Generation System Reliability Evaluation

Important terms and definitions

- **Unit**: is a group of components which are functionally related to generation (Generating unit, steam turbine unit,).
- **Component**: is a device which performs a major operating function. (As transformer, Switchgear, circuit breaker, isolator, resistor, inductor, capacitor, transistor, etc.).

The component can be classified into two groups

1. Non-repairable component
2. Repairable component.

State of events for units and components : can be in divided in two states:

1. In-service state (**Up state**)
2. Outage state (**Down state**)

- **The outage states or (not in service) are** :

(a) Forced outages

(i) Transient forced outage

(ii) Permanent forced outage

(iii) Temporary forced outage

(b) Schedule outage

A planned outage for purposes of testing, maintenance, construction or repair.

Forced outage rate and Availability:

Consider a single generating unit shown in Fig.1. Let:-

-the set of service time is $S_s = \{ T_{u1}, T_{u2}, T_{u3}, T_{u4} \}$ and

-the set of down time is, $S_f = \{ T_{d1}, T_{d2}, T_{d3} \}$

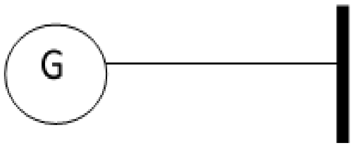


Fig.1

The history of this generator is shown in Fig.2.

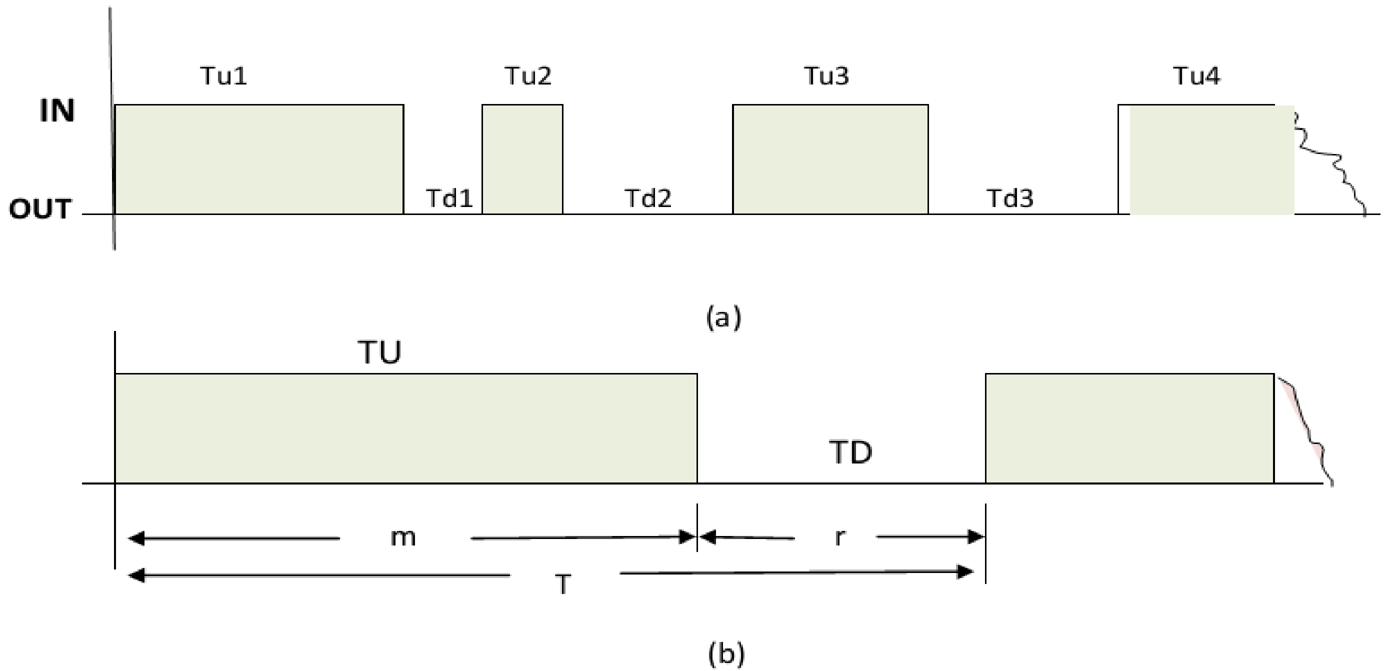


Fig.2 Generator service history.

