PROBABILISTIC OPTIMAL SCHEDULING OF ENERGY LIMITED MULTIHYDRO UNITS

BY

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ABSTRACT

Two most important steps in generation expansion planning process are: the evaluation of reliability indices and production cost. Because of the non existent operating cost of the hydro units, special care is taken in planning so that these units are used upto their capacity. This makes the simulation of hydro unit different from the thermal unit. The complexity in simulation increases if the hydro unit is energy limited and it grows further if more than one energy limited hydro units compete for the same position in the loading order. Again the possible energy generation by a energy limited hydro unit is a deterministic quantity only for a reservoir of smaller (limited) capacity for abundant water supply to the reservoir. However, this is not the case for most of the situations.

This thesis presents a methodology of scheduling any number of energy limited hydro units competing for the same position in the loading order. This method is an extension of the conventional approach of simulating energy limited hydro units. This thesis also presents a novel approach of scheduling energy limited unit. This approach takes into account the randomness in energy constraints of hydro unit by developing a probabilistic model of water levels and water flows of the reservoir or of run of river. The developed methodologies are applied to IEEE Reliability Test System and Bangladesh Power System. In the numerical evaluation, the segmentation method is utilized.

ABBREVIATIONS

AC - Available Capacity.

BPDB - Bangladesh Power Development Board.

BPS - Bangladesh Power System.

CLC - Chronological Load Curve.

DE - Demand Energy.

DNS - Demand Not Served.

ECS - Economic Commitment Schedule.

EL - Energy Limited.

ELDC - Equivalent Load Duration Curve.

ENS - Energy Not Served.

FAD - Frequency and Duration.

FOH - Forced Outage Hours.

FOR - Forced Outage Rate.

HR - Heat Rate.

HSD - High Speed diesel.

HV - Heat Value.

IC - Installed Capacity.

IEEE - Institution of Electrical and Electronic Engineers.

IFC - Incremental Fuel Cost.

IHR - Incremental Heat Rate.

LDC - Load Duration Curve.

LDO - Light Diesel Oil.

LOEP - Loss of Energy Probability.

LOLP - Loss of Load Probability.

MCS - Monte Carlo Simulation.

PDF - Probability Density Function.

RTS - Reliability Test System.

RV - Random Variable.

SKO - Superior Kerosene Oil.

UFC - Unit Fuel Cost.

WASP - Wien Automatic System Package.

r = Mean down time.

T = Time period.

UE_n = Unserved energy after convolving n- th unit.

UE_n' = Unserved energy before convolving n- th unit.

Z = Normalized variable.

(DNS) = Expected demand not served.

(ENS) = Expected energy not served.

λ = Unit failure rate.

λ_k = Average incremental cost of k-th unit.

μ = Unit repair rate.

Δ = Segment size.

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CHAPTER 1

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Even a most casual look at the modern civilization shows the important part played by electricity. Almost every function of present day halts when the supply of electricity stops. The electrical energy is the most common and versatile form of energy used in the industrial sector as well as domestic purposes. As technology advances the consumption of electrical energy increases steadily. Economists consider the per capita consumption of electricity as a measure of economic development of a nation. To meet the increasing demand of electrical energy it is required to develop a generation expansion plan which benefits most.

Generation expansion planning process begins with the estimates of the variation of demand with time and the total energy consumption. The next important two aspects of planning are: (1) the evaluation of reliability indices and (2) the production cost. Selecting a generation expansion plan among many alternatives is a complicated task, since it depends on an environment of uncertainty. In addition to the uncertainty inherent in load forecasting, the planner must also deal with the uncertainties associated with [1,2],

i) Generating unit availability.
ii) Generating unit maintenance schedules.
iii) Fuel cost.
iv) Pollution abatement legislation and costs.
v) Construction costs.
vi) Start-up times.
vii) Availability and cost of capital.

Given some alternative plans, it is a common practice to evaluate each plan on the basis of reliability first [3]. The simple and most common of all reliability indices is the loss of load probability (LOLP) [4]. When a given plan satisfies a desired reliability level, then it is required to evaluate it on the basis of economics.

Usually, generation system may include different types of generating unit. Depending on the sources of energy utilization, the generating units are classified as

(1) Thermal unit.

(2) Nuclear unit.

(3) Hydro unit.

The thermal units produce about the fifty percent of the total electrical energy. The amount of fuel cost associated with the thermal unit is dependent on the amount of energy it produces. For nuclear units, the fuel cost is relatively low. However, the availability of suitable nuclear fuel and disposal of the radio active waste [5], shortage of well-trained personnel prohibit these plants to enjoy a popular status in many regions of the world. For the hydro unit the incremental fuel cost is zero, as in this type of unit the source is water. The water is used to run the turbo-alternators and this water is made available from natural rainfall in the form of direct run-of-river or constructing a dam within a suitable catchment area or from natural reserve basin in a hilly region. That is, so far the incremental fuel cost is concerned the hydro energy is the cheapest. However, the maximum generation energy available from most of the conventional hydroelectric unit is limited [6].

1.2 BACKGROUND

Now a days, probabilistic simulation is widely used for generation expansion planning and in many respects, this approach is superior to the deterministic approach. In 1947, a large group of papers [7,8,9] on simulation techniques proposed some of the basic concepts upon which some of the methods in use at the present time are based. In 1954, utilizing the benefits of digital computers Watchorn [10] proposed the system expansion studies. Brown et al. [11] published the results of a statistical study of five years data on 387 hydroelectric generating units in 1960. Due to the introduction of a recursive approach [12,13,14,15] the calculation of outage frequency and duration indices in generating capacity reliability evaluation was modified. Baleriaux and Booth [16,17] further modified the technique for probabilistic simulation. Cumulant method was first suggested by N.S.Rau, P.Toy and K.F.Schenk [18] which utilizes Gram-Charlier series expansion. An exact technique as well as computationally efficient probabilistic simulation approach is suggested recently by K.F.Schenk et al [20]. This approach is commonly known as "Segmentation Method".

The simulation of energy limited (EL) hydro unit is different from that of the base loaded hydro unit. For a single energy limited unit the loading order position for having maximum energy output from the unit, becomes a moving target. If multiple EL units are considered, then the complexity of the simulation problem increases [6]. Until 1970's there has not been any work on the simulation of EL units. However, the author is aware of several approaches that have been taken to solve the difficulties faced by the EL unit simulation. Most of these methods resort to aggregate the energy limited units into a single composite unit. For example, in early versions of the Wien automatic system planning package (WASP) [21], the approach was used to simulate single/aggregated conventional hydroelectric unit which peak shaves the original load curve. Also in the improved version of WASP program the equivalent load curve was used to consider the random outages of units, but the energy limited hydro units were still aggregated to a single pseudo unit whose capacity was equal to the sum of the individual capacities. The assigned energy to pseudo hydroelectric unit was the summation of all the individual assigned energies. Billinton et al [22] and Dechamps et al [23] have developed methods which represents each EL unit individually. However, similar to the early versions of WASP, these methods used original load curves rather than the equivalent load curve. In Tennessee Valley Authority's FORGONE program [24], a rigorous approach was developed to simulate multiple EL hydro units. In this case the equivalent load curve was represented analytically by Fourier series. However, the simulation results became distorted whenever any of the EL units compete for the same loading order position. D.S.Joy of Oak Ridge National Laboratory and Henrich of International Atomic Energy Agency [25] have improved the WASP program by including many of the features of the FORGONE program. Feiler and Zahavi [26] have developed a rigorous simulation which includes multiple EL hydro units. The energy served by a group of interacting EL units was calculated directly, therefore, it was not possible for all EL units to exhaust their full assigned energy. In this technique as the number of EL units within a interacting group increases, a practical limitation on the maximum number of units arises [26]. This limitation can introduce distortions in the simulation. In 1980, a simulation technique capable of simulating multiple EL units was suggested by Brian Manhire [27]. However, in this technique an approximate representation of the equivalent load curve is made. In 1982, Manhire and Jenkins [6] developed an efficient technique for the energy limited multihydro units. However, in this approach, it is always required to store two distributions of LDC/ELDC in the memory of the computer to simulate one or two EL units. This paper does not provide any simulation results of more than two energy limited units, although it has been claimed that the methodology is capable of doing so. Moreover, the proposed technique in [6] utilized the cumulant method in the numerical evaluation and the cumulant method is always prone to the inherent inaccuracies of series expansions. In [28], Rau and Necsulescu have presented a methodology for probabilistic simulation of energy storage devices. In this method the modification of hourly load distribution is made by shifting the impulses to consider the energy limitation. Eventually, the method uses the Gram-Charlier series for the evaluation. To the best of the author's knowledge, no generation expansion planning algorithm has yet been formulated using segmentation method for rigorous treatment of simulating multiple energy limited hydro units.

1.3 THESIS ORGANIZATION

This thesis consists of nine chapters. As an introductory approach, chapter 1 gives the background of the energy limited hydro unit simulation. In this thesis, primary stress is given on the simulation of multiple energy limited hydro units together with other conventional generating units, therefore, in chapter 2 a very brief idea is given about the hydro units from the physical as well as operational point of view. Discussions in chapter 3 is directed towards the development of generation and load models that are generally used in different probabilistic simulation techniques. In chapter 4 different probabilistic simulation techniques are described except the segmentation method. Segmentation method is presented in detail in chapter 5 depicting binary state, multistate and multiblock loading of generating units. Evaluation of LOLP and production cost using segmentation method is also described in the same chapter. In chapter 6 conventional approach to the simulation of energy limited units are given. Methodology for simulating energy limited multihydro units which is capable of handling if many (or all) of these units are competing is described in chapter 7. In this chapter as a new approach, multistate representation of energy limited hydro units is also provided. Using the algorithm developed, numerical evaluation is carried out in chapter 8 with two different utilities namely, IEEE reliability test system (IEEE-RTS) and Bangladesh power system (BPS). Numerical evaluation for BPS is carried out with generation and load data supplied by Bangladesh Power Development Board (BPDB). In chapter 9 observations, conclusions and discussions are presented on the basis of the results found in chapter 8. Recommendations for further work are also provided in chapter 9.

CHAPTER 2

CHAPTER 2

HYDRO UNIT

2.1 INTRODUCTION

The perpetual interchange of water between the earth's surface and the atmosphere is sometimes known as the hydrologic cycle and is one of the sources of electrical energy. The heat of the sun evaporates water from oceans and rivers; the water that falls on land runs back to the sea through rivers. The water on a land surface has potential energy due to the difference in elevation of water between two points, called the head. When water flows to a lower elevation, a portion of the potential energy is converted to kinetic energy. Hydro-electric plants utilizes this kinetic energy to move turbine to which electric generators are mechanically coupled. Among all the conventional type power plants, the operation and maintenance costs involved with a hydro-electric plant is the lowest, and it generates least environmental pollution. Therefore, the maximum utilization of the hydro unit is desired.

In this chapter, a brief discussion of the general features of a conventional hydro-electric power plant is presented. This chapter also presents some basic concepts underlying with the energy limitation of conventional hydro-electric power plant.

2.2 EVOLUTION OF WATER POWER

The first hydro-electric plants were built during the last decade of the nineteenth century. Prior to about 1920, water power sites were usually developed for one or two purposes. The first of these was to supply electricity to a specially established industry - usually metallurgical or electrochemical [29]. The second purpose was to provide electric power to a local community for general industrial and domestic use. Implicit in a policy dictated by the requirements of orthodox finance was the selection of those water power sites, within easy transmission distance of the community to be served, which afforded the opportunity of providing relatively small blocks of power at attractively low cost. Frequently this led to the partial development of resources and to the restriction of the installed generating capacity to a size which could be justified by the natural stream flow. The early schemes were extravagant in the sense that a large part of the water available was often wasted over the spillways. As time went on the ever increasing demand for electric power resulted in the construction of plants of steadily increasing size and the concentration of generation into larger individual schemes.

At present artificial regulation of the river flow is provided using a reservoir. A reservoir is built in the catchment area by constructing a dam, therefore, the water flow can be regulated. Thus the firm capacity of the station is increased to a considerably higher value due to the fact that reservoir supplies the necessary water during the dry season or during the lower rate of water flow in the river. The most important factor behind the tremendous achievements occurred during the last few decades in the field of hydro electricity is that hydro power presents a renewable sources of energy. The pressure of steadily increasing demand led to the gradual discovery of many potential independent source of water power. A water power site in a relatively well developed country is regarded not as an isolated source of energy but as a possible means of providing additional generating capacity to an existing network of interconnected power stations.

2.3 WATER CYCLE

For the reliable generation by hydroelectric plant continuous availability of water is a basic necessity. For this purpose water collected in natural lakes at high altitudes may be utilized or water may be artificially stored by constructing dams across flowing streams. The rainfall is the primary source of water and it depends upon such temperature, humidity, cloudiness, wind direction and velocity etc. The utility of rainfall for power generation further depends upon several complex factors which include its intensity and time distribution, topography of land and its drainage characteristics, etc.

However, it is observed that only a small part of the rainfall can actually be utilized for power generation. A significant part is exhausted by direct evaporation, while another part sweeps into the soil. Some water is also absorbed by vegetation. Thus, only a part of the water falling as rain actually flows over the ground surface as direct run off and forms the streams which can be utilized for hydro electric schemes.

Figure 2.1 depicts a typical water cycle. Moisture evaporated from the ocean is carried away by warm air masses.

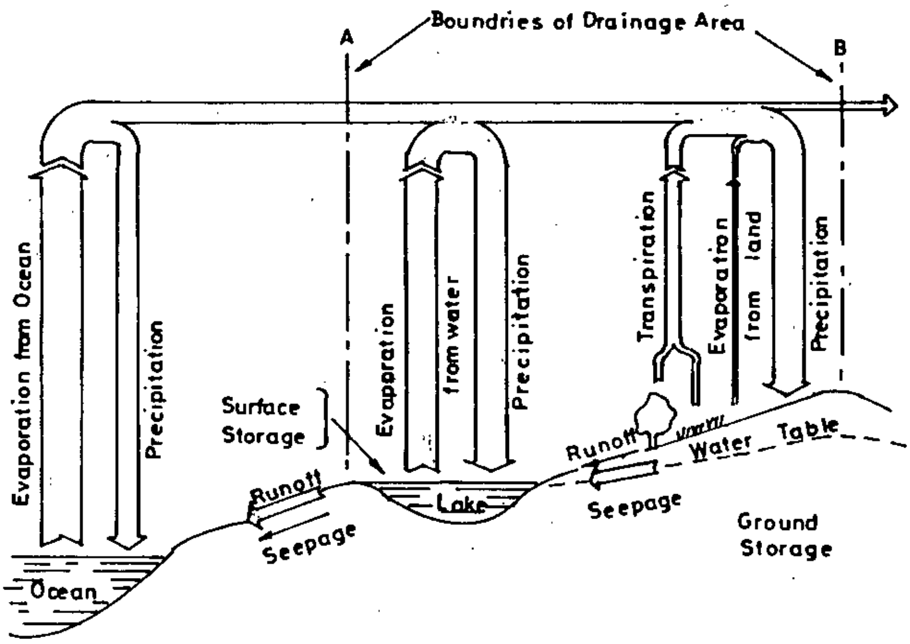


Figure- 2.1 A typical water cycle.

Some of the water vapor condenses and drops back into the ocean, but a part of the water vapor reaches continents to fall as rain or snow. Only a fraction of precipitation appears as river flow. The equation for the water cycle is

Run off + seepage = precipitation - evaporation and

$\pm$ change in storage. ....(2.1)

2.4 SELECTION OF SITES FOR HYDRO-ELECTRIC POWER PLANT

The essential characteristics for selecting a excellent site of a hydro-electric power plant are

1. Large catchment area
2. Steep gradient in the area
3. High average rainfall
4. Favorable sites for impounding reservoir.

The most important factors which have to be considered in this selection are:

a) Quantity of water available

b) Quantity of water that can be economically stored

c) Head of water which can be utilized

d) Distance of load center from the power station

e) Accessibility of the site.

Quantity of water available is estimated on the basis of measurements of stream flow over as long a period as possible. Rainfall records taken at various locations in the catchment area for many years also serve as source of information for availability of water. The determination, within reasonable limits, of the maximum and minimum variations from the average, depends on the number of years for which data is available. Therefore, for dependable forecast of the water potential, information recorded over a large number of years is desirable.

Storage of water is necessary for maintaining its availability during all seasons of the year so that operation of the plant can be ensured at all times. Rainfall is varying from year to year and also during different months of a year, with the result that flow of water in rivers and streams is never uniform. Storage of water using a reservoir helps to smoothen out this non uniformity of flow. Availability of water head has considerable effect on cost of a scheme and economy of power generation. Low falls on unregulated streams are subject to wide variations which affect the net head, and sometimes reduce it to an abnormally low value resulting in reduced power generation. For a given power output an increase in effective head reduces the quantity of water required to be stored and to be passed through the turbine.

2.5 CLASSIFICATION OF HYDRO-ELECTRIC PLANTS

There are several ways of classifying the hydro-electric plants. The most common form of classification [5,29,31] is based on

a) The superstructure

b) Availability of head

c) The nature of load

d) The nature of water availability

2.5.1 The Superstructure

According to the superstructure the hydro units are classified as

i) Outdoor stations

Outdoor stations have been constructed in which the superstructure of the building is dispensed with. The sets are usually of vertical-shaft arrangement, the generators being prominent and provided with weather-proof casings.

ii) Semi-outdoor stations

In this case the entire sets, of either vertical or horizontal shaft arrangement, are housed below the upper-most floor level, these are termed as semi-outdoor stations. Access to the equipment for maintenance is gained by removal of hatch covers. Therefore, these type of plants need only a low building.

iii) Underground hydro stations

At some locations it is cheaper to place the hydraulic station underground instead of on the surface. If the foot of the rapids has poor foundation conditions, or is in a narrow canyon without room for a surface plant, or if there is danger from rock slides, it may be necessary to locate the power station underground with a turned to the river.

2.5.2 Availability of Head

Depending on the nature of the site the useful head available may vary from some meters to a few hundred meters. The net head available for power generation can be substantially increased by using a suitable dam. According to the availability of water head the hydro plants are classified as

i) Low head plants

When the available water head is below 30 meters, the plant is known as the low head plant. In this case, a dam is built across the river to create the necessary water head. In general, Kaplan turbine or sometime Francis turbine are used in this type of plant.

ii) Medium head plants

The plants working under a net head of 30 meters to 100 meters are belong to this group. In this case the forebay provided at the beginning of penstock provides the reservoir facility and open canals are used to direct the water from the main river basin to the penstock and finally to the power house. In most of the cases Francis turbines are used for this type of plant.

iii) High head plants

If the working head of a hydro-electric power plant is greater than 100 meters, the plant is called a high head plant. In this type of plant the water is carried out by tunnels to the surge tank from the main reservoir and through the penstock it enters to the entry valve of the turbine. Pelton wheel is the most common form of water turbine for these type of units. Francis turbine is also sometime used.

2.5.3 The Nature of Load

As the hydro units are efficient to take care the rapid changes of load, a variety of operation of hydro unit is possible. Depending on the loading they are classified as

i) Base load unit

If the energy associated with hydro unit permits that uniform output is possible throughout the day or year then the units are loaded in the initial portion or constant load portion of the load curve. These type of units are called base loaded unit.

ii) Peak load unit

This type of units are used to serve the peak load portion of the consumer demand. As the operation of hydro unit is adaptable to varying load requirements, the operation of hydro unit as peak load unit is much more attractive than other conventional units. Depending on pondage and storage facilities available, the peaking unit stores the water during off peak period and supplies the consumer in the peak load period.

2.5.4 The Nature of Water Availability

Depending on the nature of water availability , the hydro units are classified as [5,31]

i) Run-of-river plants without pondage

A run-of-river plant without pondage, as the name indicates, does not store water and uses the water as it flows through the river. There is no control on flow of water. During high rate of flow water is wasted, while during low rate of flow the plant capacity is considerably reduced. Run-of-river plants without pondage may sometimes be made to supply the base load, but the firm capacity depends on the minimum flow in the river.

ii) Run-of-river plants with pondage

The importance of run-of-river plants increases when it has a pondage facility. Pondage usually refers to the collection of water behind a dam near the plant, and increases the stream capacity for short periods. The pond permits to store water during off peak hours and uses the water during peak hours. This type of units are usually used as peak load units.

iii) Storage plants

In this type of plants the reservoir size is such that it is possible to carry-over the storage from rainy season to dry season. In general, storage means collection of water at the upstream of the plant which can be used over an extended period of several months. Storage plants may work satisfactorily as base load or peak load stations depending on the total amount of water available and the consumer load demand.

iv) Pumped-storage hydro units

This type of units are used as peak load plants. Pumped-storage units deliver electricity to the consumer during peak load period and in the off peak periods it pumps back a portion of water from tailrace pond to the headrace pond. Therefore, in this type of plant there should be headwater pond as well as tailwater pond. In general, such plant has a prime mover which acts a turbine to develop power when revolving in one direction and as a pump to send the water back to head water reservoir when revolving in the other direction.

2.6 CAPACITY CALCULATIONS FOR HYDRO POWER

Energy available from stored water can be calculated from the relation

$$E = VW(H_g - h_f)e \qquad \text{.......(2.2)}$$

where

E is the energy

V is the volume of water flowing through the turbine

W is the weight of the water per unit volume

H_g is the gross head

h_f is the head lost in the system above entrance to the scroll and below draft tube exist; and

e is the plant efficiency expressed as a fraction.

The power developed in hydro plant is given by

$$P = QW(h_g - h_f)e \qquad \text{.......(2.3)}$$

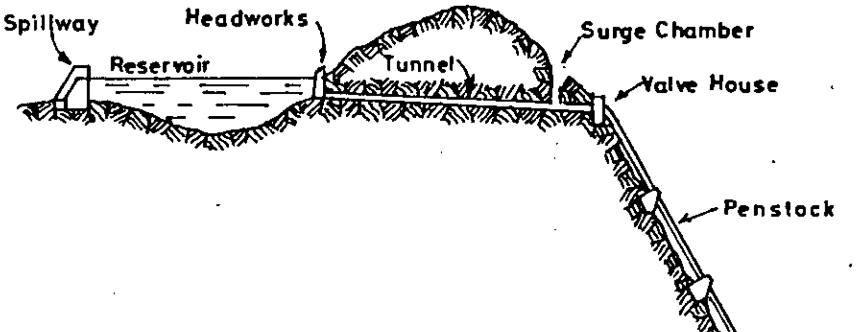
where

P is the developed power

Q is the flow rate

2.7 OUTDOOR ARRANGEMENT OF A HYDRO-ELECTRIC PLANT

The most common form of hydro unit is the storage type unit and the different components of such unit is depicted in figure 2.2.



Figaure- 2.2 Outdoor arrangement of a hydro unit.

The most essential component of a storage type hydro-electric project is the reservoir with sufficient catchment area. The reservoir stores water in the high flow season and uses this water in the low flow season. The water from the reservoir is drawn to the valve house through headworks and open channel or tunnel. The water then flows through the penstocks and drives the water turbine to which the generators are coupled.

2.8 DIFFERENT COMPONENTS OF HYDRO UNIT

In what follows a brief description of the main components of a hydro unit is given.

a) Reservoir

A storage is used to retain the excess water commonly known as reservoir. The primary purpose of a reservoir is to regulate the flow so that a firm supply can be generated, and the principal gain to offset the cost of increased storage is in the increased proportion of firm output and the increased kilowatt revenue.

b) Dam

The main function of the dam is to increase the water volume in the reservoir area, thus increasing the capacity and energy output of the hydro-electric project. Depending on the topography of the site dams are built of concrete or store masonry, earth or rock fill or even timber. Each dam is designed to fit the natural features of the location.

c) Spillway

With rare exceptions, there are times when the river flow at any site exceeds the rating of the generating equipment or the storage capacity of the reservoir. For that reason spillways are needed to discharge the surplus water past the dam.

d) Headworks

The headworks of a hydro unit consists of the diversion structures at the head of an intake. They usually include booms and rocks for diverting floating debris, sluices for by-passing debris and sediments, and headgates or valves for controlling the flow of water to turbines or conduit intakes.

e) Surge tank

Surge tank is usually provided in high-head or medium-head plants when there is a considerable distance between the water source and the power unit, requiring a long penstock. The surge tank furnishes space for holding water during load rejection by the turbine, and for furnishing additional water when load on the turbine increases. It also relieves water hammer pressures within the penstock conditions of sudden changes of water flow.

f) Penstock

Water may be conveyed to turbine through closed pressure pipes called penstocks made of reinforced concrete or steel. The thickness of the penstock increases as working pressure or water head increases. The penstock is supposed to withstand very high pressure.

g) Power house

This is the most important part of the hydro-electric unit. The power house contains the turbo-alternator set, control room as well as other accessories. In power house the energy associated with water is transformed to rotational energy through water turbine and this rotational mechanical energy is converted to electrical energy through alternators.

2.9 ENERGY LIMITATION OF CONVENTIONAL HYDRO POWER PLANT

The energy generated by hydro plant depends on the amount of water energy. The amount of water available or the amount that can be stored in the reservoir is limited. Therefore, the maximum generator energy available from such unit is fixed. When such unit is used to supply the consumers demand it may not be possible to load the unit in the base load region of the load curve. If this is the situation then the hydro unit is called the energy limited unit. A conventional hydro unit becomes energy limited due to some constraints which are independent of the operation of the remaining units of the power system. The main constraints are

1) Reservoir size
2) Run-of-the-river
3) Seasonal rainfall

2.9.1 Reservoir Size

A huge amount of water flows during the rainy season and it is required to store this huge amount of water in a reservoir which can be utilized during dry season. Therefore, a large reservoir area is required for this purpose. But in most cases the size of the reservoir is determined by the topography of the site. It is not always possible to increase the reservoir size by substantial amount due to the constructional as well as financial limitations. Therefore, a reservoir size became limited as it cannot store substantial amount of water in the reservoir for smooth operation of the plant during the whole season.

2.9.2 Run-of-the-River

In hydro-electric engineering, run-off usually denotes the water which actually reaches a given interception point. It is often related to some definite period, for example, a year or a month, and is expressed either as an average rate of flow throughout that period, or as a total in inches over the catchment area. Run off depends on the condition and type of soil, the character of the terrain, and the vegetation. Run-off is usually divisible into two distinct portions, the surface run-off and the water run-off or base flow. A large surface runoff is experienced when the ground is saturated from previous rain, or is impervious, such as rock or clay. Run-of-river in general depends on the various types of run off losses such as [29]:

a) Evaporation Losses

b) Transpiration loss

c) Interception loss

d) Losses due to consumptive use

e) Leakage loss

2.9.3 Seasonal Rainfall

Rainfall varies widely from one part of the world to the another, ranging from desert regions where rain is a climatic freak to the hills of Assam where the average annual rainfall is over 450 inches [29]. Rainfall also varies widely from one season to another within a year. Depending on the nature of the climate total rainfall may also vary from one year to the another. There are different types of rainfall. Convectional rainfall occurs when part of the surface layer of the atmosphere becomes heated and is thus displaced by the cooler air around it. Cyclonic rainfall occurs when air masses are carried up by air currents associated with the passage of barometric depressions.

2.10 IMPORTANCE OF HYDRO UNIT SIMULATION

As the technology advances more and more natural resources are required to meet the growing demand of energy. From the traditional sources which includes coal, petroleum and natural gases, the production of electrical energy is associated with fuel cost. The most important fact is that these sources have almost limited reserve throughout the world. Therefore, in last thirty to forty years much emphasis is given on the use of renewable sources of energy. Water power differs fundamentally from thermal power in that the former represents an inexhaustible source of energy which is continually replenished by the direct agency of the sun, whereas the latter represents the use of chemical energy which has been created and stored within the earth's crust during the past geological ages. The water power is a renewable source of energy and it is found in natural river flow or natural reservoirs.Thus, the incremental fuel cost associated with this energy is zero. Now for minimum production cost of a power system, the optimum scheduling of existing hydro units are badly needed. Also from the environmental pollution point of view, the hydro unit has the lowest affect on it.

2.11 APPLICATION OF HYDRO-ELECTRIC PLANTS

Hydro-electric plants have been used as exclusive source of power with thermal stations in a power pool. As a self-contained and independent power source, a hydro-plant is most effective with adequate storage capacity otherwise the maximum load capacity of the station has to be based on minimum flow of stream and there is a great wastage of water over the dam for greater part of the year. This increases cost of installation.

By coordinating hydro power with thermal, a great deal of saving in cost can be achieved. Hydro units are especially suitable for carrying fluctuating and peak loads. Thus the steam stations can carry a continuous base load with better efficiency. Hydro units can be put on the line in a matter of seconds, while a steam turbine and boiler may require several hours. Therefore, by proper coordination of hydro and thermal power more flexible operation of the units are possible.

CHAPTER 3

CHAPTER 3

GENERATION AND LOAD MODELS

3.1 INTRODUCTION

The principal objective of an electric utility is to ensure an economic supply of electrical energy to customers maintaining a desired level of reliability. The evaluation of LOLP and production costs for generation expansion planning using any method require two basic models; the generation and the load. The various models for generation and those for the system load, differ greatly in their degree of accuracy. The models suitable for incorporation of the probabilistic or stochastic nature of system behaviour are presented here.

3.2 GENERATING CAPACITY MODEL

Various types of generating units are in use today and all types of units are randomly forced off-line because of technical problems during normal period of operation. To account for the random outage or availability of a unit, it is necessary to determine the probability density function (PDF) that describes the probability that a unit will be forced off line or will be available during its normal operation. It may be assumed on the basis of historical data that the availability of the generating capacity of a given unit may be graphically represented as shown in figure 3.1. This figure conveys the idea that random failure and repair of a unit can be defined as a two-state stochastic process. A stochastic process is defined as a process that develops in time in a manner controlled by probabilistic laws.

The figure shows that the system alternates between an operating state, or up state, followed by a failed state or down state, in which repair is effected. For the i-th cycle, let

m_i = UP time

r_i = DOWN time

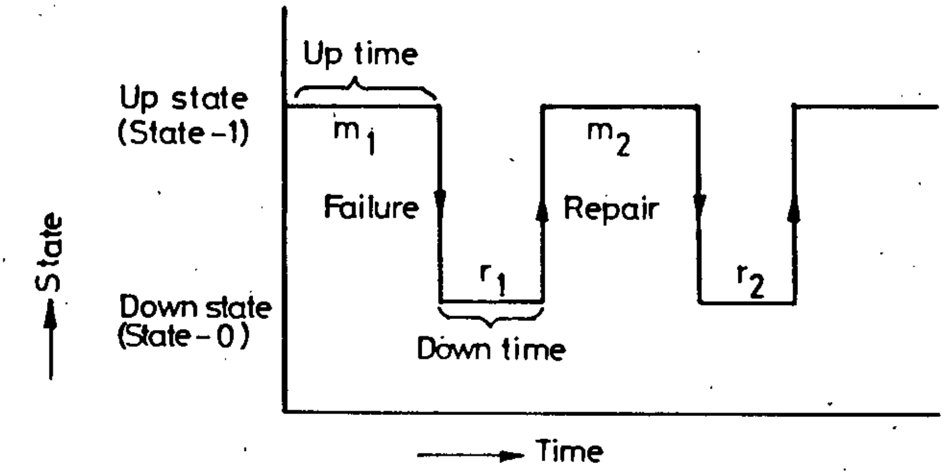


Figure-3.1 Run-fail repair-run cycle for generating unit.

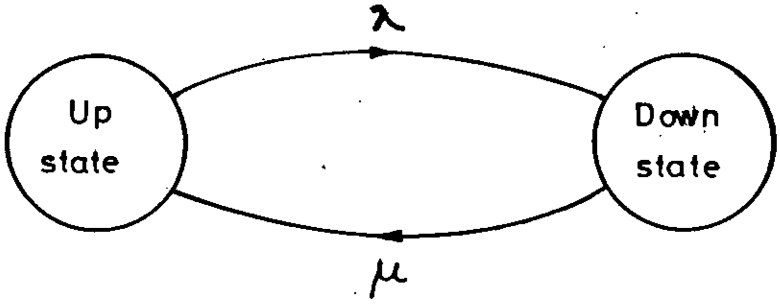


Figure-3.2 Generating unit state-space diagram.

The random history of a generating unit may be represented in terms of an average (mean) UP time and an average DOWN time as:

$$m = \text{mean up time} = \frac{1}{N}\sum_{i} m_i \qquad \text{.......(3.1)}$$

$$r = \text{mean down time} = \frac{1}{N}\sum_{i} r_i \qquad \text{.......(3.2)}$$

where N is the total number of run-fail-repair-run cycles. Thus the unit failure rate λ and the repair rate μ may be expressed as

$$\lambda = \text{unit failure rate} = \frac{1}{m} \qquad \text{.......(3.3)}$$

$$\mu = \text{unit repair rate} = \frac{1}{r} \qquad \text{.......(3.4)}$$

with these two parameters the random failure and repair of a generating unit can be defined as a state-space diagram (two state) as shown in figure 3.2.

Two important parameters can be obtained from this model[1]:

1. Unit availability - the long term probability that the unit will be in the up state.
2. Unit unavailability - the long term probability that the unit will be in the down state.

To obtain the expression for long-term availability and unavailability of a generating unit, it is first necessary to recognize that the stochastic process we are considering is a very special one, called a zero-order, discrete state, continuous transition Markov Process. Such a stochastic process has the following properties [1] :

1. Mutually exclusive and discrete states, that is the generating unit can be in either the up or the down state, but not in both simultaneously.

2. Collectively exhaustive states, that is, since we assure that only possible states for a generating unit are the up and the down states, then these states define all the possible states we ever expect to find a unit in.

3. Changes of state are possible at any time.

4. The probability of departure form a state depends only on the current state and is independent of time.

5. The probability of more than one change of state during a small interval Δt is negligible.

Let

$P_1(t + \Delta t)$ = Probability that the unit will be in the up state at time $(t + \Delta t)$ ....(3.5)

Thus

$$P_1(t+\Delta t) = \begin{bmatrix}\text{Probability of being}\\ \text{in state 1 at time t}\\ \text{and not leaving that}\\ \text{state during interval}\\ \text{t}\end{bmatrix} + \begin{bmatrix}\text{Probability of being}\\ \text{in state 0 at time t and}\\ \text{moving to state 1 during}\\ \text{interval t}\end{bmatrix} \qquad \text{.........(3.6)}$$

Consider that the distribution of a unit failure can be described by the exponential distribution.

$F_1(t) = e^{-\lambda\Delta t}$ = Probability of unit being available upto time t. ....(3.7)

Expanding the right hand side of equation (3.7) into infinite series and neglecting higher order terms, it is obtained as

$$F_1(t) = 1 - \lambda\Delta t + (\lambda^2(\Delta t)^2)/2! + \ldots\ldots.$$

$\cong 1 - \lambda\Delta t$ = Probability of unit being available during time Δt ....(3.8)

where

$\lambda\Delta t$ = Probability of transferring from state 1 to state 0 in timeΔt.

Again

$F_2(t) \triangleq e^{-\mu\Delta t}$ = Probability of unit being unavailable upto time t. ....(3.9)

Expanding into an infinite series and neglecting higher order terms, it is obtained as

$F_2(t) \triangleq 1 - \mu\Delta t$ = Probability of unit being unavailable during time Δt. ....(3.10)

where

$\mu \Delta t$ = Probability of transferring from state 0 to state 1 in time Δt.

Using the definitions of equations (3.7) to (3.10), equation (3.6) may be written as

$$P_1(t+\Delta t) = P_1(t)\,[1-\lambda\Delta t] + P_2(t)[\mu\Delta t] \qquad \text{.........(3.11)}$$

Similarly

$$P_2(t+\Delta t) = P_2(t)\,[1-\mu\Delta t] + P_1(t)[\lambda\Delta t] \qquad \text{.........3(12)}$$

where

$P_2(t)$ = Probability of being in the down state at time t.

Upon rearranging the equations (3.11) and (3.12), we have

$$\frac{P_1(t+\Delta t) - P_1(t)}{\Delta t} = -\lambda P_1(t) + \mu P_2(t)$$

$$\frac{P_2(t+\Delta t) - P_2(t)}{\Delta t} = \lambda P_1(t) - \mu P_2(t)$$

Letting $\Delta t \rightarrow 0$, one obtains the following differential equations:

$$\frac{dP_1}{dt} = -\lambda P_1 + \mu P_2 \qquad \text{.........(3.13)}$$

$$\frac{dP_2}{dt} = \lambda P_1 - \mu P_2 \qquad \text{.........(3.14)}$$

with

$$P_1(t) + P_2(t) = 1$$

Equations (3.13) and (3.14) can be written in the matrix form as follows:

$$\begin{bmatrix} P_1\cdot(t) \\ P_2\cdot(t) \end{bmatrix} = [P_1(t) \quad P_2(t)] \begin{bmatrix} -\lambda & \lambda \\ \mu & -\mu \end{bmatrix} \qquad \ldots\ldots\ldots\ldots(3.15)$$

Solving [2],

$$P_1(t)=\frac{\mu}{\lambda+\mu}[P_1(0)+P_2(0)] + \frac{e^{-(\lambda+\mu)t}}{\lambda+\mu}[\lambda P_1(0)-\mu P_2(0)] \quad \ldots.(3.16)$$

$$P_2(t)=\frac{\lambda}{\lambda+\mu}[P_1(0)+P_2(0)] + \frac{e^{-(\lambda+\mu)t}}{\lambda+\mu}[\mu P_2(0)-\lambda P_1(0)] \quad \ldots.(3.17)$$

where $P_1(0)$ and $P_2(0)$ represent initial conditions such that

$$P_1(0) + P_2(0) = 1$$

Now consider that at t=0 the generating unit is in the up state.

