ON SOME ASPECTS OF RELIABILITY OF INTER CONNECTED POWER SYSTEMS

Thesis submitted in partial fulfilment of
the requirements for the award of the Degree
of
MASTER OF ENGINEERING
in
POWER SYSTEM ENGINEERING

By
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December 1979

CERTIFICATE

Certified that the dissertation entitled, " ON SOME ASPECTS OF RELIABILITY OF INTERCONNECTED POWER SYSTEMS ", which is being submitted by Sri Arun Kumar Srivastava in partial fulfilment for the award of the Degree of Master of Engineering in POWER SYSTEM ENGINEERING of the University of Roorkee, is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

This is to further certify that he has worked for a period of 5 1/2 months from July to Dec. 1979 for preparing dissertation for Master of Engineering Degree at the University.

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The author is highly grateful to Dr.K.B.Misra, Professor, Electrical Engineering Department, University of Roorkee, Roorkee for the valuable help he has rendered in the course of this work.

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Finally, the author assumes personal responsibility for the accuracy and validity of the text, and for any errors that still remain.

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CONTENTS

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ABSTRACT

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In the following pages, an effort has been made to present a comprehensive picture on some of the aspects of power system interconnections. The basic elementary theory of probability applied to non-interconnected and interconnected systems have been discussed, and the significance of conventional methods of outage probability calculation has been illustrated. Computer programs have been developed for finding probability of capacity outages, adding units and then rounding across a suitable increment. A representative example is considered having two systems, and risk levels are calculated for each system individually on non-interconnected basis and then on an interconnected basis by the application of loss of load probability method. The results are compared and benefits of interconnection is shown. The role of computers and development of computer programs for further probabilistic study of interconnected systems on a larger scale has been stressed. The need and scope for further research have been indicated.

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CONTENTS

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CHAPTER I

1.1. INTRODUCTION.

In the past reliability has been recognised only as a qualitative aspect. Engineering systems earlier were so simple that an acute need for quantitative study of reliability was not felt. It was only after the second world war that the need for reliability was felt when several studies revealed some startling results which served as an impetus for further investigations. Now, reliability has become an absolute necessity and a recognised engineering discipline. A high degree of reliability is desired when dealing with modern complex systems such as space mission and aircraft system. In such systems, the failure of a part or component results not only in the loss of failed item but most often results in the loss of some larger assembly or system, of which it is a part. The reliability of such costly and sophisticated systems has to be ensured before these are actually commissioned.

The most accepted definition for Reliability is "It is the probability that a device will operate satisfactorily for a given period of time in its intended application". The device may refer to some component, equipment, system or subsystem or a block in a particular application. The definition includes the term 'probability' which indicates the use of a quantitative measure for reliability. Further it involves three other considerations : "Satisfactory operation, length of time, and intended application". For the reliability assessment the satisfactory operation is to be clearly understood. An equipment does not necessarily have to be totally inoperative for it to be unsatisfactory. Satisfactory operation is defined for a meaningful measure of reliability.

The length of time of operation is more definitive. A mission is defined as covering some specific length of time.

The last consideration, intended application, is also a part of reliability definition. Any equipment is designed to operate in a given manner under particular sets of condition. These include environmental condition (temperature, pressure, humidity, acceleration, vibration, shock, accoustic noise etc.) and operation condition (voltage, current, torque corrosive atmosphere etc.) which will be encountered in manufacturing, transportation, storage and use.

A well designed, tested, engineered and properly maintained equipment should never fail in operation. Experience shows, however, that even best design, manufacturing and maintenance efforts do not completely eliminate the occurrence of failures. Reliability distinguishes three characteristic types of failures which may be inherent in the equipment and occur without any fault on the part of operator.

Firstly, there are ' early failures' which result from poor manufacturing and quality control techniques and occur early in life of an equipment. Such failures can be eliminated by 'debugging' process.

Secondly, 'wear-out failures' are caused by wearout of parts. These failures are a symptom of component ageing. To avoid these failures, the parts of an equipment are designed for a longer life than the intended life of an equipment.

Thirdly, there are so-called 'chance-failures' which are caused by sudden stress accumulations beyond the design strength of the component. These failures occur at random intervals, irregularly and unexpectedly. These are the most common type of failures during the useful operational life of an equipment. Hence, maximum attention in the reliability literature has been given to these 'chance' or 'catastrophic failures'.

A power system is composed of group of elements or components that act in series or parallel or both with each other to carry power from generation sources to load centres. Hence there is a need to (i) supply improved service as customers become more dependent on their electric source, (ii) to use new system voltage and designs whose reliability is not well known to supply the heavier load demands of future.

A power system as a whole is composed of generating unit, transmission and distribution systems, hence main requirement is continuity of supply, which depends upon the capacity outages of the generating units and the frequency of the capacity outages, and on availability of transmission and distribution system. In this dissertation, it is assumed that generating stations are systems that are indopendent of environmental conditions as they are housed in-doors and transmission and distribution systems are exposed to weather conditions. Hence failure rate of unit under stormy weather is quite high as compared to failure rate during normal weather.

The development of high speed of protective equipments, improvements in maintenance techniques and interconnection of generating stations are some of the factors which contribute in improving the reliability of power systems. The reserve requirements in the past were based on 'rule of thumb' criteria such as fixed percentage of the installed capacity, or the outage of largest generating unit. A current 'rule of thumb' in industry is that reserve capacity should be 15% of system requirements.

However, if the power stations are inter-connected it is preferable to expansion, since an interconnected system experiencing a deficiency may be able to borrow power from one with an excess.

1.2. <u>LITERATURE REVIEW</u>.

The application of probability methods to the capacity problems provides an analytical basis for capacity planning which can be extended to cover partial or complete integration of systems, capacity of interconnections, effects of unit size and design, effect of maintenance schedules and other system parameters. The economic aspects associated with different standards of reliability can only be compared using probability techniques.

A considerable number of papers have been published in this area(1,2 etc.) and the techniques used at the present time are extremely interesting. Although the studies started much earlier, but a large group of papers(3,4,5,6) was published in 1947 by A.I.E.E. which evoked keen response. These papers made the application of probability methods to solve reserve problems of many of the problems of power systems in U.S. Moreover, the inadequacy of the present system due to growth of load and increased complexities in the generation and transmission of equipments also warranted the development of a new method by which reserve problems could be tackled in a more reasonable and realistic manner. Calabrese(3) gave a mathematical treatment of factors involved in investigation of forced outages on several systems of boilers and steam turbo-generator units covering a period of six years. Lyman(4) gave a short-cut method applicable to a system with any number of generating units of different sizes. Watchorn and Loane(5) dealt with probability applications for hydro unit treatments. Seelye(6,7) gave a mathematical development of relatively simple algebraic formulas for the study of reserves necessary to take care of forced or emergency outages of generators. He extended this method to determine charts whereby percentage of reserve in terms of total system capability or total system load may be found directly. Watchorn(9,10) showed complex composite effect of all factor effecting system capacity requirements and that these can be calculated by use of two basic probability principles applied airthmetically.

Calabrese(11,12) presented methods for determination of index of reliability level using load duration curve based on daily maximum loads. He put forth some ideas regarding treatment of interconnected systems and suggested three methods to determine "Loss of load probability" with interconnection and "Frequency and Duration of outage approach".

Till 1954, most of the probability studies were done by hand or desk calculators. The benefits of using digital computers to reduce tedious arithmetic required were noted by Watchorn(13) and illustrated by Kirchmayer et al.(14,15) in the evaluation of economic unit additions in system expansion studies.

Several excellent papers appeared each year until in 1958, a second large group of papers appeared(15,16,17,18,19, 20). Brenneh et al.(15) discussed about the computer applications to calculate the capacity outage and probability of loss of load for a non-interconnected system. After the LOLP method of Calabrese(12) for interconnected systems, a classical treatment of this problem was done by Cook et al.(23). The authors established simple formulas for non-interconnected as well as system with finite and infinite interconnections, by means of VENN diagrams. A digital programme was also developed and the work confines to problems involving two interconnected systems.

The two A.I.E.E. Committee reports on equipment forced outage experience(8,21), were generally restricted to thermal unit equipment information with the exception of a short section on hydraulic equipment. Broun et al.(22) presented the results of a statistical study of five years of data on 387 hydroelectric generating units using punched cards for the initial collection and sequential processing of the data. Vassel(24) determined capacity deficiency and energy deficiency curve and applied these deficiency curves to the specific situation, and discussed a short cut method to examine capacity reserve requirements, and in(38) 1972, developed fundamental principles of applying probability calculations to the analysis of generating capacity reserve requirements for two or more interconnected power systems. Building on concepts developed for a single power system, the author analysed the effect of support interaction between interconnected but otherwise independent systems.

In spite of the above excellent publications available there is still considerable reluctance among many power system engineers to accept the application of probability methods. The initial approach to the calculation of outage frequency and duration indices in generating capacity reliability evaluation has been recently modified by introduction of a recursive approach. This technique is describod in detail in a series of two recent papers(26,27), and can be applied virtually to all areas of reliability evaluation.

Langdren(30) used probability methods to investigate effect of outage of Key transmission lines on the reliability of an interconnected P-System. Weiss(31) developed an interconnected model and studied system reliability both from the standpoint of failure and also the expected value of unserved load. He presented explicit algorithms (for use on digital computers) for calculation of both these values. He gave examples whereby showing that interconnection could produce a more reliable pair of systems than an expansion would. Ramamoorthy and Gupta(32) divided a complex system into two or more subsystems. Reliability of each subsystem was evaluated using Markov process methods assuming each subsystem as a single input-multi-O/P, or multi input-single O/P system.

Gambirasio(33) presented a paper wherein he found a simpler procedure for LOLP studies. When the reliability of an P.S. is evaluated by LOLP method, the uncertainty in load forecasts is considered by associating a peakload distribution (as a parameter expressing uncertainty) with the assumed daily peak load duration curve, then to compute the unconditional LOLP as an average of the conditional LOLP weighted by the parameter distribution. He modified the first-daily peak load curve so that uncertainty is incorporated in it and then applied to the usual LOLP method.

Billington & Harington(34) in the assessment of reliability of operating capacity procedure to the unit commitment problem in which the basic question is which units should be scheduled to adequately meet a future uncertain load; and in "evaluation of reliability the energy limited generating capacity studies" seems to be one of the latest publication on this topic.

A survey of the published literature indicates that LOLP method using a daily peak load variation curve appears to be most widely accepted technique and used most often. The ability to indicate both duration and interval of a given outage condition adds a significance to results of 'Frequency and Duration method', but it is relatively inflexible in considering effects of load characteristics, load forecast uncertainty and the reliability aspects of multiple interconnection facilities. Simulation method is relatively complicated and undesirable from a practical view point.

The applications of all the methods have been vast and a great wealth of information exists in the form of technical papers.

1.3. DEFINITIONS.

The IEEE Committee Report(29) gave several basic definitions applicable to all areas of power systems. The definitions useful to this work are given below:

Outage :- An outage describes the state of a component when it is not available to perform its intended function due to some event directly associated with that component. An outage may or may not cause an interruption of service to consumers depending on system configuration.

Forced outage :- A forced outage is an outage that results from emergency conditions directly associated with a component requiring that component be taken out of service immediately either automatically or as soon as switching operations can be performed, or an outage caused by improper operation of equipment or human error.

Scheduled outage :- A scheduled outage is an outage that results when a component is deliberately taken out of service at a selected time, usually for purposes of construction, preventive maintenance, or repair. The Key test to classify forced or scheduled outage is as follows :

If it is possible to defer the outage when such deferment is desirable, the outage is a scheduled outage, otherwise the outage is a forced outage. Deferring an outage may be desirable for example to prevent overload of facilities or an interruption of service to consumers.

CHAPTER - II

PROBABILISTIC APPROACH TO GENERATION - SYSTEM RELIABILITY ANALYSIS.

2.0. INTRODUCTION.

Generation Reserve planning is one of the most crucial steps in planning the expansion of a modern electric power system. Decisions and commitments made at this stage have a tremendous effect on all other phases of system expansion and dictate the financial posture a system may assume.

In broad terms a suitable generation expansion plan must provide the electric utility with the capability of meeting customer needs for a reasonably priced, reliable, quality electric energy store. In addition to the uncertainty inherent in forecasting future load requirements, the planner must deal with the uncertainties associated with

(1) Unit Reliability and maintenance schedule
(2) Fuel and construction costs
(3) Availability and cost of capital

Loss of load probability (LOLP) determines whether a generation expansion plan satisfies a desired level of reliability or not. The analysis of the reliability of an expansion strategy for isolated and interconnected systems is considered by studying (a) Forecast uncertainty (b) Unit availabilities (c) Unit maintenance schedules (d) Interconnection constraints.

Further, in addition to LOLP method, there is another approach to reliability analysis, generally referred to as frequency and duration method (FD). Frequency and Duration method enables to determine the frequency of a particular generation system outage as well as its expected duration. The impetus for development of the FD method has come from the need for a generation system reliability technique compatible with transmission system reliability methods and historical transmission system outage data. Moreover, the LOLP method is preferred over FD technique for generation system planning.

Another approach is to determine capacity requirements over the horizon period using analytical methods. Various expansion plans can then be determined by varying the type and timing of unit additions(25,36,37).

2.1. NECESSITY OF APPLICATION OF PROBABILITY THEORY.

The past methods of determining reserve requirements were becoming inadequate because of the growth and increasing complexity of the generating and transmission components of the power system. The reserve requirements were app arently based upon the loss of largest unit and it was satisfactory under the conditions which then existed, where applied. Hence some substitute for the previous method is essential and in this, the probability theory fulfils the requirements. The close agreement between the calculated service reliability based upon probability theory and the actual service reliability has been extremely gratifying(3,11, 12).

2.1.1. Description of Basic PROB Theory :- Pertaining to system reserve requirements this can be studied in four parts :

(a) Definition of statistical probability - Probability is a measure of the chance of a certain event by the ratio between the no. of events that can occur in that certain way, and the number of total possible events.

If a generating equipment has operated a total time T (hrs or days) and has been on forced outage or out of service the total time O (unplanned shut downs), the probability q of forced outage (hrs or days) is then $q = \frac{O}{T+O}$.

And probability p of equipment remaining in service is

$$p = (\frac{T}{T+O}).$$

In general, for n machines,

$$q = \frac{\sum_{k=1}^{n} O_K}{\sum_{k=1}^{n} (T_K + O_K)} \quad \text{.....................(2.1)}$$

(forced outage factor)

$$\text{and} \quad p = \frac{\sum_{k=1}^{n} T_K}{\sum_{k=1}^{n} (T_K + O_K)} \quad \text{...................(2.2)}$$

(operating factor)

Calabrese(3) has taken F.O.R. as 0.03. Further detailed investigations in U.S. have established a National average of 0.02. Studies have shown that there is no characteristic variation in frequency and duration of individual generator outages with size, age or manufacture technique of the machine.

(b) Multiplication -

If p_1 is probability of Generator G_1 operating, p_2 of Generator G_2, then combined probability of simultaneous operation = $p_1 p_2$, when the generators are independent as regards operating condition.

Further if q_1 and q_2 are outage probabilities of G_1 and G_2 generators,

> The probability of first unit operating and second on forced outage = $p_1 \, q_2$
>
> the probab. of first unit being on forced outage and second unit operating = $q_1 \, p_2$.

(c) Addition - The probability of occurrence of either one or the other of two mutually exclusive events is the sum of the respective probabilities. Thus, the probability of having either of the two units on forced outage is $(p_1 \, q_2 + q_1 \, p_2)$. Also $p_1 + q_1 = 1$, and $p_2 + q_2 = 1$.

For two units of same capacity and outage factor, the expansion becomes

$$(p+q)^2 = p^2 + 2pq + q^2 = 1$$

If n units of the group are assumed to be similar, using same outage rate q for all of them.

Then the well known Binamial formula

$$(p+q)^n = (p^n + n\,p^{n-1}\,q + \frac{n(n-1)}{2!}\,p^{n-2}\,.q^2 + \ldots\ldots\ldots$$

$$\frac{n}{(n-r)!\,r!}\,.p\,.\,q^{\,r} + \ldots\ldots n \text{ tems})$$

$$\text{or } (p+q)^n = \sum_{r=0}^{n} {}^{n}C_r .\, p^r \,.\, q^{n-r}$$

This expansion provides the basis for determining the probability of finding various numbers of 'n' units available for service. The first term in the expansion represents the probability for no outage, the second term for the forced outage of one unit, the third for the forced outage of two units and so on.

(d) Expectation - Expectation is a mathematical method of placing a value on a probable event and may be described as the product : the probability of an event occuring multiplied by the results realized if the system occurs.

Consider a system with outcomes $x_1, x_2, x_3 . x_n$ and probability of each $p_1, p_2, p_3 \ldots$. pn.

The expected value of variable $E_{(x)} = \sum_{i=1}^{n} p_i . x_i$.

= weighted mean of possible values with probab. of occurrence as weighted factor.

2.1.2. Probabilistic Generating Models :- The reliability of a system depends upon the reliability of its generation system which contains many different type of units, their outages being due to technical problems. Hence it is necessary to model the random availability of a unit.

Basically, the units fall in one of the following classes:

(i) Base load
(ii) Mid Range Load
(iii) Peakers.

The base load units operate at very high capacity factors, ideally at 90-95 % but often lower if the unit is immature or fraught with technical problems. Units in base load class are usually large fossil-steam, nuclear, or to some extent hydro units. Midrange units operate at capacity factor of 30-75 %. For these combined cycle combustion turbines, hydro units, and small fossil-steam units are usually employed.