Referred to Fig.2 (a) ,

Sum of total time period

Numbers of period

In this case N_u=4 and n_d=3

Mean service time = $T_U = \sum_{i=1}^{n} \frac{T_{ui}}{n_u} = m$

Mean repair time = $T_D = \sum_{i=1}^{n} \frac{T_{Di}}{n_d} = r$

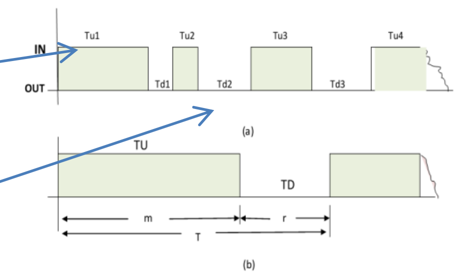


Fig.2 Generator service history.

Let : m = mean time to failure $= \frac{1}{\lambda}$ = MTTF

r = mean time to rapier $= \frac{1}{\mu}$ = MTTR

T= m+r = mean time between failure $= \frac{1}{f}$

f= cycle frequency.

The forced outage rate (FOR) is defined as:

$$FOR = \frac{r}{m+r} = \frac{1/\mu}{1/\lambda + 1/\mu} = \frac{\lambda}{\lambda+\mu}$$

The forced outage rate is also called the unavailability U.

The availability is defined as:

$$\text{Availability} = \frac{m}{m+r} = \frac{1/\lambda}{1/\lambda + 1/\mu} = \frac{\mu}{\lambda+\mu}$$

- State probability of one component

The state probability or Markov model of one component is shown in Fig.3.

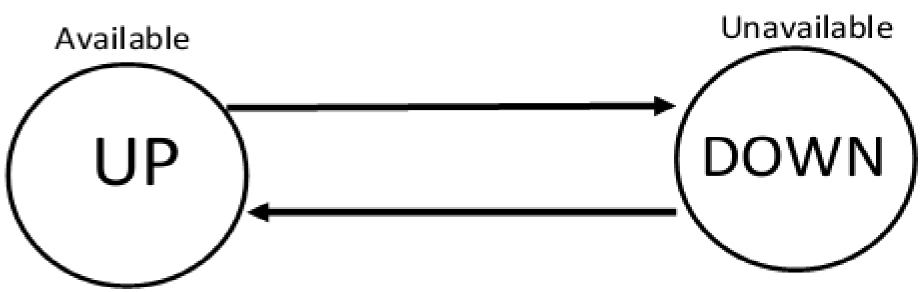


Fig.3 Markov model of one component.

Generation System Reliability Evaluation

In all power system studies, the time period is divided into two periods:

1. **Planning period** : For planning period, we have (Static generating capacity reliability evaluation) and in this case the reserve must be provided for the following reasons:
   - Scheduled or maintenance outage
   - Forced , unplanned or unscheduled outages
   - Load growth in excess of expectation

2. **Operation period** :. For operation period, we have, (Spinning generating capacity reliability evaluation) or (spinning reserve) for forced outages and load forecast uncertainties

Note: In this set of notes only static evaluation will be considered.

Static Generating Capacity Reliability Evaluation (Planning period)

There are two methods in static capacity reliability evaluation:

1- The deterministic (non- probabilistic) method

2- The probabilistic approach

In the deterministic (non-probabilistic) method there are two most common rule methods:-

(a) The percentage reserve margin

(b) one additional largest unit

These two methods do not account for differences in :

- system size,
- different load characteristics
- effect of different size and
- type of units.

In both deterministic and probabilistic methods, the outage probability of the capacities must be constructed first.

Note: Two systems having the same percentage reserve and can have different probabilistic risk, i.e. probability of not meeting the load (not same loads).

Capacity outage probability table

This table is also known as the generation model. It is constructed using Binomial distribution. Although the Binomial distribution has limited applications when the unit sizes and FOR's (forces outage rate) are differs m (mean time of failure) ,but it can be applied in such cases by starting with the smallest unit and continue to odd one unit at a time to the table until all units have been processed. These concepts can be illustrated in the following example:

Example: Construct the capacity outage probability table for the following system:

The system consists of three units:

2x3 MW Units, each has FOR =0.02

1x5 MW Unit, with FOR =0.02

No of unit Unit capacity MW forces outage rate

Solution:

- Consider first the $\boxed{\text{2x3 MW Units in service and 5MW unit out of service :}}$

For these two units, the individual probability table is,

Since q =FOR = 0.02. Hence P = 1-q = 1- 0.02 = 0.98.

