EE – 456: Hydropower Plants: Generating and pumping units

L3 –Equipement and control systems for hydroelectric units

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Vogelgrun run of river power plant (France)

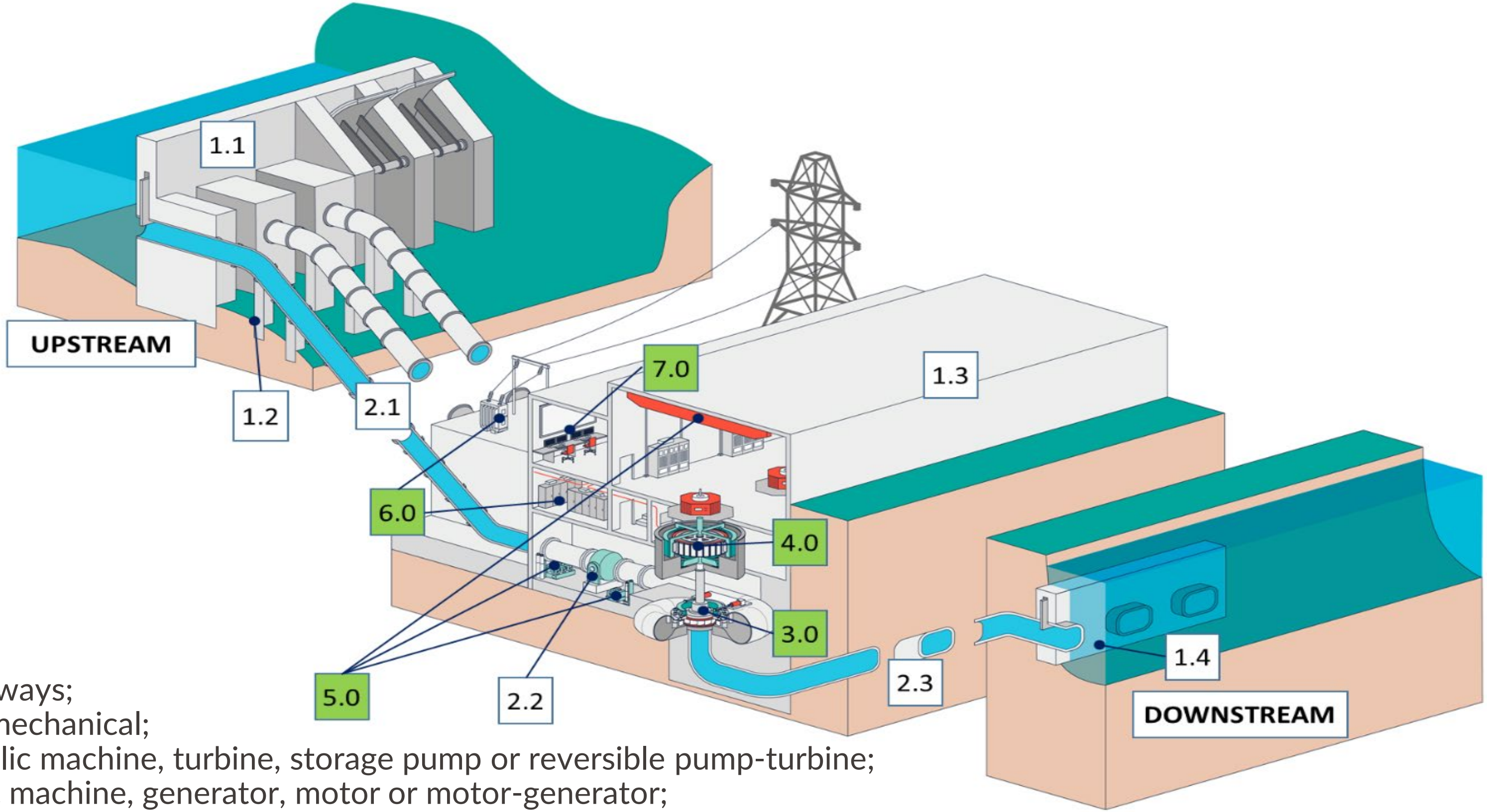
Content of the lecture

- Hydroelectric units components
- Shaft line
- Types of hydraulic machines
- Types of electrical machines
- Control system

1 GW Linthal PSP

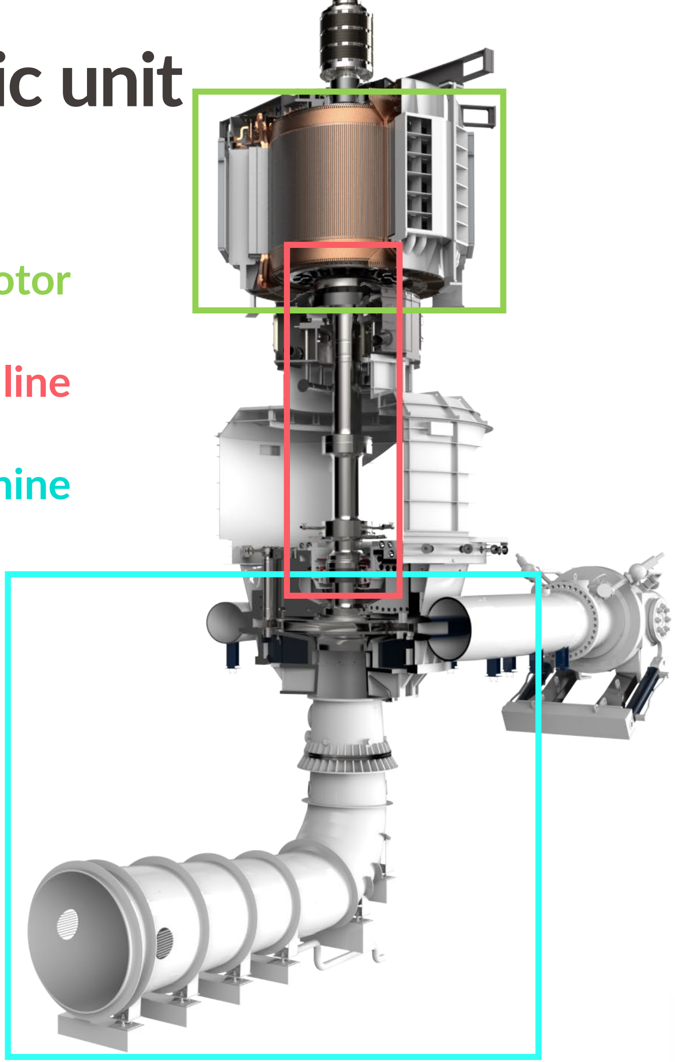
- Limmern Lake 92 10^6 m^3 Capacity
- MuttLake 25 10^6 m^3 Capacity
- 560 mWC to 724 mWC Head Range

Overview of a hydropower plant



1.0 Water ways;
2.0 Hydromechanical;
3.0 Hydraulic machine, turbine, storage pump or reversible pump-turbine;
4.0 Electric machine, generator, motor or motor-generator;
5.0 Mechanical Balance of Plant;
6.0 Electrical Balance of Plant;
7.0 Control Systems.

Overview of an hydroelectric unit



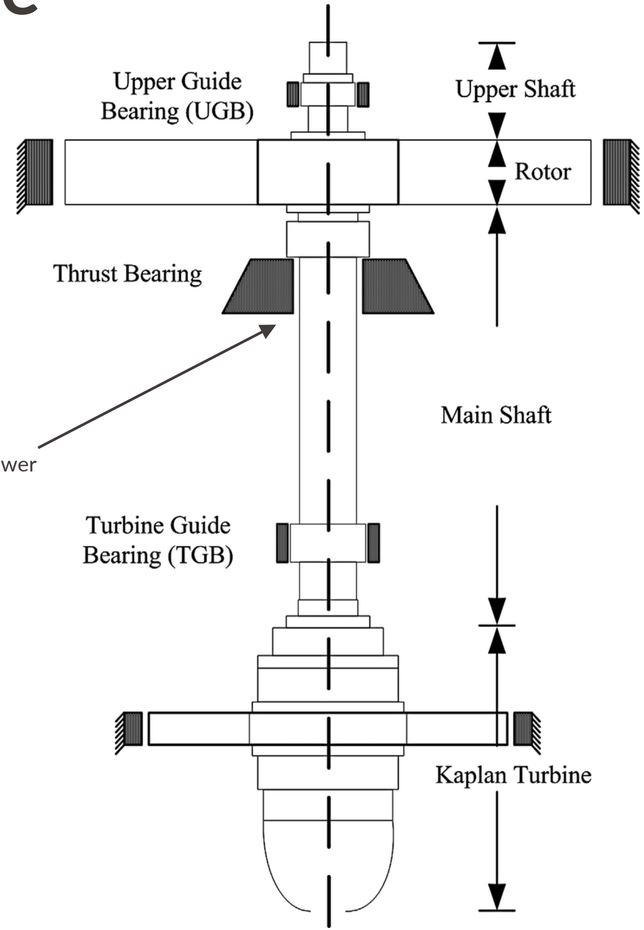
Generator/motor

Shaft line

Hydraulic Machine

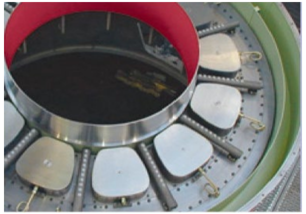
Linthal Variable Speed Pump-Turbine Unit
250 MW Capacity
560 mWC to 724 mWC Head Range
500 min^{-1} ± 6 % Variable Speed

