6. PLANNING OF POWER SYSTEM RESERVES

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Reliability terms

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Forced outage rate (FOR)

$$FOR = FOH/(FOH+SH) \times 100\ \%$$

FOH = forced outage hours

SH = service hours

Reliability terms, continued

Equivalent forced outage rate (EFOR)

$$EFOR = \frac{FOH + EFDH}{FOH + SH + EFDH} \times 100\ \%$$

EFDH = equivalent forced derated hours

(output reductions + forced hours)

Reliability terms, continued

Equivalent forced outage rate demand

$$EFORd = \frac{f \times FOH + f_p \times EFDH}{SH + f \times FOH} \times 100\ \%$$

$f = (1/r + 1/T)/(1/r+1/T+1/D)$

$f_p = SH/AH$

AH= available hours

r = averge forced outage duration = FOH/number of forced outages

T = average times between calls of unit to run

D = average run time = SH/number of successful starts

Reliability terms, continued

Starting reliability (SR)

$$SR = \frac{\text{actual unit starts}}{\text{attempted starts}} \times 100\ \%$$

US Statistics (1999-2003)*

	EFORd	SR
Conventional plants	6.2%	98.4%
- Coal-fired plants	6.4%	97.4%
- Oil-fired plants	5.7%	99.4%
- Gas-fired plants	5.9%	99.2%
Nuclear plants	5.4%	98.5%
Hydro plants	3.6%	99.5%
Combined cycles	5.6%	97.6%
Gas turbines (GT)	7.5%	95.5%
Aero-derivative GT	6.8%	97.2%
Diesel engines	5.4%	99.4%

*Source: North American Reliability Council (NERC)

Reliability of power system

Probability that exactly m of n units are in operation

$$P(M=m|n, R) = \frac{n!}{m!\,(n-m)!} R^m(1-R)^{n-m}$$

n = number of units in the system

n! = 1 x 2 x 3 x …x n

m = number of units in operation

m!= 1 x 2 x 3 x … x m

R = reliability of an unit = 1 - EFORd

Probability that at least m of n units are in operation

$$P(M=m|n, R) = \sum \frac{n!}{m!\,(n-m)!} R^m (1-R)^{n-m}$$

n = number of units in the system

n! = 1 x 2 x 3 x …x n

m = number of units in operation

m!= 1 x 2 x 3 x … x m

R = reliability = 1 - EFORd

SYSTEM RELIABILITY
R = 95 % (EFORd = 5 %)

Number of units n	3	4	5	10	20	100
Units in operation						
n	0.8574	0.8145	0.7738	0.5987	0.3585	0.0059
n-1	0.9928	0.9859	0.9774	0.9139	0.7358	0.0371
n-2	0.9999	0.9995	0.9988	0.9885	0.9245	0.1183
n-3		0.9999	0.9999	0.9989	0.9841	0.2578
n-4				0.9999	0.9974	0.4360
n-5					0.9997	0.6160
n-6					0.9999	0.7660
n-7						0.8720
n-13						0.9995
n-15						0.9999

Normal utility system*
Reliability target (Rs = 99.9 %)

System	Reserve need
3 x 100 %	200 %
4 x 50 %	100 %
5 x 33 %	67 %
13 x 10 %	30 %
25 x 5 %	25 %
113 x 1 %	13 %

*Unit relaibility = 95 %

Modern utility system*
Reliability target Rs = 99.99 %

System	Reserve need
4 x 100 %	300 %
5 x 50 %	150 %
14 x 10 %	40 %
26 x 5 %	30 %
115 x 1 %	15 %

*Unit reliability = 95 %

Reserve margin (RM)

$$RM = \frac{\text{Capacity-Peak load}}{\text{Peak load}} = \frac{1 - R + Z \times \text{sigma}/n}{R - Z \times \text{sigma}/n}$$

