3. PLANNING OF POWER SYSTEM RESERVES

Asko Vuorinen

10.3.2016

Aalto University

Reliability terms

Reliability terms

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 %)

n	1	2	3	4	5	10	20	50	100
n	95,0000	90,2500	85,7375	81,4506	77,3781	59,8737	35,8486	7,6945	0,5921
n-1		99,2750	99,2750	98,5981	97,7408	91,3862	73,5840	27,9432	3,7081
n-2			99,9875	99,9519	99,8842	98,8496	92,4516	54,0533	11,8263
n-3				99,9994	99,9970	99,8972	98,4098	76,0408	25,7839
n-4						99,9936	99,7426	89,6383	43,5981
n-5						99,9997	99,9671	96,2224	61,5999
n-6							99,9966	98,8214	76,6014
n-8							99,9997	99,6812	87,2040
n-9								99,9244	93,6910
n-10								99,9970	97,1812
n-11								99,9995	99,5726
n-12									99,8536

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 reliability = 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)

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

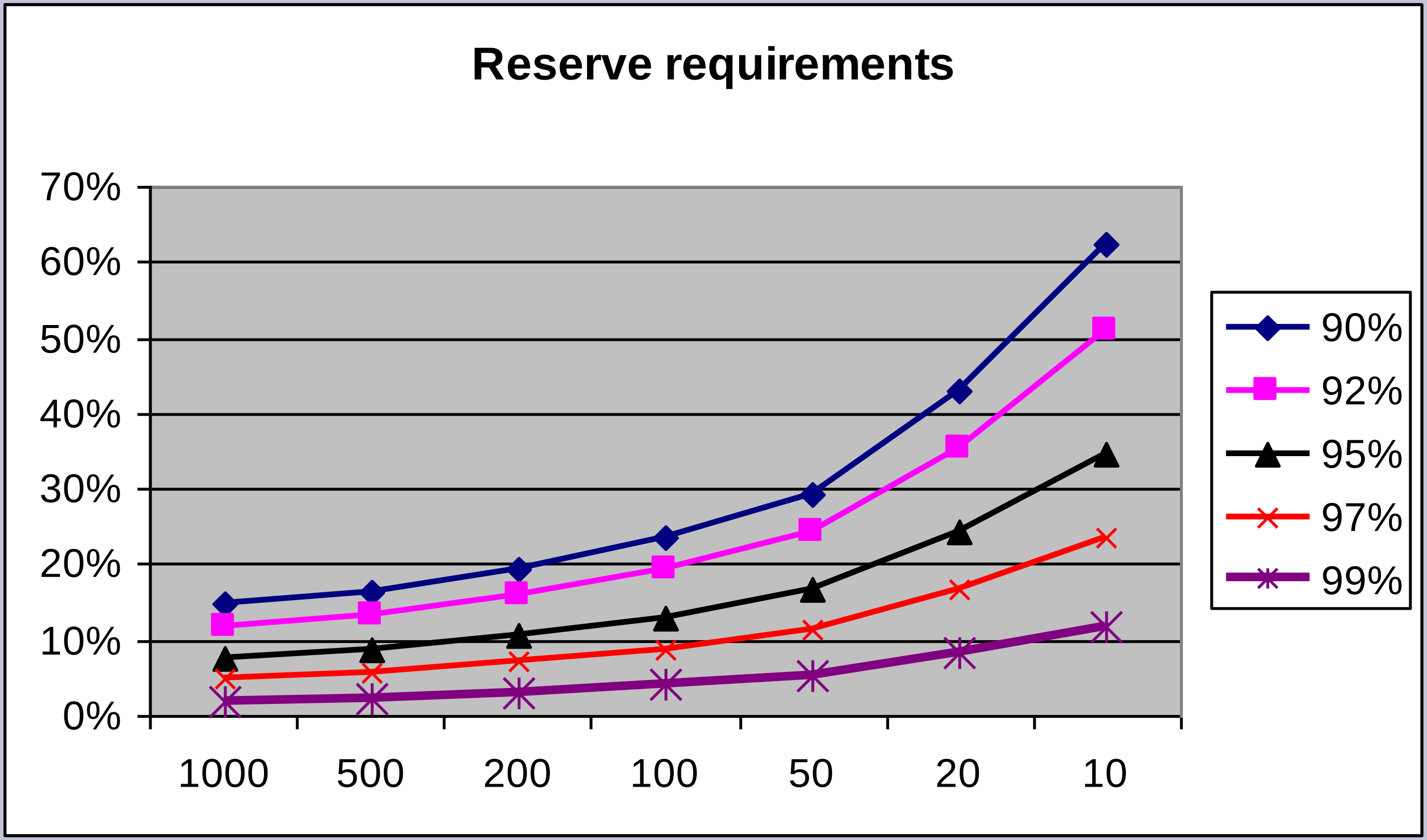
R = reliability of unit

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 unreliability of other units is 5 %, then

RR = 5 % + 10 % = 15 %

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 12 for configurations)

OPERATING RESERVES

- Spinning reserves
  - Synchronised reserves
- Non-spinning reserve
  - Unsynchronised reserves
- Supplemental reserves
  - 30 – 60 minute reserves
- Slow reserves
  - 1 – 12 hours reserves

Spinning reserves

- Spinning reserves = rotating reserves act immediately by the rotating mass of the generator

- If the frequency starts dropping, the genertor intertia tends to resist the slowing down motion

Spinning reserve by Combustion Engines

- Operating power plants which can change their output by ΔP in Δt

  -Ten minute spinning reserves in USA (Δt =10 min)

