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Economic of Power System Reliability

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Overview of Presentation

- Introduction
- Key Indices of Power System Reliability
- Generator Forced Outage Rate
- Basic Capacity Outage Probability
- Calculation of Power Generation System Reliability Indices
- Calculation of Distribution System Reliability Indices
- Reliability VS Capacity Planning
- Conclusion

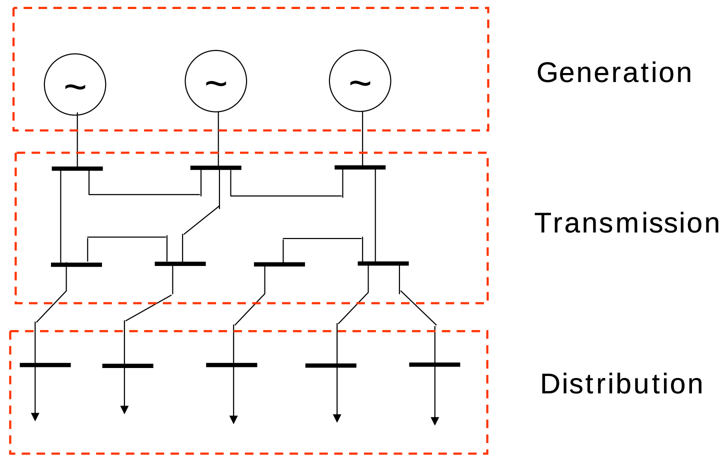
Introduction

Electric Power System Function

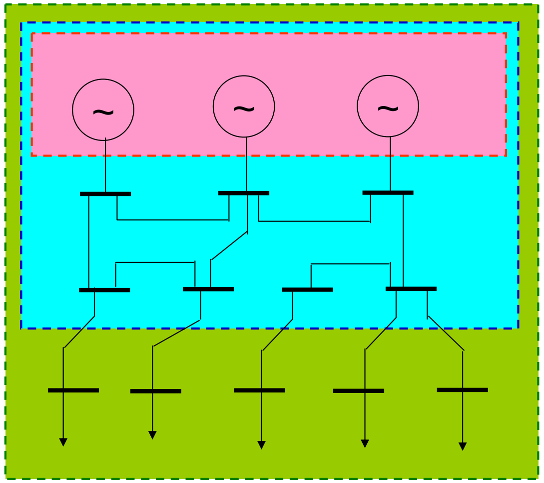
supply customers with electrical energy **as economically as possible** with an **acceptable degree of reliability and quality**

The ability of the system to provide an **adequate** supply of electrical energy is usually designed by the term **reliability**.

Introduction



Introduction

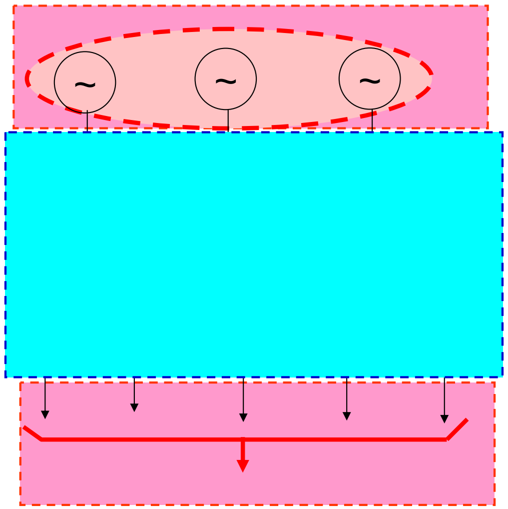


Hierarchical level I

Hierarchical level II

Hierarchical level III

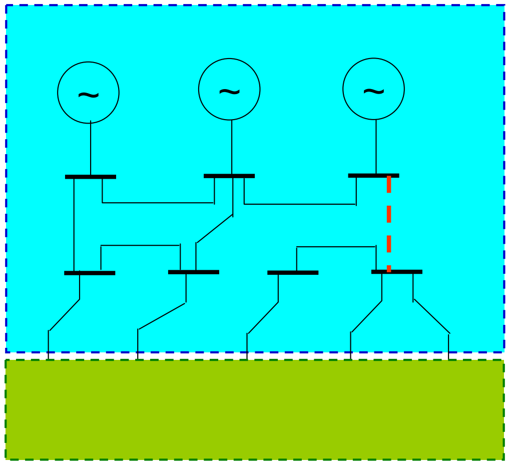
Introduction



Hierarchical level I

Total System Generation *VS* Total System Demand

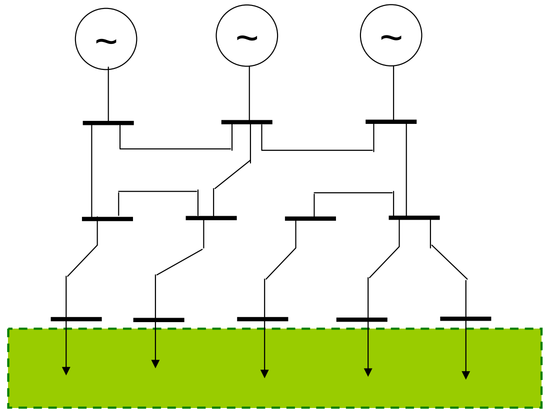
Introduction



Hierarchical level II

Ability of system to satisfy the individual load requirements at the **major** load points

