FREQUENCY CONTROL

Lectures 5-6
in
EG2050 System Planning

Mikael Amelin

KTH Electrical Engineering

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

There is no practical storage of electric energy in a power system!

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- 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.

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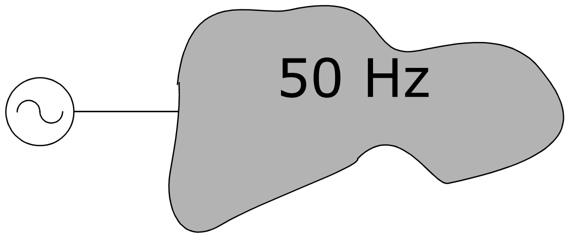
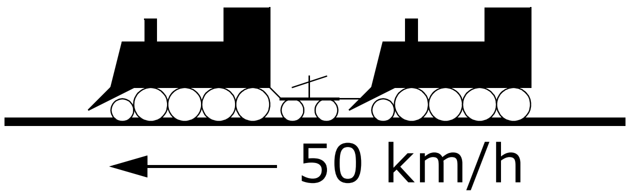
Analogy

A synchronous machine can be compared to a trolley between two locomotives—it must go at the same pace as the rest of the system, otherwise it will be crushed.





SYNCHRONOUS GRIDS - Nordel

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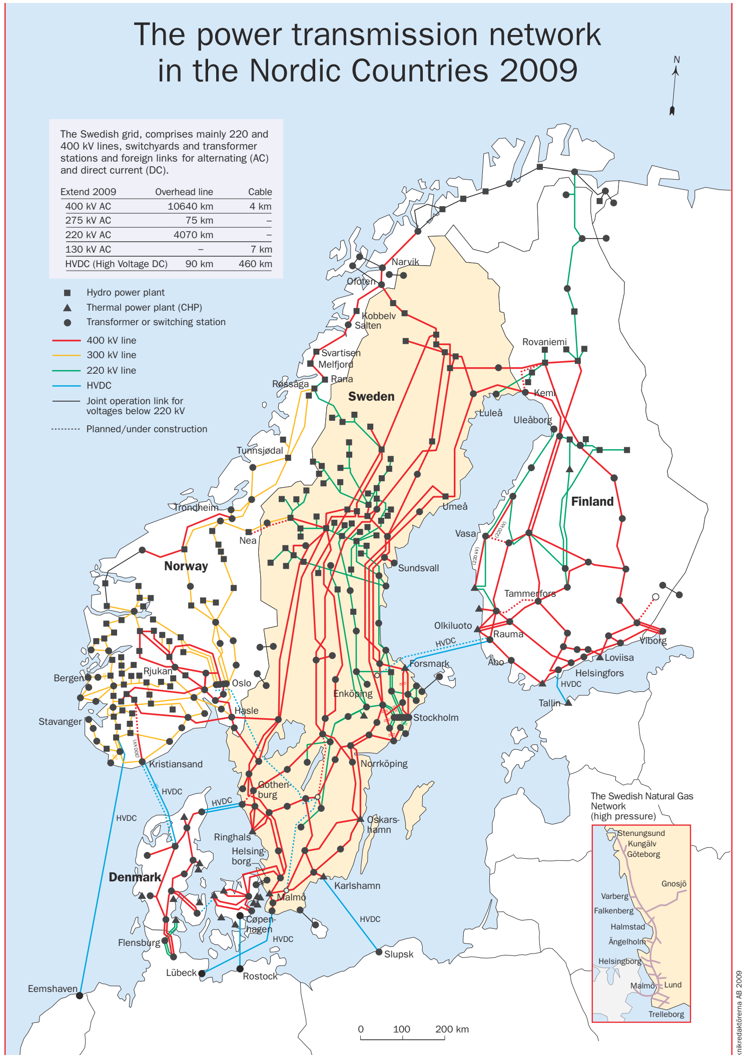

FREQUENCY RANGE

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

- Automatic control systems:
  - Normal operation (In Sweden: 49.9 - 50.1 Hz)
  - Disturbance reserve (In Sweden: 49.5 - 49.9 Hz)
- Disconnection of interruptible loads (export on HVDC lines, electric boilers, heat pumps, pumped storage hydro (In Sweden: 49.0 - 49.8 Hz)
- Automatic load shedding (In Sweden: 48.0 - 48.8 Hz)
- Manual load shedding (rotating load curtailment (In Sweden: < 48.0 Hz)

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FREQUENCY CONTROL SYSTEMS

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- Primary control
  - Response time: seconds
  - Automatic control system
- Secondary control
  - Response time: minutes
  - Automatic control system
- Tertiary control
  - Response time: 10–15 minutes
  - Manually activated