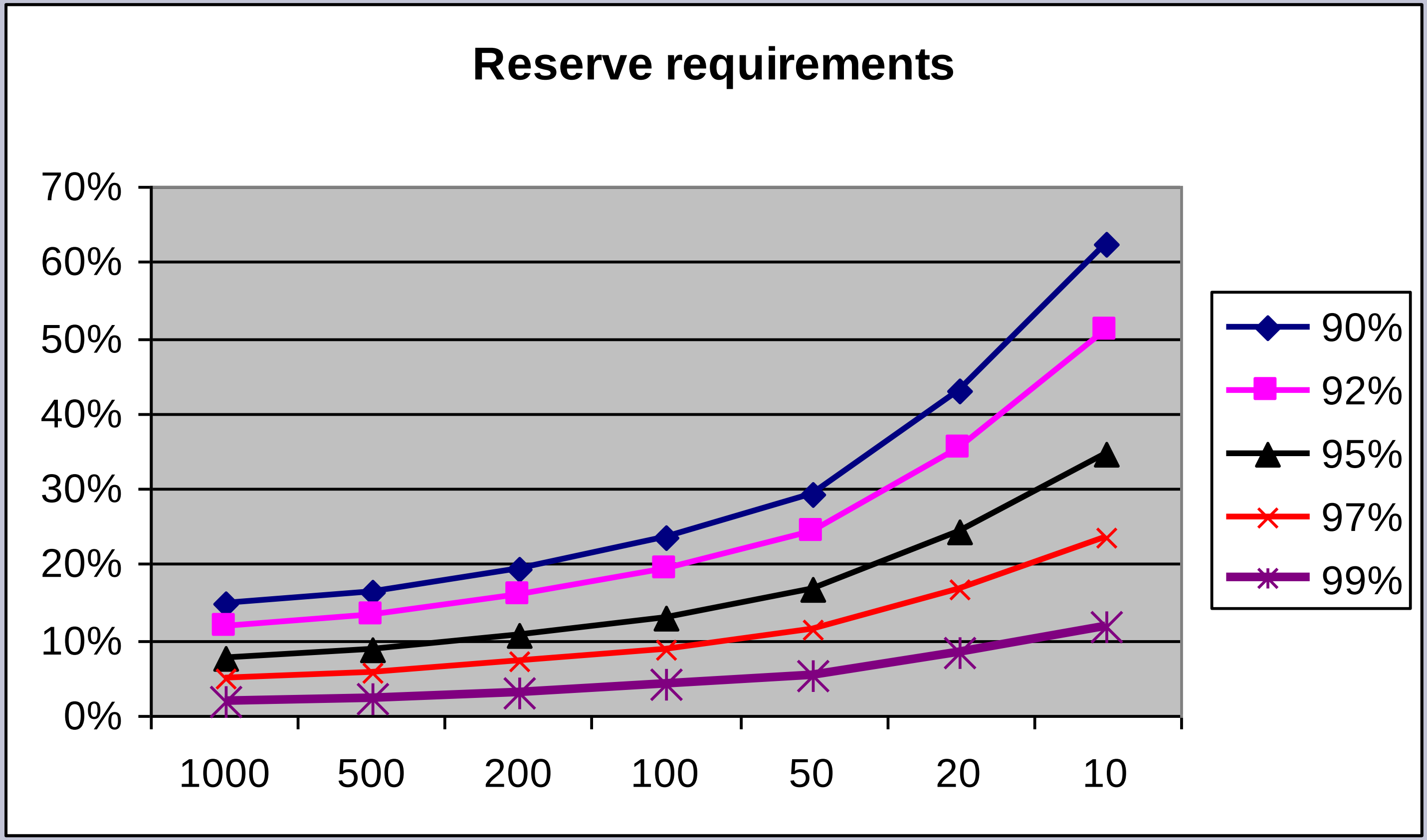
R = reliability of unit

Z = level of confidence

Sigma = standard deviation of reliability

n = number of units in the system

Reserve requirements at three sigma level (Rs = 99.7 %)



General

Utility system needs less reserves, if the number of units (n) will grow and if the reliability of units (R) increases

System with 100 units needs 10 – 20 % reserves when the reliability of units varies from 92 to 97 %

Reserve requirements with one large and several small units

Simplified formula

$$RR = \sum ((1-R) \times Pui) + P_{max}$$

Where

RR = reserve requirement

P_{max}= largest unit in the system

R = reliability of the other units

Pui = output of unit i

Reserve requirements with one large and several small units

If the largest unit is 10 % of system size and the reliability of other units is 5 %, then

RR = 5 % + 10 % = 15 %

Adequacy of power system capacity

Adequacy of power system capacity

Practical Criteria of Adequacy

LAC > MPL

Where

LAC = lowest available capacity

MPL = maximum peak load

Adequacy of power system capacity, continued

Lowest availiable capacity (LAC)=

Total capacity - Unavailability

Where

Unavailability = ∑ (EFORdi) + Z x $sigma_C$

∑(EFORdi) = sum of average unavailabilities of power plants

Z = coeficient of confidence (= 1.29 for 90 % confidence)

