Frequency Control

Lectures 5-6 in EG2050 System Planning

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Course Objectives

To pass the course, the students should show that they are able to

- explain how the balance between production and consumption is maintained in an electric power system,
- and calculate how the frequency is affected by various events in the power system.

To receive a higher grade (A, B, C, D) the students should also show that they are able to

- determine if the frequency control of an electric power system has sufficient margins, and
- if necessary be able to choose between various measures to increase the margins.

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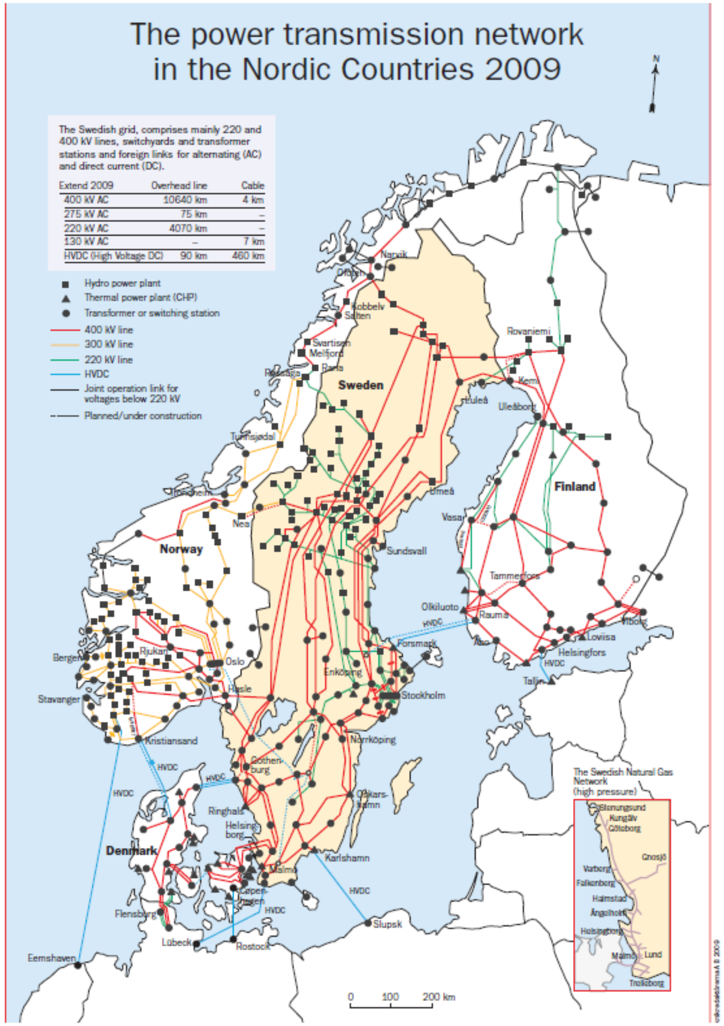
Power Systems

- Electric energy cannot be stored in practical power system applications
  - Power lines do not store energy
  - Plate capacitors store electric energy
    - Not much, not for so long
  - Non-electric energy storage in power systems
    - Pump storage (potential energy)
    - Chemical capacitors, (chemical energy, batteries)
    - Flywheels, rotating masses of generators (kinetic energy)
- Electricity has to be generated the instant it is used
- Automatic control systems are necessary in all larger power systems

Synchronous Grids

- A power system connected by AC lines and transformers constitutes a synchronous grid.
- There can only be one frequency in a synchronous grid.
- Analogies:
  - Trains – each wagon has to travel in the same speed
  - If one locomotive stops, the speed goes down
    - Until the other locomotive(s) have compensated
    - The stable speed will be lower (primary control)
    - Create speed increase – stop when satisfied (secondary control)

Synchronous Grids – Nordel



Frequency Range (1/4)

The frequency of a large power system must be kept around the nominal value!

- Certain frequencies can harm important equipment in the power system.
  - Harmonic vibrations in turbine blades and shafts.
  - Heating of generators and transformers.
- Some loads might be disturbed.

