L9 – Reversible pump-turbines and pumping units

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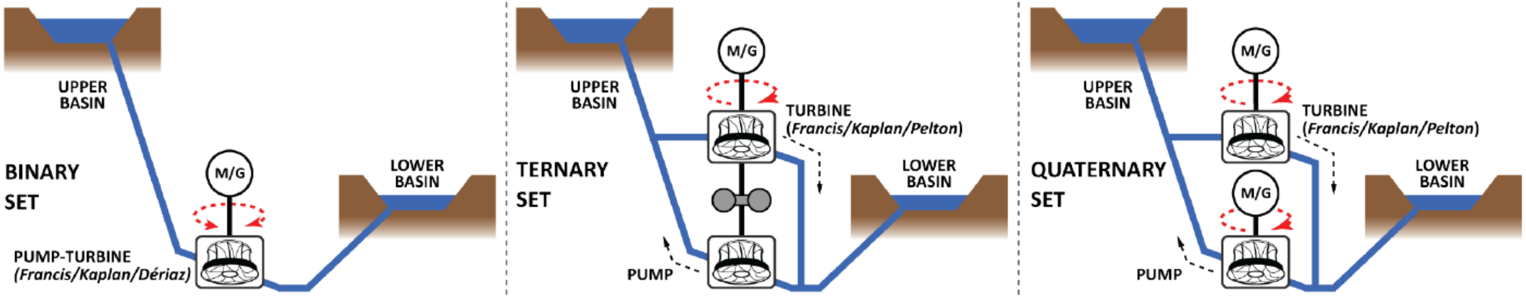
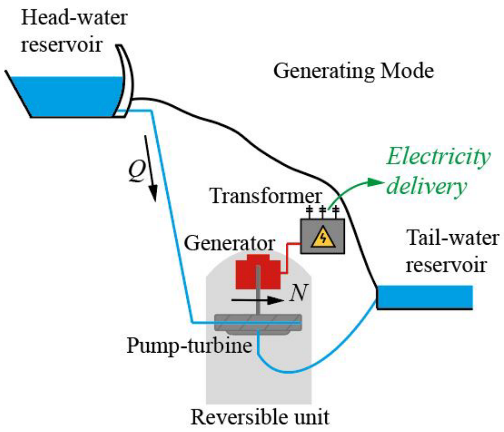
Types of pumping units

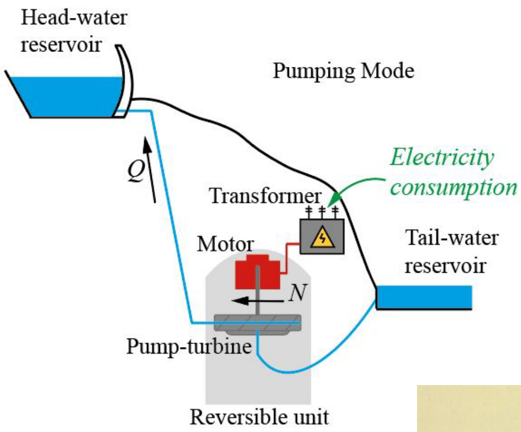
- **Binary Group**: unit equipped with reversible pump-turbines
- **Ternary Group**: turbine and pump on the same shaft
- **Quaternary Group**: separated pumping and generating units



Binary group

Francis-type reversible pump-turbine

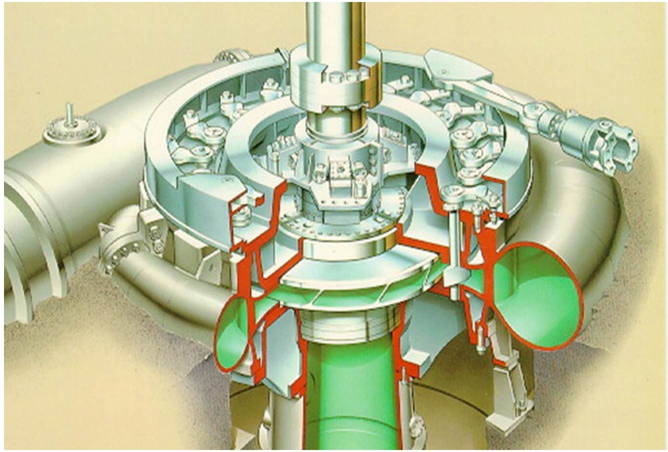




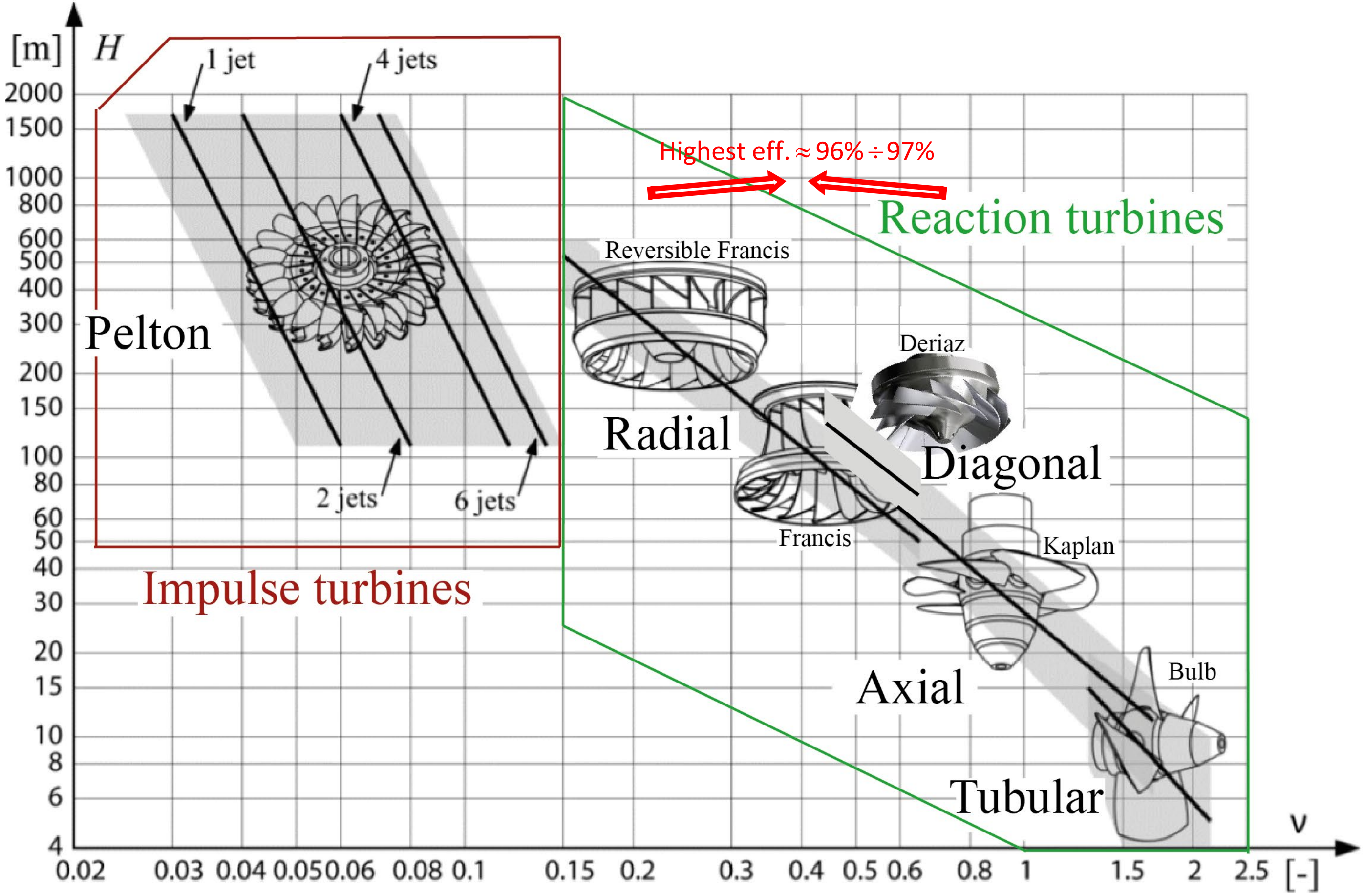
Two machines: electrical machine+ hydraulic machine.

Most common: Francis-type reversible pump-turbine

Used for a total installed power capacity of 7.4 GW in 2018



From L2: Classification of Hydraulic Runners



Head $= H$ (m)

Discharge $= Q$ $(m^3 \cdot s^{-1})$

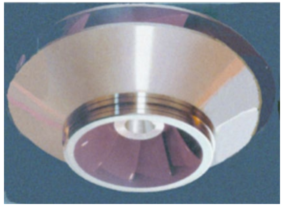
Speed $= N$ (min^{-1})

$$\nu = 2^{\frac{1}{4}} \pi^{\frac{1}{2}} \times n \times \frac{Q^{\frac{1}{2}}}{E^{\frac{3}{4}}}$$

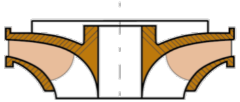
From L2: Classification of Hydraulic Runners

Francis Runners and Impellers

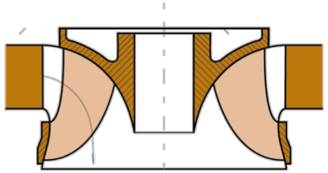
- Francis-type turbine and pump-turbine
  - Reaction machine
  - Radial flow
  - Medium Head