Table-1

	Capacity out Of service	Probability
No outage 2 units working	0 MW	$p_1p_2 = (0.98)(0.98)=0.9604$
1 outage 1 units working	3MW	$p_1q_2+p_2q_1= (0.98)(0.02)+ (0.98)(0.02=0.0392$
2 units outage no working	6MW	$q_1q_2= (0.02)(0.02) = 0.0004$
		1.0000

- For 5MW unit in service (q3=0-02 ,p=0.98)

Table-2

Capacity out Of service	Probability
0+0 MW	(0.9604) (0.98) =0.941192
3+0MW	(0.0392) (0.98) = 0.038416
6+0 MW	(0.0004) (0.98) =0.000392
	0.98000

- 5MW unit in service

Table-3

Capacity out Of service	Probability
0+5=5 MW	(0.9604) (0.02) =0.019208
3+5=8MW	(0.0392) (0.02) = 0.000784
6+5=11 MW	(0.0004) (0.02) =0.000008
	0.020000

The final table can be found by combining Table-2 and Table-3 as:

Table-4

The 3 combination of 3,3,5 is
0+0+0=0
3+0+0=3
0+0+5=5
3+3+0=6
3+0+5=8
3+3+5=11

Capacity out Of service	Individual Probability	Cumulative Probability	
0 MW	0.941192	1.000000	1.ooooo-0.941192=0.058808
3 MW	0.038416	0.058808	0.58808-0.038416=0.020392
5 MW	0.019208	0.020392	0.020392-0.019208=0.001184
6 MW	0.000392	0.001184	0.001184-0.000392=0.000792
8MW	0.000784	0.000792	0.000792-0.000784=0.000008
11MW	0.000008	0.000008	0.000008--.000008=0
	1.000000		

+ +

Note: The above tables can be truncated by omitting all capacity outages for which the probabilities are less than 10^{-6} or 10^{-8}.

1. The Deterministic Method

To illustrate the application of the deterministic method, consider the following four generating systems:

No of units

System 1 -	24x10MW	Units having a forced outage rate of 0.01
System 2 -	12x20MW	Units having a forced outage rate of 0.01
System 3 -	12x20MW	Units having a forced outage rate of 0.03
System 4 -	22x10MW	Units having a forced outage rate of 0.01

In each of these systems the units are identical and therefore,the binomial distribution can be used to evaluate the capacity outage probability tables.

From the binomial distribution , the probability of given capacity on forced outage or unavailability is given by:

240MW each

$$\boxed{P_r = P[X = r, n, q] = \frac{n!}{r!(n-r)!} q^r \, p^{n-r}}$$

$$P_r = P[X = r, n, q] = \frac{n!}{r!(n-r)!} q^r\, p^{n-r}$$

Where

n= number of units

r = number of units on forced outage (unavailable)

p = availability (probability of having in-service)

q = unavailability (forced outage rate)

Consider system -1 as an example, the probability of 30 MW out of service is ;

$P[X = 3{,}24{,}0.01] = \frac{24!}{3!(24-3)!} 0.01^3 (1-0.01)^{24-3} = 0.001639$ (to six decimal places).

Using this technique for all systems, the following outage probability tables can be evaluated with truncation of the table to 10^{-6}.

Table-1 Capacity outage probability tables for systems 1-4

System 1

Capacity (MW)		Probability	
Out	In	Individual	Cumulative
0	240	0.785678	1.000000
10	230	0.190467	0.214322
20	220	0.022125	0.023855
30	210	0.001639	0.001730
40	200	0.000087	0.000091
50	190	0.000004	0.000004

System 2

Capacity (MW)		Probability	
Out	In	Individual	Cumulative
0	240	0.886384	1.000000
20	220	0.107441	0.113616
40	200	0.005969	0.006175
60	180	0.000201	0.000206
80	160	0.000005	0.000005

System 3

Capacity (MW)		Probability	
Out	In	Individual	Cumulative
0	240	0.693841	1.000000
20	220	0.257509	0.306159
40	200	0.043803	0.048650
60	180	0.004516	0.004847
80	160	0.000314	0.000331
100	140	0.000016	0.000017
120	120	0.000001	0.000001