So, $P_1(0) = 1$ and $P_2(0) = 0$

Therefore, from equation (3.16) and (3.17)

$$P_1(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda^{e^{-(\lambda+\mu)t}}}{\lambda+\mu} \qquad \ldots\ldots\ldots(3.18)$$

$$P_2(t) = \frac{\lambda}{\lambda+\mu} - \frac{\lambda^{e^{-(\lambda+\mu)t}}}{\lambda+\mu} \qquad \ldots\ldots\ldots(3.19)$$

In generating expansion planning long-term (steady-state) probabilities are required. So, letting $t\rightarrow\propto$, equation (3.18) and (3.19) are obtained as

$$P_1(\propto) = \frac{\mu}{\lambda+\mu}$$

$$P_2(\propto) = \frac{\lambda}{\lambda+\mu}$$

Therefore the long term probabilities of unit availability and unavailability are given as

$$\text{Prob. [UP State]} = p = \frac{\mu}{\lambda + \mu} = \frac{m}{m + r} \qquad \text{......(3.20)}$$

$$\text{Prob. [DOWN state)} = q = \frac{\lambda}{\lambda + \mu} = \frac{r}{m + r} \qquad \text{......(3.21)}$$

thus

$$p + q = 1 \qquad \text{......(3.22)}$$

The traditional term for the unit unavailability is 'forced outage rate' (FOR), a misnomer in fact, since the concept is not a rate. An estimate for this important parameter may be given as

$$\text{FOR} = \frac{\text{Forced outage hours}}{\text{Forced outage hours + service hours}}$$

or,

$$\text{FOR} = \frac{\text{FOH}}{\text{FOH + SH}}$$

3.2.1 Probability Density Function of Binary State Generating Unit.

From the two state model of figure 3.2, the probability density function (PDF) of available and forced outage capacity for a generating unit of capacity C MW, FOR = q and availability p may be depicted as in figure 3.3.

The representation of figure 3.3 is also known as the binary state representation of generating units. The PDFs of forced outage capacity is expressed as

$$f_{L_o}(X_o) = p\,\delta(X_o) + q\,\delta(X_o - C)$$

where

f_{L_o} = PDF of forced outage capacity

$\delta(.)$ = Dirac - delta function.

X_o = Outage capacity

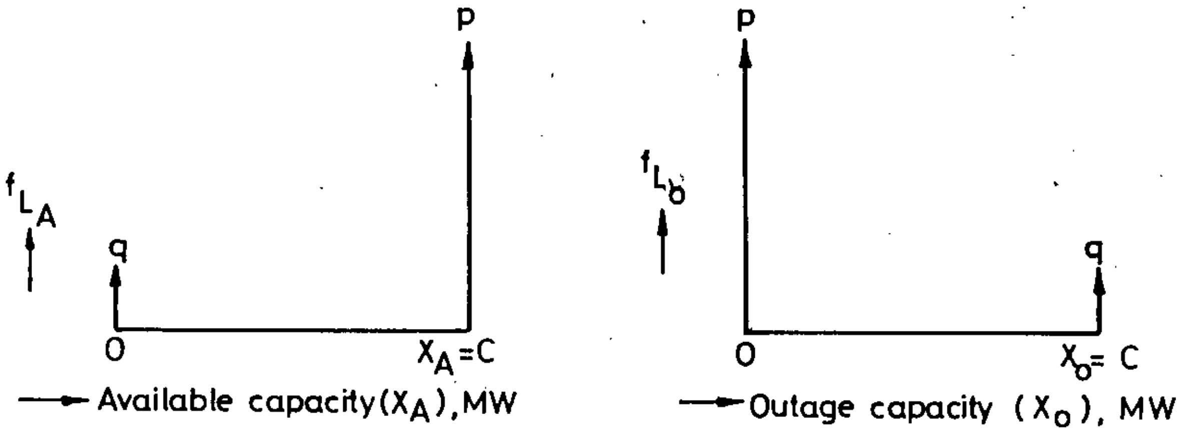


Figure -3.3. PDFs of available and forced outage capacity.

3.2.2 <u>Multi-state Representation of Generating Unit</u>

For a generating unit of capacity 100MW, a three-state model of the unit with one derated state is shown in figure 3.4. For this type of unit a partial outage is possible.

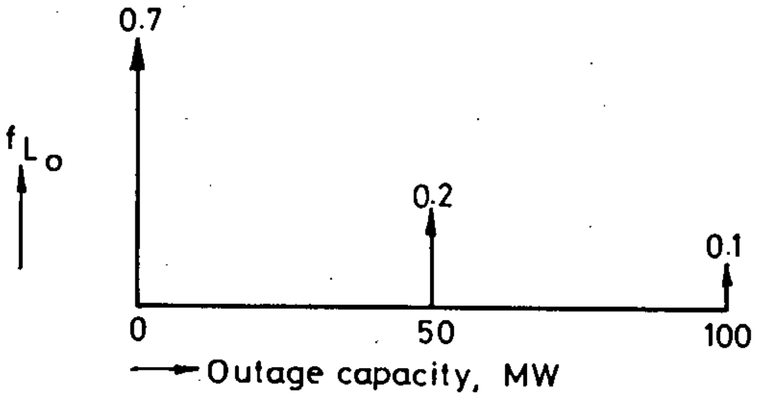


Figure-3.4 PDFs of outage capacity of a multistate unit.

3.2.3 Multi-block Representation of Generating Unit

On the basis of economic commitment schedule as will be described in Chapter 4 the generating units are loaded in the order of their average incremental costs. In actual operation, it is seldom economical to commit one generating unit fully before another unit is loaded. To simulate this fact the generating unit capacities are segmented into several capacity blocks; each block defined by its average incremental cost. A typical heat rate curve is shown in figure 3.5

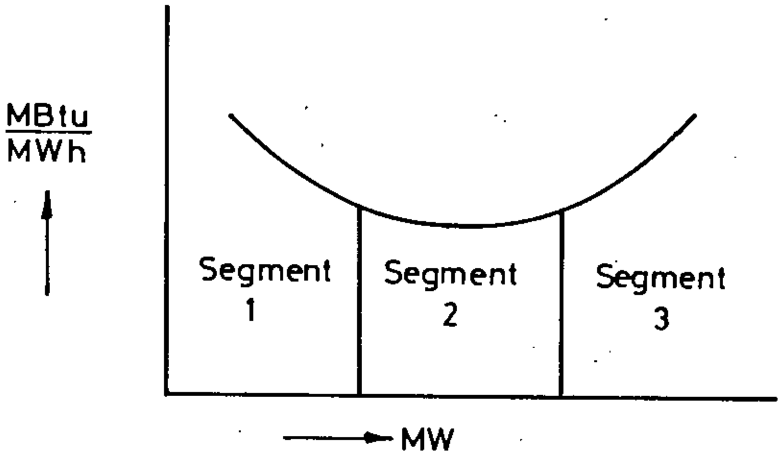
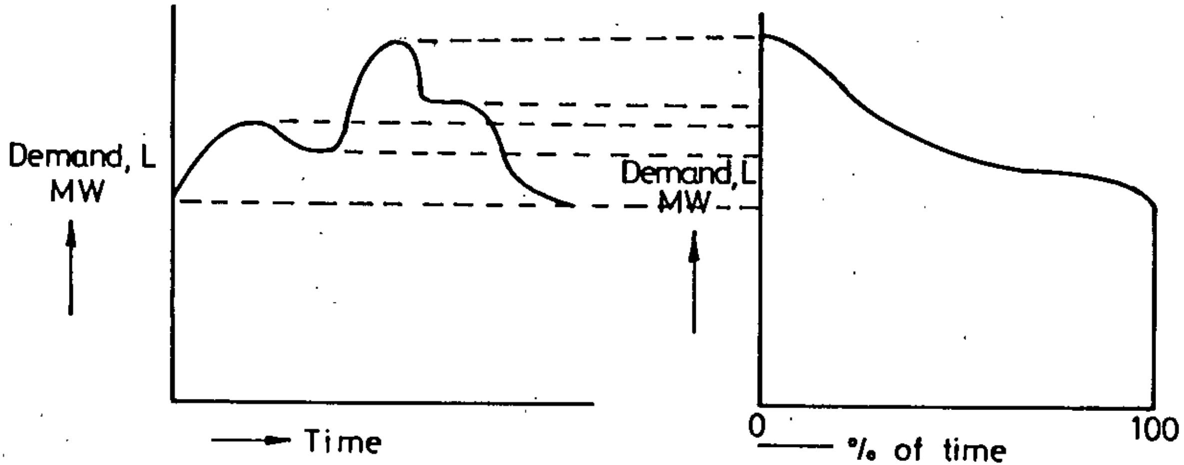


Figure- 3.5 Typical heat rate curve.

A unit may, for example, be divided into three blocks: a lower, middle and upper block with corresponding capacities and average incremental costs. The basic consideration in the simulation of multi block loading is that an upper block of a unit cannot be loaded unless the corresponding lower blocks have been already loaded.

3.3 PROBABILISTIC LOAD MODELS

The proper modeling of load is an important factor in the probabilistic simulation. The data required to develop probabilistic load model are readily available. Since continuous readings of system demand and energy are usually obtained on a routine basis by all electric utilities. If a recording of instantaneous demands were plotted for a particular period of time, a curve such as depicted in figure 3.6(a) might result. This is known as the chronological load curve (CLC). From this curve the so called load duration curve(LDC) in Figure 3.6(b) is easily constructed. The load duration curve is created by determining what percentage of time the demand exceeded a particular level.

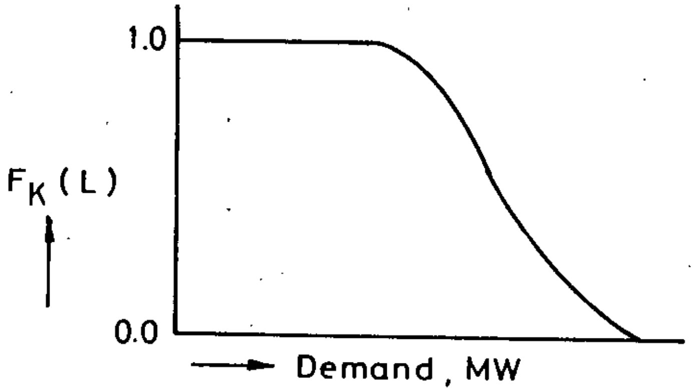


a) Instantaneous demand vs time b) Load duration curve

Figure-3.6 Chronological load curve and load duration curve.

3.3.1 Load Probability Distribution

For generation system studies it is necessary to interchange the axis parameters of figure 3.6(b) and normalize time, producing the load probability distribution in figure 3.7, where the y-axis shows the probability that the load exceeds the corresponding x-axis value. This load distribution will be denoted generally by $F_k(L)$, where k indicates the time period for which the distribution is applicable. This curve is also known as 'inverted load duration curve'.



Figure–3.7 Load probability distribution for week K.

3.3.2 Development of Hourly Load

Hourly load model is often used in various probability methods for evaluating LOLP and production cost. This hourly load model is developed from the chronological load curve (CLC). Figure 3.8 shows a CLC except that the time axis is being divided into n number of small equal intervals.

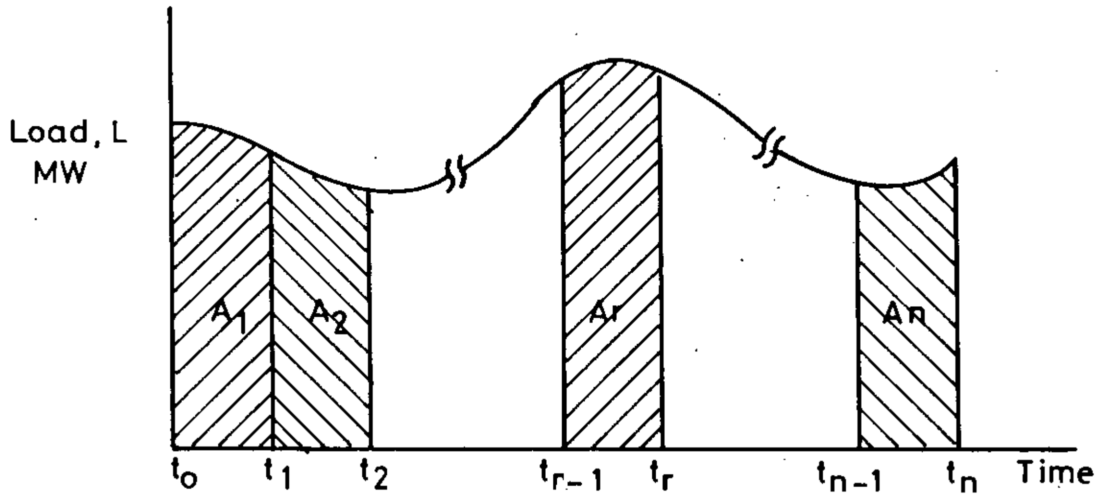


Figure- 3.8 CLC with time axis divided into n small interials.

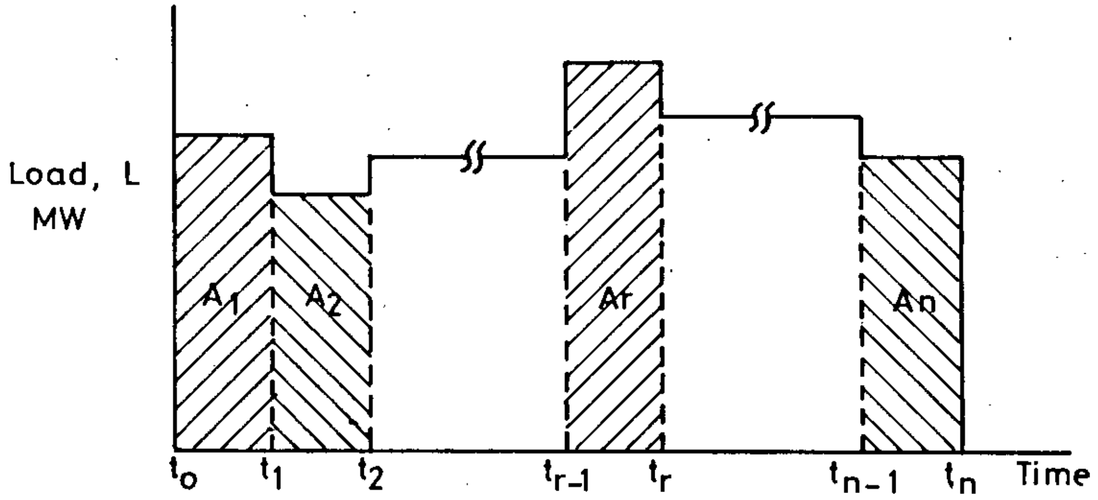


Figure- 3.9 Load distribution assuming constant load for each interval.

In the figure, the energy demand during the period between t_{r-1} and t_r is given by the area A_r under the CLC between t_{r-1} and t_r. Hence

$$A_r = \int_{t_{r-1}}^{t_r} L dt \qquad ....(3.23)$$

The average load during the period of time $(t_r - t_{r-1})$ can be obtained using the following equation:

$$L^r_{avg} = \frac{A_r}{(t_r - t_{r-1})} \qquad ....(3.24)$$

In this way the average load for all other time intervals are obtained. If the average load for each interval is assumed to remain constant for the corresponding interval, then a distribution of load of figure 3.9 is obtained. The most important point to note that by such construction the total energy demand as well as energy demand for each interval remains unchanged. If the time intervals is made equal to one hour then the resulting curve is known as 'hourly load curve'.

3.3.3 Effective Load

So far the probabilistic models for both the generating units and the load were developed. Now these two models will be combined to define the effective load of the system. The randomness in the availability of generating capacity is taken into account by defining a fictitious load, known as 'effective load' (L_e) [1]. Figure 3.10 depicts the relationship between the system load and generating units, where the actual units have been replaced by fictitious perfectly reliable units and fictitious random loads, whose probability density functions are the outage capacity density functions of the units.

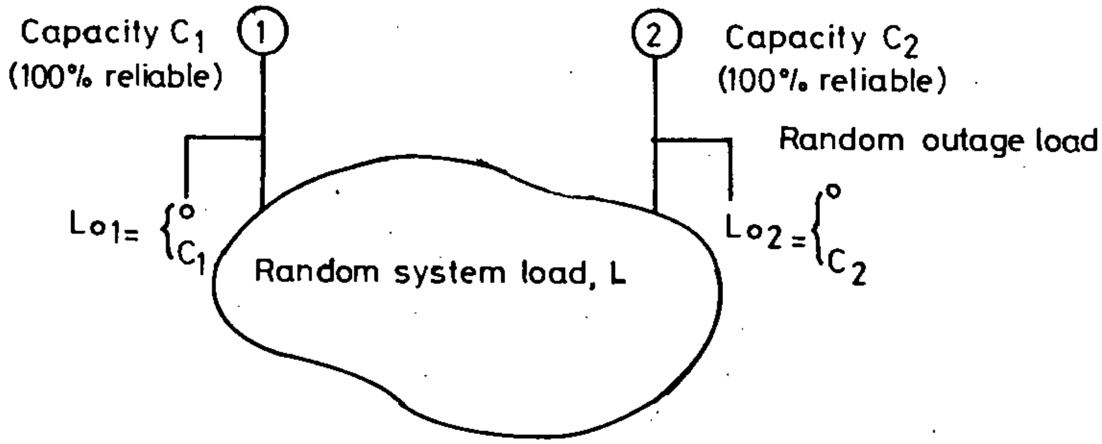


Figure-3.10 Fictitious generating units and system load model.

If L_{oi} represents the random outage load corresponding to the i-th unit, the equivalent load (L_e) may be expressed as

$$L_e = L + \sum_{i=1}^{n} L_{oi} \qquad \text{........(3.25)}$$

where n is the total number of generating units. When $L_{oi} = C_i$, the net demand injected into the system for the ith unit is zero, just as it would be if the actual unit of capacity C_i were forced off-line. The installed capacity of the system is given by

$$IC = \sum_{i=1}^{n} C_i \qquad \text{.......(3.26)}$$

The PDF of outage capacity of generating units may be taken as independent of system load. Then the distribution of effective load will be the convolution of two distributions; f_L and f_{Lo} representing the PDFs of the system load and outage capacity of generating units respectively. For the discrete case the

PDFs, f_L and f_{Lo} respectively, can be written as

$$f_L(l) = \sum_{i} P_{Li}\ \delta(l-l_i) \qquad \ldots\ldots.(3.27)$$

$$f_{Lo}(l_o) = \sum_{i} P_{Loj}\ \delta(l_o - l_{oj}) \qquad \ldots\ldots.(3.28)$$

Therefore, the PDF of equivalent load f_{Le} is

$$\begin{aligned} f_{Le}(l_e) &= f_L(l) * f_{Lo}(l_o) \\ &= \sum_{i,j} P_{Li}\ P_{Loj}\ \delta(l_e - (l_i + l_{oj})) \qquad \ldots\ldots.(3.29) \end{aligned}$$

where * indicates the convolution and P_L and P_{Lo} are the probabilities of load and outages of generating unit respectively. The small letters within bracket of equation (3.29) are the values of corresponding random variables (RVs).

CHAPTER 4

CHAPTER 4

PROBABILISTIC SIMULATION

4.1 INTRODUCTION

Probabilistic simulation may be defined as method for obtaining the expected energy generation, reliability index and production cost of a system of generating units meeting a consumer demand by taking into consideration the random nature of generation and demand [35]. In generation expansion planning, probabilistic simulation method finds its wide use throughout the power industries. For the probabilistic simulation a number of different techniques have been developed with an ultimate goal to improve its computational efficiency and flexibility. The probabilistic simulation techniques, developed till now, can be classified broadly into two categories exact and approximate.

In this chapter, a brief description of different simulation techniques is given. Prior to the discussion on simulation techniques a very brief analysis is given on power system reliability and economic commitment schedule.

4.2 POWER SYSTEM RELIABILITY

In mathematical evaluation, reliability is defined as the probability of a device or system performing its purpose adequately for the period of time intended under the operating conditions encountered [36]. The different probabilistic approaches are used to evaluate the power system reliability. For comparative study of reliability of power system a number of probabilistic reliability indices are being used. Some of commonly used indices are described here.

i) Loss of Load Probability (LOLP)

The loss of load probability is the probability that the available generating capacity of a system will be insufficient to meet its demand. Thus

$$\text{LOLP} = \text{Prob}[AC<L] \qquad ....(4.1)$$

where 'AC' and 'L' are the available capacity and system load respectively.

The evaluation of LOLP take into consideration the forced and scheduled outages of generating units as well as load forecast uncertainty and assistance due to interconnections. LOLP does not give an indication of the magnitude or duration of generation deficit. This reliability index only provides the probability of occurrence of the loss of load. As LOLP is the simplest and most commonly used reliability index [16,37], it will be used here to find the reliability of a power system having energy-limited multi hydro units.

ii) Loss of energy probability (LOEP)

The ratio of the expected amount of energy not supplied during some long period to the total energy required during the same period is defined as the loss of energy probability. The true loss of energy cannot be accurately computed on the basis of the cumulative load curve. For this reason, the loss of energy index is rarely used.

iii) Frequency and duration (FAD)[37].

This gives the average number of times and length of time during which available generation is inadequate to the load. This requires consideration of load cycle and data on the frequency and duration of unit outages. One problem with FAD technique is that it requires more detailed data than is usually available. In addition to failure rates of various components, repair times must also be available.

iv) Monte Carlo Simulation (MCS)

Monte Carlo simulation methods are more popular in Europe than in Canada or USA. In MCS, the actual realization of the life process of a component or a system is simulated on the computer and, after having observed the simulated process for some time, estimates are made of the desired reliability indices. MCS is best suited to problems in which reliability is significantly affected by system operating policies. The method is computationally expensive. However, it may produce a solution in cases where more traditional analytical techniques fail. This may happen when the failure and repair processes have non exponential distribution.

4.3 ECONOMIC COMMITMENT SCHEDULE

In reliability assessment, it is the number of units and their PDFs which account for the value of LOLP rather than the order in which the units are loaded. However, in cost analysis the loading order is also important. For the economic operation of the system, the schedule for the commitment of the units in the order of their increasing average incremental cost called 'economic commitment schedule' (ECS) or merit order of loading, is made.

The most economically efficient generating unit is the one with the lowest incremental cost, this generating unit is loaded first. Next in line will be the generating unit with again the lowest incremental cost among the remaining units. But it is seldom economical to commit one unit completely before another unit is loaded. To simulate this fact the generating unit capacities are segmented into several capacity blocks. The reason for segmenting the unit capacity is the shape of the heat rate (HR) curve. A typical HR curve is shown in figure 4.1. Clearly on this curve the second segment corresponds to higher efficiency. In ECS, the segment with lowest incremental cost is committed first. But it should be noted that in the commitment of capacity blocks of a generating unit the lower capacity block should be committed before any higher capacity block is loaded, since physically it is not possible to commit any higher capacity blocks before committing all the lower capacity blocks of that unit.

From the basic HR curve of figure 4.1 the input/output (I/O) curve can be obtained by multiplying every y-axis value by its corresponding x-axis value. A typical I/O curve is shown in figure 4.2.

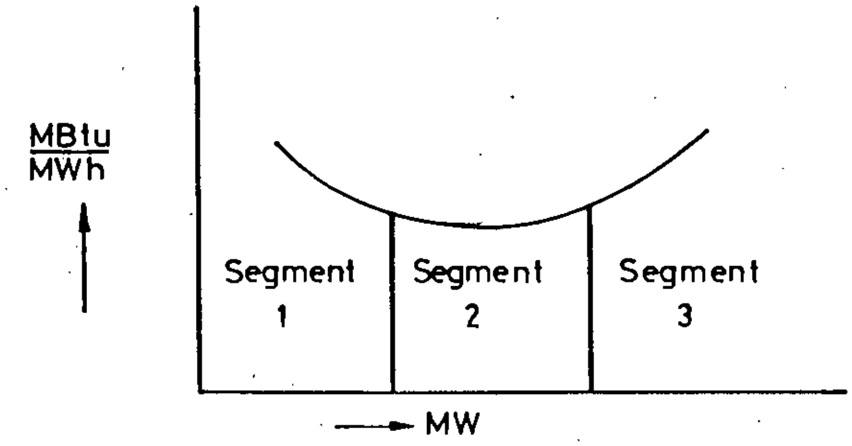


Figure- 4.1 Typical heat rate curve.

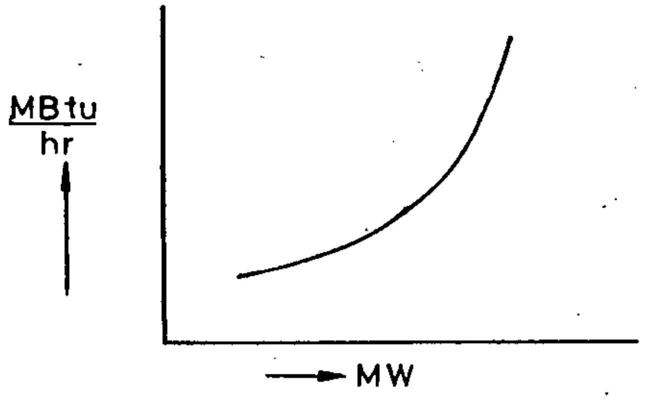


Figure-4.2 Typical input/output curve

Differentiating the I/O curve with respect to load (L), the incremental heat rate (IHR) curve is obtained as shown in figure 4.3. The IHR curve is used to obtain the incremental fuel cost of the generating units.

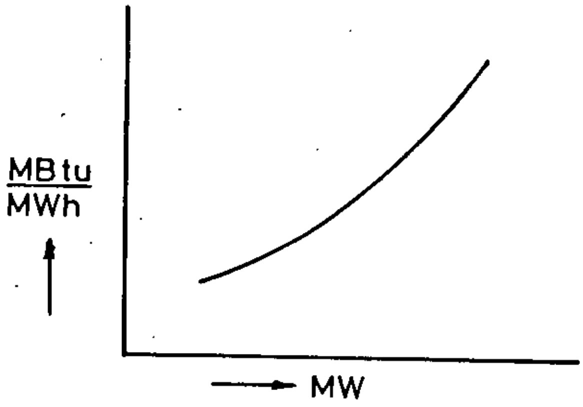


Figure – 4.3 Typical incremental heat rate curve

To quantify these relations for the k-th unit (or segment), one should do the following:

$$I/O_k(L) = L\ HR(L) \qquad \ldots\ldots\ (4.2)$$

$$IHR_k(L) = \frac{d(I/O_k(L))}{dL} \qquad \ldots\ldots\ (4.3)$$

In the special case when HR curve is assumed to be constant, the whole curve $HR_k(L) = HR_k$, then

$$IHR_k(L) = HR_k \frac{dL}{dL} = HR_k \qquad \ldots\ldots\ (4.4)$$

This special case is important, because in economic analysis the assumption that $HR_k(L)$ is constant makes computation simpler. For the k-th unit (or segment)

$$IFC_k = \frac{IHR_k(L) \times UFC_k}{HV_k} \qquad \ldots\ldots\ (4.5)$$

where

IFC_k = incremental fuel cost for k-th unit (Tk./MWh)

UFC_k = unit fuel cost for k-th unit (Tk./bbl or Tk./ton)

HV_k = heat value for k-th unit(MBtu/bbl or MBtu/ton)

If $HR_k(L)$ is constant then, for the k-th unit (or segment)

$$IFC_k = \frac{HR_k \times UFC_k}{HV_k} \qquad \text{.......} \ (4.6)$$

4.4 EXACT TECHNIQUES OF PROBABILISTIC SIMULATION

Two exact techniques for probabilistic simulation have so far been developed: one is the 'Baleriaux-Booth' [6,7] technique more commonly known as the 'recursive' method and the other one is the 'segmentation method' [20]. The segmentation method is described in detail in Chapter 5.

4.4.1 Recursive Method

The starting point of this method is the load probability distribution, F(L) and the generation system with the outage model of each unit. The probability distribution of equivalent load, $F(L_e)$ is obtained by convolving F(L) and the PDF of the ith generator outages $F(l_o)$ using the following equation

$$F^i(L_e) = F^{i-1}(L_e)P_i + F^{i-1}(L_e - C_i)q_i \qquad \text{.......}(4.7)$$

where

$F^i(L_e)$ = Probability distribution of equivalent load after convolving up to the ith unit

C_i = Capacity of ith unit

p_i = Availability of capacity C_i of the ith unit

q_i = Forced outage rate of ith unit.

In $F(L_e)$ the load axis represents a fictitious load called equivalent load. The units are convolved in F(L) in their economic merit of loading in order to simulate the way the units are actually loaded in a practical system.

In a n unit system, when r units are convolved, the probability distribution of equivalent load is represented as $F_r(L_e)$ and is shown in the following figure

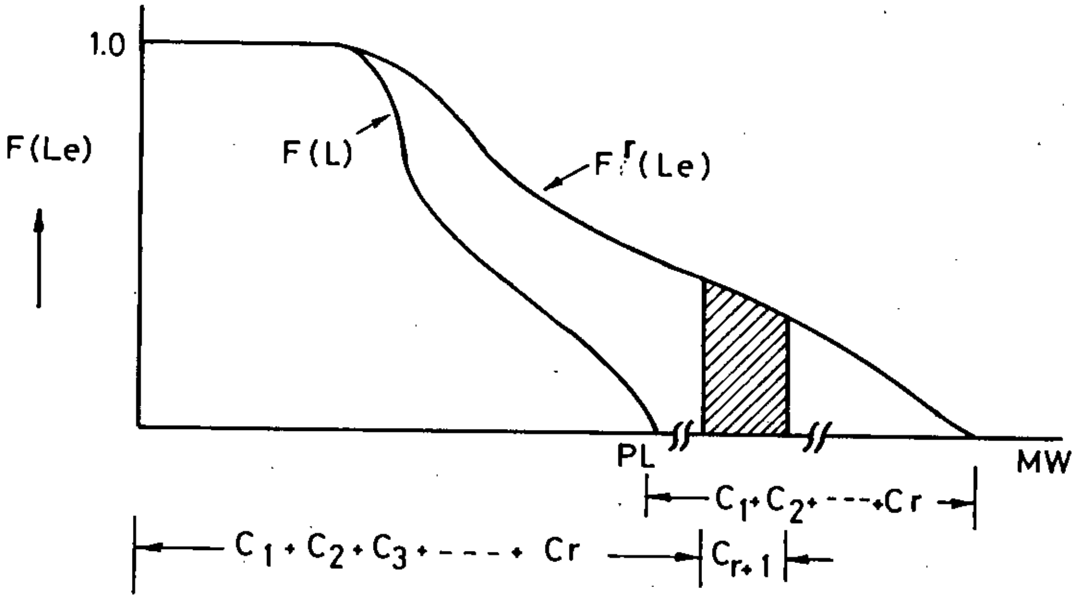


Figure-4.4 Load probability distribution of equivalent Load.

Where PL is the peak load of the system. The expected energy generation (E_{r+1}) by the (r+1) unit is represented by the area it occupies under $F_r(L_e)$ given as

$$E_{r+1} = T\,p_{r+1}\int_{A}^{B} F^r(L_e)\,dL_e \qquad \ldots\ldots\ldots (4.8)$$

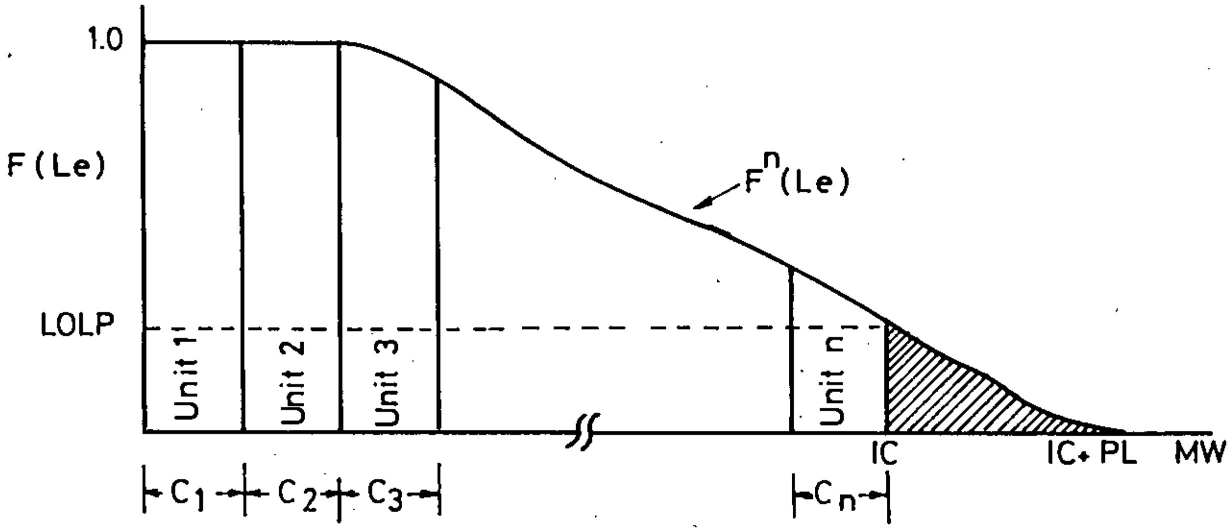
where

T = Period of hours considered

p_{r+1} = Availability of unit (r+1)

$A = \sum_{i=1}^{r} C_i$ and $B = \sum_{i=1}^{r+1} C_i$

The cost of energy produced by (r+1)th unit, assuming single block for each unit, is obtained by multiplying E_{r+1} by its average incremental fuel cost. When all the n units are convolved the final equivalent load probability distribution $F^n(L_e)$ is shown in the following figure.



Figure–4.5 Equivalent load probability distribution.

In this figure IC denotes installed capacity and is given by

$$IC = \sum_{i=1}^{n} C_i$$

The loss of load probability is simply the probability obtained from the curve $F^n(L_e)$ at point corresponding to IC. The expected demand not served is obtained from the area under $F^n(L_e)$ between the points IC and (IC + PL). The expected demand not served is expressed as

$$\epsilon(DNS) = \int_{IC}^{IC+PL} F^n(L_e)\,dL_e \qquad \text{........ (4.9)}$$

So the expected energy not served is given by

$$\in(ENS) = T \int_{IC}^{IC+PL} F^n(L_e)dL_e \qquad ....\ (4.10)$$

Recursive method can incorporate multi-block loading of generator. In this case the capacity blocks are convolved in the order of their increasing incremental fuel cost. Therefore the capacity blocks of a unit can occupy non adjacent loading order. But the important point is that the upper capacity block of a unit can not be loaded until all the lower blocks of that unit already loaded. To carry out the probabilistic simulation correctly whenever a upper block of a unit is to be committed, the corresponding lower blocks must be deconvolved and then joint lower and upper block is convolved. Deconvolution of ith unit is carried out using the following recursive relation

$$F^{i-1}(L_e) = \frac{F^i(L_e) - F^{i-1}(L_e - C_i)q_i}{p_i} \qquad ....(4.11)$$

4.5 APPROXIMATE TECHNIQUES OF PROBABILISTIC SIMULATION

Approximate techniques are evolved on the basis of Gram-Charlier series and it is faster than recursive method. But the accuracy of these techniques are system dependent i.e. depends on number of units, unit size, FOR, load shape etc. The technique is popularly known as 'cumulant method'.

4.5.1 Cumulant Method

The 'method of moments' commonly known as 'cumulant method' approximates the discrete distribution of equivalent load as a continuous function through Gram-Charlier series expansion. The convolution of PDF of generating unit with the load duration curve (LDC) is performed on the basis of economic commitment schedule. In this technique, the convolution is carried out by using the additive property of cumulants. For energy calculation i.e. the area under ELDC is not found by numerical integration rather it is found by normal probability table.

A discrete density function f(Z) can be expressed as a continuous function through the Gram-Charlier series [18,19] as

$$f(Z) = N(Z) - G_1 N^{(3)}(Z)/3! + G_2 N^{(4)}(Z)/4! - G_3 N^{(5)}(Z)/5! + (G_4 + 10G_1^2) N^{(6)}(Z)/6! \quad ..... (4.12)$$

where the normal PDF N(Z) and its derivatives are given by

$$N(Z) = \frac{1}{2} \exp(-Z^2/2) \quad ..... (4.13)$$

$$N^{(r)}(Z) = \frac{d^r}{dZ^r} N(Z) \quad ..... (4.14)$$

The normal PDF and its derivatives are related by the recursive relations

$$N^{(1)}(Z) = -ZN(Z) \quad ....(4.15)$$

$$N^{(2)}(Z) = (Z^2-1)N(Z) \quad ....(4.16)$$

and

$$N^r(Z) = -(r-1)N^{(r-2)}(Z) - ZN^{(r-1)}(Z) \quad ....(4.17)$$

for r = 3,4........

Using these recursive relations, equation (4.12) can be expressed as a polynomial of N(Z) and Z. G_1, G_2, ... etc. in equation (4.12) are expansion factors expressed in terms of the moments of individual distributions. The n-th moment, m_n, of any PDF p(x) is defined as

$$m_n = \int_{-\infty}^{\infty} x^n p(x) dx \quad ...... (4.18)$$

To obtain the expansion of equation (4.12) from the generator outage model and the LDC, six moments (n=1 to 6) about the origin for the normalized LDC (f(x)) are obtained as

$$m_{nL} = \frac{1}{A} \int_{0}^{PL} x^n f(x) dx \qquad \text{...... (4.19A)}$$

where A = Area under LDC, PL = Peak Load

In case of hourly load, the moments of order n about origin may be calculated from the following relation

$$m_n(l) = \frac{1}{T} \sum_{i=1}^{T} (L)^n \qquad \text{.......(4.19B)}$$

where T is the total no. of hours. n=1,2,3,........