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, but generation is 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 and 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

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

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

where

$$G_0 = \text{base generation},$$
$$R = \text{gain},$$
$$f_0 = \text{nominal frequency}.$$

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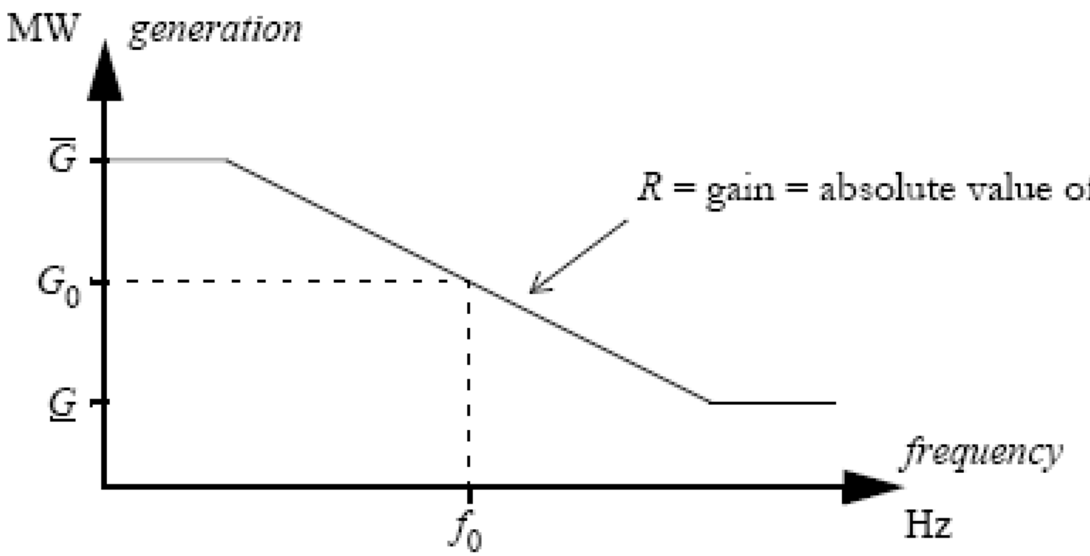

Figure 4.1 The relation between frequency and generation in a power plant participating in the primary control.

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In general, it is better to just consider the changes, i.e., $\Delta G = R \cdot \Delta f$, and then think!

Example 1:

- Generation $1\,000$ MW
- Load $1\,000$ MW
- Gain 200 MW/Hz
- Frequency 49.98 Hz.

What is the new frequency going to be if the load increases by 10 MW?

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Example 1 — Solution

- $\Delta f = \dfrac{\Delta G}{R} = \dfrac{10}{200}$ Hz $= 0.05$ Hz,
- Load increase $\Rightarrow$ Frequency decrease
- Hence, the new frequency is

$$f = 49.98 - 0.05 = 49.93 \text{ Hz}.$$

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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?

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Example 2 — Solution I

Compare to the situation after the load increase in example 1, i.e.,

- $\Delta f = \dfrac{\Delta G}{R} = \dfrac{6}{200}$ Hz $= 0.03$ Hz,
- Load decrease $\Rightarrow$ Frequency increase
- Hence, the new frequency is

$$f = 49.93 + 0.03 = 49.96 \text{ Hz.}$$

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Example 2 — Solution II

Compare to the situation before the load increase in example 1, i.e.,

- $\Delta f = \dfrac{\Delta G}{R} = \dfrac{4}{200}$ Hz $= 0.02$ Hz,
- Load increase $\Rightarrow$ Frequency decrease
- Hence, the new frequency is

$$f = 49.98 - 0.02 = 49.96 \text{ Hz}.$$

LIMITATIONS IN PRIMARY CONTROL

When designing a power system, it is important to consider that there are limitations to the primary control:

- The power plants participating in primary control have limited primary control reserves.
- The gain must be fairly evenly distributed in the system, because otherwise the trans-mission grid might be overloaded.

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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.

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EXAMPLE 4.1 - Solution

- Same gain $\Rightarrow$ 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 60 MW.
- $\Delta f = \dfrac{\Delta G}{R} = \dfrac{60}{300}$ Hz $= 0.2$ Hz.
- New frequency $f = 50 - 0.2 = 49.8$ Hz.