Shaft line



Often there is also a lower guide bearing

Thrust bearing: to balance axial forces

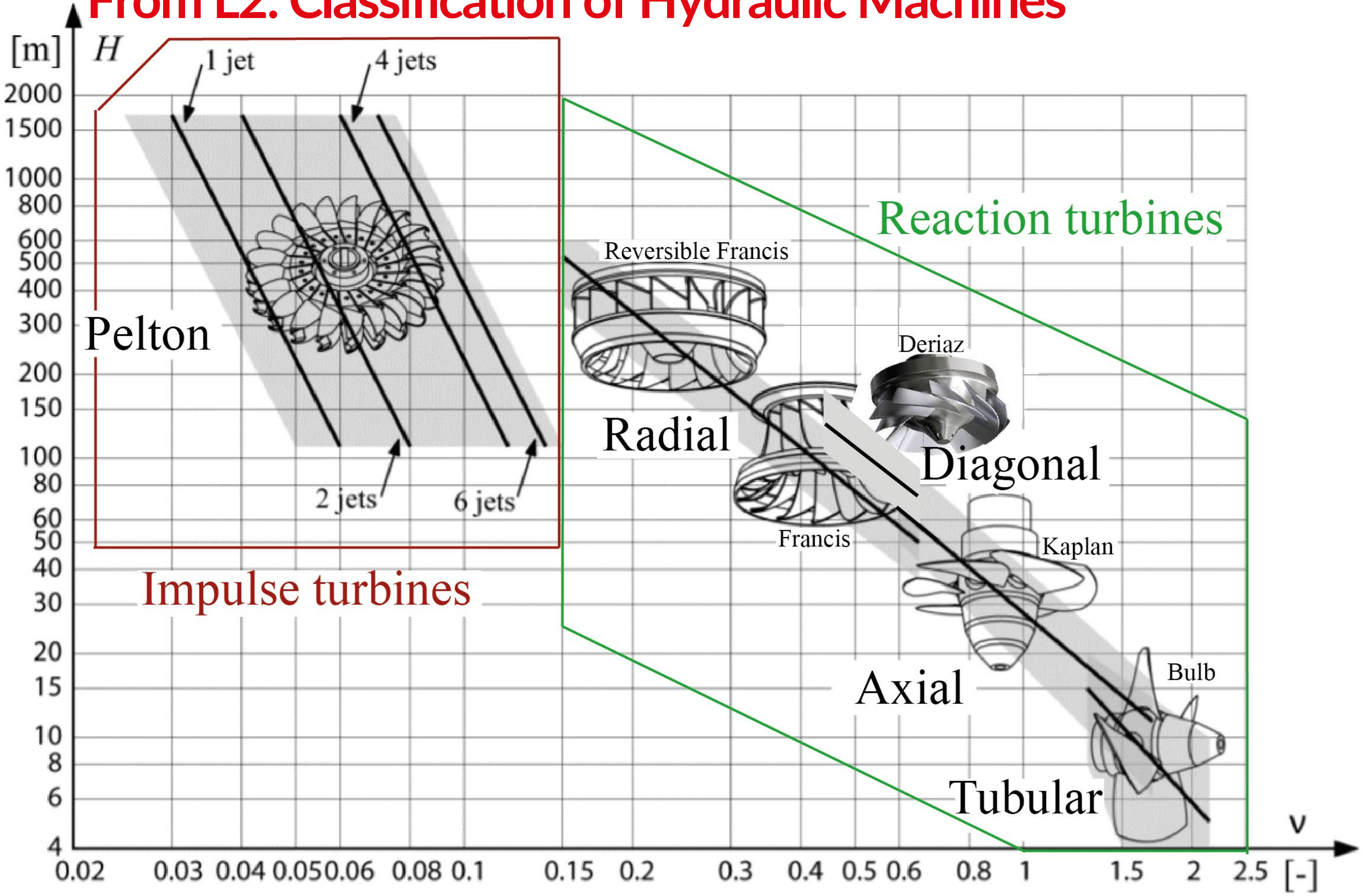


Guide bearing: to balance radial forces

https://www.youtube.com/watch?v=IQKaD0pBNlY

Hydraulic Machines

From L2: Classification of Hydraulic Machines



Head $= H$ (m)

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

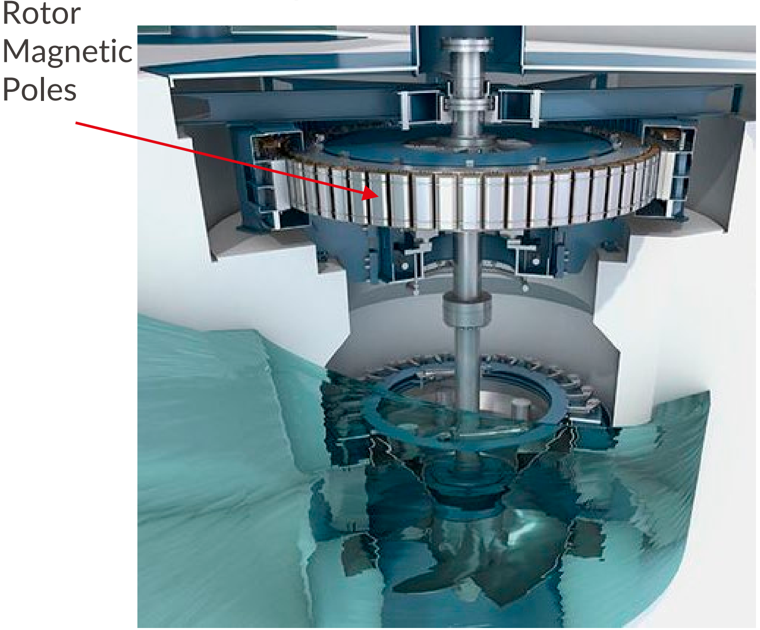
Speed $= N$ (min^{-1})

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

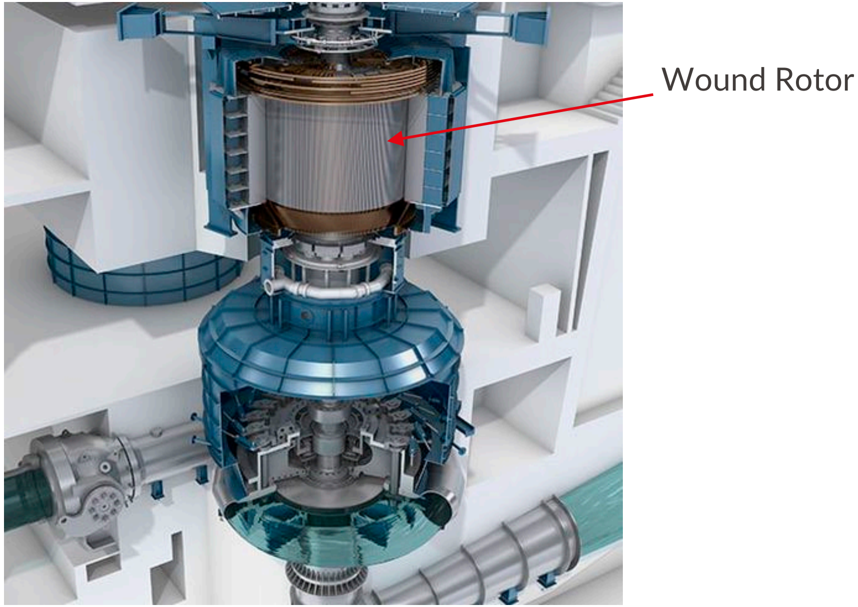
Generator/Motor

- → Generators convert the mechanical energy from the turbine into electrical energy using an excitation system.
- → Typically, they have a stator and a cylindrical rotor with three phases winding.

