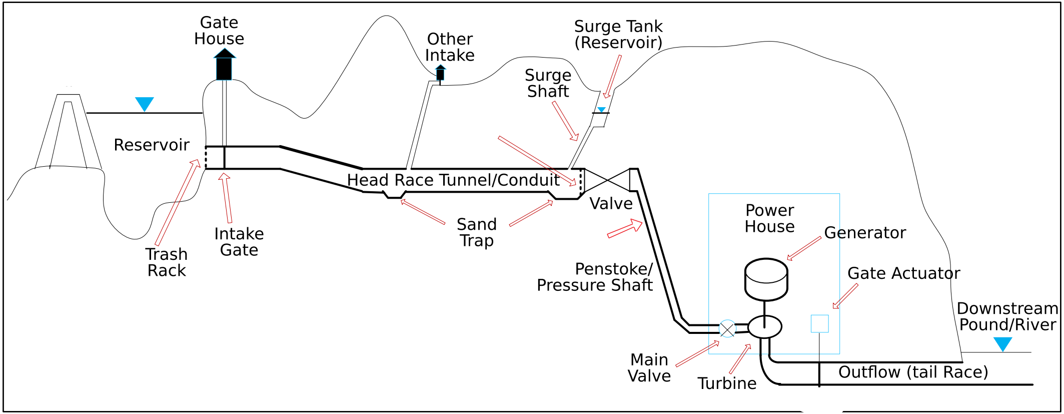
① Tegn HPS vcnn veien

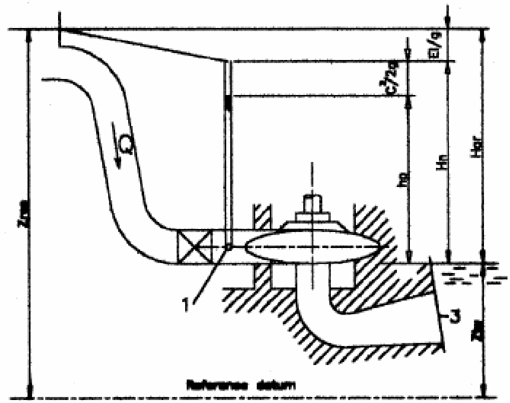
Overview

Typical high-head hydro power system



General theory

Gross quantities



Definition (Head and Energy)

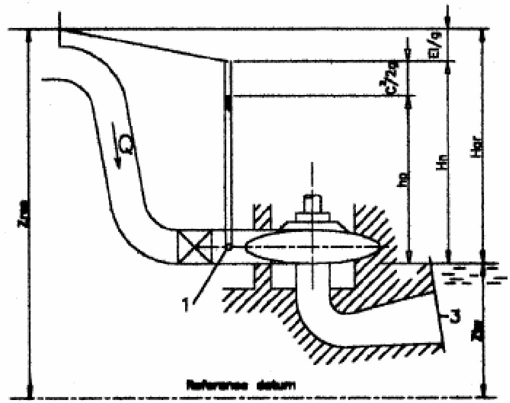
$$H_{gr} = z_{res} - z_{tw}$$

Definition (Power)

$$P_{gr} = \rho Q g H_{gr} \tag{1}$$

General theory

Net quantities



Definition (Head and Energy)

$$
\begin{aligned}
H_n &= H_{gr} - \frac{E_L}{g} = H_{gr} - H_L \\
&= h_p + \frac{c^2}{2g} \\
E_n &= gH_n
\end{aligned}
$$

Definition (Power)

$$P_n = \rho Q g H_n \tag{2}$$

Løs oppgave:

$Q = 1 \, m^3/s \qquad H = 100m$

Hva er Power?