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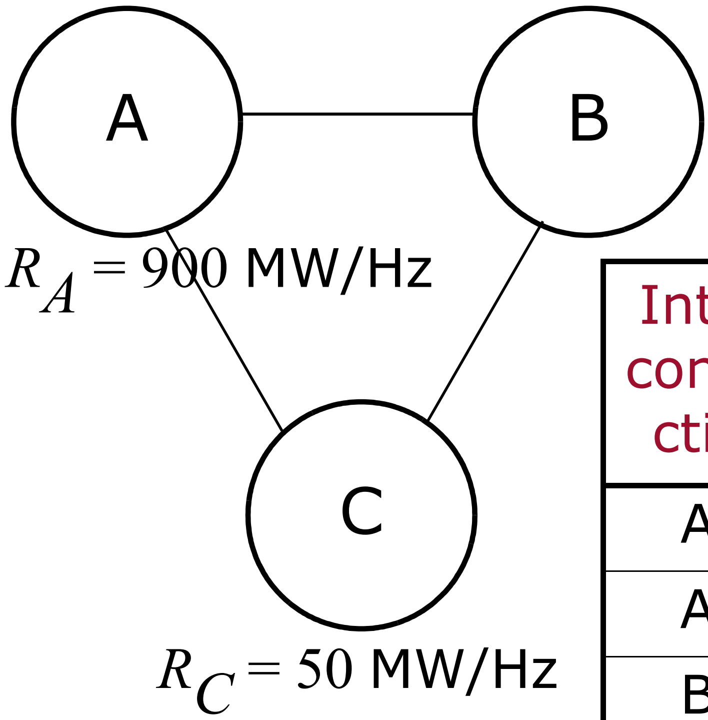
EXAMPLE 4.2 - Problem



Inter-connection	Current power flow [MW]	Maximal power flow [MW]
AB	200	300
AC	100	150
BC	−40	120

- 240 MW generation is lost in area B.

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EXAMPLE 4.2 Solution

- Generation has to increase by 240 MW.
- The increase is distributed between the areas according to their share of the total gain, $R_{ABC} = 1\ 000$ MW/Hz.

$$\Delta G_A = \frac{R_A}{R_{ABC}} \cdot 240 = 216 \text{ MW.}$$

$$\Delta G_B = \frac{R_B}{R_{ABC}} \cdot 240 = 12 \text{ MW.}$$

$$\Delta G_C = \frac{R_C}{R_{ABC}} \cdot 240 = 12 \text{ MW.}$$

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EXAMPLE 4.2 Solution

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Area A

- Same load, increased generation $\Rightarrow$ increased export.
- However, only 150 MW export capacity available $\Rightarrow$ both transmission lines will eventually be overloaded.
- The area is isolated from the rest of the system $\Rightarrow$ reduced export 300 MW (compared to before the fault).

  Reduced export equivalent to a load reduction!
- Frequency increase $\Delta f_A = 300/900 = 0.33$ Hz.

EXAMPLE 4.2 Solution

Areas B and C

- Total deficit 540 MW (240 MW lost generation, 300 MW lost import).
- Equal gain $\Rightarrow$ both areas increase generation by 270 MW.

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EXAMPLE 4.2 Solution

Area C

- Decreased import 100 MW, increased generation 270 MW $\Rightarrow$ increased export by 170 MW.
- Only 80 MW export capacity $\Rightarrow$ transmission line overloaded.
- The area is isolated from the rest of the system $\Rightarrow$ deficit 60 MW compared to before the fault (lost 100 MW import and 40 MW export).
- Frequency decrease $\Delta f_C = 60/50 = 1.2$ Hz.

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EXAMPLE 4.2 Solution

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Area B

- The area is isolated from the rest of the system $\Rightarrow$ deficit 480 MW compared to before the fault (lost 240 MW import and 240 MW generation).
- Frequency decrease $\Delta f_B = 480/50 = 9.6$ Hz.

EXAMPLE 4.2 Solution

Summary

- All transmission 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

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PRIMARY CONTROL IN RESTRUCTURED ELECTRICITY MARKETS

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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.

PRIMARY CONTROL PRICING

The players who supply primary control to the system can be reimbursed for

- provision of primary control capacity (€ per MW/Hz)
- utilisation of primary control (€/MWh)

  The energy price may for example be obtained from the real-time market.

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COSTS OF PRIMARY CONTROL

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The costs of supplying primary control capacity depends on the generation technology.

- Wind power, photovoltaics: Non-dispatchable units ⇒ very high costs.
- Hydro power: Negligible fuel costs, small efficiency losses ⇒ low costs.
- Large thermal units: Fuel costs, efficiency losses ⇒ high costs.
- Nuclear power plants: Designed to be operated at installed capacity ⇒ quite high costs.
- Small thermal units: Fuel costs, small efficiency losses ⇒ rather high costs.

