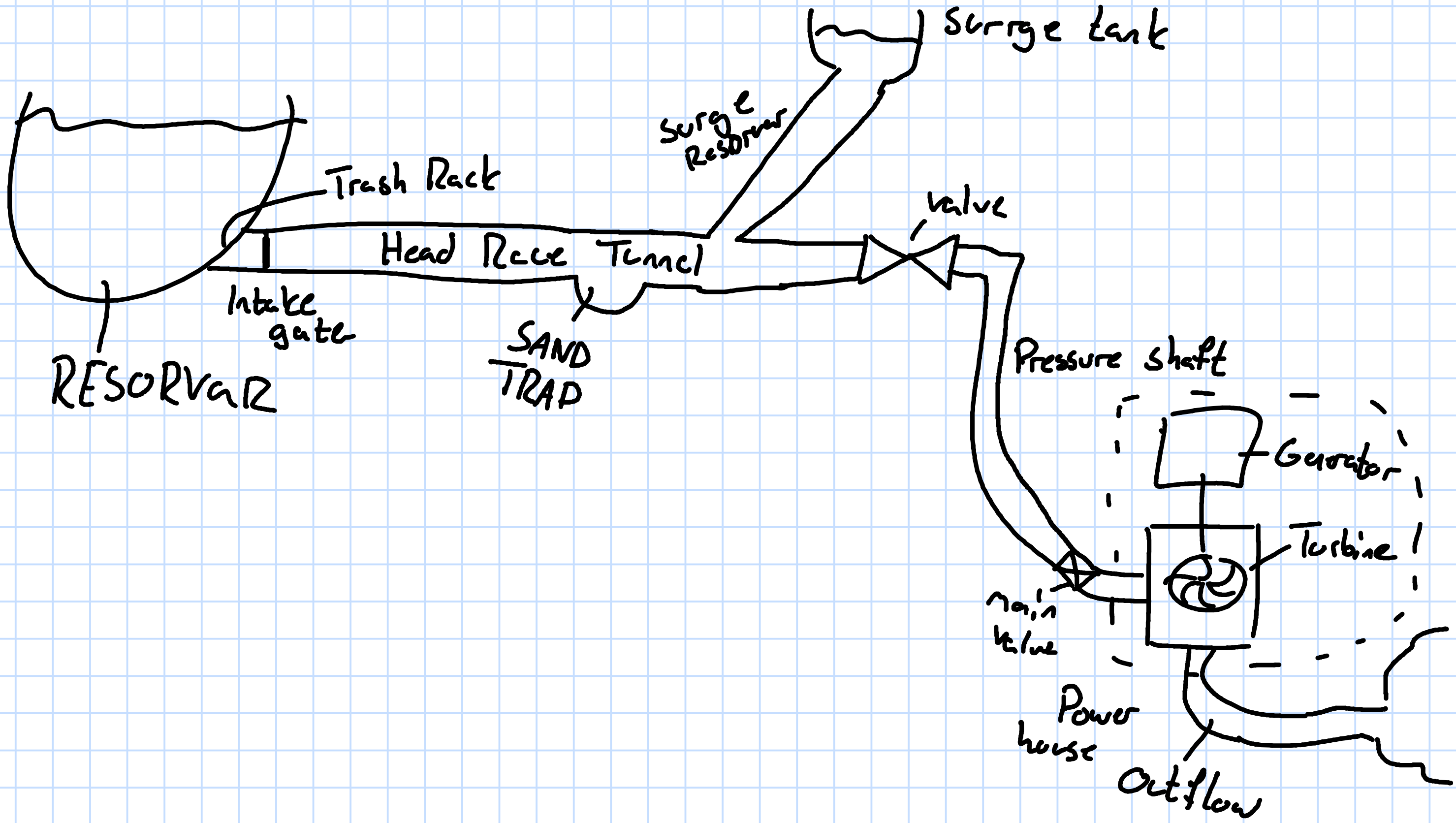
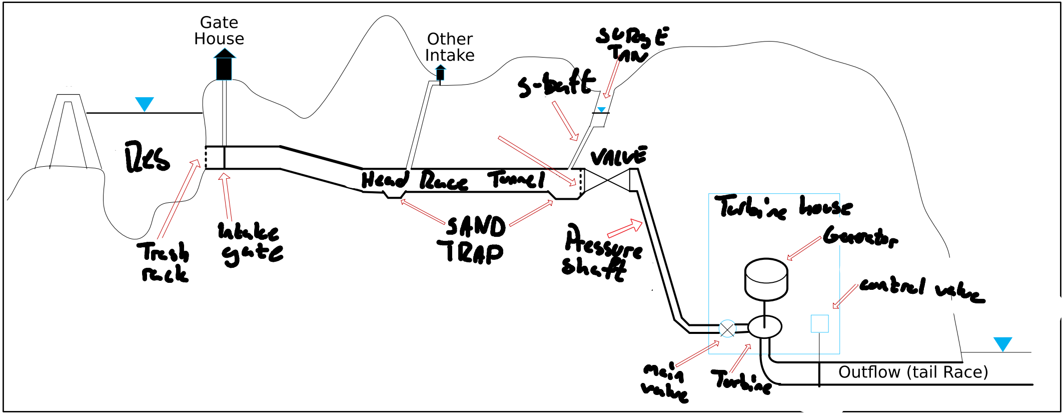
① Tegn HPS vann veien