Turbine types

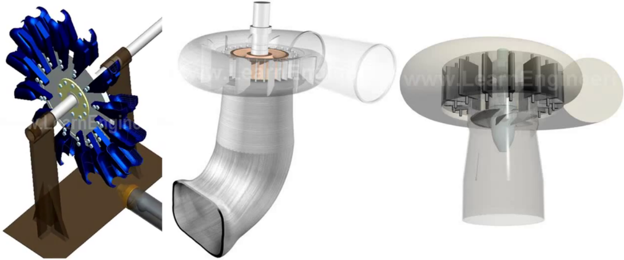


Figure: https://youtu.be/k0BLOKEZ3KU

Hydraulic efficiency

Part 1

Definition (Total available power)

$$P_n = \rho Q g H_n \tag{3}$$

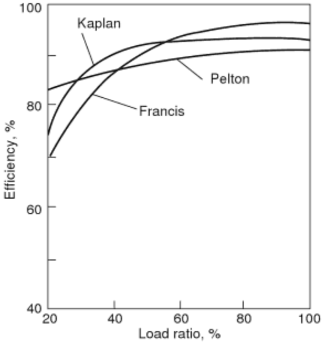
Definition (Power of the runner)

$$P_R = \rho Q(u_1 c_{u_1} - u_2 c_{u_2}) \tag{4}$$

Definition (Hydraulic efficiency)

$$\eta_h = \frac{P_R}{P_n} = \frac{1}{gH_n}(u_1 c_{u_1} - u_2 c_{u_2}) \tag{5}$$

Turbine efficiencies



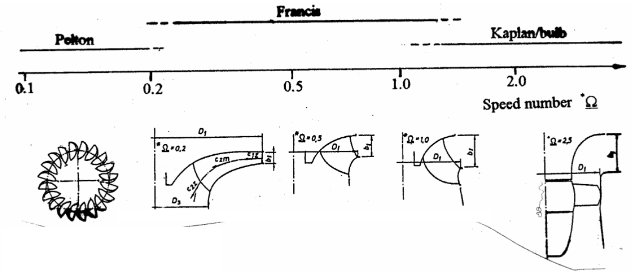
Variation of hydraulic efficiency for various types of turbine over a range of loading, at constant speed and constant head.

Turbine Classification

Speed Number and Specific Speed

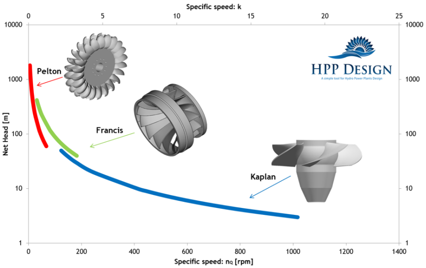
Speed Number

$$\frac{n_q}{89} = {}^*\underline{\Omega} = {}^*\underline{\omega}\sqrt{{}^*\underline{Q}} = \frac{\pi\,{}^*n\sqrt{{}^*Q}}{30\sqrt[4]{(2gH_n)^3}}$$



Specific Speed

$$n_q = \frac{{}^*n\sqrt{{}^*Q}}{\sqrt[4]{H_n^3}} \qquad k = \frac{{}^*\omega\sqrt{{}^*Q}}{\sqrt[4]{gH_n^3}}$$



Lecture Outline

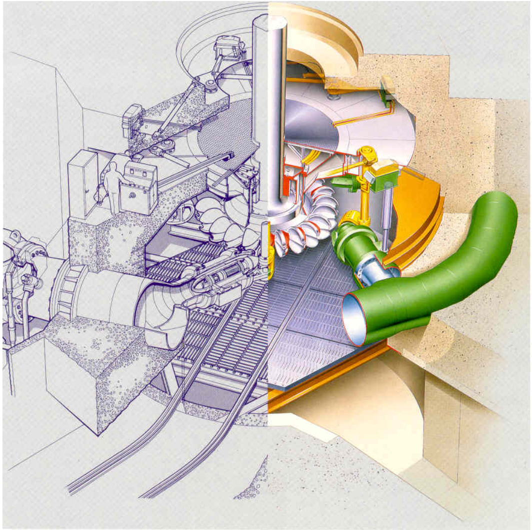
Slides

- Design of a Pelton turbine
  - Calculation of the different parameters
  - Two example calculation

Black board

- Introduction of a “Control Volume”
- In- and extensive properties
- General formulation of change of properties
- Lumped parameter model

Design of Pelton turbines



Design of Pelton turbines

Speed number range for an ideal Pelton turbine

Minium speed number

For the diameter $\mathrm{D} = 10 \cdot \mathrm{d_s}$ and one nozzle $\mathrm{z} = 1$:

$$\underline{\Omega} = \frac{\mathrm{d_s}}{\mathrm{D}}\sqrt{\frac{\pi \cdot \mathrm{z}}{4}} = \frac{1}{10}\sqrt{\frac{\pi \cdot 1}{4}} = 0.09$$