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Frequency Range (2/4)

- Automatic control systems–primary control
  - Normal operation (In Sweden: 49.9 - 50.1 Hz)
  - Disturbance reserve (In Sweden: 49.5 – 49.9 Hz)
- Disconnection of interruptible loads
  - (In Sweden: 49.0 - 49.8 Hz)
  - Export on HVDC lines
  - Electric boilers,
  - Heat pumps
  - Pumped storage hydro (no such in Sweden)
- *Continues ...*

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Frequency Range (3/4)

- *Continued ...*
- Automatic load shedding
  - Stepwise, parts of distribution grids
  - (In Sweden: 49.0 - 49.8 Hz)
- Manual load shedding (rotating load curtailment)
  - Larger areas, e.g. Stockholm Metropolitan Area
  - (In Sweden: < 48.0 Hz)
  - Never happened
  - Note!
    - We assume here the grid works perfectly
    - Blackouts have occurred at major transformer outages
    - Different countermeasures for that

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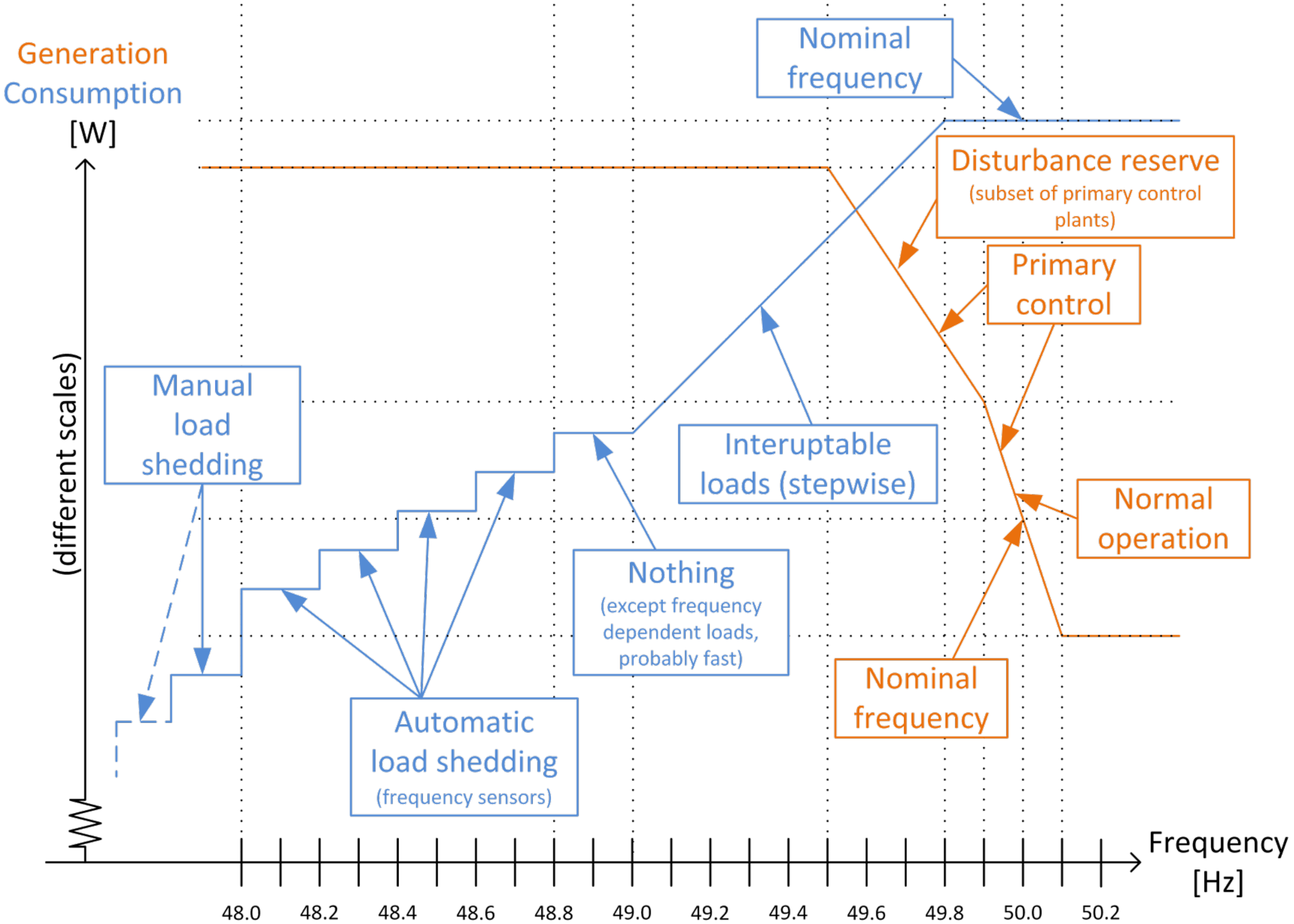
Frequency Range (4/4)