System 4

Capacity (MW)		Probability	
Out	In	Individual	Cumulative
0	220	0.801631	1.000000
10	210	0.178140	0.198369
20	200	0.018894	0.020229
30	190	0.001272	0.001335
40	180	0.000061	0.000063
50	170	0.000002	0.000002

(a) *Percentage reserve margin*

Assume that the expected load demands in systems 1, 2, 3 and 4 are 200, 200, 200 and 183 MW respectively. The installed capacity in all four cases is such that there is a 20% reserve margin, i.e. a constant for all four systems. The probabilistic or true risks in each of the four systems can be found from Table -1 and are:

risk in system 1 = 0.000004
risk in system 2 = 0.000206
risk in system 3 = 0.004847
risk in system 4 = 0.000063

These values of risk show that the true risk in system 3 is 1000 times greater than that in system 1. A detailed analysis of the four systems will show that the variation in true risk depends upon the forced outage rate, number of units and load demand. The percentage reserve method cannot account for these factors and therefore, although using a 'constant' risk criterion, does not give a consistent risk assessment of the system.

(b) *Largest unit reserve*

Assume now that the expected load demands in systems 1, 2, 3 and 4 are 230, 220, 220 and 210 MW respectively. The installed capacity in all four cases is such that the reserve is equal to the largest unit which again is a constant for all the systems. In this case the probabilistic risks are:

risk in system 1 = 0.023855
risk in system 2 = 0.006175
risk in system 3 = 0.048650
risk in system 4 = 0.020229

The variation in risk is much smaller in this case, which gives some credence to the criterion. The ratio between the smallest and greatest risk levels is now 8:1 and the risk merit order has changed from system 3–2–4–1 in the case of 'percentage reserve' to 3–1–4–2 in the case of the 'largest unit' criterion.

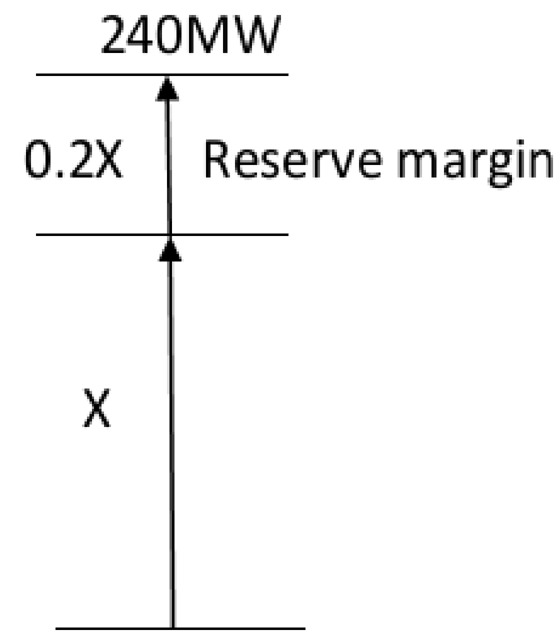
It is seen from these comparisons that the use of deterministic or 'rule-of-thumb' criteria can lead to very divergent probabilistic risks even for systems that are very similar. They are therefore inconsistent, unreliable and subjective methods for reserve margin planning.

Note : Assume 20% reserve : For systems 1,2 and 3 :

$$X+0.2X = 240$$

$$X(1.2) = 240$$

Hence $X = 200$ MW.



For system 4:

$$X+0.2X = 220$$

Hence $X = 183.3$

2. Probabilistic Method

Loss of Load probability Method (LOLP)

Earlier m the capacity outage probability tables were used to evaluate the probabilistic risk assuming constant load level. In practice, however, loads vary and therefore a load model as well as a generation model is required.

The loss of load probability method is probably the most widely accepted and used of all methods for evaluating the risk level in generating systems.

The load model used in this method is the load characteristic shown in Fig.1 below.