Synchronous Generator



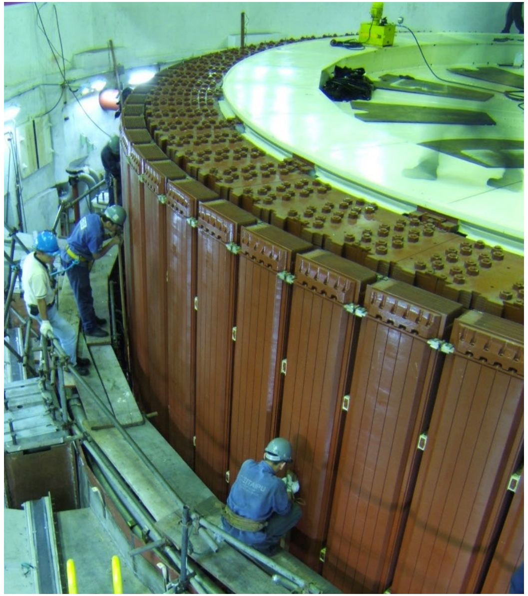
Asynchronous or Induction Generator

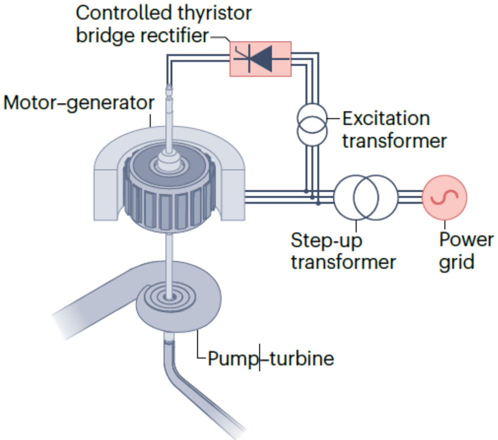


Electric Machines

Synchronous Generator

- **Operation**: These generators operate at a constant speed, synchronized with the frequency of the grid. They require an external excitation source to generate a magnetic field.
- **Usage**: Commonly used in large hydropower plants due to their ability to maintain voltage stability and provide reactive power support. Typically used in a vertical shaft configuration.
- **Advantages**: High efficiency, ability to operate at varying loads, and good voltage regulation.
- **Characteristics:** Require DC excitation of the rotor winding to create a magnetic field. Slip rings are used to supply this DC current from an external excitation system to the rotating rotor winding. Rotor poles are typically salient-type poles.





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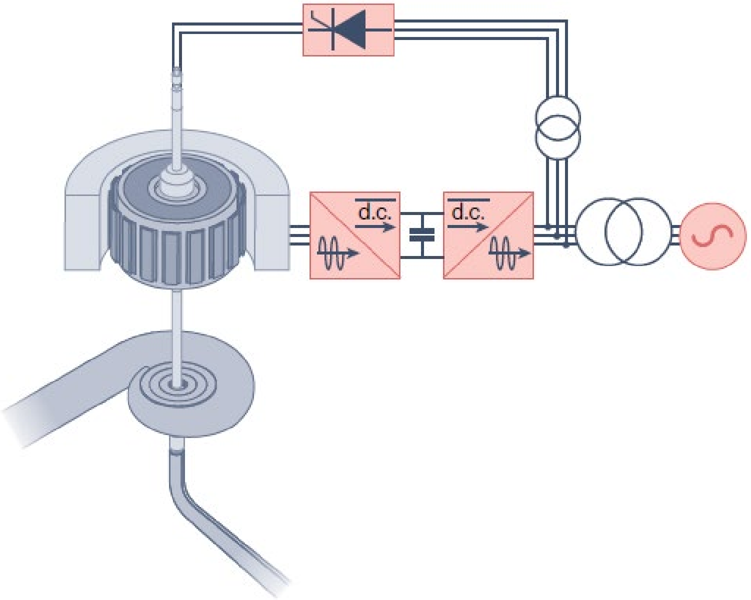
Converter-fed synchronous generator

- Synchronous generator + Full-size Frequency Converter (FSFC).
- Back-to-back power converter controlling the full stator power.
- Allows for speed variations of +- 100%
- Max 100 MW power capacity

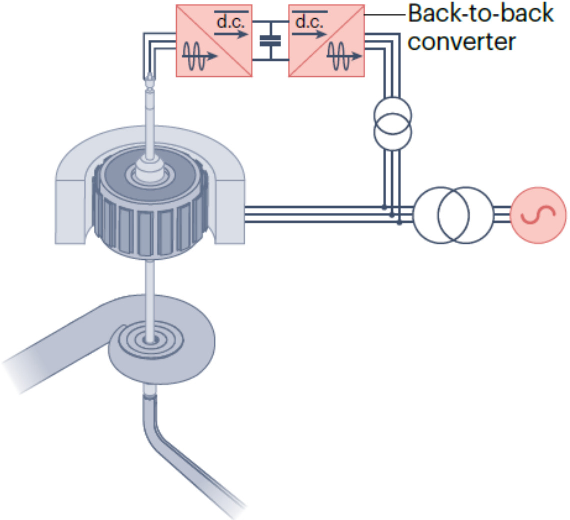


Electric Machines

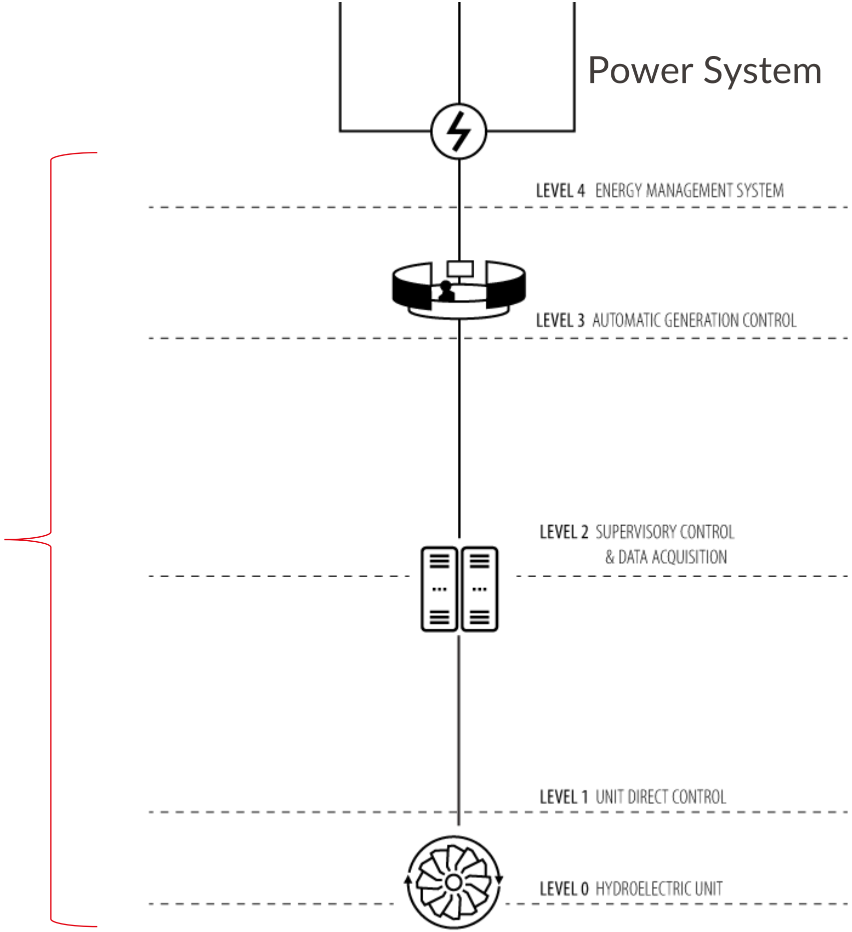
Asynchronous Generator

- **Characteristics**: for large plants typically doubly-fed induction machines (DFIM) having a wound rotor with slip rings to control rotor current and allowing for variable speed thanks to a back-to-back power converter on the rotor side. It allows for +/- 10% rotational speed variations. There exists also asynchronous generators with squirrel cage rotor and without slip ring which are used for smaller plants.
- **Operation**: These generators do not require an external excitation source and can operate at varying speeds.
- **Usage**: More commonly used for large plants requiring variable speed due to significant variation of head or in smaller plants.
- **Advantages**: Simplicity in design, lower cost, and robustness.