Let us consider a binary state representation of the generating units as given in section 3.2.1. For the i-th machine in a system, the outage PDF consists of just two impulses, one of magnitude p_i at 0 MW and the other of magnitude q_i at C_i MW. The moments about the origin of such two state outage PDF are given by

$$m_n(i) = C_i^n q_i \; ; \; n=1,2 \qquad \text{...... (4.20)}$$

At any level where r generators are convolved with the LDC, for each generator the following six moments about the origin are calculated using equation (4.20)

$$m_1(i) = C_i q_i \, , \quad m_2(i) = C_i^2 q_i \qquad \text{.......(4.21)}$$

$$m_3(i) = C_i^3 q_i \, , \quad m_4(i) = C_i^4 q_i \qquad \text{.......(4.22)}$$

$$m_5(i) = C_i^5 q_i \, , \quad m_6(i) = C_i^6 q_i \qquad \text{.......(4.23)}$$

For each generator i.e. i=1 to r, the moments about the mean are calculated using the following relations

$$M_1(i) = m_1(i) \qquad \text{........ (4.24)}$$

$$M_2(i) = v_i^2 = m_2(i) - m_1^2(i) \qquad \text{........ (4.25)}$$

$$M_3(i) = m_3(i) - 3m_2(i)m_1(i)+2m_1^3(i) \qquad \text{........ (4.26)}$$

$$M_4(i) = m_4(i) - 4m_3(i)m_1(i)+6m_2(i)m_1^2(i)-3m_1^4(i) \qquad \text{....(4.27)}$$

$$M_5(i) = m_5(i)-5m_4(i)m_1(i)+10m_3(i)m_1^2(i)-10m_2(i)$$

$$m_1{}^3(i) + 4m_1{}^5(i) \qquad \text{........} \quad (4.28)$$

$$M_6(i) = m_6(i)-6m_5(i)m_1(i)+15m_4(i)m_1{}^2(i) -$$

$$20m_3(i)m_1{}^3(i)+15m_2(i)m_1{}^4(i)-5m_1{}^6(i) \qquad \text{........} \quad (4.29)$$

For each machine upto r, the cumulants are calculated using the following relations

$$k_1(i) = M_1(i) \qquad \text{.........}(4.30)$$

$$k_2(i) = M_2(i) \qquad \text{.........}(4.31)$$

$$k_3(i) = M_3(i) \qquad \text{.........}(4.32)$$

$$k_4(i) = M_4(i) - 3m_2{}^2(i) \qquad \text{.........}(4.33)$$

$$k_5(i) = M_5(i) - 10M_3(i)M_2(i) \qquad \text{.........}(4.34)$$

$$k_6(i) = M_6(i) - 15M_4(i)M_2(i)-10M_3{}^2(i) \qquad \text{.........}(4.35)$$

$$+30M_2{}^3(i)$$

From the six moments of LDC obtained from equation (4.19), the moments about the mean for the normalized LDC are calculated as given by equations (4.24) to (4.29). Then the cumulants for the normalized LDC are calculated as indicated by equations (4.30) to (4.35).

For the complete system the r units and the LDC, the cumulants of equivalent load are calculated using the relation

$$K_n(EL_r) = K_n(L) + \sum_{i=1}^{r} K_n(i) \qquad \text{....}(4.36)$$

where

$K_n(EL_r)$ = n-th cumulant of equivalent load curve when r units have been convolved.

$K_n(L)$ = n-th cumulant of LDC

$K_n(i)$ = n-th cumulant of the ith generating unit.

It is clear that the first cumulant of equivalent load curve is the mean (M) and the second cumulant is the square of standard deviation (V^2) of the distribution.

Now G-coefficients are calculated as

$$G_i = K_{(i+2)}(EL_T)/K_2^{(i+2)/2}(EL_T) \qquad .....(4.37)$$

$$i = 1,2,3,.......$$

These G-coefficients are utilized in the Gram Charlier series to obtain ELDC. Now the area 'A' under the equivalent load duration curve between values Z_1, and Z_2 may be calculated as

$$A = \int_{Z_1}^{\infty} f(Z)dZ - \int_{Z_2}^{\infty} f(Z)dZ \qquad .... (4.38)$$

where

$f(Z)$ = Equivalent load distribution

Z_i = Standardized random variables

$= (X_i - K_1(EL))/K_2(EL)$

in which X_i is any capacity, $K_1(EL)$ and $K_2(EL)$ are the 1st and 2nd cumulant of ELDC.

The integral in equation (4.38) is obtained by

$$\int_{Z_i}^{\infty} f(Z)dZ = \int_{Z_i}^{\infty} N(Z)dZ + F(Z_i) \qquad .... (4.39)$$

where

$$F(Z_i) = G_1 N^{(2)}(Z_i)/3! - G_2 N^{(3)}(Z_i)/4!$$
$$+G_3 N^{(4)}(Z_i)/5! - (G_4+10G_1^2)N^{(5)}(Z_i)/6! \qquad ..... (4.40)$$

The LOLP of the system is the value of the ordinate of the final equivalent load distribution at installed capacity.

The expected energy generation of a particular unit is the area under ELDC between the limits where the unit is convolved multiplied by the time period as well as availability of the unit.

CHAPTER 5

CHAPTER 5

SEGMENTATION METHOD

5.1 INTRODUCTION

In generation expansion planning, the evaluation of reliability index and production cost are the two most important factors that are being widely used by the utilities for comparison among the potential alternative plans. The most recent development in the evaluation of LOLP and production cost by probabilistic simulation is suggested by Schenk et al [20] which is commonly known as 'segmentation method'. The segmentation method is an exact and computationally most efficient method [20,32,33].

This chapter describes the segmentation method for evaluating loss of load probability, expected energy generation and production cost for each type of unit. The method is then examplified with a simple but revealing example. Discussion on Multi-state generating unit and multi-block generating unit loadings are also presented in the chapter.

5.2 PROCEDURE

The method uses the probability density function of demand by sampling the chronological load curve every hour or any other suitable interval. The segmentation method is based on segmenting the demand or load axis into equal capacity segments. Each segment size is equal to the largest common factor of the capacities of all units. If there are multi-block representation of generating units, then the segment size should be a common factor of all the blocks of the units. These segments are filled with the zeroeth and first order moments obtained from the distribution of load. As generating units are convolved, the zeroeth and first order moments for each segment are recalculated. After the convolution of each unit the unserved energy is calculated from the moments of the segments. The expected generation of a particular unit is the difference of unserved energies before and after the convolution of the unit. The total number of segments is decided through the knowledge of the installed capacity of the system as well as the segment size and one segment beyond the installed capacity is considered.

Thus, the segmentation method avoids the inherent errors present in the evaluation of unserved demand when using a numerical convolution formula or in a statistical approximation such as Gram-Charlier expansion. The method uses hourly loads and the frequency distribution of demand thus obviating the use of LDC. In addition the numerical errors in calculating the area under the LDC are also avoided.

5.2.1 Evaluation of Loss of Load Probability (LOLP)

As explained in Section 3.3.3, the LOLP of a system is the probability that the equivalent load will be greater than the installed capacity of the system and it is expressed as,

$$\text{LOLP} = \text{Prob.}[L_e > IC] \qquad \ldots\ldots\ (5.1)$$

In order to account for the random outages of units it is necessary to get a new distribution of each segment incorporating the outages of all units. Prior to find this new distribution each segment is assigned with a probability value which is equal to the sum of the probabilities i.e. zeroeth moments of the impulses of PDF of load lying in the range of that segment. Now the zeroeth moment of all the segments are recalculated as generating units are convolved. Let us consider the n-th segment, when a unit is convolved, the new value of zeroeth moment of n-th segment is found from the relation

$$P_n'' = P_n(1-q) + P_n'q \qquad \ldots\ldots\ (5.2)$$

where

P_n'' = Zeroeth moment of n-th segment after the convolution

P_n' = Zeroeth moment of n-th segment after the shift

P_n = Zeroeth moment of n-th segment before convolution

q = Forced outage rate of the unit to be convolved.

Following steps are used to convolve a generating unit:

a) The original moment of segments are multiplied by the availability of the unit.

b) The original segments are then shifted by the capacity of the unit to be convolved and are multiplied by the FOR of the unit.

c) The values obtained in (a) and (b) of corresponding segments are added to obtain the final distribution.

Note that the probability value of the last segment is the sum of the probabilities of all the segments exceeding the installed capacity. After all the generating units are convolved, the zeroeth moment of the last segment is the LOLP of the system.

5.2.2 Evaluation of Expected Energy Generation

The expected energy generated by a particular generating unit is obtained from the difference of unserved energies before and after the convolution of that unit. In segmentation method the evaluation of expected energy generation also starts with the formation of segments as described in Section 5.2.1. A probability value is assigned to each segment from the knowledge of load impulses lying within the segment size. Each segment is also assigned with another value which is the first order moment of the load impulses lying in the range of corresponding segment. The first order moment is given by

$$m_1 = \int_{-\infty}^{\infty} x f_x(x) dx \qquad \ldots\ldots\ (5.3)$$

where x is the random variable and $f_x(x)$ is the probability density function. For discrete case as in hourly load model, the first order moment for a particular segment is

$$m_1 = \sum_i x_i p_i \qquad \ldots\ldots(5.4)$$

where

x_i = value of the random variable

p_i = probability of the random variable x_i

Initially, the expected unserved energy is the summation of the first moment of all the segments. The generating units are then convolved according to the merit order of loading. As the generators are convolved, the first moment is recalculated for each segment. In this case, unlike the shifted zeroeth order moments the shifted first order moments are changed [34]. The first moment of any shifted segment is calculated by using the following relation

$$m_1^{new} = m_1^{old} + \text{shift} \times m_0 \qquad \ldots\ldots\ldots(5.5)$$

where m_0 is the zeroeth moment of the segment. As the first moment of a segment prior to convolution of a unit and shifted first moment are known, the first moment of the segment after convolution is found by

$$m_1'' = m_1(1-q) + m_1'q \qquad \ldots\ldots\ldots(5.6)$$

where

m_1'' = First order moment of the segment after convolution of a generating unit of FOR=q

m_1' = Shifted first moment of that segment

m_1 = First moment of the segment prior to convolution

Unserved demands are calculated before and after the convolution of each unit. The unserved demands multiplied by the period of study is the expected unserved energies. For n-th unit, expected energy generation is found from the relation

$$E_n = UE_n' - UE_n \qquad \ldots\ldots\ldots(5.7)$$

where

E_n = Expected energy generated by n-th unit

UE_n' = Unserved energy before convolving n-th unit

UE_n = Unserved energy after convolving n-th unit.

It should be noted that the first moment of last segment is the sum of the moments of all segments exceeding the installed capacity. When all the generating units are convolved the first moment of the last segment is the expected energy not served.

5.2.3 Evaluation of Production Cost

As the expected energy generated by a unit is known, the production cost associated with the unit is found by multiplying the expected energy generation with the average incremental cost of the unit.

$$EC_n = \lambda_n E_n \qquad \ldots\ldots\ (5.8)$$

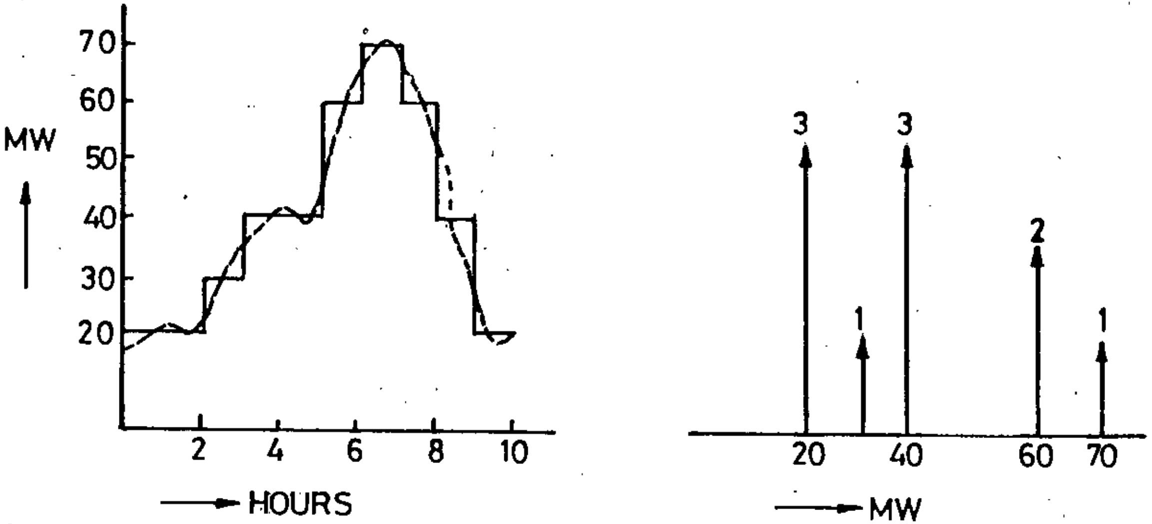
where

EC_n = Production cost of n-th unit

λ_n = Average incremental cost of the n-th unit.

5.3 NUMERICAL EXAMPLE TO CLARIFY THE METHOD

In what follows an example is given to clarify the segmentation method. Let us consider the hourly load as shown in figure 5.1. The dotted line represents the chronological load and firm line represents the hourly load. Hourly load, as described in section 3.3.2, is obtained from chronological load assuming that the average load over an hour exists for that particular hour. The PDF of load as shown in figure 5.1(b) is obtained from the chronological load curve of figure 5.1(a) by sampling at an interval of one hour. All impulses of PDF is assigned with a probability value.



(a) Chronological and hourly load

(b) PDF of hourly loads (all impulses to be divided by 10)

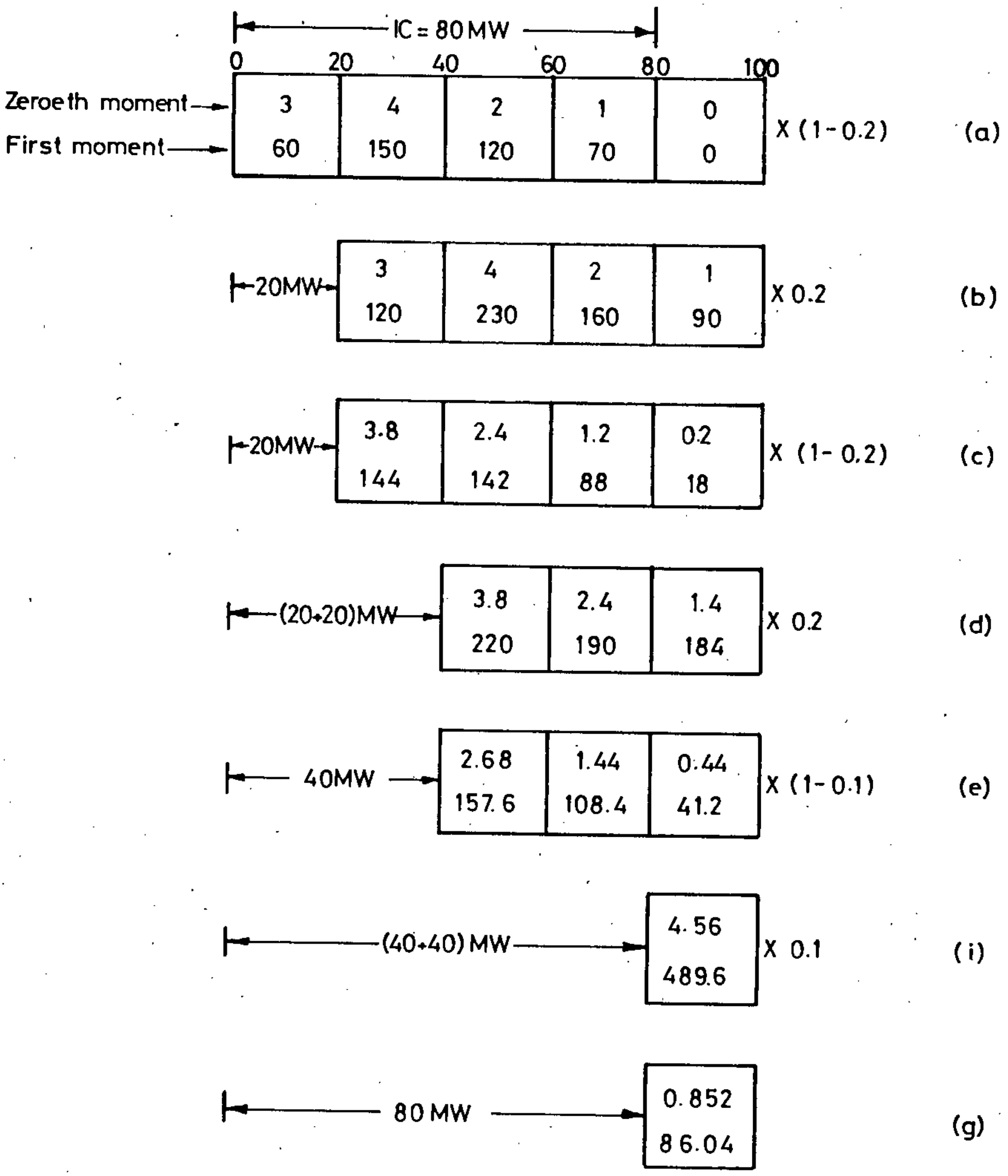
Figure-5.1 Load representation

Let us consider the generating system as shown in table 5.1.

Table 5.1 : Generating System

Merit order of loading	No. of Units	Capacity (Mw)	FOR	Average incremental cost (Tk./Mwh)	Installed Capacity
1	1	20	0.2	200	80
2	1	20	0.2	250	
3	1	40	0.1	300	

The segment size is chosen to be 20 Mw using the largest common factor of the generating unit capacities of table 5.1. The demand axis upto 80 Mw of the system is divided into 4 segments. One additional segment is considered



Figure–5.2 Schematic of convolution procedure (all number in boxes to be divided by 10) beyond the installed capacity in figure 5.2(a). The probability value of each segment is sum of the probabilities of different impulses lying in the range of that segment. Each segment in figure 5.2 contains two quantities. Upper quantity is the zeroeth moment and the other quantity is the first moment.

The different steps of convolution of load of figure 5.1 and the generating units of table 5.1 is shown in figure 5.2. According to the merit order of loading the first 20 Mw unit should be convolved first as it has the lowest average incremental cost.

To convolve the first 20 Mw unit the segments of figure 5.2(a) are shifted towards right in figure 5.2(b) by the capacity of the unit, 20 Mw. During the shift the zeroeth moment of each segment remain unchanged but the first moment is recalculated using the equation (5.5). The distribution of figure 5.2(a) is multiplied by the availability of the unit 0.8 and that of figure 5.2(b) by the unavailability of the unit, 0.2. This is shown in figure 5.2(c) and similar procedure is followed for the remaining units. As the segments are shifted, the zeroeth and first moments are accumulated at the last segment for those segments lie beyond the installed capacity. This is the case for the last segment of figure 5.2(d) and 5.2(f). The LOLP and unserved energy for the above example is calculated in what follows.

The LOLP is simply the probability value of the last segment of figure 5.2(g). Thus

LOLP = (0.852/10) = 0.0852.

Initial unserved energy= (First moment of all segments prior
to any unit convolution)xtime
= 10x(60+150+120+70)/10
= 400 Mwh.

Unserved energy after convolving 1st unit:

UE_1 = 10x((144+142+88+18)-20x(3.8+2.4+1.2+0.2))/10
= 240 Mwh.

Therefore, expected energy generation of 1st unit:

E_1 = (400-240)=160 Mwh.

Cost of energy generation of 1st unit:

EC_1 = (160x200)=32,000 Taka.

Unserved energy after convolving 2nd unit:

UE_2 = 10x((157.6+108.4+41.2)-40x(2.68+1.44+0.44))/10

= 124.8 Mwh.

Expected energy generation by 2nd unit:

E_2 = (240-124.8)=115.2 Mwh.

Cost of energy generation of 2nd unit:

EC_2 = (115.2x250)=28,800 Taka.

Unserved energy after convolving last unit:

UE_3 = 10x(86.04-80x0.852)/10

= 17.88 Mwh.

Therefore, expected energy generation of last unit:

E_3 = (124.8-17.88)=106.92 Mwh.

Cost of energy generation of last unit:

EC_3 = (106.92x300)=32,076 Taka.

Energy demand:

ED = Initial unserved energy=400 Mwh.

Total expected energy generation:

$\in(EG) = E_1+E_2+E_3$ = 382.12 Mwh.

Expected energy not served:

$\in(ENS) = UE_3$ = 17.88 Mwh.

Total energy production cost:

$EC = EC_1+EC_2+EC_3$ = 92,876 Taka.

For a given system and for the period under study the energy balance (EB) is the difference between the energy demand (ED) and the sum of the total expected energy generation (EG) and expected energy not served (ENS) as

$$EB = (ED)-((EG)+\epsilon(ENS)) \qquad \text{........(5.9)}$$

For the above example energy balance is:

$$EB = 400-(382.12+17.88)=0.0$$

It is again important to emphasize that there are no approximations made in the evaluations (except in the hourly sampling of the load) and hence the LOLP and unserved energies are exact.

5.4 MULTISTATE GENERATING UNIT LOADING

The segmentation method is capable of considering a multistate representation of the generating units. Consider the hourly load as described in figure 5.1 and let the generating system have only one generating unit of 80 Mw for simplicity. Consider a five state model of generating unit with three derated state as shown in figure 5.3. The method to convolve this unit in the system load is described in what follows. The steps are shown in figure 5.4.

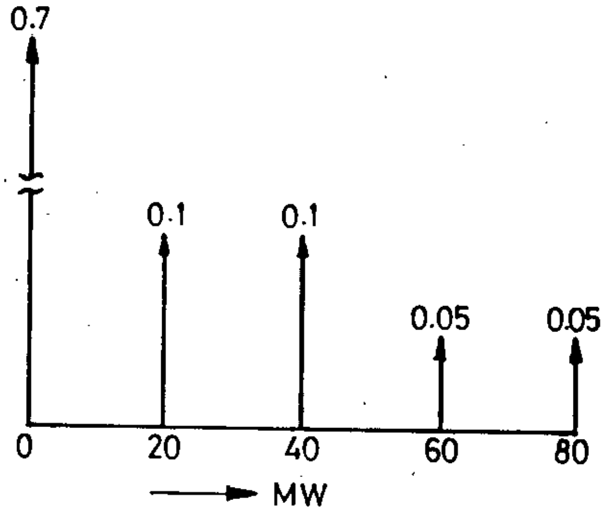


Figure-5.3 Multistate representation of outage capacity of generating unit

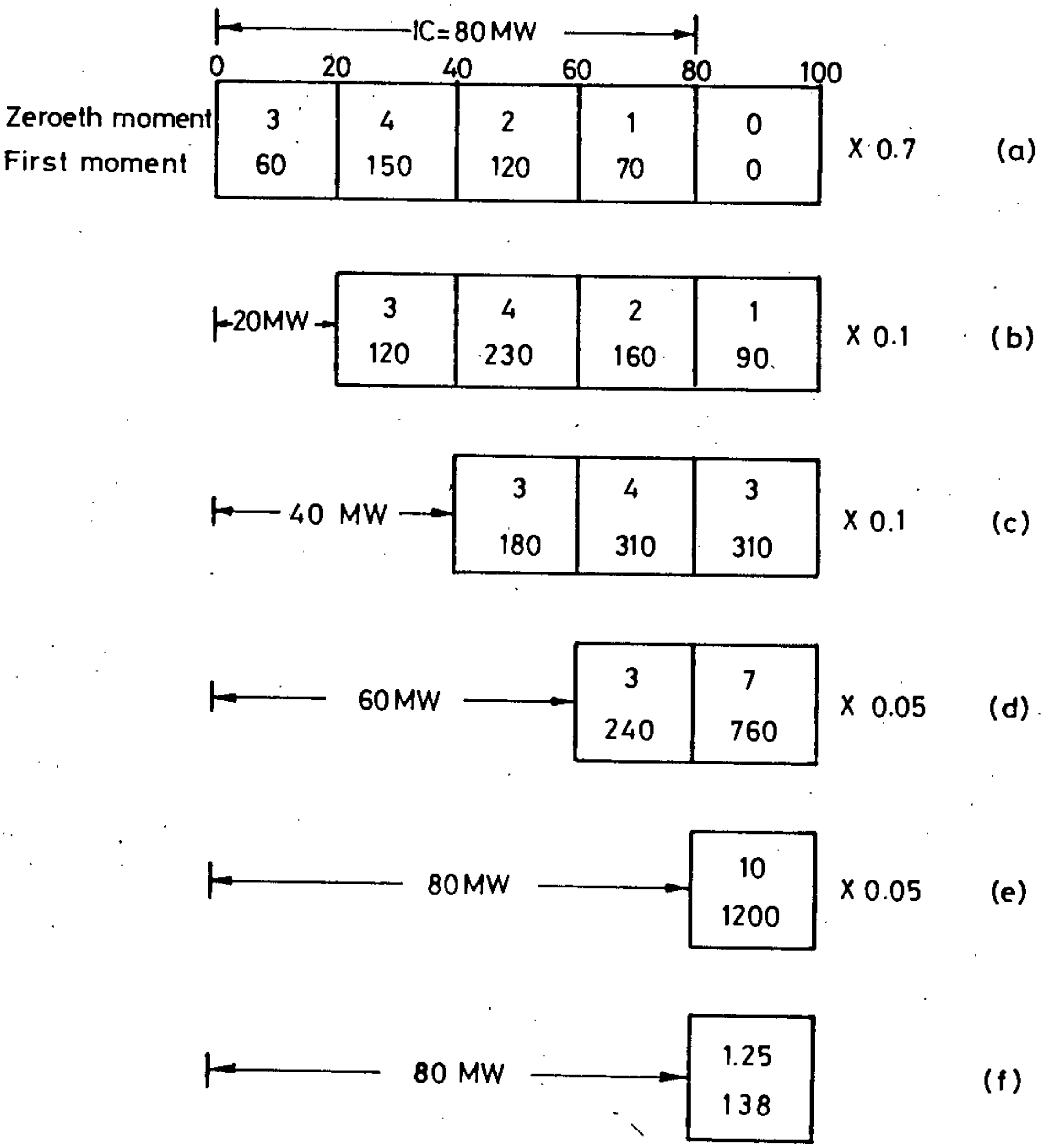


Figure-5.4 Schematic of convolution procedure of multistate generating unit. (all numbers in boxes to be divided by 10)

In this case the shifting of segments for multistate unit is done corresponding to each capacity outage. The zeroeth and first moments for this shifted segments are calculated using the formulas already given. However, it may be noted that this requires only a few more computations.

Therefore the system LOLP is:

$$LOLP = (1.25/10) = 0.125$$

Initial unserved energy = 400 Mwh.

Expected energy not served:

$$\epsilon(ENS) = 10x(138-80x1.25)/10$$

$$= 38 \text{ Mwh.}$$

Therefore the expected energy generation by the unit:

$$E = (400-38) = 362 \text{ Mwh.}$$

If the average incremental cost of the unit is known, then cost for energy generation can be easily calculated.

5.5 MULTIBLOCK GENERATING UNIT LOADING

The simulation will be more accurate towards optimal scheduling if multiblock loading of a unit is considered. A unit may, for example, be divided into two blocks: a lower and upper block with corresponding capacities and average incremental costs. In this way the increasing nature of incremental cost of a unit may be approximately taken into consideration. Clearly the capacity blocks of a unit may occupy non adjacent positions in the merit order of loading as this order depends on the average incremental cost. The basic consideration in the simulation of multiblock loading is that an upper block of a unit cannot be loaded unless the corresponding lower blocks are loaded before. In order to correctly carry out the probabilistic simulation procedure, lower blocks must be deconvolved before the joint lower and upper blocks are convolved. The deconvolution procedure for each block is carried out in what follows.

Consider the convolution formula

$$f_z(x) = pf_y(x)+qf_y(x-c) \qquad ....(5.10)$$

in which

$f_y(x)$ = the PDF of equivalent load prior to adding the new block or unit.

$f_z(x)$ = the new PDF of equivalent load after convolving a new block, or unit, of capacity C and FOR=q, (p+q=1)

Equation (5.10) may be written as a deconvolution formula as follows:

$$f_y(x) = (f_z(x)-qf_y(x-c))/p \qquad ....(5.11)$$

In order to satisfy the constraints of the deconvolution process, equation (5.11) is modified as follows:

$$f_y(x) = \begin{cases} f_z(x)/p & 0<x<c \\ (f_z(x)-qf_y(x-c))/p & c<x<IC \\ \text{Subtraction from the total moment} & x>IC \end{cases} \qquad ..(5.12)$$

In order to evaluate the first moment equation (5.11) is multiplied throughout by x to yield:

$$xf_y(x) = (xf_z(x)-xqf_y(x-c))/p \qquad ....(5.13)$$

or, in terms of the first moment

$$m_1^{old}(n)=(m_1^{new}(n)-q(m_1^{old}(j)+Cm_0^{old}(j)))/p \qquad ....(5.14)$$

where, n is the segment number currently under consideration, and $j=n-C/\Delta$, where Δ is the segment size.

Equations (5.12) and (5.14) are applied to calculate the zeroeth and the first moments of each segment after deconvolution of the appropriate block or unit. In what follows, an example is given to clarify the deconvolution.

Consider hourly load as described in figure 5.1 and the generating system contains only a single generator of 80 Mw capacity and FOR=0.1. Let this generator is segmented into two blocks of capacity 40 Mw each. As this blocking is done on the basis of incremental cost i.e. heat rate curve, so the blocking will have no effect on the FOR of the unit. That is, each block will have the same FOR=0.1 as that of the generating unit. Let the average incremental cost of 1st block is Tk.190 /Mwh. and that of the 2nd block is Tk.210/Mwh.

Table 5.2:Generating system for multiblock loading.

Merit order of loading	Type of unit	Block No.	Capacity (Mw)	FOR	Average incremental cost(Tk./Mwh)	Installed capacity (Mw)
1	Multi-block	1st	40	0.1	190	80
2		2nd	40	0.1	210	

The steps for convolving multi-block unit is shown in figure 5.5. Here with the moments of 5.5(a) the first block of the unit is convolved and the moments of figure 5.5(c) is obtained. Upto this, one can find the expected unserved energy. As previously shown for calculation of unserved energy and LOLP of the system after convolution of 1st block, it is not necessary to know the moments of first two segments of figure 5.5(c). But for the purpose of deconvolution, it is necessary to know the moments of all the segments including the last segment. Now from the distribution of moments of figure 5.5(c), the 1st block is deconvolved using the relations given by equations (5.12) and (5.14), and the distribution of figure 5.5(d) is obtained. Now the joint 1st and 2nd block is convolved and finally the distribution of figure 5.5(f) is obtained. Now the LOLP, the energies as well as production cost for the above example will be calculated.

LOLP = (1.0/10) = 0.1

Initial unserved energy = 400 Mwh.

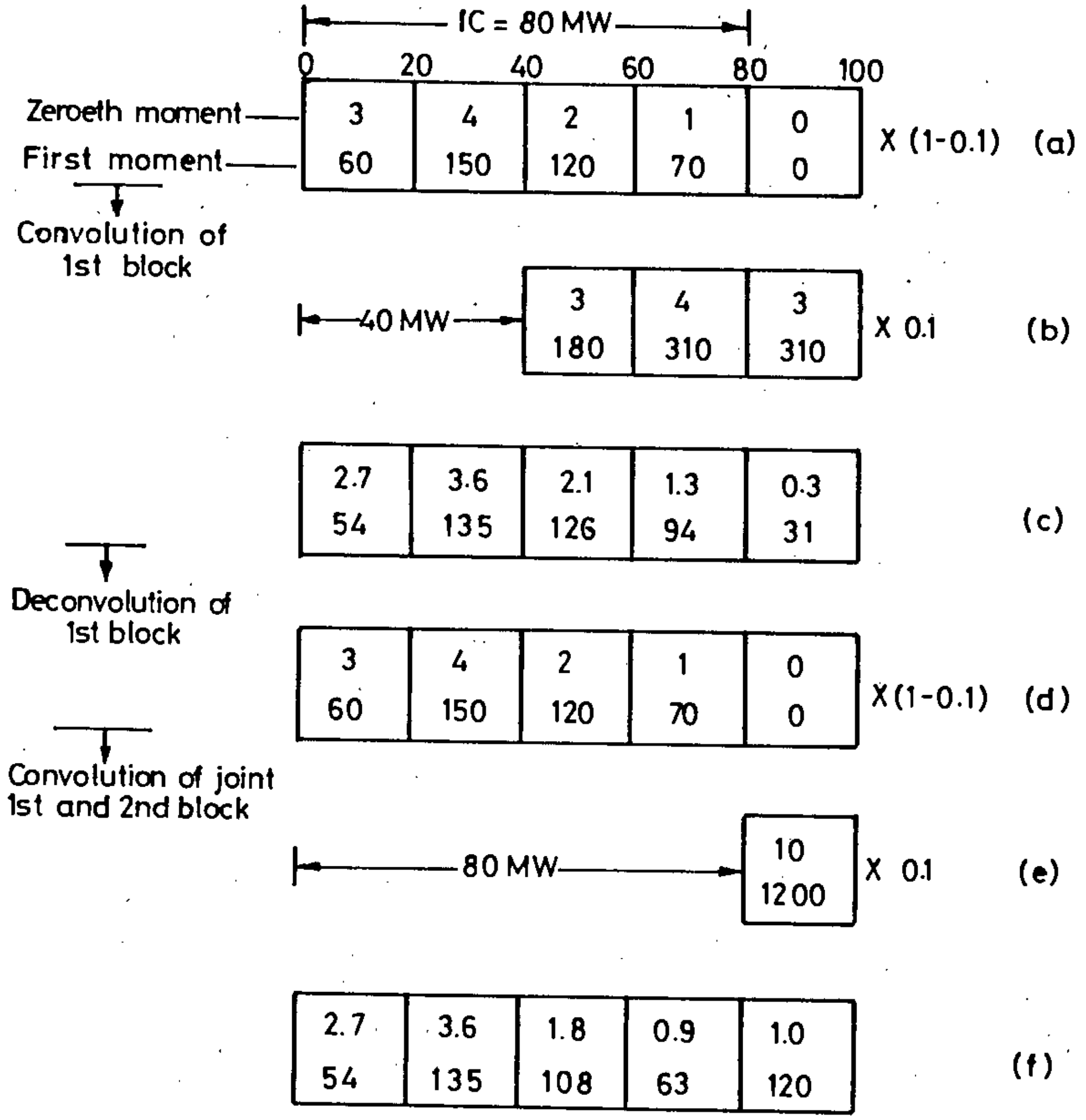


Figure-5.5 Schematic of convolution procedure for multiblock generating unit. (all numbers in boxes to be divided by 10)

Unserved energy after convolution of 1st block:

$UE_1 = 10x((126+94+31)-40x(2.1+1.3+0.3))/10$

$= 103$ Mwh.

Energy generation by 1st block:

$E_1 = (400-103) = 297$ Mwh.

Cost of energy generation of 1st block:

$EC_1 = (297x190) = 56,430$ Taka.

Unserved energy after convolving joint 1st and 2nd block:

$UE_{12} = 10x(120-80x1.0) = 40$ Mwh.

Energy generation by 2nd block:

$E_2 = (103-40) = 63$ Mwh.

Cost of energy generation of 2nd block:

$EC_2 = (63x210) = 13,230$ Taka.

Total cost of energy generation

$= (56,430+13,230) = 69,660$ Taka.

Expected energy not served:

$\epsilon(ENS) = UE_{12} = 40$ Mwh.

Now if the generating unit is considered as a single block unit, the final distribution as shown in figure 5.5(f) will remain the same. But in that case the production cost will be different as the average incremental cost of the total unit is different from the incremental cost of each block.

CHAPTER 6

CONVENTIONAL APPROACH OF SIMULATING ENERGY LIMITED HYDRO UNITS

6.1 INTRODUCTION

Most probabilistic simulation studies assume that there are no inherent energy limitations of generating units and therefore concentrate on considering the effect of unit forced outages and uncertain load requirements. It appears, however, that the era of abundant energy is disappearing and that limitations of energy generation of different units must be included in conventional studies. Only from the last decade, a few researchers have given their attention to incorporate the energy limitation of hydro unit in probabilistic simulation [6,22]. Some of these papers have utilized cumulant method for the numerical evaluation and therefore, it is prone to the inherent inaccuracies of series expansion.

In this chapter, different conventional approaches so far developed for the simulation of energy limited hydro units are described.

6.2 DEMAND-ENERGY UNIT AND ENERGY-LIMITED UNIT

Generally, the generating units are classified according to the type of fuel used for the generation of electrical energy, for example, thermal unit, nuclear unit etc. In this thesis the various generating units are also characterized by two identities, namely, demand-energy unit and energy-limited unit.

A demand-energy unit serves consumer load upon demand, provided the unit is available to do so and the dispatcher call on it to operate. Thus the energy served by a demand-energy unit is limited only by its generating capacity and availability but not by any inherent energy limitation. The energy limited generating units, also called assigned energy unit, are those which can generate only a fixed amount of energy. The maximum energy generation by conventional hydroelectric units are limited by many constraints which have been discussed in section 2.9.

6.3 PSEUDO-HYDROELECTRIC UNIT CONCEPT [21]

The probabilistic simulation model in WASP [21] is capable of simulating hydroelectric units. However, in this package it was not considered necessary to simulate all hydroelectric units separately, rather the individual hydroelectric units are combined into a single pseudo unit whose capacity is equal to the sum of the project capacities. Thus

$$MW_H = \sum_{i=1}^{m} (MW_h)_i \qquad \ldots\ldots.(6.1)$$

where,

MW_H = Capacity of pseudo-hydroelectric unit

$(MW_h)_i$ = Capacity of ith hydroelectric project

m = Number of hydroelectric projects.

For energy limited type hydroelectric units, the energy to be generated by the pseudo-hydroelectric unit is defined as the sum of the energy generations of the individual units. Therefore

$$E_H = \sum_{i=1}^{m} (E_h)_i \qquad \ldots\ldots.(6.2)$$

where,

E_H = Energy to be generated by pseudo-hydroelectric unit.

$(E_h)_i$ = Energy generated by the ith hydroelectric project.

The total capacity of the pseudo-hydroelectric unit can be divided into two capacity blocks. The base block represents the amount of capacity that will be continuously on-stream (i.e. run-of-the-river hydroelectric). The remaining capacity is assumed to be available only for peak-shaving operation.

The peak shaving operation is discussed in detail in section 6.4. The amount of energy that would be generated by the base block is deducted from the total energy specified, and the remainder is assigned to the pseudo-hydroelectric unit.