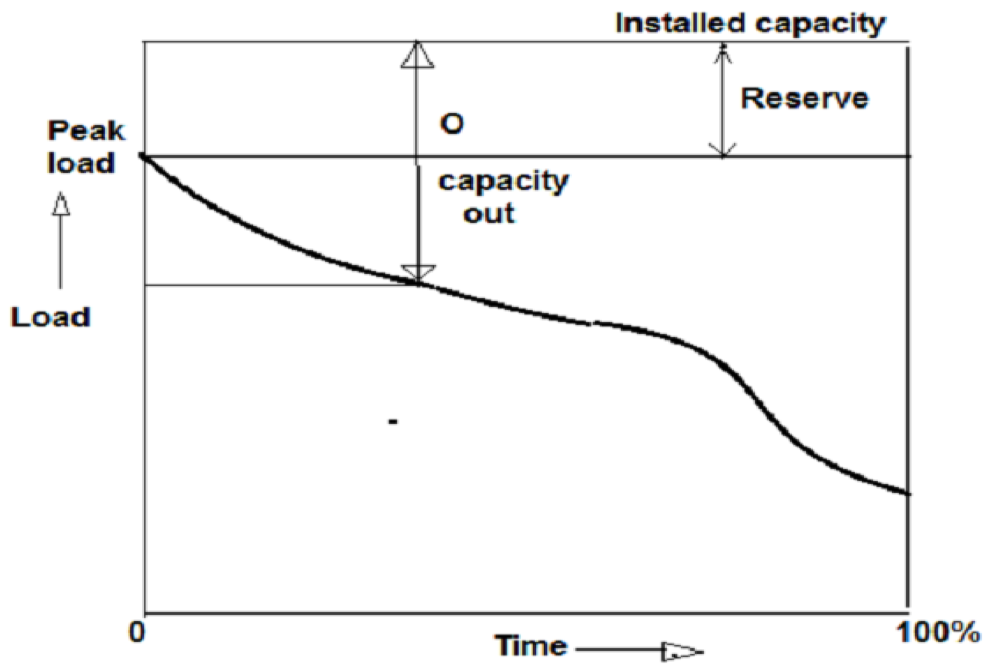


Fig.1

This load characteristic is the load duration curve (LDC) that had been discussed previously. (It is a plot of the load as a function of the number of time units which a load exceeded the indicated value. It may represent a daily peaks loads in a year , the hourly peak loads in a day or any other appropriate time interval of interest ,e.g. deep summer period in a middle east country with a time duration of ,say, 3 months . Similarly it may or may not includes all the days in that period for instant , weekends may be neglected since loss of load is very improbable during these periods).

For simplicity in the following examples :

We will consider the load characteristic to be a plot of daily peak load in a year and therefore the abscissa axis represents 365 days.

It is clear from the load characteristic that a capacity outage less than the reserve will not cause a loss of load. Consider now:

Oi– Is the i^{-th} outage in the system outage probability table.

Pi – the probability of this i^{-th} outage.

ti– the number of time units which this outage causes loss of load .

Then the contribution to the system loss of load by outage Oi is Pi ti time units.

Therefore, the total expected loss of load for the time interval (E) is:

$$E(t) = \sum_{i=1}^{n} \mathrm{P_i}\ t_i \qquad \text{time units}$$

Note: if we consider the load characteristic is the daily peak load variation over a year, the units are expected loss of load in days per year.

To illustrate these principles consider a system having 5x60 MW units (total =300MW) each with forces outage rate (FOR) of 0.03. For simplicity, consider the load characteristic to be linear with a peak load of 240MW and a low load of 100MW as shown in Fig.2.