Doubly-fed induction machine



Communication or Field Bus



Hydropower plant control system

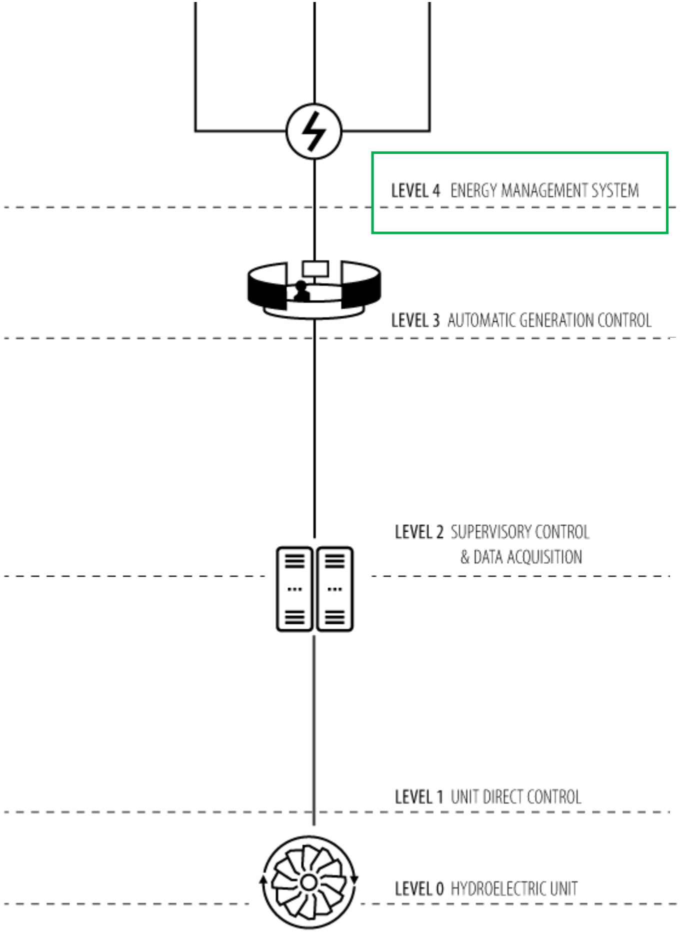
Communication Bus

Hydropower plants are operated either locally with a unit control board, or remotely through a central control room and/or dispatching center called **Energy Management System (EMS)**

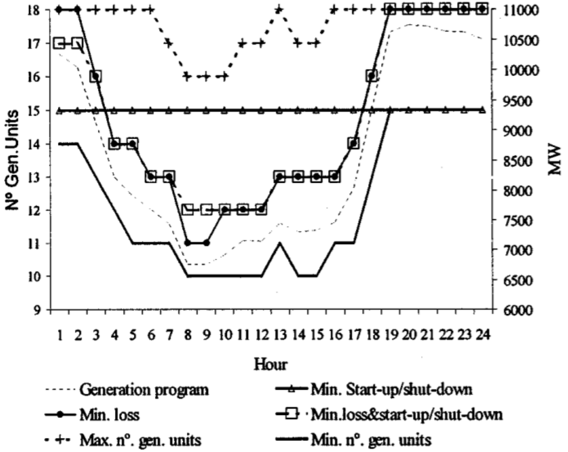
OUTPUT:

Set-point in power: P

For run of river power plants it can be given as discharge set-point



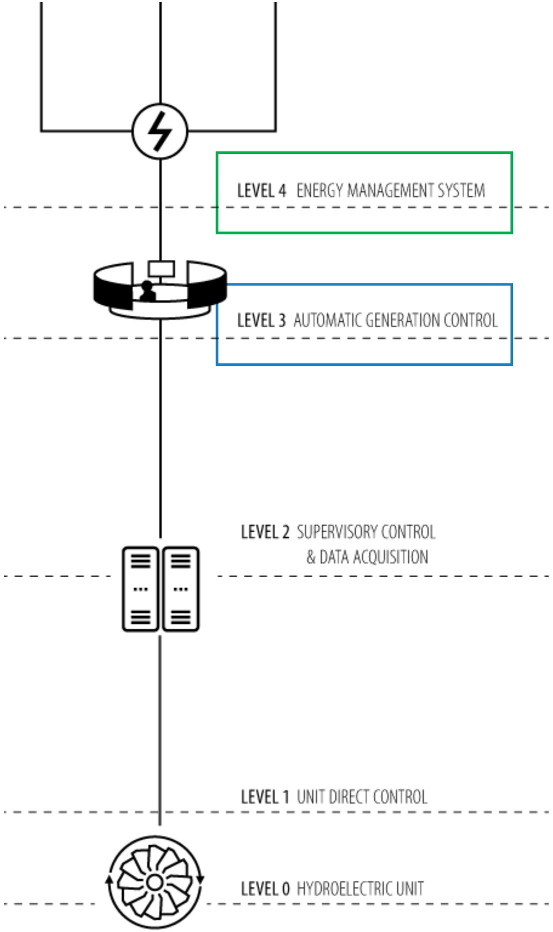
Dispatch plan and power system communication



Example dispatch plan Itaipu Hydropower plant (Brazil)

Communication Bus

- **Automatic Generation Control (AGC)** assures that the real-time desired power set-point is attained by a proportional gain controller or droop control.
- **Primary-frequency controllers** act immediately after a power imbalance resulting in a frequency deviation (locally measured).
- **Secondary-frequency controllers** are responsible for compensating the frequency deviation from the rated value after the primary control intervention.
- It maintains or attempts to return the frequency of the system to scheduled value as soon as a deviation occurs.
- It maintains each unit generation at the most economic value.
- In case of a power plant with more than 2 units, AGC is supported by a Joint Control



Dispatch plan and power system communication

Power (active or reactive) dispatch between different groups

OUTPUT:

Set-point in active power for each generating unit:

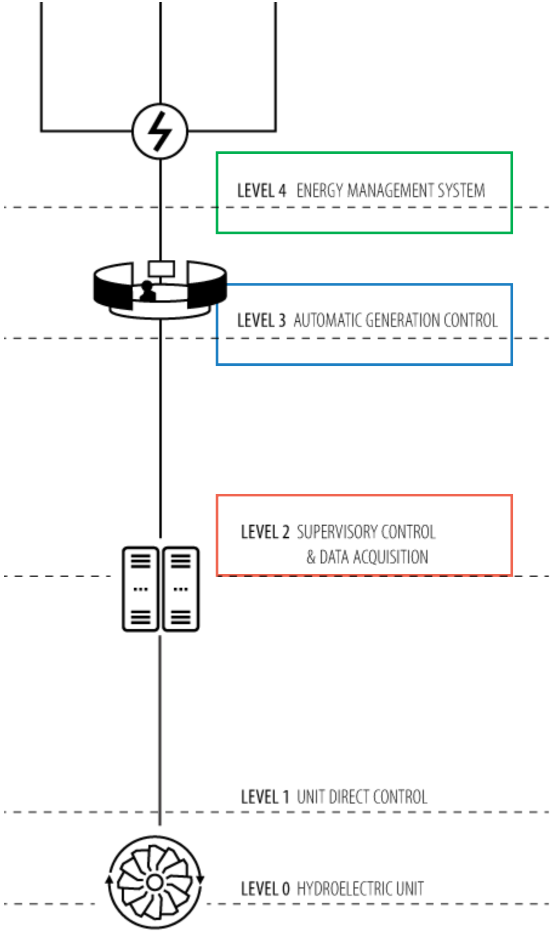
$$\boxed{P} = \sum_{i=1}^{N_{unit}} \boxed{P_{unit}}$$

Set-point in rotational speed of the unit generator: ω

Communication Bus

SCADA: type of Industrial Control System (ICS) based on computer controlled systems

- It provides all necessary functions for operation, supervision, protection and control of plant processes.
- Is it used at all automation levels - from the turbine controller and unit controls right up to large central control rooms
- Particular important for predictive and planned maintenance



Dispatch plan and power system communication

Power (active or reactive) dispatch between different groups

Control and supervision of the plant

Communication Bus

The **Unit Direct Control** decides the operating conditions of each component of the hydroelectric unit through Programmable Logic Controllers (PLC):

- Automatic Start Sequence
- Automatic Shutdown
- Speed Governor
- Position Control
- Excitation Control
- Protection System
- Alarm and Annunciation

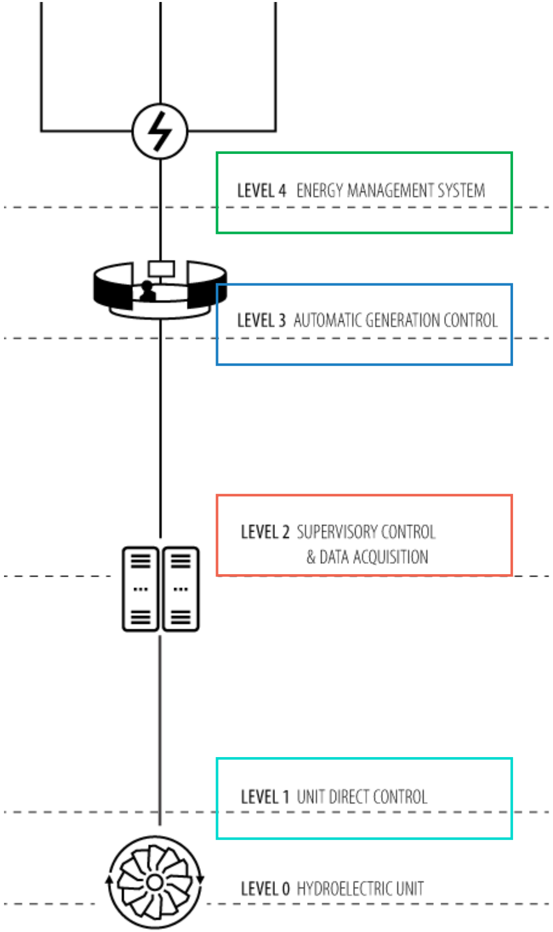
OUTPUT:

Set-point in active power for each generating unit:

$$P = \sum_{i=1}^{N_{unit}} P_{unit}$$

$$P_{unit} = \eta_e P_m = \eta_e \eta_t \rho Q_{unit} g H$$

$$P_{unit} = f\left(\alpha, \beta, \omega, \eta_e, H\right)$$



Dispatch plan and power system communication

Power (active or reactive) dispatch between different groups

Control and supervision of the plant

Unit operating condition

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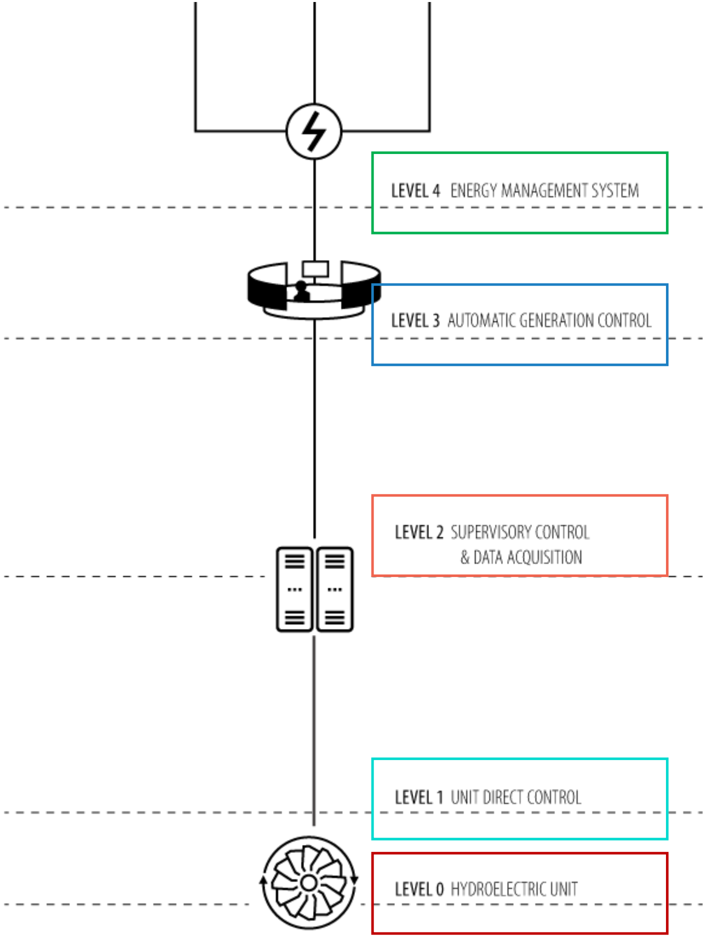
Communication Bus