- CEs change their output from 40 % to 100 % in ten minutes

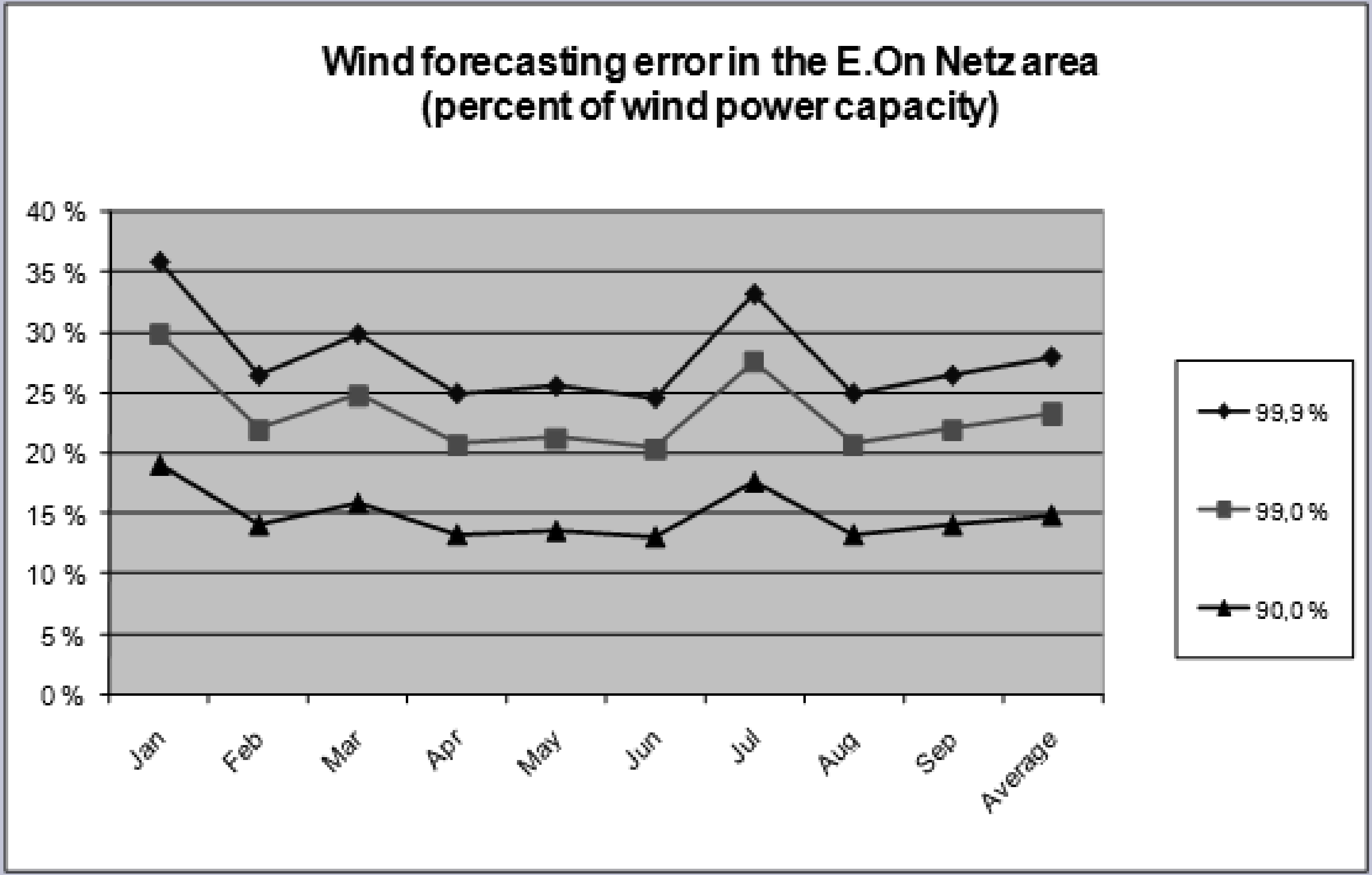
Non-spinning reserves

Power plants, which can start up in Δt minutes to full output P