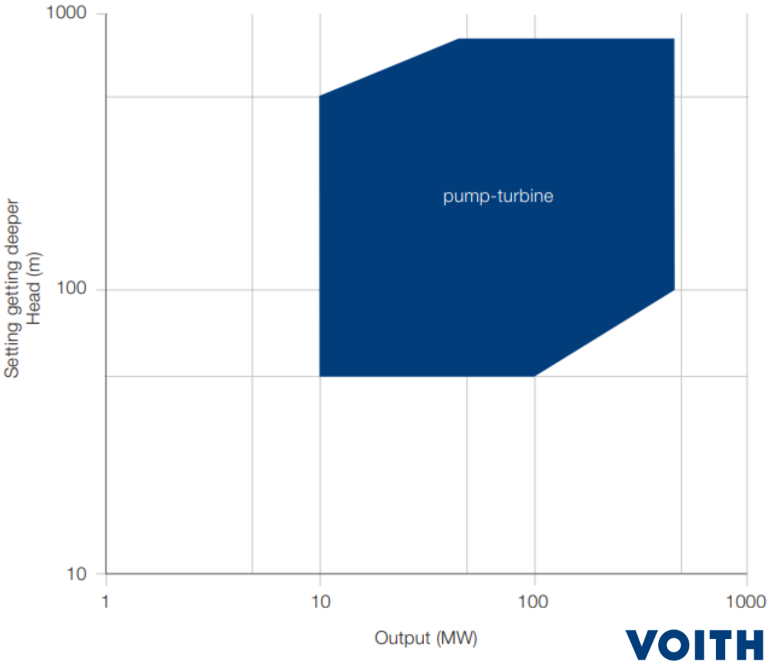


n_q = 12........35
ν = 0.10....0.22
n_{QE} = 0.04....0.10



n_q = 35.......80
ν = 0.22....0.50
n_{QE} = 0.10....0.24



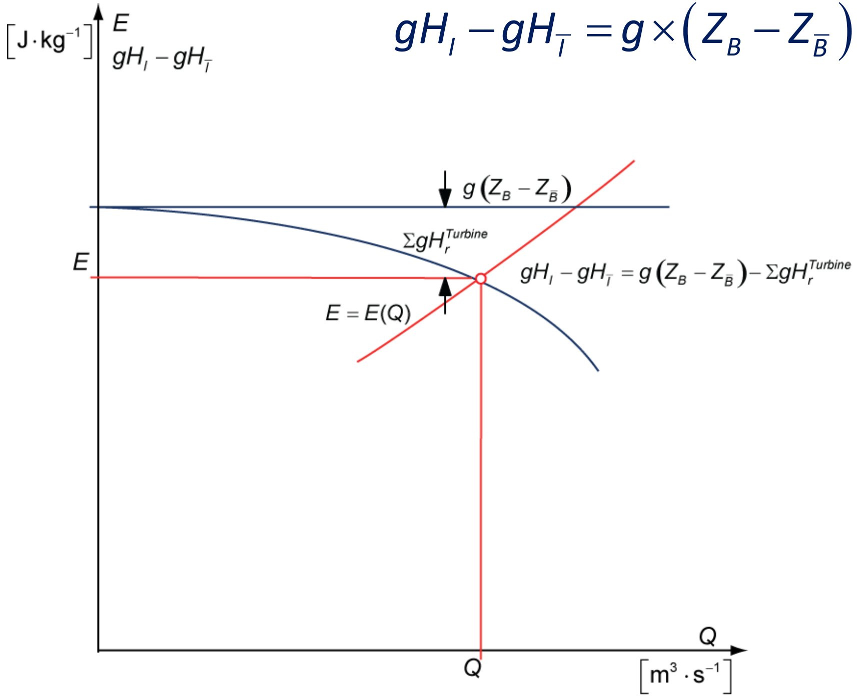


VOITH
Engineered Reliability

From L2: Specific Hydraulic Energy

Hydraulic Characteristics : generating mode

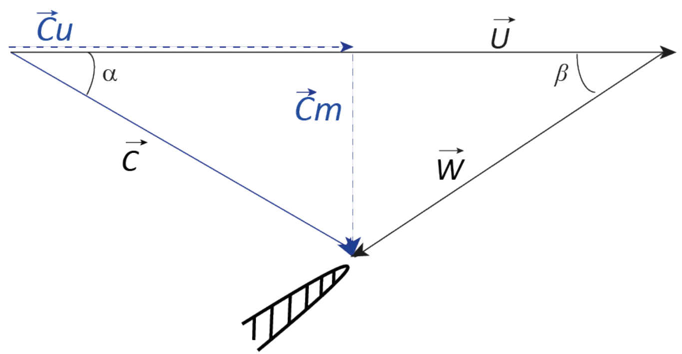
$$gH_I - gH_{\bar{I}} = g \times (Z_B - Z_{\bar{B}}) - \sum gH_r$$



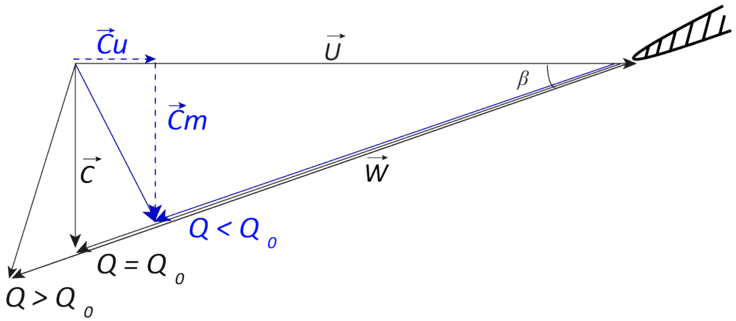
Reversible pump-turbines

Velocity triangles in generating mode

Inlet



Outlet

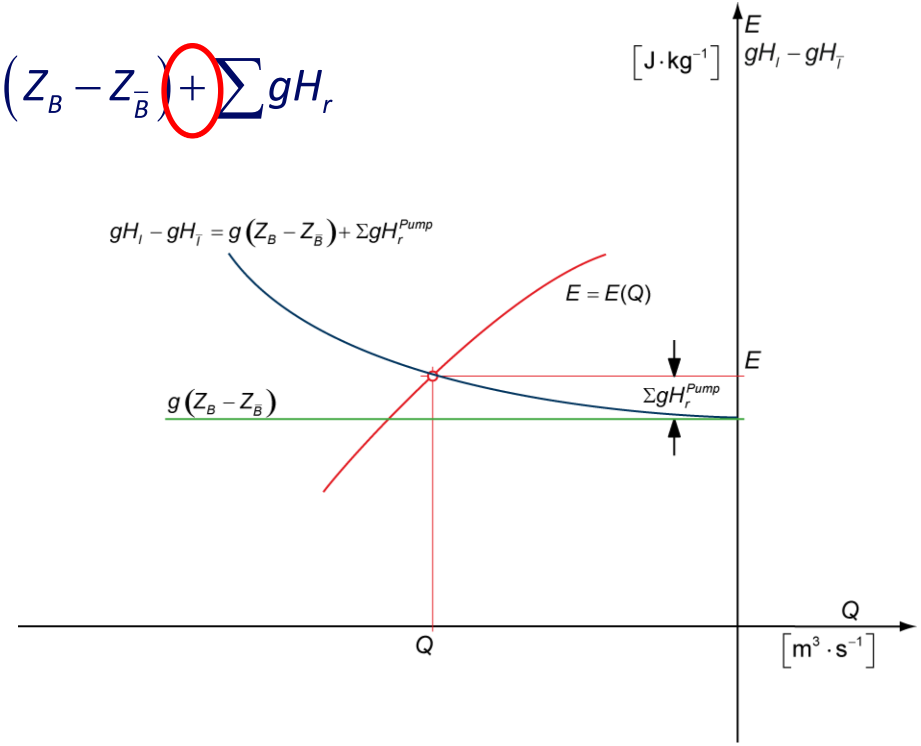


Q0 → Best Efficiency Point (BEP)
Q > Q0 → Full Load
Q < Q0 → Part load

From L2: Specific Hydraulic Energy

Hydraulic Characteristics: pumping mode

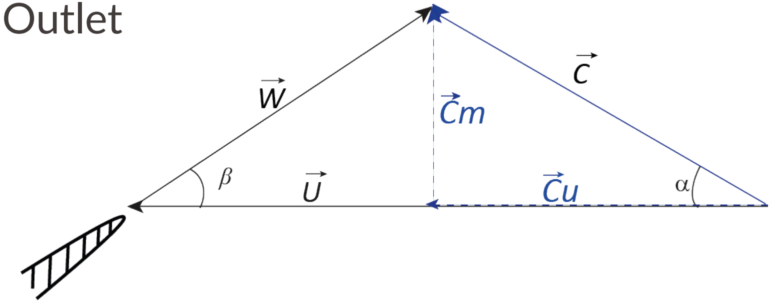
$$gH_I - gH_{\bar{I}} = g\left(Z_B - Z_{\bar{B}}\right) + \sum gH_r$$



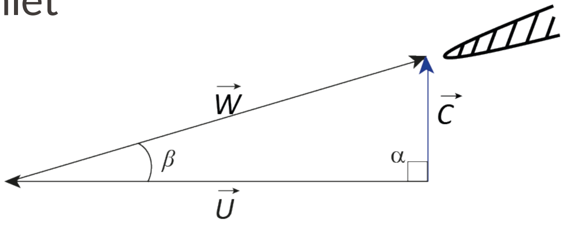
Reversible pump-turbines

Velocity triangles in pumping mode

Outlet



Inlet



- ✓ Axial Flow at the inlet $Cu_1 = 0$
- ✓ Maximum power → at the outlet $Cu_1 = \frac{U_1}{2}$

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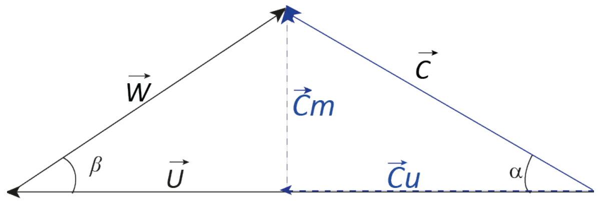
Reversible pump-turbines

Velocity triangles in pumping mode

Euler equation $E_t = U_1 \cdot Cu_1 - U_{\bar{1}} \cdot Cu_{\bar{1}}$

Inlet Axial Flow $E_t = U_1 \cdot Cu_1 \cancel{- U_{\bar{1}} \cdot Cu_{\bar{1}}}$



Tangential component of the absolute flow velocity $Cu_1 = U_1 - \frac{Cm_1}{\tan\beta_1} = U_1 - \frac{Q}{A_1 \tan\beta_1}$

Transferred specific energy $E_t = U_1^2 - \frac{Q \cdot U_1}{A_1 \tan\beta_1}$

Stored Transferred Power $P_t = \rho Q E_t = \rho Q \left(U_1^2 - \frac{Q \cdot U_1}{A_1 \tan\beta_1} \right)$

Maximum stored Transferred Power $\frac{\partial P_t}{\partial Q} = 0 \rightarrow U_1^2 - \frac{2U_1}{A_1 \tan\beta_1} Q = 0$ $\rightarrow Q_{opt} = \frac{1}{2} U_1 A_1 \tan\beta_1$

Maximum specific Energy $E_{t,\max} = U_1^2 + \frac{Q_{opt} \cdot U_1}{A_1 \tan\beta_1} = U_1^2 - \frac{U_1 A_1 \tan\beta_1}{2 A_1 \tan\beta} U_1 = \frac{U_1^2}{2}$ $\rightarrow Cu_{1,opt} = \frac{U_1}{2}$

