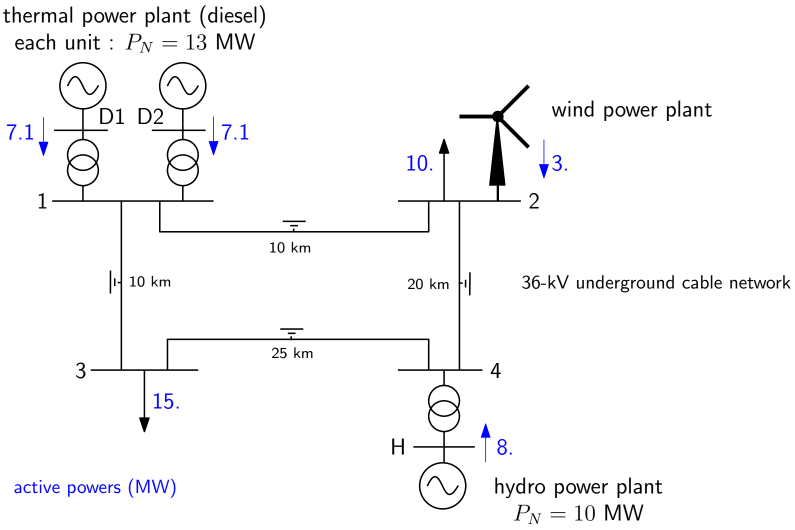
Exercise 1. Analysis of the Van Cutsem island system



All units : $\sigma = 0.04$. Load sensitivity coefficient : $D = 0.01$ /Hz

Initial frequency : 50 Hz

Incident: tripping at $t = 1$ s of the wind power plant at bus 2

Generator H :

$$P_m = 8 - \left(\frac{10}{0.04}\right) \times \left(\frac{f-50}{50}\right) \qquad \text{with } 0 \leq P_m \leq 10 \text{ MW}$$

Generators D1 and D2 :

$$P_m = 7.08 - \left(\frac{13}{0.04}\right) \times \left(\frac{f-50}{50}\right) \qquad \text{with } 0 \leq P_m \leq 13 \text{ MW}$$

Composite frequency response characteristic[1] :

$$\beta = 0.01 \times 22.16 + \frac{1}{50}\left(\frac{10}{0.04} + \frac{13}{0.04} + \frac{13}{0.04}\right) = 18.2216 \text{ MJ}$$

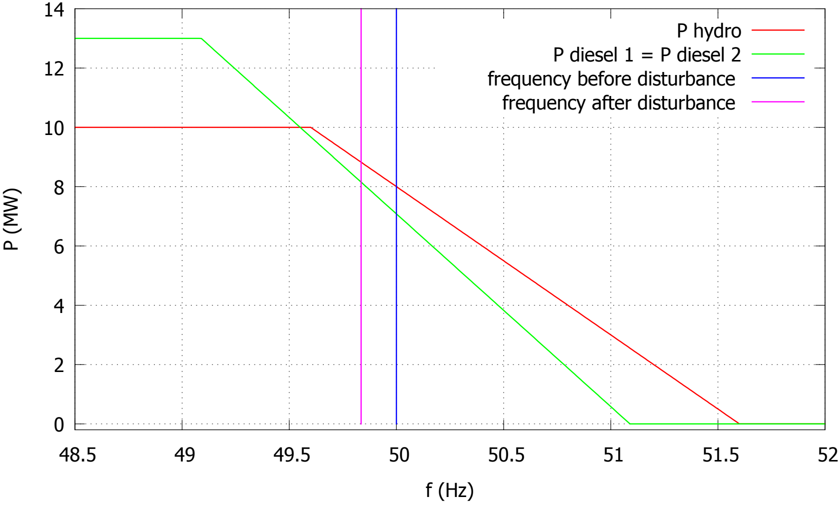
Final frequency deviation :

$$\Delta f = -\frac{\Delta P_c}{\beta} = -\frac{3}{18.2216} = -0.1646 \text{ Hz}$$