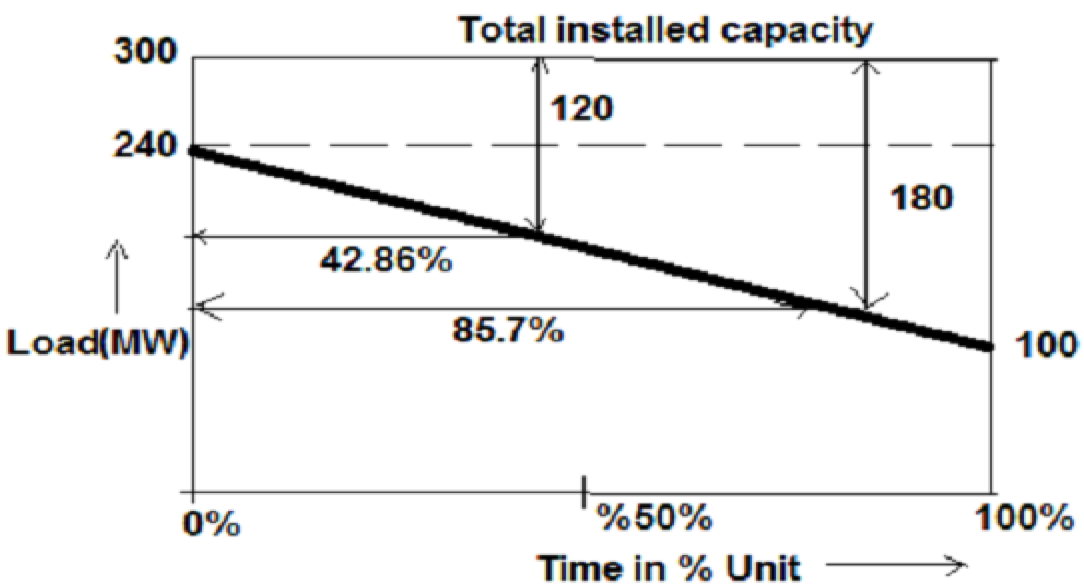


Fig.2

The table of capacity outage probability (generation model) and expected loss of load is therefore:

Capacity out (MW)	Individual probability (P_i)	Time t_i %	Expected Load loss $[P_i * t_i]$
0	0.858734	0	-----
60	0.132794	0	-----
120	0.008214	42.86	0.352052
180	0.000254	85.71	0.021770
240	0.000004	100.00	0.000400
	1.000000		$\sum P_i t_i = 0.374222\%$

$$P_r = P[X = r, n, q] = \frac{n!}{r!(n-r)!} q^r p^{n-r}$$

Expected loss of load if 100% = 365 days is

the total expected loss of load for the time interval

E(t) = 0.374222 x (365 /100) = 1.365910 days/year

This value would reasonably be called excessive. A value often considered as reasonable is **0.1** days /year. (Which means this value is not responsible since its greater than 0.1)

- **Effect of forced outage rate variation**

Forces Outage Rate

Now we shall consider the effect of changing the value of FOR on the loss of load by considering the same system but each unit having a FOR of 0.01. The tables are therefore:

Capacity out (MW)	Individual probability (P_i)	Time t_i %	Expected Load loss $[P_i * t_i]$
0	0.950990	0	-----
60	0.048030	0	-----
120	0.000970	42.86	0.041574
180	0.000010	85.71	0.000857
240	0.000000	100.00	0.000000
	1.000000		$\sum P_i t_i = 0.042431\%$

(Which means this value is accepted since its less than 0.1)

- **Effect of peak load variation**

If the same generating system is analysed for its ability to feed a load characteristic having the same load factor used previously but having peak loads between 120MW and 300MW(120MW instead of 100MW the increse is 20MW)

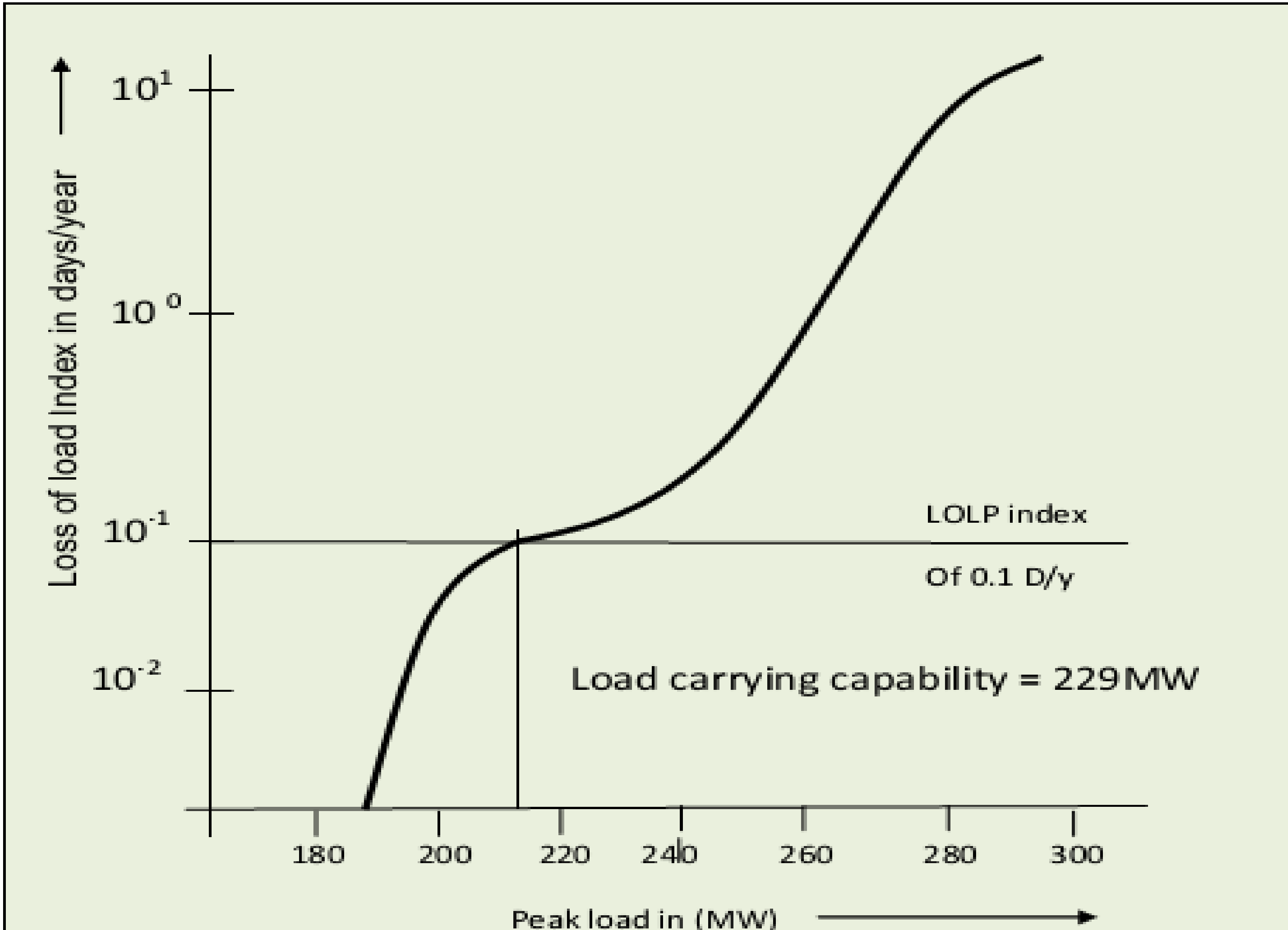
, then the following expected loss of loads would be obtained.