$\rightarrow P_{opt} = \rho A_1 \tan\beta_1 \frac{U_1^3}{4}$

From L2: Classification of Hydraulic Runners

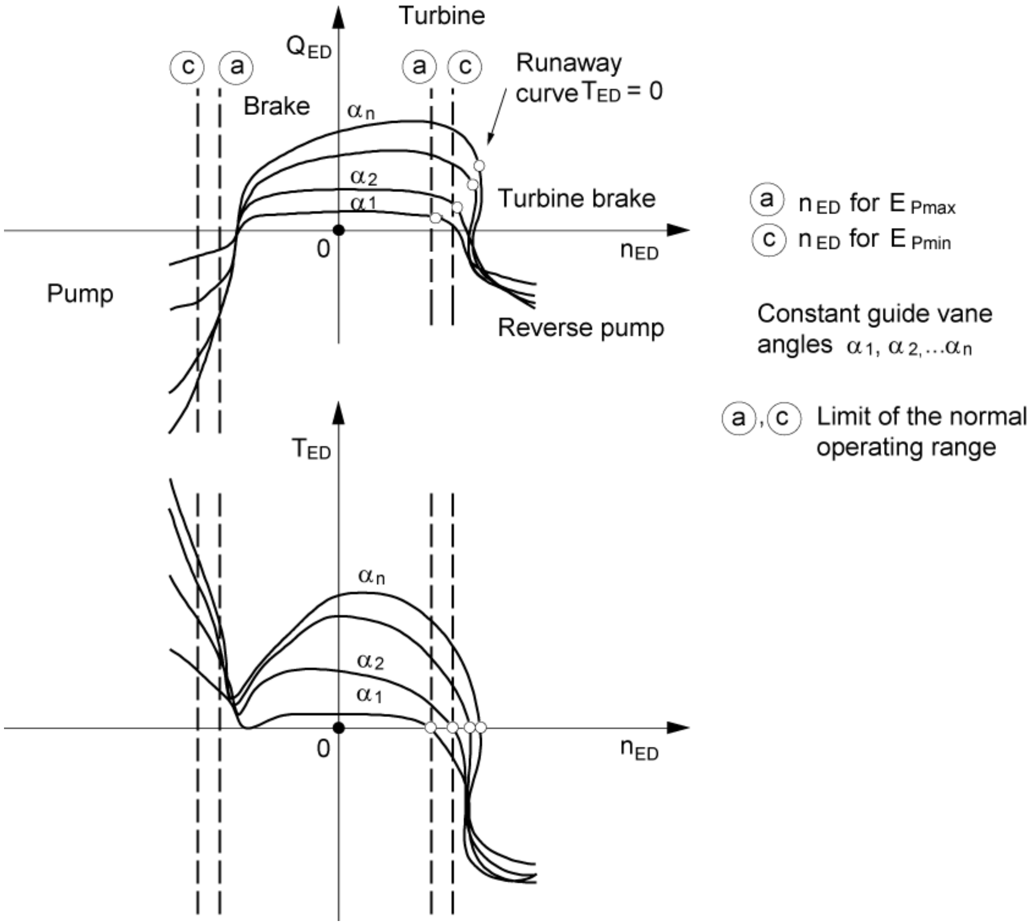
Operating range

- IEC Discharge Factor

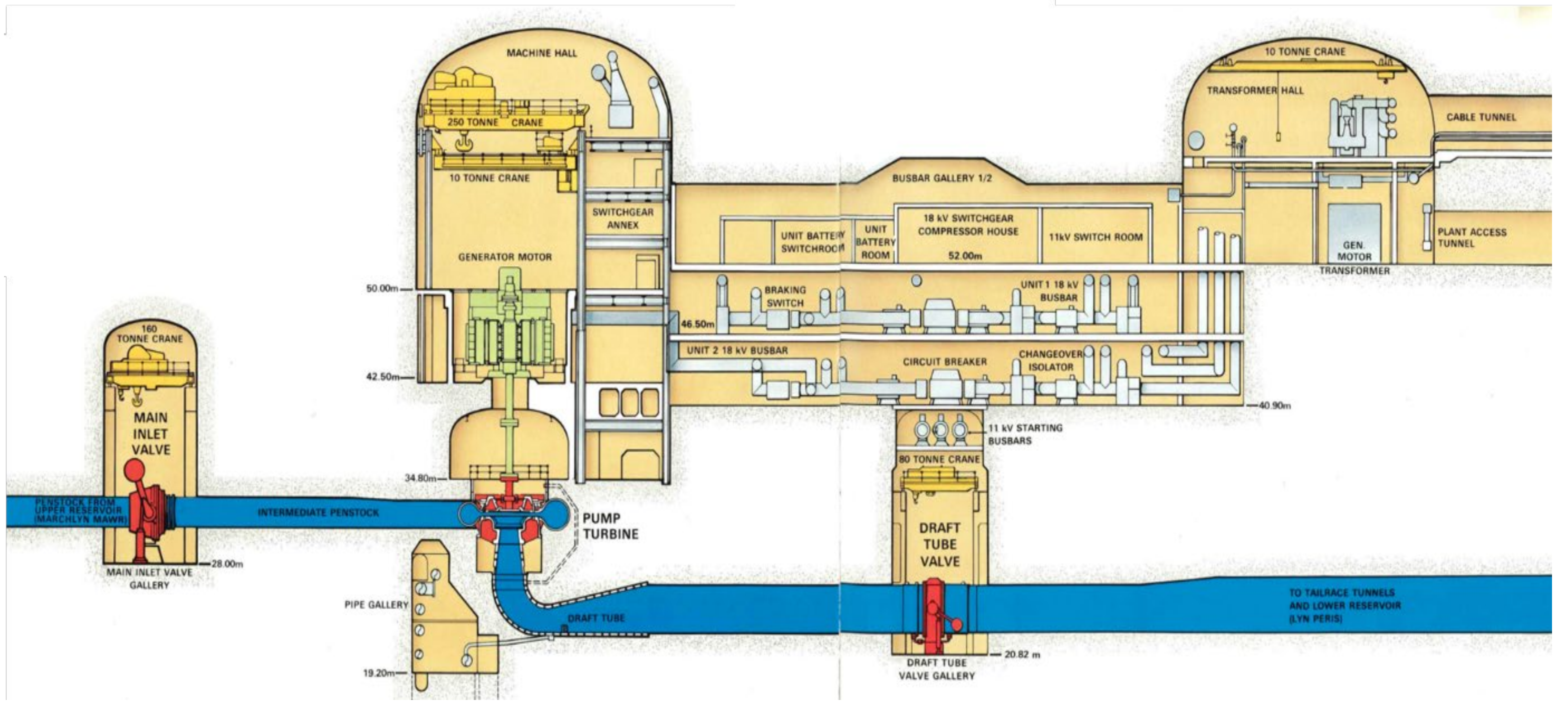
$$Q_{ED} = \frac{Q}{D^2 E^{\frac{1}{2}}}$$

- IEC Speed Factor

$$n_{ED} = \frac{nD}{E^{\frac{1}{2}}}$$



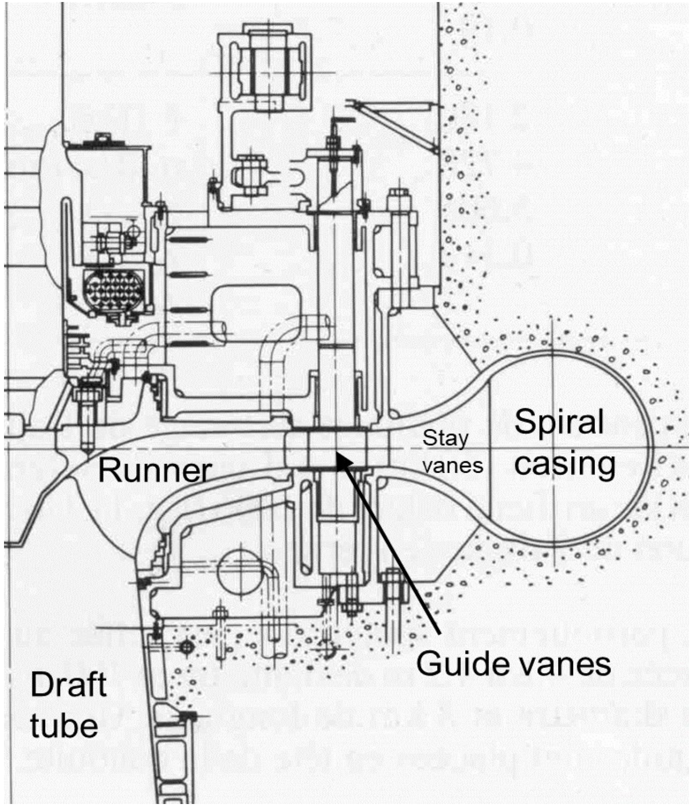
Design Characteristics



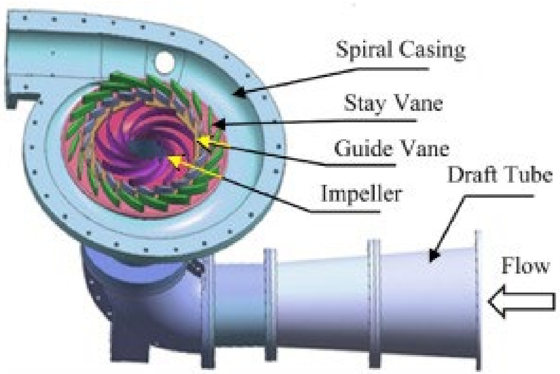
Arrangement of reversible pump-turbine at Dinorwig power plant in Wales. Source: Kværner

Long draft tube allowing for an uniform axial flow at the inlet in pumping mode

Design Characteristics



Runner/impeller design has to satisfy generating and pumping mode efficient operations

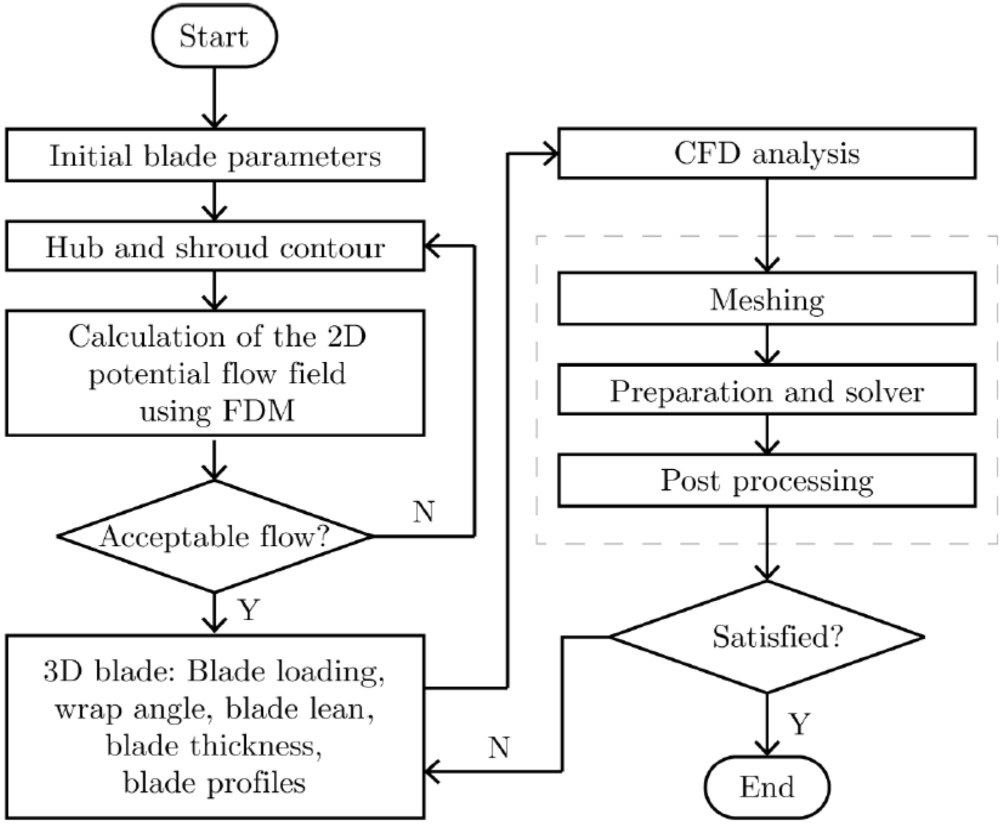


In pumping mode

→ Pumping mode is leading design choice in respect to the generating mode to avoid cavitation at the pump inlet section.

→ Longer blades are needed to uniformly distribute the velocity in the blades channel.