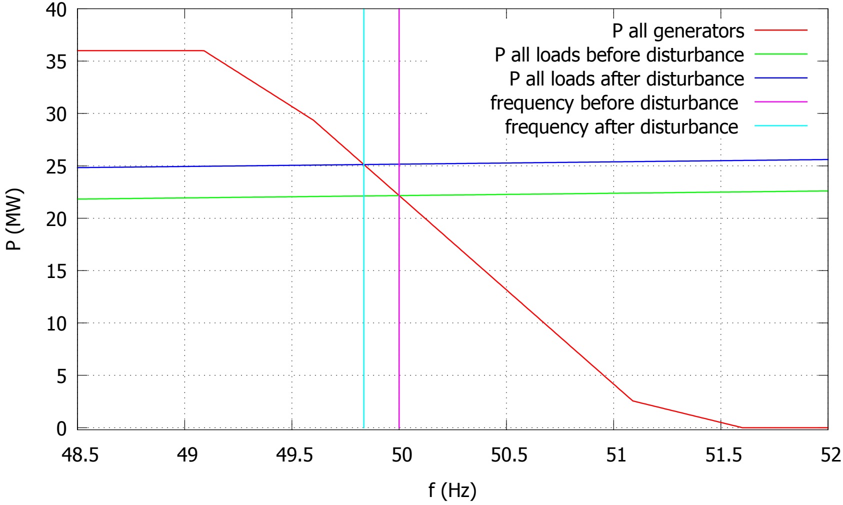
Final frequency :

$$f = 50 - 0.1646 = 49.86 \text{ Hz} = 0.9967 \text{ pu}$$

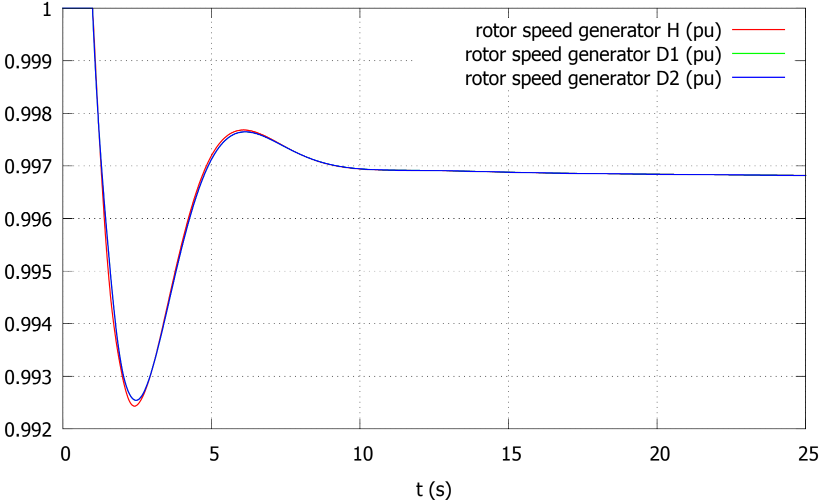
[1] en français: énergie réglante



Steady-state characteristics of individual turbine-governor sets



Steady-state characteristics of all turbine-governors combined



Comparison with dynamic simulation : rotor speeds of generators (pu)

Exercise 2. Frequency control of UCTE synchronous area

Reference: ENTSO-E, "Continental Europe Operation Handbook, Policy 1: Load-Frequency Control and Performance", https://www.entsoe.eu/publications/system-operations-reports/operation-handbook

In the UCTE synchronous area, the primary frequency control has the following characteristics:

- total primary control reserve requested on generators: 3 000 MW
- contribution of generators to composite frequency response characteristic β:
  - minimum requested value: 15 000 MW/Hz
  - average value: 19 500 MW/Hz
- load sensitivity coefficient D : 1 %/Hz
- total generation:
  - mean value: 306 000 MW
  - in low load conditions: 150 000 MW
- "reference incident": largest cumulated loss of generation, resulting from common-mode failures: 3 000 MW.

Compute the frequency drop resulting from:

- *the outage of a very large generator: a nuclear group producing 1 300 MW*
- *the reference incident*

assuming the minimum β, and for the mean and the low generation, respectively.