Primary Control

- The objective of the primary control is to maintain the balance between generation and load
- In control theory, the primary control corresponds to a proportional controller (P controller).

Primary Control – Load increase

- System in balance
- Load increases – generation unaffected
- Energy is taken from the kinetic energy of all synchronous machines.
  - The synchronous machines will rotate slower.
  - The frequency decreases.
- Frequency sensors in some power plants
  - detect the frequency decrease
  - increase generation in that power plant until the frequency is stable again.

Primary Control - Overview

Event | Frequency change | Compensation

$$+\Delta D \Rightarrow -\Delta f \Rightarrow +\Delta G$$

$$-\Delta D \Rightarrow +\Delta f \Rightarrow -\Delta G$$

$$+\Delta G \Rightarrow +\Delta f \Rightarrow -\Delta G$$

$$-\Delta G \Rightarrow -\Delta f \Rightarrow +\Delta G$$

Physics | Control system

Gain (1/7)

Definition 1: The gain states the change in generation for specific change in frequency:

$$G = G_0 - R(f - f_0)$$

where G_0 denotes the base generation, R the gains, f_0 the nominal frequency, and f the actual frequency.

Gain (2/7)

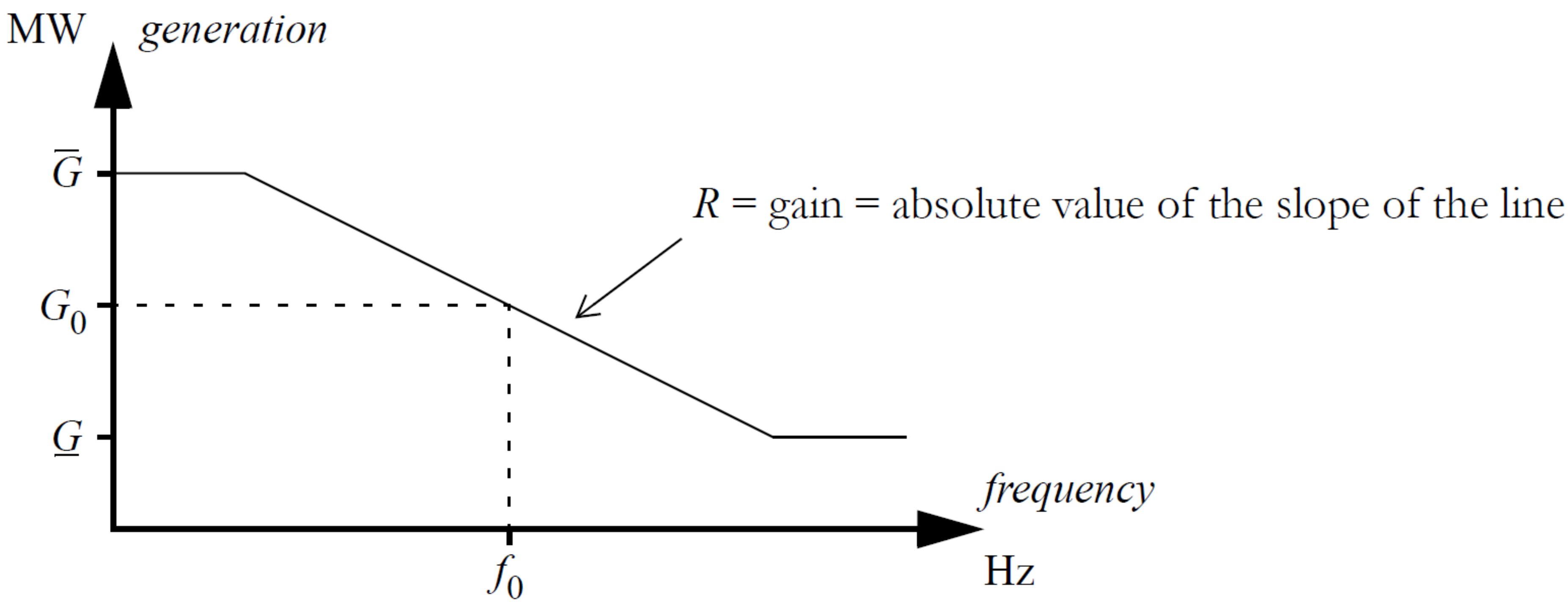


Figure 4.1 The relation between frequency and generation in a power plant participating in the primary control.

Gain (3/7)