Servomotors and drives allow for a correct operation of the hydroelectric unit



Dispatch plan and power system communication

Power (active or reactive) dispatch between different groups

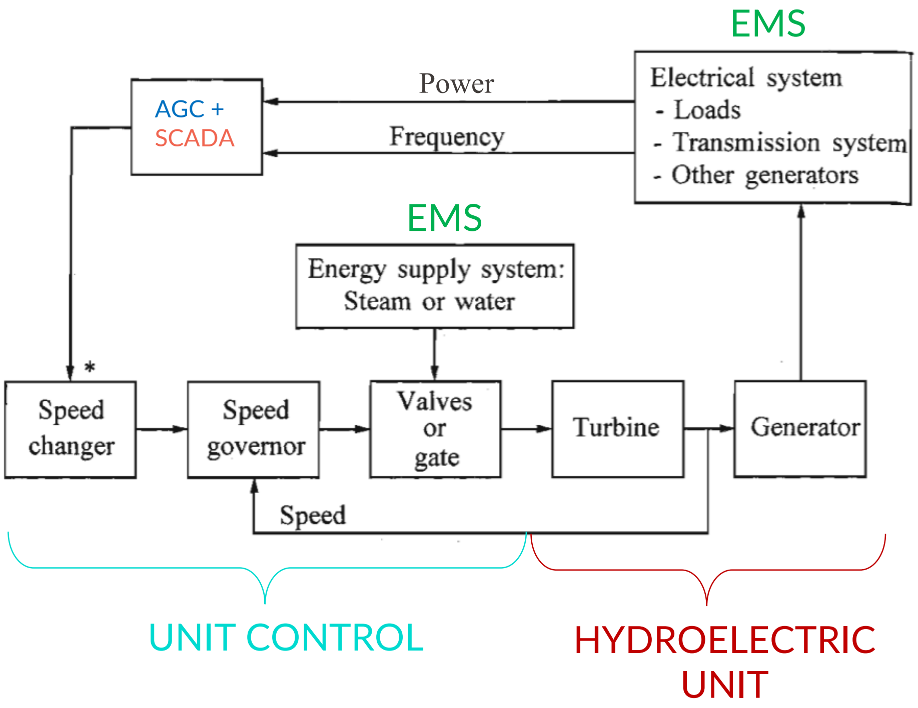
Control and supervision of the plant

Unit operating condition

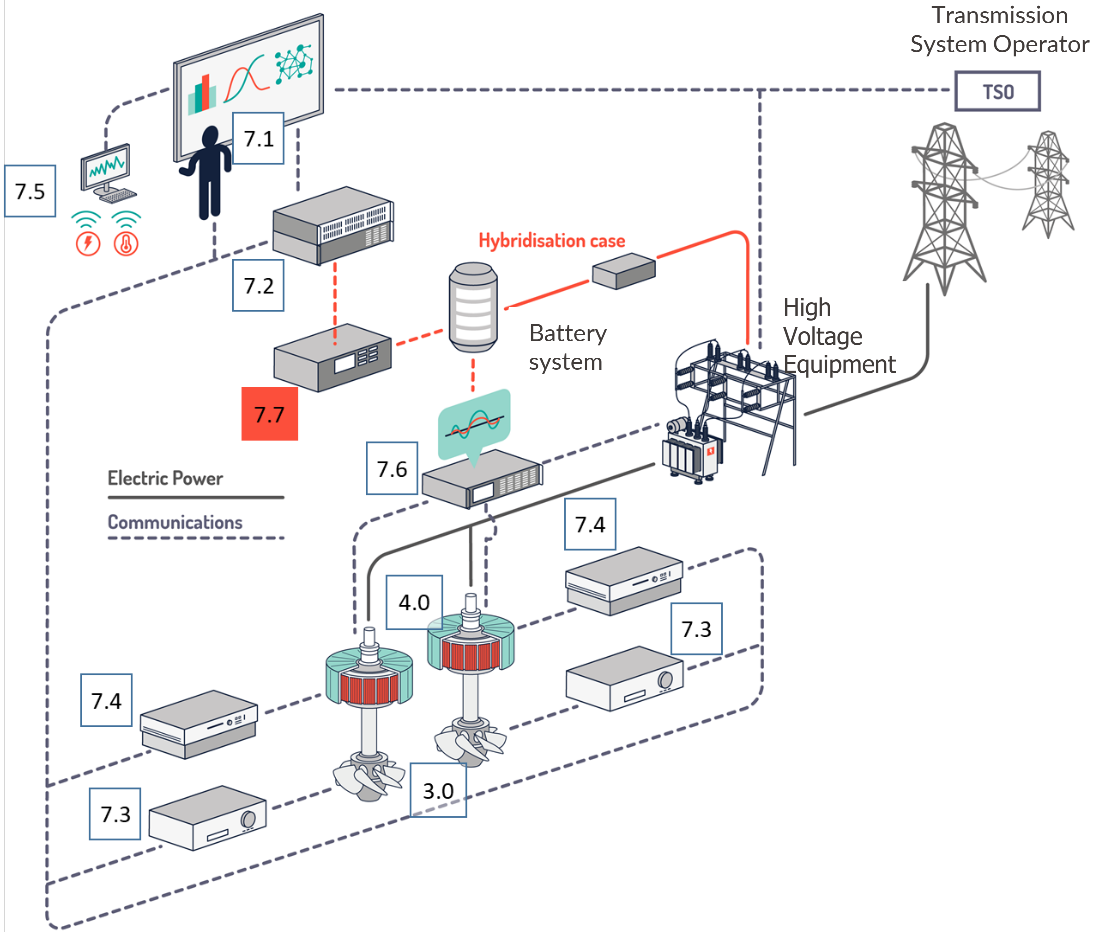
Components Operation

Control System

Functional block diagram



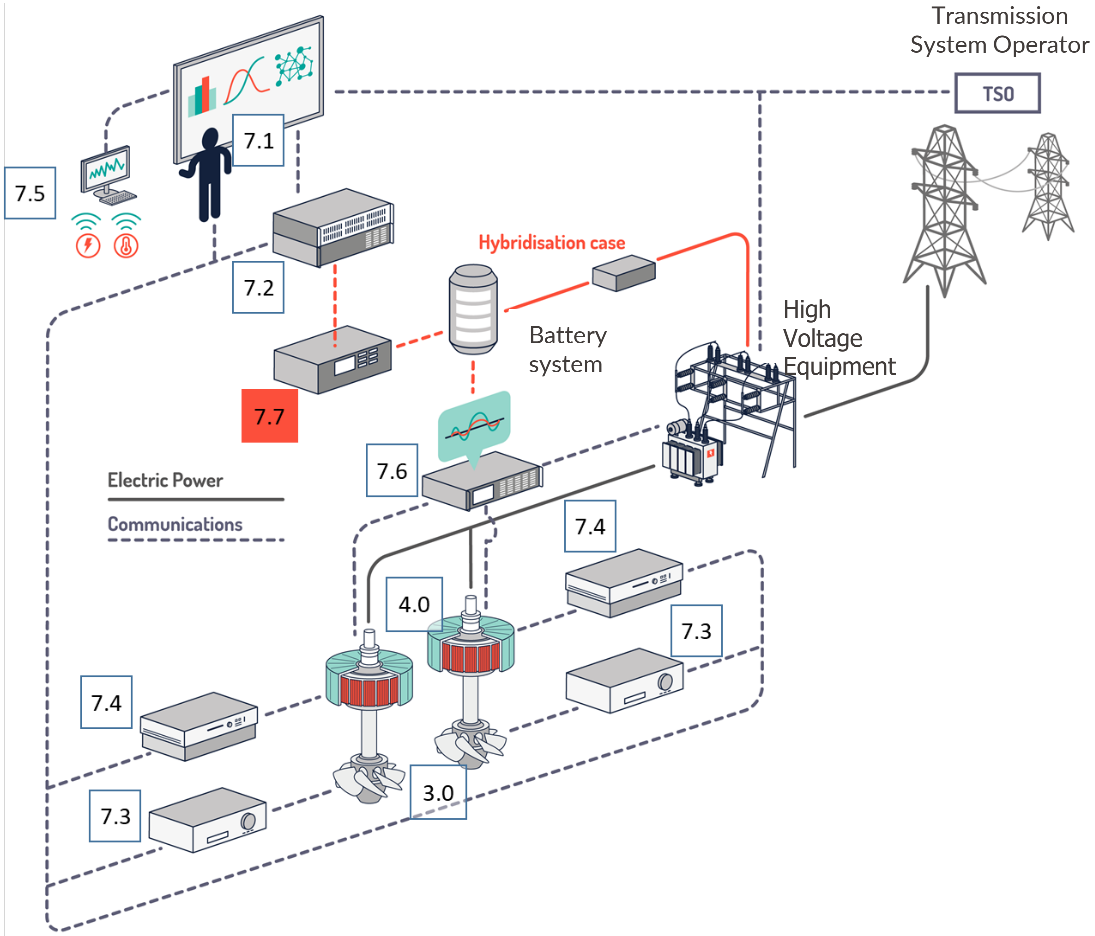
Control System



Systems, hardware and software engineered for operation, supervision and control processes that guarantee a safe, reliable and economic operation of the plant.

- 7.1 Energy Management System (EMS);
- 7.2 Automatic Generation Control (AGC) + Supervisory Control and Data Acquisition (SCADA) systems;
- 7.3 Turbine Governor;
- 7.4 Generator Control;
- 7.5 Condition Monitoring System;
- 7.6 Electrical Protection;
- 7.7 Battery Controller (only for Battery Hybridisation cases).

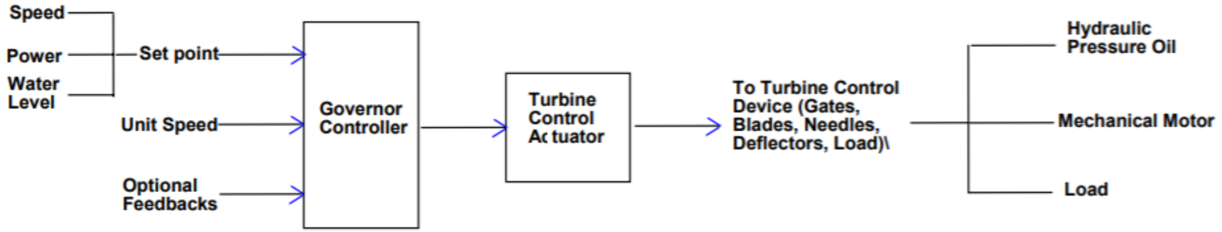
Control System



- 7.1: includes the management of the Hydropower Plant Systems, Sequences and Automation, Safety and Protection, Operating Modes (Turbine/Pumping), dispatch and communication.
- 7.2 is a supervisory controller coordinating the energy dispatch between the storage systems (if any) and the generating units. It also controls the speed reference of variable speed units.
- 7.3 is the governor which define the operating condition of the hydraulic turbine.
- 7.4 is the Automatic Voltage Regulation (AVR) linked to a DC excitation system of the generator. It also refers to the Voltage Source Inverter (VSI) controller for variable speed cases.
- 7.5 includes diagnostics systems and a sensors network linked to each monitored component

Unit direct control

Governor



- Governor control system for hydraulic turbines is basically a **feed back control system** which senses the **speed and power of the generating unit** or discharge and takes control action for operating the discharge/load controlling devices in accordance with the deviation of actual set point from the reference point.

- **Water level controlled power output controllers** can be used for grid connected units, especially in case of a cascade of run-of-river power plants.

Unit direct control

Governor

The governor PLC of the hydraulic machine includes a **digital Proportional and Integral (PI) controller or a Proportional Integral and Derivative (PID)** with three-term control.
Digital PID algorithm is applied to the **speed input** from which a signal is developed to adjust with the guide vanes, Kaplan blades or Pelton nozzle opening. This signal is based on the results of PID algorithm, given speed droop curve and governing dead-band.

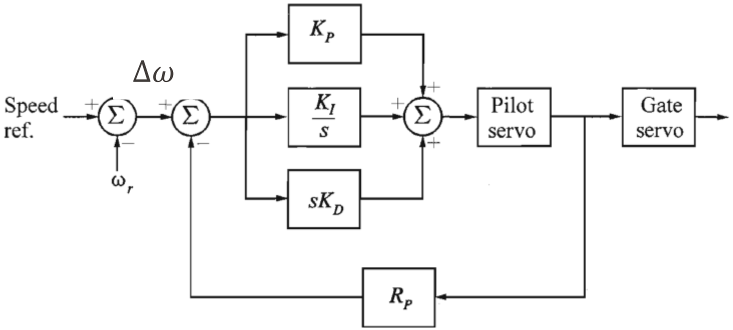
PID transfer function: $M(s) = K_P + \dfrac{K_I}{s} + K_D s$

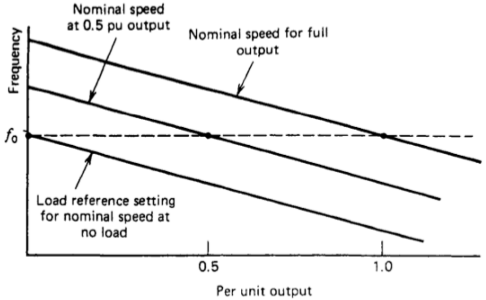
$s = \dfrac{d}{dt}$ Laplacian Operator

Typically: $K_P = 3$

$K_D = 0 - 0.5$

$K_I = 0.7$





The permanent droop R_P indicates the slope of the frequency variation as a function of the unit power output. It is set at about 5%. This means that a frequency deviation of 5% results into a 100% change in the output power.