Introduction



Hierarchical level III

Individual customer adequacy

Introduction

***Reliability** is the probability of a device or system performing its purpose adequately for the period of time intended under the operating conditions encountered.*

Introduction

System Reliability

System Adequacy

Sufficient capacity and facilities of transmission

System Security

Ability of system to response to disturbances

Introduction

Key factor is

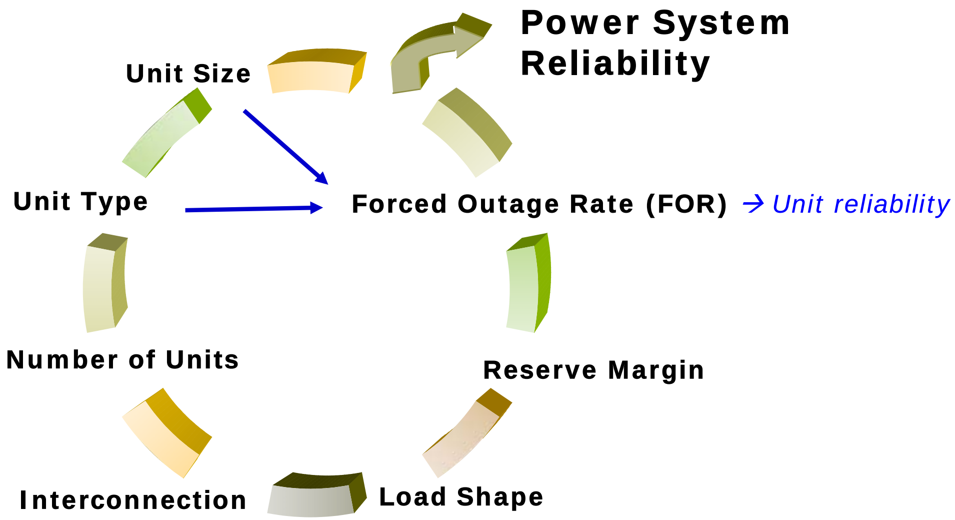
Excess Capacity

How much should it be?
And who should pay for it?

Introduction

- Reliability has become one of the most important design criteria of electric power system.
- It is most complex quantity, as it depends upon many factors.

Introduction



Key Indices of Power System Reliability

- Percent reserve margin (%RM)
- Loss of largest unit (LLU)
- Loss-of-load probability (LOLP)
- Loss-of-load expectation (LOLE) or
  Loss-of-load hours (LOLH)
- Frequency and duration of capacity shortages (F&D)
- Expected loss of load (XLOL)
- Expected energy not served (ENS)
- Loss-of-energy probability (LOEP)
- Expected demand not serve (EDNS)

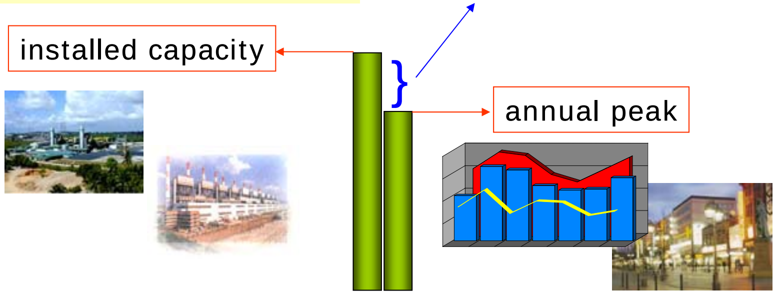
Key Indices of Power System Reliability

Percent reserve margin (%RM)

is the excess of installed capacity over annual peak load expressed in percent of annual peak.

%RM can be used as approximate guide to reliability when there is little diversity in plant types

$$\%RM = \frac{\text{Installed Cap.} - \text{Annual Peak Load}}{\text{Annual Peak Load}} \times 100$$



Key Indices of Power System Reliability

Loss of largest unit (LLU)

compares the system reserve with the largest unit of the system.

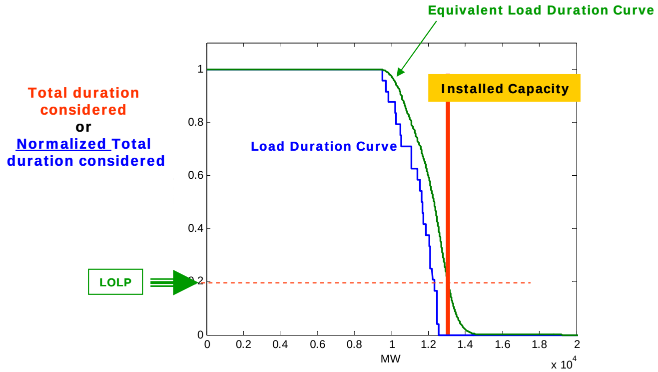
$$LLU = \frac{\text{Installed Cap.} - \text{Annual Peak Load}}{\text{Capacity of the Largest Unit}}$$

How many number of largest unit equal to the excess of capacity over peak load?

Key Indices of Power System Reliability

Loss-of-load probability (LOLP)

is the **proportion** of days/year or hours/year on which available capacity is insufficient to serve the peak load.



Key Indices of Power System Reliability

Frequency and duration of capacity shortages (F&D)

is the expected number of shortage events per year (F), while the duration (D) is the expected length of capacity-shortage periods when they occur.