-Ten minute non-spinning reserves in USA (Δt= 10 min)

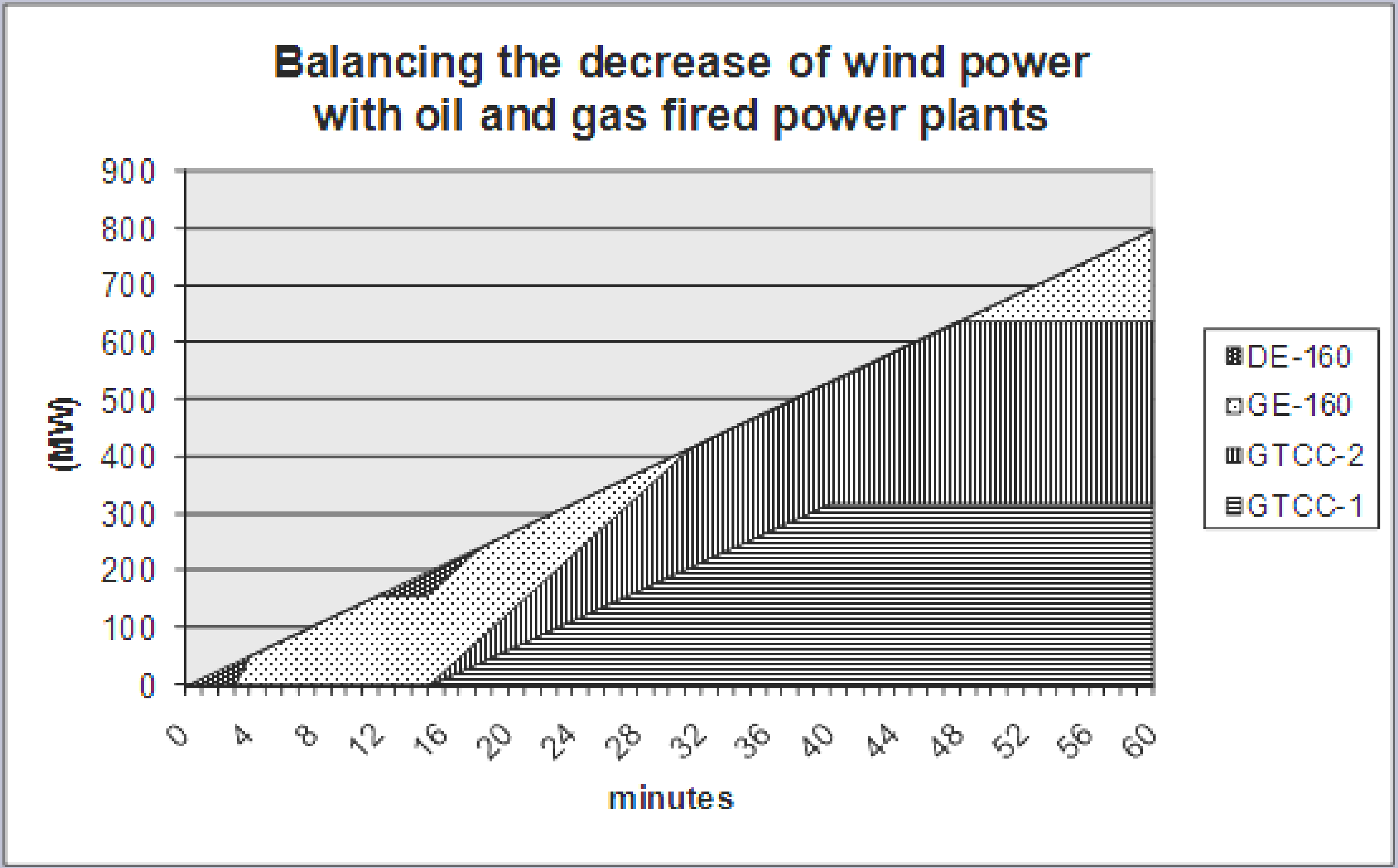
-Fast reserves in UK (Δt = 5 min) and Nordel (Δt = 15 min)