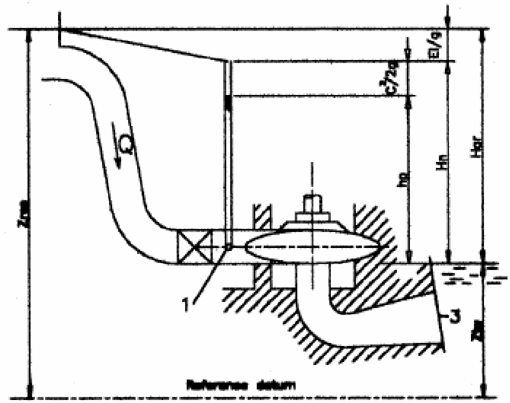
Overview

Typical high-head hydro power system



General theory

Gross quantities



Definition (Head and Energy)

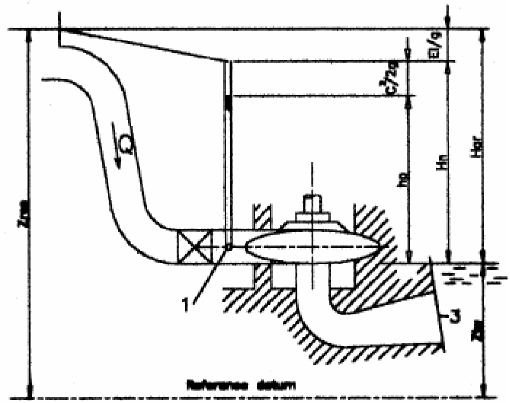
$$H_{gr} = z_{res} - z_{tw}$$

Definition (Power)

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

General theory

Net quantities



Definition (Head and Energy)

$$H_1 = H_{gr} - \frac{E_L}{g} = H_{gr} - H_L$$
$$= h_e + \frac{c^2}{2g}$$
$$E_1 = H_1 g$$

Definition (Power)

$$P_1 = \rho g H_1 Q \quad (2)$$

Løs oppgave:

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

Hva er Power?

$P = \rho g H Q = 1000 \cdot 9{,}81 \cdot 1 \cdot 100 = 981\ kW \approx 1\ MW$

Turbine types

Pelton Francis Kaplan

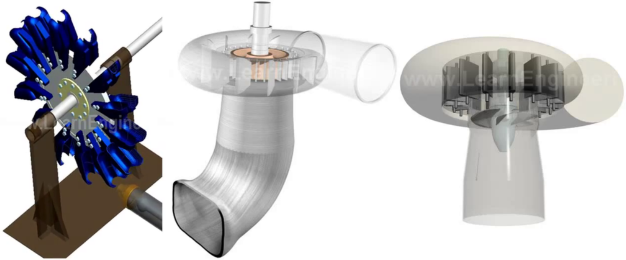


Figure: https://youtu.be/k0BLOKEZ3KU

Hydraulic efficiency

Part 1

Definition (Total available power)

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

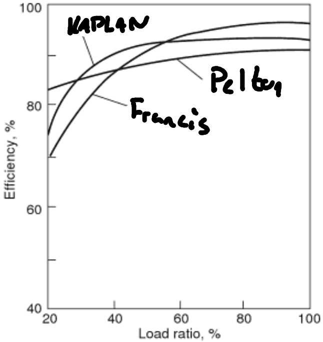
Definition (Power of the runner)

$$P_r = \rho Q (U_1 C_{u1} - U_2 C_{u2}) \tag{4}$$

Definition (Hydraulic efficiency)

$$\eta = \frac{P_r}{P_n} = \frac{\rho Q (U_1 C_{u1} - U_2 C_{u2})}{\rho g H_1 Q} = \frac{U_1 C_{u1} - U_2 C_{u2}}{g H_1} \tag{5}$$

Turbine efficiencies



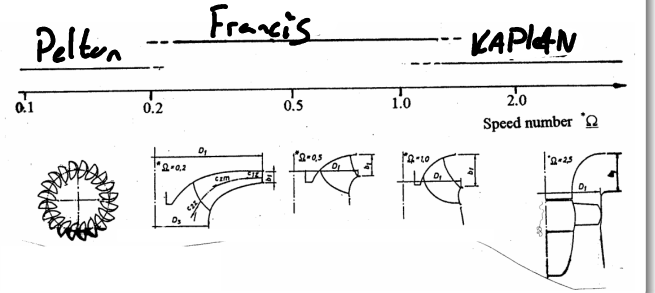
Variation of hydraulic efficiency for various types of turbine over a range of loading, at constant speed and constant head.