$E(t) = \sum_{i=1}^{n} P_i \, t_i$ time units

Peak Load (MW)	Loss of Load D/y	Peak Load (MW)	Loss of Load D/y
200	0.052679	300	7.820810
180	0.001564	280	5.265140
160	0.001043	260	2.712127
140	0.000522	240	0.154874
120	0.000000	220	0.103754

If a risk level of 0.1 days/year is considered acceptable, then the above generating system is capable of supplying a load characteristic of the assumed shape having a peak load of 220MW. This is known as the load carrying capability of the generating system.

A plot of the previous table showing loss of load in days /year as a function of peak load is shown in Fig.3.



10^1
10^0
10^{-1}
10^{-2}
Loss of load Index in days/year
LOLP index
Of 0.1 D/y
Load carrying capability = 229MW
180
200
220
240
260
280
300
Peak load in (MW)

Fig.5

Expansion Study

It takes a considerable period of time and new generating unit that becomes necessary, using expansion planning studies. (The loss of load probability method can be extremely valuable in such studies). To do this,

- The expected load growth must be known.
- The accepted risk level must be determined
- The size of unit to be added must be decided .

To illustrate the technique consider an acceptable risk level of 0.1 days/year and annual growth rate of **10%** .Also consider that in year 1 of study the peak is **220MW** supplied by the previous generating system of 5x60MW units each having a FOR of 0.01. Also assume that the shape of the load characteristic remains unchanged and is given by the previous linear characteristic.

If the period of study is 8 years, the peak load in each year will be:

Year	1	2	3	4	5	6	7	8
Peak load (MW)	220	242	266	293	322	354	390	429

(220x10%)+220=242 (242x10%)+242=266 and so

Using the previous technique to deduce the expected loss of load in each year of study , the following expansion plan would be attained if 60 MW units are added .

Year	Generating system (MW)	Loss of load (D/year)	Comment
1	5x60	0.10	
2	5x60	0.15	New unit to be added
	6x60	0.01	
3	6x60	0.09	
4	6x60	0.19	New unit to be added
	7x60	0.01	
5	7x60	0.11	New unit to be added
	8x60	0.01	
6	8x60	0.01	
7	8x60	0.23	New unit to be added
	9x60	0.01	
8	9x60	0.1	

It is evident therefore that for the system being considered , a 60 MW unit should be added in years 2,4,5, and 7 , but the system can remain unchanged in years 1,3,6, and 8.
Clearly this expansion study cannot be done in isolation and a present worth cost analysis would need to be done to determine the optimum expansion plan. However, this type of analysis should form an integral part of the planning exercise.