Key Indices of Power System Reliability

Loss-of-load expectation (LOLE) or Loss-of-load hours (LOLH)

is the days/year or hours/year on which available capacity is in sufficient to serve the peak load.

$$LOLH = F \times D$$

or

$$LOLE = LOLP \times (\text{Total Duration Considered})$$

Key Indices of Power System Reliability

Expected loss of load (XLOL)

is the expected **magnitude** of load loss when a load loss event occurs.

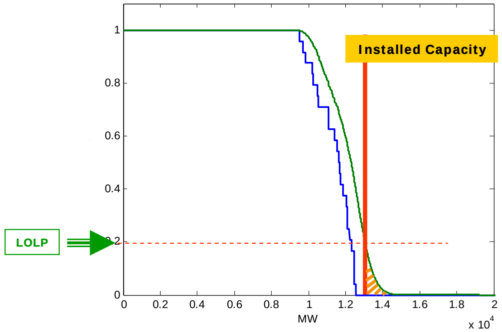
This attempts to quantify, in MW (average), the expected magnitude of the unserved load given that a failure has occurred

$$XLOL = \frac{ENS}{LOLE}$$

Key Indices of Power System Reliability

Expected energy not served (ENS) or Expected Unserved Energy (EUE)

is the expected amount of energy which is not served over a given interval due to insufficient capacity.



Key Indices of Power System Reliability

Loss-of-energy probability (LOEP) → **Normalized ENS**

is the expression of ENS as a fraction of total electrical energy demanded.

$$LOEP = \frac{ENS}{\text{Total Yearly Energy Requirement}}$$

Key Indices of Power System Reliability

Expected demand not serve (EDNS)

is the expected average demand in MW of load that can not be met during the total duration considered.

$$EDNS = \frac{ENS}{\text{Total Duration Considered}}$$

Generator Unit Forced Outage Rate

Unit reliability is one of the major factor influencing the reliability of the system as it determines the frequency with which a unit is likely to be out of service because of an **unplanned** outage.

The unit forced outage rate or FOR can be expressed as,

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

Basic Capacity Outage Probability

Given the outage probabilities and assuming that Each generating unit can be either (one of two possible states)

- operative and thus capable of full power generation, or
- non-operative and incapable of delivering any energy

The distributed level of available capacity take on 2^N , equal to the number of combinations of **“up”** and **(unplanned) “down”** for N-unit system.

Basic Capacity Outage Probability

Example 1

A three-unit system with the following capacities;

Unit	1	2	3
Capacity (MW)	400	300	250
FOR	0.06	0.04	0.02

Basic Capacity Outage Probability

Example 1

Unit	1	2	3
Capacity (MW)	400	300	250
FOR	0.06	0.04	0.02

Case	Up = 1, Down = 0			Total MW Available	Capacity on Outage	Probability
1	1	1	1	950	0	0.94 x 0.96 x 0.98 = **0.884352**
2	1	1	0	700	250	0.94 x 0.96 x 0.02 = **0.018048**
3	1	0	1	650	300	0.94 x 0.04 x 0.98 = **0.036848**
4	0	1	1	550	400	0.06 x 0.96 x 0.98 = **0.056448**
5	1	0	0	400	550	0.94 x 0.04 x 0.02 = **0.000752**
6	0	1	0	300	650	0.06 x 0.96 x 0.02 = **0.001152**
7	0	0	1	250	700	0.06 x 0.04 x 0.98 = **0.002352**
8	0	0	0	0	950	0.06 x 0.04 x 0.02 = **0.000048**

Basic Capacity Outage Probability

Example 1

Capacity on Outage	Probability	Cumulative Probability
950	0.000048	**0.000048**
700	0.002352	**0.002400**
650	0.001152	**0.003552**
550	0.000752	**0.004304**
400	0.056448	**0.060752**
300	0.036848	**0.097600**
250	0.018048	**0.115648**
0	0.884352	**1.000000**

Probability of X MW outage **or more**

Basic Capacity Outage Probability

Example 2

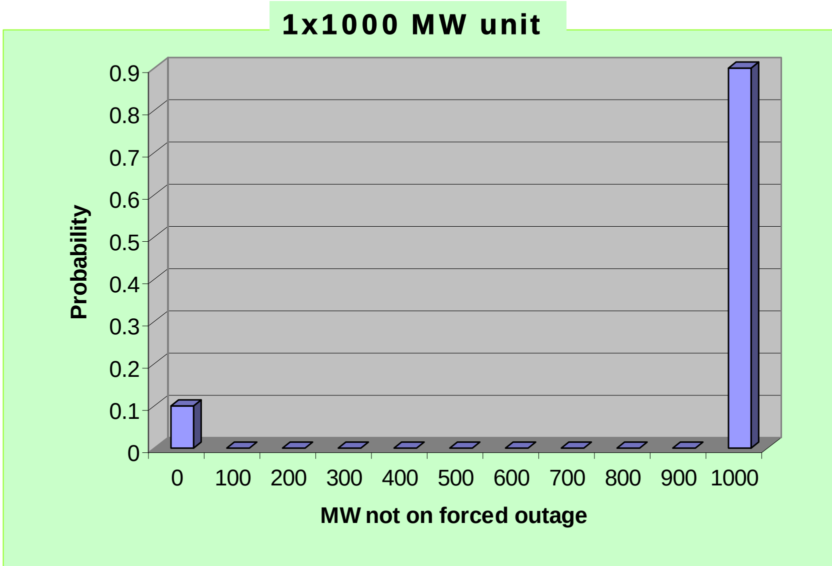
Comparison between 1x1000 MW unit (FOR = 0.1) and 10x100 MW units (FOR = 0.1).