Peakers operate only during peak demand periods(3,6) and have v-low capacity factor, 5-10 %. Combustion turbines in thermal systems and hydro units in hydro systems are used as peakers. Midrange units and peakers cannot be base-loaded as these devices are designed for less than full time operation, and prolonged use beyond their design capability results in high maintenance costs.

To account for the random outage or availability of a unit, it is necessary to determine the probability density function that describes the probability that a unit will be on outage or will be available during its normal period of operation. On the basis of historical data the availability of the generating capacity of a given unit may be graphically represented as shown in Fig.2.1 which conveys the idea that random failure and repair of a unit can be defined as a two state stochastic process, whereas, a stochastic process is defined as a process that develops the time in a manner controlled by probabilistic laws. The so-called "state-space diagram" for stochastic process shown in Fig.2.2, shows that a unit may be in state 1 (up-state or state corresponding to maximum available capacity) and then randomly transfer to state 2 (the down state, or the state corresponding to no available capacity) and vice versa. In this context two important titles are defined.

1. Unit <u>availability</u> (denoted by variable p) : the long term probability that the generating capacity of a unit will be

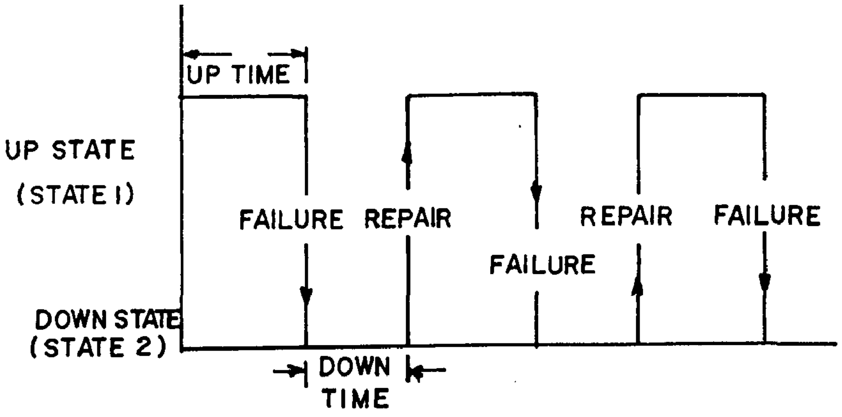


FIG.2.1 RANDOM UNIT PERFORMANCE RECORD IGNORING SCHEDULED OUTAGES.

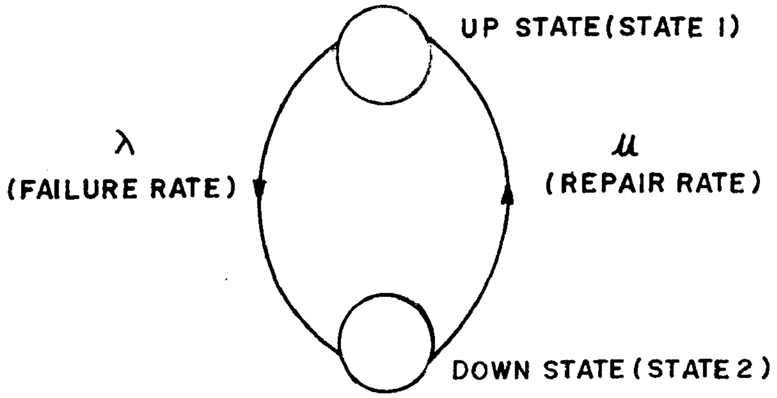


FIG.2.2 GENERATING UNIT STATE SPACE DIAGRAM.

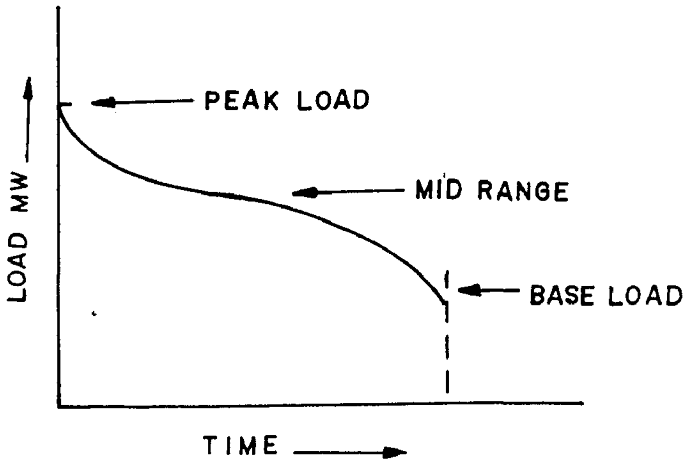


FIG 2.3 GENERATION LOAD MODEL

available.

2. Unit <u>forced outage</u> : the long term probability that the generating capacity of a unit will be unavailable, or forced off-line.

For obtaining an expression for the long term availability of the generating capacity of a unit, it is first necessary to recognize the stochastic process, which is called zero-order, discrete state, continuous transition Markov process. Such a stochastic process has the following properties:

(a) The system described (here the available capacity of a generating unit) can be characterized as being in one of a set of mutually exclusive, discrete states S_1, S_2, ...Sn, at any time. A generating unit can be in either the upor the down state but not in both simultaneously, thus the states are mutually exclusive and discrete.

(b) Changes of state are possible at any time.

(c) The probability of departure from a state depends only on the current state and is independent of the independent variable time.

(d) The probability of more than are change of state during an appropriate small time interval Δt is negligible.

Markov process provides a fairly accurate model of real life and has a simple mathematical description.

2.1.3. Markov Process :-

If $P_i(t)$ is probability of finding a generating unit in state i

$$\left.\begin{array}{l}(i = 1 \longrightarrow \text{upstate} \\ \ i = 2 \longrightarrow \text{down state}\end{array}\right\} \text{—— at time } t.$$

λ —— Transition rate from state 1 to state 2. This parameter obtained from Fig.2.1.

$1/\lambda$ —— The average time a generating unit stays in up-state.

u —— Transition rate from state 2 to state 1

1/u —— Average time a generating unit stays in downstate.

To find probability of generating unit in up-state at time $t+ \Delta t$, there are two ways a unit can be in up state — if it was in up state at time t and did not transfer to down state in time Δt, or if were in down state at time t, and transferred to up-state in time Δt.

If probability of a unit failure is defined by

$F_1(t) = e^{-\lambda t} \quad \underline{\underline{\Delta}}$ probab. of a unit being available upto time t.

$$\therefore F_1(t) = 1 - \lambda\Delta t + \frac{\lambda^2 \Delta t}{2} + \ldots\ldots$$

$= 1 - \lambda\Delta t$. $\doteqdot$ probability of unit being available during time Δt.

Where $\lambda\Delta t$ = probability of transferring in time Δt,

Hence probability that first event to occur

$$= p_1(t)\ (1 - \lambda\Delta t) \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Similarly, Let $F_2(t) = e^{-ut} \triangleq$ probability of unit being unavailable in time Δt.

$F_2(t) = e^{-ut} \triangleq$ Probab. of unit being unavailable upto time Δt

$\doteqdot 1 - u\Delta t \triangleq$ probab. of unit being unavailable in time Δt. ....(2)

Where $u\Delta t$ — probability of transferring in time Δt,

Hence the probability that second event occurs in $P_2(t)\ u\Delta t$,

$P_2(t)$ is the probability of being down-state at time t

$u\Delta t$ " " " that a transfer from down state to up state occurs in time increment Δt.

$$\therefore P_1(t + \Delta t) = P_1(t)\ (1 - \lambda\Delta t) + P_2(t)\ u\Delta t \quad \ldots\ldots\ldots\ldots(3)$$

Similarly $P_2(t+\Delta t) = P_2(t)(1-u\Delta t) + P_1(t)\lambda\Delta t.$

On rearranging these two equations

$$\frac{P_1(t+\Delta t) - P_1(t)}{\Delta t} = -\lambda P_1(t) + uP_2(t)$$

$$\frac{P_2(t+\Delta t) - P_2(t)}{\Delta t} = \lambda p_1(t) - uP_2(t)$$

As $\Delta t \longrightarrow 0$

$$\frac{dP_1(t)}{dt} = -\lambda P_1(t) + uP_2(t)$$

$$\frac{dP_2(t)}{dt} = \lambda P_1(t) - uP_2(t)$$

Since we are interested in long term (steady state) probabilities of being in either state 1 or 2, set derivates to zero and solve equations for $P_1(t)$ and $P_2(t)$

$$P_1(t) = \frac{u}{\lambda+u} = p \quad = \text{available}$$

$$P_2(t) = \frac{\lambda}{\lambda+u} = q \quad \text{Forced outage rate.}$$

and $P_1(t) + P_2(t) = \dfrac{u}{\lambda+u} + \dfrac{\lambda}{\lambda+u} = 1.$

2.2. LOSS OF LOAD PROBABILITY METHOD.

2.2.1. Determination of probability tables for a generating system for Reliability calculation :-

All the components of generation and transmission are included in reliability calculations. We commence with the combination of the selected forced outage probabilities applying for each component of system by methods of multiplication and addition. The forced outage probability of a series arrangement of components like boilers, turbine, generator and transformer, where outage of any one renders the whole system inoperative, is computed by multiplication principle, probability of system with respective components probabilities being p_1, p_2, p_3, p_4, is then equal to $p_1p_2p_3p_4$, and probability of forced outage for the series is $(1-p_1p_2p_3p_4)$. This reduces all elements of the series to one unit for further probab. calculations(10).

Example : Consider a generating plant containing five units, three of 25 Mw capacity and two of 40 Mw, assume $q = 0.02$ for each smaller unit and 0.03 for larger unit.

For $\overset{3}{\text{two}}$ smaller units combinational of probabilities is accomplished by binamial expansion,

$$(p+q)^3 = (0.\overset{9}{4}8 + 0.02)^{\overset{3}{2}} = 1$$

$$= 0.941192 + 0.057624 + 0.001176 + 0.000008\ldots\ldots(1)$$

PROB. of applying 40 Mw units = $(0.97 + 0.03)^2$

Add this with 3x25 Mw units in a similar manner

$$=(0.97 + 0.03)^2 (0.941192 + 0.057624 + 0.001176 + 0.000008)$$

..........(ii)

Multiplying (i) and (ii) yields the following table 2.1 and table 2.2 when arranged in ascending order.

Table 2.1

(1) Capacity outage (MW)	(2) Probability	(3) Units on forced outage
0	0.8855676	0
40	0.0547774	1
80	0.00084708	2
25	0.0542182	1
65	0.00335371	2
105	0.0000318616	3
50	0.00110649	2
90	0.00006844	3
130	0.000000058	4
75	0.000007527	3
115	0.0000004656	4
155	0.0000000072	5

Table 2.2 when rearranged in ascending order for capacity outage is,

Table 2.2

(1) Capacity outage (MW)	(2) Probability	(3) Units in forced outage
0	0.885567500	0
25	0.05421842	1
40	0.054777314	1
50	0.001106498	2
65	0.003353717	2
75	0.00000752	3
80	0.000847073	2
90	0.00006844	3
105	0.00005186	3
115	0.000000465	4
130	0.000001059	4
155	0.0000000072	5

Rounding of probability outage tables :

The proration of forced outage probabilities to multiples of 25 MW produces reasonable results and reduction in number of terms.

Hence it is desired to eliminate 40 MW, 65 MW etc. rows and introduce 50 MW, 75 MW units etc. after considering proration. Linear proration between 25 MW and 50 MW assigns $\frac{10}{25}$ of the outage factor for 25 MW and $\frac{15}{25}$ of outage factor to 50 MW. But 50 MW outage condition is further modified by the proration of the 65 MW outage condition. This results in a new table 2.3 shown below:

Table 2.3

(1) MW outage	(2) Probability of outage
0	0.88556756
25	0.5761294
50	0.0353144
75	0.002724793
100	0.000252156
125	0.000011583
150	0.0000002173
175	0.000000000144

Cummulative outage Probability table :

The method described above determines exact outage probabilities for various capacity outage. The term cummulative probability is introduced when the planners are desirous of obtaining outage probabilities of losing a certain capacity or more. In table 2.2, the exact probability of losing 0.0 MW is 0.8855675, and it can be easily explained that probability of losing 0.0 MW or more is summation of all terms of column 2 in table 2.2, which is equal to 1.00. This is cummulative probability of losing 0.0 MW or more. For 25 MW, it is the summation of all terms in column 2 except the first one for 0.0 MW. Hence table 2.2 can be modified as below:

Table 2.4

(1) Capacity outage (MW)	(2) Cummulative probability
0	1.00000
25	0.11443244
40	0.0602140256
50	0.00543665
65	0.004330153
75	0.000976436
80	0.000968909
90	0.000121836
105	0.000053393
115	0.000130073
130	0.0001065600
155	0.0000000072

2.2. PROBABILISTIC LOAD MODELS.

In LOLP method, the capacity outage table is combined with the system peak load duration curve in order to find loss of generation which may or may not result in a loss of load(35,36). This depends upon reserve generating capacity as well as peak load.

As shown in figure 2.4,

o_K = Magnitude of K^{th} outage in system capacity outage table

p_K = Probability of outage of capacity equal to o_K.

t_K = No.of time units in study period that an outage magnitude o_K would cause a loss of load.

Obviously, any capacity outage loss than reserve will not contribute to the system expected load loss. Capacity outages more than of reserve will result in loss of load with varying time periods t_K.

Total loss of load for study interval

$$E(t) = \sum_{k=1}^{n} p_K \, t_K$$

. time units (days or year).

The period of study could be a week, month or year. The simplest application is use of curve on a yearly basis. When using daily peak load variation curve on an annual basis, the expected loss of load is in days per year. The reciprocal of this value in years/day is often quoted as reliability index. The days/year result is a mathematical expectation of load loss in time units for period under study. This method is further explained below with the help of an example.

Example : Consider a system containing 4 units of 60 MW each.

System installed capacity = 240 MW

Capacity outage table is shown below for this system:

Table 2.5

(1) Capacity outage	(2) Probability	(3) Cummulative probability
0	0.9223669	1.00000
60	0.07529523	.07763171
120	0.00230495	.002336476
180	0.0000313598	.0000315198
240	0.000000159	.000000159

System load model is represented by annual peak load variation curve shown in Fig.2.5.

100 % on x-axis corresponds to 365 days. In many studies the weekends and holidays are neglected as their contribution to the expected load loss is negligible. The time span is then 260 days. The forecast peak load is 160 MW for this system

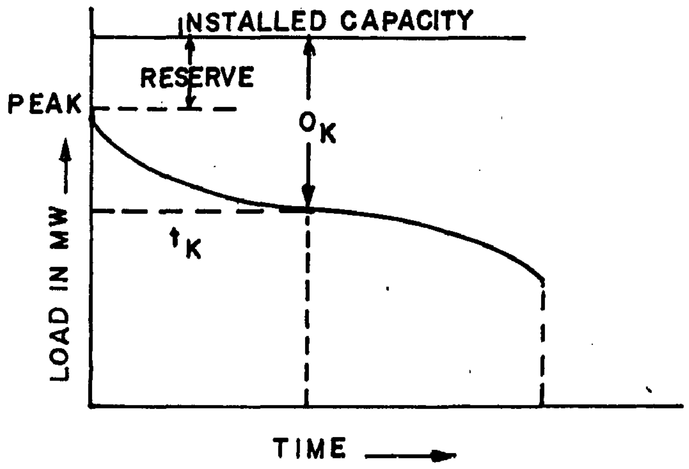

INSTALLED CAPACITY
RESERVE
PEAK
O_K
t_K
LOAD IN MW
TIME

FIG. 2.4

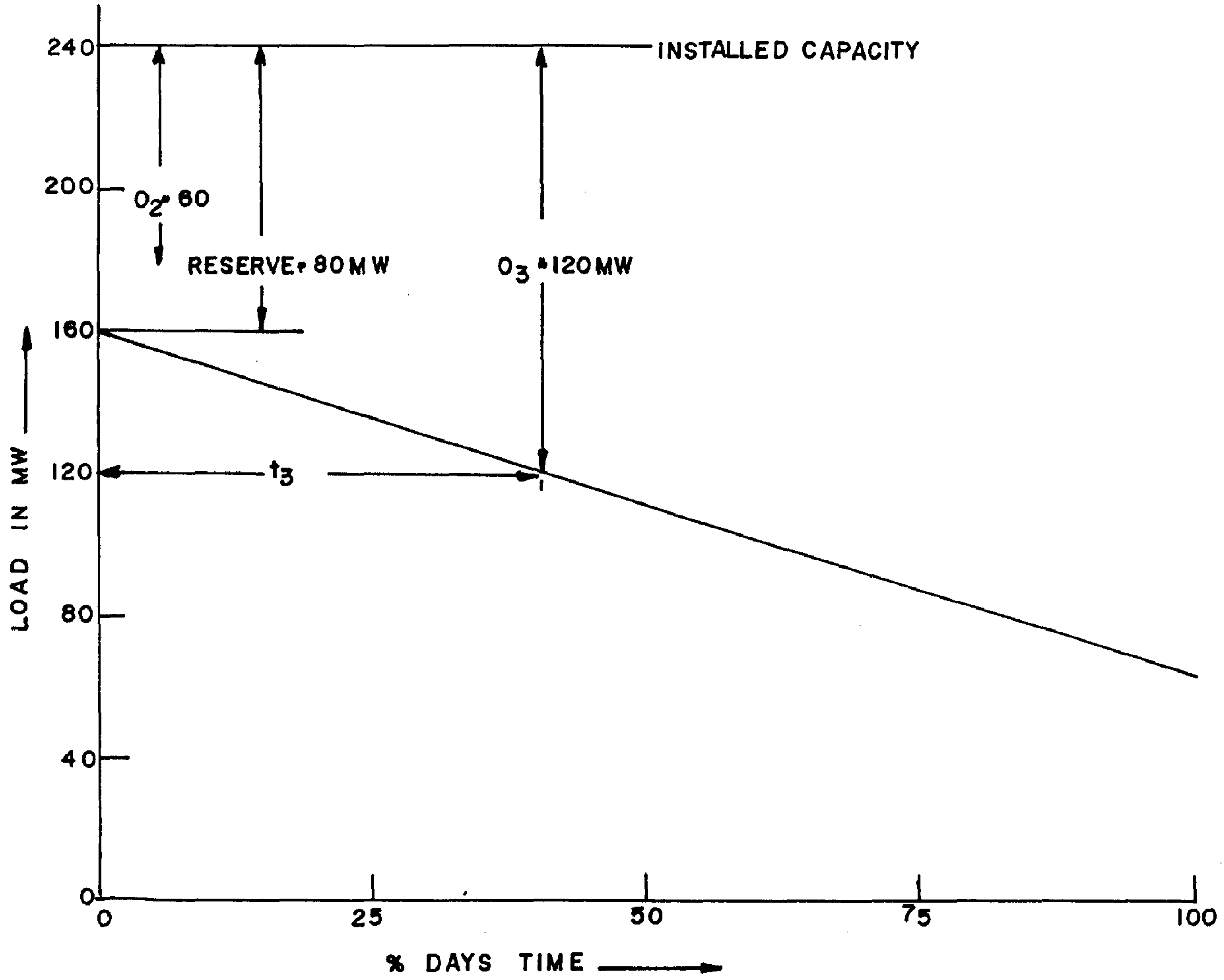

240
200
160
120
80
40
0
INSTALLED CAPACITY
O_2 = 60
RESERVE = 80 MW
O_3 = 120MW
t_3
LOAD IN MW
0
25
50
75
100
% DAYS TIME

FIG. 2.5

which is equivalent to 100 % condition on ordinate. Expected load loss can be found using either the individual capacity outage probabilities or using cummulative values, the results for both are same.