Design Characteristics



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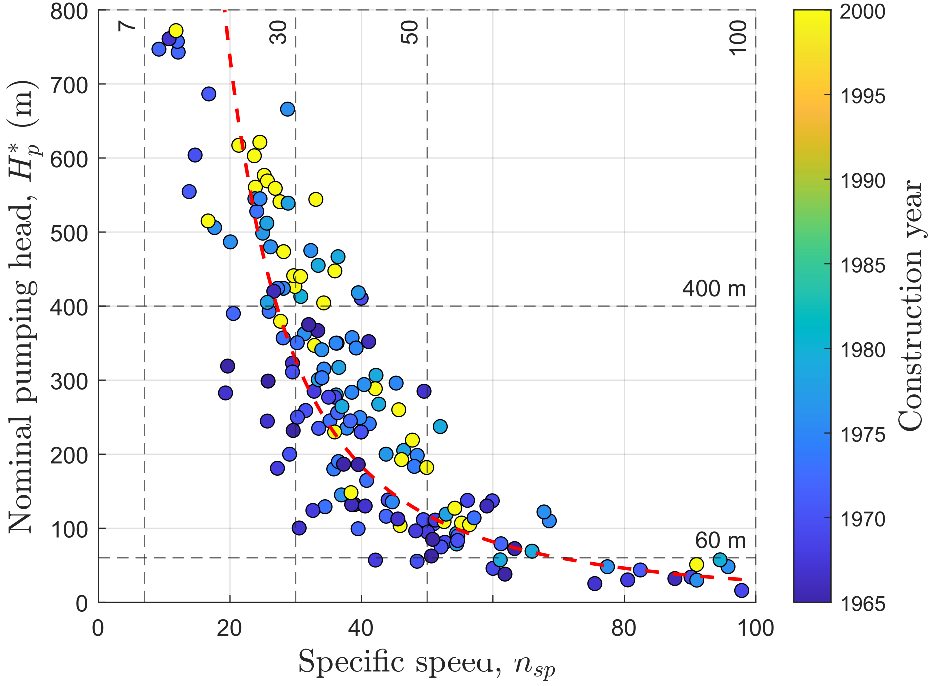
Design Characteristics

Rotational speed choice

Nominal pumping head plotted against pump specific speed for various pump-turbines constructed between 1965 and 2000



Similar criteria as for radial pumps, see lecture L8!

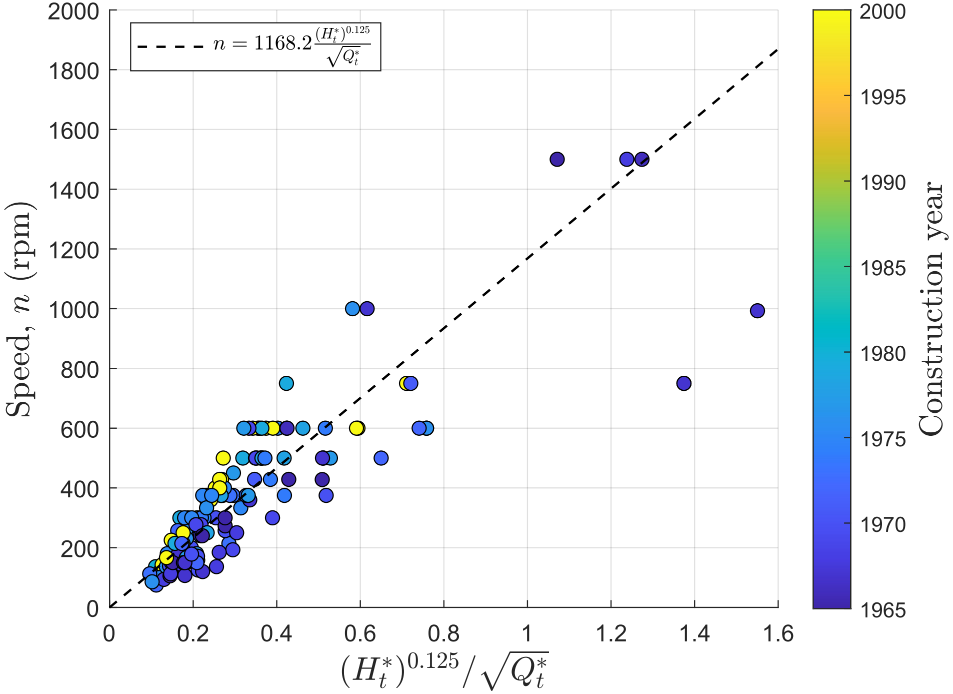
For reversible pump-turbines:

$$n \approx 542.5 \cdot \frac{\left(H_p^*\right)^{0.25}}{\sqrt{Q_p^*}}$$

Design Characteristics

Rotational speed choice

Nominal turbine head plotted against pump specific speed for various pump-turbines constructed between 1965 and 2000



Rotational speed in generating mode will be the same as in pumping, as the electrical machine is the same → fixed number of poles!

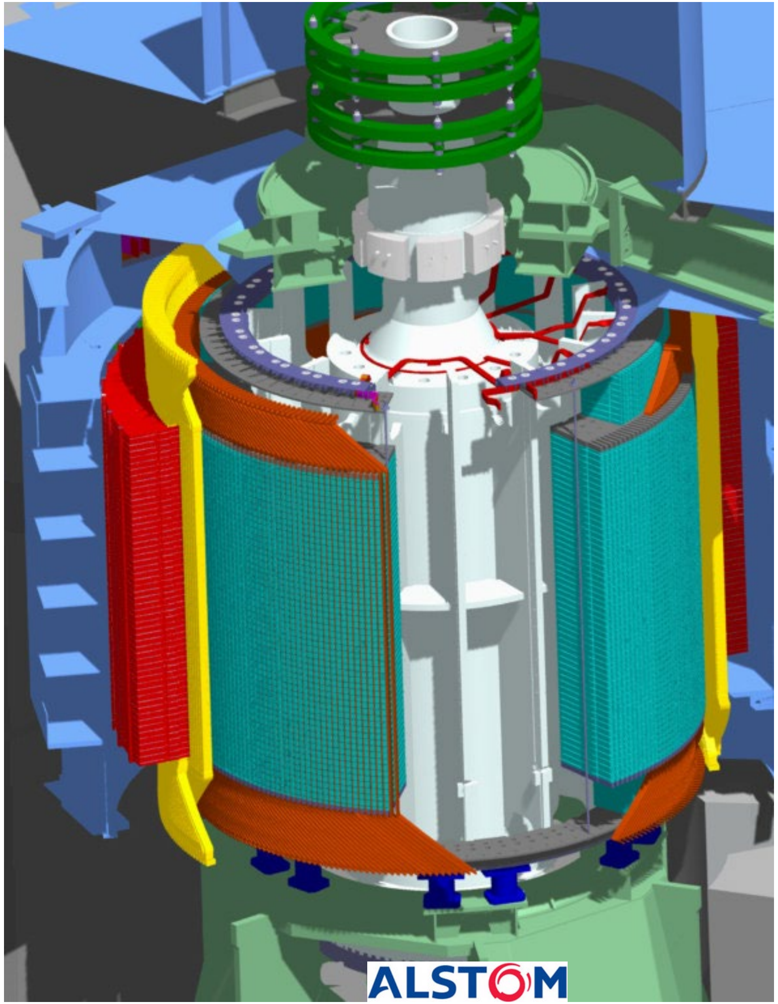
For Francis: $n \approx 1168.2 \cdot \frac{(H_t^*)^{0.125}}{\sqrt{Q_t^*}}$

For reversible pump-turbines: $n \approx 542.5 \cdot \frac{\left(H_p^*\right)^{0.25}}{\sqrt{Q_p^*}}$

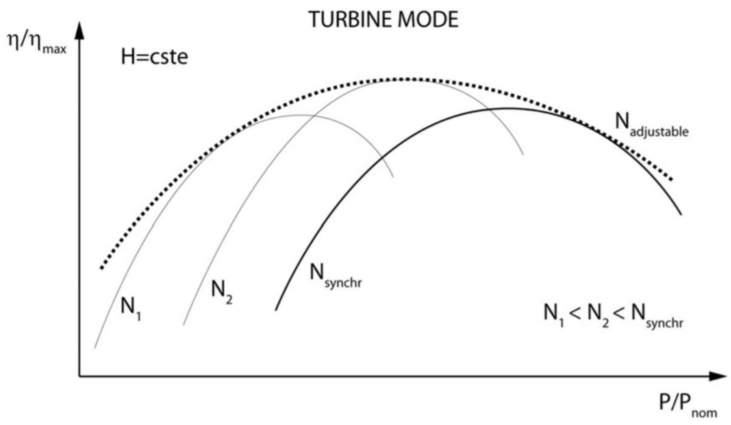
Variable speed Technology

- Full-size Frequency Converter
  - Max 100 MW
- Double Feed Asynchronous Machines
  - Cylindrical Rotor with Three Phases Winding
  - Slip Rings for Excitation