When generation is at its mean value, and assuming an equal value for the total load:

$$\beta = 15\,000 + 0.01 \times 306\,000 = 18\,060 \text{ MW/Hz}$$

In low load conditions:

$$\beta = 15\,000 + 0.01 \times 150\,000 = 16\,500 \text{ MW/Hz}$$

A generator outage is equivalent to a load increase.
We assume that β remains unchanged (owing to the large size of the system)

Outage of 1 300 MW

$$\Delta f = -\frac{1\,300}{18\,060} = -0.072 \text{ Hz} \quad \text{at mean generation}$$

$$\Delta f = -\frac{1\,300}{16\,500} = -0.079 \text{ Hz} \quad \text{at low load}$$

Outage of 3 000 MW

$$\Delta f = -\frac{3\,000}{18\,060} = -0.166 \text{ Hz} \quad \text{at mean generation}$$
$$\Delta f = -\frac{3\,000}{16\,500} = -0.182 \text{ Hz} \quad \text{at low load}$$

Maximum permanent frequency drop expected in the UCTE system $\simeq$ 180 mHz

In practice, 20 mHz can be added to account for *deadbands* in speed governors (intentional or unavoidable, they prevent the speed governor from responding to small frequency deviations).

This gives a total permanent frequency drop of 200 mHz.

Assuming for simplicity $\sigma = 4$ % for all speed governors in operation, compute the percentage of the total generation participating in primary frequency control, for both values of β.

The contribution of generators to β is : $\beta_{gen} = \frac{1}{f_N} \sum_i \frac{P_{Ni}}{\sigma_i}$

- if the i-th generator participates in frequency control : $\sigma_i = 0.04$
- if it does not participate : $\sigma_i \to \infty$

Hence : $\beta_{gen} = \frac{1}{50} \sum_{i \in \mathcal{P}} \frac{P_{Ni}}{0.04}$ where $\mathcal{P}$ denotes the set of participating generators.

Minimum value of $\beta_{gen} = 15\,000$ MW/Hz $\Rightarrow \sum_{i \in \mathcal{P}} P_{Ni} = 30\,000$ MW

9.8 % (resp. 20 %) of the generators participate at mean (resp. low) load

Average value of $\beta_{gen} = 19\,500$ MW/Hz $\Rightarrow \sum_{i \in \mathcal{P}} P_{Ni} = 39\,000$ MW

12.7 % (resp. 26 %) of the generators participate at mean (resp. low) load

Consider the outage of a Belgian nuclear generator producing 1 000 MW. Assuming that the total generation in Belgium is 13 000 MW, β is at its minimum value and the UCTE generation is at its mean value, determine:

- *the increase of production of Belgian generators under frequency control*
- *the additional power coming from the rest of the UCTE system through interconnection tie-lines.*

Consider for simplicity that the sensitivity of loads to frequency and the units participating in frequency control are uniformly distributed over the UCTE system.

Frequency deviation due to the generator outage:

$$\Delta f = -\frac{1\,000}{18\,060} = -0.0554 \text{ Hz}$$

By adding the steady-state characteristics of the Belgian generators, their total increase of power is given by:

$$\Delta P_{m,\mathcal{B}} = -\frac{\Delta f}{f_N} \sum_{i \in \mathcal{B}} \frac{P_{Ni}}{\sigma_i} \tag{1}$$

where $\mathcal{B}$ denotes the set of Belgian generators.

The composite frequency response characteristic of the Belgian system is:

$$\beta_{\mathcal{B}} = \frac{13\,000}{306\,000}\ 18\,060 = 767.26 \text{ MW/Hz}$$

while $\beta_{\mathcal{B}}$ is given by:

$$\beta_{\mathcal{B}} = D\ P^{o}_{c,\mathcal{B}} + \frac{1}{f_N} \sum_{i \in \mathcal{B}} \frac{P_{Ni}}{\sigma_i}$$

Hence: $\displaystyle\sum_{i \in \mathcal{B}} \frac{P_{Ni}}{\sigma_i} = f_N \left(\beta_{\mathcal{B}} - D\ P^{o}_{c,\mathcal{B}}\right) = 50\,(767.26 - 0.01 \times 13\,000) = 31\,863 \text{ MW}$

Introducing this result in (1):

$$\Delta P_{m,\mathcal{B}} = +\frac{0.0554}{50}\ 31\,863 = 35.3 \text{ MW}$$

Additional power coming from the rest of the UCTE system through interconnection tie-lines:

$$1\,000 - 35.3 = 964.7 \text{ MW}$$