The base block of pseudo-hydroelectric unit is placed in the first position in the loading order. The remaining peak-shaving block is used to shave the system peak, and not included in the probabilistic simulation. The pseudo-unit is obviously not the rigorous representation of the individual hydroelectric units. Therefore, the simulation results are distorted. In what follows, the peak shaving operation is discussed

6.4 PEAK-SHAVING OPERATION OF ENERGY LIMITED HYDRO UNITS

In the peak shaving technique [6,21] the capacity and energy limitation of the unit are used to modify the original load duration curve or load probability distribution curve. The modified curve is then used for the remaining units of the system to evaluate the expected energy generated as well as the expected energy not served. In what follows, this peak shaving operation is described assuming the energy limited unit as hundred percent reliable for simplicity.

Figure 6.1(a) illustrates the initial loading of a power system consisting of many demand energy units and a single energy limited hydro unit. The demand energy capacity is stacked under the load probability distribution in order of increasing incremental fuel cost. This demand capacity loading order minimizes the total fuel cost of the demand responsive capacity of the system since units with highest operating cost will operate the least.

The energy limited hydro unit of generating capacity H is initially loaded above the demand responsive capacity of the system which is shown by the hatched area in figure 6.1(a). The portion of the load curve spanned by the capacity H in the figure 6.1(a) represents the compulsory load imposed on the energy limited hydro unit. Like the demand energy units, the energy generated by the energy limited unit is the difference between unserved energies before and after convolution of the unit.

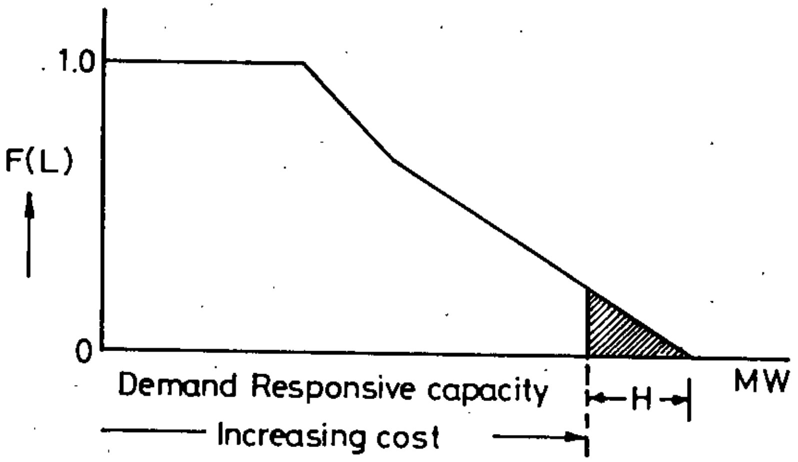


Figure- 6.1(a) Initial loading units

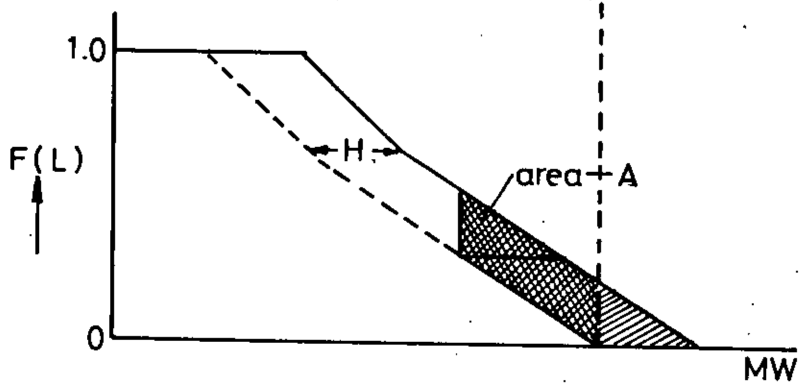


Figure- 6.1(b) Peak-shaving operation of energy limited hydro unit.

It may happen that if the energy limited unit is committed to peak shave, the compulsory energy generated by the energy limited unit may be less than the energy assigned to it. Now, if the compulsory energy generation is less than the assigned energy then the commitment of the unit must be changed so that it delivers its full assigned energy. This may be achieved in the following ways.

In this commitment procedure the LDC is modified by subtracting a portion of it in such a way that this portion of LDC subsumes the amount of energy equal to the assigned energy. This is shown by hatched area of figure 6.1(b). It is noted that in this case the energy limited unit of capacity H is committed at full capacity, H Mw, most of the time. However, the commitment capacity reduces as it moves upward in the left. That is, in the hatched area, A, the commitment capacity is less than the rated capacity. This modified load duration curve is then convolved with outages of energy limited unit and the resulting equivalent load curve is used for the rest of the units to evaluate the expected energy generation by these units.

6.5 MODIFICATION OF PEAK-SHAVING OPERATION FOR PROBABILISTIC SIMULATION

The simulation procedure described in section 6.4 does not provide the minimum production cost. The reason behind is that in the equivalent load approach the unit which is committed after must see the actual random load plus the fictitious inflated load due to the random outages of the units already committed. However, in section 6.4 although the hydro unit is committed last in the loading order the inflated load due to its outage will have to be supplied by the units which are in the beginning of the loading order.

The above problem can be overcome by committing the energy limited unit in the stage of the loading order where it discharges its total assigned energy. The peak shaving operation of an energy limited hydro unit is equivalent to placing the unit in the generating unit loading order at exactly the left most position of the cross-hatched area of figure 6.2(a). The proof of this equivalence is given in Appendix A. This merging of the energy limited unit into the demand responsive capacity loading order is depicted in figure

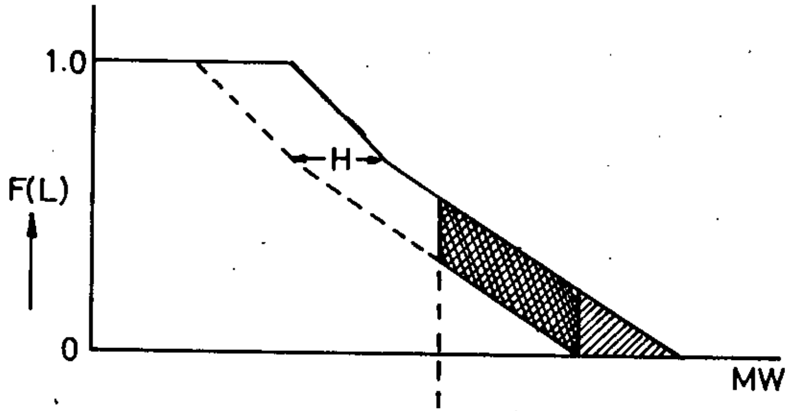


Figure-6.2(a) Peak-shaving operation of energy limited hydro unit.

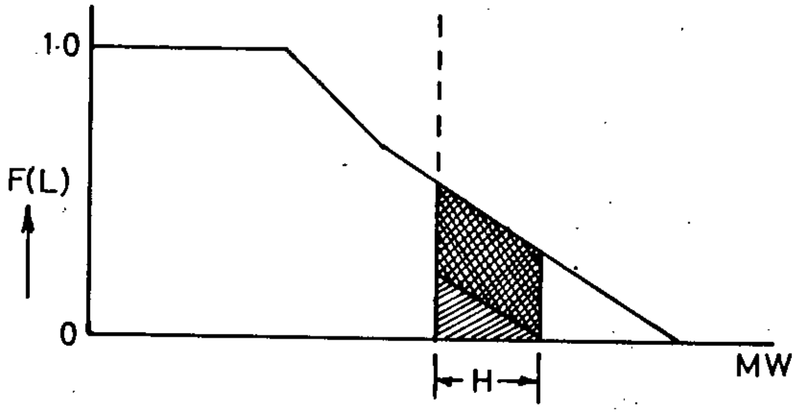


Figure-6.2(b) Equivalent peak-shaving operation.

6.2(b). A full probabilistic treatment requires the use of an equivalent load curve or effective load probability distribution [17]. The energy limited unit should be placed in the highest possible position under the equivalent load curve such that its assigned energy is exhausted. Unfortunately, the equivalent load curve changes as the forced outage effects of the various generating units are included in the curve. Thus the loading order position of energy limited hydro unit becomes a moving target. For the solution of this problem methodology is given in chapter 7.

CHAPTER 7

CHAPTER 7

METHODOLOGY

7.1 INTRODUCTION

Many utilities have hydroelectric plants. Among these hydro units all are not energy abundant units, rather some units are energy limited. Probabilistic simulation is, now, a common practice for generation expansion planning in utilities. Therefore, the simulation technique must be capable of proper scheduling of energy limited hydro units. These units should be simulated so that they can exhaust their full amount of energy. This is because, the incremental fuel cost associated with hydro units are essentially zero. The incorporation of energy limited unit in the probabilistic simulation increases the complexity [6]. The complexity of simulation increases exponentially, if more than one hydro units compete for the same position in the loading order.

In this chapter, an efficient methodology is developed to incorporate the competing as well as non-competing energy limited hydro units in the simulation. The developed methodology is capable of handling any number of energy limited hydro units. The method is an extension of the technique developed by Manhire et al [6]. To take the randomness of the availability of water head for hydro units another method is also developed in this chapter.

7.2 METHODOLOGY FOR NON-COMPETING UNITS

The terms competing unit and non-competing unit are essentially applied to energy limited hydro units. The energy limited units which compete for the same loading order position are called competing units and those do not are called non-competing units. Clearly, the energy limited units with same capacity, same FOR and same assigned energy are competing units. The energy limited units with different capacities, FORs and assigned energies may be non-competing or competing units. The methodology for probabilistic simulation of non-competing unit is somewhat easier compared to that for competing unit. In what follows, the methodology for non-competing unit is described.

Consider a system consisting of a single EL unit together with other demand energy units. In figure 6.2(b) the position for a single EL hydro unit to exhaust its total assigned energy is shown. However, as the FORs of different units are considered the ELDC changes and it is most likely that in a single position of LDC the EL unit may not be able to exhaust its total assigned energy. Therefore, initially a loading order position for the EL unit should be chosen such that it can disburse its maximum possible assigned energy. To do so, the following trial-error procedure is followed.

In this trial-error method primarily, the non-competing unit is loaded above its actual loading order position in the LDC so that the expected energy generation must not be less than the assigned energy. Consider that the EL unit is loaded just below the (n-1)th demand energy unit. That is in the nth position of loading order the EL unit is committed, which is shown in figure 7.1(a). Now the energy generated by the EL unit is compared with its assigned energy. If the expected generated energy at nth position is greater, then the EL unit will be pushed to the lower loading order position and simultaneously the nth demand energy unit will be pushed to the upper loading order position, that is nth loading order position. Again the energy generated by the EL unit in its new position of the loading order is compared with its assigned energy and this process is repeated until the energy generated by the EL unit becomes less than or equal to the assigned energy of the unit. If the energy generation in this position is exactly equal to the assigned energy then this is the appropriate loading order position for the EL unit. However, if the energy generation is less than the assigned energy the simulation is not straight forward. In section 7.2.1 the procedure is described.

$f_1(Le)$ is equivalent load probability distribution with all units to left of DE_{n-1} convolved

$f_2(Le)$ includes convolutions of f_1+DE_{n-1}

$f_3(Le)$ includes convolutions of f_2+EL

$f_4(Le)$ includes convolutions of f_3+DE_n

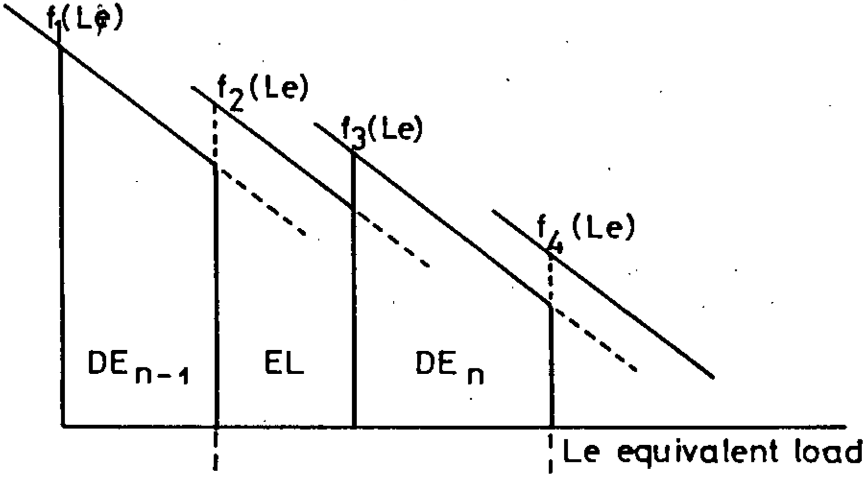
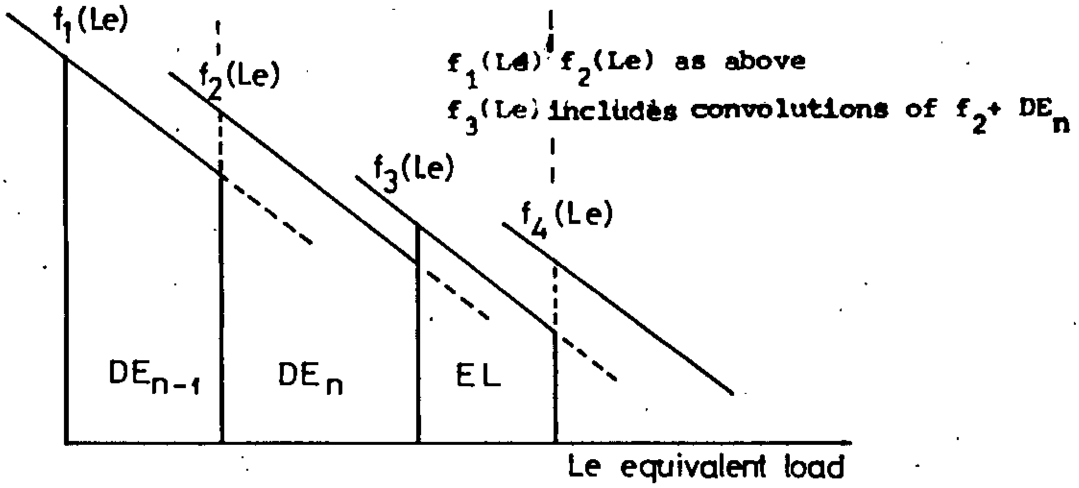


Figure-7.1(a) Trial loading order position



$f_1(Le)$ $f_2(Le)$ as above

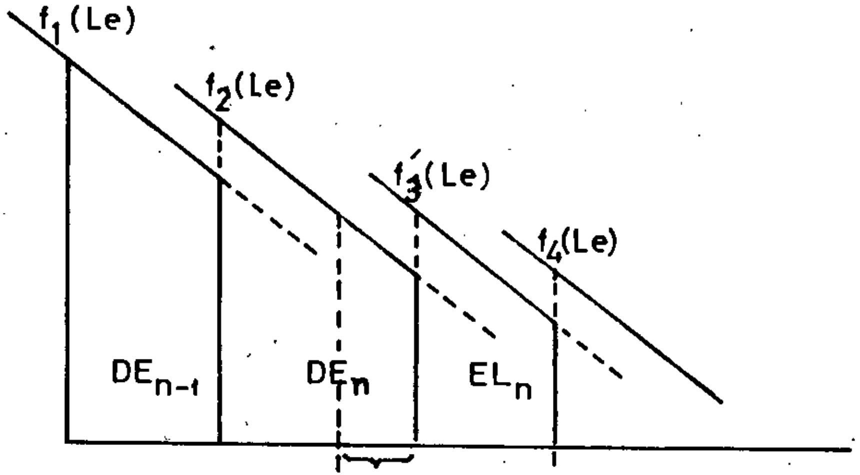
$f_3(Le)$ includes convolutions of f_2+DE_n

Figure-7.1(b) Determining the loading order position of EL unit

Now some features of convolution are discussed here. In Appendix B it is shown that the equivalent load curve does not depend on the order in which the random forced outage effects of generating units are convolved. This implies that if any number of adjacent blocks of capacity in the loading order is rearranged the resultant equivalent load curve remains unchanged. Therefore, $f_4(L_e)$ in both figures of 7.1(a) and 7.1(b) represents the same curve. Again as due to the reversal of loading order position of any number of adjacent blocks, the equivalent load curve remains unaltered, therefore, the total energy served by any number adjacent blocks of capacity in the loading order is invariant with respect to their relative positions in the loading order.

7.2.1 Inherent Blocking

So far it is observed that if the EL unit is committed in the (n+1)th loading order position the energy generated by this unit is less than its assigned energy and if it is pushed upward and committed in the nth loading order position the energy generated by the EL unit is greater than its assigned energy. These two loading conditions are depicted in figures 7.1(b) and 7.1(a) respectively. Therefore, to exhaust all the assigned energy the EL unit must be loaded in between the above two positions. To do so the trimming of the demand energy unit DE_n committed in the nth position of figure 7.1(a) is necessary. This is accomplished through the capacity blocking of the demand energy unit. That is, the demand energy unit is divided into two capacity blocks. The lower capacity block is loaded in the nth position and the upper capacity block is committed after the commitment of the EL unit. The amount of capacity block that will be offloaded from DE_n unit must be such that in the new position the EL unit should deliver its full assigned energy. The commitment of two capacity blocks of DE_n along with the EL unit is depicted in figure 7.2(b). The resultant distribution is then convolved with DE_n unit which results $f_4(L_e)$.



Amount of capacity block to be off loaded from trimming unit

Figure-7.2(a) Blocking of trimming unit.

f_1(Le), f_2(Le) and f_4(Le) as above

f_3^*(Le) includes convolutions of f_2+ DE_{1n}

f_{2n}(Le) includes convolutions of f_3^*+ EL

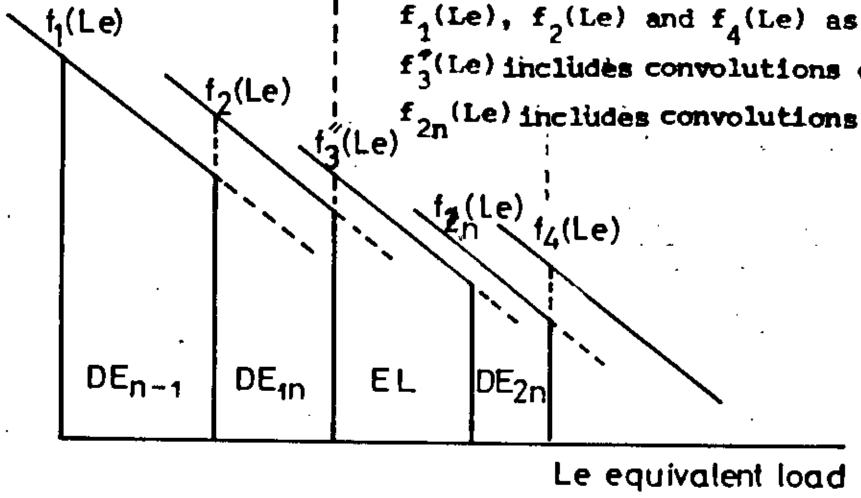


Figure-7.2 (b) Loading order position of EL unit to exhaust all of its assigned energy

Note that in obtaining $f_4(L_e)$ the above procedure is equivalent to the convolution of 1st block with DE_n unit with $f_2(L_e)$, then EL unit, and finally after deconvolution of 1st block of DE_n unit convolution of DE_n again. In figure 7.2(a), $f_4(L_e)$ is obtained by convolving DE_n with $f_2(L_e)$ and then convolving EL unit with resultant distribution. Although the sequence of convolution in figures 7.2(a) and 7.2(b) is not same, the total energy generated by DE_n and EL units are same in both cases. The proof of it is given in Appendix B. Now, one can write,

$$E_{DEn} + E_{EL} = E_{DE1n} + E_{EL}' + E_{DE2n} \qquad ....(7.1)$$

where

E_{DEn} = Energy supplied by DE_n unit in figure 7.2(a).

E_{EL} = Energy supplied by EL unit in figure 7.2(a).

E_{DE1n}= Energy supplied by 1st block of DE_n unit in figure 7.2(b).

E_{DE2n}= Energy supplied by 2nd block of DE_n unit in figure 7.2(b).

E_{EL}' = Energy supplied by EL unit in figure 7.2(b).

Recall that E_{EL}'=assigned energy of the EL unit and E_{EL}<assigned energy of the EL unit. If x represents the difference, that is

$$E_{EL}' - E_{EL} = x \qquad ....(7.2)$$

then using equation (7.1), we get

$$E_{DEn} - (E_{DE1n} + E_{DE2n}) = x \qquad ....(7.3)$$

If, $E_{DEn}' = E_{DE1n} + E_{DE2n}$

then equation (7.3) may be written as

$$E_{DEn} - E_{DEn}' = x \qquad ....(7.4)$$

In the above equations x represents the increased amount of energy generated by EL unit or the decreased amount of energy generated by DE_n unit in the case shown in figure 7.2(b). In actual system operation the EL unit is loaded after loading the 1st block of DE_n unit and the 2nd block of DE_n unit is loaded after the loading of EL unit. However, for simulation there is no need of actual blocking of DE_n unit, since the main concerns of the probabilistic simulation are the system LOLP, expected energy supplied by each unit and its corresponding production cost. Mathematically, the expected energies generated by EL and DE_n are simply determined by reducing the energy generation of DE_n unit at nth loading order position by x Mwh and increasing the energy generation of EL unit at (n+1)th position by x Mwh, once the position of EL unit is determined by trial-error method.

For more than one energy limited non-competing hydro unit the above procedure is applicable. Because the non-competing units do not occupy the adjacent loading order positions. That is, there is atleast one demand energy unit in between any two EL units.

7.2.2 Numerical Example to Clarify the Methodology

A chronological load curve which has a linear load variation of the following nature is considered for the example.

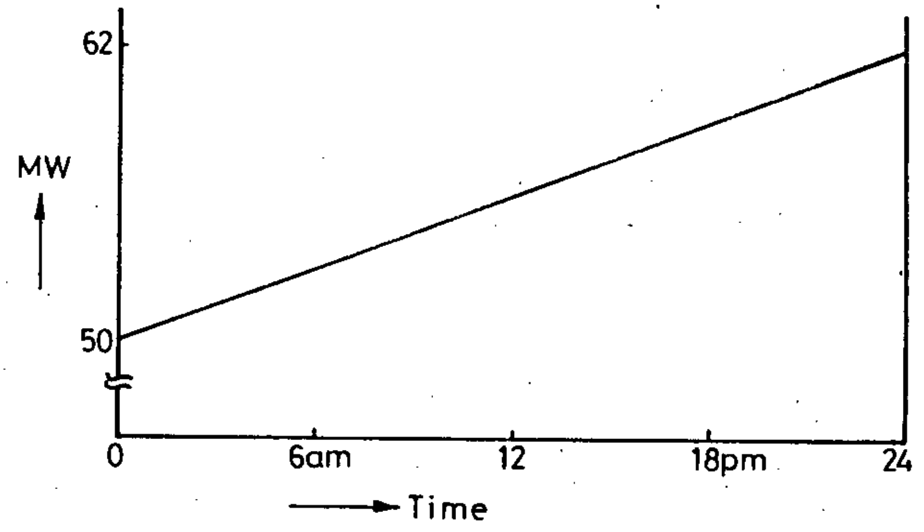


Figure - 7.3 Chronological load curve depicting variations of 24 hours.

The load probability distribution for the above load curve is found by the method described in section 3.3.1 and is depicted in figure 7.4.

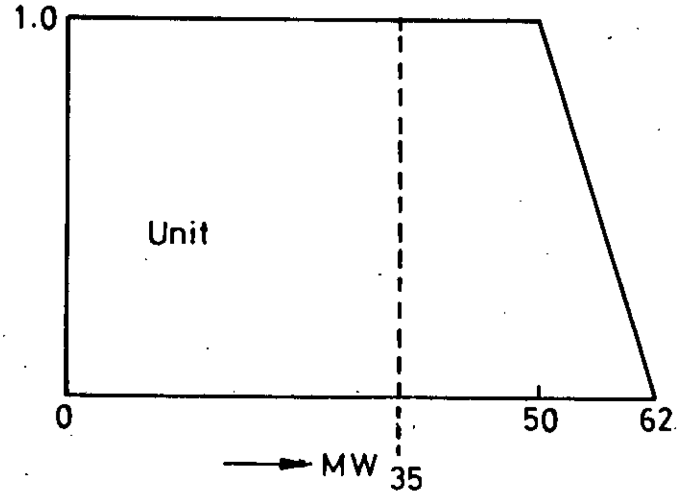


Figure-7.4 F(L)

Let us consider the generating system as shown in table 7.1. In this generating system the energy limited hydro unit has assigned energy of 186.864 Mwh.

Table 7.1: Generating system description

Capacity MW	FOR	Average incremental fuel cost Tk./Mwh	Assigned energy, Mwh
35.0	0.1	200.0	
20.0	0.2	225.0	
20.0	0.2	0.0	186.864
20.0	0.2	250.0	

As said in section 4.3, the generating units are loaded according to their increasing cost. In this case the EL hydro unit is loaded in 3rd position because prior to this position, the hydro unit cannot be loaded as then the energy generation became greater than the assigned energy and this will become evident when expected energy generation of each unit is found. In what follows, the expected energy generation of each unit is calculated from the equivalent load curve.

Now for finding the equivalent load curve or effective load probability distribution the generating units are convolved using equation (4.7) according to their loading order. The expected energy generation by 1st unit is found from figure 7.4 using the equation (4.8). Therefore energy supplied by 1st unit

$$E_1 = T\ p_1 \int_0^{C_1} F(L_e)\,dL_e \qquad \ldots\ldots.(7.5)$$

Here,

T = period of hours considered

= 24 hours

p_1 = availability of 1st unit

= 1 - 0.1 = 0.9

C_1 = 35 Mw

Equation (7.5) denotes nothing but the area under the curve $F(L_e)$ between 0 Mw and C_1 Mw multiplied by period and availability of the unit. Thus,

E_1 = 24 x 0.9 x 35

= 756 Mwh

Now the PDF of outage capacity of unit 1 is convolved with $F(L_e)$ giving the equivalent load curve $F^1(L_e)$ using the following relation.

$$F^1(L_e) = F(L_e)p_1 + F(L_e - C_1)q_1 \qquad \ldots\ldots.(7.6)$$

The equivalent load curve $F^1(L_e)$ is shown in figure 7.5

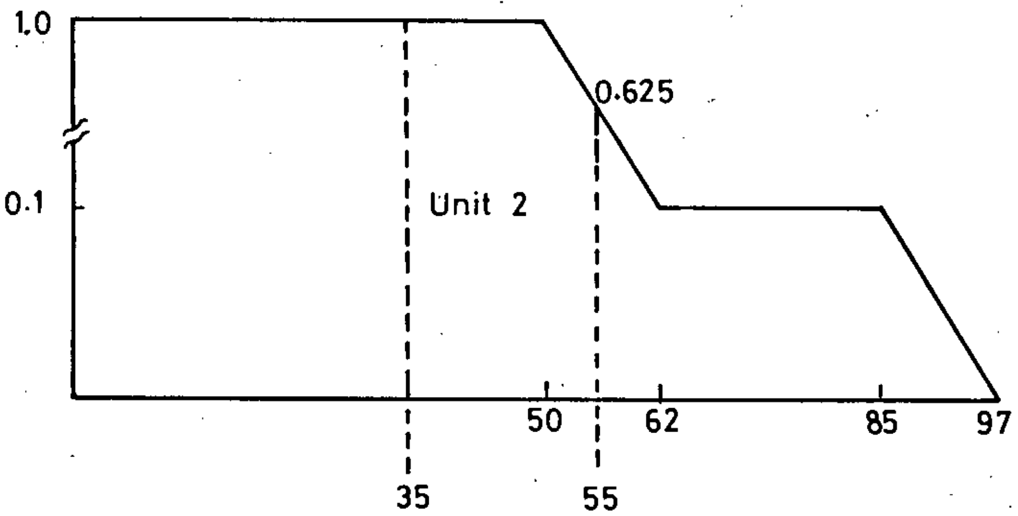


Figure- 7.5 $F^1(Le)$

Now the expected energy generation of unit 2 is

$$E_2 = T\ p_2 \int_{C_1}^{C_1+C_2} F^1(L_e)dL_e \qquad \text{.......(7.7)}$$

$$= 24 \times 0.8 \int_{35}^{55} F^1(L_e)dL_e$$

$$= 366 \text{ Mwh.}$$

Unit 2 is now convolved with $F^1(L_e)$ using equation (7.8) giving $F^2(L_e)$ and is shown in figure 7.6.

$$F^2(L_e) = F^1(L_e)p_2 + F^1(L_e - C_2)q_2 \qquad \text{.......(7.8)}$$

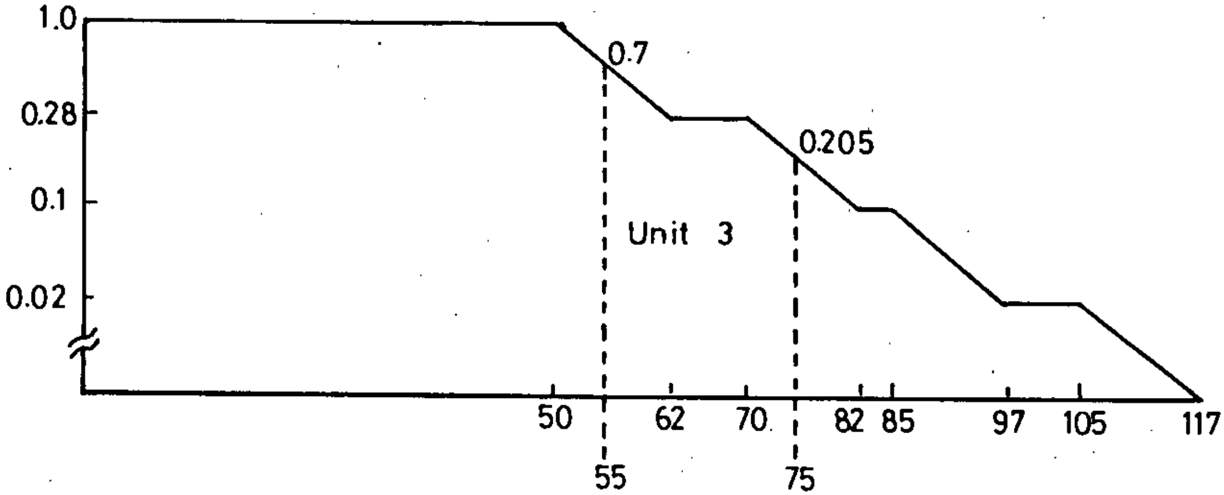


Figure-7.6 F^2 (Le)

The expected energy generation of unit 3 is given by

$$E_3 = T\,p_3 \int_{C_1+C_2}^{C_1+C_2+C_3} F^2(L_e)\,dL_e \qquad \text{.......(7.9)}$$

$$= 24 \times 0.8 \int_{55}^{75} F^2(L_e)\,dL_e$$

$$= 132.144 \text{ Mwh.}$$

Therefore, the energy generation of hydro unit at 3rd loading order position is 132.144 Mwh. Now if the hydro unit was loaded at 2nd position then the energy generation seems to be 366 Mwh (as the capacities and FORs of 2nd and 3rd units are identical) which is greater than the assigned energy of the unit. So the current loading order position is the correct position for hydro unit. But in this position the full 186.864 Mwh assigned energy is not possible to exhaust. So blocking of 2nd unit which is the trimming unit in this example is needed. Prior to this blocking the expected energy generation of 4th unit and expected energy not served are found out to show that blocking of trimming unit will have no effects on these energies. The expected energy generation of 1st unit will remain same after blocking of trimming unit.

Now to find the expected energy generation of unit 4 the equivalent load curve $F^3(L_e)$ is obtained using the relation given by equation (7.10), and $F^3(L_e)$ is depicted in figure 7.7.

$$F^3(L_e) = F^2(L_e)p_3 + F^2(L_e - C_3)q_3 \qquad ....(7.10)$$

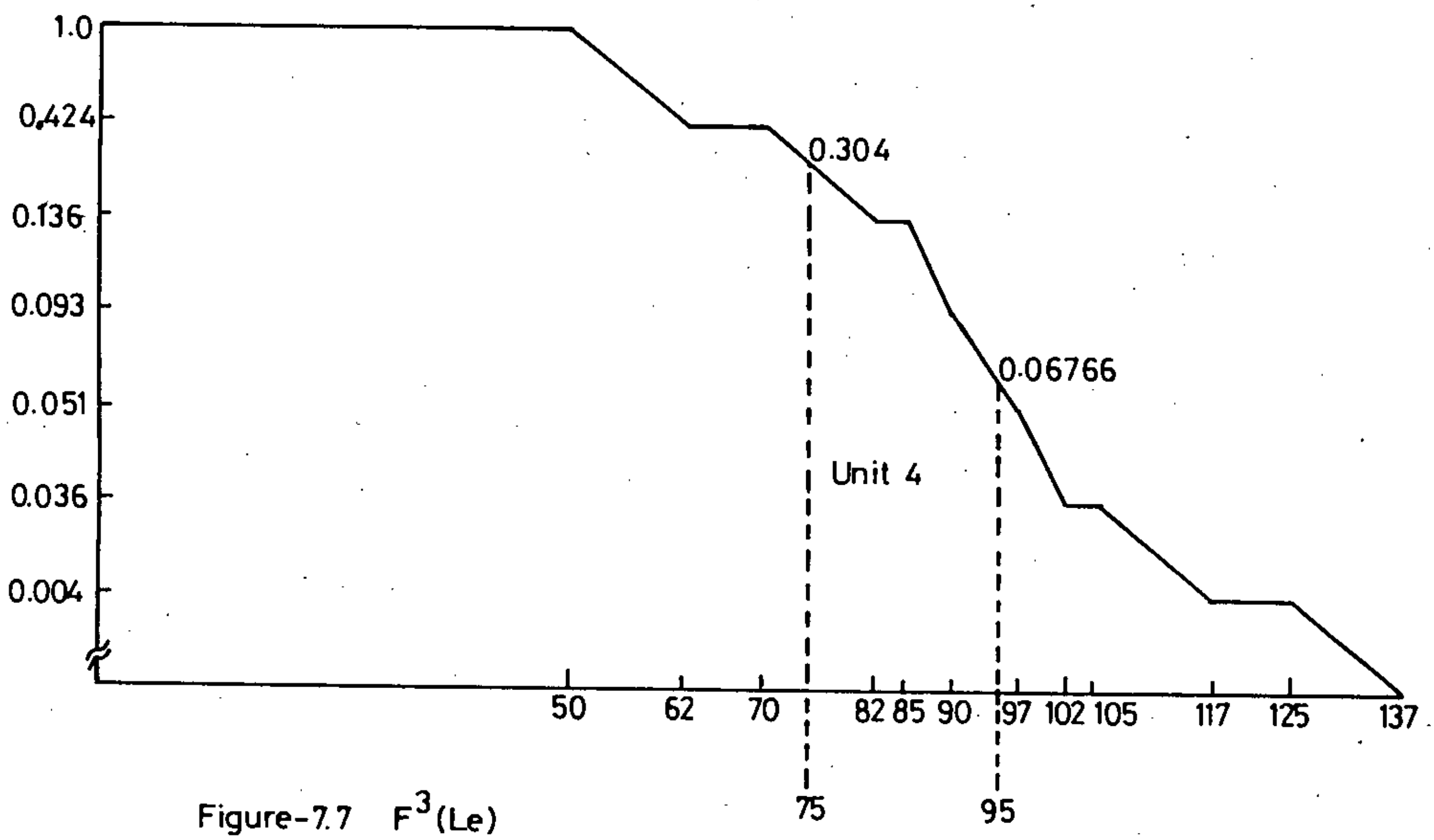


Figure-7.7 $F^3(Le)$

The expected energy generation of unit 4 is given by

$$E_4 = T\ p_4 \int_{C_1+C_2+C_3}^{C_1+C_2+C_3+C_4} F^3(L_e)\,dL_e \qquad \ldots\ldots.(7.11)$$

$$= 24 \times 0.8 \int_{75}^{95} F^3(L_e)\,dL_e$$

$$= 57.674 \text{ Mwh.}$$

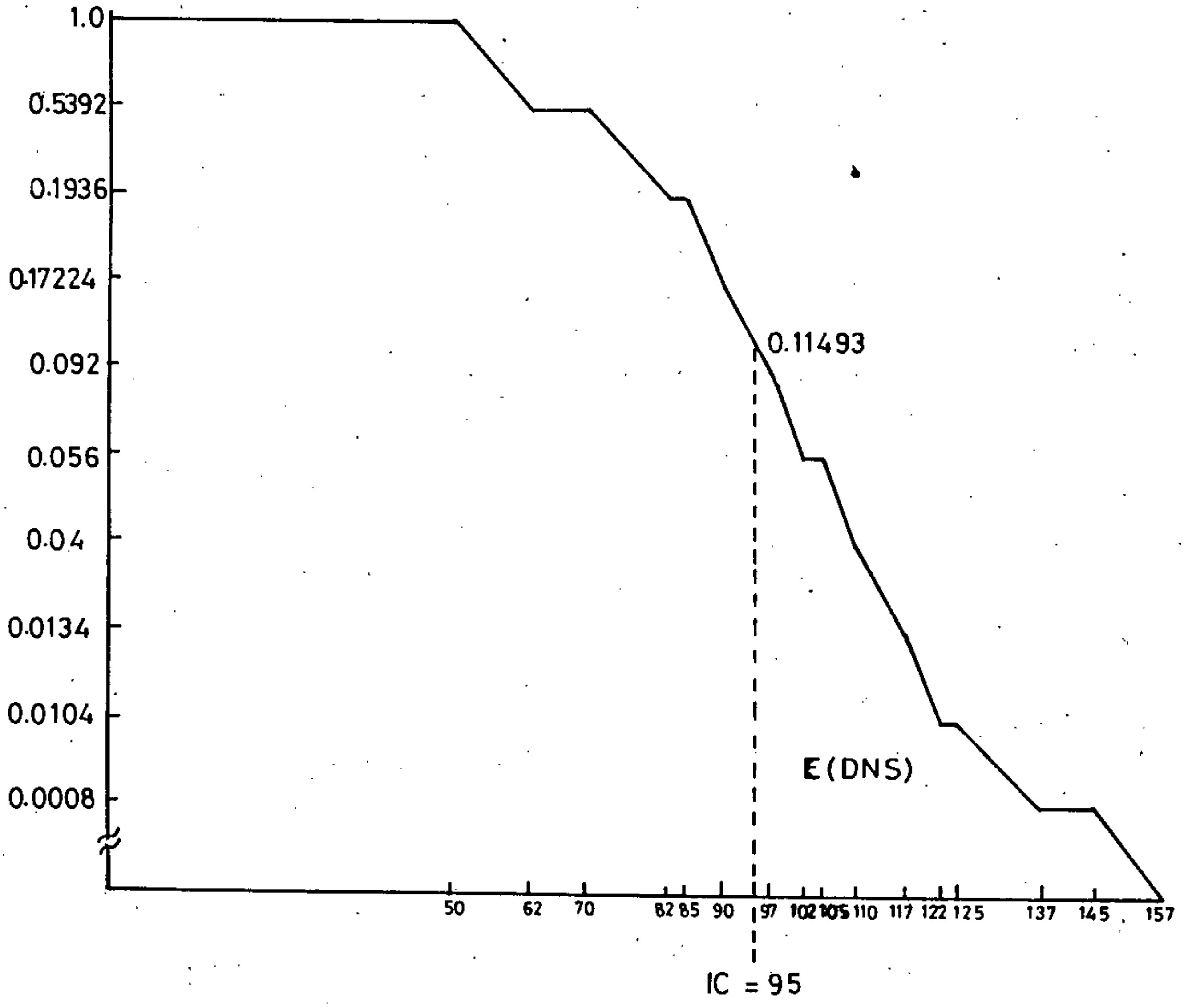


Figure- 7.8 $F^4(Le)$

Now the unit 4 is convolved with $F^3(L_e)$ and resulting distribution $F^4(L_e)$ is given by

$$F^4(L_e) = F^3(L_e)p_4 + F^3(L_e - C_4)q_4 \qquad ....(7.12)$$

The equivalent load probability distribution is depicted in figure 7.8. The equation (4.10) is utilized to find the expected energy not served, (ENS). For this example (ENS) is rewritten as

$$(ENS) = T\int_{IC}^{IC+PL} F^4(L_e)dL_e \qquad ....(7.13)$$

$$= 24\int_{95}^{157} F^4(L_e)dL_e$$

$$= 32.182 \text{ Mwh.}$$

If the trimming unit is not blocked, above mentioned results are obtained and these results are shown in table 7.2.