→ Variable SpeedTechnology Enabling Pumping Control

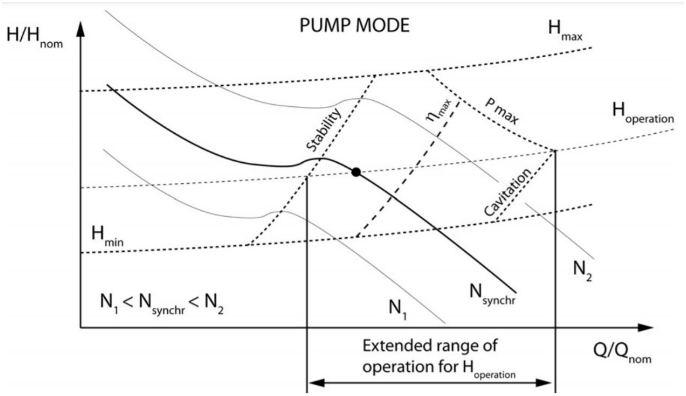


Characteristics Variable speed units

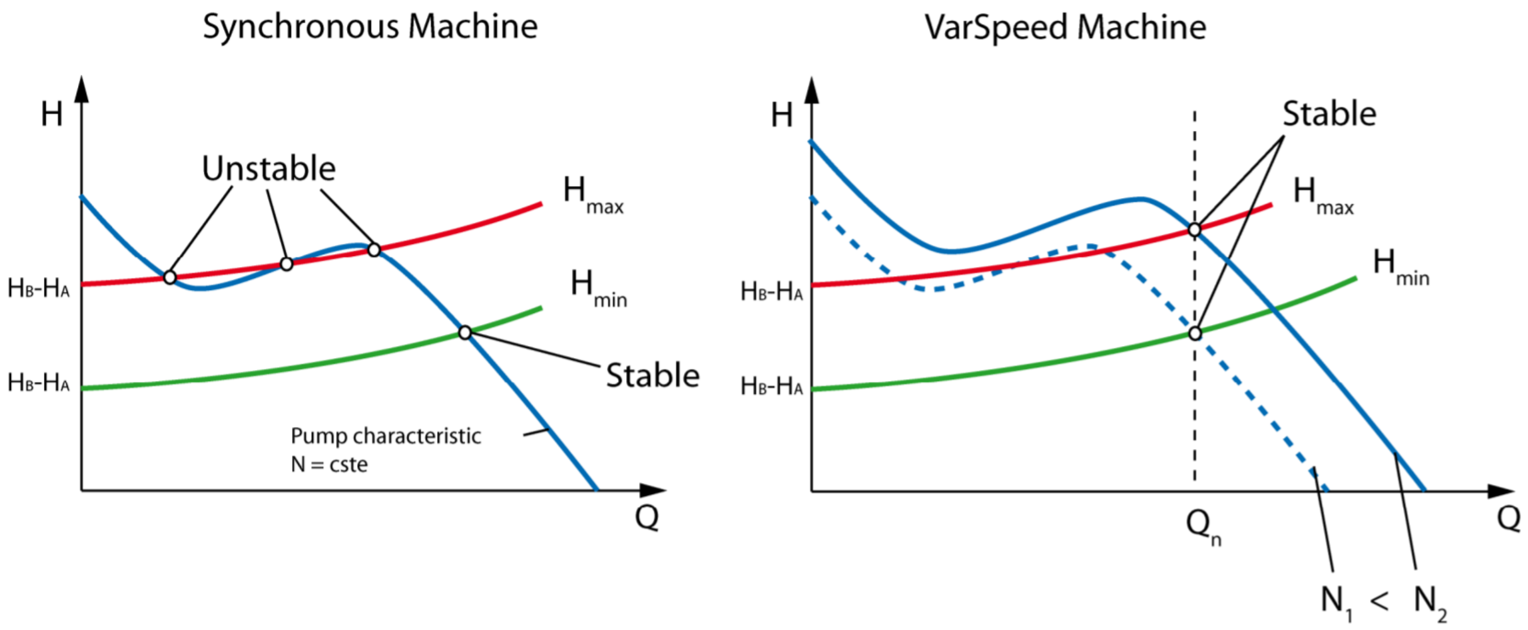


Extended operating range with high performance

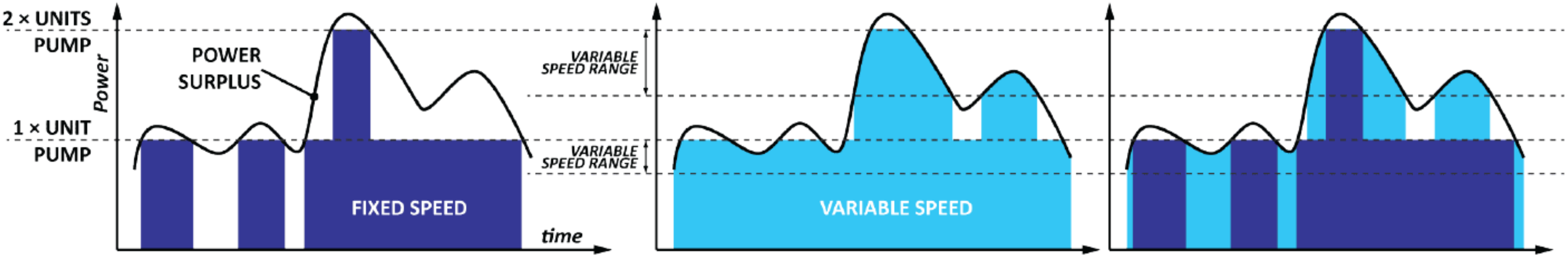
Extended operating range
Allows compensating head variations
Allows avoiding cavitation



Characteristics Variable speed units

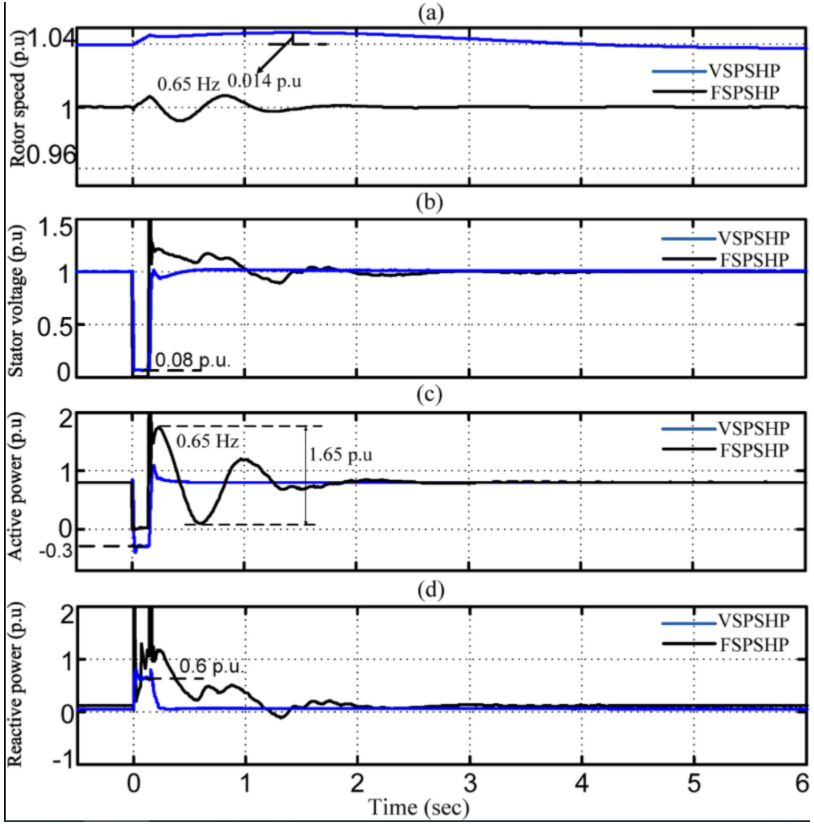


Benefits for variable speed units

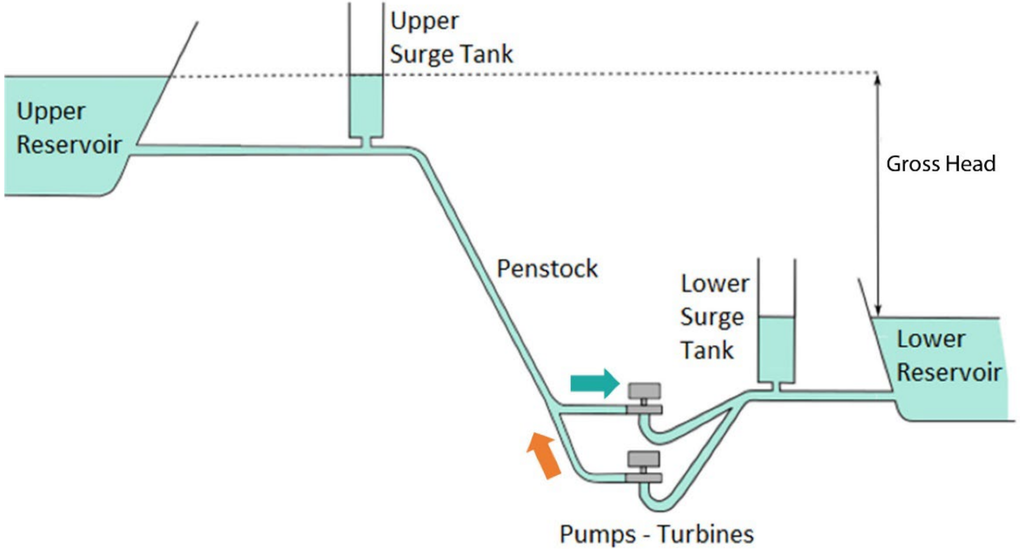


Benefits during transient operations for variable speed units

Fault Right Through: capability to stay connected in short periods of lower electric network voltage



Hydraulic Bypass

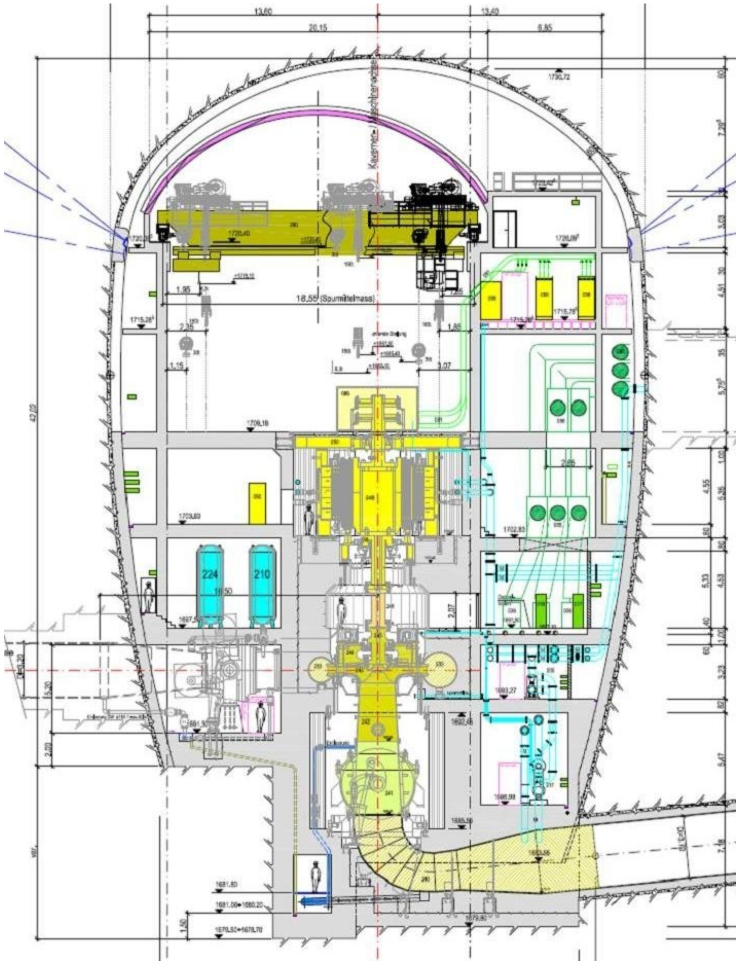


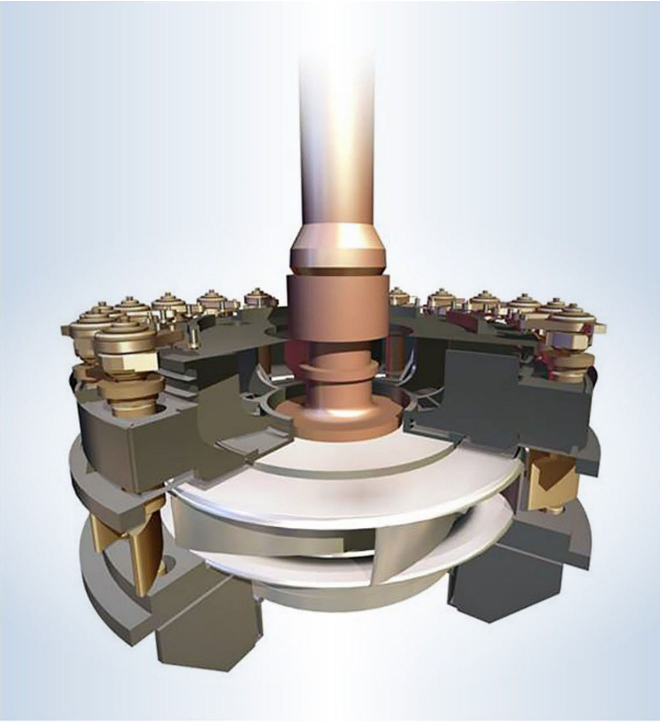
$$P_{TOT} = P^{T} + P^{P}$$

Nant de Drance Variable Speed PSP

- Emosson Lake: 210 10^6 m^3 Capacity
- Vieil Emosson Lake:11 10^6 m^3 Capacity & 25.5 m Dam Height Increase
- 250 mWC to 390 mWC Head Range
- 6 x 150 MW Single Stage Pump-Turbines
- 428.6 min^{-1} ± 7 % Variable Speed Drive

