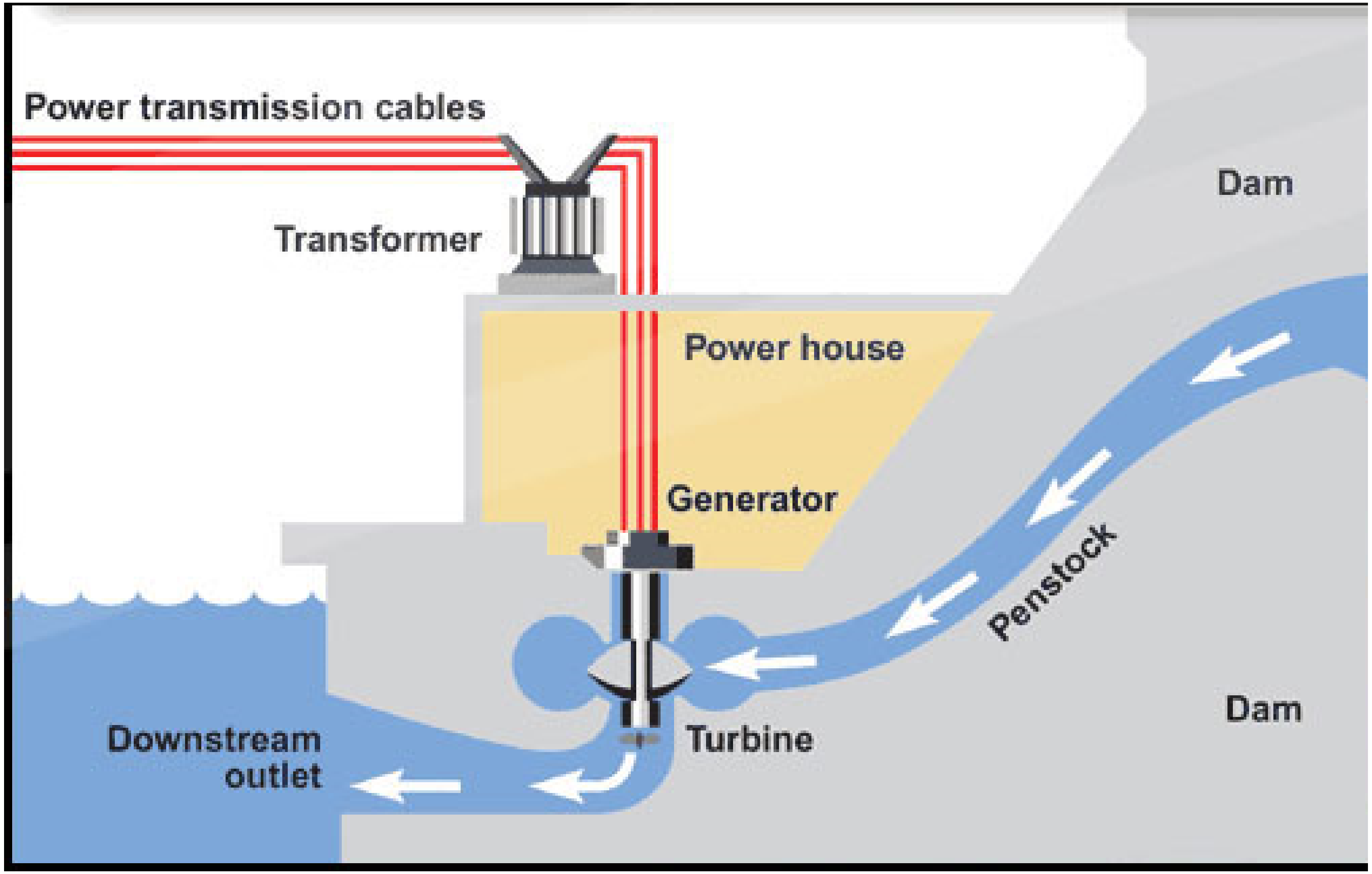
PRIME MOVERS AND GOVERNORS

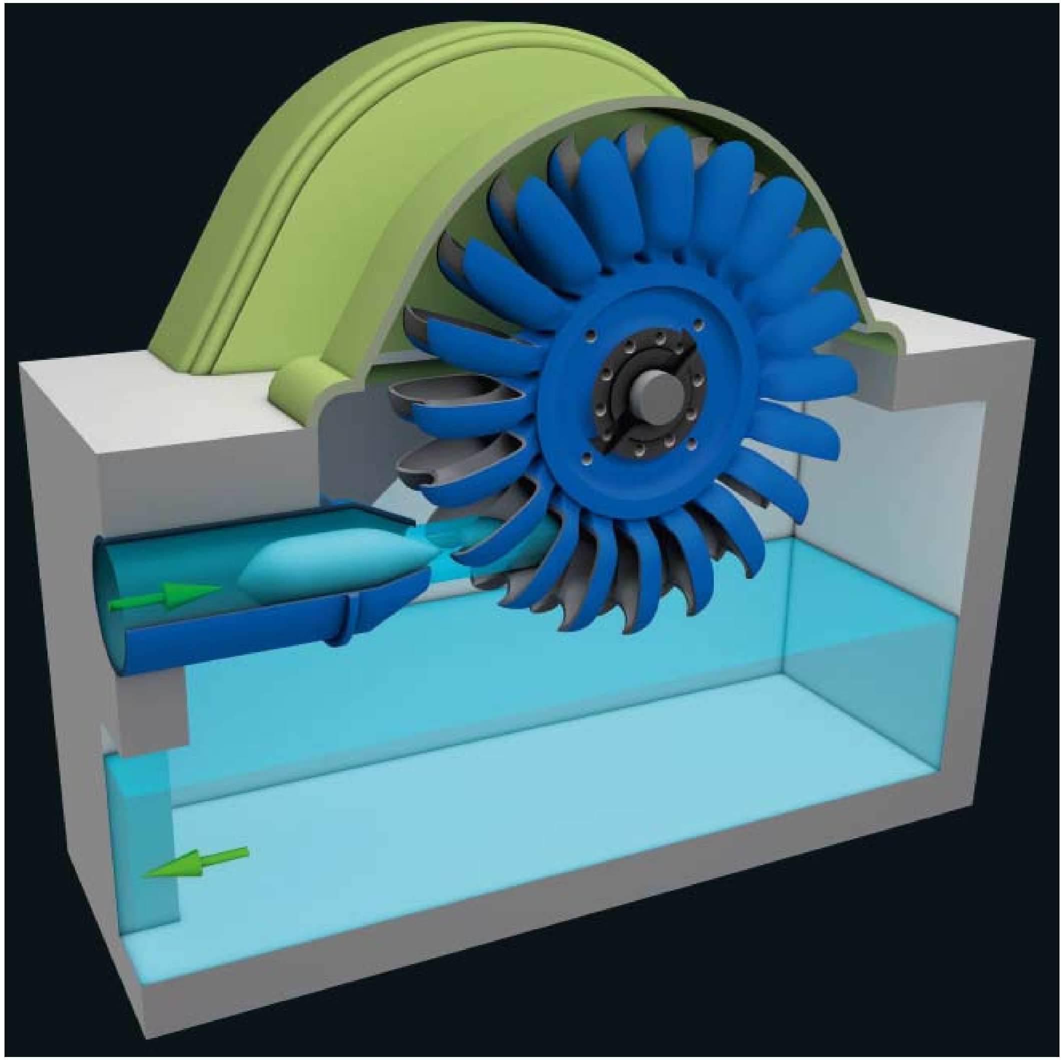
OUTLINE

1. Hydraulic turbine transfer function
   - special characteristics of hydraulic turbines
   - nonlinear hydraulic turbine model
   - governors for hydraulic turbines
   - tuning of speed governors
2. Steam Turbines and Governing Systems
   - steam turbine configurations
   - steam turbine models
   - steam turbine controls