Unit direct control
Supplementary control action

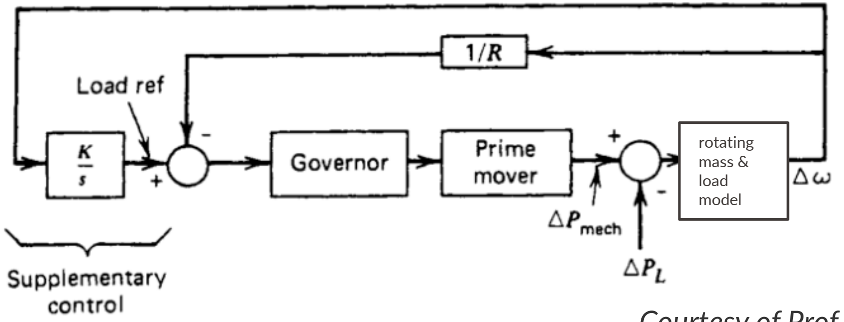
A load change will produce a frequency change $\Delta\omega$ with a magnitude that depends on

- The droop characteristics of the governor
- The frequency characteristics of the system load.
- The load change magnitude
- The characteristics of the interconnected power system

A **supplementary control** must act to restore the frequency to the nominal value. The **reset (integral) control action** of the supplementary control will force the frequency error to zero by adjustment of the speed reference set point. The rate of change of each unit's output with respect to a change in total generation is called the unit's participation factor, PF.

$$P_{i_{des}} = P_{i_{base}} + PF_i \cdot \Delta P_{total}$$
$$\Delta P_{total} = P_{new\ total} - \textstyle\sum_{all\ gen} P_{i_{base}}$$

$P_{i_{des}}$ = new desired output from unit i
$P_{i_{base}}$ = base-point generation for unit i
PF_i = participation factor for unit i
ΔP_{total} = change in total generation
$P_{new\ total}$ = new total generation



Courtesy of Prof. Paolone

Unit direct control

Prime mover

$$P_m = \rho \eta_t Q g H = f(QH)$$

$$Q = A_{ref} K_u \alpha \sqrt{H}$$ **Penstock model discharge characteristics**

$$\frac{\Delta Q}{Q_0} = \frac{\Delta \alpha}{\alpha_0} + \frac{\Delta H}{2H_0} = \Delta\bar{\alpha} + \frac{\Delta \bar{H}}{2} = \Delta \bar{Q}$$ Small discharge variations (linearization)

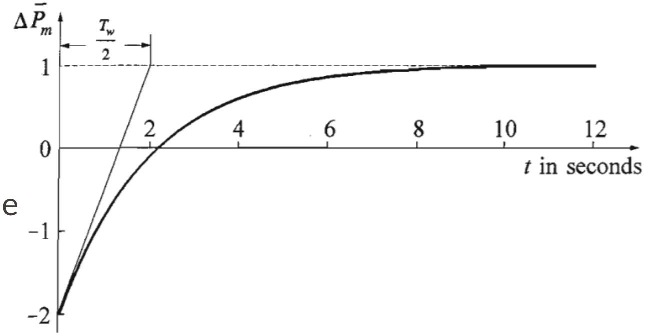
$$\frac{\Delta P_m}{P_{m,0}} = \frac{\Delta Q}{Q_0} + \frac{\Delta H}{H_0} = \Delta \bar{Q} + \Delta \bar{H} = \Delta \bar{P}_m = 2\Delta\bar{\alpha} + 3\Delta\bar{H}$$ Small power variations (linearization)

$$\rho L_{ref} \frac{d\Delta Q}{dt} = -A_{ref} \rho g \Delta H$$ Newton second law of motion

$$T_w = \frac{L_{ref} Q_0}{g H_0 A_{ref}}$$ Water starting time to reach the nominal discharge from standstill at a given head *H*

$$T_w \frac{d\Delta\bar{Q}}{dt} = -\Delta\bar{H} = 2\left(\Delta\bar{\alpha} - \Delta\bar{Q}\right)$$

$$\frac{\Delta\bar{P}_m}{\Delta\bar{\alpha}} = \frac{1 - T_w s}{1 + \frac{1}{2} T_w s}$$ **Transfer Function** of an ideal lossless hydraulic turbine



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Unit direct control

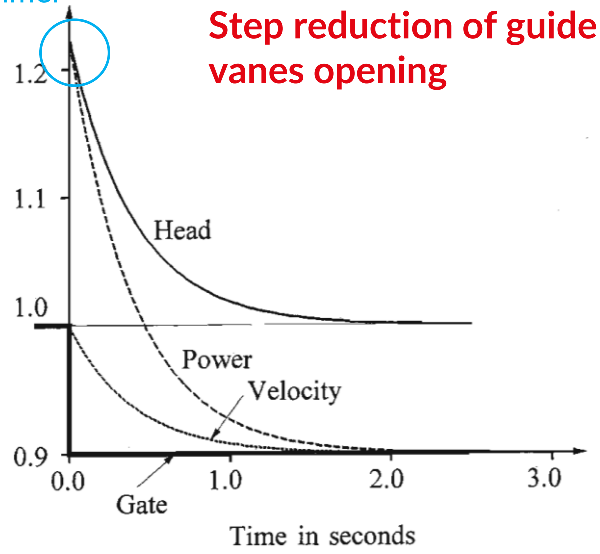
Prime mover

Transfer Function of an ideal lossless hydraulic turbine

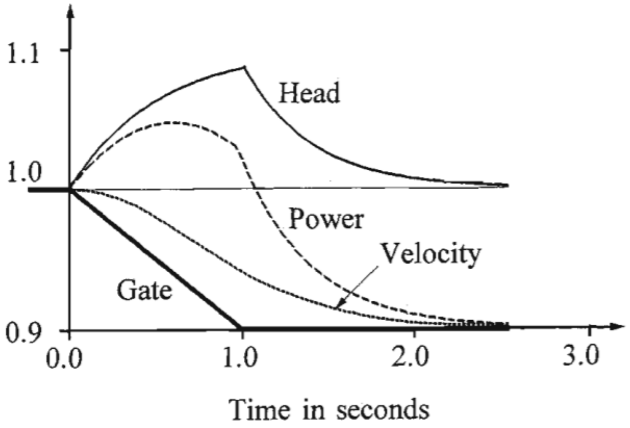
$$\frac{\Delta \overline{P}_m}{\Delta \overline{\alpha}} = \frac{1 - T_w s}{1 + \frac{1}{2} T_w s}$$

Water hammer

Step reduction of guide vanes opening

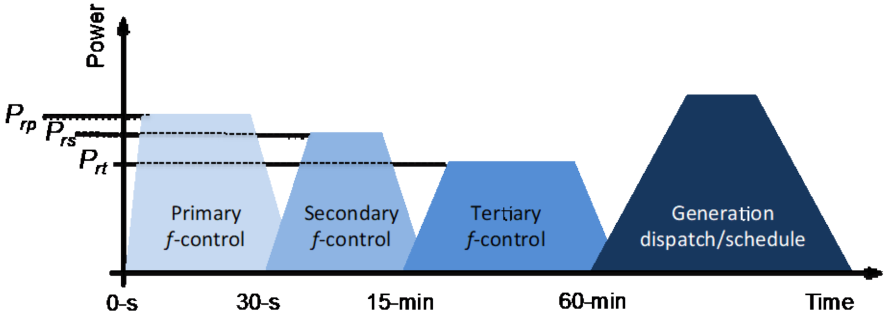


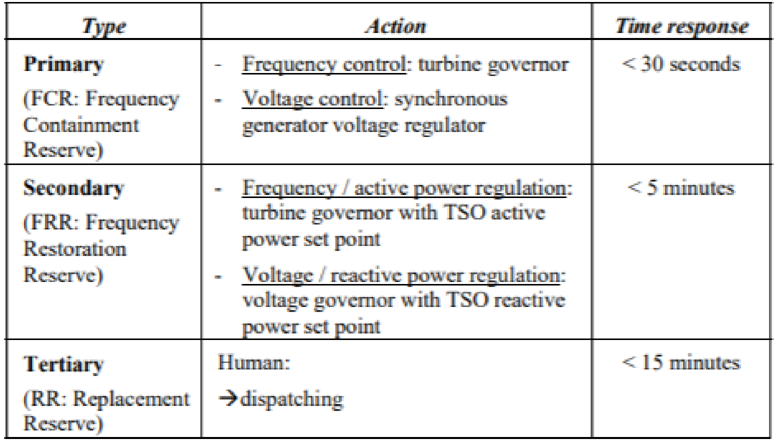
1-second ramp reduction of guide vanes opening