Table 7.2 : Expected energy generation and fuel cost of different generators without blocking of trimming unit

Unit	Capacity	AIC	ϵ(Energy Generation)	ϵ(Fuel cost) ϵ(F. cost)=ϵ(E.Gen)AIC
	Mw	Tk./Mwh	Mwh	Tk.
1	35.0	200.0	756.0	151200.00
2	20.0	225.0	366.0	82350.00
3	20.0	0.0	132.144	0.00
4	20.0	250.0	57.674	14418.50

LOLP = 11.493 % ϵ(ENS) = 32.182 Mwh

Total ϵ(E. Generation) = 1311.818 Mwh

Total ϵ(Fuel cost) = 247968.50 Tk.

To disburse all the assigned energy of EL unit it is necessary to offload the trimming unit by suitable amount of capacity and in this case to exhaust 186.864 Mwh, 5 Mw capacity should be offloaded. To show that the EL unit can exhaust its full assigned energy when trimming unit is offloaded by 5 Mw the following generation system is considered.

Table 7.3: Generation system with trimming unit offloaded by 5 Mw

Unit	Capacity (Mw)	FOR	AIC (Tk./Mwh)
1	35.0	0.1	200.0
12*	15.0	0.2	225.0
3	20.0	0.2	0.0
22**	5.0	0.2	225.0
4	20.0	0.2	250.0

* means 1st block of 2nd unit

** means 2nd block of 2nd unit

In what follows, the energy generation by each unit or block after blocking trimming unit will be denoted by superscript('). Now to obtain E_1', equation (7.5) will be utilized, therefore E_1' is the same as that given in table 7.2 and is equal to 756.0 Mwh. To find the E_{12}' i.e. the expected energy generation by 1st block of 2nd unit (trimming unit) has to be convolved with $F(L_e)$ of figure 7.4, thus giving $F^1(L_e)$ of figure 7.5. So

$$E_{12}' = T\, p_{12} \int_{C_1}^{C_1+C_{12}} F^1(L_e)\,dL_e \qquad ....(7.14)$$

$$= 24 \times 0.8 \int_{35}^{50} F^1(L_e)dL_e$$

$$= 288 \text{ Mwh.}$$

Now to find the energy that can be generated by hydro unit in the new position after offloading 5 Mw of trimming unit 1st block of trimming unit is convolved with $F^1(L_e)$ using the relation

$$F^{12}(L_e) = F^1(L_e)p_{12} + F^1(L_e - C_{12})q_{12} \qquad ....(7.15)$$

and $F^{12}(L_e)$ is depicted in figure 7.9.

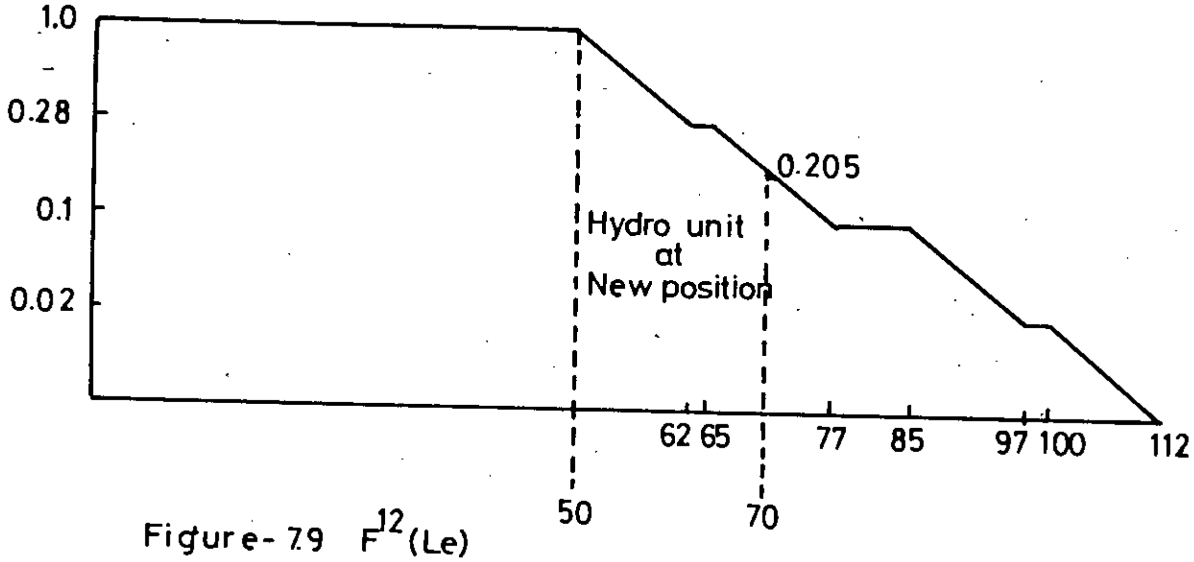


Figure- 7.9 $F^{12}(Le)$

So the energy that can be supplied by hydro unit at new position is found by equation (7.16).

$$E_3' = T\,p_3 \int_{C_1+C_{12}}^{C_1+C_{12}+C_3} F^{12}(L_e)dL_e \qquad ....(7.16)$$

$$= 24 \times 0.8 \int_{50}^{70} F^{12}(L_e)dL_e$$

$$= 186.864 \text{ Mwh.}$$

Which is equal to the assigned energy of the EL unit. So this is the position where EL unit should be loaded to exhaust full of its assigned energy. Now the energy generation of other units are found out. To find E_{22}' i.e. the energy supplied by 2nd block of 2nd unit, it is necessary to convolve the 3rd unit with $F^{12}(L_e)$ and then deconvolve the 1st block of 2nd unit, which actually means that unit 3 should be convolved with $F^1(L_e)$. But this resultant distribution is nothing but the same as that given by $F^2(L_e)$ Of figure 7.6. So E_{22}' is the area between 70 Mw ($C_1 + C_{12} + C_3$) to 75 Mw ($C_1 + C_{12} + C_3 + C_{22}$) of figure 7.6 multiplied by period and availability of the unit. Thus

$$E_{22}' = 24 \times 0.8 \times 1.2125$$
$$= 23.28 \text{ Mwh.}$$

Therefore total amount of energy supplied by 2nd unit

$$E_{12}' + E_{22}' = 288.0 + 23.28 = 311.28 \text{ Mwh.}$$

Now joint 1st and 2nd block of 2nd unit i.e. capacity of 20 Mw and FOR of 0.2 is convolved with the distribution of figure 7.6 and results the same distribution given by $F^3(L_e)$ of figure 7.7. Therefore, E_4' will be same as that given in table 7.2 for 4th unit. For similar reason the expected energy not served remains same. After blocking the trimming unit the various results obtained are given in table 7.4.

Table 7.4: Expected energy generation and fuel costs of different units after blocking the trimming unit.

Unit	capacity Mw	AIC Tk./Mwh	ϵ(E. generation) Mwh	ϵ(F. cost) Tk.
1	35.0	200.0	756.000	151200.0
2	20.0	225.0	311.280	70038.0
3	20.0	0.0	186.864	0.0
4	20.0	250.0	57.674	14418.5

LOLP = 11.493% ϵ(ENS) = 32.182 Mwh

Total ϵ(E. generation) = 1311.818 mwh

Total ϵ(F. cost) = 235656.5 Tk.

Now comparing the tables 7.2 and 7.4 it is clear that except the energies supplied by trimming unit and EL unit and hence total fuel cost, other things remain same as a result of blocking the trimming unit. As the EL unit delivers all of its assigned energy, therefore increased amount of energy supplied by EL unit is equal to (186.864 - 132.144) = 54.72 Mwh. It is evident from tables 7.2 and 7.3 that the same amount of energy is reduced from trimming unit as (366.0 - 311.28) = 54.72 which conforms with the discussion given in section 7.2.1.

Now the same problem will be solved using the program that has been worked out to simulate the energy limited hydro units utilizing segmentation method as the probabilistic simulation technique. The program has the inherent blocking capability for EL hydro units and this will be shown in what follows.

For this purpose the load profile of figure 7.3 is modified to hourly load model using the discussion of section 3.3.2, as segmentation method utilizes hourly load rather than chronological load. The hourly load model is given in figure 7.10.

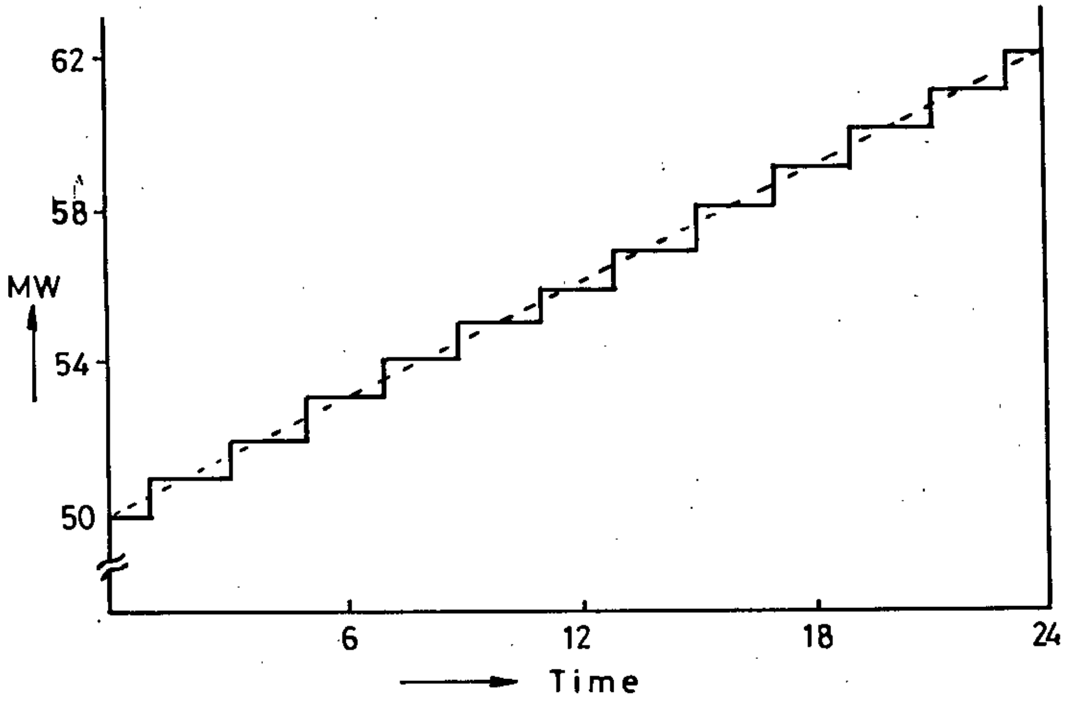


Figure- 7.10 Hourly load model

The same generating system as shown in table 7.1 is utilized. Here the segment size is chosen as 5 Mw. The results are shown in table 7.5.

Table 7.5: Results to show the inherent blocking capability of algorithm for EL units.

Unit	capacity Mw	AIC Tk./Mwh	∈(E. generation) Mwh	∈(F. cost) Tk.
1	35.0	200.0	756.000	151200.0
2	20.0	225.0	311.280	70038.0

3	20.0	0.0	186.864	0.0
4	20.0	250.0	57.674	14418.5

LOLP = 10.92% $\in$(ENS) = 32.182 Mwh

Total $\in$(E. generation) = 1311.818 mwh

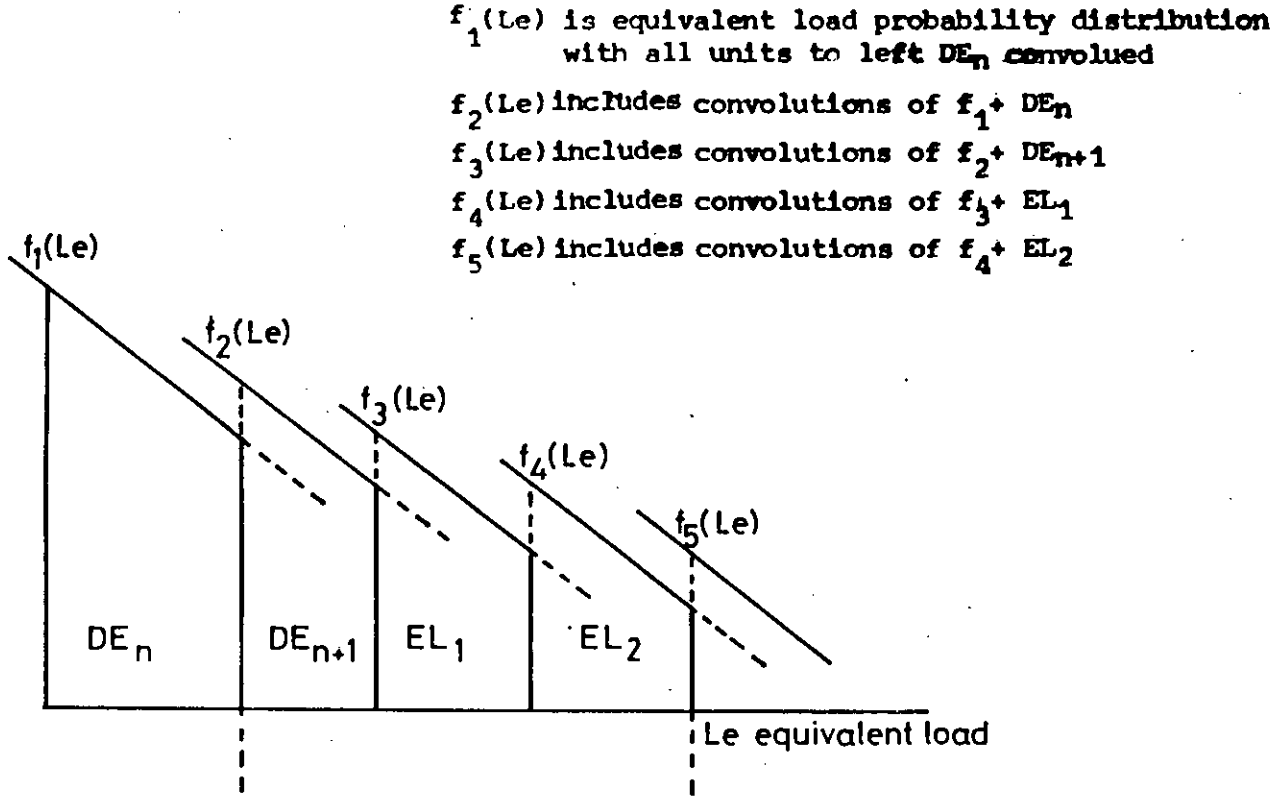
Total $\in$(F. cost) = 235656.5 Tk.

Comparing the tables 7.4 and 7.5 it is clear that except the slight variation of LOLP, other results are same. The slight variation of LOLP is due to the fact that in this method the hourly loads are used instead of actual load profile. The table 7.5 shows that all the assigned energy of EL hydro unit has been exhausted with proper reduction of energy of trimming unit. So this is equivalent of offloading 5 Mw from trimming unit as shown by table 7.4. But in this case the generating system data did not contain any actual blocking of trimming unit. Therefore, this means that the inherent blocking of trimming unit is done by exhausting all the assigned energy of EL unit and thus resulting minimum production cost for the system.

7.3 METHODOLOGY FOR COMPETING UNITS

Consider a system consisting of two energy limited units together with other demand energy units. The energy limited units denoted by EL_1 and EL_2 compete for the same or part of the same loading order position under the equivalent load curve. This case is illustrated in figure 7.11(a). In the process of positioning the EL units, EL_1 is correctly positioned following the procedure discussed in section 7.2. Let the energy generation by EL_1 in this position be E_{EL1}. Assume that the energy delivered by unit EL_2 in figure 7.11(a) is E_{EL2}, whose total attempted operating hours have been precalculated to be less than or equal to the attempted operating hours of unit EL_1.

Now if E_{EL1} becomes less than the assigned energy of EL_1, then it is possible to exhaust all assigned energy of EL_1 by inherent blocking of trim



$f_1(Le)$ is equivalent load probability distribution with all units to left DE_n convolued

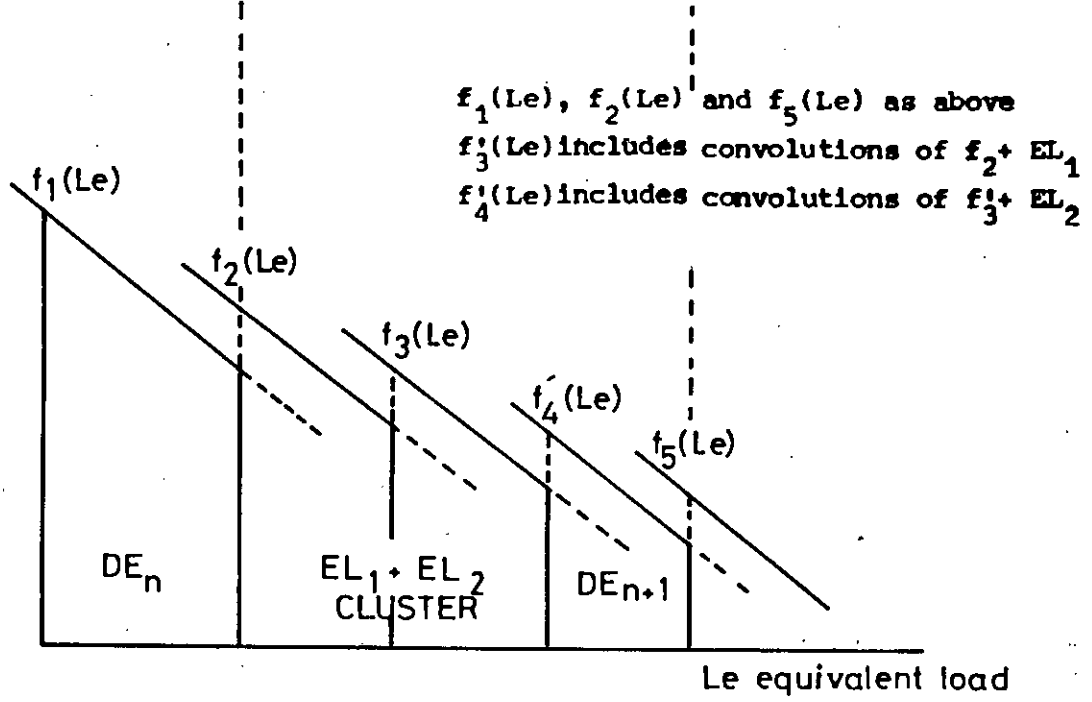
$f_2(Le)$ includes convolutions of $f_1 + DE_n$

$f_3(Le)$ includes convolutions of $f_2 + DE_{n+1}$

$f_4(Le)$ includes convolutions of $f_3 + EL_1$

$f_5(Le)$ includes convolutions of $f_4 + EL_2$

Figure-7.11(a) Trial loading order positions of competing units.



$f_1(Le)$, $f_2(Le)$ and $f_5(Le)$ as above

$f_3'(Le)$ includes convolutions of $f_2 + EL_1$

$f_4'(Le)$ includes convolutions of $f_3' + EL_2$

Figure-7.11(b) Determining the loading order position for cluster to exhaust maximum of its assigned energy.

ming unit and in figure 7.11(a) the trimming unit is (n+1)th demand energy unit DE_{n+1}. As EL_2 is a competing unit, so it will have adjacent loading order position with respect to EL_1. Thus EL_2 can not be adjusted to supply its whole assigned energy as there remains no demand energy unit in between EL_1 and EL_2. Therefore, the methodology for non-competing units is not applicable here. In this case the total energy generations of EL_1 and EL_2 is tested against the total assigned energy of the EL units. Consider that in figure 7.11(a) the total energy generation of EL units is less than the total assigned energy of EL units. So both the EL units should be moved at somewhat upper loading order position.

Since the equivalent load curve is invariant with respect to convolution order, $f_1(L_e)$, $f_2(L_e)$, $f_3(L_e)$ in figures 7.11(a) and 7.11(b) are unchanged by the relative loading order positions of the adjacent units: DE_{n+1}, EL_1 and EL_2. The desired objective is to find a position in the loading order for the two adjacent units such that they can exhaust their total assigned energy as maximum as possible. Such a group of energy limited units is designated as a cluster. The situation when the unit DE_{n+1} is pushed to a loading order position after the cluster is depicted in figure 7.11(b). Now again the energy generation of cluster is tested against the assigned energy of cluster. This process is repeated until the energy generation of the cluster exceeds its assigned energy. Consider for the cluster the correct position is depicted in figure 7.11(b). But in most cases it is likely that cluster cannot exhaust whole of its assigned energy at this position. Therefore, partial offloading of DE_n is necessary. This procedure is described in following section. The demand energy unit preceding the cluster, DE_n, is called the trimming unit.

7.3.1 Inherent Blocking of Trimming Unit

As said in previous section, figure 7.11(b) represents the position for cluster to exhaust maximum assigned energy of the cluster but not all assigned energy. Again the complete offloading of unit DE_n is not possible. So it means that partial offloading of DE_n should be done such that the cluster can deliver all of its assigned energy. Let the amount of capacity that will be offloaded from DE_n is given by DE_{2n} and is depicted in figure 7.12(a). The situation after offloading this capacity is shown in figure 7.12(b).

Now from figures 7.12(a) and 7.12(b), the invariance of $f_4(L_e)$ with respect to the relative loading order positions of the adjacent units or capacity blocks leads to the energy relationship

$$E_{DEn}+E_{EL1}+E_{EL2}=E_{DE1n}+E_{EL1}'+E_{EL2}'+E_{DE2n} \qquad ......(7.17)$$

where,

E_{DEn}= Energy delivered by unit DE_n in figure 7.12(a)

E_{EL1}= Energy delivered by unit EL_1 in figure 7.12(a)

E_{EL2}= Energy delivered by unit EL_2 in figure 7.12(a)

E_{DE1n}= Energy delivered by 1st block of DE_n in figure7.12(b)

E_{DE2n}= Energy delivered by 2nd block of DE_n in figure7.12(b)

E_{EL1}'= Energy delivered by unit EL_1 in figure 7.12(b)

E_{EL2}'= Energy delivered by unit EL_2 in figure 7.12(b)

Now in figure 7.12(b) the amount of capacity DE_{2n} offloaded from trimming unit such that the cluster can supply all of its assigned energy. So

$$E_{EL1}' + E_{EL2}' = \text{Total assigned energy of cluster} \; ....(7.18)$$

$$= \text{Assigned energies of } (EL_1 + EL_2)$$

Now rearranging equation (7.17) as

$$(E_{EL1}'+ E_{EL2}')-(E_{EL1} + E_{EL2})=E_{DEn} - (E_{DE1n} + E_{DE2n}) \; ..(7.19)$$

The equation (7.19) implies that to adjust the cluster to exhaust all of its assigned energy requires the equivalent amount of energy reduction from trimming unit. If this is done then from simulation point of view the operation of figures 7.12(a) and 7.12(b) are equivalent though there has not been any blocking in figure 7.12(a). Without actual blocking of trimming unit, producing the same effects as that can be obtained by actual blocking is known

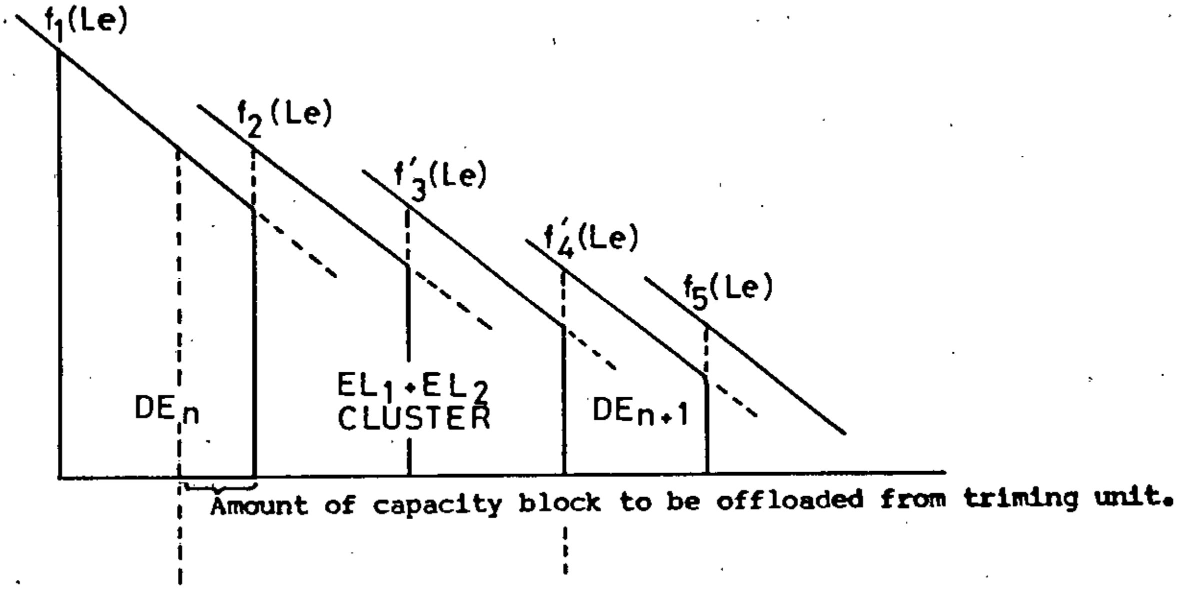
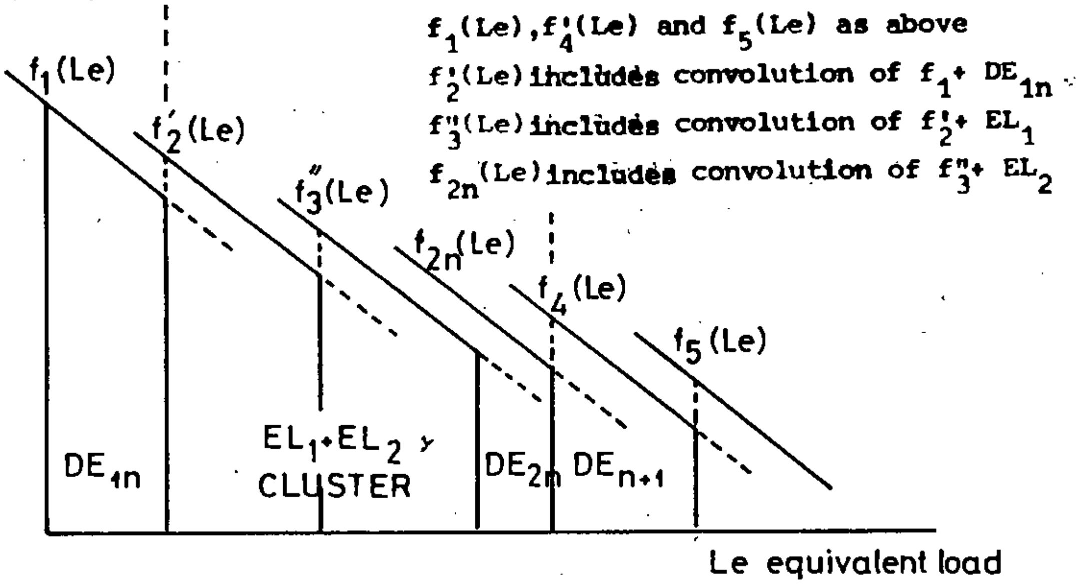


Figure-7.12(a) Blocking of triming unit



f_1(Le),f_4'(Le) and f_5(Le) as above
f_2'(Le) includes convolution of $f_1 + DE_{1n}$
f_3''(Le) includes convolution of $f_2' + EL_1$
f_{2n}(Le) includes convolution of $f_3'' + EL_2$

Figure-7.12(b) Loading order position of cluster to exhaust all of its assigned energy.

as inherent blocking of trimming unit and also for the simulation of competing unit this technique is utilized in algorithm. The procedure described in this section can be easily applied to any number of competing energy limited hydro units.

7.3.2 Inherent Blocking within Cluster

In figure 7.12(b) the position of cluster is shown to exhaust total assigned energy of cluster. This total assigned energy of cluster is made of individual assigned energies of EL units. Therefore, in figure 7.12(b) the cluster is capable of delivering total assigned energy but the individual energies supplied by EL units within cluster may not be exactly equal to the assigned energies of each unit. The situation must be such that cluster should deliver total assigned energy by adjusting each EL unit to deliver its own assigned energy. But it may not always possible for each EL unit to exhaust exactly its own assigned energy at the positions dictated by figure 7.12(b).

Let us consider that both EL units of figure 7.13(a) have same capacity, same FOR as well as same assigned energy. So it is most unlikely that units EL_1 and EL_2 can deliver their assigned energies in adjacent loading order positions. In general energy generation of EL_1 will be greater than that of EL_2. So to adjust EL units to exhaust their individual assigned energies, it is required to offload some amount of capacity from EL_1 so that each assigned energies are met. This situation is depicted in figure 7.13(b). The invariance of $f_{2n}(L_e)$ in figures 7.13(a) and 7.13(b) gives the following energy relationship

$$E_{EL1}' + E_{EL2}' = E_{EL11} + E_{EL2}'' + E_{EL21} \quad ....(7.20)$$

where,

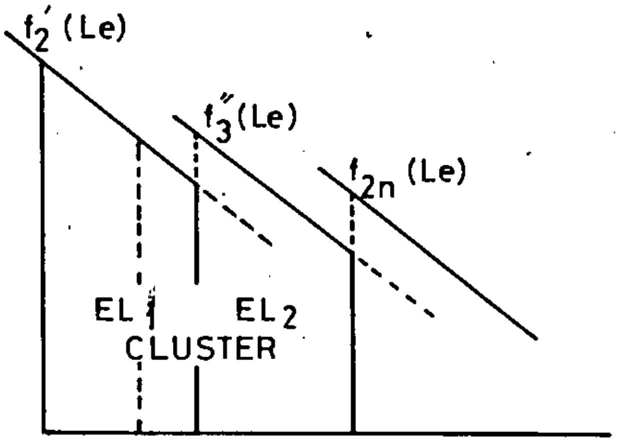
E_{EL1}' = Energy delivered by EL_1 in figure 7.13(a).

E_{EL2}' = Energy delivered by EL_2 in figure 7.13(a).

E_{EL11} = Energy delivered by 1st block of EL_1 in figure 7.13(b).

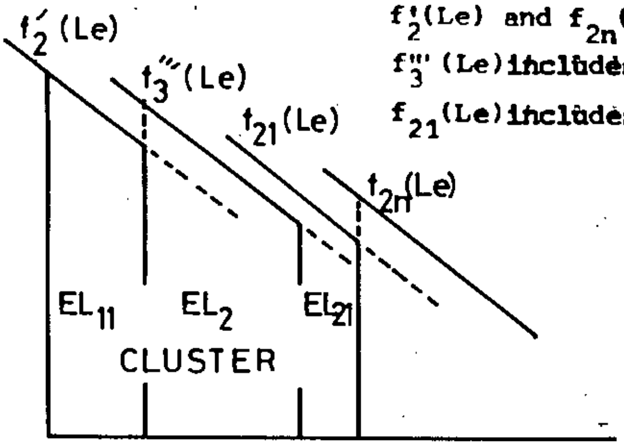
E_{EL21} = Energy delivered by 2nd block of EL_1 in figure 7.13(b).

E_{EL2}'' = Energy delivered by EL_2 in figure 7.13(b).



Amount of capacity block to be offloaded from EL_1 to adjust EL_1 and EL_2 to their own assigned energies.

Figure-7.13(a) Cluster portion of equivalent load curve.



$f_2'(Le)$ and $f_{2n}(Le)$ as above

$f_3'''(Le)$ includes convolution of $f_2' + EL_{11}$

$f_{21}(Le)$ includes convolution of $f_3''' + EL_2$

Figure-7.13(b) After blocking within cluster.

Now using equation (7.18), the equation (7.20) gives

$E_{EL11} + E_{EL21} + E_{EL2}''$ = Assigned energy of EL_1 + Assigned

Now from table 7.2 it is clear that the energy generations of 3rd and 4th units are less than the assigned energies of each unit if they are loaded at 3rd and 4th positions respectively. So they can be loaded at these positions. The results are shown in table 7.7.

Table 7.7: Results with competing units

Unit	capacity Mw	FOR	ϵ(E. generation) Mwh	ϵ(F. cost) Tk.
1	35.0	0.1	756.000	151200.00
2	20.0	0.2	130.250	29306.25
3	20.0	0.2	212.784	0.00
4	20.0	0.2	212.784	0.00

LOLP = 10.92% ϵ(ENS) = 32.182 Mwh

Total ϵ(E. generation) = 1311.818 mwh

Total ϵ(F. cost) = 180506.25 Tk.

Now from table 7.2, total energy generation of cluster

= (132.144 + 57.674) = 189.818 Mwh.

But the total assigned energy of cluster

= (212.784 + 212.784) = 425.568 Mwh.

Therefore, increased amount of energy supplied by cluster (425.568 - 189.818) = 235.75 Mwh is relieved from the trimming unit (2nd unit) because now the 2nd unit generates only 130.25 Mwh where as in table 7.2 it generates 366.0 Mwh. The operation of units in table 7.7 is equivalent of offloading of trimming unit by 15 Mw capacity. To show this equivalence the trimming unit is divided into two capacity blocks and the results are shown in table 7.8. Here the hydro units are declared without any energy restriction.

Table 7.8: Results with offloading of trimming unit

Unit	capacity Mw	FOR	ϵ(E. generation) Mwh	ϵ(F. cost) Tk.
1	35.0	0.1	756.000	151200.00
12	5.0	0.2	96.000	21600.00
3	20.0	0.2	322.800	0.00
4	20.0	0.2	102.768	0.00
22	15.0	0.2	34.250	7706.25

LOLP = 10.92% ϵ(ENS) = 32.182 Mwh

Total ϵ(E. generation) = 1311.818 mwh

Total ϵ(F. cost) = 180506.25 Tk.

Now the total energy supplied by trimming unit (96.0 + 34.25) ≐ 130.25 Mwh which is equal to the energy supplied by trimming unit in table 7.7. Again from table 7.8, the total energy supplied by units 3 and 4 is (322.8 + 102.786) = 425.568 which is equal to the total energy assignment of cluster. This is the correct loading order position for cluster. But within cluster offloading is required as none of the hydro units have the energy generation equal to their assigned energies. In this case 11.5 Mw capacity block should be offloaded from 1st hydro unit. To check this blocking within cluster, the 1st hydro unit is now divided into two capacity blocks and the result is shown in table 7.9.

Table 7.9: Results with blocking within cluster

Unit	capacity Mw	FOR	ϵ(E. generation) Mwh	ϵ(F. cost) Tk.

1	35.0	0.1	756.000	151200.00
12	5.0	0.2	96.000	21600.00
13	8.5	0.2	163.200	0.00
4	20.0	0.2	212.784	0.00
23	11.5	0.2	49.584	0.00
22	15.0	0.2	34.25	7706.25

LOLP = 10.92% $\mathcal{E}$(ENS) = 32.182 Mwh

Total $\mathcal{E}$(E. generation) = 1311.818 mwh

Total $\mathcal{E}$(F. cost) = 180506.25 Tk.

From table 7.9, the total energy supplied by 3rd unit (163.2 + 49.584) = 212.784 Mwh which is equal to the assigned energy of the unit and thus the energy assignment of each hydro unit is met. Therefore, from simulation point of view the operations of competing EL hydro units as shown in table 7.7 are equivalent to that of table 7.9. So the algorithm has the provision for correct simulation of competing units.

7.4 MULTISTATE APPROACH TO ENERGY-LIMITED HYDRO UNITS

Generally, the hydro units having limitation over the total amount of energy generation are known as energy limited units. For probabilistic simulation energy limited unit is associated with an assigned energy. This assigned energy for a period is determined on the basis of total amount of useful energy available from water during that period. Therefore, this assigned energy of an EL unit is calculated in a deterministic fashion. However, in true sense the energy that can be supplied by a hydro unit is probabilistic in nature, because this energy is a function of water head available in reservoir and the flow rate of the river [30]. These factors are related with the rainfall, river flow etc. which are probabilistic in nature.