Table 2.6

Capacity out 1.	p_K 2.	t_K 3.	p_K t_K=Expected load loss 4.
0	0.9223669	----	---
60	0.07529523	----	----
120	0.00230495	38.12	0.0878627
180	0.0000313598	100.0	0.00313598
240	0.000000159	100.0	0.0000159
		p_K t_K =	0.0910145

Expected load loss is 0.0910145 % of the time base units. Assuming a 365 days year, expected load loss is 0.3322029 days or 3.0102085 years per day.

2.3. FREQUENCY AND DURATION METHOD.

In modelling the generation system, the units are assumed to be connected in parallel. Each unit is defined by a given maximum capability and by a long run behaviour pattern with regard to the occurrence of the available repair cycles through which it passes. The technique differs from loss of load since, in this model, each unit may be described by its own capability and duration of available and repair periods. The method presents a reliability calculation for generation system that incorporates the frequency and duration of unit outages and includes consideration of theloads. This method calculates reliability parameters viz. availability, frequency of occurrence and outage duration for a number of generating units connected in parallel to form a single system(26).

2.3.1. Stochastic Processes :- A single repairable device which is either available (up) or in repair (down) may be defined by its mean behaviour. It is assumed that repair and failure rates are constant. It is further assumed that mean time to failure 'm' and mean time to repair 'r' are finite. With finite 'r' and 'm', we say thatboth up and down states are 'accessible' and that over a long interval of time, the availability, or fraction of time, the machine will be in an upstate, is a number greater than zero and less than one.

The mean cycle shown in Fig.2.6 defines the following terms :

$T = 1/f$, cycle time (days)

$f =$ frequency (cycle per unit time)

$m = 1/\lambda$, mean up time (days)

$r = 1/u$, mean repair time (days)

= failure rate (failures p.u time)

$u =$ repair rate (repairs p.u. time)

$$A = \frac{m}{(m+r)} = \frac{m}{T} = \text{availability (steadystate)} \text{......(2.3.}$$

$$\bar{A} = (1-A) = r/T, \text{ unavailability (steady state)}$$

The availabilities, transition rates and mean cycle time are related by

$$\lambda = 1/_{AT} \text{ ....(2.3.2)}$$

$$u = 1/_{\bar{A}T} \text{ ....(2.3.3.)}$$

$$f = A = \bar{A}/u \text{ ....(2.3.4)}$$

Fig.2.7 shows the state transition diagram for the two state device.

From diagram $f(up) = A\lambda$

= (steady state probability of being in state) x (rate of departure)............ (2.3.5)

$f(up) = \bar{A}\, u$ = (steady state probab. of not being in the state) x rate of entry -------------(2.3.6)

<u>Example 1</u> :- Assume a single, repairable generator unit

capacity = 20 MW

$A = 0.98$

$r = 2.040816$ days.

Hence, $u = 1/r = 0.4900$

$$= \frac{\bar{A}}{rA} = U\frac{\bar{A}}{A} = 0.0100$$

So that $T = \frac{1}{\bar{A}\,u} = 102.0408$ days

is the mean cycle time for encountering either the up or down states.

2.3.2. Two machines in parallel :- Equations 2.3.1, 2.3.2 are general even if there are more than one mode of entering or leaving a state. In this case number of possible states is $i^2 = 4$. Fig.2.8 shows the transition diagram for these states.

Table 2.7

State number	Machine 1	Machine 2	Rate of departure
1	up	up	$\lambda_1 + \lambda_2$
2	down	up	$\lambda_2 + U_1$
3	up	down	$\lambda_1 + U_2$
4	down	down	$U_1 + U_2$

The last column indicates the rates of departure from each of the states. Mean time in residence in a state is equal to the reciprocal of the rate of departure. The cycle time between encountering state 2, on the average is,

$$T_2 = 1/ \quad \Lambda_{state\ 2}\ (\lambda_2 + u_1)$$

Example 2 : Two generator in parallel

Table 2.8

Unit	Capacity MW	Availability	Repair time in days	Failure rate	Repair rate
1	20	0.9800	2.040816	0.01	0.49
2	30	0.9800	2.040816	0.01	0.49

Referring to state transition diagram for Fig.2.8, the availabilities and mean time between encountering the states are as follows in table 2.9.

Table 2.9

State	Capacity available MW	Availability per unit	Rate of departure(days)	Cycle time (days)
1	50	0.9604	$\lambda_1 + \lambda_2 = 0.02$	52.0616
2	30	0.0196	$u_1 + \lambda_2 = 0.50$	102.0408
3	20	0.0196	$\lambda_1 + u_2 = 0.50$	102.0408
4	0	0.0004	$u_1 + u_2 = 0.98$	2551.0200

2.3.3. Cummulative Event :- In the example considered above, the mean time between encountering an outage of exactly 30 MW is 102.0408 days, but it would be more valuable to know the frequency of encountering an outage of 30 MW or more. That is, how often (frequency) will the outage change from less than 30 MW to an outage of 30 MW or more.

Therefore, it becomes necessary to redefine the states so that each state represents occurrence of a given or larger capacity outage. The previous, two parallel machines transition diagram may be used to illustrate this transformation procedure and the steps necessary to obtain the frequency of encountering the newly defined states. In Fig.2.84, the new states are denoted by primes and are numbered differently.

State 1' = state 4.

State 2' = state 3 and 4 and so on.

The frequency of encountering state 1' is the same as that of encountering state 4.

$$f_{1'} = A_4 (u_1 + u_2) = f_4$$

The frequency of encountering the new state 2' is equal to the sum of the frequencies with which transfers take place from old state 3 to old state 1, $A_3 u_2$ and from old state 4 to old state 2, $A_4 u_2$. Obviously, the result will be less than the sum of the frequencies of encountering states 3 and 4 by the sum of the encounters of states 4 and 3, $A_3 \lambda_1$ and of states 3 from 4, A_4 u_1. Transfer between 3 and 4 represents failure and repair of machine I. The frequency of transfer may be given by the product of the unavailability of machine 2 and the freq. of encounter of machine 1 "up" state. The freq. of encounter of cummulative state 2', $f_{2'}$, is given by the sum of the frequencies of encounter of state 1', $f_{1'}$, plus the freq. of encounter of old state 3 from old state 1, A_3 u_2, less than freq. of encounter of old state 4 from old state 3, $A_3 \lambda_1$.

$$f_{2'} = f_{1'} - A_3 \lambda_1 + A_3 u_2$$

The following transition rates are defined so as to generalize the procedure:

Let

$\lambda_{+K} = \lambda_{up}$ = rate of transition out of a given capacity state K to one in which more capacity is available.

$\lambda_{-K} = \lambda_{down}$ = rate of transition out of a given capacity state K to one in which less capacity is available.

The frequency of encountering a state with a given capacity or less than that is given by the recursive relationships given in equation below (2.3.7). In this relationship, exact (i.e. uprimed) state K is being added to cummulative state n-1 (i.e. primed) to obtain the new cummulative capacity n,

$$f_n = f_{n-1} - A_K \lambda_{-K} + A_K \lambda_{+K} \quad \ldots\ldots\ldots\ldots(2.3.7)$$

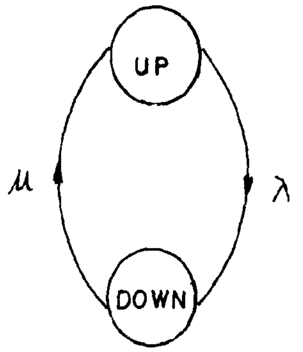


FIG.2.7 TWO STATE TRANSITION DIAGRAM FOR A REPAIRABLE MACHINE.

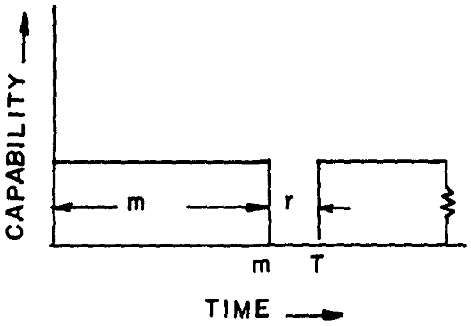


FIG.2.6 AVERAGE HISTORY OF UNIT CAPABILITY.

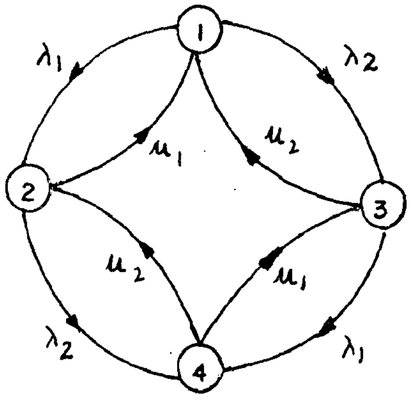


FIG.2.8 FLOW GRAPH REPERSENTATION FOR THE MACHINES IN PARALLEL.

In equation (2.3.7)

A_K = availability of the exact state K and the primes have been discorded and replaced by subscripts, n, n-1,

The availability of a cummulative capacity state n may be found from the following relation,

$$A_n = A_{n-1} + A_K \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.3.8)$$

where again, the exact capacity state K is being appended to the cummulative state n-1 to arrive at n.

2.3.4. Identical capacity states :- In the construction of the exact capacity state availability and frequency tables for larger systems, identical states may be generated by different combinations of units. In the sense of transition diagrams, there is no direct linkage between these states. That is, the only way that a system may transit within a given instant of time from one exact capacity state to another state with the same capacity available, is to have one m/c repaired and another fail within the same instant. The probability of this occurrence is of second order. That is, it is so unlikely that it is ignorable relative to the occurrence of a single event. Therefore, the two capacity states may be merged as states separated in time.

Since transfer cannot occur directly from one state to the other, their availabilities and frequencies of encountering will add directly. Let i and J designate two states which have exactly the same capacity available and K designate the merged state. Then the capacity, availability and cycle frequency of the merged state are as follows:

Capacity $C_K = C_i = C_J$ 2.39

Availability $A_K = A_i + A_J$ 2.4

Frequency $f_K = f_i + f_J$ 2.41

Therefore, the total rates of departure to greater and lesser capacity states may be found from:

$$A_K \cdot \lambda_{up, K} = A_i \lambda_{up, i} + A_J \lambda_{up, J} \quad .... 2.42$$

$$A_K \cdot \lambda_{down, K} = A_i \lambda_{down, i} + A_J \lambda_{down, J} \quad .... 2.43$$

Those relations complete the set of those that are required to permit construction of non-redundant, exact capacity availability tables.

Using the data of example 2 and the transition diagram of two machines in parallel case the cummulating availability and the cycle time are calculated for the four cummulative states and the results are tabulated in table below (table 2.91).

Table 2.91

State no.	Capacity MW	Exact capacity Availability	λup	λ down	State No.	Capacity MW	Cummulative capacity Availability	Cycle time days
1	50	0.9604	0	0.02	4	50	1.000	-
2	30	0.0196	0.49	0.01	3	30	0.0396	52.06
3	20	0.0196	0.49	0.01	2	20	0.0200	102.04
4	0	0.0004	0.98	0	1	0	0.0004	2551.02

Example 3: 5 m/cs system.

Table 2.92

Capacity MW	Mean repair time	Availability per unit
20	2.000	0.980
30	2.000	0.980
40	2.000	0.975
50	5.000	0.975
60	5.000	0.975

The results are tabulated in table below (2.93). A graph is plotted between outage (MW) and cummulative cycle time shown in Fig.2.82. These data along with the more well known information about existence probability (i.e. availabi-

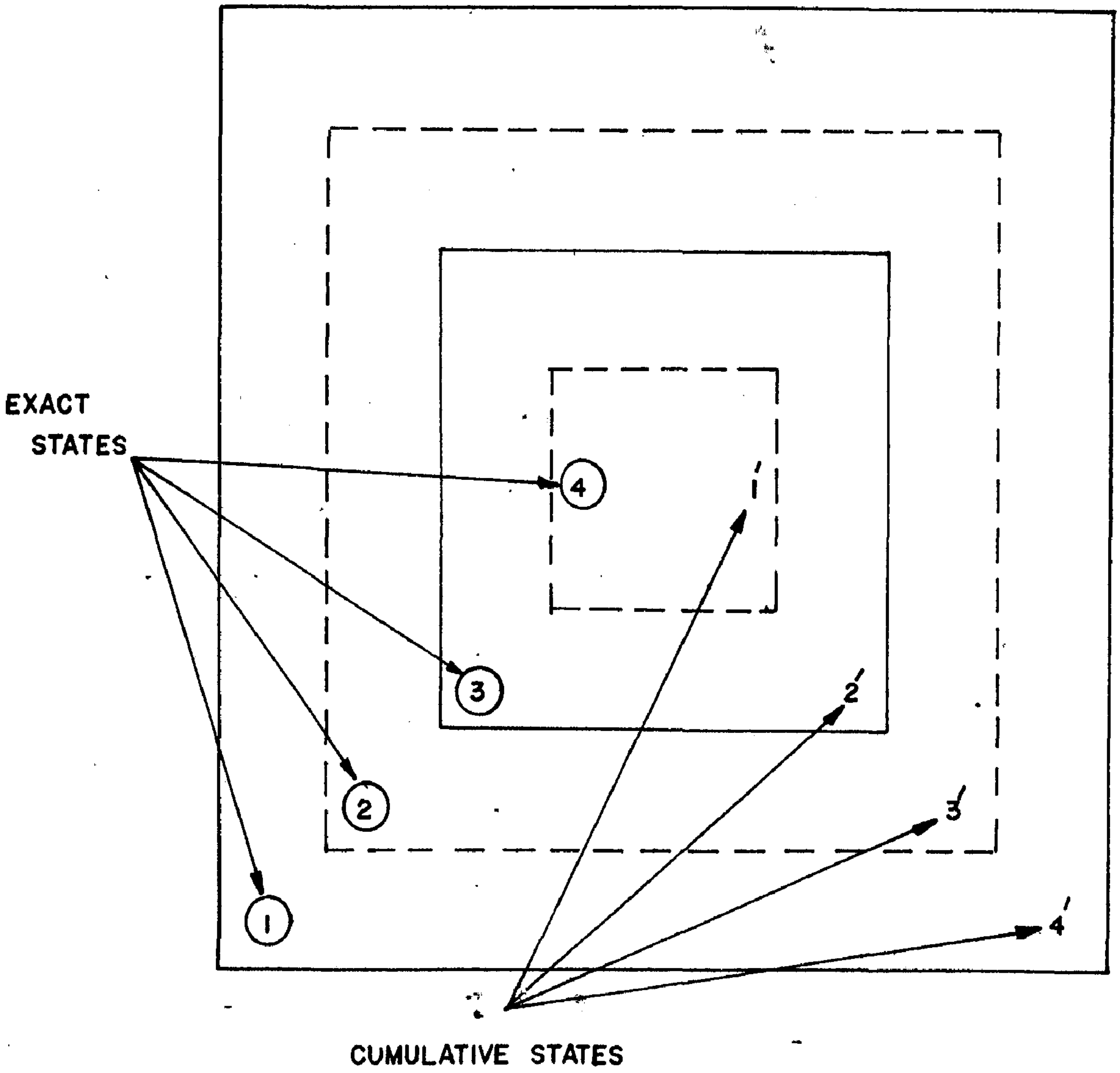


FIG.2.81 REPRESENTATION OF CUMULATIVE STATES.