Nant de Drance Variable Speed PSP





- 155 MW, 250 m ÷ 390 m Head
- 428.6 min^{-1} ± 7 %

1 GW Linthal PSP

- Limmern Lake 92 10^6 m^3 Capacity
- Mutt Lake 25 10^6 m^3 Capacity
- 560 mWC to 724 mWC Head Range
- 4 x 250 MW Single Stage Pump-Turbines
- 500 rpm ± 6 % Variable Speed Drive

Linthal Variable Speed Pump-Turbine Unit

- Static Frequency Converter
  - Voltage Source Inverter
- Double Feed Asynchronous Machines
  - Cylindrical Rotor with Three Phases Winding
  - Slip Rings for Excitation
- 250 MW Capacity
- 560 mWC to 724 mWC Head Range
- Single Stage
- 500 min^{-1} ± 6 % Variable Speed

Reversible Pump-Turbine Units

Advantages:

Fixed speed:

- Compact
- Low investments costs for both civil works and electro-mechanical equipment

With additional variable speed:

- Efficient active power control in pumping mode
- Comply with large head variations
- Extended operating range in turbine and pumping mode
- Fast active power injection in pump and turbine mode Pump start-up without supplementary equipment
- Reactive power control

Disadvantages:

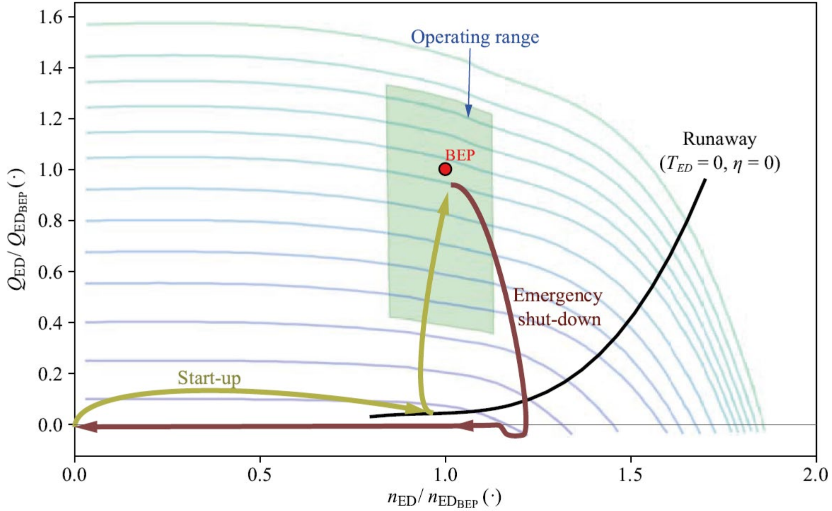
- Fixed speed:
  - Hydraulic design: trade-off between pumping and generating mode (lower efficiency in respect to standard Francis or Pelton)
  - Operating range restricted due to flow instabilities at partial load
  - Long start-up time and switch of operating mode
- With additional variable speed:
  - Investment costs for the electromechanical equipment
  - Specific power limited for a given rotational speed

Sciences and Technology Challenges

- Safety, Reliability and Flexibility
  - Meeting Demand of Peaking Power
  - Grid Primary Control
    → Short Time Response
  - Frequent Starts & Stops
  - Extended operating Range

Sciences and Technology Challenges

- Investigating, Modeling and Harnessing Unsteady Flows;
- Fluid Structure Coupling;
- Rotor-Stator Interactions;
- Performance Curve Stability;
- Extended Operating Range.
- Operating sequences optimization



Flow Separation Rotation: rotating stall

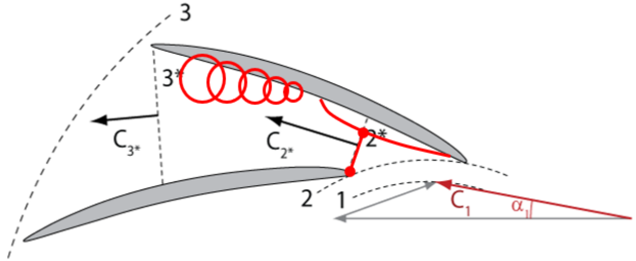
Characteristics of Rotating Stall:
1. Formation of stall zones on adjacent channels due to high incidence.
2. Propagation from blade to blade at a fraction of rotational speed.
3. Direction and speed of stall rotation (50-70% of angular velocity).

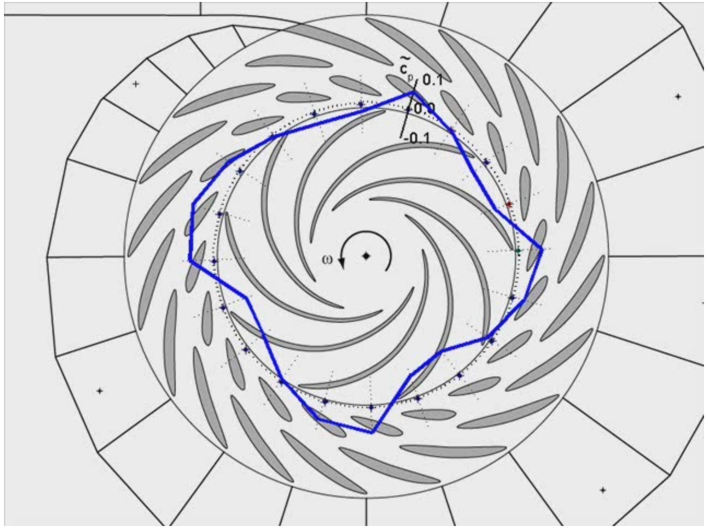
Effects on Flow:
1. Local modification of flow near walls.
2. Creation of recirculation zones causing reverse flow.
3. Impact on pressure fluctuations and vibrations.

Types of Rotating Stall:
1. Forward/backward rotating stall.
2. Alternate blade stall asymmetric stall.

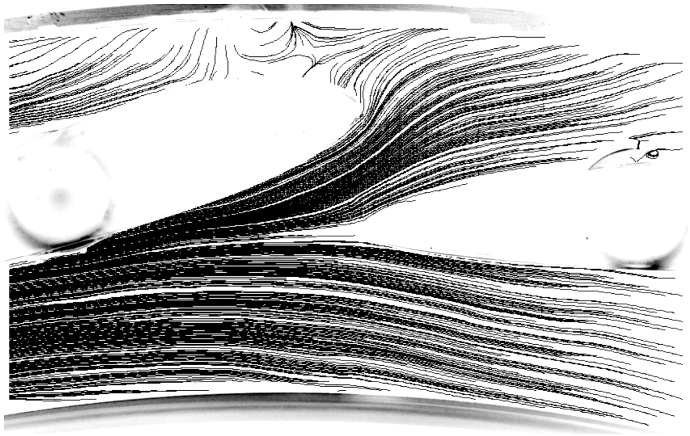
Pressure Fluctuations in Pumping Mode:
1. Larger pressure fluctuations on the vane suction side near the trailing edge.
2. Dependence on the vaneless gap between impeller blades and guide vanes.

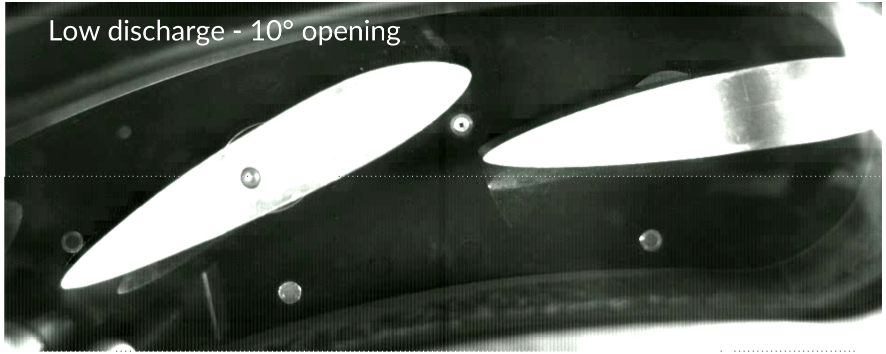
Runaway and Low Discharge Operating Conditions:
1. Flow separation and single stall cell at runaway and low discharge.
2. Reduction in relative flow velocity angle at the impeller inlet.
3. Observations of pressure fluctuations in stator.

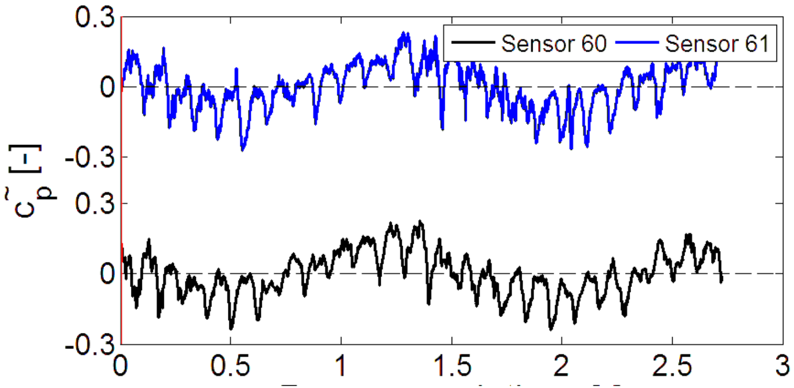




Experimental Evidence: 0.7 x n Rotating Stalled Cell







Vlad HASMATUCHI et al., "Experimental Evidence of Rotating Stall in a Pump-Turbine at Off-Design Conditions in Generating Mode", Journal of Fluids Engineering, May 2011

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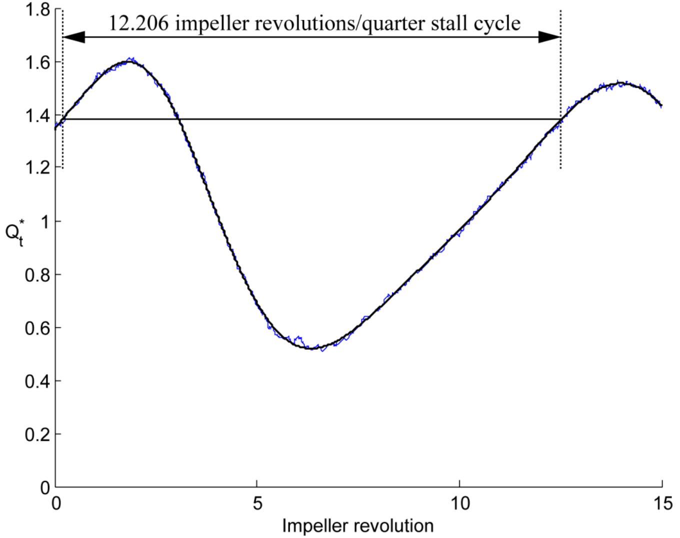
Flow Separation Rotation: rotating stall