Unit	1	
Capacity (MW)	1000	
FOR	0.1	
Total MW Available	**Capacity on Outage**	**Probability**
1000	**0**	**0.9**
900	100	0
800	200	0
700	300	0
600	400	0
500	500	0
400	600	0
300	700	0
200	800	0
100	900	0
0	**1000**	**0.1**

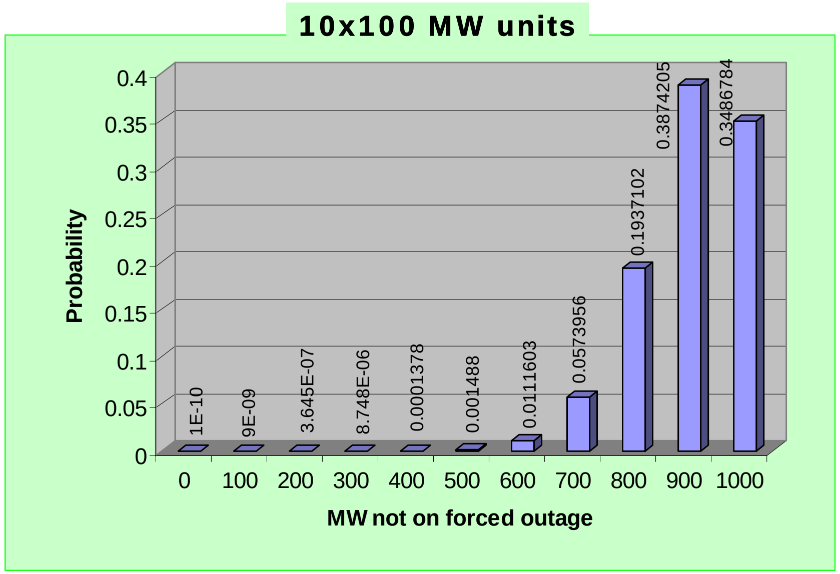
Unit	1				
Capacity (MW)	100	(10 units)			
FOR	0.1				
Total MW Available	**Capacity on Outage**	**Number of unit on outage**	**Probability**		
1000	0	0	(0.9^10)	=	0.34867844
900	100	1	{10,1} * (0.9^9)*(0.1^1)	=	0.387420489
800	200	2	{10,2} * (0.9^8)*(0.1^2)	=	0.193710245
700	300	3	{10,3} * (0.9^7)*(0.1^3)	=	0.057395628
600	400	4	{10,4} * (0.9^6)*(0.1^4)	=	0.011160261
500	500	5	{10,5} * (0.9^5)*(0.1^5)	=	0.001488035
400	600	6	{10,6} * (0.9^4)*(0.1^6)	=	0.000137781
300	700	7	{10,7} * (0.9^3)*(0.1^7)	=	8.748E-06
200	800	8	{10,8} * (0.9^2)*(0.1^8)	=	3.645E-07
100	900	9	{10,9} * (0.9^1)*(0.1^9)	=	9E-09
0	1000	10	(0.1^10)	=	1E-10

Note: {N,r} = N! / ((N-r)! * r!)

Basic Capacity Outage Probability



Basic Capacity Outage Probability



Calculation of Power Generation System Reliability Indices

Reliability indices should be

- measurable from historical data,
- calculable using available data, and
- responsive in a predictable way to differences in system alternatives.

Calculation of Power Generation System Reliability Indices

Example 3 **Recall Example 1**

A three-unit system with the following capacities;

Unit	1	2	3
Capacity (MW)	400	300	250
FOR	0.06	0.04	0.02

If the daily peak load of the system is as follow

Day	Peak Load (MW)
Sunday	390
Monday	800
Tuesday	610
Wednesday	470
Thursday	560
Friday	750
Saturday	310

Calculation of Power Generation System Reliability Indices

Capacity on Outage	Probability	Cumulative Probability
0	0.884352	1.000000
250	0.018048	0.115648
300	0.036848	0.097600
400	0.056448	0.060752
550	0.000752	0.004304
650	0.001152	0.003552
700	0.002352	0.002400
950	0.000048	0.000048

Calculation of Power Generation System Reliability Indices

Day	Peak Load (MW)	Capacity on Outage above which load would not be met	Probability of Not meeting Load
Sunday	390	560	0.003552
Monday	800	150	0.115648
Tuesday	610	340	0.060752
Wednesday	470	480	0.004304
Thursday	560	390	0.060752
Friday	750	200	0.115648
Saturday	310	640	0.003552
		LOLP =	0.364208

Days/week

Calculation of Power Generation System Reliability Indices

Equivalent Load Duration Curve

To determine units are loaded under the LDC according to a **merit order** that reflects increasing operating cost per MWhr produced.

However, generating units are sometimes forced out of service resulting in increased calls for generation on units higher in the merit order.