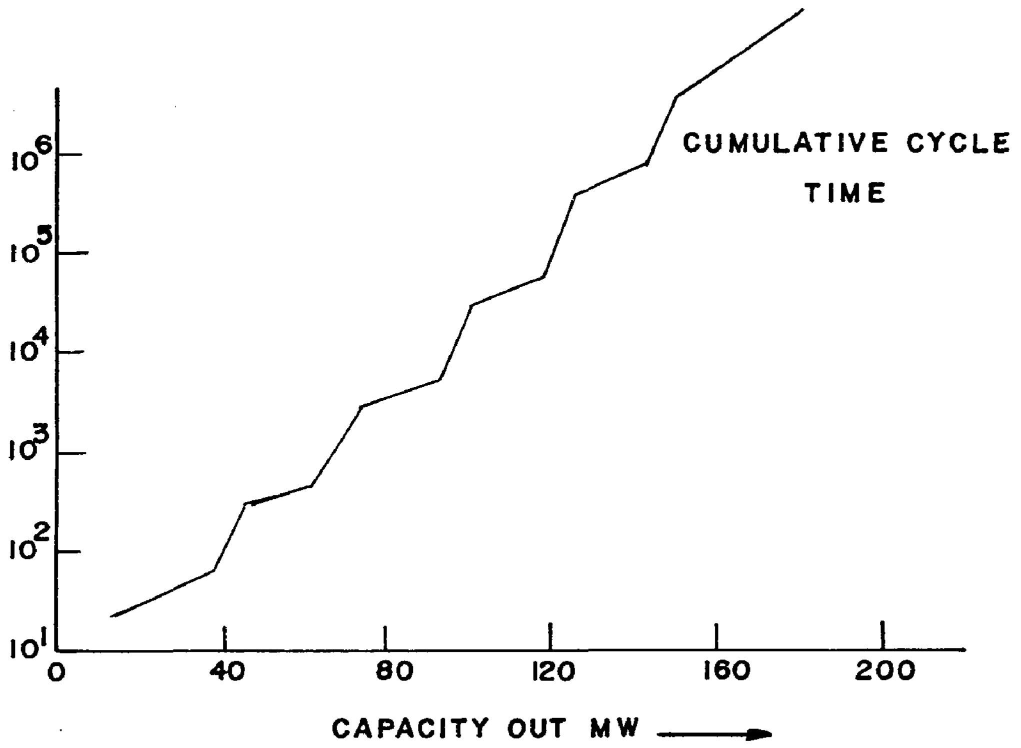


FIG.2.82 CUMULATIVE CYCLE TIME VARIATION AS A FUNCTION OF CAPACITY OUTAGE.

lity) of cummulative outage states provide a comprehensive reliability picture of the generation system. The frequency of occurrence of a zero outage or more is zero, meaning that the system is always in this state. The curve of Fig.2.82 below are shown by smooth curves for sake of clearity only. On same lines reliab. parameter for more number of units can be evaluated.

Table 2.93

Capacity outage MW	Exact capacity out		Cummulative outage state	
	Available	Cycle time (days)	Availability	Cycle time (days)
0	0.8947	27.34	1.000	-
20	$.1825x10^{-1}$	103.20	0.1053	27.34
30	$.1825x10^{-1}$	103.20	$0.8702x10^{-1}$	35.72
40	$.1825x10^{-1}$	103.20	$0.6876x10^{-1}$	51.48
50	$.2331x10^{-1}$	172.75	$0.5050x10^{-1}$	92.11
60	$.2331x10^{-1}$	172.75	$0.2718x10^{-1}$	148.74
70	$0.8408x10^{-3}$	1388.96	$0.3872x10^{-1}$	386.15
80	$0.9364x10^{-3}$	1471.92	$0.3032x10^{-1}$	523.88
90	$0.9439x10^{-3}$	1447.45	$0.2094x10^{-1}$	782.93
100	$0.4777x10^{-3}$	2846.53	$0.1151x10^{-1}$	1576.39
110	$0.6074x10^{-3}$	3616.23	$0.6731x10^{-1}$	3254.58
120	$0.1911x10^{-4}$	43057.05	$0.6581x10^{-1}$	14852.44
130	$0.2156x10^{-4}$	41135.73	$0.4670x10^{-1}$	22376.37
140	$0.1220x10^{-4}$	87858.03	$0.2510x10^{-1}$	43838.49
150	$0.1220x10^{-4}$	87858.03	$0.1294x10^{-1}$	83885.58
160	$0.24450x10^{-6}$	2894356.00	$0.7400x10^{-1}$	969932.10

contd..

170	0.2450×10^{-6}	2894356.00	0.4950×10^{-1}	1448225.90
180	0.2450×10^{-6}	2894356.00	0.2500×10^{-1}	2857142.80
200	0.5000×10^{-8}	105263150.00	0.5000×10^{-1}	105263150.00

CHAPTER - III

COMPUTER AIDED PROBABILISTIC EVALUATION OF LOSS OF LOAD FOR TWO SYSTEMS.

3.0. INTRODUCTION.

The digital computer provides an effective means for evaluation of probability of simultaneous forced outages for determining generator reserve requirement and for calculation of loss of load probability as a reliability index. Arithmetical computations are reduced to a fair degree and enables an engineer to concentrate more time on technical aspect of the work.

Brennen et al.(15) have discussed a method to calculate probability of capacity outage for determination of system reserve requirements. The procedure is followed to obtain a cumulative outage table by adding one unit to an existing system. In the present investigation a computer program has been developed, the program does the addition of various number of units at a stretch to an existing system and finally obtaining capacity outage table for various rounded values. The table thus obtained is combined with system load model for determining loss of load probability for a non-interconnected system.

As an illustration, the Roorkee and Bareilly Area controls has been chosen and probability tables with the aid of digital computer TDC-312 have been developed. A yearly-peak load duration curve has been plotted after obtaining the relevant data for Roorkee (Fig.3.0) and an approximate straight line curve has been assumed for Bareilly control (Fig.3.1). The loss of load probability for both these systems is then calculated assuming no interconnection between them.

In the work that follows, it has been assumed that the outage rate of all units is 0.02, so that p = 0.02 and q = 0.98. All units considered are assumed to be of unit scheme type for each turbine generator or hydro-generator. The value of p = 0.02 then applies to overall series arrangement of generator, turbine etc.

3.1. <u>REPRESENTATIVE EXAMPLE</u> -(Roorkee and Bareilly Area Control).

U.P.State Electricity Board has four area controls for the whole grid of U.P.power system. They are Roorkee, Bareilly, Sahupuri and Panki, with Lucknow as central control. The generating units which come under the Roorkee and Bareilly area controls are shown in Appendix-II (Tables 1 and 2).

For making the procedure for calculating probability, easier and also for making it simpler for computer, the smaller machines in both the systems viz. Roorkee and Bareilly areas are grouped together, without losing much in accuracy. Arranging in descending orders, the system A and B can thus be shown in Table 3.1 and 3.2 shown below:

Table 3.1

(System A - Roorkee)

S.No.	No.of machines	Capacity of Each (MW)	Total capacity (MW)
(i)	7	60	420
(ii)	2	50	100
(iii)	3	30	90
(iv)	2	25	50
(v)	4	17	68
(vi)	6	10	60

Total No.of Machines = 24

Total installed capacity = 788 MW

F.O.R. = 0.02

Table 3.2

(System B - Bareilly)

(i)	3	66	198
(ii)	1	20	20
(iii)	5	15	75
(iv)	3	12	36

Total No.of machines = 12

Total installed capacity = 330 MW

F.O.R. = 0.02

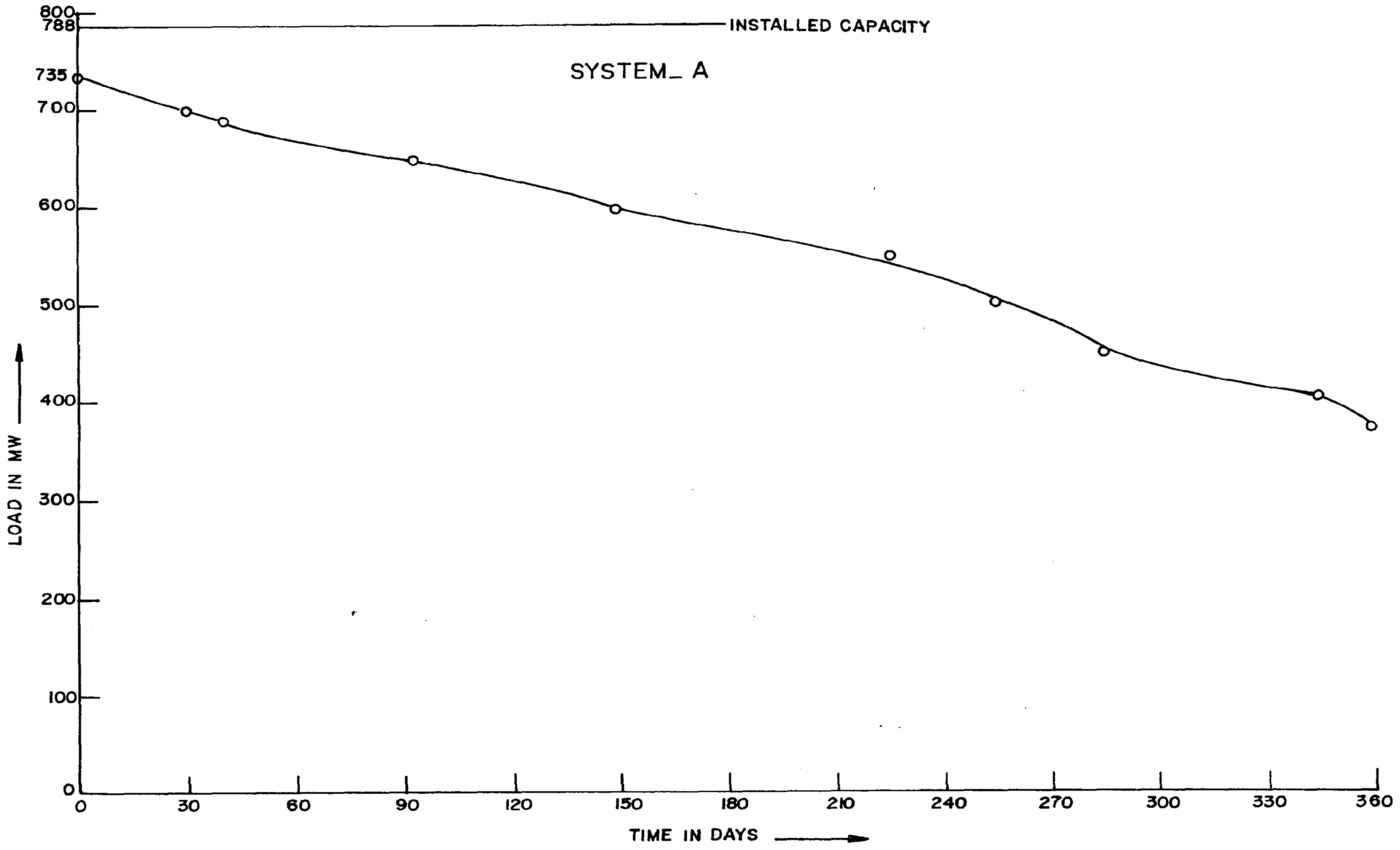


FIG.3.0 ANNUAL PEAK LOAD DURATION CURVE FOR ROORKEE AREA CONTROL.

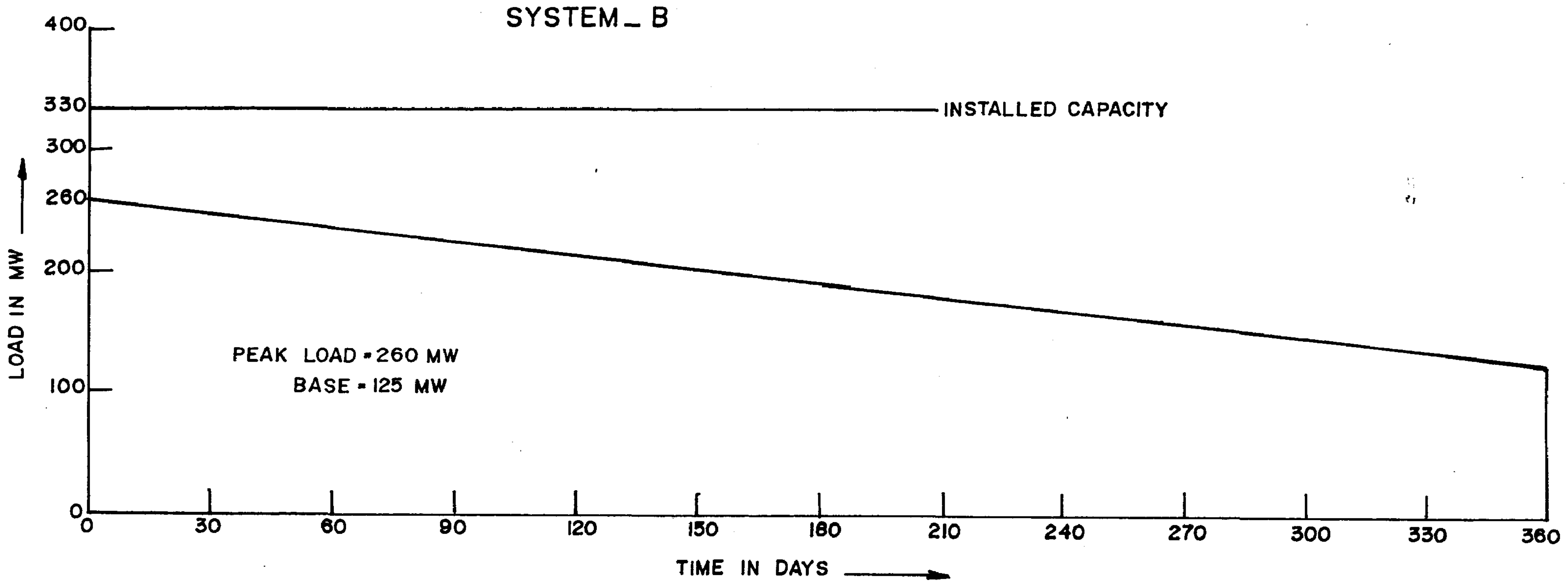


FIG. 3.1 PEAK LOAD DURATION CURVE.

Now, for system A, the capacity outage tables were developed. First of all (4x60 MW) system is considered and a cumulative outage table developed for this is shown below. Computer programs are shown in Appendix- I.

Table 3.3

Determination of cumulative probability of occurrence of capacity outages.

Capacity (MW)	Cumulative probability
0	1.0000
60	0.07763171
180	0.0000315198
240	0.0000001599

In a similar manner, we go on adding units and a combined probability table is obtained for the whole system as shown in table 3.4 below:

Table 3.4

Combined probability table for System A with all units added as tabulated by computer.

S.No. 1.	Outage capacity 2.	Cumulative probability 3.
1	0.000000E-1	9.999988E-1
2	1.000000E+1	3.842176E-1
3	2.000000E+1	2.928405E-1
4	2.500000E+1	2.455630E-1
5	3.000000E+1	2.329961E-1
6	3.500000E+1	1.827451E-1
7	4.000000E+1	1.808802E-1
8	4.500000E+1	1.727031E-1
9	5.000000E+1	1.717383E-1
10	5.500000E+1	1.432362E-1
11	6.000000E+1	1.422107E-1
12	6.500000E+1	4.980038E-2
13	7.000000E+1	4.963350E-2
14	7.500000E+1	3.415502E-2
15	8.000000E+1	3.357335E-2
16	8.500000E+1	2.515895E-2
17	9.000000E+1	2.327303E-2
18	9.500000E+1	1.581254E-2
19	1.000000E+2	1.549666E-2
20	1.050000E+2	1.198104E-2
21	1.100000E+2	1.180932E-2
22	1.150000E+2	7.686288E-3

contd....

23	1.200000E+2	7.534031E-3
24	1.250000E+2	2.947470E-3
25	1.300000E+2	2.875724E-3
26	1.350000E+2	1.852846E-3
27	1.400000E+2	1.768702E-3
28	1.450000E+2	1.195600E-3
29	1.500000E+2	1.101997E-3
30	1.550000E+2	6.607522E-4
31	1.600000E+2	6.398559E-4
32	1.650000E+2	4.104910E-4
33	1.700000E+2	3.988162E-4
34	1.750000E+2	2.091476E-4
35	1.800000E+2	2.001510E-4
36	1.850000E+2	9.071999E-5
37	1.900000E+2	8.603662E-5
38	1.950000E+2	5.233728E-5
39	2.000000E+2	4.846893E-5
40	2.050000E+2	2.922990E-5
41	2.100000E+2	2.699592E-5
42	2.150000E+2	1.413300E-5
43	2.200000E+2	1.344049E-5
44	2.250000E+2	7.434275E-6
45	2.300000E+2	7.043814E-6
46	2.350000E+2	3.253203E-6
47	2.400000E+2	2.992310E-6
48	2.450000E+2	1.494277E-6

contd...