The minimum speed number for a Pelton turbine with one nozzle is:

$$\boxed{\underline{\Omega}_{\text{min}} = 0.09}$$

Maximum speed number

For the diameter $\mathrm{D} = 10 \cdot \mathrm{d_s}$ and six nozzles $\mathrm{z} = 6$:

$$\underline{\Omega} = \frac{\mathrm{d_s}}{\mathrm{D}}\sqrt{\frac{\pi \cdot \mathrm{z}}{4}} = \frac{1}{10}\sqrt{\frac{\pi \cdot 6}{4}} = 0.22$$

The maximum speed number for a Pelton turbine with one nozzle is:

$$\boxed{\underline{\Omega}_{\text{max}} = 0.22}$$

Active power and frequency control

Frequency response

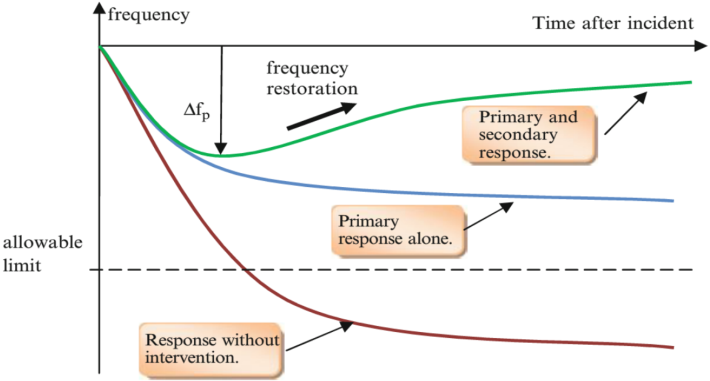


Figure: Planned frequency profile in response to large and sudden loss of generation

Active power and frequency

Primary Control

Droop: slope of frequency-power characteristic

$$R_{g_i} = -\frac{\Delta f / f_r}{\Delta P_{g_i} / P_{g_{i,r}}}$$

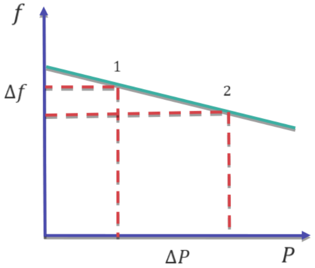
R_{g_i} droop (regulation) of generator i [pu]

Δf change in system frequency [Hz]

f_r nominal rated frequency [Hz]

ΔP_{g_i} change in active power of generator i [MW]

$P_{g_{i,r}}$ nominal rated power of generator i [MW]

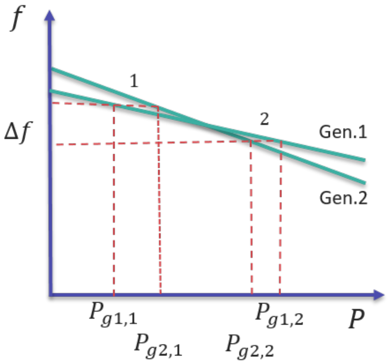


Active power and frequency: Primary Control

Two generators in parallel

Example

- $P_{g1_r} = P_{g2_r} = 200\,\mathrm{MW}$, $R_{g1} = 0.02$, $R_{g2} = 0.06$
- Balance (1): $f_r = 50\,\mathrm{Hz}$
- Sudden increase in of load $\Delta P \rightarrow$ frequency drop Δf
- Power distributed over two generators:
  $\frac{\Delta P_{g1}}{\Delta P_{g2}} = \frac{R_{g2}}{R_{g1}} = 3$
- Power increase in ratio 3:1 (75% G_1 and 25% G_2)