Calculation of Power Generation System Reliability Indices

Equivalent Load Duration Curve

The increased demand for generation by a specific unit resulting from the forced outages of all previously loaded units is accounted for by modifying the LDC to reflect these forced outages.

This is done by computing the "**equivalent load**" on a particular unit which is the sum of customer demand and forced outage of previously loaded its.

Calculation of Power Generation System Reliability Indices

Equivalent Load Duration Curve

The cumulative probability distribution is also called **equivalent load duration curve (ELDC)** which gives the total probability that customer load plus the capacity on forced outage equals or exceeds a given value *x* when the generating system through the *i* the unit out of NG total units is being considered.

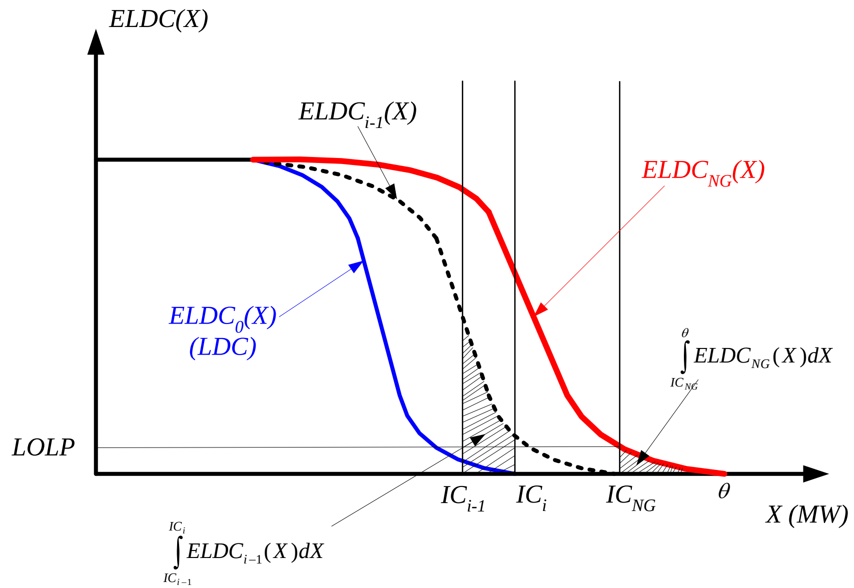
Calculation of Power Generation System Reliability Indices

Equivalent Load Duration Curve

A new curve is computed each time a unit and is brought on line.

$$ELDC_i(X) = (1 - FOR_i)ELDC_{i-1}(X) + FOR_i \cdot ELDC_{i-1}(X - P_{Gi}),$$

Calculation of Power Generation System Reliability Indices



Calculation of Power Generation System Reliability Indices

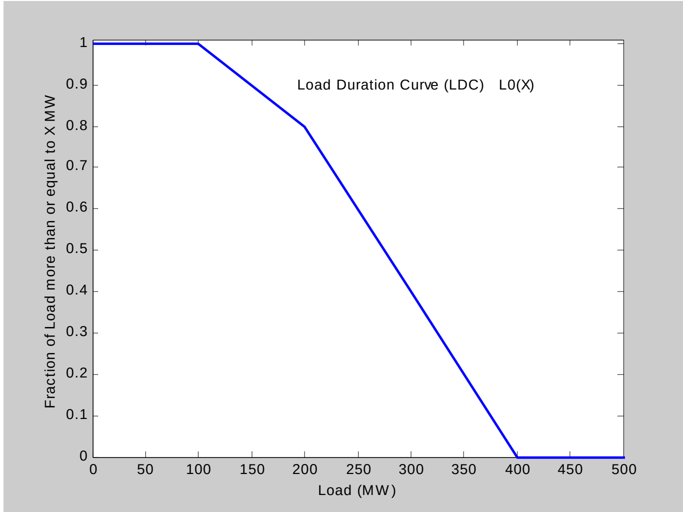
Equivalent Load Duration Curve

Example 4: 2 units system

Load ***X*** MW	Fraction of time
0	1.000
100	1.000
200	0.800
300	0.400
400	0.000

Calculation of Power Generation System Reliability Indices

Example 4: 2 units system



Calculation of Power Generation System Reliability Indices

Example 4: 2 units system

	Unit 1	**Unit 2**
Capacity (MW)	300	300
Operating Cost ($/MWhr)	6.500	7.000
Forced outage rate	***0.200***	***0.100***