49	2.500000E+2	1.372649E-6
50	2.550000E+2	7.876679E-7
51	2.600000E+2	7.116609E-7
52	2.649999E+2	3.737214E-7
53	2.700000E+2	3.432557E-7
54	2.749999E+2	1.511242E-7
55	2.800000E+2	1.398454E-7
56	2.849999E+2	6.884424E-8
57	2.900000E+2	6.249273E-8
58	2.949999E+2	2.930067E-8
59	3.000000E+2	2.054472E-8
60	3.049999E+2	1.041497E-8
61	3.100000E+2	9.302467E-9
62	3.149999E+2	5.066806E-9

The results shown in table 3.4 were then rounded across 25 MW and 50 MW and the results are tabulated as shown in table 3.5 and table 3.6 :

Table 3.5

Computer tabulation of results for probability of capacity outage (25 MW rounding)

S.No.	Capacity out	Probability
1.	0.000000E-1	6.800639E-1
2.	2.500000E+1	1.317230E-1
3.	5.000000E+1	1.044053E-1
4.	7.500000E+1	6.114424E-2
5.	1.000000E+2	1.427126E-2
6.	1.250000E+2	6.642651E-3
7.	1.500000E+2	1.285128E-3
8.	1.750000E+2	3.682888E-4
9.	2.000000E+2	7.727875E-5
10.	2.250000E+2	1.501359E-5
11.	2.500000E+2	2.756198E-6
12.	2.749999E+2	4.452000E-7
13.	3.000000E+2	2.780001E-8
14.	3.249999E+2	0.000000E-1

Table 3-6

(Rounding Across 50 MW)

S.No.	Capacity out	Probability
1.	0.000000E-1	7.459254E-1
2.	5.000000E+1	2.008389E-1
3.	1.000000E+2	4.816468E-2
4.	1.500000E+2	4.790594E-3
5.	2.000000E+2	2.689297E-4
6.	2.500000E+2	1.048558E-5
7.	3.000000E+2	2.503999E-7

In a similar manner, the results obtained by computer for capacity outages and their corresponding probabilities are tabulated below for System B :

Table 3.7

Cumulative Probability table for 66x3 MW machine

Capacity outage	Cumulative probability
0.0	1.0000
66.0	0.0588079
132.0	0.00118398
198.0	0.00000799

Table 3.8

Combined computer results for all units considered for system B

S.No.	Capacity outage	Cumulative probability
1.	0.000000E-1	9.999988E-1
2.	1.200000E+1	2.152829E-1
3.	1.500000E+1	1.672391E-1
4.	2.000000E+1	8.716611E-2
5.	2.400000E+1	7.115150E-2
6.	2.700000E+1	7.017101E-2
7.	3.000000E+1	6.526856E-2
8.	3.200000E+1	6.200030E-2
9.	3.500000E+1	6.101982E-2
10.	3.600000E+1	5.938566E-2
11.	3.900000E+1	5.937900E-2
12.	4.200000E+1	5.927895E-2
13.	4.400000E+1	5.907885E-2
14.	4.500000E+1	5.905883E-2
15.	4.700000E+1	5.899213E-2
16.	5.000000E+1	5.889209E-2
17.	5.100000E+1	5.882538E-2
18.	5.400000E+1	5.882471E-2
19.	5.600000E+1	5.882062E-2
20.	5.700000E+1	5.882049E-2
21.	5.900000E+1	5.881639E-2
22.	6.000000E+1	5.881435E-2

contd..

23.	6.200000E+1	5.881366E-2
24.	6.500000E+1	5.880959E-2
25.	6.600000E+1	5.880822E-2
26.	6.900000E+1	1.076434E-2
27.	7.100000E+1	1.076426E-2
28.	7.200000E+1	1.076424E-2
29.	7.400000E+1	1.076420E-2
30.	7.500000E+1	1.076411E-2
31.	7.700000E+1	1.076411E-2
32.	7.800000E+1	1.076403E-2
33.	8.000000E+1	7.822573E-3
34.	8.100000E+1	7.822558E-3
35.	8.400000E+1	2.920121E-3
36.	8.600000E+1	2.920121E-3
37.	8.700000E+1	1.939633E-3
38.	8.900000E+1	1.939633E-3
39.	9.000000E+1	1.939632E-3
40.	9.200000E+1	1.879602E-3
41.	9.300000E+1	1.879601E-3
42.	9.500000E+1	1.579451E-3
43.	9.600000E+1	1.579451E-3
44.	9.800000E+1	1.379351E-3
45.	9.900000E+1	1.319322E-3
46.	1.010000E+2	1.319322E-3
47.	1.020000E+2	1.219272E-3
48.	1.040000E+2	1.218864E-3

contd..

49.	1.050000E+2	1.218864E-3
50.	1.070000E+2	1.212738E-3
51.	1.080000E+2	1.212738E-3
52.	1.100000E+2	1.200487E-3
53.	1.110000E+2	1.199262E-3
54.	1.130000E+2	1.195178E-3
55.	1.160000E+2	1.189053E-3
56.	1.170000E+2	1.184969E-3
57.	1.190000E+2	1.184928E-3
58.	1.200000E+2	1.184928E-3
59.	1.220000E+2	1.184677E-3
60.	1.230000E+2	1.184669E-3
61.	1.250000E+2	1.184419E-3
62.	1.260000E+2	1.184294E-3
63.	1.280000E+2	1.184252E-3
64.	1.310000E+2	1.184002E-3
65.	1.320000E+2	1.183919E-3
66.	1.350000E+2	2.035156E-4
67.	1.370000E+2	2.035105E-4
68.	1.380000E+2	2.035097E-4
69.	1.400000E+2	2.035072E-4

Table 3.9

Computer tabulated results for probability of capacity outages for 25 MW rounded values.

S.No. 1.	Capacity outage 2.	Probability 3.
1.	0.000000E-1	8.449710E-1
2.	2.500000E+1	9.381131E-2
3.	5.000000E+1	1.969920E-2
4.	7.500000E+1	3.776218E-2
5.	1.000000E+2	2.553600E-3
6.	1.250000E+2	7.973968E-4
7.	1.500000E+2	3.956056E-4
8.	1.750000E+2	9.124796E-6

3.2. DETERMINATION OF LOSS OF LOAD PROBABILITY.

For the system A, we have probability of capacity outages shown intable 3.4. The table does not indicate the probable loss of load, but confines itself to loss of generation only. In order to know what is the probable loss of load, the load duration curve for the system must be combined with the information relating to the probability of capacity outage.

The first piece of information required is a knowledge of the shape of daily peak load variation curve for the system. If for a given year the maximum hourly load that occurred each day were known, these could be rearranged so that the largest value was shown as occurring on day 1, the next largest on day 2, the base load existing for the whole year. In this study, the maintenance has not been considered, as in our country, maintenance is never planned, and it is done only when the machine is on forced outage. The load duration curve for Roorkee Area control is shown in Fig.3.0. From table 3.5, the probability for capacity outage for 0.0 MW is 0.6800639. On the load duration curve in Fig.3.0, the corresponding time in days for this outage = 0.0 days. Hence expected loss of load is zero for this outage. Similarly, corresponding to 75 MW, outage, the probability is 0.06114424, and time corresponding for this outage is 30 days. The expected load loss is thus $p_K T_K$ = 1.8334 days. The summation of all values of loss of load thus obtained for all the values of capacity outages shown in table 3.5, gives the total expected loss of load for the whole year. The values thus obtained for system A is tabulated in Table 3.91, and for system B in Table 3.92.

Tablo 3.91

Loss of load probability for Roorkoo Aroa - Systom A

Capacity outago 1.	Probability (p_K) 2.	Time (days) t_K 3.	Expoctod load loss $p_K t_K$ 4.
0.0 MW	0.6800639	0	0
25 MW	0.1317230	0	0
50	0.1044053	0	0
75	0.06114424	30	1.8334
100	0.01427126	42	0.5993904
125	0.006642651	75	0.498195
150	0.001285128	105	0.1349355
175	0.000368288	135	0.049707
200	0.000077278	150	0.011580
225	0.0000150136	202	0.00303
250	0.0000027561	232	0.0006264
275	0.00000044520	248	0.0000992
300	0.000000028	262	728.36×10^{-8} = .000072836

Expected load loss $p_K t_K$ = 3.1354059 day

Table 3.92

Loss of load probability for Bareilly Area - System B

Capacity outage 1.	p_K 2.	Time in days t_K 3.	Expected load loss $p_K t_K$ 4.
0	0.844971	0	0
25	0.09381131	0	0
50	0.0196992	0	0
75	0.0377622	11	0.4153842
100	0.0025536	60	0.153216
125	0.00079739	147	0.1172178
150	0.000395606	210	0.083076
175	0.000009125	277	.0025207

Expected loss of load = $\Sigma\, p_K t_K$ = 0.7714147

The expected load loss for the system A and B are respectively 3.1354059 days/year and 0.7714147 days/year. If the cumulative probability values were used, the results can be shown to be the same.

CHAPTER - IV

PROBABILISTIC EVALUATION OF RELIABILITY FOR AN INTERCONNECTED POWER SYSTEM.

4.0. INTRODUCTION.

The benefits of interconnecting two power systems or areas to form an integrated power pool, derive from (a) interchange of energy (b) gain in the reliability of the generating systems when an interconnection is constructed.

The extensive development of interconnections has been due to following advantages :

(i) Reduction in Installed reserve
(ii) Reduction in Spinning Reserve.
(iii) Economy loading of large unit sizes.
(iv) Staggering of capacity installation.

Previously, the application of probability methods in power system planning had been primarily in the area of planning generating capacity requirements for single integrated power systems. The evaluation of loss of load probability for interconnected systems is a more complex problem. The introduction of a tie line between two previously unintegrated systems to form a power pool generally has the effect of reducing the loss of load probability in each of the systems and reducing the total generating reserve capacity required to maintain a given reliability level(23).

4.1. GENERATING CAPACITY RESERVE REQUIREMENTS FOR INTERCONNECTED SYSTEMS.

The concepts used are based on use of daily capacity margin characteristics of single system. Such a characteristic can be developed for a future period by inter-relating daily peak loads and available capacity for particular period, considering maintenance as well as forced outages. This characteristic can be expressed in two ways : as a probability density distribution of the daily generating capacity margins or as a cumulative probability distribution of such margins (Figs. 4.1 and 4.2).

The basic density distribution of daily capacity margins (Fig. 4.1) defines the probability of occurrence - which can be expressed in p.u. of time or in days per period of each daily capacity deficiency or surplus expected to occur during a given period. For a given power system, the S-curve for Fig.4.2 also indicates measures of reliability as indicated in Fig.4.3, useful for evaluating generating reserve capacities.

The capacity deficiency occurs only if no remedial measures are taken, making the system to depend upon various supplemental resources of capacity available to the system for emergency purposes. Such supplemental capacity may be supplied either from within the system, as in the case of interruptible load curtailments or extra load capability of generators, or from external sources, such as emergency back up from neighbouring

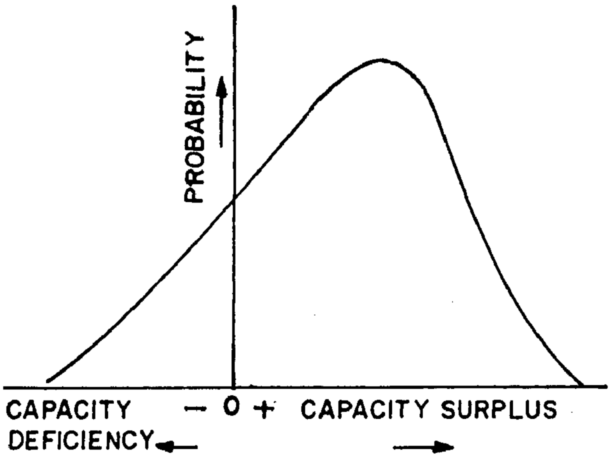


FIG.4.1 PROBABILITY DENSITY DISTRIBUTION OF DAILY GENERATING CAPACITY MARGIN.

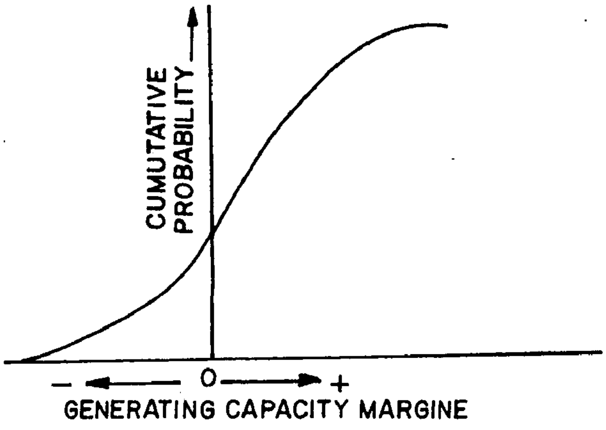


FIG.4.2 CUMULATIVE PROBABILITY DISTRIBUTION OF DAILY GENERATING CAPACITY MARGIN.

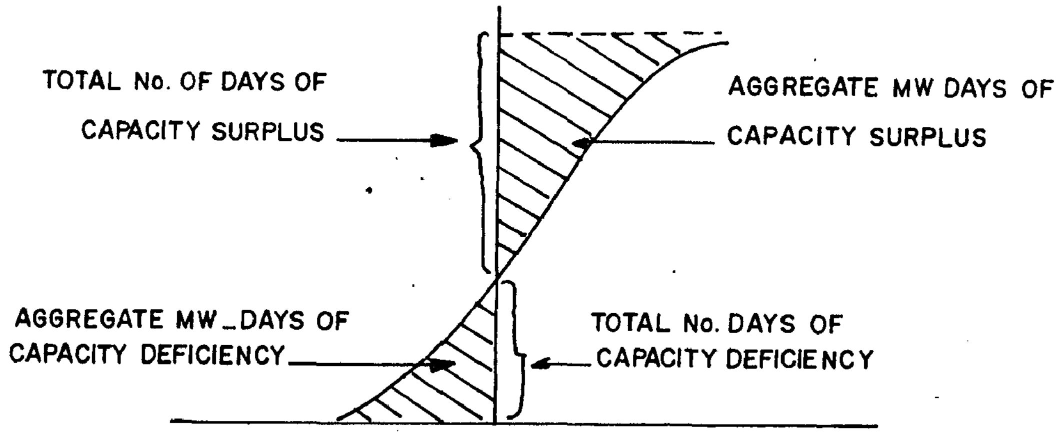


FIG.4.3 EXTANT OF CAPACITY SURPLUS AND DEFICIENCY FROM CUMULATIVE CAPACITY MARGIN DISTRIBUTION.

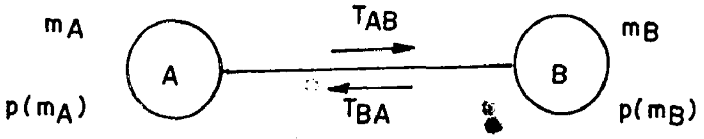


FIG.4.4 TWO INTERCONNECTED SYSTEMS.

systems via interconnections. These capacity surpluses are on the other hand, a measure of systems potential ability to accomodate the capacity deficiencies of neighbouring utilities.

4.11. Two Interconnected Systems:-

(A) General Concepts : - The basic capacity-margin distribution curves for each system is developed in the exactly same manner previously described for 1-system. The likelihood of occurrence of a capacity deficiency on either system must then be correlated with the availability of surplus capacity by the other. For the two system group shown in Fig.4.4, the effect of either system on other depends upon (i) the transmission capability limitations between systems A and B ($T_{AB} + T_{BA}$), (ii) the nature of the capacity margins in systems A and B, in terms of magnitude and likelihood of occurrence and (iii) the diversity of capacity margins between the two systems.

(B) Determination of overall capacity,- Margin characteristic:-

For the simple two-systems interconnected configuration in Fig.4.4 if it is assumed that no transmission constraints are present, the probability of occurrence of a given overall net capacity margin, K MW's, is determined using the familiar convolution equations as follows:

$$P(m_{AB}=K) = \Sigma P(m_A) P(m_B)$$

$$\text{for all } m_A+m_B = K \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.1)$$

or

$$P(m_{AB}=K) = \Sigma P(m_A) P(m_B= K-m_A)$$

$$\text{for all } m_A \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.2)$$

where $P(m_A)$, $P(m_B)$, $P(m_{AB})$ represent the probabilities associated with the discrete capacity margins m_A, m_B and m_{AB} in systems A, B, and overall area AB respectively.

If continuous rather than discrete probability distributions are used, then equation (4.2) becomes

$$p_{AB}(K) = \int p_A(m_A)\, p_B(K-m_A)\, dm_A$$

$$\text{for all } m_A \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4.3)$$

where p_A, p_B and p_{AB} represent the probability density distribution of capacity margins in system A, B, overall area AB etc.

The convolution process (as seen from equations 4.1, 4.2, 4.3 provides a mean for evaluating the benefits associated with utilising the interconnection, namely a decrease in capacity deficiencies which would otherwise occur in the two systems if they were not interconnected, and thus unable to assist each other during times of capacity deficiency.

(C) Determination of the Interaction effect on each system :-

The condition process permits the evaluation of combined effect of both S systems upon the whole area, but evaluation of effect of interaction of either system upon the other is also required. Whenever one of system is in danger of incurring a capacity deficiency, the other system would provide emergency capacity only to the extent possible without jeopardizing its own reserve situation. Consequently, emergency capacity would be transmitted over the interconnection only in those instances when a capacity surplus exists in the sending system and a capacity deficiency in the receiving system. In all other cases, that is when both systems have capacity surpluses or when both are deficient, the reserve capacity margins are retained and no transfer of emergency power would take place.

In Fig.4.5, such interactions are summarized assuming no transmission constraints.The shaded regions of the arrays represent the situation in which capacity deficiencies still exist even after interaction between the two systems has occurred.