This probabilistic nature of energies of hydro units is incorporated in by developing a completely new simulation technique. In this new technique, the hydro units are no longer declared as energy limited units rather they are declared as multistate units. In what follows, the methodology to develop the multistate model of hydro unit is described.

The capacity available from a hydro station is a function of both water power and generating unit capacity, giving

$$C_H = f(C_W, C) \qquad \text{.......(7.24)}$$

where

C_H = Capacity available from hydro station.

C_W = Water power capacity.

C = Generating unit capacity.

The functional relation of equation (7.24) is such that C_H is always minimum of two capacities, C_W and C. Now the water power capacity at any time can be found out by using equation (2.3) if the corresponding water head and flow rate are known. Therefore, the time variation of capacity as far as the water head and flow rate are concerned can be determined. Now for a certain period of time this capacity variation can be sampled at a suitable interval of time (for example hourly interval) and one can obtain the PDFs of available capacity from water power. In general, these PDFs will be of following nature

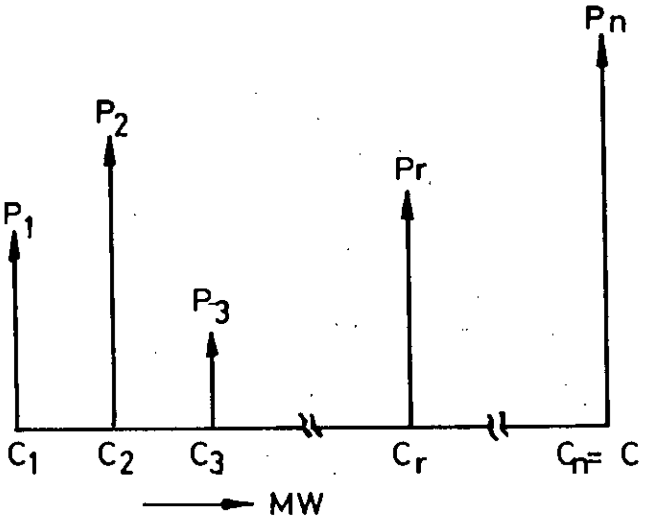


Figure-7.14 PDFs of available capacity so far water is concerned.

Here the probability value p's are such that

$$\sum_{i=1}^{n} p_i = 1 \qquad ....(7.25)$$

In figure 7.14, each capacity value is assigned with a probability impulse for example, C_r is assigned with p_r. The probability value p_r is found from the following relation

$$p_r = \frac{\text{number of occurrences of capacity } C_r \text{ in all the samples}}{\text{Total number of samples}}$$

For figure 7.14 it is necessary to consider the capacities up to the generating unit capacity as dictated by equation (7.24). If there is any impulse lying to the right of capacity C, then the probability value of these impulses are added to that of the capacity C. Thus, C_n of figure 7.14 will be equal to the capacity of generating unit.

Now, the PDFs of available capacity of generating unit is given by the following figure.

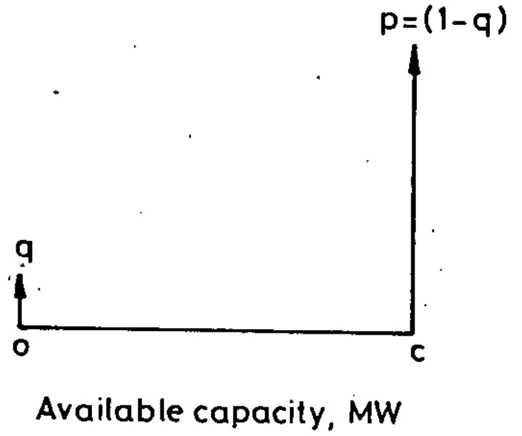


Figure-7.15 PDFs of available capacity of generating unit.

The available capacity of generating unit and available capacity from water are two independent random variables (RV$_s$). Therefore, the PDFs of available capacity for overall hydrostation is obtained using following probability relation

$$\text{Prob.}\left\{\begin{array}{l}C_r \text{ Mw is}\\ \text{available for}\\ \text{hydrostation}\end{array}\right\} = \left\{\begin{array}{l}\text{Probability that the}\\ \text{the generating unit}\\ \text{is available with}\\ \text{capacity } C_r\end{array}\right\} \times \text{Prob.}\left\{\begin{array}{l}C_r \text{ Mw is}\\ \text{available}\\ \text{from water}\end{array}\right\} \qquad \ldots\ldots.(7.26)$$

Therefore, using equations (7.26) and (7.24) the following distribution is obtained from figures 7.14 and 7.15.

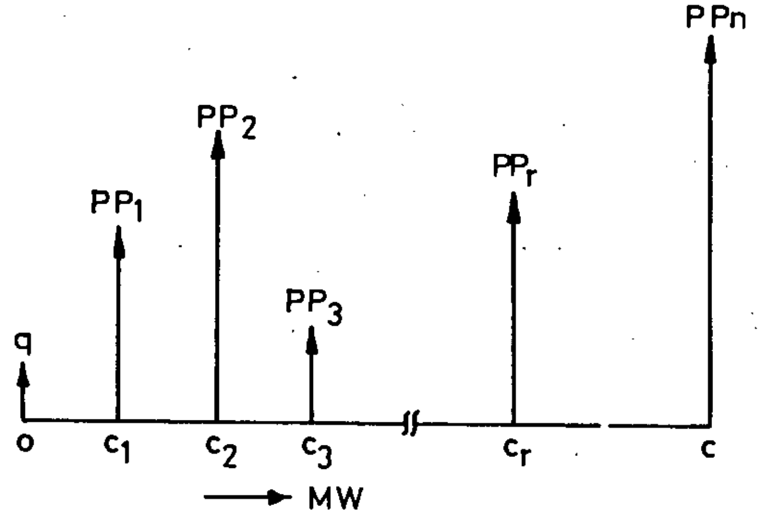


Figure-7.16 PDFs of available capacity for hydrostation

The impulse at 0 Mw is due to the fact that generating unit is not available for certain time depending on the forced outage rate, q. The final distribution for the outage capacity of the station is obtained by subtracting each capacity value of figure 7.16 from the generating unit capacity C and is depicted in figure 7.17.

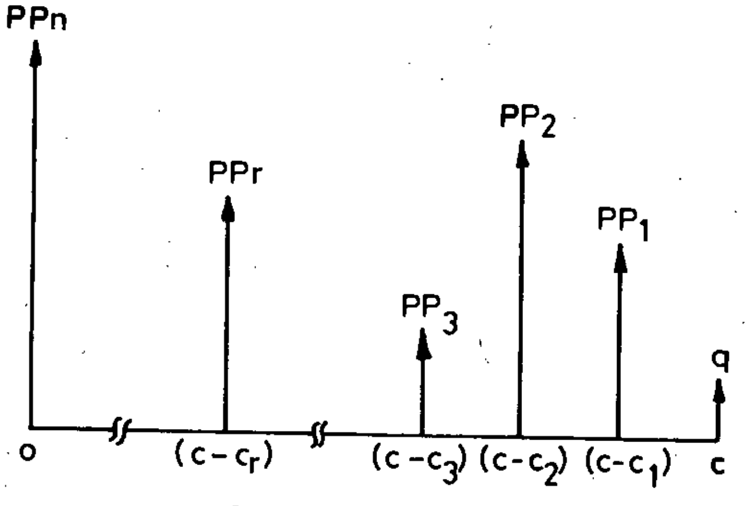
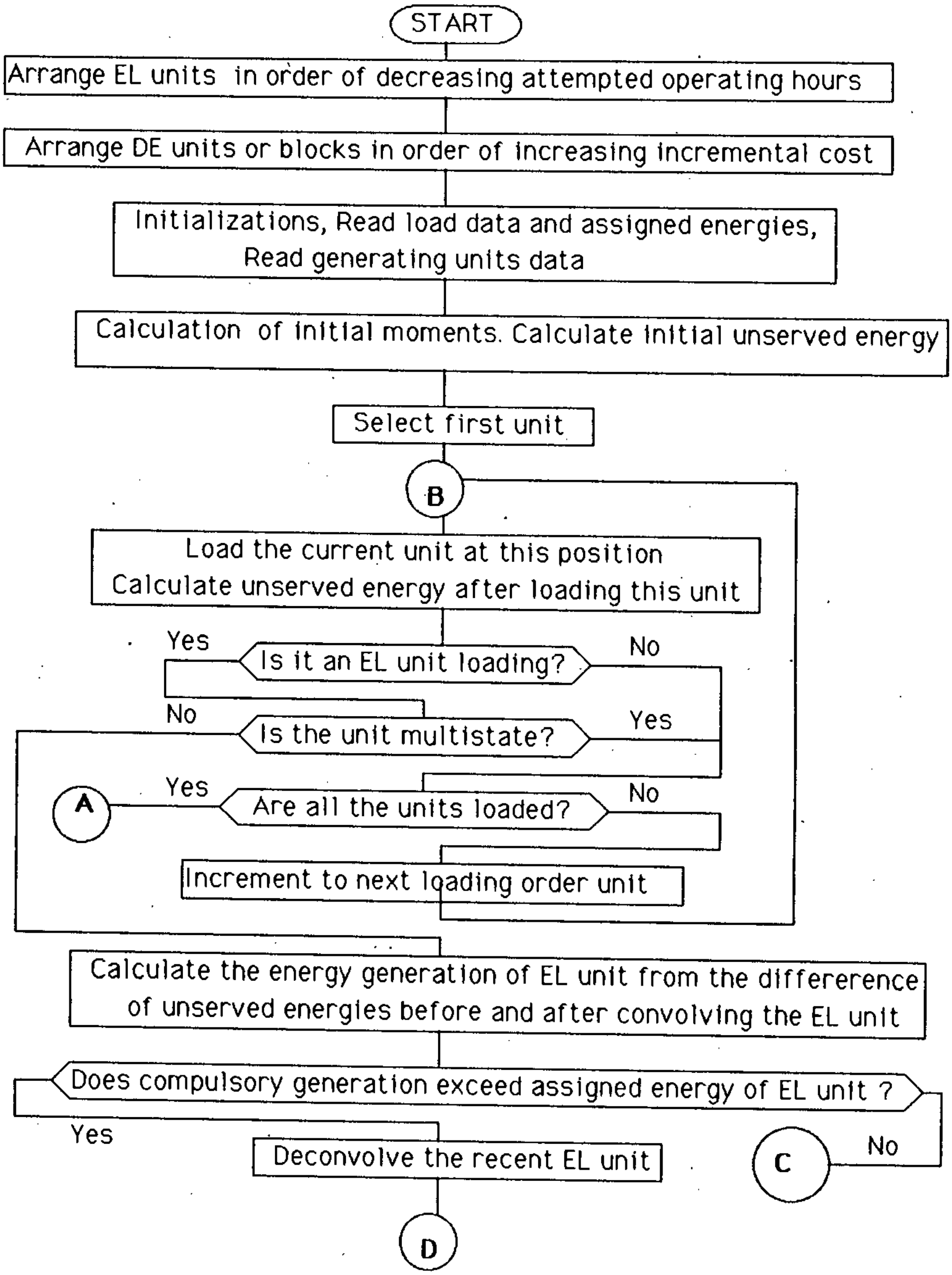
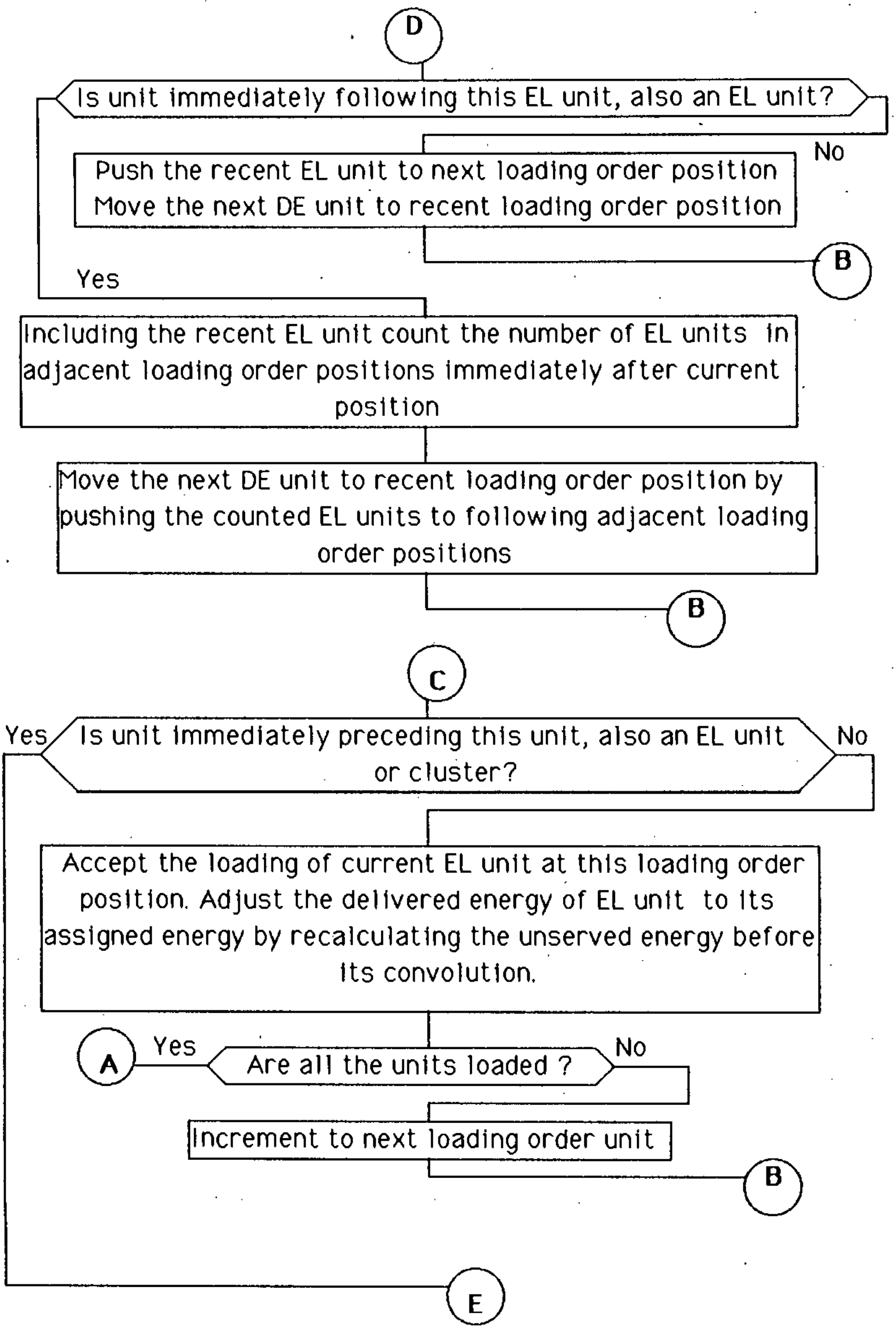


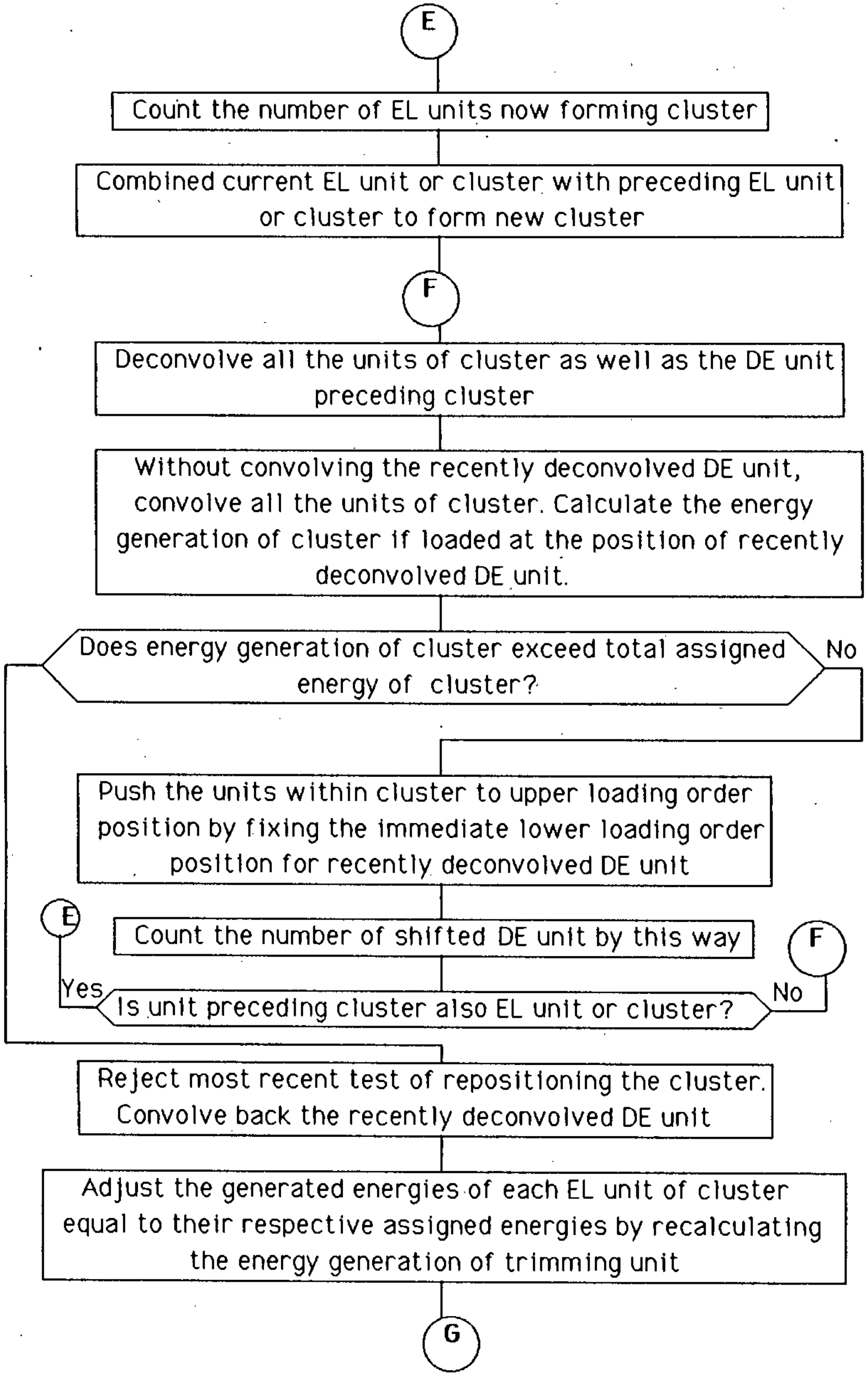
Figure-7.17 Outage capacity model of hydrostation.

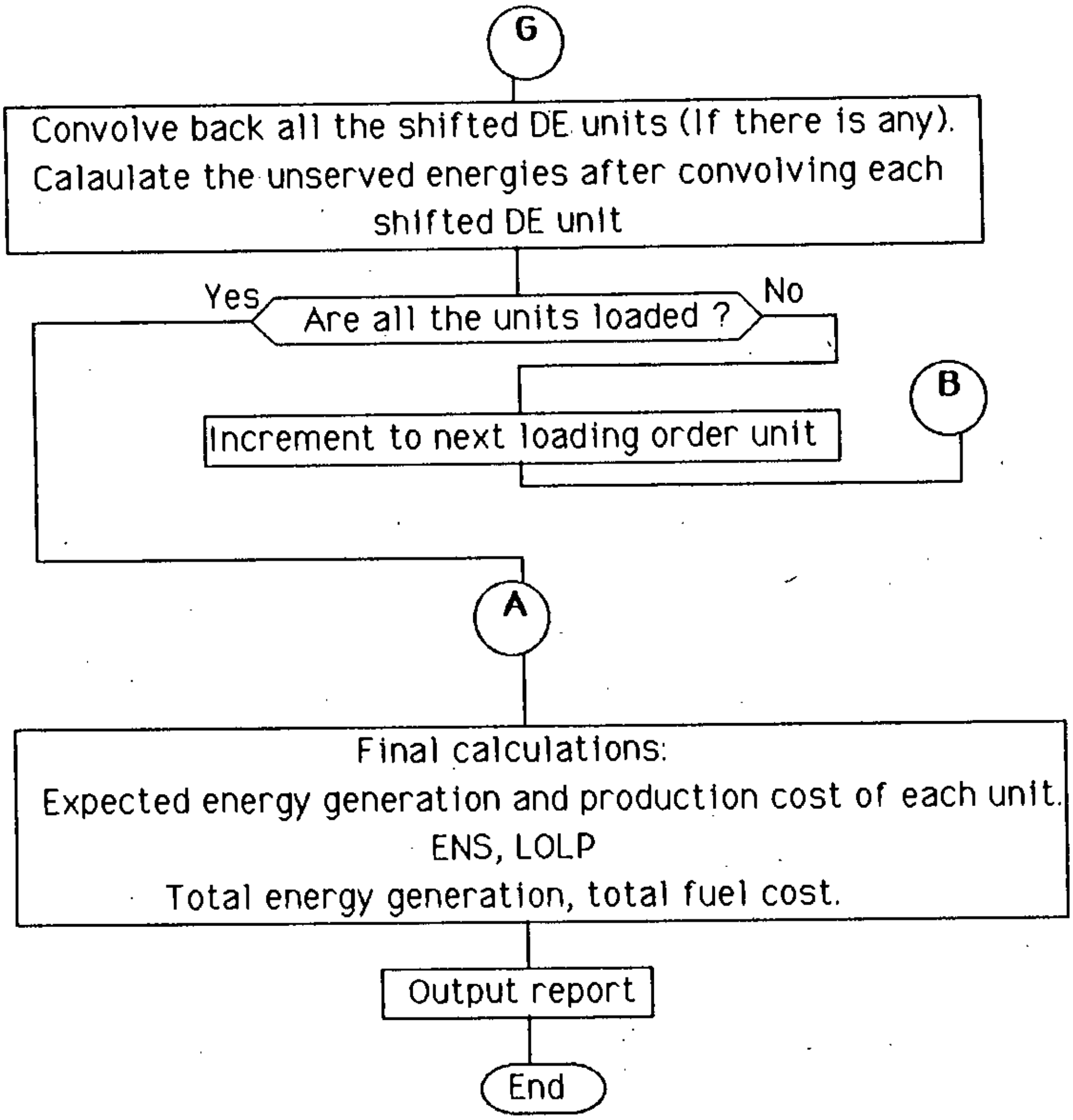
Now, if, for the hydro generating unit the outage capacity model of figure 7.17 is used instead of binary state model, then this means that the energy limitation of hydro unit is obviously incorporated within the multi-state model of hydro unit and this incorporation is probabilistic in nature. Therefore, for the purpose of simulation the energy limited hydro unit is declared as multistate unit with any external energy limitation.

7.5 FLOW CHART OF THE METHODOLOGY




D
Is unit immediately following this EL unit, also an EL unit?
No
Push the recent EL unit to next loading order position
Move the next DE unit to recent loading order position
B
Yes
Including the recent EL unit count the number of EL units in adjacent loading order positions immediately after current position
Move the next DE unit to recent loading order position by pushing the counted EL units to following adjacent loading order positions
B
C
Yes
Is unit immediately preceding this unit, also an EL unit or cluster?
No
Accept the loading of current EL unit at this loading order position. Adjust the delivered energy of EL unit to its assigned energy by recalculating the unserved energy before its convolution.
A
Yes
Are all the units loaded ?
No
Increment to next loading order unit
B
E


E
Count the number of EL units now forming cluster
Combined current EL unit or cluster with preceding EL unit or cluster to form new cluster
F
Deconvolve all the units of cluster as well as the DE unit preceding cluster
Without convolving the recently deconvolved DE unit, convolve all the units of cluster. Calculate the energy generation of cluster if loaded at the position of recently deconvolved DE unit.
Does energy generation of cluster exceed total assigned energy of cluster?
No
Push the units within cluster to upper loading order position by fixing the immediate lower loading order position for recently deconvolved DE unit
E
Count the number of shifted DE unit by this way
F
Yes
Is unit preceding cluster also EL unit or cluster?
No
Reject most recent test of repositioning the cluster. Convolve back the recently deconvolved DE unit
Adjust the generated energies of each EL unit of cluster equal to their respective assigned energies by recalculating the energy generation of trimming unit
G


G
Convolve back all the shifted DE units (If there is any).
Calaulate the unserved energies after convolving each shifted DE unit
Yes
Are all the units loaded ?
No
B
Increment to next loading order unit
A
Final calculations:
Expected energy generation and production cost of each unit.
ENS, LOLP
Total energy generation, total fuel cost.
Output report
End

CHAPTER 8

CHAPTER 8

NUMERICAL EVALUATION

8.1 INTRODUCTION

For the simulation of energy limited hydro units two different methodologies have been developed in chapter 7. These two developed methodologies are applied to two realistic systems; i) IEEE-Reliability test system, ii) Bangladesh power system. In the numerical evaluation the segmentation method is used. The segmentation method is described in details in chapter 5.

This chapter presents a brief description of the two systems. The simulation results are presented in this chapter. The results includes the cases of multihydro competing units and also non competing unit. In this chapter, also the results obtained using multistate approach for an energy limited unit are presented.

8.2 IEEE RELIABILITY TEST SYSTEM (IEEE-RTS) [38]

The IEEE test system provides the basic data required in the evaluation of reliability and production cost. The test system is widely used in different simulation techniques to provide a basis for comparison of results. The system is also used in this thesis to test the applicability of the developed methodologies. The test system has load, generation and transmission network models. The load model provides hourly loads on per unit basis expressed in chronological fashion. The generating system consists of 32 units of different sizes varying from 10 to 400 Mw. The load model and generating system are briefly described in following two sections.

8.2.1 Load Data [38]

The thirteen winter weeks hourly loads are utilized in this research.

These weeks are: 1-8 and 48-52. The peak and base loads of this 13 weeks are 2850 Mw and 1102.6 Mw respectively. The total energy demand for this period is equal to 4163.48 Gwh. For this thirteen weeks the weekly peak loads in percentage of the annual peak load are given in table 8.1 and table 8.2 gives a daily peak load in percentage of the weekly peak.

Table 8.1: Weekly peak load in percent of annual peak load

Week	Peak load
1	86.2
2	90.0
3	87.8
4	83.4
5	88.0
6	84.1
7	83.2
8	80.6
48	89.0
49	94.2
50	97.0
51	100.0
52	95.2

Combining tables 8.1 and 8.2 together with annual peak load defines a daily peak load model of 13x7=91 days.

Table 8.2: Daily peak load in percent of weekly peak

Day	Peak load
Monday	93.0
Tuesday	100.0
Wednesday	98.0
Thursday	96.0
Friday	94.0
Saturday	77.0
Sunday	75.0

Weekday and weekend hourly load models for winter season is given in table 8.3. Combination of tables 8.1, 8.2 and 8.3 with annual peak load defines an hourly load model of 91x24=2184 hours.

Table 8.3: Hourly load in percent of daily peak

Hours	Winter weeks 1-8 and 48-52 Weekday	Weekend
12-1 AM	67	78
1-2	63	72
2-3	60	68
3-4	59	66
4-5	59	64
5-6	60	65
6-7	74	66
7-8	86	70

8-9	95	80
9-10	96	88
10-11	96	90
11-12	95	91
12-1 PM	95	90
1-2	95	88
2-3	93	87
3-4	94	87
4-5	99	91
5-6	100	100
6-7	100	99
7-8	96	97
8-9	91	94
9-10	83	92
10-11	73	87
11-12	63	81

Hourly load for any hour of the weekday may be expressed as:

HL=WKPKxDPKxHLWDxAPK

where, HL=Hourly load

WKPK=Weekly peak as a fraction of annual peak.

DPK=Daily peak as a fraction of weekly peak.

HLWD=Hourly load as a fraction of daily peak for weekday.

APK=Annual peak load.

Similarly hourly load for any hour of the weekend day may be expressed as:

HL=WKPKxDPKxHLWExAPK

where, HLWE=Hourly load as a fraction of daily peak for weekday.

8.2.2 Generation Data [38]

Generating system comprises nuclear, coal, oil and hydro generating units. Generation system data of IEEE-RTS is given in table 8.4. For the above 13 week period each energy limited hydro unit is considered to have an assigned energy of 40 Gwh.

Table 8.4:Generation data of IEEE-RTS

Type of unit	Unit size (Mw)	No. of units	FOR	Average incremental cost ($/Mwh.)
Hydro	50	6	0.01	0.000
Nuclear	400	2	0.12	5.450
Coal	150	4	0.04	10.704
Coal	350	1	0.08	10.883
Coal	80	4	0.02	13.494
Oil	200	3	0.05	20.730
Oil	100	3	0.04	20.853
Oil	10	5	0.02	25.875
Oil	20	4	0.10	37.500

8.3 BANGLADESH POWER SYSTEM (BPS) [39]

Bangladesh power system is a small system. This power system may be divided into two zones: the East zone and the West zone separated by the rivers Padma, Jamuna and Meghna. These two zones are interconnected by the East-West interconnector forming an integrated national grid. There are a number of power stations in the East and in the West zones. The large power stations are Karnafuli Hydroelectric Station, Ashuganj Steam Power Station and Combined Cycle Power Station, Ghorashal Thermal Power Station, Siddhirganj Thermal Power Station, Shahjibazar and Bheramara Gas Turbine Power Stations.

Most of the thermal stations in East zone uses natural gas as fuel whereas in the West zone costly liquid fuels are used for generating electrical energy. Bangladesh Power Development Board (BPDB) has the sole responsibility of generating, transmitting and distributing the electrical energy in Bangladesh.

8.3.1 BPS Generation Data [39]

Generation data of BPS used in this research are given in Appendix C. Some of the small unit capacities are rounded off to decrease the computer time. In the West zone the small diesel units with capacities less than 5 Mw are aggregated to form five units of 5 Mw capacity and are shown in Appendix C in the name of "Small Diesel stations". The total generation capacity of the integrated system is 1022 Mw.

8.3.2 BPS Load Data

Hourly load data of August, 1985 are used in this research for simulating BPS. These hourly loads are given in Appendix D. For this load model it is found that the daily peak load occurs during 7:00 to 9:00 PM. In this month the peak and base loads are 765.05 Mw and 287.09 Mw respectively. The total amount of energy demand during the same period is 369.1723 Gwh.

8.4 DEVELOPMENT OF MULTISTATE MODEL FOR HYDRO UNIT OF BPS

For August, 1985 the hourly generation available from hydro station of BPS at Kaptai are given in Appendix E. Though hydro station at Kaptai has three units, but BPDB could not supply the individual hourly generation of each hydro unit. So in Appendix E the capacity available at each hour are given for entire hydro station and these hourly capacities are calculated on the basis of water head and flow rate available at corresponding hours. Now for constructing the multistate model that replaces the energy limitation of hydro unit, the variation of capacity with respect to water power at a suitable interval of time is needed. As this variation is given for total hydro unit, therefore, the hydro units of BPS are replaced by a single unit of 142 Mw capacity without any appreciable loss of accuracy. Now for this unit the multistate model will be developed.

Histogram depicting the hourly possible generation from water power at hydro station of BPS is shown in figure 8.1.

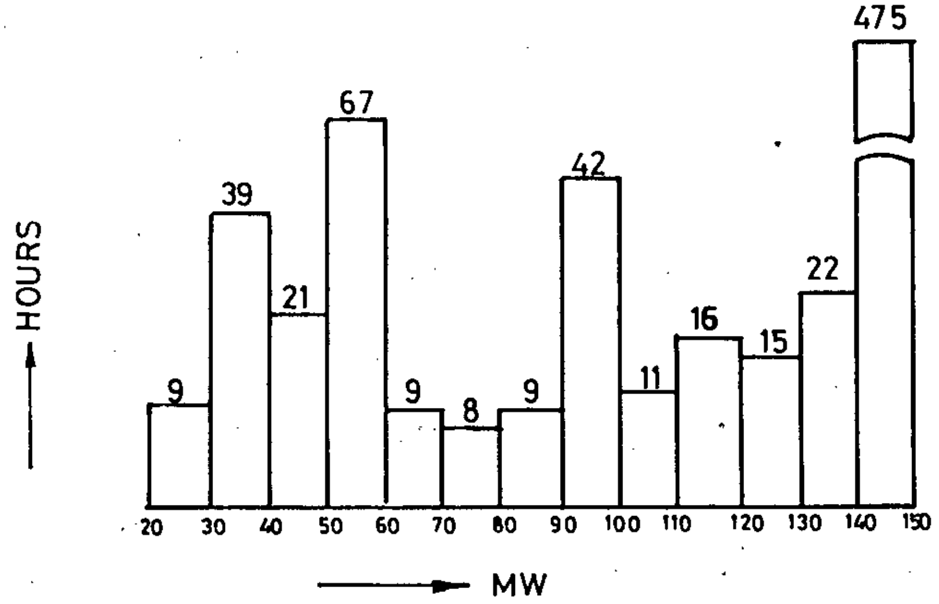


Figure- 8.1 Histagram of hourly generation from water power of BPS hydrostation

Total number of samples (hours) are (31x24) 744. The PDFs of hourly generations of figure 8.1 are depicted in figure 8.2.

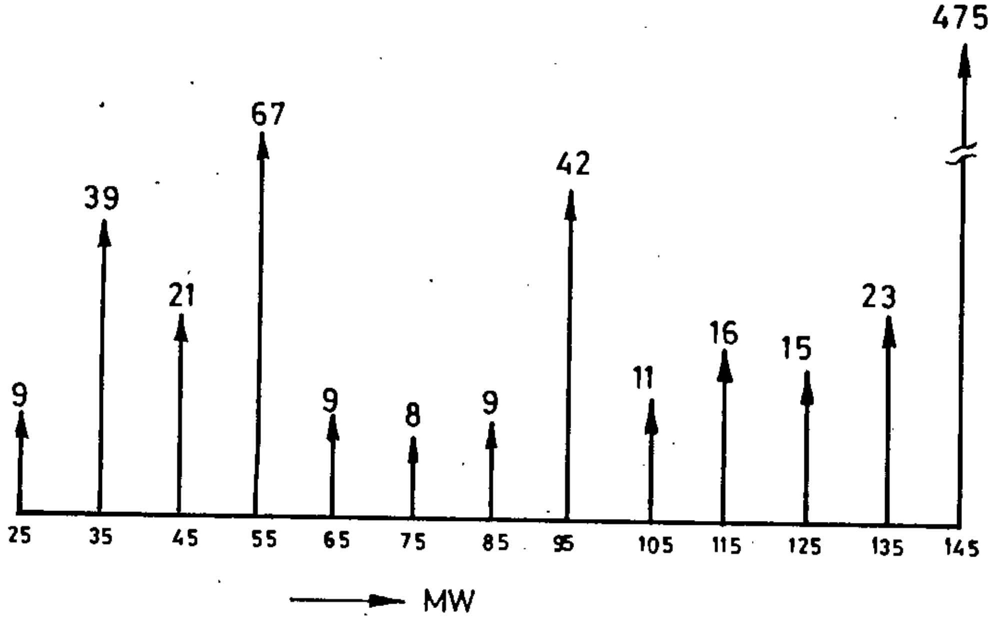


Figure- 8.2 PDFs of available capacity for BPS hydrostation so far water power concerned (all impulses to be divided by 744)

For figure 8.1 it was found that all samples lying in the last interval have capacity value equal to 142 Mw, so in the figure 8.2 last impulse is shown with a 142 Mw capacity. The PDFs of available capacity of hydro generating unit is shown in figure 8.3.

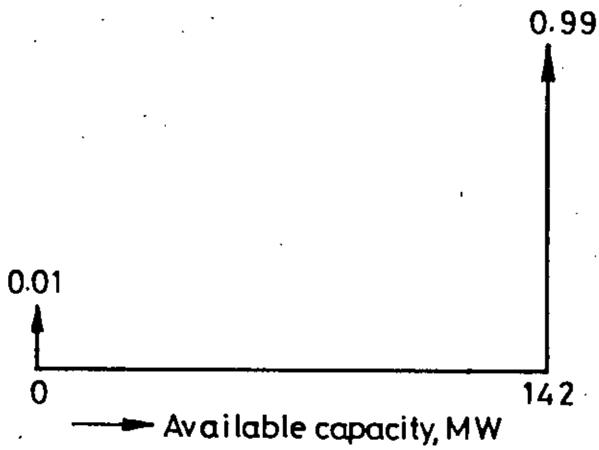


Figure-8.3 PDFs of available capacity of binary state hydro generating unit

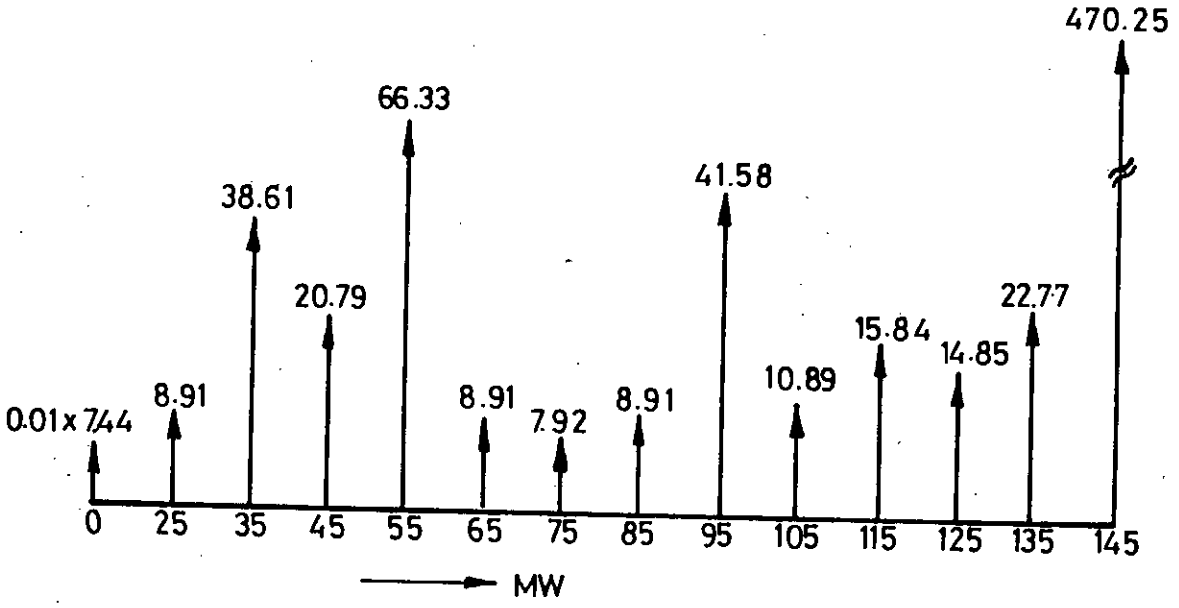


Figure-8.4 Distribution of available capacity of hydro unit accomoddting energy limitation(all impulses to be divided by 744)

Now using the methodology given in section 7.4, the PDFs of available capacity of hydro station after accommodating the energy limitation is shown in figure 8.4. Finally the outage capacity model is obtained by subtracting each capacity value of figure 8.4 from generating unit capacity 142 Mw and the distribution is shown in figure 8.5.