Active power and frequency: Primary Control

Many generators in parallel

Network Power-Frequency Characteristic

$$\lambda = -\frac{\Delta P[\mathrm{MW}]}{\Delta f[\mathrm{Hz}]} \quad \text{(bias factor)}$$

$$\Delta P = \sum_i \Delta P_{g_i} = \sum_i \left(-\frac{1}{R_{g_i}} \cdot \frac{P_{g_{i,r}}}{f_r} \cdot \Delta f \right)$$

$$\Rightarrow \lambda = -\frac{\Delta P}{\Delta f} = \sum_i \left(\frac{1}{R_{g_i}} \cdot \frac{P_{g_{i,r}}}{f_r} \right)$$

Active power and frequency: Primary Control

Many generators in parallel

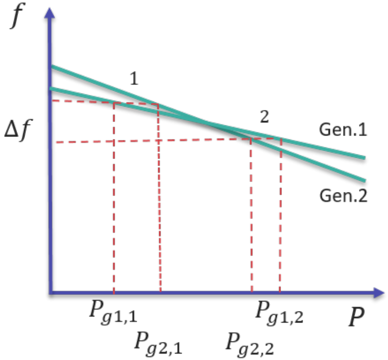
Example

- $\mathrm{P_{g1_r} = P_{g2_r} = 200\,MW, R_{g1} = 0.02, R_{g2} = 0.06}$

$$\Rightarrow \lambda = \frac{1}{\mathrm{f_r}} \sum_{\mathrm{i}} \frac{\mathrm{P_{g_{i,r}}}}{\mathrm{R_{g_i}}} = \frac{1}{50\,\mathrm{Hz}} \left(\frac{200\,\mathrm{MW}}{0.02} + \frac{200\,\mathrm{MW}}{0.06} \right)$$

$$= \frac{13,333}{50\,\mathrm{Hz}} = 266.6\,\frac{\mathrm{MW}}{\mathrm{Hz}}$$

$$\Delta \mathrm{P} = 133.3\,\mathrm{MW} \Rightarrow \Delta \mathrm{f} = -0.5\,\mathrm{Hz}$$



Active power and frequency: Primary Control

Self-regulation

Definition of Self-regulation

Motors cause the system load to be slightly frequency dependent.

$$\lambda = -\frac{\Delta P}{\Delta f} = \sum_i \left(\frac{1}{R_{g_i}} \cdot \frac{P_{g_{i,r}}}{f_r} \right) + \frac{\mu}{100} \cdot P$$

$$\mu = -\frac{\Delta P'/P}{\Delta f} \cdot 100\,\%$$

μ the self regulation effect of the load P $[\%/\mathrm{Hz}]$

$\Delta P'$ the change in the power consumption of the loads beacuse of the change in frequency Δf $[\mathrm{MW}]$

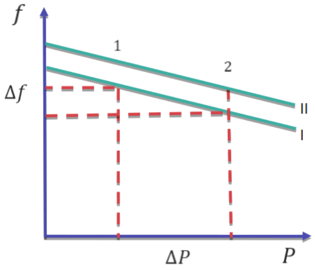
P the value of the original load of the system plus the change ΔP at the orginal system frequency $[\mathrm{Hz}]$

Active power and frequency: Secondary Control

Load Frequency Control (LFC)

Principle

1. Droop regulation – from point 1 to 2
   $\rightarrow$ Restore balance of active power
2. LFC – from characteristic I to II
   $\rightarrow$ Increase frequency (power remains constant)



Active power and frequency: Tertiary Control

Area Control Error (ACE)

Definition

$$\mathrm{ACE_i} = (\mathrm{P_{a_i}} - \mathrm{P_{s_i}}) + \lambda_\mathrm{i}(\mathrm{f_a} - \mathrm{f_s}) = \Delta\mathrm{P_i} + \lambda_\mathrm{i}\Delta\mathrm{f}$$

$\mathrm{ACE_i}$ Are Control Error of control area i $[\mathrm{MW}]$,

$\mathrm{P_{a_i}}$ actual power export of control area i $[\mathrm{MW}]$,

$\mathrm{P_{s_i}}$ scheduled power export of control area i $[\mathrm{MW}]$,

λ_i network $\mathrm{P/f}$ caracteristic of control area i $[\mathrm{MW/Hz}]$,

$\mathrm{f_a}$ actual frequency $[\mathrm{Hz}]$,

$\mathrm{f_s}$ scheduled frequency $[\mathrm{Hz}]$.