From the array of possible capacity margins (Fig.4.5) for system, A, the overall likelihood of any given margin resulting from interaction with system B can be determined, as indicated by following:

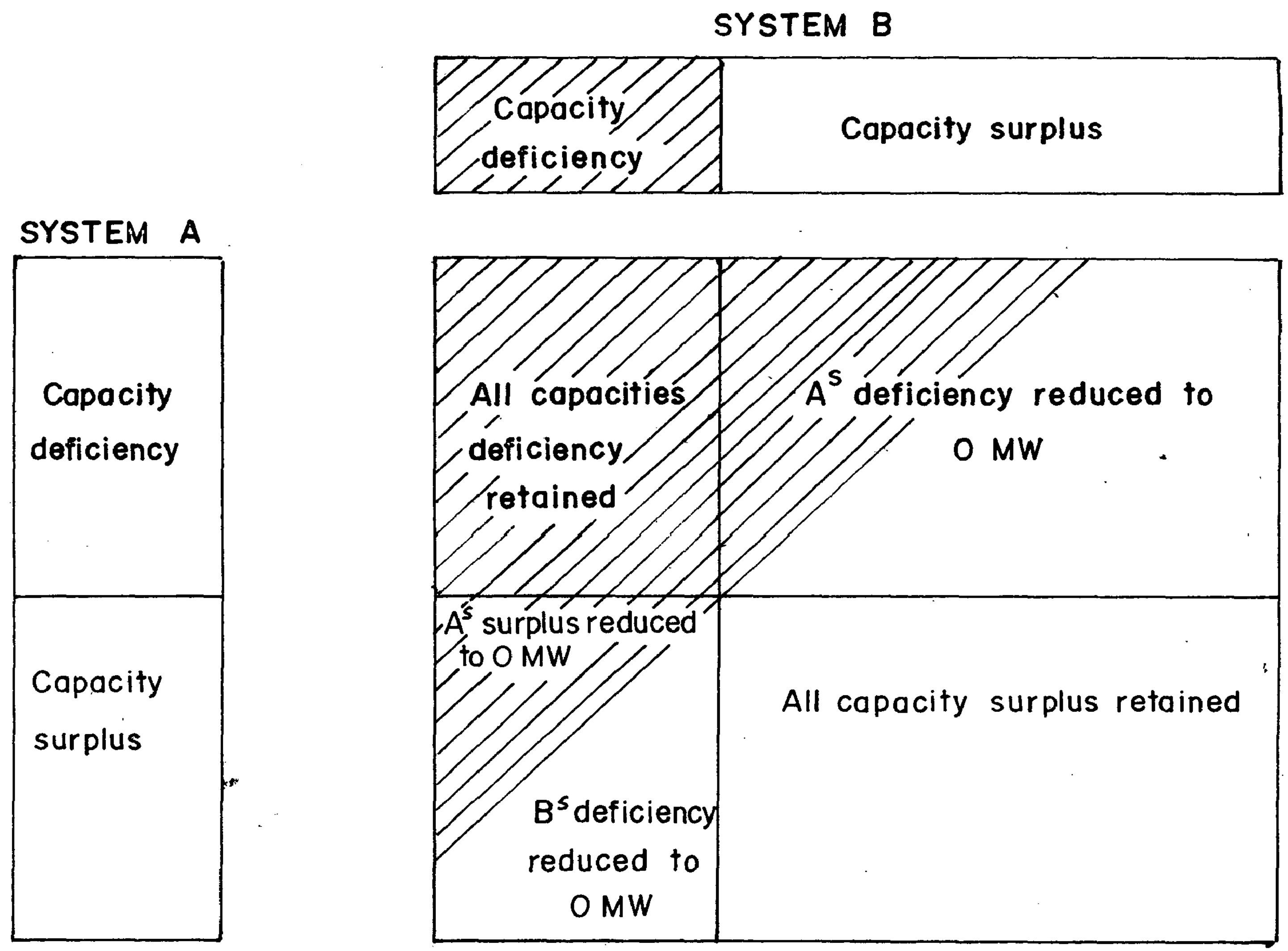


FIG. 4.5 TWO SYSTEM CAPACITY MARGIN PROBABLITYARRAY, ASSUMING NO TRANSMISSION CONSTRAINTS.

For positive margins in System A :-

$$\underset{K>0}{P(m_A=K)} = p(m_A=K) \sum_{\substack{\text{for all}\\ m_B \geqslant 0}} p(m_B) + \sum_{\substack{\text{for all } m_B<0\\ m_A+m_B = K}} p(m_A)\, p(m_B) \;\ldots\ldots\ldots\; (4.4)$$

For negative margins in System A :-

$$\underset{K<0}{p(m_{A_B}=K)} = p(m_A=K) \sum_{\substack{\text{for all}\\ m_B \leq 0}} p(m_B) + \sum_{\substack{\text{for all } m_B>0\\ m_A+m_B = K}} p(m_A)\, p(m_B) \;\ldots\ldots (4.5)$$

For 0-MW margins in system A :-

$$p(m_{A_B}=0) = p(m_A=0) + \sum_{\substack{\text{for all } m_A>0\\ m_B<0\\ m_A \leqslant (m_B)}} p(m_A)\, p(m_B) + \sum_{\substack{\text{for all } m_A<0\\ m_B \geqslant (m_A)}} p(m_A)\, p(m_B) \;\ldots\ldots (4.6)$$

where m_A and m_B $\longrightarrow$ capacity margin of A and B prior to interaction

m_{AB} - capacity margins on System A as modified by effect of interaction with System B.

$p(m_A)$, $p(m_B)$, $p(m_{AB})$ = Probability of occurrence associated with m_A, m_B, m_{AB}.

A similar set of equations also apply to system B. The first term in each of above equations represent the events in which the original capacity margins are retained in system A, while the other terms correspond to those events in which capacity margins are modified as a result of interaction with system B.

In the above analysis, the effect of transmission that exists and is an important aspect of overall evaluation of generating capacity reserves has been neglected. The numerical determination of such effect is made by use of load flow studies, stability analysis etc.

4.2. PROBABILITY TABLES FOR TWO SYSTEMS.

The loss of loadapproach can be applied easily to a two system interconnected study. Assuming no transmission limitations and that each system will share deficiencies equally, them the total generating capacity can be used to develop combined capacity outage probability table. This can be then combined with load duration model to obtain LOLP for the two systems, while analysing two interconnected systems, it is impractical to adopt 'one company concept', hence to maintain the identity of the generating facilities in each system, two dimensional array of probabilities covering the various simultaneous outage levels in each system is maintained.

For our systems A and B (Roorkee and Bareilly Area) (See Appendix-II), and simplified form as shown in Tables 3.1 and 3.2. The table 4.21 shows the individual system capacity outage probability tables, as obtained by computer.

Table 4.21

Capacity outage probability tables for systems A and B

System A		System B	
Capacity outage in MW (i)	Probability (ii)	Capacity outage (i)	Probability (ii)
0	0.680064	0	.8440171
25	0.131723	25	.09381131
50	0.104405	50	.0196992
75	.0611442	75	.0377622
100	.01427126	100	.0025536
125	.00664265	125	.00079739
150	.00128512	150	.000395606
175	.00036828	175	.000009125
200	.000077278		
225	.000015013		
250	.000002756		
275	.000000445		
300	.0000000278		

In table 4.22, the probabilities of simultaneous capacity outages are shown, and all values less than 10^{-8} have been neglected. For example, the probability of 75 MW outage service in system A and 50 MW outage in system B is .00120449 at some time in future.

Probability of simultaneous outage in systems A and B

System B

System A

MW outage (System B) / MW outage (System A)	0	25	50	75	100	125	150	175
0	0.5746343	0.0637976	0.0133967	.002568.7	.00173661	.0005429	.000269033	.00000619
25	.1113021	0.0123571	.0025948	.00497415	.00033636	.00010502	.0000521096	.00000119867
50	0.0882191	.00979436	.00205669	.00394256	.00026608	.00008324	.0000413026	.000000950085
75	0.051665	0.0637972	.00120449	.0023089	.000156137	.00004875	.000024187	.000000556392
100	0.0120587	.00133879	.00028113	.000538911	0.0142712	.00001137	.0000056457	.000000129867
125	.0056128	.000623148	.00013085	.00025083	.0000169625	.000005296	.0000026278	.00000006044
150	.00108587	.000120556	.000025315	.000048528	.000003281	.000001025	.000000508	.00000001169
175	.00031118	.000034541	.000007253	.00001390	.0000009412	.000000295	.0000001456	
200	.00006523	.000007242	.0000015207	.000002915	.000000197	.000000305		
225	.000012674	.000001407	.000000295	.000000566	.0000000383	.00000000119		
250	.0000228142	.0000002533	.0000000 531	.0000001019	.0000000069	.0000000021	.00000000 107	
275	.000000337	.0000000375	.00000000 787	.0000000151	.00000000102			
300	.0000000234	.0000000026						

4.3. LOSS OF LOAD APPROACH.

The probability array shown in Table 4.22 does not provide a useful risk index until it is combined with the load model in a much similar way as in a single system.

Assume the load duration curve shown in Fig.3.0 to be divided into three straight line segments. Take the average load for each segment and find the corresponding number of days for which it persists. Taking this average load for the system, we find the systems reserve capacity (see Fig.4.6). Assuming the interconnected tie line capacity as 25 MW, 50 MW, and 75 MW successively, we find the expected risk level for each segment of a system. The summation of risk levels for the three segments will give the combined expected risk for the system A. We can proceed in a similar fashion for system B.

(A) Let the firm capacity of the interconnected tie line = 25 MW and assume a negligible probability of outage. Under these conditions a load loss array can be created for each system as shown in tables 4.31 and 4.33.

(a) For segment AB (see Fig. 4.6)

Tie line capacity = 25 MW Installed capacity = 788 MW

Average load = 665 MW Reserve capacity = 123 MW

Days 't_1' = 150 days

The table 4.31(a) gives the loss of load in system A for this average load.

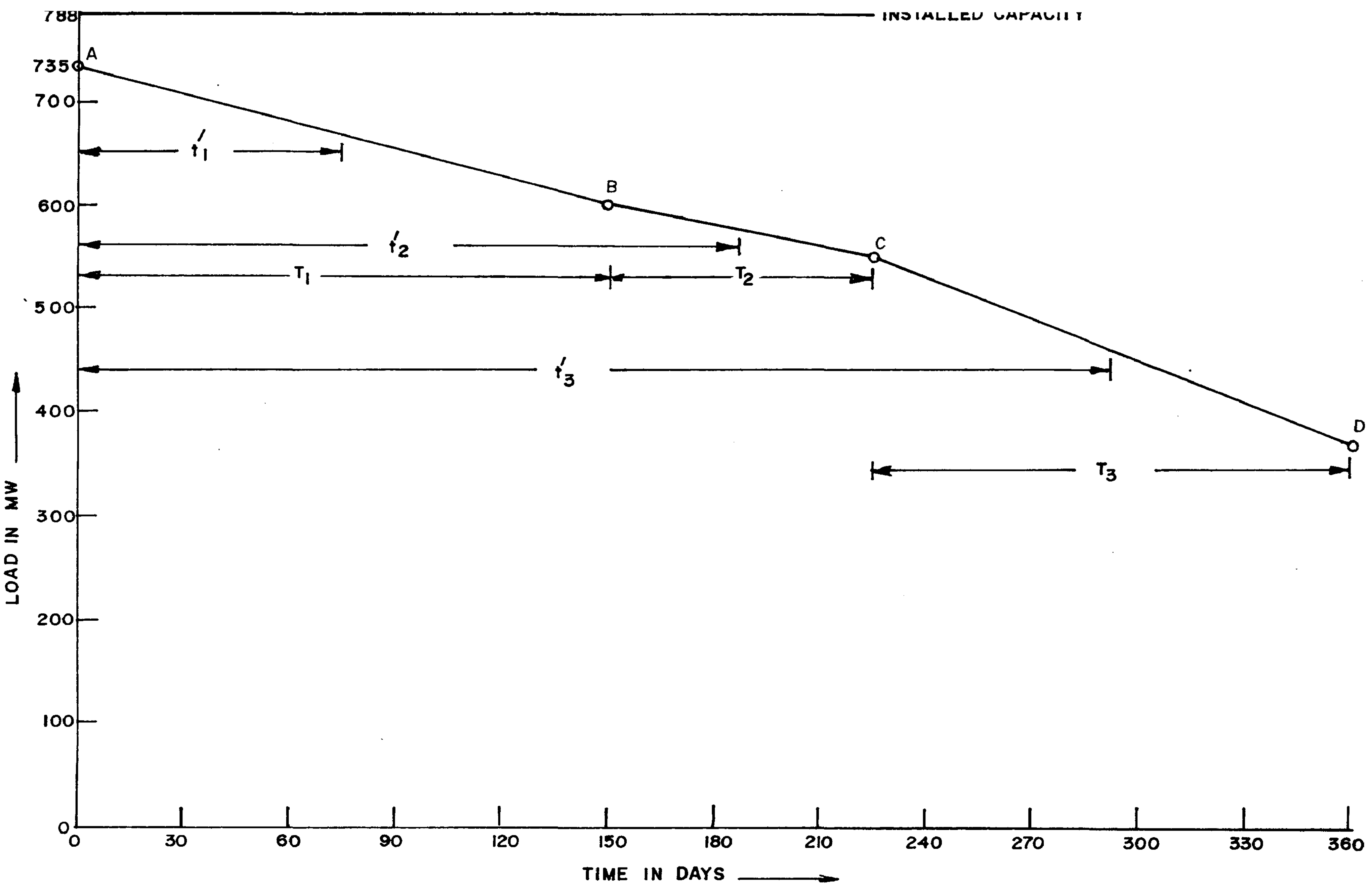


FIG.4.6 SIMPLIFIED CURVE FOR SYSTEM A .

(b) For second segment BC :

Installed capacity = 788 MW
Average load = 575 MW
Time = 75 days.
Reserve capacity = 213 MW

Table 4.31(b) gives loss of load in system A for this average load in segment BC.

(c) For third segment CD :

Installed capacity = 788 MW
Average load = 460 MW
Reserve capacity = 328 MW
Time = 135 days

Table 4.31(c) gives the loss of load in system A for this average load.

The loss of load array is shown in table 4.31 for system A, where it is assumed that system B will assist A upto the point at which B suffers load curtailment. The maximum assistance is limited to the 25 MW tie capacity. For example considering the 150 MW capacity outage row in table 4.31 A,

150 MW out in A and '0' out in B, means 27 MW outage in A; assistance from B = 25 MW. Hence load curtailment in A = 2 MW.

150 MW out in A and '25' MW in B, assistance from B = 25 MW. Hence load curtailment in A = 2 MW.

150 MW out in A and 150 MW out in B, No assistance from system B. Hence load curtailment in A = 27 MW

(etc., etc.)

The rest of the values are obtained in table 4.31 and 4.33 likewise. In table 4.22, the probabilities are given associated with each of these load loss conditions. The values which correspond to actual load losses have been repeated and are shown in tables 4.32 and 4.34. The probability of any loss of load in the given day for system A is the sum of values given in table 4.33 and similarly in table 4.34 for system B. If it was required to find the expected load loss in MW, the probabilities of tables 4.32 and 4.34 would have to be multiplied by the corresponding load losses in tables 4.31 and 4.33 and then summed. The peak load for the day is assumed to represent the system load for the entire day in either case. Summing the probabilities in tables 4.32 and 4.34 gives an expected load loss for system A of 2.7069075 days and for system B 0.02535 days. The system risk expectancy on a day basis for each system considered on a non-interconnected basis can be obtained from capacity outage probability values in table 4.21. The expected value is equal to the cumulative probability of the capacity outage exceeding the reserve.

Table 4.31

Loss of load in System A

(a) For segment AB

	System B							
MW out MW out	0	25	50	75	100	125	150	175
0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0
125	0	0	0	0	0	0	2	2
150	2	2	2	2	2	12	27	27
175	27	27	27	27	27	37	52	52
200	52	52	52	52	52	62	77	77
225	77	77	77	77	77	87	102	102
250	102	102	102	102	102	112	127	127
275	127	127	127	127	127	137	137	137
300	152	152	152	152	152	162	177	177

(b) <u>For segment BC</u>

MW out MW out	0	25	50	75	100	125	150	175
0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0
125	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0
175	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0
225	0	0	0	0	0	0	12	12
250	12	12	12	12	12	22	37	37
275	37	37	37	37	37	47	62	62
300	62	62	62	62	62	72	87	87

(c) **For segment - CD** - The loss of load is approximately zero in this segment.