Simpler to only consider the changes

$$\Delta G = R \cdot \Delta f$$

Example 1:

- Generation 1000 MW
- Load 1000 MW
- Gain 200 MW/Hz
- Frequency 49.98 Hz
- What is the new frequency going to be if the load increases by 10 MW?

Gain (4/7)

Example 1 (continued):

$$\Delta f = \frac{\Delta G}{R} = \frac{10}{200} = 0.05$$

- Load increase => Frequency increase
- The new frequency: 49.98 – 0.05 = 49.93 Hz

Gain (5/7)

Example 2:

- One minute after the load increase in Example 1, the load decreases by 6 MW.
- What is the new frequency going to be?

Gain (6/7)

Example 2 – Solution I

Compare to the situation after the load increase in Example 1

$$\Delta f = \frac{\Delta G}{R} = \frac{6}{200} = 0.03$$

- Load decrease => frequency increase
- The new frequency is 49.93 + 0.03 = 49.96 Hz

Gain (7/7)

Example 2 – Solution II

Compare to the situation before the load increase in Example 1

$$\Delta f = \frac{\Delta G}{R} = \frac{10-6}{200} = \frac{4}{200} = 0.02$$

- Load increase => frequency decrease
- The new frequency is 49.98 – 0.02 = 49.96 Hz

Limitations in primary control

- When designing a power system, it is important to consider that there are limitations to the primary control:
  - Plants in primary control have limited primary control reserves
  - The gain must be fairly even distributed in the system – in order not to overload transmission