Unit direct control

Governor actions for ancillary services provision





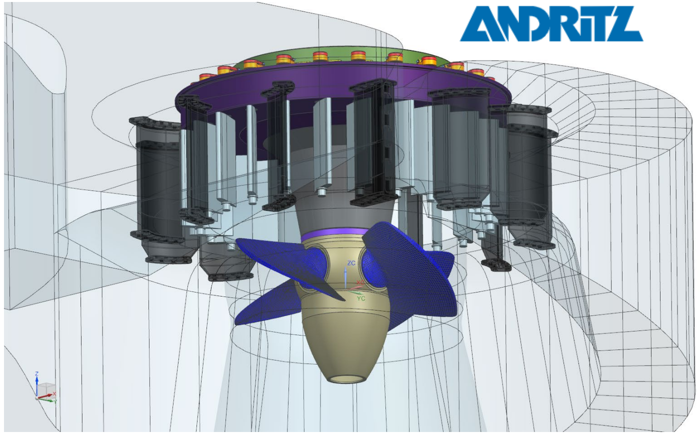
Type	*Action*	*Time response*
Primary (FCR: Frequency Containment Reserve)	- Frequency control: turbine governor - Voltage control: synchronous generator voltage regulator	< 30 seconds
Secondary (FRR: Frequency Restoration Reserve)	- Frequency / active power regulation: turbine governor with TSO active power set point - Voltage / reactive power regulation: voltage governor with TSO reactive power set point	< 5 minutes
Tertiary (RR: Replacement Reserve)	Human: →dispatching	< 15 minutes

Description of the actions for power network control

Example: Control System of a Run of River Power plant

Double regulated turbines in RoR

- Controllable variables:
    - Guide vanes angle α
    - Blades angle β
- External conditions:
    - Head H
    - Rotational speed ω
- Controlled variables:
    - Efficiency $\eta_t = f_1(H, \omega, \alpha, \beta)$
    - Discharge $Q = f_2(H, \omega, \alpha, \beta)$



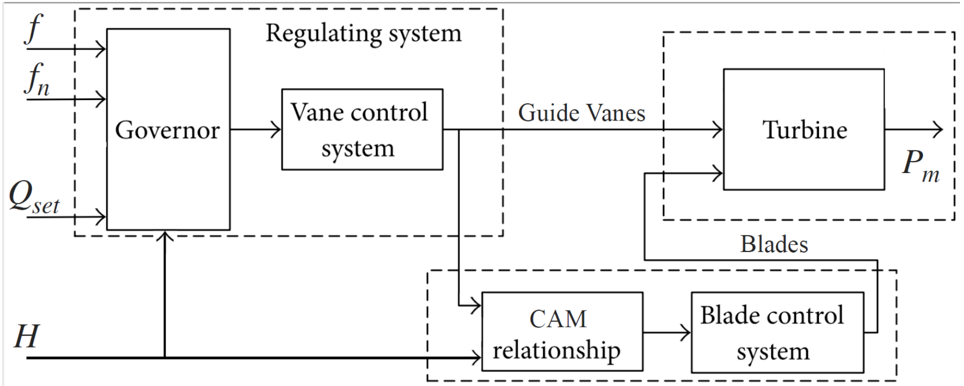
$$P = \sum_{i=1}^{N_{unit}} P_{unit}$$

$$P_{unit} = \eta_e P_m = \eta_e \eta_t \rho Q_{unit} g H$$

$$P_{unit} = f\left(\alpha, \beta, \omega, \eta_e, H\right)$$

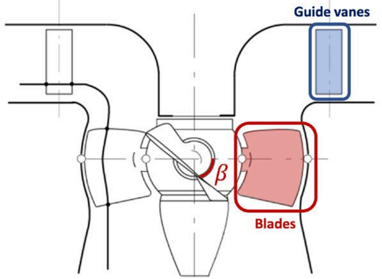
Example: Control System of a Run of River Power plant

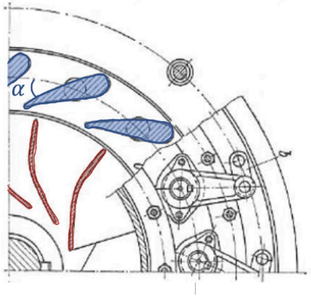
- Governor block to sense the generator speed and adjusts the turbine power output
- Typically PI / PID
- In a double regulated turbine control the two variables α and β are not independent.
- A block called Combinator (CAM) or Blade Angle Control computes the value of β as function of α and H

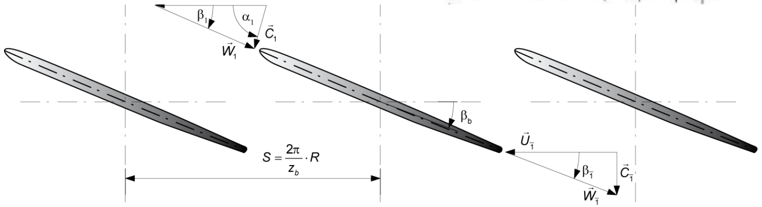


Example: Control System of a Run of River Power plant

- A block called <u>Combinator</u> (CAM) or Blade Angle Control computes the value of β as function of α and H

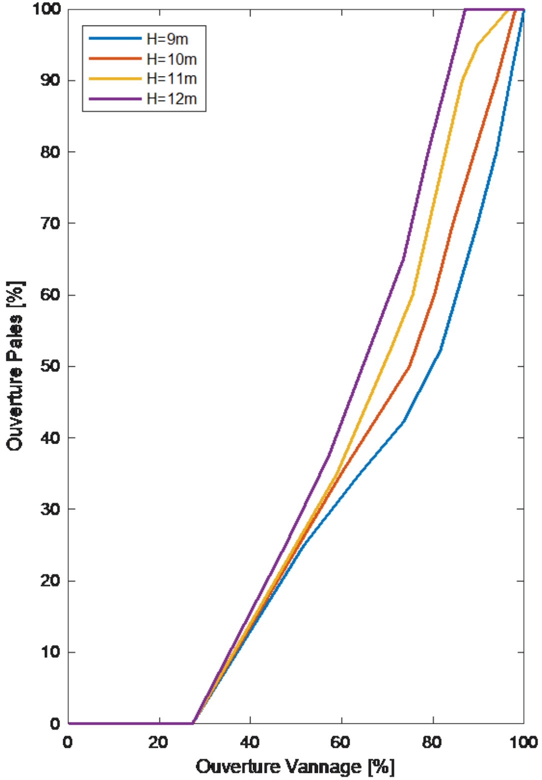






- In some cases **optimal control** has been exploited to control the system, <u>decoupling α and β</u>

Example of CAM or combinator curve



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Example: Control System of a Run of River Power plant

Control of Run-of-River hydropower plants for Frequency Containment Reserve (FCR) provision:

Advantages :

- Turbine double regulation
- No water hammer phenomenon

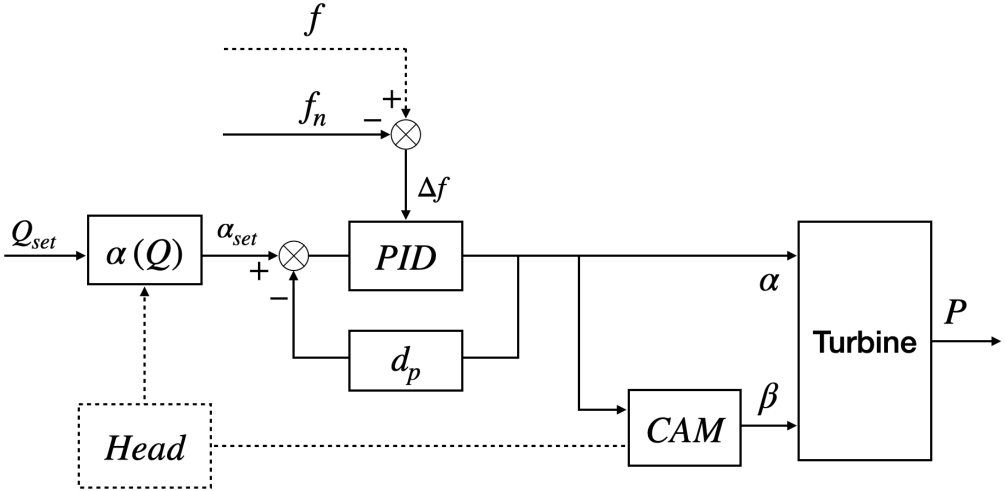
Challenges:

- Slower response of Kaplan turbines compared to Francis or Pelton
- Need for respecting the discharge set-point with good accuracy:
  - Controlling the river head to preserve navigability
  - Safety issues
  - Presence of cascade HPPs
- Wear and tear

Example: Control System of a Run of River Power plant

The control strategy for Frequency Containment Reserve provision:

- The original set-point given by the day-ahead dispatch plan;
- A droop-based frequency regulation originating a deviation from the the main set-point;
- An offset discharge term, computed periodically, to ensure that the cumulate variation of discharge is contained within certain limits



THANK YOU!

QUESTIONS?

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