Table 4.32

Load loss probability in system A

(a) **For segment - AB**

MW out MW out	0	25	50	75	100	125	150	175
0								
25								
50								
75								
100								
125							2	2
150	.00217174	.000241112	0.000050630	0.000097 056	.0000064	.000012	.0000135	.000000315
175	.0083997	.0009315	.0001944	.0003753	.0000243	.0000111	.0000052	
200	.0033904	.0003744	.000078	.000156	.0000104	.0000186		
225	.0009702	.0001078	.0000231	.0000462	.00000295	.000001035		
250	.0002244	.0000204	.000005416	.0000102	.00000071	.000000235		
275	.0000381	.00000476	.000000119	.00000229	.000000155			
300	.0000035568	.0000003952						

Total load loss probability $P_1 = 0.0180236$

$T_1 = 150$

$\therefore \quad P_1 T_1 = 2.70354$ days

MW out MW out	0	25	50	75	100	125	150	175
0								
25								
50								
75								
100								
125								
150								
175								
200								
225								
250	.0000264	.0000024	.000000632	.0000012	.00000084	.00000004		
275	.0000111	.0000001381	.00000029	.00000055				
300	.00000145	.0000001612						

Total load loss probability

P_2 = .0000449

T_2 = 75 days

P_2T_2 = .0033675

(For system A)

FOR SYSTEM B

Table 4.33 - Loss of load in system B

(a) **System B** I.C. = 330 MW
Average load = 190 MW
Reserve = 140 MW
Tie = 25 MW

System A **Segment AB**
I.C. = 788 MW
Average load = 665 MW
Reserve = 123 MW
Tie = 25 MW

(a)	System B							
System A MW out / MW out	0	25	50	75	100	125	150	175
0	0	0	0	0	0	0	0	10
25	0	0	0	0	0	0	0	10
50	0	0	0	0	0	0	0	10
75	0	0	0	0	0	0	0	10
100	0	0	0	0	0	0	0	12
125	0	0	0	0	0	0	10	35
150	0	0	0	0	0	0	10	35
175	0	0	0	0	0	0	10	35
200	0	0	0	0	0	0	10	35
225	0	0	0	0	0	0	10	35
250	0	0	0	0	0	0	10	35
275	0	0	0	0	0	0	10	35
300	0	0	0	0	0	0	10	35

(b) For segment BC System B

	MW out MW out	0	25	50	75	100	125	150	175
System A	0	0	0	0	0	0	0	0	10
	25	0	0	0	0	0	0	0	10
	50	0	0	0	0	0	0	0	10
	75	0	0	0	0	0	0	0	10
	100	0	0	0	0	0	0	0	10
	125	0	0	0	0	0	0	0	10
	150	0	0	0	0	0	0	0	10
	175	0	0	0	0	0	0	0	10
	200	0	0	0	0	0	0	0	22
	225	0	0	0	0	0	0	10	35
	250	0	0	0	0	0	0	10	35
	275	0	0	0	0	0	0	10	35
	300	0	0	0	0	0	0	10	35

Table 4.34

(A) Load loss probability in system B

MW out MW out	0	25	50	75	100	125	150	175
0								.0000619
25								.0000119867
50								.0000095008
75								.000005563
100								.00000145
125							.000026278	.00000023
150							.00000508	.00000041
175							.000001456	
200								
225								
250								
275								
300								

Total expected loss in load probability = .0001236

Time T_1 = 150 days

P_1T_1 = 0.01854

(B) Load loss probability in system B (segment BC)

MW out MW out	0	25	50	75	100	125	150	175
0								.0000619
25								.0000119867
50								.0000095008
75								.0000055639
100								.000001298
125								.0000006044
150								.0000001169
175								
200								
225								
250								
275								
300								

$P_2 = .0000908$

$T_2 = 75$

$\therefore \; P_2T_2 = .00681$

Total expected load loss in system B (25 MW tie)
= .01854 + .00681
= 0.02535

Table 4.35

Tie capacity = 50 MW

Loss of load in system A

(a) Segment AB

		System B							
	MW out MW out	0	25	50	75	100	125	150	175
	0	0	0	0	0	0	0	0	0
	25	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0
System A	125	0	0	0	0	0	0	2	2
	150	0	0	0	0	0	22	27	27
	175	2	2	2	2	12	37	52	52
	200	27	27	27	27	37	62	77	77
	225	52	52	52	52	62	87	102	102
	250	77	77	77	77	87	102	127	127
	275	102	102	102	102	112	127	152	152
	300	127	127	127	127	137	152	177	177

(b) Segment BC Loss of load in system A

		System B							
	MW out MW out	0	25	50	75	100	125	150	175
	0	0	0	0	0	0	0	0	0
	25	0	0	0	0	0	0	0	0
System A	50	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0
	125	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	175	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	225	0	0	0	0	0	0	12	12
	250	0	0	0	0	0	22	37	37
	275	12	12	12	12	22	37	52	52
	300	37	37	37	37	47	72	87	87

Table 4.36

(a) Loss of load probability in system A (segment AB)

		System B							
	MW out MW out	0	25	50	75	100	125	150	175
System A	0								
	25								
	50								
	75								
	100								
	125							.0000052	.0000012
	150						.000022	.0000135	.00000316
	175	.0006222	.000069	.0000144	.0000278	.0000108	.0000111	.0000052	
	200	.0012604	.0001944	.0000405	.0000783	.0000074	.0000186		
	225	.0006552	.000078	.0000156	.000026	.00000237	.00000103		
	250	.000231	.0000231	.00000408	.0000077	.0000006	.000000214		
	275	.0000408	.000003825	.000000803	.000001542	.000000114			
	300	.00000297	.00000033						

$P_1 = .0039256$

$T_1 = 150$

$P_1T_1 = 0.58884$

(b) Loss of load in system A (segment BC)

System B

System A

MW out MW out	0	25	50	75	100	125	150	175
0								
25								
50								
75								
100								
125								
150								
175								
200								
225								
250						.000000462		
275	.0000036	.0000045	.0000092	.000001181	.000000 2244			
300	.00000865	.000000162						

$P_2 = .0000298$

$T_2 = 75$

$\therefore P_2T_2 = .002235$

Total expected loss of load inSystem A (50 MW) = 0.58884 + .002235
= 0.591075

Table 4.37

System B - Loss of load with segment AB of System A

(a) System B

	MW out MW out	0	25	50	75	100	125	150	175
	0	0	0	0	0	0	0	0	0
	25	0	0	0	0	0	0	0	0
System A	50	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	12
	125	0	0	0	0	0	0	10	35
	150	0	0	0	0	0	0	10	35
	175	0	0	0	0	0	0	10	35
	200	0	0	0	0	0	0	10	35
	225	0	0	0	0	0	0	10	35
	250	0	0	0	0	0	0	10	35
	275	0	0	0	0	0	0	10	35
	300	0	0	0	0	0	0	10	35

(b) For segment BC

System B

	MW out MW out	0	25	50	75	100	125	150	175
System A	0	0	0	0	0	0	0	0	0
	25	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0
	125	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	175	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	22
	225	0	0	0	0	0	0	10	35
	250	0	0	0	0	0	0	10	35
	275	0	0	0	0	0	0	10	35
	300	0	0	0	0	0	0	10	35

Loss of load probability in system B (segment AB) = .0000348

T_1 = 150

P_1T_1 = .0052204

Loss of load probability in system B (segment BC) = 0.0 (negligible)

∴ Total expected loss of load in system B = 0.0052204

Table 4.38

Tie Capacity 75 MW - Loss of load in System A

(a) With segment AB

		System B							
	MW out MW out	0	25	50	75	100	125	150	175
System A	0	0	0	0	0	0	0	0	0
	25	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0
	100	0	0	0	0	0	0	0	0
	125	0	0	0	0	0	0	2	2
	150	0	0	0	0	0	12	27	27
	175	0	0	0	0	12	37	52	52
	200	2	2	2	12	37	62	77	77
	225	27	27	27	37	62	77	102	102
	250	52	52	52	62	87	112	127	127
	275	77	77	77	87	112	137	152	152
	300	102	102	102	112	137	152	177	177

(b) With segment BC - Loss of load in A

MW out MW out	0	25	50	75	100	125	150	175
0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0
125	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0
175	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0
225	0	0	0	0	0	0	12	12
250	0	0	0	0	0	22	37	37
275	0	0	0	0	22	47	62	62
300	12	12	12	22	47	72	87	87

Table 4.39

Loss of load probability in System A - Segment AB

(A)

MW out / MW out	0	25	50	75	100	125	150	175
0								
25								
50								
75								
100								
125							.0000052	.0000012
150						.000012	.0000135	.00000316
175					.0000108	.0000111	.0000052	
200	.0001304	.0000144	.0000030	.0000361	.0000074	.0000019		
225	.0003402	.0000378	.0000081	.0000135	.00000237	.0000008		
250	.0001144	.0000104	.00000276	.0000062	.000000609	.00000024		
275	.0000231	.00000288	.000000606	.00000131	.000000114			
300	.00000238	.000000265						

P_1 = .0008231

T_1 = 150

P_1T_1 = .0617325

= 0.123465

(B) For segment BC

MW out / MW out	0	25	50	75	100	125	150	175
0								
25								
50								
75								
100								
125								
150								
175								
200								
225								
250						.00000045		
275					.000000012			
300	.00000025	.000000032						

P_2 = 0.000000789

T_2 = 75

P_2T_2 = .0000525

Total loss in system A = 0.1235175

Table 4.40

Loss of load in system B (Tie = 75 MW)

System B

(A) For segment AB

MW out (System A) \ System B MW out	0	25	50	75	100	125	150	175
0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	12
125	0	0	0	0	0	0	10	35
150	0	0	0	0	0	0	10	35
175	0	0	0	0	0	0	10	35
200	0	0	0	0	0	0	10	35
225	0	0	0	0	0	0	10	35
250	0	0	0	0	0	0	10	35
275	0	0	0	0	0	0	10	35
300	0	0	0	0	0	0	10	35

(B) <u>For segment BC</u>

System B

	MW out MW out	0	25	50	75	100	125	150	175
	0	0	0	0	0	0	0	0	0
	25	0	0	0	0	0	0	0	0
	50	0	0	0	0	0	0	0	0
	75	0	0	0	0	0	0	0	0
System A	100	0	0	0	0	0	0	0	0
	125	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	0	0	0
	175	0	0	0	0	0	0	0	0
	200	0	0	0	0	0	0	0	0
	225	0	0	0	0	0	0	10	35
	250	0	0	0	0	0	0	10	35
	275	0	0	0	0	0	0	10	35
	300	0	0	0	0	0	0	10	35

Loss of load probability in system B (segment AB) = 0.0000348

$T_1 = 150$

$P_1T_1 = .0026102x2$

$= 0.0052204.$

Loss of load probability in system B (segment BC) = 0.0 (negligible

The table 4.5 shows the final tabulated results.

Expected loss of load in days individual system

System A	3.1354059
System B	0.7714147

Table 4.5

Interconnected system		
Tie = 25 MW	Tie = 50 MW	Tie = 75 MW
2.7069075	0.591075	0.1235175
0.02535	0.0052204	0.0052204

The values shown in the above table represent the expected contribution to the total risk for a year considering firstly the individual systems separately, and then by interconnection by a tie line of 25, 50 and 75 MW respectively.

4.4. BENEFITS DUE TO INTERCONNECTION.

Table 4.5 indicates that the expected loss of load in days decreases if we interconnect two systems than by letting it remain non-interconnected. Hence the load carrying capability of the combined system as well as individual system increases. Interconnection benefit to a system can be defined as the corresponding increase in load carrying capability at a specified risk level.

The effect of varying the interconnection capacity between the two systems A and B has been studied, for 25 MW, 50 MW and 75 MW as tie capacities. Fig. 4.7 (a,b) and table 4.5 show that as the tie capacity increases, the risk in each system decreases until it reaches a point at which any increase in tie capacity has no further effect. This point is a function of operating reserve in the two systems, the load models and the generating capacity models. This point is designated as 'infinite tie capacity' (35). This is clearly seen in Fig.4.7.(a,b).

4.5. RELIABILITY EVALUATION IN MORE THAN TWO SYSTEMS.

The method employed to evaluate risk levels for two systems which are interconnected can be suitably extended when a third system is added. An assistance probability table of the third system can be obtained which contains the different capacity assistance levels each of which has a probability of availability. The table is developed using the capacity outage probability table, the available system reserve and the tie capacity. For a given capacity on outage, the assistance is equal to the difference between the operating reserve and the capacity on outage or the tie capacity whichever is less. The probability of this assistance is the probability of the capacity outage itself. For instance, in the figure 4.8, if system A is connected to systems B and C, the risk level in system A is obtained using the combined capacity model of systems A and B, adding the capacity assistance from system C to system A directly, and multiplying the expected loss of load by the probability of the assistance from system C. The sum of the products obtained for all the levels in the assistance probability table of system C is the risk in system A (35).

The description of this method considering an hypothetical example is not attempted here, since they are lengthy and involved, and can be easily obtained in the references.

CHAPTER - V

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

5.1. CONCLUSIONS.

The apparent superfluity of the probability method has been disproved in the preceding pages and some of the very basic probability theory necessary in the study of Generation reserve capacity and interconnected power systems has been discussed. The utilization of probability techniques permits all the pertinent parameters to be incorporated into the analysis of system reliability.

In the typical case of system generating capacity reserve, the problem not only concerns the risk of outage, but also the economic balance between generator reserve and tie capacity in providing against local outage concentrations. The generating equipment tend to go through the general breaking-in, useful life and wear out phases. The useful life period can be extended considerably by preventive maintenance, and many utilities are now commencing to collect data on equipment which has progressed well into its useful life.

Methods have been discussed to obtain reliability indices to complicated probability calculations for Generation reserve and interconnections. But the actual expectation for any one year or even for a period of few years will vary considerably from the most probable mean value. The reliability index or design standard that can be used in future studies is that value obtained after intensive study of the present or past system and found to be satisfactory under these conditions(35).

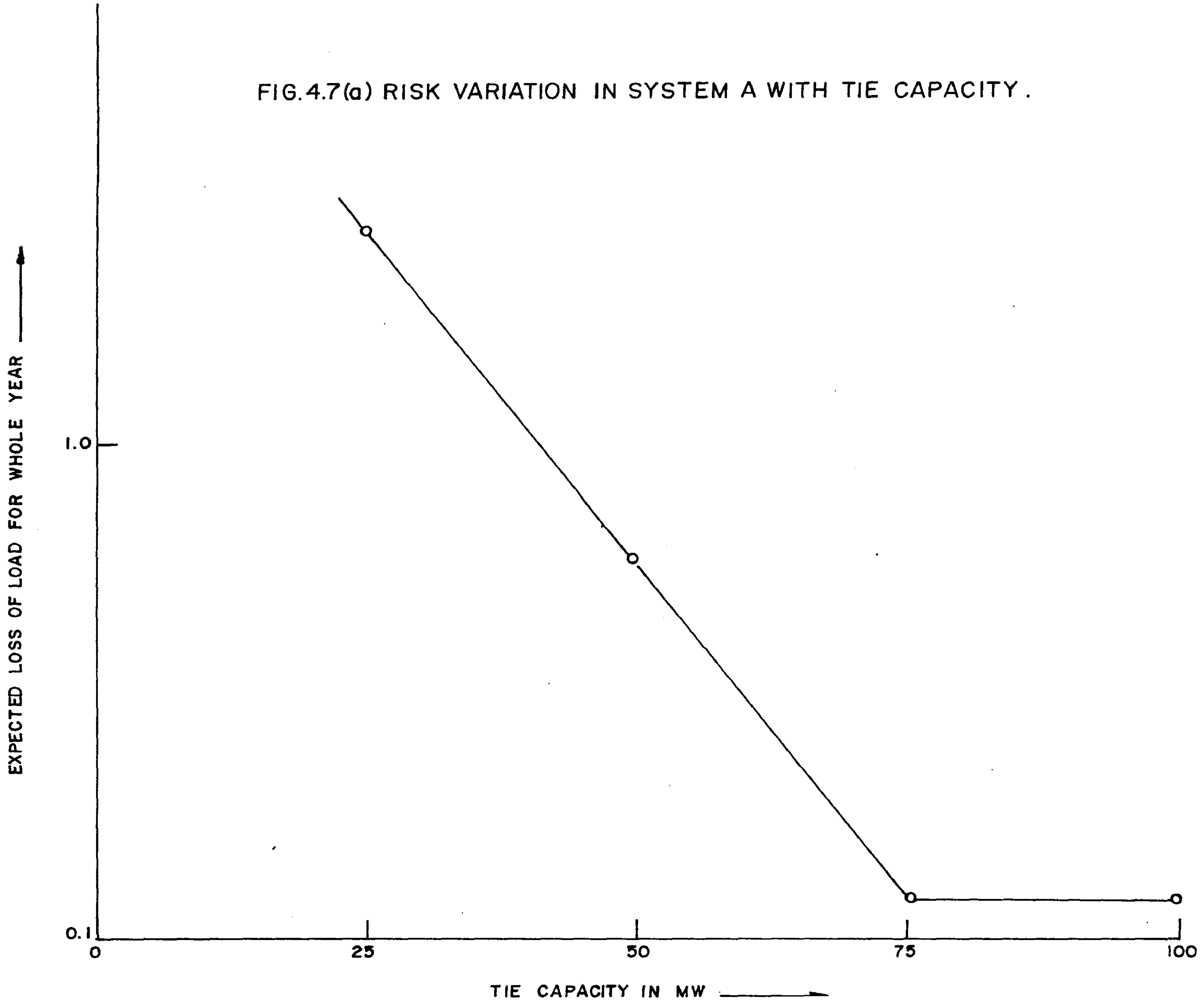
The capacity outage probability tables developed for two practical systems A and B (Chapter III) were as a result of calculations done by digital computer TDC-312, the programs for which were developed and are shown in Appendix-I. The programs can be combined and further extended for calculations of risk levels for two systems but for the limited memory locations for this computer.

The application of probability methods for an interconnected study provides an analytical approach which can include all the factors for reliability assessment, as shown in Chapter IV. For a two-system analysis, it has been shown that as the tie capacity increases, the risk in each system decreases until it reaches a point at which any increase in tie capacity has no further effect (Fig.4.7)(a b). The approach can be extended for more than two systems or for whole U.P.Power System, but this is not attempted here as it would occupy time and space as the present work itself.

5.2. SUGGESTIONS FOR FURTHER WORK.

In this dissertation, two practical systems have been considered, and the reliability index has been evaluated considering the systems individually, and then on an interconnected basis. The assumptions made, regarding tie line outages as negligible implies that the tie-lines are somewhat oversized when judged by the reliability standard set up for

FIG. 4.7(a) RISK VARIATION IN SYSTEM A WITH TIE CAPACITY.