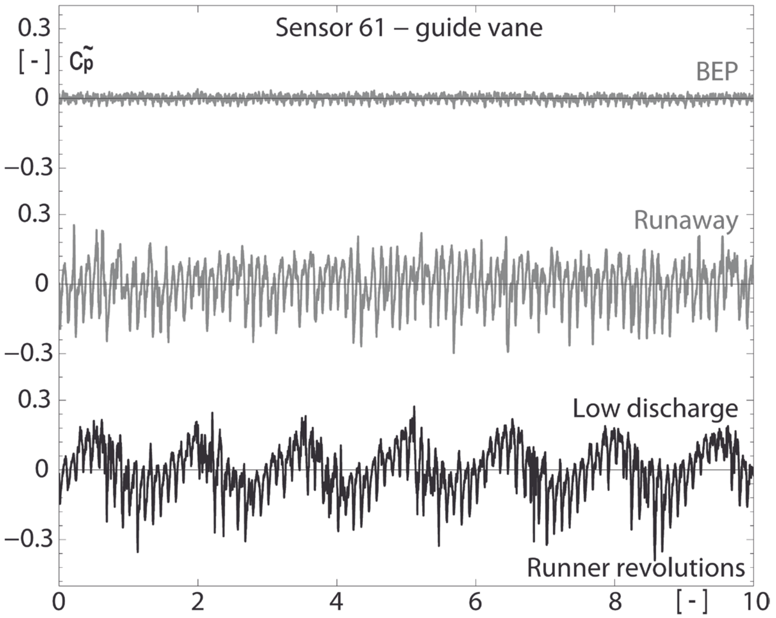


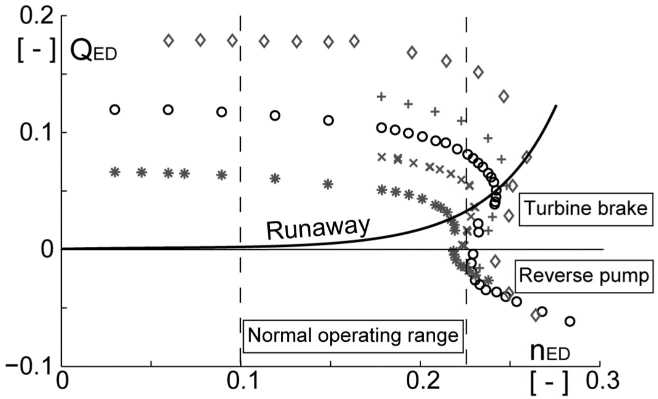
- 76% BEP
- 4 stall cells computed propagating into the diffuser

Pacot Olivier: "Large Scale Computation of the Rotating Stall in a Pump-Turbine using an Overset Finite Element Large Eddy Simulation Numerical Code", EPFL Doctoral Thesis N°6183, 2014.

Flow Separation Rotation: rotating stall

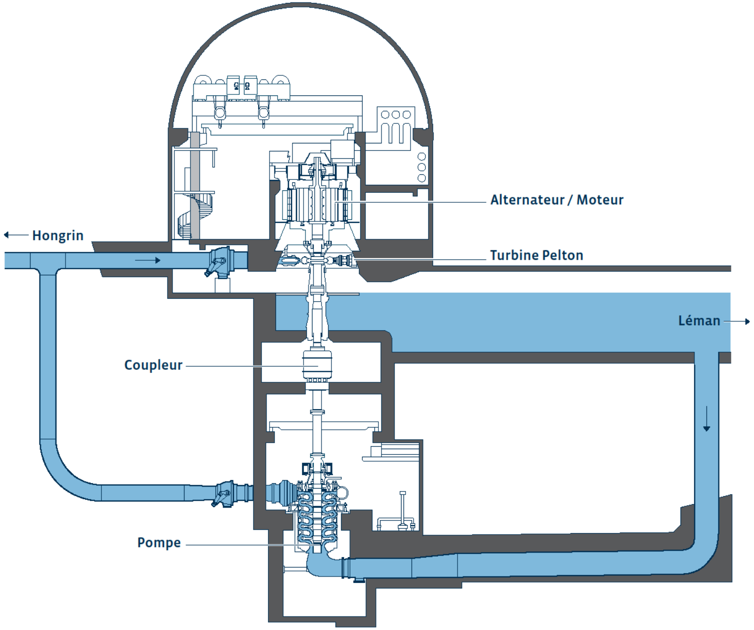
Pressure fluctuations





Ternary group

Three machines: electrical machine, hydraulic turbine, pump
They are classified based on the shaft orientation: horizontal or vertical groups



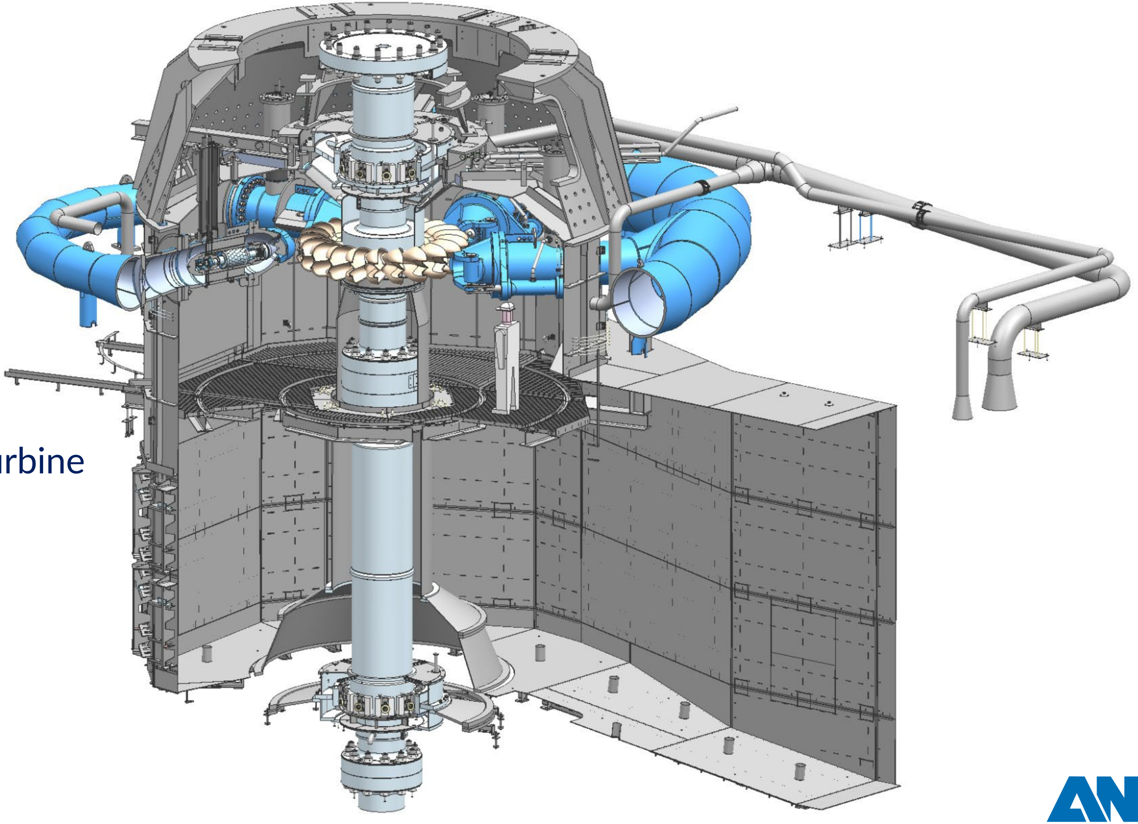
Ternary group

- Usually Pelton + pump
- Matching both Pumping and Generating Modes
  - Length of the Rotating Train;
  - Speed;
  - Required Submergence.
- High Grade Control
  - Pelton Turbine injectors regulation
  - Hydraulic By-Pass
- Turbine Drive for Starting Up
- 1 Direction of Rotation
  - Efficient Cooling
- Safe Transients

Example: Hongrin-Léman PSP

- Hongrin Lake (1969) :
  52 millions m^3 Capacity
- Veytaux Power Station (1972)
- Veytaux I: 4 Horizontal Ternary Units
  - 256 MW Pumping Power
  - 240 MW Gen. Power
  - 850 mWC Head
  - 600 min^{-1}