Inclusion of maintenance

We have assumed that the generating system remains constant throughout the year. But its not true becouse the units will be removed for scheduled maintenance.
There are several ways in which this can be achieved; only one of which is the exact method.
The exact method involving modifying the capacity outage probability table so that the true generating system is modelled **This can be time consuming** although simplified if units are removed from the table as described previously rather than building a new table with these units involved.then;

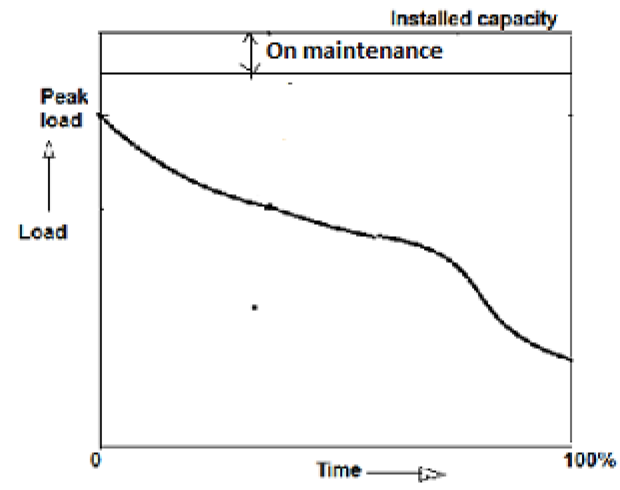
To simplify, two procedures may be used instead of modifying the table

1- Subtract the capacity on maintenance from the installed capacity and therefore reduce the reserve without changing the capacity probability table .or

2- Add the capacity on maintenance to the load. (If maintenance is done only during the low load period and the load characteristic is for the whole year, the capacity on maintenance is added only to the low load period).

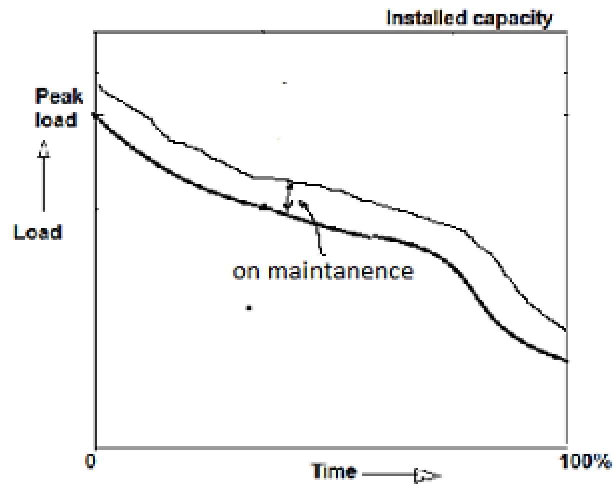
These techniques are shown below in schematic form in Fig.6.

(a)



* It is clear that the last two methods will be approximate although the errors can be negligible if the capacity on maintenance is very small compared with the installed capacity .
* The methods give calculated risks that are greater than the true risk which is increases as the percentage of capacity on outage increases .

(b)


Installed capacity
Peak load
Load
on maintanence
0
Time
100%

(b)

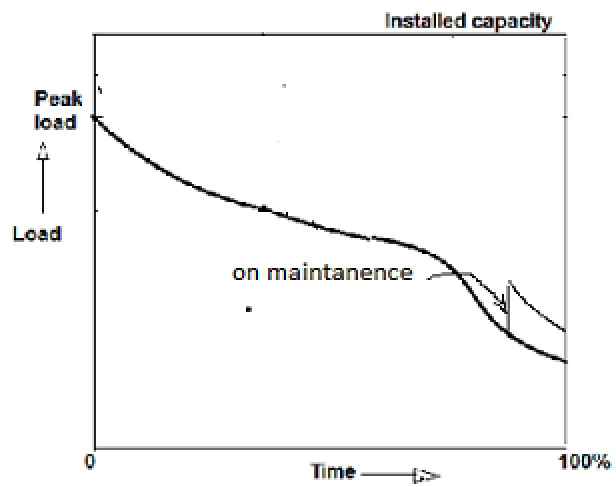

Installed capacity
Peak load
Load
on maintanence
0
Time
100%

Fig.6


Thank you for your attention!