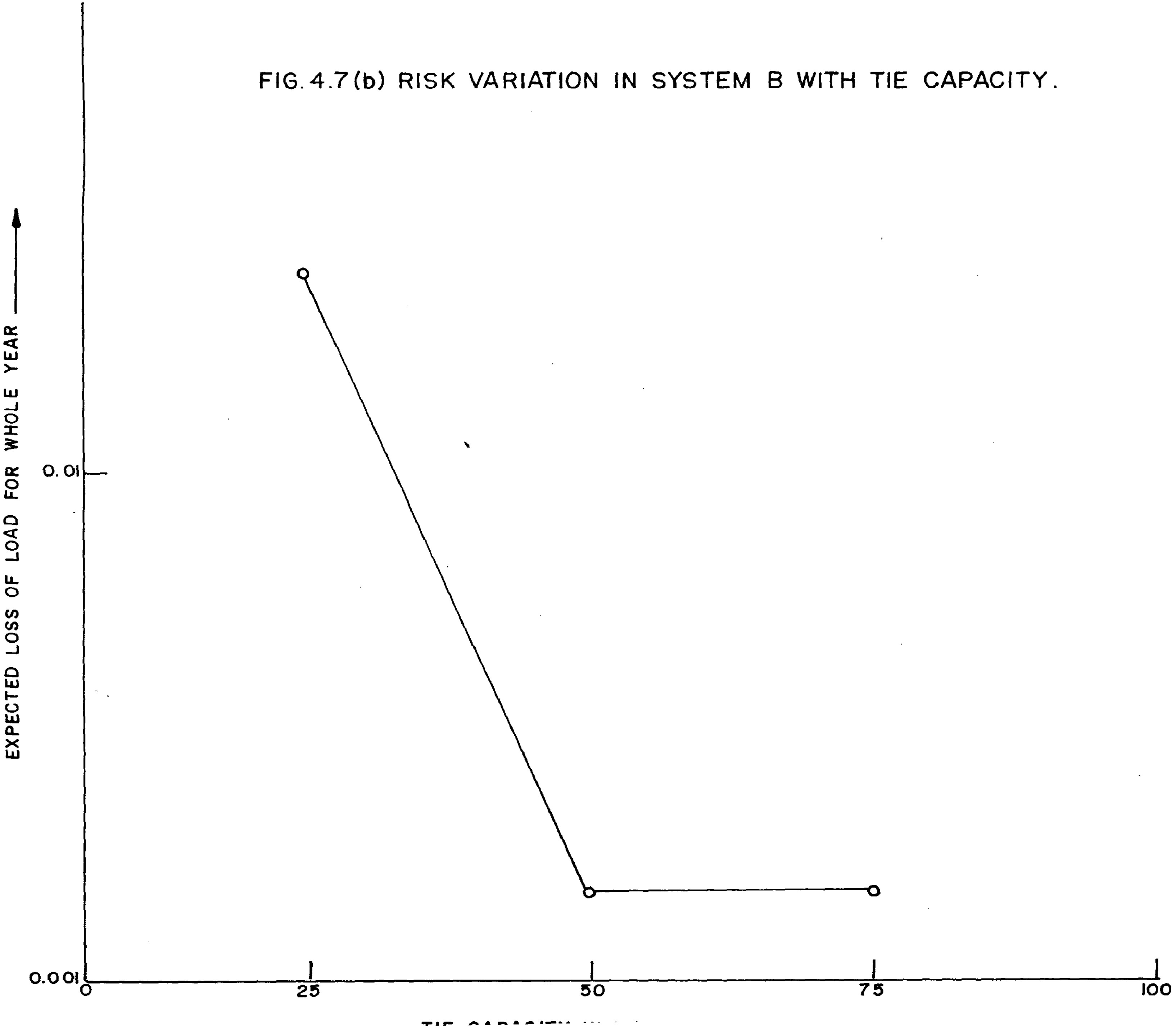


FIG. 4.7(b) RISK VARIATION IN SYSTEM B WITH TIE CAPACITY.

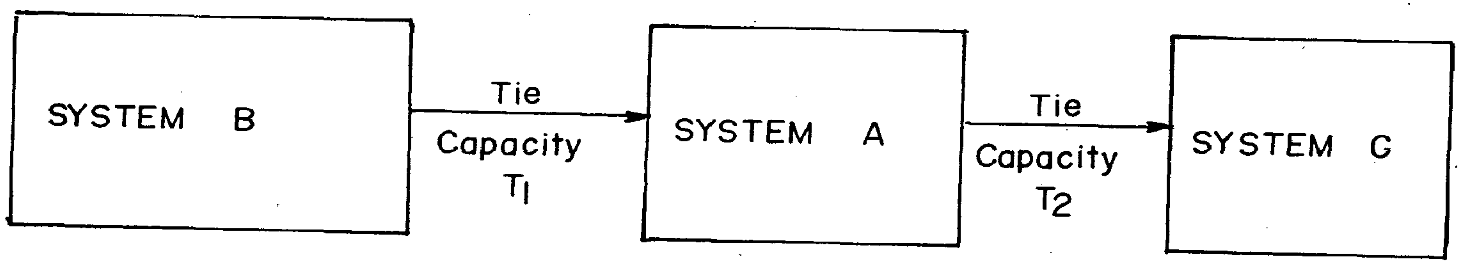


FIG. 4.8 INTER CONNECTED SYSTEM A, B, C .

the power supply. For two interconnected systems, this would not introduce any appreciable error, but if the studies are confined to more than two systems, this assumption is not justifiable and would introduce errors. This points out the need for collecting more information on transmission component outage.

Furthermore, the problem for more than two systems or for a whole U.P. power system would become quite comprehensive and tedious. The need would be recognized for improvement in the outage factors applied to the many components of generation and transmission systems for which reliable datas have to be made available. It will be indispensable to develop general computer programs to calculate the risk levels for the combined system as a whole, as well as individual systems, which would require greater dimensions in the program, greater card handling, punching, compilation and hence consume more of computer time.

In the course of time when a national grid is formed, installed capacity would increase considerably, the necessity of solving system reserve and interconnections problems and measuring the service reliabilities in a scientific manner will be felt. It would be in the interest of Indian Power companies to keep themselves abreast of the new developments on this aspect of the problem, as a lot of active research work has been published and is going on in U.S., where the problem has already been tackled effectively.

APPENDIX - I

COMPUTER PROGRAMS

```
C   C     PROBABILITY CALCULATION SRIVASTAVA
          DIMENSION CAP(30), CUMP(30), CA(2), PA(2), RCAP(30),
               RCUM(30), PR(10), CO(10), CI(10), NUO(10)
          READ TC, FOR, N1, ACAP
          WRITE 121, TC, FOR, N1, ACAP
   121:   FORMAT (/,b̸b̸b̸b̸,E, b̸b̸b̸b̸b̸, E, b̸b̸b̸b̸, I, b̸b̸b̸b̸, E)
   125:   FORMAT (/,b̸b̸b̸b̸, I, b̸b̸b̸b̸b̸, E)
          NA = N1
          I  = 1
          CR = 1.0
          AM = 0.0
          M  = 0
          NUO(I) = 0
          CO(I) = AM * ACAP
          CI(I) = TC-CO(I)
          PR(I) = CR * FOR ** M * (1. -FOR) ** (NA-M)
          AN = N1
          N  = N1
          DO 110 M = 1,N
          L = I
          I = I+1
          AM = M
          TR = M-1
          NUO(I) = L
```

```
          CO(I) = ACAP * AM
          CI(I) = TC - CO(I)
          CR = CR * (AN-TR)/AM
          PR(I) = CR * FOR ** M * (1.-FOR) ** (NA-M)
  110:    CONTINUE
          WRITE 1100
 1100:    FORMAT ("PROBABILITY NO OF UNITS OUT CAPACITY OUT
               CAPACITY IN",/)
          LM = N+1
          DO 40 K = 1, LM
          WRITE 30, PR(K), NUO(K), CO(K), CI(K)
   30:    FORMAT (E, " b̸b̸b̸b̸b̸b̸b̸ ", I, " b̸b̸b̸b̸b̸b̸ ", I, " b̸b̸b̸b̸b̸b̸ ",I,/)
   40:    CONTINUE
          STOP
          END
```

```
C     C     CUM PROB CAL   SRIVASTAVA
            DIMENSION PR(15), CUMP(15), CO(15), CI(5), CAP(15)
            READ LM
            DO 99 I = 1, LM
            READ CO(I), PR(I)
      99:   CONTINUE
            L = LM
            CUMP (L) = PR (LM)
            WRITE 17, CO(L), CUMP(L)
      17:   FORMAT (/, ' b̸b̸b̸ ', ' b̸b̸b̸b̸b̸ ', E, ' b̸b̸b̸b̸ ', E)
            M = LM
      53:   N = M
            M = N-1
            PR(M) = PR(N) + PR(M)
            L = L-1
            CUMP(L) = PR(M)
            IF(M-1), 50,61,50
      50:   WRITE 17, CO(L), CUMP(L)
            GO TO 53
      61:   WRITE 17, CO(L), CUMP(L)
            DO 115, I = 1, LM
            CAP(I) = CO(I)
     115:   CONTINUE
            NUNT = LM
            STOP
            END
```

```
C     C     PROGRAM FOR ADDING SINGLE UNIT    SRIVASTAVA
            DIMENSION CAP (70), CUMP(70), CA(2), PA(2), RCAP(70),
                 RCUM(70), ICAP(10)
            READ NONT, PO, NADD
            DO 127 I = 1, NUNT
            READ CAP(I), CUMP(I)
      127:  CONTINUE
            DO 122 II= 1, NADD
            READ ICAP(II)
            WRITE 222, II, ICAP(II)
      122:  CONTINUE
      222:  FORMAT (/, "ADDED CAP.",/, ' ƀƀƀƀ ', I, ' ƀƀƀƀƀ ',E)
            NB = 1
            DO 128 IJ = 1, NADD
            IC = ICAP (II)
            NN = NUNT + 1
            CAP(NN) = 0.0
            CUMP(NN) = 0.0
            CA(1) = 0.0
            CA(2) = IC
            PA(1) = (1.-PO)
            PA(2) = PO
            I = 1
            J = 1
            NA = 1
       51:  IF ((CAP(I) + CA(1)) - (CAP(I) + CA(2)) 2, 24, 4
        2:  IF (PA(1) * CUMP(I)) 5, 3, 5
        5:  RCAP(NA) = CAP(I) + CA(1)
            RCUM(NA) = PA(1) * CUMP(I) + PA(2) * CUMP(J)
```

```
   8:   NA = NA + 1
        I = I + 1
        GO TO 51
   3:   IF(CUMP(J)) 14, 11, 14
  14:   RCAP(NA) = CAP(J) + CA(2)
        RCUM(NA) = PA(2) * CUMP(J)
        J = J+1
        IF(NA-70) 9, 11, 11
   9:   NA = NA + 1
        GO TO 3
   4:   IF (PA(1) * CUMP(I)) 501, 3, 501
 501:   RCAP(NA) = CAP(J) + CA(2)
        RCUM(NA) = PA(1) * CUMP(I) + PA(2) * CUMP(J)
        IF (NA-70) 6, 11, 6
   6:   NA = NA + 1
        J = J + 1
        GO TO 51
  24:   IF (PA(1) * CUMP(I)) 21, 3, 21
  21:   RCAP(NA) = CAP(I) + CA(1)
        RCUM(NA) = PA(1) * CUMP(I) + PA(2) * CUMP(J)
        IF(NA-70) 7, 11, 11
   7:   NA = NA + 1
        I = I + 1
        J = J + 1
        GO TO 51
```

```
10:  FORMAT (/,/, ' b̸b̸b̸b̸ ', I, ' b̸b̸b̸b̸ ', E, ' b̸b̸b̸b̸ ', E)
11:  NUNT = NA-1
     DO 120 I = 1, NUNT
     CAP(I) = RCAP(I)
     CUMP(I) = RCUM(I)
120: CONTINUE
     NB = NB+1
128: CONTINUE
     WRITE 200
200: FORMAT (/, "FINAL RESULT", /,/, " S.NO. OUTAGE CAP CUM
            PROB" )
     DO 201 I = 1, NUNT
     WRITE 10, I, CAP(I), CUMP(I)
201: CONTINUE
     STOP
     END
```

```
C     C  PROBABILITY ROUNDING PROGRAM      SRIVASTAVA
         DIMENSION PROB(70),NOUT(70), POUT(20), PROT(70), RPRB(20)
         READ NTOT, RND, NAB
         WRITE 18, NTOT, RND, NAB
         DO 201, I = 1, NAB
         READ NOUT (I), PROB (I)
    201: CONTINUE
     18: FORMAT (' b̸b̸b̸b̸ ', I, ' b̸b̸b̸b̸b̸b̸ ', I, ' b̸b̸b̸b̸b̸ ', I, /)
         L = 1
         IRND = RND
    119: M = L+1
         PROB(L) = PROB(L) - PROB(M)
         WRITE 25, NOUT(L), PROB(L)
         L = L+1
         IF (L-NAB) 119, 139, 139
    139: NAM = (NTOT + (IRND -1)) / IRND
         NAM 1 = NAM + 1
         DO 998 I = 1, NAM 1
         AK = I-1
         PRO = 0.0
         IN = 1
         POUT(I) = AK - RND
     11: PROT(IN) = NOUT(IN)
         IF (PROT (IN) - POUT(I)) 14, 2, 3
      2: PRO = PRO + PROB(IN)
     30: IN = IN+1
         GO TO 11
```

```
  3: IF(PROT(IN) - POUT(I) + RND)) 4,5,5
 14: AB = POUT(I) - PROT(IN)
     IF (AB-RND) 4,30,30
  4: DIF = POUT(I) - PROT(IN)
     IF(DIF) 21,22,22
 21: DIF = - DIF
 22: DIF = 1 -DIF/RND
     PRO = PRO + PROB(IN) * DIF
     IN = IN+1
     GO TO 11
  5: RPRB(I) = PRO
     WRITE 25, POUT(I), RPRB(I)
998: CONTINUE
 25: FORMAT (/, ' ƀƀƀƀƀ ', E, ' ƀƀƀƀ ', E)
     STOP
     END
```

APPENDIX - II

DESCRIPTION OF ROORKEE AREA CONTROL (SYSTEM A)

Table -1

S.No. 1.	Place where generating unit installed. 2.	Installed capacity (MW) 3.	Dereated capacity 4.
1.	Yamuna Stage-I		
	a) Dhakrani	3x11.25	34.0
	b) Dhalipur	3x17	51.0
2.	Yamuna Stage-II		
	a) Chibro	4x60	240 MW
	b) Khodri (under construction)	4x30	-
3.	Yamuna stage-III		
	a) Kulbal	3x10 MW	-
4.	Ganga Canal Power Houses		
	(i) Pathri	3x6.80	-
	(ii) Mohd. Pur	3x3.1	-
	(iii) Nirgajni	2x2.5	-
	(iv) Chilaura	2x1.5	-
	(v) Salawa	2x1.5	-
	(vi) Bhola	4x0.375) 2x0.6)	-
	(vii) Sumera	2x0.6	-
5.	Harduaganj 'A' (Thermal)	3x30) 2x55)	-
6.	Haruaganj 'B' Extension	2x50) 1x60)	-
7.	Agra Fort	1x6.0	-
8.	Agra New	1x10	-

For making calculations procedure simpler, we consider all the smaller machines by grouping them together as 2x25 MW machines. Thus, the machines of Chitaura, Salawa, Mohd.pur, Nirgajni, Agra Fort and Pathri can be grouped in this fashion.

Similarly, making groups in ascending order, we get the following simplified table -II for whole Roorkee Area Control:

Table - II

System	No.of M/cs	Capacity of each	Total capacity MW
(i)	7	60 MW	420
(ii)	2	50 MW	100
(iii)	3	30 MW	90
(iv)	2	25 MW	50
(v)	4	17 MW	68
(vi)	6	10 MW	60

Table -III

Description of System B (Bareilly Area Control)

S.No.	Place	Installed capacity
1.	Ramganga	3x66
2.	Khatima	3x13.8
3.	Bareilly	4x1.25 2x12.5
4.	Chandausi	2x3.0
5.	Moradabad	(2x15 + 25)

Table - IV

(Simplified Table)

S.No.	No.of machines	Capacity MW	Total capacity
1.	3	66	198
2.	1	20	20
3.	5	15	75
4.	3	12	36

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ERRATA

	Page	Read	Instead of
(i)	15	$\frac{n}{(n-r)!\,r!}\cdot p^{n-r}.q^{r}$ in r^{th} term of expansion	$\frac{n}{(n-r)!\,r!}\ .p.q^{r}$
(ii)	15	Binomial	Binamial
(iii)	15	n terms	n tems
(iv)	15	$(p+q)^{n}=\sum_{r=o}^{n} n_{C_r}.p^{n-r}.q^{r}$	$(p+q)^{n}=n_{C_r}.p^{r}.q^{n-}$
(v)	16	p_n (2nd line)	~~P_N~~ pn
(vi)	22	For three smaller units	For two smaller
(vii)	22	$(p+q)^3=(0.98+0.02)^3=1$	$(0.48+0.02)^2 =$
(viii)		$\lambda = \frac{\bar{A}}{rA} = \frac{u\bar{A}}{A} = 0.0100$	$= \frac{\bar{A}}{rA} = \frac{u\bar{A}}{A} = ($
(ix)	69	table 4·32 (11th line)	table 4·33