$Sigma_C$ = variance of capacity

Adequacy of power system capacity, continued

Maximum peak load= Average peak load + Margin

Where

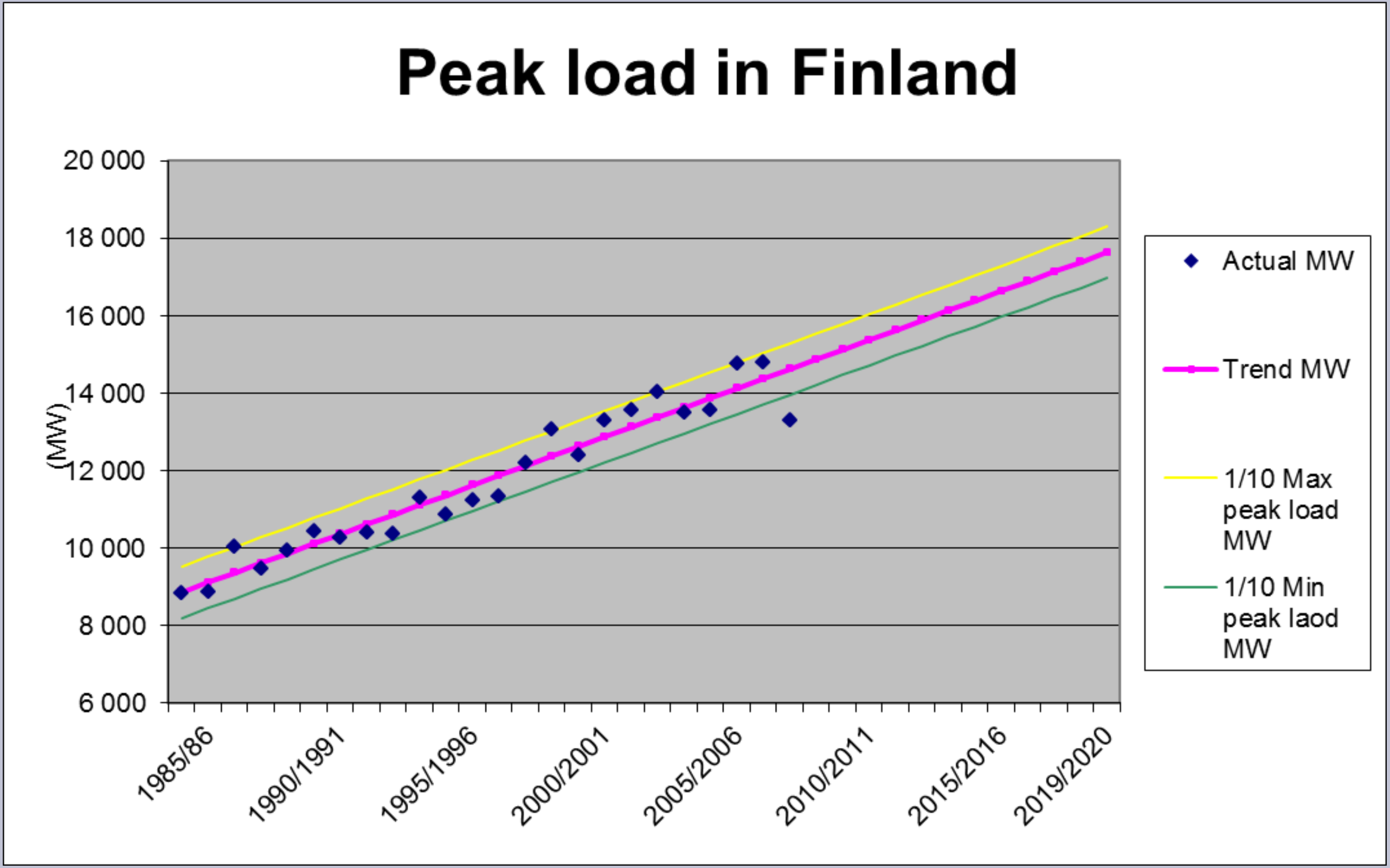
Average peak load = historical trend

Margin = Z x $sigma_{PL}$

Z = coefficient for confidence (=1.29 for 90% confidence, figures are given in the book)

