity with respect to the generation and the load difference of bus j .

Mathematical Formulation

- In a practical situation, the investment cost of a generation unit, besides the actual cost of equipment, also depends on some technical or non-technical factors such as the cost of land, the fuel supply piping cost, the interconnection cost to the main grid, etc.
- It is assumed that the effect of all terms can be reflected into β^k (R/MW) showing the generation cost in area k. A mathematical optimization problem is:

Objective Function:

$$F = \sum_{k=1}^{Na} \beta^k PG^k + \sum_{i=1}^M \gamma L_i (b_i - 1) \quad (5)$$

where the first term is the generation investment cost and the second term is the transmission enhancement cost. L_i is the length of the line i . γ is the investment cost (R/KM) of a line and b_i is the loading of the line i if the line is overloaded. If line is not overloaded b_i is set to 1. The decision variables are PG^k s and b_i s.