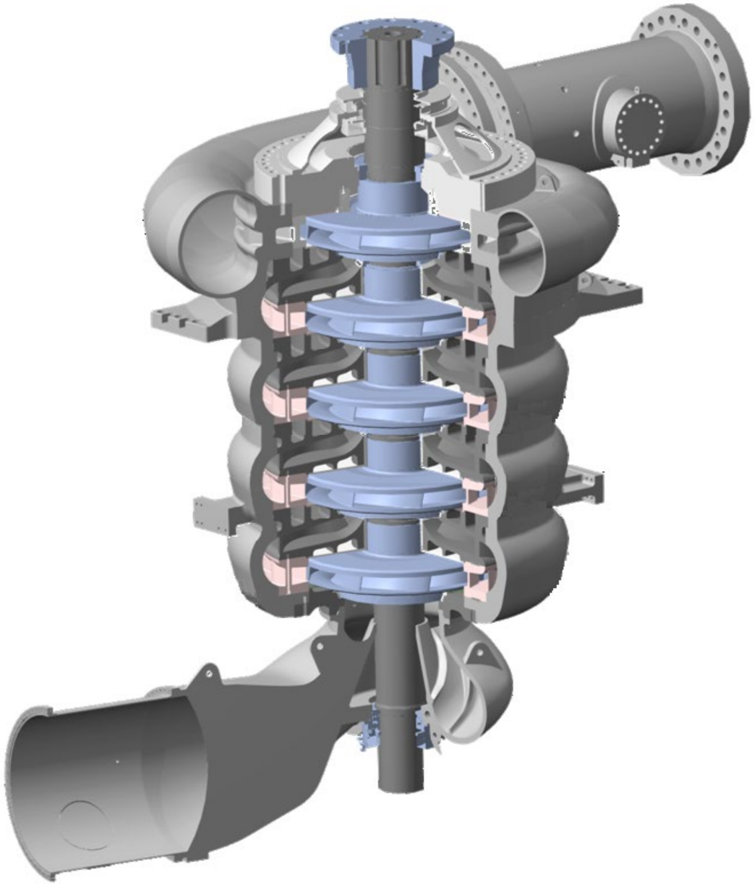
Example: Hongrin-Léman PSP



5 Injectors Pelton Turbine

Veytaux II: 2 Vertical Ternary Units

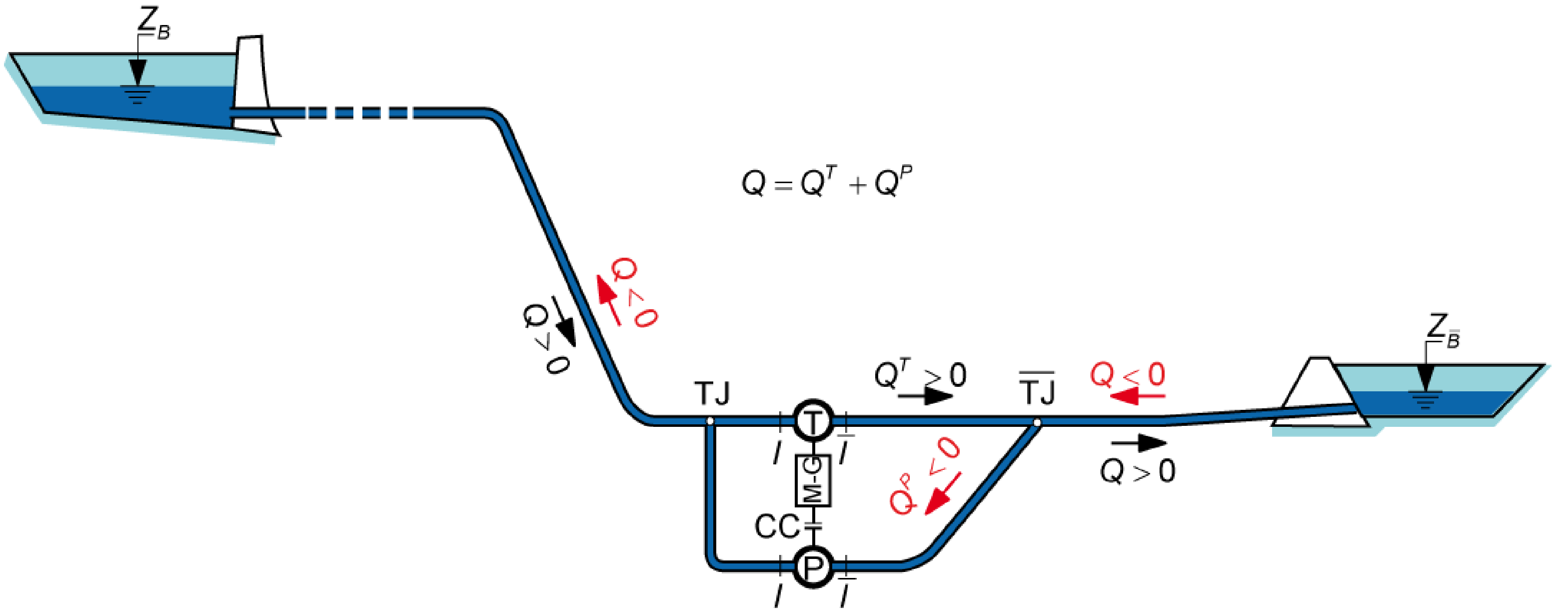
Example: Hongrin-Léman PSP



5 Stages Storage Pump

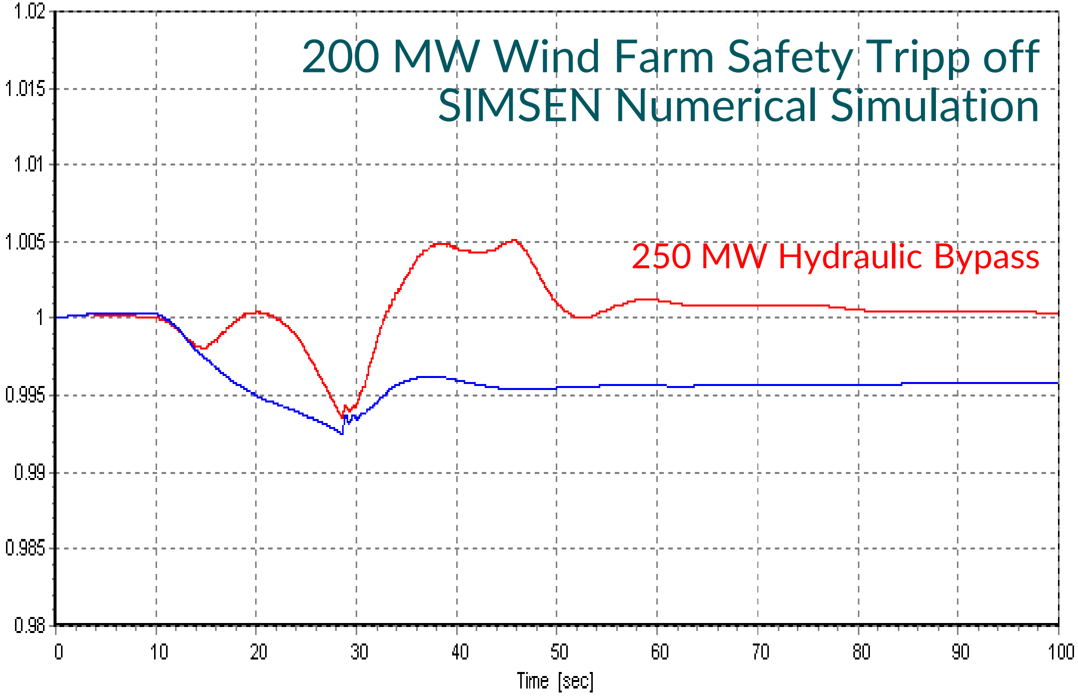
No guide vanes: single operating point (ON/OFF)

Hydraulic Bypass



$$P_{TOT} = P^T + P^P$$

Frequency Control through Hydraulic Bypass



Ternary groups

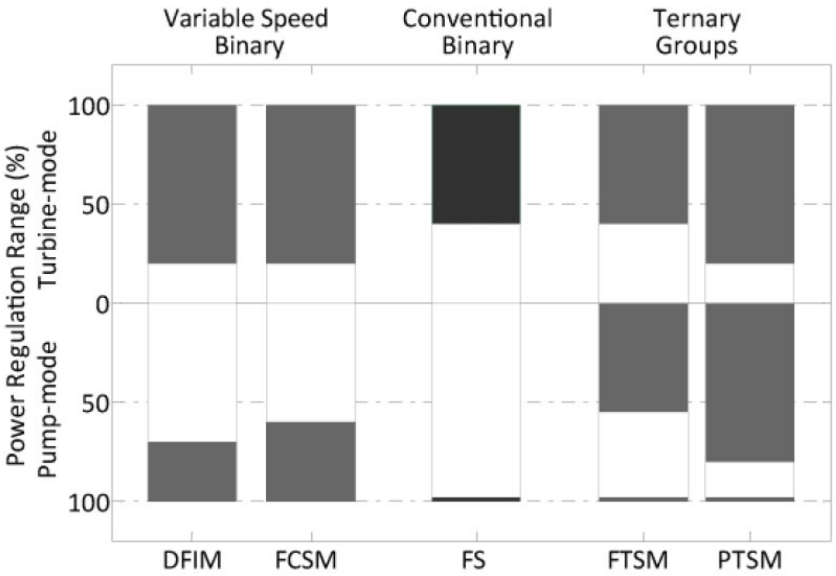
Advantages:

- High operational flexibility due to rapid change of operation mode from pump to turbine and vice-versa (same rotating direction)
- Easy and short time start-up in pump mode (start-up with the turbine as drive)
- Adjustable pump power with hydraulic by-pass
- Wide operating range with Pelton turbines
- Increased efficiency in pump and turbine modes (optimal selection of the pump and turbine)
- Proven technology
- Smooth hydraulic transients

Disadvantages:

- High investment costs (civil engineering due to total shaft line length and electromechanical equipment due to numerous components)
- Maintenance costs due to electromechanical complexity and number of components
- Increased ventilation losses in pumping mode due to turbine rotation
- Lower efficiency in case of hydraulic by-pass
- Instability risks for the rotating train for vertical units (long shaft due to low pump submergence).

Comparison for flexibility: binary VS ternary



FS: Conventional Fixed-Speed Synchronous Machine;
DFIM: Double Fed Induction Machine;
FCSM: Full Converter Synchronous Machine;
FTSM: Francis Ternary Synchronous Machines with Hydraulic Short Circuit;
PTSM: Pelton Ternary Synchronous Machines with Hydraulic Short Circuit.

Quaternary group

Four Machines: 2 electrical machines, a hydraulic turbine and a pump

Power House Configuration:

1. Consideration of Site Characteristics and Layout.
2. Construction of Two Power Houses:
   Group 1: Hydraulic Turbines for Generation.
   Group 2: Pumps for Pumping Purposes.

Turbine Selection:

1. Based on Head and Specific Speed Requirements.
2. Operation Similar to Standard Reservoir Storage Hydropower Plants.

Efficiency Optimization:

1. Each Group Independently Optimized.
2. Maximizing Efficiency for Overall Plant Performance.

Grid Services:

1. Highlighting the Role in Providing Fast Response to Grid Demands.
2. Supporting Grid Stability and Reliability.

Quaternary group

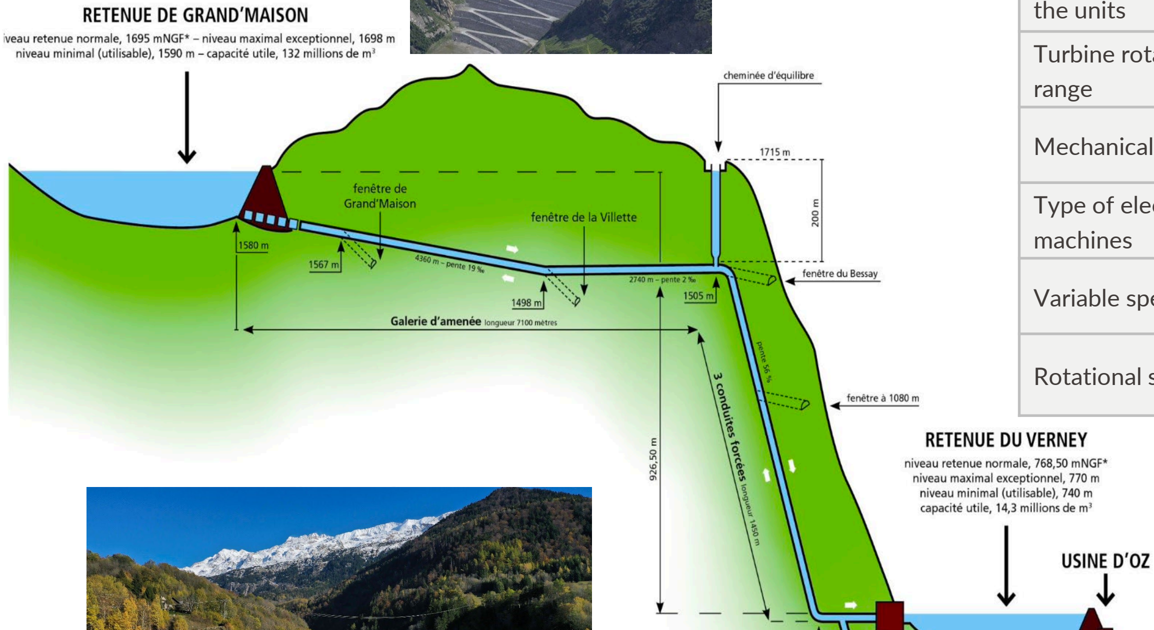
Advantages:

- Optimization for Efficiency: each Group Tailored to Plant Characteristics.
- Fastest Responding Pumped Hydro Technology.

Disadvantages:

- Space requirement for hosting 2 power houses
- Investments costs and maintenance

Grand Maison PSP



Head	Min 837 m; Rated 900 m; max 923 m
Type of hydraulic machines	Pelton turbines/ Multistage pump turbines
Number and capacity of the units	4 Pelton turbines, 170 MW 8 pump-turbines, 156 MW
Turbine rotational speed range	Fixed speed
Mechanical power	156 MW / unit
Type of electrical machines	12 synchronous machines
Variable speed	Fixed speed
Rotational speed	Pelton Turbine: 428 min^{-1}; Pump-turbine: 600 min^{-1}.

Grand Maison PSP