Calculation of Power Generation System Reliability Indices

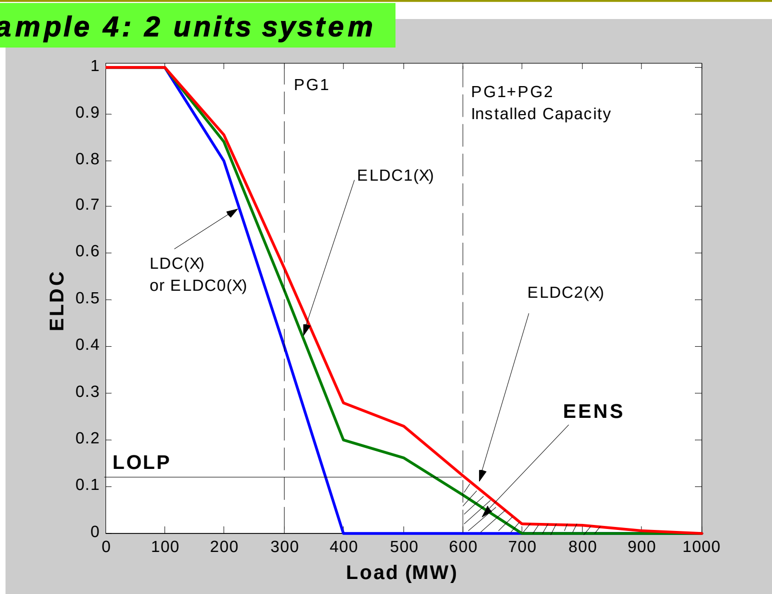
Example 4: 2 units system

Equivalent x MW	**Original System LDC (*LDC(X)*)**	**Unit 1 (*ELDC$_1$(X)*)**	**Unit 2 (*ELDC$_2$(X)*)**
0	1.000	1.000	1.000
100	1.000	1.000	1.000
200	0.800	0.840	0.856
300	0.400	0.520	0.568
400	0.000	0.200	0.280
500		0.160	0.228
600		0.080	0.124
700		0.000	0.020
800			0.016
900			0.005
1000			0.000

$$ELDC_i(X) = (1 - FOR_i)ELDC_{i-1}(X) + FOR_i \cdot ELDC_{i-1}(X - P_{Gi}),$$

Calculation of Power Generation System Reliability Indices

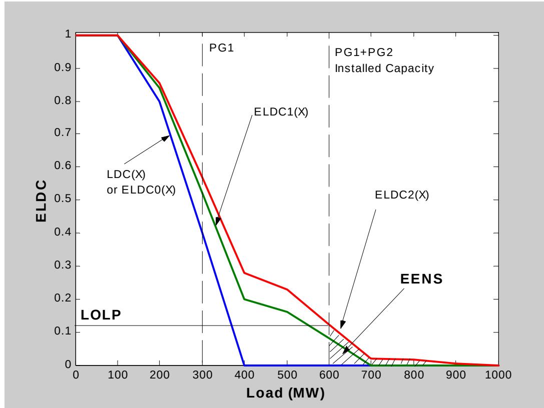
Example 4: 2 units system



Calculation of Power Generation System Reliability Indices

Example 4: 2 units system

Lost of load probability (LOLP) = ELDC2(600)
= 0.124 = 1058 hours/year



Calculation of Power Generation System Reliability Indices

Example 4: 2 units system

Expected energy generated by each unit

$$E_1 = (1 - FOR_1)(8760) \int_0^{P_{G1}} LDC(X)dX$$

$$= (0.8)(8760) \int_0^{300} LDC(X)dX$$

$$= (0.8)(8760)\left[\frac{1+1}{2}(100) + \frac{1+0.8}{2}(100) + \frac{0.8+0.4}{2}(100)\right]$$

$$= 1401600 \ \text{MWh/year}$$

Calculation of Power Generation System Reliability Indices

Example 4: 2 units system

Expected energy generated by each unit

$$E_2 = (1 - FOR_2)(8760) \int_{P_{G1}}^{P_{G1}+P_{G2}} ELDC_1(X)dX$$

$$= (0.9)(8760) \int_{300}^{600} ELDC_1(X)dX$$

$$= (0.9)(8760)\left[\frac{0.52+0.2}{2}(100) + \frac{0.2+0.16}{2}(100) + \frac{0.16+0.08}{2}(100)\right]$$

$$= 520344 \ \text{MWh/year}$$

Calculation of Power Generation System Reliability Indices

Example 4: 2 units system

Expected energy not served (EENS)

$$EENS = (8760)\int_{P_{G1}+P_{G2}}^{peak\ load} ELDC_2(X)dX$$

$$= (8760)\left[\frac{0.124+0.02}{2}(100) + \frac{0.02+0.016}{2}(100) + \frac{0.016+0.008}{2}(100) + \frac{0.008+0}{2}(100)\right]$$

$$= 92856 \text{ MWhr/year}$$

Calculation of Power Generation System Reliability Indices

Example 4: 2 units system

Expected lost of load (XLOL)

$$XLOL = \frac{EENS}{LOLE} = \frac{92856}{1058} = 87.77 \text{ MW}$$

Expected demand not serve (EDNS)

$$EDNS = \frac{EENS}{8760} = \frac{92856}{8760} = 10.6 \text{ MW}$$

Calculation of Power Generation System Reliability Indices

Example 5: large system

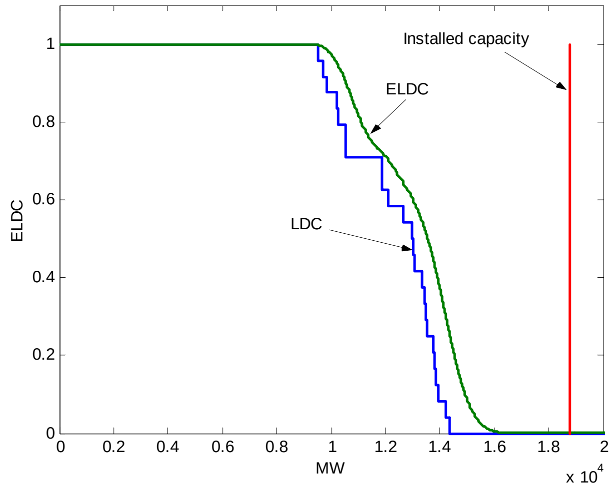
Reliability indices in system with large number of generating units is usually be done by computer software.