Turbine Classification

Speed Number and Specific Speed

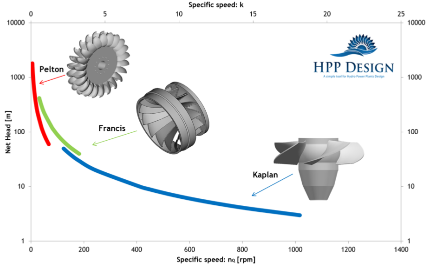
Speed Number

$$\frac{n_q}{89} = {}^*\Omega = {}^*\omega\sqrt{{}^*Q}$$



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

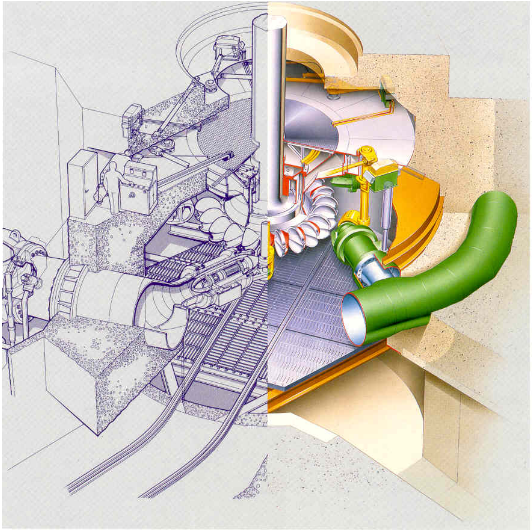
Slides

- 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

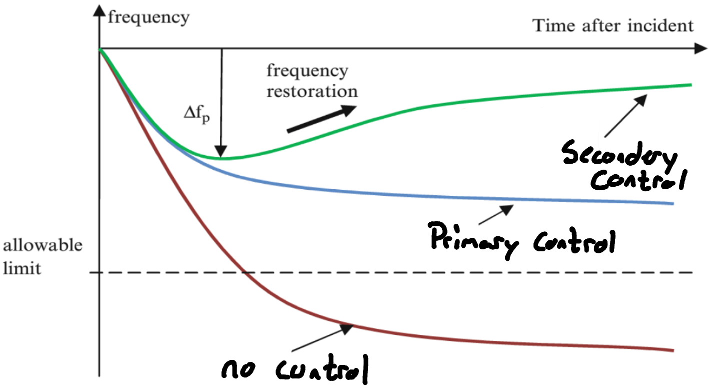


Figure: Planned frequency profile in response to large and sudden loss of generation

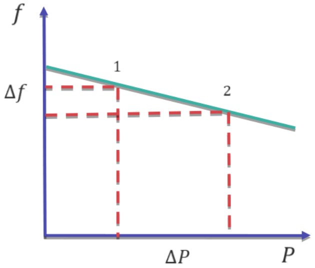
Active power and frequency

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} regulation of generator
Δf change in f
f_r nominal f
ΔP_{g_i} change in Power
$P_{g_{i,r}}$ nominal Power

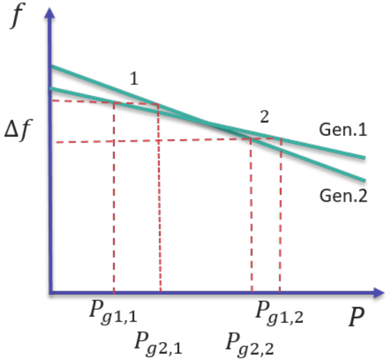


Active power and frequency: Primary Control

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

$$\lambda = \frac{\Delta P}{\Delta f} \qquad \text{(bias factor)}$$

$$\Delta P = \sum \Delta P_{gi} = \sum \left(-\frac{1}{R_g} \frac{P_{gi}}{f_r} \Delta f \right)$$

$$\Rightarrow \lambda =$$

Active power and frequency: Primary Control

Many generators in parallel

Example

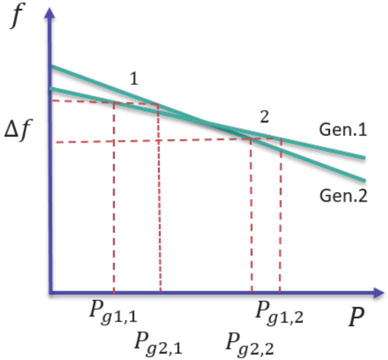
- $P_{g1_r} = P_{g2_r} = 200\,\mathrm{MW}$, $R_{g1} = 0.02$, $R_{g2} = 0.06$

$\Rightarrow \lambda = \frac{1}{50} \cdot \left(\frac{200}{0,02} + \frac{200}{0,06} \right) = 266,67$

Since λ: $\Delta P = \frac{266}{2} = 133$

$\Delta f = \frac{133}{266} = 0.5$

$\Delta P = 133,3\,\mathrm{MW} \Rightarrow \Delta f = 0.5\,\mathrm{Hz}$



Active power and frequency: Primary Control

Self-regulation

Definition of Self-regulation

Motors cause the system load to be slightly frequency dependent.