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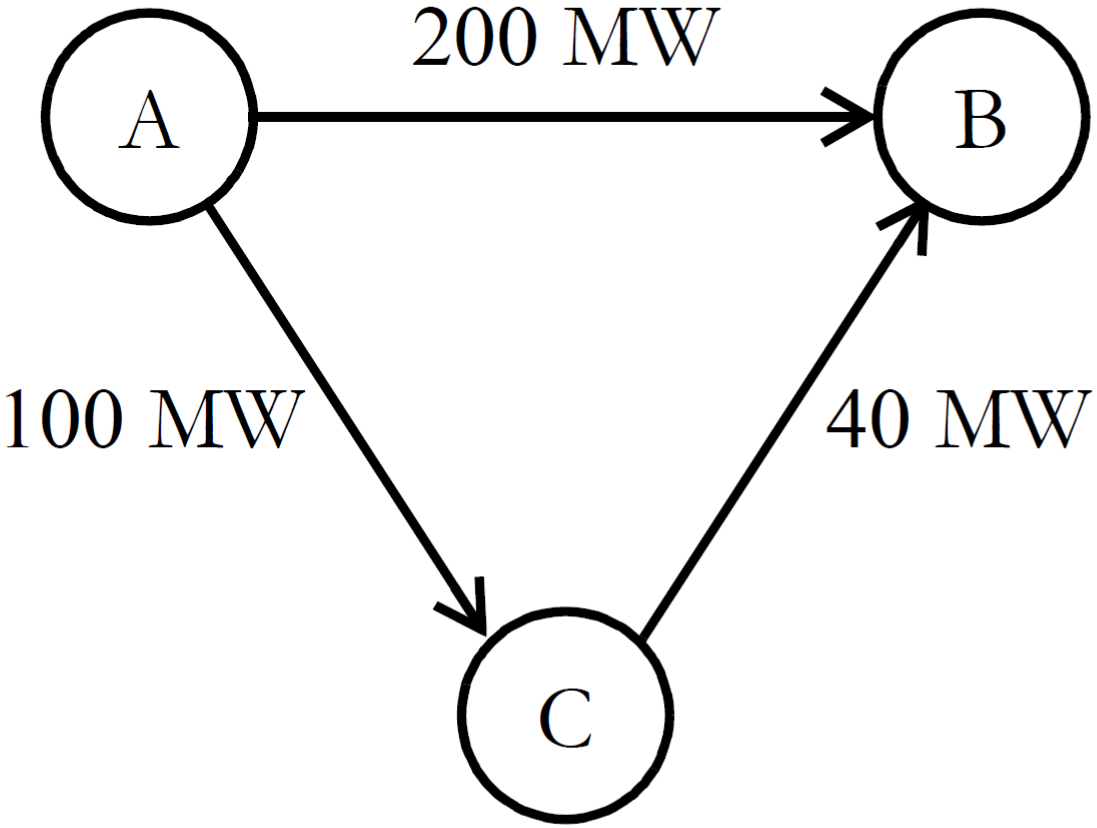
Example 4.1 - Problem

- Power system in balance, nominal frequency (50 Hz).
- Two power plants participating in primary control:
  - Unit 1:
    - 500 MW capacity,
    - current generation 420 MW,
    - gain 300 MW/Hz
  - Unit 2:
    - 100 MW capacity,
    - current generation 75 MW,
    - gain 300 MW/Hz
- 85 MW of generation is lost in another unit.
- What is the frequency after restoring balance?

Example 4.1 - Solution

- Same gain ⇒ both units increase their generation by the same amount, i.e., 85/2 = 42.5 MW.
- Unit 2 can only increase generation by 25 MW!
  - When the frequency is about 49.916 Hz unit 2 will stop regulating.
- To restore balance, unit 1 must increase its generation by 85 – 25 = 60 MW.
- $\Delta f = \frac{\Delta G}{R} = \frac{60}{300}$ Hz = 0.2 Hz.
- New frequency f = 50 – 0.2 = 49.8 Hz.

Example 4.2 - Problem



- $R_A = 900$ MW/Hz
- $R_B = 50$ MW/Hz
- $R_C = 50$ MW/Hz
- $P_{AB} = 200$ MW
- $P_{AC} = 100$ MW
- $P_{BC} = -40$ MW
- $\widehat{P_{AB}} = 300$ MW
- $\widehat{P_{AC}} = 150$ MW
- $\widehat{P_{BC}} = 120$ MW
- 240 MW lost in area B
- Calculate the resulting
  - Frequencies, and
  - power flows induced by primary control

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Example 4.2 – Solution (1/6)

- Generation has to increase by 240 MW.
- The increase is distributed between the areas according to their share of the total gain,
  - $R_{ABC} = 900 + 50 + 50 = 1000$ MW/Hz
  - $\Delta G_A = \frac{R_A}{R_{ABC}} \cdot 240 = 216$ MW.
  - $\Delta G_B = \frac{R_B}{R_{ABC}} \cdot 240 = 12$ MW.
  - $\Delta G_C = \frac{R_C}{R_{ABC}} \cdot 240 = 12$ MW.