ACE should be zero for scheduled power exchange at nominal frequency.

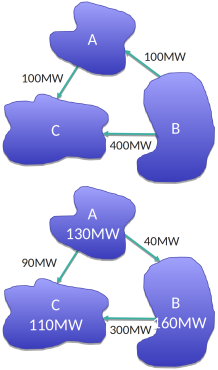
Active power and frequency: Tertiary Control

Area control

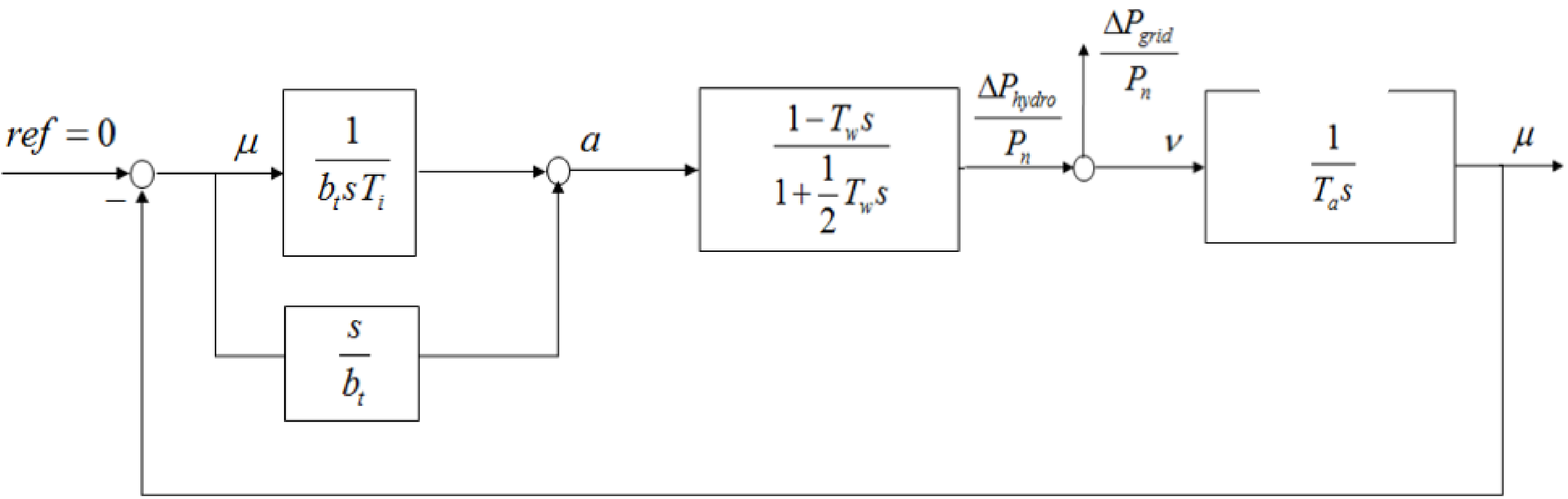
Example

Example for three areas $\mathrm{A, B, C}$:

- Scheduled $\mathrm{B} \rightarrow \mathrm{C} = 400\,\mathrm{MW}$, $\mathrm{B} \rightarrow \mathrm{A} = \mathrm{A} \rightarrow \mathrm{C} = 100\,\mathrm{MW}$
- $\lambda_{\mathrm{A}} = 13\,\mathrm{GW/Hz}$, $\lambda_{\mathrm{B}} = 16\,\mathrm{GW/Hz}$, $\lambda_{\mathrm{C}} = 11\,\mathrm{GW/Hz}$
- System $\lambda = 40\,\mathrm{GW/Hz}$
- Sudden drop in frequency $\Delta \mathrm{f} = -0.01\,\mathrm{Hz}$
- Generation in area B should be increased by $400\,\mathrm{MW}$



The transfer function of the hydro power system can be represented by:



For the determining the time constants of the transfer-function based model we need to determine the following two time constants:

- $T_a = \frac{J \cdot w_n^2}{P_n}$
- $T_w = \frac{Q_n}{g \cdot H_n}\left(\frac{L}{A}\right)$

We do not worry about the controller parameters since we are going to use a standard PID model from the standard libary.