Wind power forecasting errors and need for reserves



Maximim error is 28% from the installed wind capacity

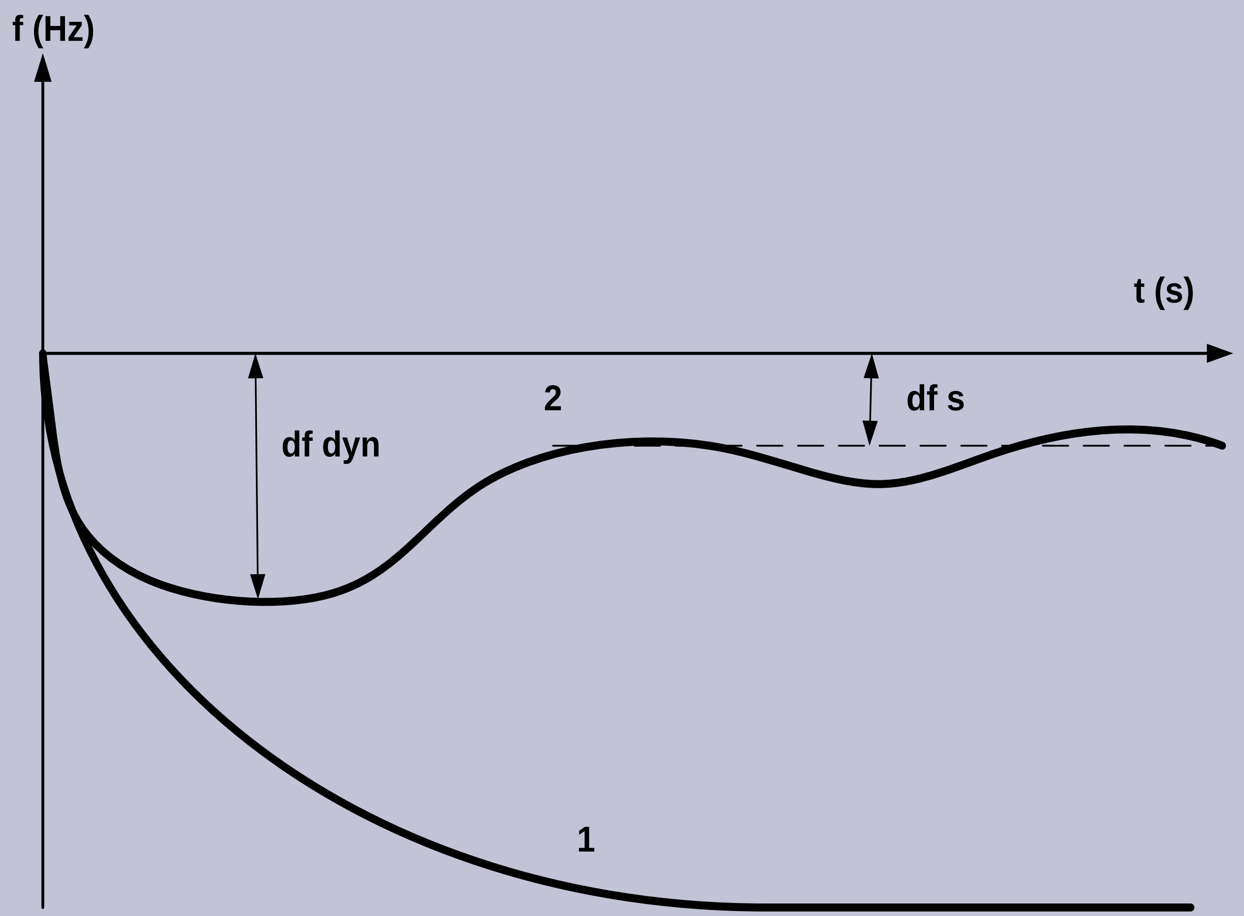
How to compensate 800 MW drop of wind power?