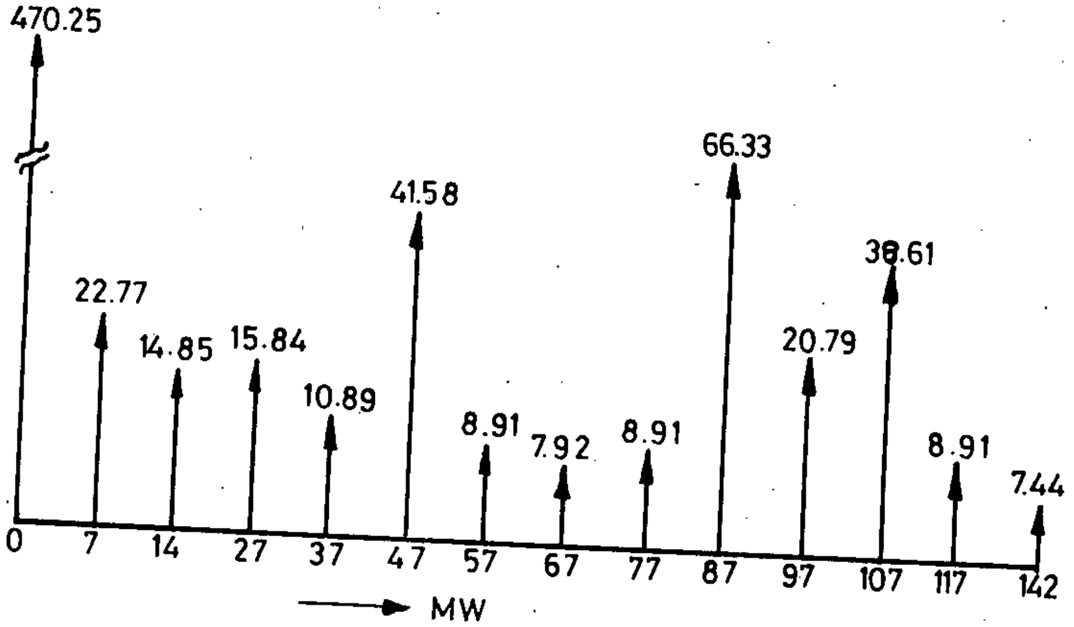


Figure- 8.5 Multistate model of hydro generating unit of BPS (all impulses to be divided by 744)

This multistate representation of energy limitation will be used for numerical evaluation of BPS.

8.5 COMPUTER PROGRAM

For numerical evaluation a computer program is developed in FORTRAN. This program resembles the methodologies developed in chapter 7. The program is general in nature and it is capable of evaluating any power system by appropriately changing the dimensions of the variables in the program. The provision of handling multiblock and multistate generating unit is also in the program. The computer program is given in Appendix F.

8.6 NUMERICAL RESULTS

For numerical results as mentioned earlier two power systems are evaluated. One is the IEEE reliability test system and the other one is the Bangladesh power system. In the following results, the base case is referred to the loading schedule where all the hydro units are base loaded. The CPU time mentioned below is applicable for an IBM 4331 computer.

8.6.1 Results for IEEE-RTS

As shown in table 8.4 the generation system of IEEE-RTS includes six hydro units. In the simulation process, the various number of hydro units are considered to energy limited units. in this process, except the EL units the remaining hydro units are used as base loaded unit. For IEEE-RTS the assigned energy associated with one EL unit it is considered to 40 Gwh.

In table 8.5 the results for the base case are given. This table presents the expected energy generation by each individual units along with the total expected energy generation.

Table 8.5: Expected energy generation of individual generators of IEEE-RTS (loading status of hydro units: base case)

Loading order posit^{n}.	Cap. (Mw)	FOR	Expected energy gen. (Gwh.)	Loading order posit^{n}.	Cap. (Mw)	FOR	Expected energy gen. (Gwh.)
1	50	0.01	108.1080	17	80	0.02	51.8486
2	50	0.01	108.1080	18	200	0.05	87.2321
3	50	0.01	108.1080	19	200	0.05	45.4079
4	50	0.01	108.1080	20	200	0.05	20.5770
5	50	0.01	108.1080	21	100	0.04	5.2003
6	50	0.01	108.1080	22	100	0.04	3.0416
7	400	0.12	768.7680	23	100	0.04	1.7280
8	400	0.12	768.7680	24	10	0.02	0.1277
9	150	0.04	312.0702	25	10	0.02	0.1200
10	150	0.04	299.2437	26	10	0.02	0.1133
11	150	0.04	272.6772	27	10	0.02	0.1058
12	150	0.04	240.7727	28	10	0.02	0.0997
13	350	0.08	417.2606	29	20	0.10	0.1660
14	80	0.02	82.5845	30	20	0.10	0.1475
15	80	0.02	73.2286	31	20	0.10	0.1310
16	80	0.02	62.5009	32	20	0.10	0.1165

Total expected energy generation = 4162.685 Gwh

Now, tables 8.6, 8.7, and 8.8 presents the expected energy generation of individual unit as well as of the whole system considering one, two, and six EL units respectively. Note that other than the EL units the remaining hydro units are considered as base loaded units in these simulations.

Table 8.6: Expected energy generation of individual generators of IEEE-RTS (loading status of hydro units: includes one energy limited unit)

Loading order posit^n.	Cap. (Mw)	FOR	Expected energy gen. (Gwh.)	Loading order posit^n.	Cap. (Mw)	FOR	Expected energy gen. (Gwh.)
1	50	0.01	108.1080	17	80	0.02	51.8486
2	50	0.01	108.1080	18	200	0.05	87.2321
3	50	0.01	108.1080	19	200	0.05	45.4079
4	50	0.01	108.1080	20	200	0.05	20.5770
5	50	0.01	108.1080	21	100	0.04	5.2003
6	400	0.12	768.7680	22	100	0.04	3.0416
7	400	0.12	768.7680	23	100	0.04	1.7280
8	150	0.04	313.7449	24	10	0.02	0.1277
9	150	0.04	305.0292	25	10	0.02	0.1200
10	150	0.04	282.7550	26	10	0.02	0.1133
11	150	0.04	252.3331	27	10	0.02	0.1058
12	350	0.08	439.8852	28	10	0.02	0.0997
13	80	0.02	87.7830	29	20	0.10	0.1660
14	80	0.02	79.2578	30	20	0.10	0.1475
15	80	0.02	67.6581	31	20	0.10	0.1310
16	50	0.01	40.0000	32	20	0.10	0.1165

Total expected energy generation = 4162.685 Gwh

In table 8.6 the 15th unit is trimmed by the energy limited unit loaded at 16th loading order position. To show this trimming operation, results are given in table 8.6(a) with declaring the energy limited unit of table 8.6 without any energy restriction. In table 8.6(a) the individual energy generation of each unit obtained with energy limited unit are also given for comparative study.

Table 8.6(a): Expected energy generations of individual units for showing trimming operation

Loading order posit^{n}.	Expected energy gen. (Gwh.)		Loading order posit^{n}.	Expected energy gen. (Gwh.)	
	5 hydro base loaded,one placed at 16th position	with one energy limited unit		5 hydro base loaded,one placed at 16th position	with one energy limited unit
1	108.1080	108.1080	17	51.8486	51.8486
2	108.1080	108.1080	18	87.2321	87.2321
3	108.1080	108.1080	19	45.4079	45.4079
4	108.1080	108.1080	20	20.5770	20.5770
5	108.1080	108.1080	21	5.2003	5.2003
6	768.7680	768.7680	22	3.0416	3.0416
7	768.7680	768.7680	23	1.7280	1.7280
8	313.7449	313.7449	24	0.1277	0.1277
9	305.0292	305.0292	25	0.1200	0.1200
10	282.7550	282.7550	26	0.1133	0.1133
11	252.3331	252.3331	27	0.1058	0.1058
12	439.8852	439.8852	28	0.0997	0.0997
13	87.7830	87.7830	29	0.1660	0.1660
14	79.2578	79.2578	30	0.1475	0.1475
15	69.4722	67.6581	31	0.1310	0.1310
16	38.1859	40.0000	32	0.1165	0.1165

Table 8.7: Expected energy generation of individual generators of IEEE-RTS (loading status of hydro units: includes two energy limited unit)

Loading order posit^n.	Cap. (Mw)	FOR	Expected energy gen. (Gwh.)	Loading order posit^n.	Cap. (Mw)	FOR	Expected energy gen. (Gwh.)
1	50	0.01	108.1080	17	50	0.01	40.0000
2	50	0.01	108.1080	18	200	0.05	87.2321
3	50	0.01	108.1080	19	200	0.05	45.4079
4	50	0.01	108.1080	20	200	0.05	20.5770
5	400	0.12	768.7680	21	100	0.04	5.2003
6	400	0.12	768.7680	22	100	0.04	3.0416
7	150	0.04	314.3941	23	100	0.04	1.7280
8	150	0.04	309.2032	24	10	0.02	0.1277
9	150	0.04	291.9142	25	10	0.02	0.1200
10	150	0.04	263.2934	26	10	0.02	0.1133
11	350	0.08	463.6391	27	10	0.02	0.1058
12	80	0.02	92.6514	28	10	0.02	0.0997
13	80	0.02	84.8157	29	20	0.10	0.1660
14	80	0.02	75.7690	30	20	0.10	0.1475
15	80	0.02	52.7228	31	20	0.10	0.1310
16	50	0.01	40.0000	32	20	0.10	0.1165

Total expected energy generation = 4162.685 Gwh

Table 8.8: Expected energy generation of individual generators of IEEE-RTS (loading status of hydro units: all hydro units are energy limited)

Loading order posit^{n}.	Cap. (Mw)	FOR	Expected energy gen. (Gwh.)	Loading order posit^{n}.	Cap. (Mw)	FOR	Expected energy gen. (Gwh.)
1	400	0.12	768.7680	17	50	0.01	40.0000
2	400	0.12	768.7680	18	50	0.01	40.0000
3	150	0.04	314.4960	19	200	0.05	45.4079
4	150	0.04	314.4960	20	200	0.05	20.5770
5	150	0.04	312.1654	21	100	0.04	5.2003
6	150	0.04	299.9276	22	100	0.04	3.0416
7	350	0.08	563.4825	23	100	0.04	1.7280
8	80	0.02	113.6873	24	10	0.02	0.1277
9	80	0.02	104.7652	25	10	0.02	0.1200
10	80	0.02	96.6100	26	10	0.02	0.1133
11	80	0.02	89.0314	27	10	0.02	0.1058
12	200	0.05	99.4056	28	10	0.02	0.0997
13	50	0.01	40.0000	29	20	0.10	0.1660
14	50	0.01	40.0000	30	20	0.10	0.1475
15	50	0.01	40.0000	31	20	0.10	0.1310
16	50	0.01	40.0000	32	20	0.10	0.1165

Total expected energy generation = 4162.685 Gwh .

In table 8.9, a comparative study for different number of EL units is made. the second column of this presents the LOLP of the system expressed in percent. The fourth column presents the expected energy not served. Recall that the expected energy not served is the difference between the energy demand and the expected energy generation. The production cost and the computational requirements in terms of CPU time are shown, respectively, in columns 5th and 6th.

Table 8.9: Simulation results of IEEE-RTS in summarized form

Status of hydro units	LOLP (%)	Total engy. gen.(Gwh)	$\mathcal{E}$(ENS) (Gwh)	Total fuel cost ($10^{6}\,\$$)	CPU time (Sec.)
Base case	0.280	4162.685	0.795	32.025	22.65
One EL unit	0.280	4162.685	0.795	32.804	24.85
Two EL units	0.280	4162.685	0.795	33.592	38.92
Three EL units	0.280	4162.685	0.795	34.388	42.44
Four EL units	0.280	4162.685	0.795	35.193	53.82
Five EL units	0.280	4162.685	0.795	36.009	55.69
Six EL units	0.280	4162.685	0.795	36.922	66.78

8.6.2 Results for Bangladesh Power System

In table 8.10, the expected energy generations of individual generating units as well as the expected energy generation of the system are given for the base case.

Table 8.10:Expected energy generation of individual generators of BPS (with base loaded hydro unit)

Loading order posit^{n}.	Cap. (Mw)	FOR	Expected energy gen. (Gwh.)	Loading order posit^{n}.	Cap. (Mw)	FOR	Expected energy gen. (Gwh.)
1	142	0.01	104.59152	19	10	0.18	1.08531
2	65	0.10	43.52400	20	5	0.18	0.51147
3	65	0.10	43.52400	21	5	0.18	0.49074
4	50	0.10	33.30169	22	110	0.10	6.39829
5	60	0.10	38.17738	23	60	0.10	1.14992
6	55	0.10	30.74888	24	5	0.12	0.05832
7	55	0.10	25.07823	25	5	0.12	0.05354
8	55	0.19	17.27920	26	5	0.12	0.04917
9	30	0.19	7.44313	27	5	0.12	0.04518
10	10	0.15	2.29631	28	5	0.12	0.04152
11	10	0.15	2.13229	29	25	0.18	0.14682
12	10	0.15	1.98142	30	25	0.18	0.09658
13	10	0.18	1.77019	31	20	0.15	0.05457
14	10	0.18	1.64298	32	20	0.18	0.03603
15	10	0.18	1.51966	33	20	0.18	0.02467
16	10	0.18	1.40098	34	20	0.18	0.01666
17	10	0.18	1.28834	35	5	0.15	0.00347
18	10	0.18	1.18188	36	5	0.15	0.00311

Total expected energy generation = 369.147 Gwh

For the time period of study for this research, it is found from Appendix-E that the total amount of energy that can be supplied by hydro station is equal to 87.227 Gwh. So this amount of energy is considered as the assigned energy of the hydro unit. For this case the expected energy generation of different generating units of BPS are evaluated and results are presented in table 8.11.

Table 8.11:Expected energy generation of individual generators of BPS (with energy limited hydro unit)

Loading order positn.	Cap. (Mw)	FOR	Expected energy gen. (Gwh.)	Loading order positn.	Cap. (Mw)	FOR	Expected energy gen. (Gwh.)
1	65	0.10	43.52400	19	10	0.18	1.08531
2	65	0.10	43.52400	20	5	0.18	0.51147
3	50	0.10	33.48000	21	5	0.18	0.49074
4	60	0.10	40.17600	22	110	0.10	6.39829
5	55	0.10	36.81440	23	60	0.10	1.14992
6	55	0.10	34.20030	24	5	0.12	0.05832
7	142	0.01	87.22700	25	5	0.12	0.05354
8	55	0.19	17.27920	26	5	0.12	0.04917
9	30	0.19	7.44313	27	5	0.12	0.04518
10	10	0.15	2.29631	28	5	0.12	0.04152
11	10	0.15	2.13229	29	25	0.18	0.14682
12	10	0.15	1.98142	30	25	0.18	0.09658
13	10	0.18	1.77019	31	20	0.15	0.05457
14	10	0.18	1.64298	32	20	0.18	0.03603
15	10	0.18	1.51966	33	20	0.18	0.02467
16	10	0.18	1.40098	34	20	0.18	0.01666
17	10	0.18	1.28834	35	5	0.15	0.00347
18	10	0.18	1.18188	36	5	0.15	0.00311

Total expected energy generation = 369.147 Gwh

The multistate model developed in section 8.4 is used for the energy limited hydro unit. Note that, in this simulation the determination of the amount of limited energy for the hydro unit is not required. From the distribution of water head the distribution of multistate hydro unit is developed. The BPS with a multistate hydro is evaluated and the results are presented in table 8.12.

Table 8.12:Expected energy generation of individual generators of BPS (with multistate model of hydro unit)

Loading order posit^{n}.	Cap. (Mw)	FOR	Expected energy gen. (Gwh.)	Loading order posit^{n}.	Cap. (Mw)	FOR	Expected energy gen. (Gwh.)
1	142	0.368	86.70915	19	10	0.18	1.46335
2	65	0.10	43.52400	20	5	0.18	0.69348
3	65	0.10	43.52400	21	5	0.18	0.66730
4	50	0.10	33.36088	22	110	0.10	9.24371
5	60	0.10	38.77837	23	60	0.10	1.97726
6	55	0.10	32.33510	24	5	0.12	0.10787
7	55	0.10	27.52874	25	5	0.12	0.10049
8	55	0.19	19.78033	26	5	0.12	0.09362
9	30	0.19	8.87962	27	5	0.12	0.08713
10	10	0.15	2.80250	28	5	0.12	0.08104
11	10	0.15	2.63533	29	25	0.18	0.29676
12	10	0.15	2.47583	30	25	0.18	0.20706
13	10	0.18	2.23805	31	20	0.15	0.12336
14	10	0.18	2.09888	32	20	0.18	0.08554
15	10	0.18	1.96284	33	20	0.18	0.06149
16	10	0.18	1.83024	34	20	0.18	0.04365
17	10	0.18	1.70233	35	5	0.15	0.00934
18	10	0.18	1.57911	36	5	0.15	0.00848

Total expected energy generation = 369.096 Gwh

The forced outage rate given for multistate hydro unit in table 8.12 is the equivalent FOR, which is the summation of probability values of all impulses of figure 8.5 except the impulse at zero Mw.

Table 8.13 presents a comparison of LOLP, expected energy generation, expected energy not served, fuel cost and computational requirement for the following three cases:

Case (i):Base case; hydro unit is considered as base loaded unit

Case (ii): Hydro unit is considered as energy limited unit

Case (iii): Multistate model of hydro unit is considered.

Table 8.13: Results obtained for BPS in summarized form.

Cases	LOLP (%)	Total engy. gen.(Gwh)	ϵ(ENS) (Gwh)	Total fuel cost(10^6 Tk.)	CPU time (Sec.)
(i)	0.094	369.147	0.025	54.3188	37.04
(ii)	0.094	369.147	0.025	57.0953	41.50
(iii)	0.258	369.096	0.076	64.6784	40.75

CHAPTER 9

CHAPTER 9

OBSERVATIONS AND CONCLUSIONS

9.1 OBSERVATIONS AND DISCUSSIONS

In what follows the important features that observed from the numerical results are presented. Along with the observations the possible discussions are also presented below.

IEEE-RTS

From table 8.5 it is observed that the hydro units generate the maximum possible amount of energy as these are base loaded in this case.

Table 8.6 shows that the EL unit occupies the 16th loading order position and exhausts all of its assigned energy by trimming the 15th demand energy unit of the same table. From table 8.6(a) it is found that if hydro unit is loaded in 16th position without any energy restriction then it generates 38.1859 Gwh and 15th unit generates 69.4722 Gwh. But to exhaust all the assigned energy, the increased amount of energy (40.0 - 38.1859) = 1.8141 Gwh must be supplied by the hydro unit by trimming the same energy from the preceding demand energy unit and this conforms with the results given in table 8.6(a).

Comparing the results of tables 8.5 and 8.6 it is observed that the units from 1st to 5th and 17th to last loading order positions and the two 400 Mw units generate the same amount of energy in both cases. However, the energy generation by the units loaded from 8th to 16th loading order positions are different in the two tables. Since one of the hydro unit is considered as energy limited unit and it occupies 16th position instead of 6th in table 8.6 the ELDCs evolved after convolution of 5th unit is different and the difference is maintained before the convolution of 16th unit. Therefore, it is natural that the units from 6th to 16th loading order positions will generate different amount of energy. However, the two 400 Mw units occupy the base loading positions in both cases and as a result their energy generations do not change. Again, the ELDCs after convolution of 16th unit are same in both cases and units below 16th loading order positions produce the same amount of energy in both cases.

The competing unit should occupy the adjacent positions in the loading order and tables 8.7 and 8.8 confirm this. From tables 8.6, 8.7, and 8.8 it is found that in all cases the energy limited units deliver their full assigned energies.

In table 8.9, it is observed that the LOLPs, total expected energy generation and expected energies not served in all cases are same. However, increase in total fuel cost is observed in table 8.9 for increased number of energy limited units and also the CPU time increases with the increased number of EL units.

The LOLP as well as the expected energy not served are evaluated from the final distribution and the final distributions in all cases are same since the total number of units with their FORs do not change although the number of EL units changes.

The total expected energy generation also depends on the distribution. In these cases, only for few loading order position the distribution is not similar. However, it has been shown in Appendix B that for the same units the total generation does not change although the energy generation by the individual unit changes for changed loading order position.

The reason of changing fuel cost for different cases is evident from the energy generations by the individual units which changes for many units for different number of EL units. Again recall that the average incremental cost of different units are different for most of the units.

The EL unit finds its position in the loading order using the trial-error approach so that it can generate its assigned in that position. Therefore, it is obvious that for the increased number of EL units the computational requirement increases.

Bangladesh Power System

Comparing the results of tables 8.10 and 8.11 it is observed that as the hydro unit became energy limited it is loaded at 7th loading order position unlike the base loading position of table 8.10.

For multistate approach the important observation from table 8.12 is that the expected energy generation of multistate hydro unit is almost equal to the assigned energy of the unit. Recall that the amount of assigned energy is determined from the same water head data. However, if the multistate model were developed from a large number of samples generated over the years the difference would not be prominent.

From table 8.13 it is observed that LOLP, expected energy generation and (ENS) obtained for multistate simulation of hydro unit are higher compared to that obtained with energy limited representation of hydro unit. It is also observed that the total expected fuel cost increases with multistate model.

As simulation complexity decreases with multistate approach it is observed from table 8.13, CPU time needed for this approach is lesser compared to that of energy limited approach. This decrease of simulation complexity will be evident if someone looks at the flow chart given in section 7.5.

9.2 CONCLUSIONS

In generation expansion planning process, the simulation of energy limited hydro units is critical since the optimal scheduling is obtained only when these units can discharge their assigned energies in their selected loading positions. A methodology is developed in this thesis to simulate multi-hydro energy limited units. This thesis also develops a novel approach for modeling energy limited hydro unit by incorporating the randomness in the availability of the water head. The following conclusions are made from this research:

1) The developed methodology for simulating the energy limited hydro unit is capable of handling any number of competing or non-competing energy limited units. The methodology is tested by applying to a system and it provides accurate result.

2) The developed multistate model of an energy limited hydro unit accurately incorporates the randomness of water head. The developed model is also applied to a realistic system which shows that for the same data the results are similar to that of the conventional approach. However, the application of multistate approach decreases the simulation complexity.

9.3 RECOMMENDATIONS FOR FURTHER WORK

In this thesis two power systems: IEEE-RTS and Bangladesh power system are evaluated using the developed methodologies for energy limited hydro units. For more realistic analysis of the above two systems multiblock loading of generating units as well as multistate representation of units may be taken into consideration. Methodology for simulating energy limited units may be extended to include the evaluation of interconnected systems having energy limited hydro units. For Bangladesh power system, simulation may be carried out using multistate approach with representing each hydro unit of BPS by its own multistate model. For more realistic generation expansion planning, the forecasted demand may be used in the simulation.

APPENDIX A

Peak Shaving Equivalence

That the peak shaving method and loading order placement are equivalent can be proven with the aid of the two identical load curves shown in figure A.1. In figure A.1(b) the position of the energy limited unit of capacity H is adjusted under the load curve to exactly exhausts its assigned energy.

This divides the loading order of the remaining units into two groups, 'a' and 'b', with the group 'a' supplying energy depicted by A and group 'b' supplying energy depicted by B under the load curve. In figure A.1(a) let the load curve be shifted to the left by the capacity of the energy limited unit, H, to form the dashed line between areas B and C. Let this line be terminated by a vertical line from the capacity value equal to the of loading order 'a'. Thus, area A is congruent with area A since both are bounded by the load curve, the x and y axes and a vertical line corresponding to the capacity value of loading order 'a'. Now note that area B is congruent to area B since the dashed portion is a horizontal linear translation of the load curve and both B and B have the same base. Thus, the units in loading order 'b' see the same load in both cases. Since the load curves are identical, and areas A and A, B and B are congruent, then the energy depicted by C must be exactly equal to that depicted by C and we have proven that system operation is identical.

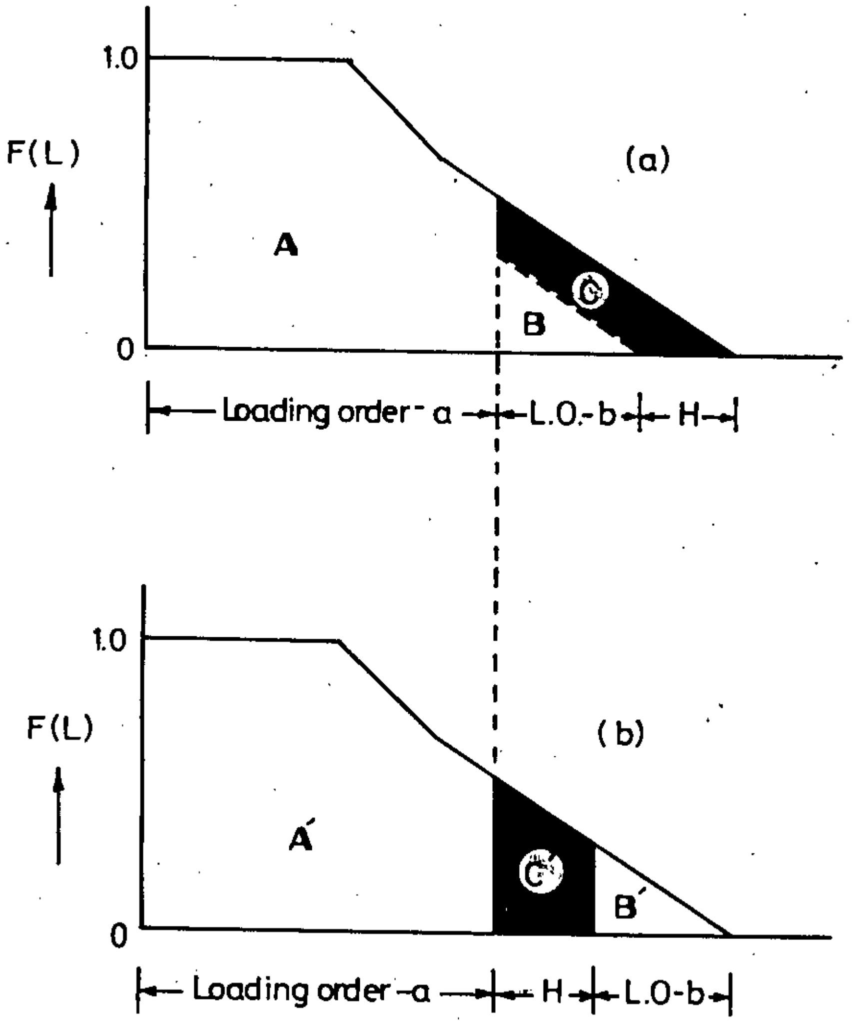


Figure-A.1 Proof that placing energy limited unit in loading order at the left most limit of peak shaving operation produces identical loading on other units and exactly exhausts assigned energy.

APPENDIX B

Equivalent Load Independent of convolution order

The formula for convolving the effects of the random forced outages of a generating unit is

$$G(L_e) = F(L_e)p + F(L_e - C)q \qquad \ldots\ldots(B.1)$$

where

L_e = Equivalent load.

$F(L_e)$ = Equivalent load curve excluding the random forced outage effects of the unit.

$G(L_e)$ = Equivalent load curve including the random forced outage effects of the unit.

p = Availability of the unit.

q = Forced outage rate of the unit
= $1- p$

C = Capacity (Mw) of the unit.

Consider two units denoted as units 1 and 2 respectively. Let the capacity and availability of units 1 as C_1 and p_1, respectively. Similarly, consider the capacity and availability of unit 2 as C_2 and p_2, respectively. Let $F(L_e)$ denote the equivalent load curve which does not include the random forced outage effects of either of the units. Let $H(L_e)$ denote the equivalent load curve which includes the random forced outage effects of both units.

$H(L_e)$ can be obtained by the sequential application of equation (B.1) by first adding the random forced outage effects of unit 1, followed by the addition of the random forced outage effects of unit 2 as follows:

$$F_1(L_e) = F(L_e)p_1 + F(L_e - C_1)q_1 \qquad \ldots\ldots(B.2)$$

$$H(L_e) = F_1(L_e)p_2 + F_1(L_e - C_2)q_2 \qquad \ldots\ldots(B.3)$$

where

$F_1(L_e)$ = The equivalent load curve which includes the random forced outage effects of unit 1, but not unit 2.

Then by equations (B.2) and (B.3):

$$\begin{aligned} H(L_e) &= p_2\{F(L_e)p_1 + F(L_e - C_1)q_1\} \\ &\quad + q_2\{F(L_e - C_2)p_1 + F(L_e - C_1 - C_2)q_1\} \\ &= p_1p_2F(L_e) + p_2q_1F(L_e - C_1) + p_1q_2F(L_e - C_2) \\ &\quad + q_1q_2F(L_e - C_1 - C_2) \qquad \text{......(B.4)} \end{aligned}$$

Alternately, $H(L_e)$ can be sequentially obtained by first adding the random forced outage effects of unit 2 followed by the addition of the random forced outage effects of unit 1 as follows:

$$F_2(L_e) = F(L_e)p_2 + F(L_e - C_2)q_2 \qquad \text{......(B.5)}$$

$$H(L_e) = F_2(L_e)p_1 + F_2(L_e - C_1)q_1 \qquad \text{......(B.6)}$$

where

$F_2(L_e)$ = The equivalent load curve which includes the random forced outage effects of unit 2, but not unit 1.

Then by equations (B.5) and (B.6)

$$\begin{aligned} H(L_e) &= p_1\{F(L_e)p_2 + F(L_e - C_2)q_2\} \\ &\quad + q_1\{F(L_e - C_1)p_2 + F(L_e - C_1 - C_2)q_2\} \\ &= p_1p_2F(L_e) + p_1q_2F(L_e - C_2) + p_2q_1F(L_e - C_1) \\ &\quad + q_1q_2F(L_e - C_1 - C_2) \qquad \text{......(B.7)} \end{aligned}$$

Because equations (B.4) and (B.7) are the same, it follows that equivalent load curves are unaffected by the order in which the effects of random forced outages of generating units are added. Note that no implicit assumptions are made regarding the relative positions of the units in the loading order.

The equivalent load curve can represent portions of units i.e. derated states, multiblock representation etc.. It follows, then that the invariance of equivalent load with to convolution order applies equally well in systems which include generating unit partial outages and multiblock loading of generating units.

APPENDIX C

Generation Data

Table C.1: Generation Data for BPS

Name of power station	Type of fuel	No. of units	Capacity (Mw)	FOR	Average incre. fuel cost(Tk./Kwh
Karnafuli Hydro	Hydro	1	50	0.01	0.00
		2	46	0.01	0.00
Ashuganj steam turbine	Gas	2	65	0.10	0.14
Siddhirganj steam turbine	Gas	1	50	0.10	0.15
		3	10	0.15	0.23
Chittagong steam turbine	Gas	1	60	0.10	0.16
Ghorasal steam turbine	Gas	2	55	0.10	0.16
Ashuganj combined cycle	Gas	1(GT)	55	0.19	0.16
		1(ST)	30	0.19	0.16
Chittagong gas turbine	Gas	2	5	0.18	0.28
Khulna steam turbine	F. oil	1	110	0.10	1.57
		1	60	0.10	1.79
		2	5	0.15	3.32
Khulna gas turbine(Barge)	SKO	2	25	0.18	2.62
Barisal gas turbine	HSD	1	20	0.15	3.01
Bheramara gas turbine	HSD	3	20	0.18	3.24
Small Diesel stations	LDO/ HSD	1	5	0.12	1.93
		1	5	0.12	2.00
		1	5	0.12	2.20
		1	5	0.12	2.35
		1	5	0.12	2.49

APPENDIX D

Table D.1: Hourly demand (Mw) of BPS of August, 1985

DATE	TIME	1:0	2:0	3:0	4:0	5:0	6:0	7:0	8:0	9:0	10:0	11:0	12:0
1	am	433.11	411.53	400.80	392.92	400.52	439.61	501.01	521.65	542.31	428.80	571.50	560.65
	pm	513.57	453.00	440.95	460.45	490.19	531.55	704.73	722.15	667.85	677.53	555.52	452.58
2	am	444.10	403.88	393.07	381.43	375.01	378.81	404.02	512.54	407.67	398.12	426.21	415.18
	pm	365.38	338.64	324.98	352.81	390.48	452.24	645.84	673.07	643.64	600.59	521.35	451.53
3	am	405.51	379.81	370.15	344.53	354.11	392.89	467.02	477.18	505.61	503.55	553.18	554.04
	pm	516.35	478.81	476.17	491.14	517.06	576.79	726.41	734.28	723.15	723.15	571.44	494.18
4	am	551.70	535.10	411.83	408.67	410.45	439.35	530.31	510.03	546.98	549.94	577.13	562.01
	pm	525.40	485.63	479.25	486.71	519.83	555.49	473.21	729.60	715.91	652.37	570.22	483.69
5	am	453.11	432.14	420.45	405.64	410.71	439.97	514.68	529.48	546.87	554.08	565.72	558.00
	pm	515.97	483.82	475.90	498.21	519.05	568.89	720.29	765.05	738.41	654.54	573.30	514.06
6	am	450.08	422.79	410.92	319.56	400.29	432.56	498.74	518.39	528.39	537.99	567.67	557.82
	pm	525.60	502.26	459.31	475.41	514.59	564.73	736.06	756.51	706.00	595.02	529.49	515.92
7	am	439.39	414.21	391.28	385.57	400.75	419.23	488.74	498.86	523.55	540.38	558.31	554.36
	pm	515.66	481.97	547.14	480.75	512.83	600.37	678.81	712.50	655.65	616.73	546.81	431.31
8	am	431.17	410.50	383.49	394.23	395.19	435.96	504.05	510.10	552.63	554.27	561.82	561.21
	pm	516.29	452.35	486.69	492.17	531.14	567.50	726.81	733.98	699.93	647.77	538.34	480.83
9	am	426.52	408.71	403.24	394.22	374.18	389.82	440.79	443.90	421.20	423.73	430.89	428.15
	pm	382.13	364.88	363.42	392.24	416.84	485.74	640.42	647.84	641.20	586.06	528.50	484.18
10	am	431.26	408.42	399.13	383.52	379.20	428.80	510.35	533.52	543.34	562.61	584.71	571.72
	pm	531.81	479.98	503.73	496.77	540.21	563.67	735.12	726.05	687.75	650.34	571.68	495.24
11	am	451.07	426.05	418.78	415.73	422.16	438.47	509.56	520.78	537.39	568.80	566.90	574.68
	pm	520.60	496.88	477.94	488.68	525.44	479.50	727.75	720.50	717.38	653.05	587.28	511.95
12	am	461.66	442.62	430.73	417.34	425.65	463.92	528.94	550.49	578.53	574.03	658.97	578.54
	pm	543.13	506.44	498.07	485.03	480.61	589.45	716.47	753.84	706.47	639.68	560.31	516.91
13	am	434.41	414.29	402.03	403.14	406.30	439.39	466.53	513.38	545.53	571.28	578.86	578.53
	pm	544.88	515.33	507.74	511.44	552.76	600.41	713.61	719.15	679.53	674.16	587.82	518.88
14	am	461.46	439.05	437.75	414.23	413.71	441.28	510.34	533.82	528.45	564.25	573.52	559.38
	pm	525.99	489.07	492.01	493.31	535.47	547.06	679.50	706.91	689.39	665.48	575.20	511.39
15	am	456.85	442.84	429.66	415.88	426.76	452.77	529.68	533.04	569.81	517.52	593.66	590.33
	pm	542.45	491.56	491.98	490.47	527.88	583.33	722.66	703.00	710.04	680.75	572.91	521.67
16	am	479.90	456.33	434.84	419.24	406.87	399.68	441.20	448.22	406.58	410.72	409.62	415.34
	pm	377.89	354.66	359.07	379.83	422.98	469.24	622.55	623.09	614.87	601.30	517.70	473.48
17	am	440.61	422.69	417.56	401.73	400.37	432.39	547.91	528.13	550.37	564.47	582.20	568.88
	pm	535.38	490.15	503.25	512.74	553.36	601.65	617.82	627.72	622.09	626.39	564.39	516.66
18	am	392.84	373.93	361.50	353.77	365.72	390.70	532.54	544.96	554.98	568.99	588.04	561.27
	pm	531.19	467.95	487.17	486.88	525.93	568.65	655.46	660.64	679.30	646.42	569.23	498.57
19	am	478.52	452.19	428.43	420.78	437.77	450.46	526.48	557.00	560.62	574.14	581.94	576.66
	pm	548.33	586.29	429.51	492.97	522.35	596.08	675.98	659.40	652.88	641.62	568.36	485.53
20	am	448.45	430.58	503.87	409.66	417.38	442.05	515.20	536.52	545.79	553.07	586.44	571.66
	pm	540.47	479.83	489.94	506.18	539.20	589.48	645.05	662.93	649.26	546.27	498.69	498.35
21	am	419.06	426.17	415.76	414.33	417.74	435.54	527.46	541.63	556.58	555.50	557.24	558.02
	pm	549.39	493.08	480.01	503.27	528.37	586.65	575.97	609.03	678.52	633.04	553.69	478.48
22	am	456.71	432.13	422.00	411.02	414.37	441.56	432.69	441.37	550.83	558.20	599.83	593.50
	pm	560.49	514.53	508.52	505.99	546.91	600.61	731.90	728.99	703.27	661.34	558.72	496.66
23	am	447.73	429.77	413.73	408.76	420.89	386.38	459.45	469.48	469.65	472.70	474.18	450.80
	pm	405.00	390.65	394.65	425.97	485.31	570.22	696.47	703.65	637.47	602.76	548.82	489.67
24	am	463.48	439.95	422.54	410.02	408.78	428.15	490.00	524.32	534.39	547.87	578.10	561.96
	pm	532.24	489.90	467.20	479.60	525.55	593.68	606.06	700.94	697.40	628.87	528.69	460.51
25	am	451.14	431.56	408.05	396.26	397.05	407.75	461.33	494.39	516.49	520.56	544.46	529.92
	pm	484.92	451.42	440.00	446.12	476.10	573.03	688.02	675.11	635.64	593.63	518.61	453.20
26	am	412.34	393.54	378.67	361.36	364.62	366.42	404.02	414.77	412.69	403.97	433.15	437.47
	pm	421.97	383.16	373.93	375.66	412.16	468.21	584.87	587.50	584.60	577.70	499.57	444.69
27	am	400.31	380.32	359.93	350.77	358.45	365.80	371.41	333.65	303.59	290.21	287.09	287.30
	pm	294.66	293.73	317.25	334.89	352.84	415.49	579.02	586.89	601.00	531.25	554.50	395.93
28	am	366.88	345.08	336.51	332.24	326.81	321.95	348.84	365.35	344.95	338.07	342.08	357.84
	pm	348.84	324.09	315.09	317.50	344.22	415.56	608.80	596.41	553.44	520.19	445.88	416.80
29	am	381.78	347.38	346.24	333.96	390.56	322.65	352.72	375.30	367.80	373.03	379.40	396.67
	pm	391.94	341.12	323.61	323.66	367.78	423.20	642.26	604.42	572.11	526.90	447.96	393.96
30	am	373.75	357.70	347.34	340.09	344.39	347.27	362.24	372.65	362.29	370.89	387.33	366.53
	pm	340.81	307.47	293.98	311.55	363.77	473.10	656.05	657.38	603.14	545.77	468.83	406.68
31	am	373.37	365.09	339.62	335.66	342.05	356.18	407.50	435.12	438.87	458.04	478.07	483.21
	pm	453.96	425.94	405.97	411.24	446.55	514.82	707.62	706.94	631.83	575.62	485.84	403.72