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

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

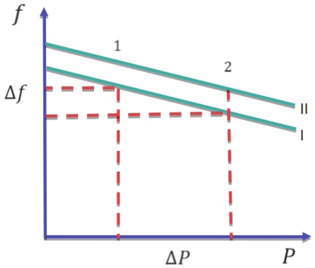
- μ the self regulation effect of the load P $[\%/\mathrm{Hz}]$
- $\Delta P'$ the change in the power consumption of the loads beacuse of the change in frequency Δf $[\mathrm{MW}]$
- P the value of the original load of the system plus the change ΔP at the orginal system frequency $[\mathrm{Hz}]$

Active power and frequency: Secondary Control

Load Frequency Control (LFC)

Principle

1. Change setpoint to P_2
2.



Active power and frequency: Tertiary Control

Area Control Error (ACE)

Definition

$$\mathrm{ACE_i} = (P_a - P_s) + \lambda (f_a - f_s)$$

$\mathrm{ACE_i}$ = Area control error
P_{a_i} = active Power
P_{s_i} = setpoint Power
λ_i = characteristic for controller
f_a = f active
f_s = setpoint

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

Active power and frequency: Tertiary Control

Area control

Example

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

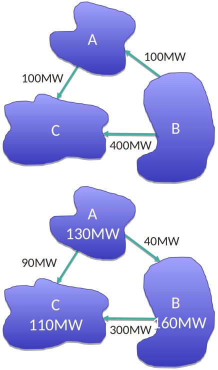
- Scheduled $\mathrm{B} \rightarrow \mathrm{C} = 400\,\mathrm{MW}$, $\mathrm{B} \rightarrow \mathrm{A} = \mathrm{A} \rightarrow \mathrm{C} = 100\,\mathrm{MW}$
- $\lambda_{\mathrm{A}} = 13\,\mathrm{GW/Hz}$, $\lambda_{\mathrm{B}} = 16\,\mathrm{GW/Hz}$, $\lambda_{\mathrm{C}} = 11\,\mathrm{GW/Hz}$
- System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

$A: (130 - 0) + 13 \cdot 10^3(-0{,}01) = 0$

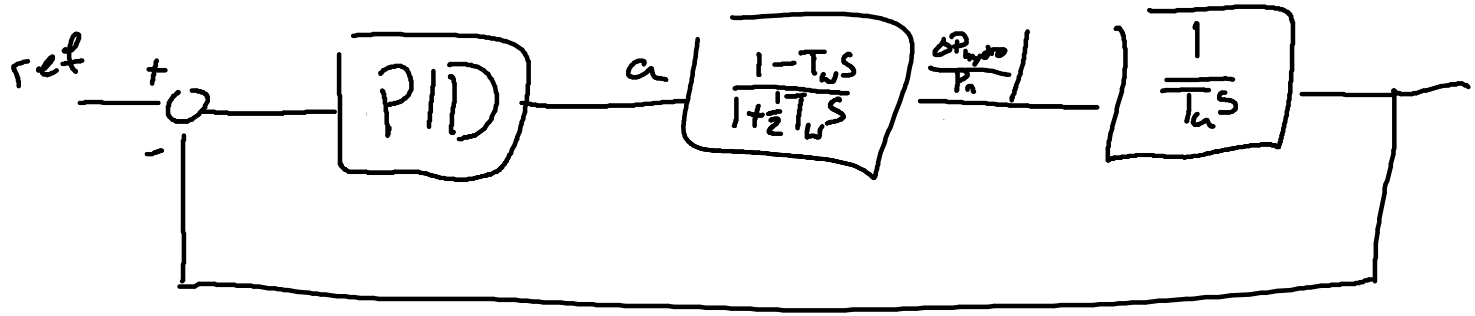
$B: (260 - 500) + 16 \cdot 10^3(-0{,}01) = -400\,MW$

$C: (-390 + 500) + 11 \cdot 10^3(-0{,}01) = 0$

- 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:

$$T_w = \frac{Q}{gH}$$

$$T_a = \frac{J\omega^2}{P_n}$$

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