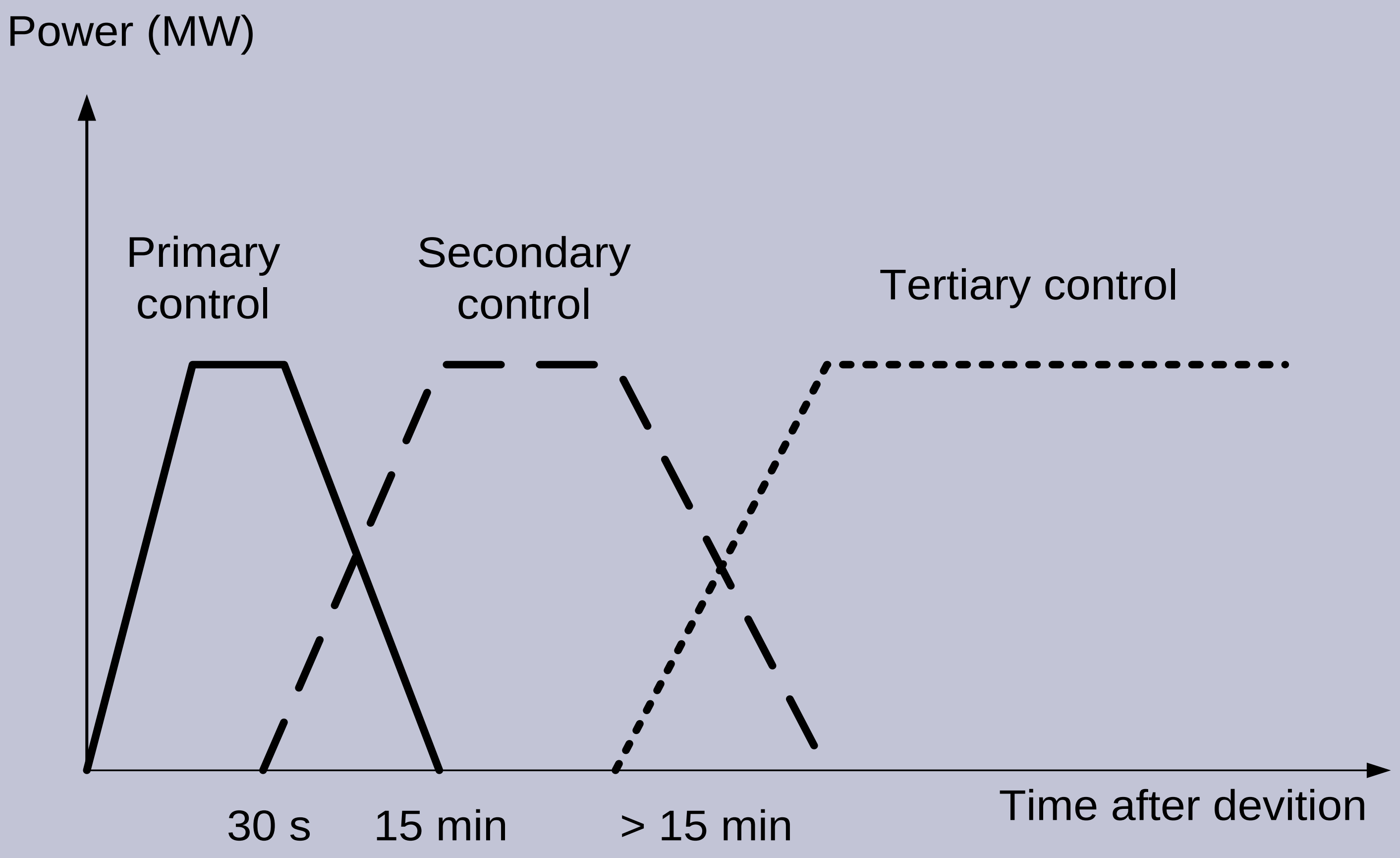
220 MW Plains End Plant in Colorado (2001 20 x 5,5 MW+2005 12 x 8 MW)