Example 4.2 – Solution (2/6)

- Area A
  - Same load, increased generation => increased export
  - Only 150 MW export capacity available
  - Both transmission lines will be overloaded
  - The area is isolated from the rest of the system
  - Export reduced by 300 MW (compared to before fault)
    - Equivalent to a load reduce
  - Frequency increase $\Delta f_A = \frac{300}{900} \approx 0.33$ Hz

Example 4.2 – Solution (3/6)

- Areas B and C
  - Total deficit 540 MW
    - 240 MW lost generation
    - 300 MW lost import
  - Equal gain => both areas increase generation by 270 MW

Example 4.2 – Solution (4/6)

- Area C
  - Increased export by 170 MW
    - Decreased import 100 MW
    - Increased generation 270 MW
  - Only 80 MW export capacity left
  - Transmission line overloaded
  - Area C is isolated from A since before, now also from B
  - Now there is a deficit of 60 MW compared to before fault
    - Lost 100 MW import from A
    - Lost 40 MW export to B
  - Frequency increase $\Delta f_C = \frac{60}{50} = 1.2$ Hz

Example 4.2 – Solution (5/6)

- Area B
  - Area is isolated – as well as the other two areas
  - Deficit of 480 MW
    - Lost 240 MW import and
    - Lost 240 MW generation
  - Frequency decrease $\Delta f_B = \frac{480}{50} = 9.6\ \mathrm{Hz}$

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Example 4.2 – Solution (6/6)

- Summary
  - All lines overloaded
  - New frequency in Area A: 50.33 Hz
  - New frequency in Area B: 40.4 Hz
  - New frequency in Area C: 48.8 Hz

Primary control in restructured electricity markets

- The system operator is responsible for primary control, but does not have sufficient generation capacity.
- Two solutions:
  - Require producers to supply certain amounts of gain to be allowed to connect to the grid.
  - Pay producers to supply gain.

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Primary control pricing

- The players who supply primary control to the system can be reimbursed for
  - provision of primary control capacity (€/(MW·Hz)
  - utilization of primary control (€/MWh)
    - The energy price may for example be obtained from the real-time market.

Costs of primary control (1/3)

- The costs of supplying primary control capacity depends on the generation technology.
  - Wind power, photovoltaics:
    - Non-dispatchable units ⇒ very high costs.
    - (ickereglerbara)
  - Hydro power:
    - Negligible fuel costs,
    - small efficiency losses
    - ⇒ Low costs.
  - *Continues ...*

Costs of primary control (2/3)

- The costs of supplying primary control capacity depends on the generation technology.
  - *Continued ...*
  - Large thermal units:
    - Fuel costs,
    - efficiency losses
    - ⇒ high costs.
  - Nuclear power plants:
    - Designed to be operated at installed capacity
    - ⇒ quite high costs.
  - *Continues ...*

Costs of primary control (3/3)

- The costs of supplying primary control capacity depends on the generation technology.
  - *Continued ...*
  - Small thermal units:
    - Fuel costs,
    - small efficiency losses
    - ⇒ rather high costs.

Primary control reserves

- The capacity available for primary control depends on the requirements for the system.
- Example: The Nordic system
  - Total gain R = 6 000 MW/Hz
  - Primary control should work properly for frequencies within 50 ± 0.1 Hz
  - The necessary reserves are $\Delta G = R \cdot \Delta f$ = 600 MW.

Secondary control (1/2)

The objective of the secondary control is to

- restore the frequency to its nominal value,
- release used primary control reserves,
- reduce the integrated time error.

In control theory, the secondary control corresponds to an integral controller (I controller).

Secondary control (2/2)

Secondary control operates by changing the base generation* of the system.

Examples of such:

- Change generation in a power plant that is not participating in the primary control.
- Change base generation in a power plant that is participating in the primary control.