$Sigma_{PL}$ = variance from the historical trend

Maximum peak load in Finland



Adequacy of capacity in Finland without imports

Winter		2005/6 A	2010/11 B	2020/21 C
Capacity	*MW*	13650	*13950*	*20500*
Average unavailability	*MW*	-683	*-698*	*-1025*
1,29 sigma contingency	*MW*	-483	*-485*	*-809*
Available capacity	*MW*	12485	*12768*	*18666*
Peak load (1/10)	*MW*	-14826	*-16005*	*-18302*
Reserve capacity	***MW***	**-2341**	***-3237***	***364***
Reserve capacity	*%*	*-16%*	*-20%*	*2%*

Planning reserves

$$= \text{Average Unavailability} + Z \times \sqrt{(Vc + Vp)}$$

Where

Average Unavailability = $\sum ((1-Ri) \times Pui)$

Ri = reliability of unit i

Pui = output of unit i

Z = level of confidence

Vc = variance of capacity

Vp = variance of peak load

Optimal capacity deficit by value of lost load

Criteria VOLL = Fc/t + Vc

Then t = Fc/(VOLL – Vc)

Where

VOLL = value of lost load (=5000 €/MWh)

t = hours of load is more than capacity

Fc = fixed costs of peaking plant

Vc = variable costs of peaking power plant

Optimal capacity deficit by value of lost load

With a diesel engine peaking plant

$t = 81.5/(5000-138.7) = 16.8$ deficit hours

Loss of load probability (LOLP) =

16.8 hours / 8760 h/a = 0.002= 2×10^{-3}

Reliability of power system is then 99.8 %

Optimal reliability targets

National power system = 99.9 %

Interconnected system = 99.99%

Safety related power system = 99.9999%*

* Can be planned by adding standby diesel engines, which start within one minute when the interconnnected system fails (see slide 9 for configurations)

SUMMARY

- Reserve needs become lower by planning systems with smaller and more reliable units
- Largest unit determines the need of reserve capacity, if the unit sizes are unevenly distributed
- The modern electronic age requires higher system reliability figures because everything depends on computers

For details see reference text book
"Planning of Optimal Power Systems"

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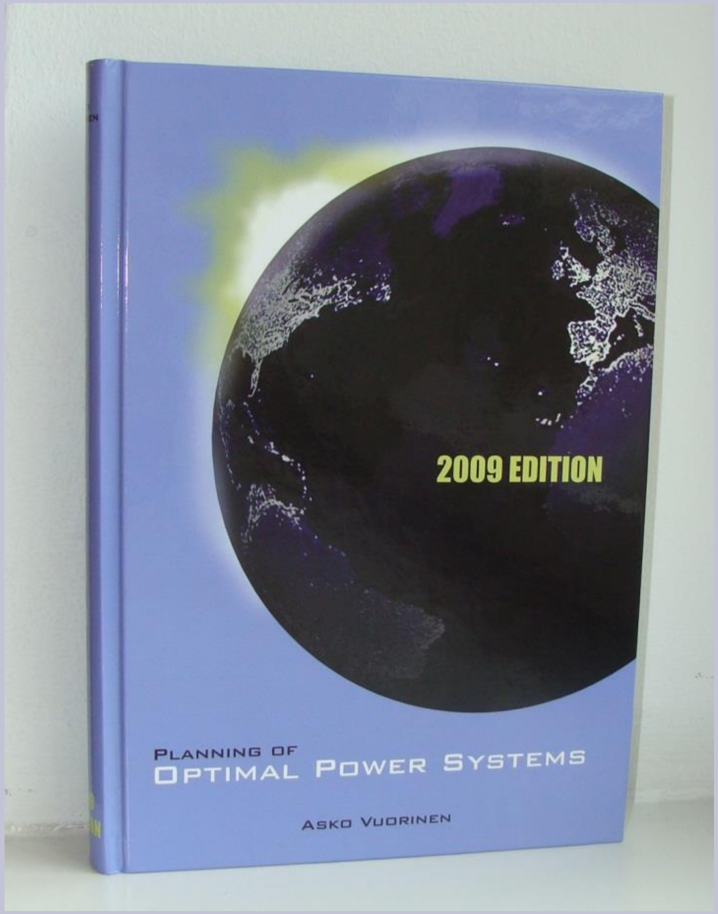

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