Bild to compensate 1000 MW wind power variations

How to compesate a trip of 1600 MW nuclear plant?



A trip of a 1600 MW nuclear plant



Fast Actions Needed

- Primary control
  - Spinning reserves should act within 30 seconds
- Seconadry control
  - Non-spinning and spinning reserves should restore spinning reserves within 15 minutes
- Tertiary control
  - Supplementary reserves should restore secondary control within 30 to 60 minutes

Secondary Control

$$dP = - K \times ACE - 1/Tr \int ACE\, dt \, *$$

where

dP = output set point of secondary controller
K = gain of P – controller
ACE = Area Control Error
Tr = time constant of secondary controller
* Note: The control action dP increases by integral formula, if the deviation of ACE remains constant (PI-type controller)

ACE = Area Control Error

$$ACE = dB + K \times df$$

Where

dB = deviation in power balance (= Generation-Load + Import - Export)

df = deviation of frequency from (f_N)

K = dependency between deviation of power and system frequency

Note: ACE is calculated in ten second intervals by computers in the dispatch center in USA

If ACE > given limit, penalties will be given to utilities

250 MW non-spinning reserve plant Kiisa , Estonia

Includes 27 Wärtsilä 34DF 10 MW engines

Black-start diesel generators

Emergency Diesel Generators (EDG)

Station Blackout Diesel Generators (SBO)

Starting reliability (SR=97 %)

n	1	2	3	4	5	6	7	8	100
n	97,0000	94,0900	91,2673	88,5293	85,8734	73,7424	54,3794	21,8065	4,7553
n-1		99,7354	99,7354	99,4814	99,1528	96,5493	88,0162	55,5280	19,4622
n-2			99,9973	99,9894	99,9742	99,7235	97,8992	81,0798	41,9775
n-3				99,9999	99,9996	99,9853	99,7331	93,7240	64,7249
n-4						99,9995	99,9980	98,3189	81,7855
n-5							99,9999	99,6264	91,9163
n-6								99,9296	96,8772
n-8								99,9886	98,9376
n-9								99,9984	99,6784
n-10								99,9998	99,9126
n-11									99,9785
n-12									99,9952