PRIMARY CONTROL RESERVES

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The amount of capacity available for the primary control depends on the requirements for the system.

Example: The Nordic system

- Total gain $R = 6\ 000$ MW/Hz
- Normal operation: frequency within 50 ± 0.1 Hz
- The necessary normal operation reserves are

$$\Delta G = R \cdot \Delta f = 600 \text{ MW}.$$

SECONDARY CONTROL

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).

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SECONDARY CONTROL

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

- 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.

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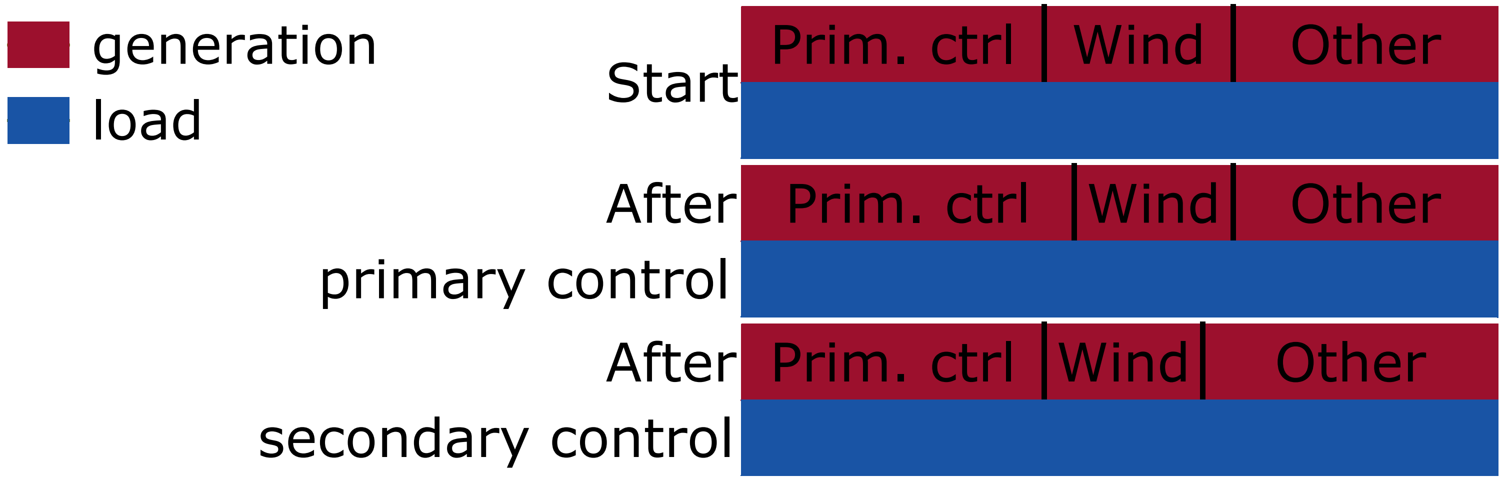
* By which we mean the generation at nominal frequency.

SECONDARY CONTROL

- 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.



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CONTROLLING THE FREQUENCY

Secondary control can be performed by

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

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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 in a 50 Hz system is given by

$$t_i = \int_0^t \frac{(f(\tau) - 50)}{50} d\tau.$$

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CONTROLLING THE TIME ERROR

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- 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 less than the nominal value for some time (generally not a problem).
- 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 $0.1/50 \cdot 300 = 0.6$ s compared to normal time.
- Time error after five minutes $t_i = -2 + 0.6 = -1.4$ s.

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TIME ERROR - Practical usage

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. they have sold 3 000 MWh to the power pool, and 3 560 MWh directly to consumers.

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TIME ERROR - Practical usage

- 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 (G_0) 2 000 MW
  - Gain (R) 1 000 MW/Hz
  - Neglect limitations in primary control reserves
- The time error 9:00 is –0.42 and the time error 10:00 is +0.30.

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TIME ERROR - Practical usage

- The relation between frequency and time deviation is linear $\Rightarrow$ 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 $\Rightarrow$ $f = 50.01$ Hz.
- At $f = 50.01$ Hz, the power plants participating in primary control generate $G = G_0 - R(f - f_0) = 1\,990$ MW.

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TIME ERROR - Practical usage

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

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

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

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FREQUENCY CONTROL IN SMALLER POWER SYSTEMS - Load Control

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- 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).

Example: Stand-alone hydro power plant, which is always operating at installed capacity.

FREQUENCY CONTROL IN SMALLER POWER SYSTEMS - Load Control

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Kisiizi Hydro Power Plant, Uganda

FREQUENCY CONTROL IN SMALLER POWER SYSTEMS - DC Generation

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- 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.