The cumulative probability of outage

MW on outage	Original LDC	ELDC With Unit 1 FOR	ELDC With Unit 2 FOR		ELDC With Unit NG FOR
0	$LDC(0)$	$ELDC_0(0)$	$ELDC_0(0)$	...	$ELDC_0(0)$
ST	$LDC(ST)$	$ELDC_1(ST)=(1-FOR_1)(ELDC_0(ST)) + FOR_1(ELDC_0(0))$	$ELDC_2(ST)=(1-FOR_2)(ELDC_1(ST)) + FOR_2(ELDC_1(0))$	...	$ELDC_{NG}(ST)=(1-FOR_{NG})(ELDC_{NG-1}(ST)) + FOR_{NG}(ELDC_{NG-1}(0))$
⋮	⋮	⋮	⋮	...	⋮
P_{G1}	$LDC(P_{G1})$	$ELDC_1(ST)=(1-FOR_1)(ELDC_0(P_{G1})) + FOR_1(ELDC_0(0))$	$ELDC_2(ST)=(1-FOR_2)(ELDC_1(P_{G1})) + FOR_2(ELDC_1(0))$	...	$ELDC_{NG}(P_{G1})=(1-FOR_{NG})(ELDC_{NG-1}(P_{G1})) + FOR_{NG}(ELDC_{NG-1}(P_{G1}-P_{GNG}))$
$P_{G1}+ST$	$LDC(P_{G1}+ST)$	$ELDC_1(ST)=(1-FOR_1)(ELDC_0(P_{G1}+ST)) + FOR_1(ELDC_0(ST))$	$ELDC_2(ST)=(1-FOR_2)(ELDC_1(P_{G1}+ST)) + FOR_2(ELDC_1(0))$	...	$ELDC_{NG}(P_{G1}+ST)=(1-FOR_{NG})(ELDC_{NG-1}(P_{G1}+ST)) + FOR_{NG}(ELDC_{NG-1}(P_{G1}+ST-P_{GNG}))$
⋮	⋮	⋮	⋮	...	⋮
P_{G2}	$LDC(P_{G2})$	$ELDC_1(ST)=(1-FOR_1)(ELDC_0(P_{G2})) + FOR_1(ELDC_0(P_{G2}-P_{G1}))$	$ELDC_2(ST)=(1-FOR_2)(ELDC_1(P_{G2})) + FOR_2(ELDC_1(0))$	...	$ELDC_{NG}(P_{G2})=(1-FOR_{NG})(ELDC_{NG-1}(P_{G2})) + FOR_{NG}(ELDC_{NG-1}(P_{G2}-P_{GNG}))$
$P_{G2}+ST$	$LDC(P_{G2}+ST)$	$ELDC_1(ST)=(1-FOR_1)(ELDC_0(P_{G2}+ST)) + FOR_1(ELDC_0(P_{G2}+ST-P_{G1}))$	$ELDC_2(ST)=(1-FOR_2)(ELDC_1(P_{G2}+ST)) + FOR_2(ELDC_1(ST))$	...	$ELDC_{NG}(P_{G2}+ST)=(1-FOR_{NG})(ELDC_{NG-1}(P_{G2}+ST)) + FOR_{NG}(ELDC_{NG-1}(P_{G2}+ST-P_{GNG}))$
⋮	⋮	⋮	⋮	...	⋮

Calculation of Power Generation System Reliability Indices

Example 5: large system



Calculation of Distribution System Reliability Indices

Distribution system

↓

Relatively cheap

↓

Outages have a very localized effect

Calculation of Distribution System Reliability Indices

Contributor	Average unavailability per customer per year	
	minute	%
Generation and Transmission	0.50	0.50
132 kV	2.30	2.40
33 kV, 66kV	8.00	8.30
6.6 kV, 11 kV	58.80	60.70
Low Voltage	11.50	11.90

Calculation of Distribution System Reliability Indices

Customer-oriented indices

System average interruption frequency index (SAIFI)

$$SAIFI = \frac{\text{total number of customer interruptions}}{\text{total number of customers served}} = \frac{\sum \lambda_i N_i}{\sum N_i}$$

λ_i is the failure rate of load point *i*

N_i is the number of customers of load point *i*

Calculation of Distribution System Reliability Indices

Customer-oriented indices

System average interruption duration index (SAIDI)

$$SAIDI = \frac{\text{sum of customer interruption durations}}{\text{total number of customers served}} = \frac{\sum U_i N_i}{\sum N_i}$$

U_i is the annual outage time of load point *i*

Calculation of Distribution System Reliability Indices

Customer-oriented indices

Customer average interruption frequency index (CAIFI)

$$CAIFI = \frac{\text{total number of customer interruptions}}{\text{total number of customers affected}}$$

Calculation of Distribution System Reliability Indices

Customer-oriented indices

Customer average interruption duration index (CAIDI)

$$CAIDI = \frac{\text{sum of customer interruption durations}}{\text{total number of customers interruptions}} = \frac{\sum U_i N_i}{\sum \lambda_i N_i}$$

Reliability VS Capacity Planning

Planning Issues

- Reliability Analysis
- Reserve Planning
- Operating Cost Analysis
- Generation Planning and Cost
- Fuel Budgeting
- Rate Structure Analysis (Tariff Policy)
- Financial Planning and Operating Cost

Reliability VS Capacity Planning

Reserve Planning Problem

The higher reserve margin, the higher reliability performance of the system.