Emergency Diesel Generators (EDG) in Nuclear Plants

Single Diesel Generator

1 x 100 %, R > 0.9700

American nuclear plants

2 x 100 %, R > 0.9974

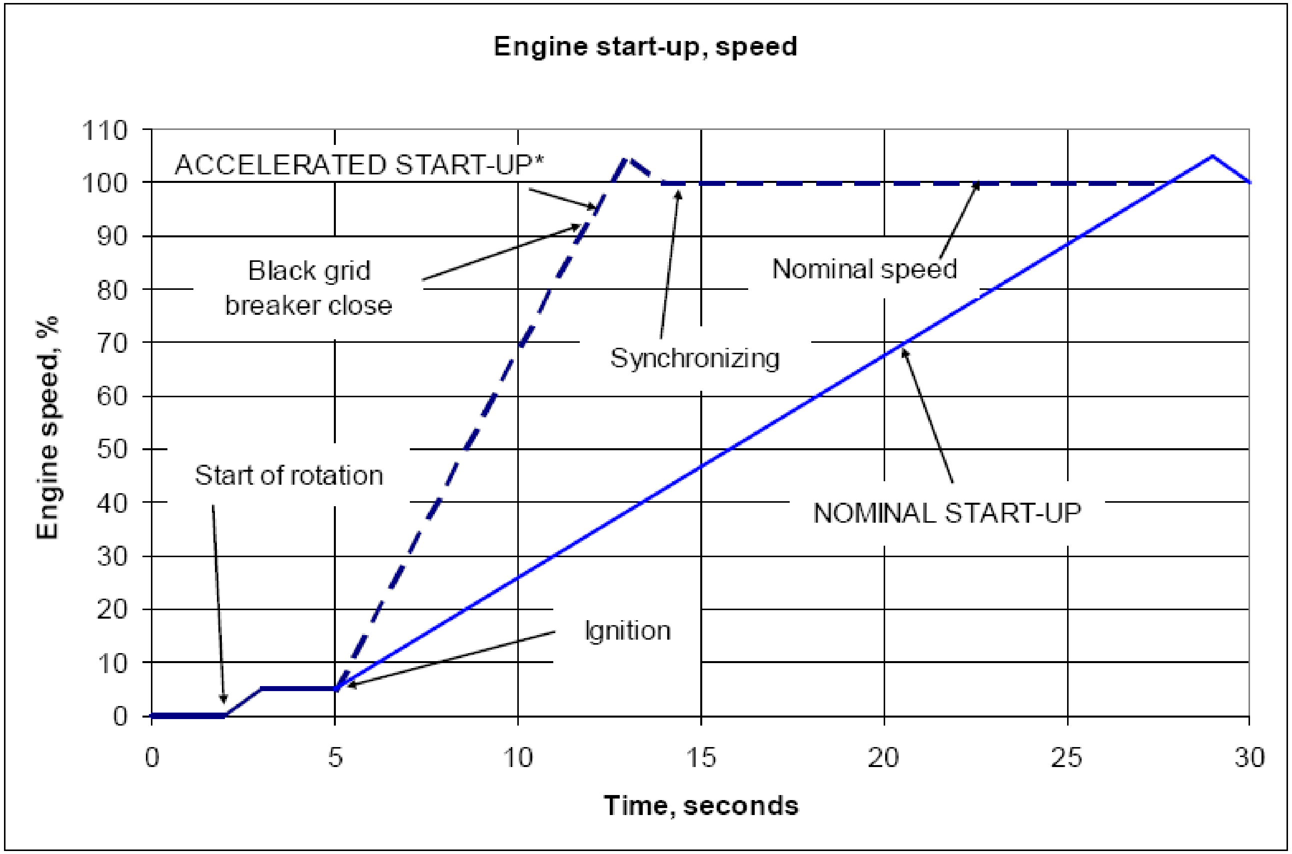
Finnish and German Nuclear plants

4 x 50 %, R > 0.9989

One of four will start with probability

4 x 100 % R>0.999999

EDG Start-up time



* Accelerated start-up criteria:
- engine must be pre-heated
- visible smoke may occur
- not possible with engine driven fuel pump
- start air pressure must be a minimum of 28 bar

Loviisa 10 MW SBO/Fast Reserve Diesel plant

Need for Diesel Generators and Fast Reserves

Emergency Diesel (EDG)	4 x (3 – 8 MW)
Swing Diesels (SDE)	1 x (3 – 8 MW)
Station Blackout (SBO)	1-2 x (1 – 10 MW)
Fast reserve capacity	1,18 x largest unit
	1,18 x 1700 MW = 2000 MW
	in Finland

Investment costs

Reserve diesel generator plant	600-700 €/kW
Gas engine CHP plant	700-800 €/kW
EDG plant	1000 -2000 €/kW
Coal or peat CHP plant	1000-1500 €/kW
Wind power park	1000-1500 €/kW
Nuclear plant	4000-6000 €/kW

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”

Author:
Asko Vuorinen

Publisher:
Ekoenergo Oy

Printed:
2008 in Finland

Further details:
www.ekoenergo.fi