* By which we mean the generation at nominal frequency

Controlling the frequency (1/2)

- If the frequency is less than the nominal then
  - some generation capacity needs to be started, or
  - the load decreased.
- If the frequency is larger than the nominal then
  - some generation capacity needs to be stopped, or
  - the load increased.
- In both cases, some primary control reserves will be released.

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Controlling the frequency (2/2)

Secondary control can be performed by

- Automatic control systems
  - (AGC – Automatic Generation Control).
- Manual control (using real-time trading).

Time Error

- The integrated time error is the deviation between
  - normal time and
  - synchronous time
    - (i.e., a clock controlled by the grid frequency).
- The time deviation during a certain period T in a 50 Hz system is given by

$$t_d = \int_0^T \frac{f(\tau) - 50}{50} d\tau$$

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Controlling the time error

- To reduce a negative time error, the frequency must be larger than the nominal value for some time.
- To reduce a positive time error, the frequency must be lower than the nominal value for some time.
  - generally not a problem
  - system components less sensitive for under-frequencies
- The time error is not considered very important for the operation of the power system.

Time Error - Example

- Current time deviation: –2 s.
- Frequency the next five minutes: 50.1 Hz.
- What is the time deviation after this period?
- Solution:
- During each second the grid clock will pass 0.1 cycles more than normal time.
- Grid clock will gain 0.1/50·(5·60) = 0.6 s compared to normal time.
- Time error after five minutes

$$t_d = -2 + 0.6 = -1.4 \text{ s}$$

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Time Error – Practical usage (1/4)

The time error can be used to calculate the real-time trading of a balance responsible player participating in primary control:

Example:

- Power Ltd. is a balance responsible player.
- During the trading period 9-10 am. (09.00-10.00) they have sold
  - 3 000 MWh to the power pool, and
  - 3 560 MWh directly to consumers.

Time Error – Practical usage (2/4)

- The generation in the base power plants of the company (i.e., power plants not participating in primary control) was 4 650 MWh.
- Power Ltd. also has power plants participating in the primary control
  - Base generation (G0) 2 000 MW
  - Gain (R) 1 000 MW/Hz
  - Neglect limitations in primary control reserves
- The time error
  - 09:00 is –0.42 and
  - 10:00 is +0.30.

Time Error – Practical usage (3/4)

- The relation between frequency and time deviation is linear ⇒ Assume constant frequency during the hour.
- The grid clock changes by (f – 50)/50 s every second.
- The total change during 3 600 s is +0.72 s ⇒ f = 50.01 Hz.
- At f = 50.01 Hz, the power plants participating in primary control generate

$$G = G_0 - R(f - f_0) = 2000 - 1000(50 - 50.01) = 2000 - 10 =$$
$$= 1990 \text{ MW}$$

Time Error – Practical usage (4/4)

- Hence, Power Ltd. is buying 10 MWh from the system operator during the real-time trading.
- The imbalance of Power Ltd. Is

$$4\,650 + 1\,990 + 10 - 3\,000 - 3\,560 = 70 \text{ MWh}$$

- i.e., the company must sell 70 MWh imbalance power to the system operator.

Frequency control in smaller power systems – Load control (1/2)

- It might be preferable to let the primary control govern the electrical load instead of the mechanical input.
- If the generation is larger than the load, the load is increased in a “dummy load” (for example a water heater).
  - In railways – voltage control instead of frequency control:
    - If braking too hard regeneratively – heating resistors
- Example:
  - Stand-alone hydro power plant, which is always operating at installed capacity.

Frequency control in smaller power systems – Load control (2/2)

Kisiizi Hydro Power Plant, Uganda

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Frequency control in smaller power systems – DC generation

- DC generators can feed an AC grid via an inverter.
- A control system for the DC generator and inverter is necessary if there is no synchronous generator in the system.
- Example: Solar home system.

Time for ”Lecture Assignments”

- On another slideshow ...