Providing excess electric generation capacity for reliability purposes has an economic cost.

Reliability VS Capacity Planning

Evaluation of Reliability Worth

Implicit Cost

- Deterministic criteria
- Fixed quantitative reliability indices based on experience and judgment
- Compare the capital + Operating cost of each alternative to others

Explicit Cost

- Incorporate reliability in costing process
- Comparing overall cost including the societal costs of unreliability

Use present worth in both methods

Reliability VS Capacity Planning

Investment Planning Model → **Implicit Cost**

Objective function

$$\text{Minimize} \sum_{\text{Caddidate Plant}} (\text{Capacity Cost} - \text{Salvage Value}) + \sum_{\text{All Plant}} (\text{Operating Cost})$$

Use the discounted value or annualized value along the planning period

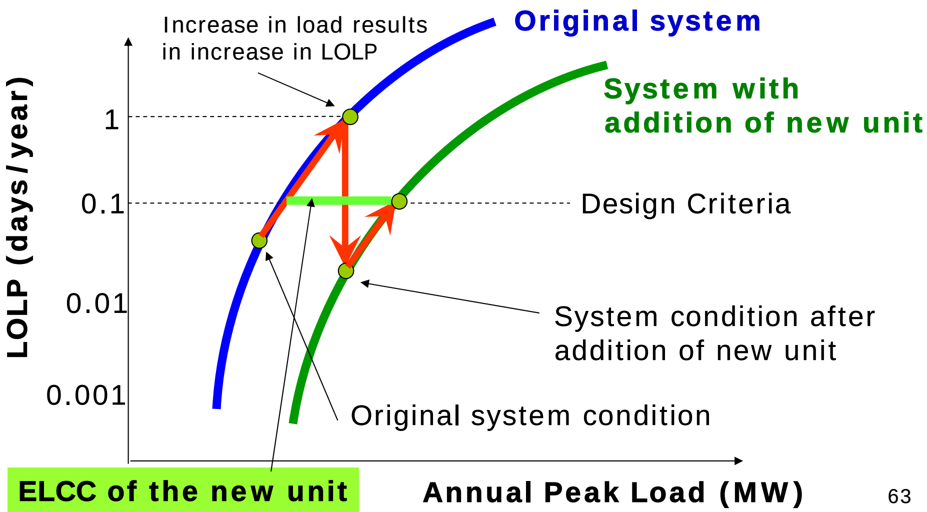
Subject to

Power Demand Constraint
Min-Max Capacity Constraint (Plant Technology-Economic)
Emission limit
Individual Capacity Constraint (Availability)
Hydro Energy Availability Constraint
Reliability Constraint (Guarantee condition, reserve)
Resource Availity Constraint
Etc.

} **Reliability Concern**

Reliability VS Capacity Planning

Effective Load Carrying Capability (ELCC)



Reliability VS Capacity Planning

Interruption Cost as Reliability Worth → **Explicit Cost**

The worth or benefit of reliability **<u>cannot</u>** be measured or evaluated directly.

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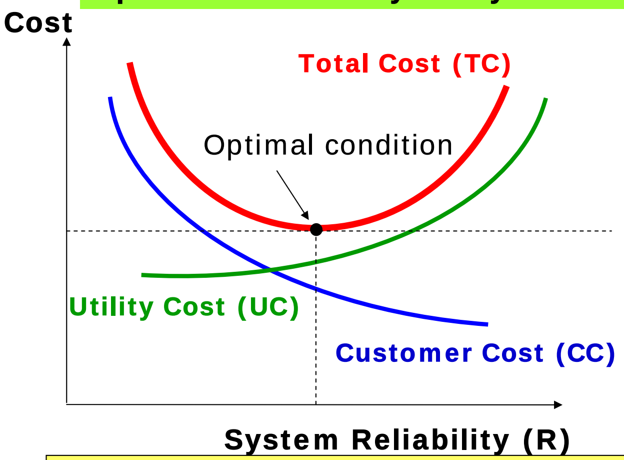
Interruption costs are used as a measure of reliability.

Reliability VS Capacity Planning

Optimum Reliability VS System Planning



$$TC = UC + CC$$

At optimal condition

$$\frac{\partial TC}{\partial R} = \frac{\partial UC}{\partial R} + \frac{\partial CC}{\partial R} = 0$$

$$\frac{\partial UC}{\partial R} = -\frac{\partial CC}{\partial R}$$

Marginal utility cost = Marginal saving due to outage cost

Conclusion

- The two aspects, adequacy and economic, can be consistently appraised by comparing adequacy cost (investment) with adequacy worth (benefit derived by society).
- Cost to society of providing quality and continuity of electricity supply should be related to worth or benefit to society of having quality and continuity.

Conclusion

- Two difficulties arise in its assessment;
  - The calculated indices are usually derived only from adequacy assessment at the various hierarchical levels.
  - There are great problems in assessing consumer perceptions of outage costs.
- Until this problem is fully solved, it is still beneficial for individual utilities to arrive at some consistent criterion by which they can assess the benefit of expansion and reinforcement schemes.

Thank You