APPENDIX E

Table E.1: Hourly capacity (Mw) available from hydrostetion of BPS of August, 1985

DATE	TIME	1:0	2:0	3:0	4:0	5:0	6:0	7:0	8:0	9:0	10:0	11:0	12:0
1	AM	142	142	142	142	142	142	142	142	142	142	142	142
	PM	142	142	139	139	138	138	138	139	141	141	142	142
2	AM	142	142	142	142	139	142	127	92	92	92	92	92
	PM	92	122	90	142	142	142	142	142	142	142	142	142
3	AM	142	142	116	113	120	142	142	142	142	142	142	142
	PM	142	142	142	142	142	142	142	142	142	142	142	142
4	AM	142	142	142	142	142	142	142	142	142	142	142	142
	PM	142	142	142	142	142	142	142	142	142	142	142	142
5	AM	142	142	142	142	142	142	142	142	142	142	142	142
	PM	142	142	142	142	142	142	142	142	142	142	142	142
6	AM	142	142	142	142	142	142	142	142	142	142	142	142
	PM	142	142	142	142	142	142	142	142	142	142	142	142
7	AM	142	130	121	110	116	142	142	142	142	142	142	142
	PM	142	142	142	142	142	142	142	142	142	142	142	142
8	AM	142	142	142	142	142	142	142	142	142	142	142	142
	PM	142	114	97	95	142	142	142	142	142	142	142	142
9	AM	142	142	142	142	142	142	96	96	96	96	96	96
	PM	96	96	96	96	110	142	142	142	142	142	142	142
10	AM	120	130	106	106	101	123	142	142	142	142	142	142
	PM	142	114	97	95	142	142	142	142	142	142	142	142
11	AM	142	142	142	142	142	142	142	142	142	142	142	142
	PM	142	142	142	142	142	142	142	142	142	142	142	142
12	AM	142	142	142	142	142	142	142	142	142	142	142	142
	PM	142	142	142	142	142	142	142	142	142	142	142	142
13	AM	142	142	142	142	142	142	142	142	142	142	142	142
	PM	142	142	142	142	142	142	142	142	142	142	142	142
14	AM	142	142	142	142	142	142	142	142	142	142	142	142
	PM	142	142	142	142	142	142	142	142	142	142	142	142
15	AM	142	142	142	142	142	142	142	142	142	142	142	142
	PM	142	142	142	142	142	142	142	142	142	142	142	142
16	AM	142	142	142	142	142	142	142	142	142	142	142	142
	PM	142	142	142	142	142	142	142	142	142	142	142	142
17	AM	142	142	142	142	142	142	142	142	136	137	137	138
	PM	138	142	142	142	132	137	138	142	142	142	142	142
18	AM	142	142	142	142	142	142	142	142	142	142	142	142
	PM	142	142	142	142	142	142	142	142	142	142	142	132
19	AM	127	98	85	82	90	100	142	142	130	142	142	142
	PM	142	142	142	142	142	142	142	142	142	142	142	142
20	AM	113	79	63	69	80	94	142	142	142	142	142	142
	PM	142	142	142	142	142	142	142	142	142	142	142	142
21	AM	142	137	110	110	120	142	142	142	142	142	142	142
	PM	142	142	142	142	142	142	142	142	142	142	142	40
22	AM	30	30	30	30	30	30	58	75	80	102	124	120
	PM	117	62	60	70	110	123	142	142	142	116	96	63
23	AM	37	35	35	35	35	30	46	25	27	27	27	44
	PM	20	20	20	20	26	65	82	96	96	96	96	86
24	AM	35	35	35	35	35	37	45	78	96	110	126	134
	PM	142	96	66	57	91	142	142	142	142	142	142	142
25	AM	55	54	58	56	56	56	110	142	142	142	142	142
	PM	135	57	56	55	55	110	142	142	142	142	142	65
26	AM	55	55	55	55	90	100	96	98	94	70	129	109
	PM	103	56	55	55	90	104	142	142	142	142	142	142
27	AM	55	55	55	55	55	85	73	55	55	55	55	55
	PM	55	55	55	55	56	142	142	142	142	142	115	80
28	AM	55	55	55	55	55	55	55	55	55	55	55	55
	PM	55	55	55	55	55	55	142	142	142	142	107	38
29	AM	30	30	30	30	30	55	55	55	55	55	57	65
	PM	55	55	55	55	55	55	142	142	142	142	102	42
30	AM	30	30	30	30	30	30	92	55	34	40	37	30
	PM	30	30	30	30	30	70	142	142	142	120	55	50
31	AM	40	40	40	40	40	40	40	40	40	40	90	90
	PM	80	40	40	40	40	40	70	90	96	96	96	30

APPENDIX F

COMPUTER PROGRAM

```
C     ****************************************************************
C     1. ARRANGE THE BLOCKS IN THE INCREASING ORDER OF INC. COST.
C        NOTE: 2ND BLOCK OF ANY UNIT SHOULD BE AFTER THE 1ST EVEN THE
C        INC. COST OF 2ND IS LOWEER THAN THE 1ST .SAME FOR 3RD & 2ND.
C    2. ARRANGE THE HYDRO UNITS ACCORDING TO DECREASED NO HOURS USED
C    3. READ SERIAL NO AND TYPE OF EACH UNIT.
C        A. TYPE 1 = SINGLE BLOCK & BINARY STATE UNIT
C        B. TYPE 2 = MULTISTAE UNIT & SINGLE BLOCK
C        C. TYPE 3 = MULTIPLE BLOCKS
C    4. TO USE MORE THAN 5 STATES OF UNIT CHANGE THE DIMENSION
C       OF SFOR,SCAP
C    5. FOR MORE THAN TWO ENERGY LIMITED UNITS COMPETING FOR THE SAME
C       POSITION ; PUT ONE THERMAL AFTER EVERY TWO ENERGY LIMITED
C       UNITS IN THE INPUT DATA AND PUT THESE EL UNITS LOWER THAN
C       THE ACTUAL POSITION. FOR ODD NUMBER OF EL UNITS PUT IST
C       UNIT SOMEWHERE ABOVE THE ACTUAL POSITION.
C    6. TO PUT MORE THAN 5 HYDRO UNITS ONE AFTER ANOTHER IN THE INPUT
C       DATA CHANGE THE DIMENSION OF C1,Q,A,NNSL,NUNT
C    7. TO USE 1 MW BLOCK SIZE CHANGE THE DIMENSION OF AMOM,BMOM,CMOM
C    8. TO DECREASE THE CPU TIME GUESS THE POSITION OF HYDRO UNIT
C       (NON COMPETING UNITS) (BUT DO NOT PUT BELOW THE ACTUAL POSITION)
C    9. IN ONE FORM OF THE OUTPUT ONLY THE INCREMENTAL COST OF LAST
C       BLOCK OF EACH UNIT IS PRINTED.
C    ******************************************************************
C
       IMPLICIT REAL*8 (A-H,O-Z)
       COMMON /ONE/ HDIST(3000),HYDLIM,PKLOAD,NH
       COMMON /TWO/ AMOM,CMOM,SUMOM,BLOCK,DCAPP,NBLK,K,IDEL
       DIMENSION AMOM(2,3420),BMOM(2,3420),CMOM(2,3420),SUMOM(2),
     + UNENGY(65),EENGY(65),EFUEL(65),NTYP(65),CAP(65),FOR(65),AIC(65)
     + ,SFOR(65,15),SCAP(65,15),NST(65),SBMOM(2,3420),NSLG(65),NBC(65)
     + ,DCAP(65),TCAP(40),TEENGY(40),TEFUEL(40),HYDLIM(15)
     + ,C1(15),Q(15),A(15),NNSL(15),NUNT(15)
C
       OPEN(UNIT=8,FILE='IN',STATUS='OLD')
       OPEN(UNIT=9,FILE='OUT',STATUS='NEW')
       BLOCK=10.
       DCAPP=0.
       ENGGEN=0.
```

```
      FUELCT=0.
      TOTEN=0.
      TOTCAP=0.
      XCAP=0.
      N=0
      M=0
      K=1
      LIM=0
      NHB=0
      WRITE(9,7003)
C
      CALL LOAD
C     READ 3120, (HDIST(I),I=1,NH)
C3120 FORMAT(8F8.2)
C
      BSLOAD=HDIST(1)
      PKLOAD=HDIST(1)
C
C    READ DATA OF THE GENERATING UNITS
C
      READ (8,3000)NBB,NOUNIT
      DO 14 I=1,NOUNIT
      TCAP(I)=0.
      TEENGY(I)=0.
      TEFUEL(I)=0.
      NBC(I)=0
 14   DCAP(I)=0.
      DO 105 NU=1,NBB
      READ(8,1310)NSLG(NU), NTYP(NU),FOR(NU),CAP(NU),AIC(NU)
      WRITE(9,7000)NSLG(NU), FOR(NU),CAP(NU),AIC(NU),NTYP(NU)
      TOTCAP=TOTCAP+CAP(NU)
      IF(NTYP(NU).EQ.2) GO TO 110
      GO TO 105
 110  READ(8,300)NST(NU)
      NS=NST(NU)
      READ(8,301)(SFOR(NU,I),SCAP(NU,I),I=1,NS)
      WRITE(9,7001) (SFOR(NU,I),SCAP(NU,I),I=1,NS)
 105  CONTINUE
      NBLK=TOTCAP/BLOCK+1
      WRITE(9,8005)
C
C     CALCULATION OF MOMENTS
C
      DO 115 K1=1,2
      DO 115 K2=1,NBLK
 115  AMOM(K1,K2)=0.0
      DO 120 I=1,NH
      NBL=HDIST(I)/BLOCK+0.999999
```

```
      AMOM(1,NBL)=AMOM(1,NBL)+1.
      AMOM(2,NBL)=AMOM(2,NBL)+HDIST(I)
      IF(HDIST(I).LT.BSLOAD) BSLOAD=HDIST(I)
      IF(HDIST(I).GT.PKLOAD) PKLOAD=HDIST(I)
      TOTEN=TOTEN+HDIST(I)
 120  CONTINUE
      UNENGY(1)=TOTEN
C
C     CONVOLUTION OF GENERATING UNITS
C
      DO 250  J=1,NBB
 200  XCAP=XCAP+CAP(J)
      IF(NTYP(J).EQ.2) GO TO 1110
      IF(NTYP(J).EQ.3) GO TO 12
 15   N=CAP(J)/BLOCK
      M=M+N
 16   CONTINUE
C
      CALL CONV(CAP,AIC,FOR,M,N,J)
C
      GO TO 710
C
 12   CALL DECONV(NSLG,DCAP,CAP,NBC,FOR,NH,N,M,J,NHB)
      GO TO 16
C
 1110 CALL STATE (NST,J,SCAP,SFOR,M,AIC)
C
 710  UNENGY(J+1)=SUMOM(2)-XCAP*SUMOM(1)
      IF(AIC(J).GT.0.0) GO TO 240
      IF(NTYP(J).EQ.2) GO TO 240
      IF((UNENGY(J)-UNENGY(J+1)).LE.HYDLIM(LIM+1)) GO TO 235
      XCAP=XCAP-CAP(J)
C
      LMM=1
 1500 IF(AIC(J+LMM)) 1300,1300,1400
 1300 LMM=LMM+1
      GO TO 1500
 1400 CONTINUE
      DO 1501 I=1,LMM
      JH=J+I-1
      C1(I)=CAP(JH)
```

```
      Q(I)=FOR(JH)
      A(I)=AIC(JH)
      NNSL(I)=NSLG(JH)
 1501 NUNT(I)=NTYP(JH)
      CAP(J)=CAP(J+LMM)
      FOR(J)=FOR(J+LMM)
      AIC(J)=AIC(J+LMM)
      NSLG(J)=NSLG(J+LMM)
      NTYP(J)=NTYP(J+LMM)
      DO 1601 I=1,LMM
      CAP(J+I)=C1(I)
      FOR(J+I)=Q(I)
      AIC(J+I)=A(I)
      NSLG(J+I)=NNSL(I)
 1601 NTYP(J+I)=NUNT(I)
      DO 233 I1=1,2
      DO 233 I2=K,NBLK
 233  AMOM(I1,I2)=CMOM(I1,I2)
      M=M-N
      GO TO 200
 235  LIM=LIM+1
      IF(AIC(J-1).LE.0.0) GO TO 2350
      UNENGY(J)=HYDLIM(LIM)+UNENGY(J+1)
      GO TO 240
C
C     MORE THAN ONE HYDRO UNITS (ENERGY LIMITED) COMPETING FOR THE
C     SAME POSITION
C
 2350 JHYD=2
      NSHIFT=0
C
C  COUNT THE NUMBER OF ENERGY LIMITED(EL) UNITS COMPETING FOR THE SAME P
C
 1200 CONTINUE
      IF(AIC(J-JHYD).LE.0.0) GO TO 1100
      GO TO 4300
 1100 JHYD=JHYD+1
      GO TO 1200
 4300 NDECON=JHYD+1
C
C     DECONVOLVE EL UNITS & ONE THERMAL UNIT ABOVE IT
```

```
C
      DO 5400 I=1,NDECON
      NJ=J+1-I-NSHIFT
      NHB=1
      CALL DECONV(NSLG,DCAP,CAP,NBC,FOR,NH,N,M,NJ,NHB)
      XCAP=XCAP-CAP(NJ)
      JJ=NSLG(NJ)
      IF(NBC(JJ).GE.1) GO TO 7400
      DCAP(JJ)=0.
      GO TO 5400
C
C     CONVOLVE THE LOWER BLOCKS(THAN THE CURRENT BLOCK) OF THERMAL UNIT
C
 7400 CAPP=CAP(NJ)
      DCAP(JJ)=DCAP(JJ)-CAP(NJ)
      CAP(NJ)=DCAP(JJ)
      N=CAP(NJ)/BLOCK
      M=M+N
      CALL CONV(CAP,AIC,FOR,M,N,NJ)
      CAP(NJ)=CAPP
 5400 CONTINUE
C
      HASE=0.
      HSUME=0.
      NCONV=JHYD
C
C   CONV. THE EL UNITS & COMPUTE TOTAL ENG. GENERATED IN THIS POSITION
C
      DO 150 I=1,NCONV
      NJ=J-JHYD+I-NSHIFT
      XCAP=XCAP+CAP(NJ)
      N=CAP(NJ)/BLOCK
      M=M+N
      CALL CONV(CAP,AIC,FOR,M,N,NJ)
      UNENGY(NJ)=SUMOM(2)-XCAP*SUMOM(1)
      HASE=HASE+HYDLIM(LIM-JHYD+I)
 150  HSUME=HSUME+UNENGY(NJ-1)-UNENGY(NJ)
      IF(HSUME.GE.HASE) GO TO 1600
      GO TO 1800
 1600 CONTINUE
C
```

```
C       OFF-LOAD THERMAL UNIT(OR BLOCK)
C
        II=0
        DO 1700 I=1,JHYD
        K=J-I+1-NSHIFT
        UNENGY(K)=UNENGY(K+1)+HYDLIM(LIM-II)
 1700   II=II+1
C
C CONVOLVE BACK THERMAL BLOCK(CURRENT) BEFORE CONV. MUST DECON THE LOWER
C
        NJ=J-JHYD-NSHIFT
        XCAP=XCAP+CAP(NJ)
        CALL DECONV(NSLG,DCAP,CAP,NBC,FOR,NH,N,M,NJ,NHB)
C3100   DCAPP=0.
        CALL CONV(CAP,AIC,FOR,M,N,NJ)
        IF(NSHIFT.EQ.0) GO TO 8400
C
C       CONVOLVE THE REMAINING UNIT UPTO J
C
        DO 2701 I=1,NSHIFT
        NJ=J-NSHIFT+I
        XCAP=XCAP+CAP(NJ)
        CALL DECONV(NSLG,DCAP,CAP,NBC,FOR,NH,N,M,NJ,NHB)
C       DCAPP=0.
        CALL CONV(CAP,AIC,FOR,M,N,NJ)
 2701   UNENGY(NJ+1)=SUMOM(2)-XCAP*SUMOM(1)
 8400   CONTINUE
        GO TO 240
 1800   CONTINUE
C
C      PUSH THE EL UNITS IN THE UPPER POSION IN MERIT ORDER
C
        DO 51 I=1,JHYD
        JH=J-I+1-NSHIFT
        C1(I)=CAP(JH)
        Q(I)=FOR(JH)
        A(I)=AIC(JH)
        NNSL(I)=NSLG(JH)
 51     NUNT(I)=NTYP(JH)
        JH=J-NSHIFT
        JS=J-JHYD-NSHIFT
        CAP(JH)=CAP(JS)
        FOR(JH)=FOR(JS)
        AIC(JH)=AIC(JS)
```

```
      NSLG(JH)=NSLG(JS)
      NTYP(JH)=NTYP(JS)
      DO 1101 I=1,JHYD
      JS=J-I-NSHIFT
      CAP(JS)=C1(I)
      FOR(JS)=Q(I)
      AIC(JS)=A(I)
      NSLG(JS)=NNSL(I)
 1101 NTYP(JS)=NUNT(I)
      NSHIFT=NSHIFT+1
 3300 CONTINUE
C
C     CHECK-IS THERE ANY EL UNIT BEFORE THESE EL UNITS
C
      IF(AIC(J-JHYD-NSHIFT).LE.0.0) GO TO 2700
      GO TO 3700
 2700 JHYD=JHYD+1
      GO TO 3300
 3700 CONTINUE
      GO TO 4300
 240  CONTINUE
 250  CONTINUE
C
      ALOLP=AMOM(1,NBLK)*100./FLOAT(NH)
      ENNS=UNENGY(NBB+1)
C     PRINT 350
      WRITE(9,7005)
      DO 260 J=1,NBB
      EENGY(J)=UNENGY(J)-UNENGY(J+1)
      EFUEL(J)=EENGY(J)*AIC(J)
      IF(AIC(J).LT.1) EFUEL(J)=0.0
      WRITE(9,330)J,CAP(J),FOR(J),AIC(J),EENGY(J),EFUEL(J)
      ENGGEN=ENGGEN+EENGY(J)
      FUELCT=FUELCT+EFUEL(J)
C     KK=NSLG(J)
C     FOR(KK)=FOR(J)
C     AIC(KK)=AIC(J)
C     TCAP(KK)=TCAP(KK)+CAP(J)
C     TEENGY(KK)=TEENGY(KK)+EENGY(J)
```

```
C       TEFUEL(KK)=TEFUEL(KK)+EFUEL(J)
 260    CONTINUE
C       DO 2600 J=1,NOUNIT
C       IF(NBC(J).LE.1) NBC(J)=1
C2600   PRINT 330,NBC(J),TCAP(J),FOR(J),AIC(J),TEENGY(J),TEFUEL(J)
        BLNCE=TOTEN-ENGGEN-ENNS
        WRITE(9,340) PKLOAD,TOTEN,BSLOAD,ENNS,TOTCAP,ENGGEN,NH,BLNCE,
     + ALOLP,FUELCT
C
 8005   FORMAT(//,20X,'TYPE 1 = SINGLE BLOCK UNIT',/,20X,
     + 'TYPE 2 = MULTI STATE UNIT',/,20X,'TYPE 3 = MULTI BLOCK UNIT',/)
 7001   FORMAT(/,28X,F6.4,F9.0)
 300    FORMAT(I2)
 3000   FORMAT(2I3)
 301    FORMAT(10X,F10.0,5X,F10.0)
 340    FORMAT(6(/),9X,'PEAK LOAD =',F9.2,' (MW) ',30X,'E (DEMAND) =',F12
     1 .3,' (MWH )',//,9X,'BASE LOAD =',F9.2,' ( MW )',30X,'E (E N S) =
     2 ',F12.3,' (MWH) ',//,8X,'INST CAP. =',F9.2,'(MW)',28X,'E (GEN
     3 .ENGY) =',F12.3,'(MWH)',//,13X,'TIME =',I7,' (HOURS)',25X,
     4 'ENG. BALANCE =',F13.4,//,11X,'LOLP =',F9.6,' (% )',28X,
     5   'E (FUEL COST )=',F15.3,'( $)')
 330    FORMAT(/,15X,I3,5X,F9.0,5X,F6.4,5X,F7.3,6X,F12.3,5X,F15.3)
 1310   FORMAT(I2,I5,5X,F10.0,5X,F10.0,F10.0)
C350    FORMAT('1',40X,'OUTPUT',
C    + //,13X,'NO BLOCK',5X,'CAPACITY',4X,'F O R',5X,'INC. COST',6X,
C    + 'E (G. ENGY)',7X,'E (FUEL COST )',//,28X,
C    + '(MW)',17X,'($/MWH)',9X,'(MWH)',13X,'( $ )')
 7005   FORMAT(41X,'OUTPUT',
     + //,13X,'SL NO   ',5X,'CAPACITY',4X,'F O R',5X,'INC. COST',6X,
     + 'E (G. ENGY)',7X,'E (FUEL COST )',//,28X,
     + '(MW)',17X,'($/MWH)',9X,'(MWH)',13X,'( $ )')
 7000   FORMAT(/,15X,I3,5X,F9.2,5X,F6.1,5X,F7.3,6X,I5)
 7003   FORMAT(36X,'INPUT DATA',
     + //,10X,'MERIT ORDER',5X,'F O R',4X,'CAPACITY',5X,'INC. COST',6X,
     + 'TYPE',//,38X,'(MW)',7X,'($/MWH)')
        STOP
        END
C
        SUBROUTINE LOAD
        REAL*8 HDIST,HYDLIM,PKLOAD
        COMMON /ONE/ HDIST(3000),HYDLIM,PKLOAD,NH
        DIMENSION WEEK(52),DAY(7),HOUR(24),SHOUR(24),HYDLIM(15)
```

```
C
      OPEN(UNIT=8,FILE='IN',STATUS='OLD')
      OPEN(UNIT=9,FILE='OUT',STATUS='NEW')
      READ(8,300) NOWEEK,(HYDLIM(I),I=1,6)
      READ(8,405) (WEEK(I),I=1,NOWEEK)
      READ(8,405) (DAY(I),I=1,7)
      READ(8,405) (HOUR(I),I=1,24)
      READ(8,405) (SHOUR(I),I=1,24)
      DEMAND=0.0
C
C     CALCULATION OF THE HOURLY LOADS
C
      K1=1
      MM=1
      DO 307 J=1,NOWEEK
      DO 301 KK=K1,7
      DO 301 L=1,24
      IF(KK.GT.5) GO TO 3000
      HDIST(MM)=WEEK(J)*DAY(KK)*HOUR(L)*2850.
      MM=MM+1
      GO TO 303
 3000 HDIST(MM)=WEEK(J)*DAY(KK)*SHOUR(L)*2850.
      MM=MM+1
  303 IF(MM.GT.2184) GO TO 304
  301 CONTINUE
      K1=1
  307 CONTINUE
  304 NH=MM-1
C     DO 500 I=1,NH
C500  DEMAND=DEMAND+HDIST(I)
C     DEMAND=DEMAND/1000.
C     PRINT 501,DEMAND
C501  FORMAT(//,40X,'EXP.TOTAL ENERGY DEMAND= ',F9.3,' (GWHR)',//)
 405  FORMAT(12F6.0)
 300  FORMAT(I2,6F10.0)
      RETURN
      END
C
      SUBROUTINE CONV(CAP,AIC,FOR,M,N,J)
C     THIS SUBROUTINE CONVOLVE THE GENERATING UNIT
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /TWO/ AMOM,CMOM,SUMOM,BLOCK,DCAPP,NBLK,K,IDEL
      DIMENSION AMOM(2,3420),CMOM(2,3420),SUMOM(2),AIC(65),FOR(65)
```

```
     + ,CAP(65),BMOM(2,3420)
C
       DO 205 I1=1,2
       DO 205 I2=K,NBLK
 205   BMOM(I1,I2)=0.0
       DO 220 L=K,NBLK
       IF((L+N).GT.NBLK) GO TO 215
       BMOM(1,L+N)=AMOM(1,L)
       IF(AMOM(1,L).LE.0.0) GO TO 213
       BMOM(2,L+N)=AMOM(2,L)+CAP(J)*AMOM(1,L)
       GO TO 220
 213   BMOM(2,L+N)=AMOM(2,L)
       GO TO 220
 215   BMOM(1,NBLK)=BMOM(1,NBLK)+AMOM(1,L)
       BMOM(2,NBLK)=BMOM(2,NBLK)+AMOM(2,L)+CAP(J)*AMOM(1,L)
 220   CONTINUE
C      DO 6000 I=1,2
C6000  PRINT 910, (BMOM(I,II) ,II=1,NBLK)
       IDEL=M+1
       DO 230 I1=1,2
       DO 230 I2=K,NBLK
       IF(AIC(J).LE.0.0) CMOM(I1,I2)=AMOM(I1,I2)
       AMOM(I1,I2)=AMOM(I1,I2)*(1.-FOR(J))+BMOM(I1,I2)*FOR(J)
 230   CONTINUE
       DO 23 I1=1,2
       SUMOM(I1)=0.0
       DO 23 I2=IDEL,NBLK
       SUMOM(I1)=SUMOM(I1)+AMOM(I1,I2)
 23    CONTINUE
C      DO 65 I=1,2
C65    PRINT 910, (AMOM(I,II) ,II=1,NBLK)
       CAP(J)=CAP(J)-DCAPP
       DCAPP=0.0
       RETURN
       END
C
       SUBROUTINE DECONV(NSLG,DCAP,CAP,NBC,FOR,NH,N,M,J,NHB)
C      THIS SUBROUTINE DECONVOLVE THE GENERATING UNIT OR BLOCK
       IMPLICIT REAL*8 (A-H,O-Z)
       COMMON /TWO/ AMOM,CMOM,SUMOM,BLOCK,DCAPP,NBLK,K,IDEL
       DIMENSION AMOM(2,3420),CMOM(2,3420),SUMOM(2),NSLG(65),DCAP(65)
     + ,CAP(65),NBC(65),FOR(65)
```

```
C
      TMOM3=0.
      DO 80 I=1,NBLK
 80   TMOM3=TMOM3+AMOM(2,I)
C
      JJ=NSLG(J)
      IF(NHB.EQ.1) GO TO 30
      DCAP(JJ)=DCAP(JJ)+CAP(J)
      NBC(JJ)=NBC(JJ)+1
      IF(NBC(JJ).LE.1) GO TO 15
C
      GO TO 400
 30   DCAPP=DCAP(JJ)
      IF(DCAPP.LE.0.) DCAPP=CAP(J)
      M=M-DCAPP/BLOCK
      NBC(JJ)=NBC(JJ)-1
      IF(NBC(JJ).LE.0) NBC(JJ)=0
      GO TO 40
C
 400  DCAPP=DCAP(JJ)-CAP(J)
 40   CONTINUE
      II=DCAPP/BLOCK
      ML=II+1
      LL=NBLK-1
C
      PP=1.-FOR(J)
      DO 50 IM=1,2
      DO 50 I=1,II
 50   AMOM(IM,I)=AMOM(IM,I)/PP
      DO 60 I=ML,LL
      AMOM(1,I)=(AMOM(1,I)-FOR(J)*AMOM(1,I-II))/PP
 60   AMOM(2,I)=(AMOM(2,I)-FOR(J)*(AMOM(2,I-II)+DCAPP*
     + AMOM(1,I-II)))/PP
C
      TMOM1=0.
      TMOM2=0.
      DO 90 I=1,LL
      TMOM1=TMOM1+AMOM(1,I)
 90   TMOM2=TMOM2+AMOM(2,I)
```

```
      AMOM(1,NBLK)=NH-TMOM1
      AMOM(2,NBLK)=TMOM3-DCAPP*FOR(J)*NH-TMOM2
C     DO 166  IJ=1,2
C166  PRINT 910, (AMOM(IJ,IN) ,IN=1,NBLK)
      IF(NHB.EQ.1) DCAPP=0.
      IF(NHB.EQ.1) GO TO 151
      N=DCAP(JJ)/BLOCK
      M=M+CAP(J)/BLOCK
      CAP(J)=DCAP(JJ)
      GO TO 151
 15   N=CAP(J)/BLOCK
      M=M+N
 151  NHB=0
      RETURN
      END
C
      SUBROUTINE STATE (NST,J,SCAP,SFOR,M,AIC)
C     THIS SUBROUTINE CONVOLVE MULTI-STATE GENERATING UNIT
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /TWO/ AMOM,CMOM,SUMOM,BLOCK,DCAPP,NBLK,K,IDEL
      DIMENSION AMOM(2,3420),CMOM(2,3420),SUMOM(2),NST(65),SCAP(65,15)
     + ,SFOR(65,15),BMOM(2,3420),SBMOM(2,3420),AIC(65)
C
      NS=NST(J)
      NN=0
      DO 210 I1=1,2
      DO 210 I2=K,NBLK
 210  SBMOM(I1,I2)=0.0
      DO 310 II=1,NS
      N=SCAP(J,II)/BLOCK
      DO 2005 I1=1,2
      DO 2005 I2=K,NBLK
 2005 BMOM(I1,I2)=0.0
      DO 2200 L=K,NBLK
      IF((L+N).GT.NBLK) GO TO 2150
      BMOM(1,L+N)=AMOM(1,L)
      IF(AMOM(1,L).LE.0.0) GO TO 2130
      BMOM(2,L+N)=AMOM(2,L)+SCAP(J,II)*AMOM(1,L)
      GO TO 2200
 2130 BMOM(2,L+N)=AMOM(2,L)
      GO TO 2200
 2150 BMOM(1,NBLK)=BMOM(1,NBLK)+AMOM(1,L)
      BMOM(2,NBLK)=BMOM(2,NBLK)+AMOM(2,L)+SCAP(J,II)*AMOM(1,L)
```

```
 2200   CONTINUE
C       DO 650 IJ=1,2
C650    PRINT 910, (BMOM(IJ,IN) ,IN=1,NBLK)
        DO 410 I1=1,2
        DO 410 I2=K,NBLK
 410    SBMOM(I1,I2)=SBMOM(I1,I2)+BMOM(I1,I2)*SFOR(J,II)
        IF(N.GT.NN) NN=N
 310    CONTINUE
        PFOR=0.
        DO 510 JJ=1,NS
 510    PFOR=PFOR+SFOR(J,JJ)
        PP=1.-PFOR
        M=M+NN
        IDEL=M+1
        DO 2300 I1=1,2
        DO 2300 I2=K,NBLK
        IF(AIC(J).LE.0.0) CMOM(I1,I2)=AMOM(I1,I2)
        AMOM(I1,I2)=AMOM(I1,I2)*PP+SBMOM(I1,I2)
 2300   CONTINUE
        DO 13 I1=1,2
        SUMOM(I1)=0.0
        DO 13 I2=IDEL,NBLK
        SUMOM(I1)=SUMOM(I1)+AMOM(I1,I2)
 13     CONTINUE
C       DO 66  IJ=1,2
C66     PRINT 910, (AMOM(IJ,IN) ,IN=1,NBLK)
C910    FORMAT(//,10X,8F14.4,/)
        RETURN
        END
```

APPENDIX G

Mathematical Representation of Segmentation Method

Let X be the continuous random variable "mean load in an elementary time interval" (for example the "mean hourly load") and f(x) its PDF.

Let A>0 be a real number, hereafter the "segment size", S(i) the interval (i-segment)

$$S(i) = [(i-1).A, \; i.A], \quad i = 1,.....,M$$

and I(i,x) the indicator function of S(i) defined as

$$I(i,x) = 1 \quad \text{if } x \in S(i)$$

$$= 0 \quad \text{otherwise}$$

and let

$$P(i,X) = \mathrm{Prob}(X \in S(i)) = \int_{S(i)} f(x).dx$$

$$E(i,X) = E(X/X \in S(i)) = \int_{S(i)} x.f(x).dx \Big/ \int_{S(i)} f(x).dx$$

$$C(i,X) = E(i,X).P(i,X) = \int_{S(i)} x.f(x).dx$$

$$C(X) = \sum_{i=1}^{\infty} E(i,X).P(i,X) = \int_{0}^{\infty} x.f(x).dx = \sum_{i=1}^{\infty} \int_{S(i)} x.f(x).dx$$

Given N independent sample values (x(1),.....x(N)) of the random variable X (for example the hourly load diagram for one year) the natural estimators for P(i,X), E(i,X) and C(i,X) are, respectively

$$P(i,X) = \sum_{j=1}^{N} I(i,x(j))/N = n(i)/N$$

$$E(i,X) = \sum_{j=1}^{N} I(i,x(j)).x(j)/n(i)$$

$$C(i,X) = \sum_{j=1}^{N} I(i,x(j)).x(j)/N$$

where

$n(i)$ = number of observations in the interval $S(i)$.

In this way we have obtained an estimate of the PDF of the random variable X, the system load.

If X is the mean hourly load, $x(i)$ the observed mean load at hour i and N the number of hours in the period, then $P(i,X).N$ is the number of hours the system load is in the interval $S(i)$, and $C(i,X).N$ is the observed total energy demand during N hours given that the load is in the load interval $S(i)$.

The segment size must be a common factor of all generating units's capacities.

Recurrence relations for the segmentation method:

Let Y be the discrete random variable "outaged capacity of the generating unit" with PDF given by:

$\mathrm{Prob}(Y=0) = p$

$\mathrm{Prob}(Y=K) = q = 1-p, \quad K=n.A$

where n is a positive integer. Note that the capacity of the generating unit is an integer multiple of the segment size.

Let X be a random variable with PDF $f(x)$ and

$W = X + Y$

$$\begin{aligned} P(i,W) &= \mathrm{Prob}(W\ S(i)) \\ &= \mathrm{Prob}(X\ S(i)/Y=0).\mathrm{Prob}(Y=0)+\mathrm{Prob}(X\ S(i-n)/Y=n.A).\mathrm{Prob}(Y=n.A) \\ &= p.P(i,X) + q.P(i-n,X) \end{aligned}$$

$$C(i,W) = \int_{S(i)} x[p.f(x) + q.f(x-n.A)].dx$$

$$= p \int_{S(i)} x.f(x)dx + q \int_{S(i)} x.f(x-n.A).dx$$

$$= p.C(i,X) + q \int_{S(i-n)} (z+n.A)>f(z).dz$$

$$= p.C(i,X) + q.C(i-n,X) + q.n.A.P(i-n,X)$$

Then the recurrence relations for the convolution of i-th segment are:

$$P(i,W) = p.P(i,X) + q.P(i-n,X)$$

$$C(i,W) = p.C(i,X) + q.C(i-n,X) + q.n.A.P(i-n,X)$$

After all convolutions, we get the equivalent load

$$W = X + Y$$

where

X = system load

Y = outaged capacity of generating unit

Now letting Y be the system capacity, i.e., the random variable

$$Y = Y(1)+..........+Y(J)$$

taking values in the discrete set

$$[\ 0,\ A,\ 2A,......(n-1).A,\ n.A\ ]$$

where:

n = some positive integer

J = number of generating units

Y(J) = outaged capacity for generating unit J

the expressions for LOLP and ENS are, respectively:

$$LOLP = Prob(W>n.A) = \sum_{i>n} P(i,W)$$

$$ENS = E(W/W>n.A).Prob(W>n.A) - n.A.Prob(W>n.A)$$

$$= \sum_{i>n} C(i,W) - n.A.\sum_{i>n} P(i,W)$$

In the algorithm n depends on the total capacity(K) of the generating system and on the segment size A, K=n.A. For the calculation we need (n+1) segments and in the last segment we keep all the informations obtained for W>n.A. So the last segment contains the information necessary to quantify the two commonly used reliability indices (LOLP and ENS).

The expected energy generated by a particular unit is given by the difference between the ENS's before and after its commitment.

In this method the computational effort is increasing with total system capacity, when we keep the segment size constant.

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