Hydraulic turbine model



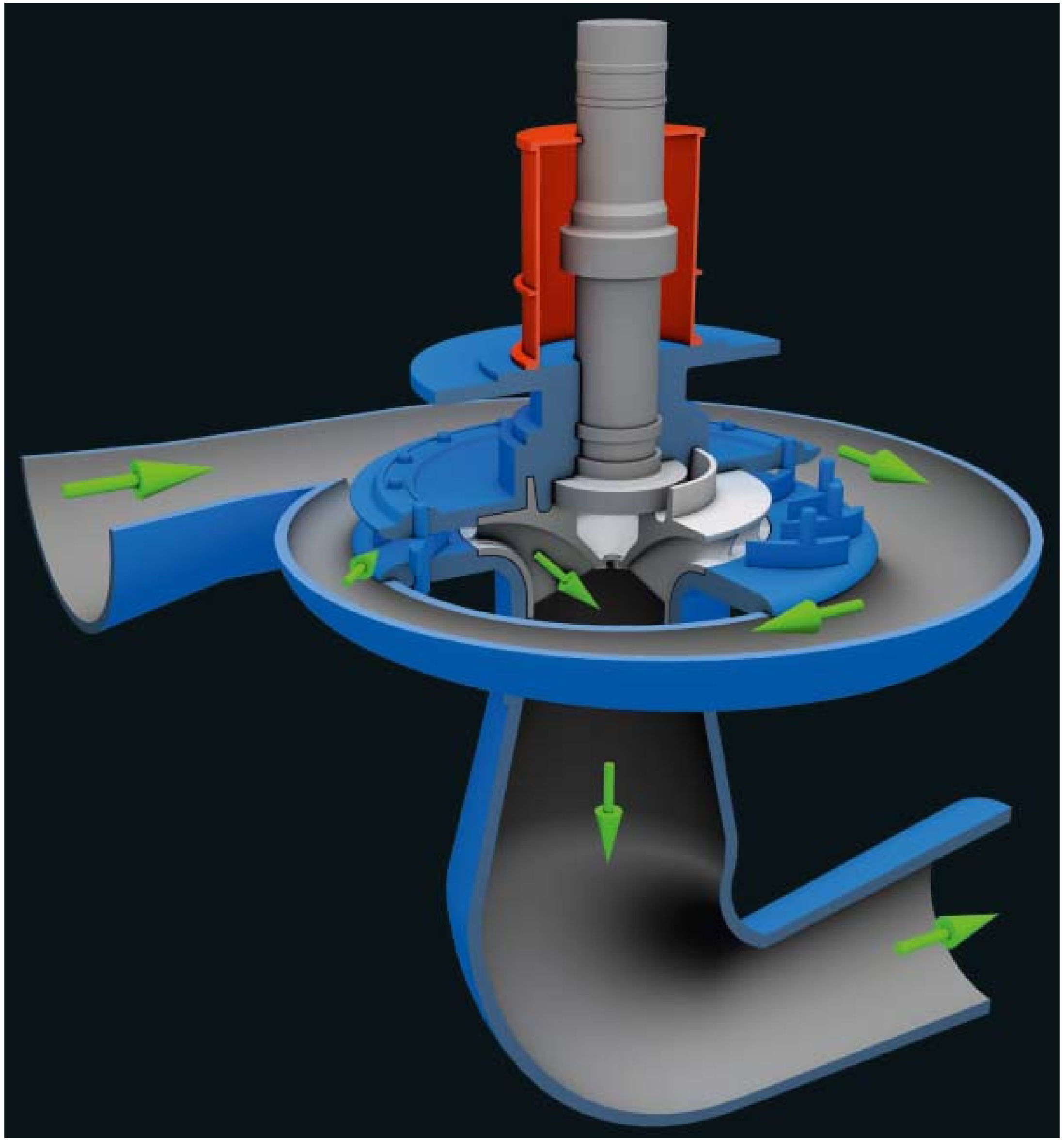
Pelton turbine



NEWTON'S SECOND LAW & IMPULSE TURBINES

- F=m.a
- The energy in high pressure water is converted directly into kinetic energy as it emerges into the lower pressure of the atmosphere (Bernoulli's principle) through a nozzle, forming a high velocity jet prior to hitting the blades.
- The change in momentum of the water jet hitting a Pelton wheel blade exerts an impulse force on the turbine.
- The series of impulse forces acting on the turbine blades creates the rotation.
- The blades move in the direction of the water jet, and the water velocity is reduced to zero.
- Pelton wheel turbines belong to the group "**impulse turbines**"
- Used for high water heads.

Francis turbine

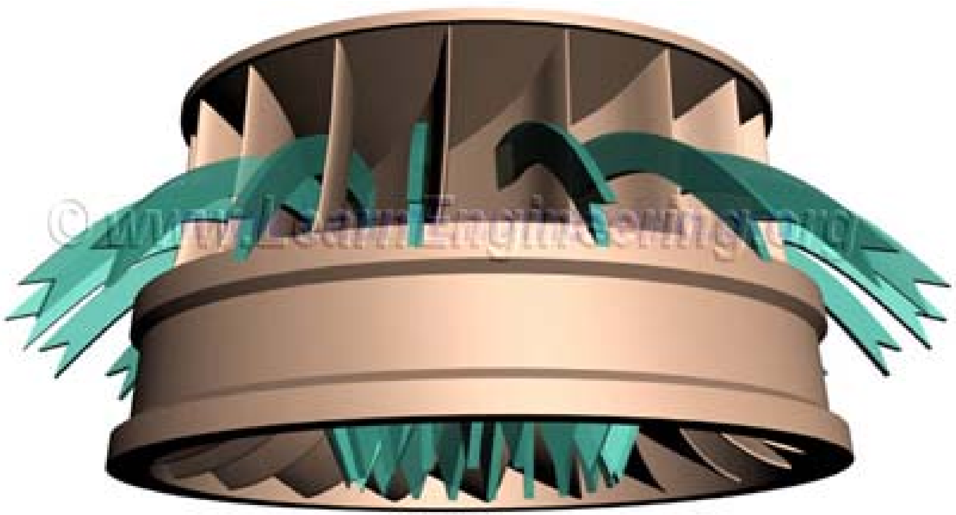


NEWTON'S THIRD LAW & REACTION TURBINES

- For every force that acts ON an object, there is an equal and opposite reaction force exerted BY the object.
- This is the principle behind the "reaction turbine" which includes the Francis turbine, the type of turbine most widely used in hydroelectric power stations.
- High pressure water moving through fixed vanes has some of its pressure converted into kinetic energy before it impacts on the blades, in this sense it is like the nozzle of a Pelton wheel (impulse turbine).
- Further pressure drop occurs through the moving blades causing the water to accelerate (Bernoulli's principle).
- The blades have an equal and opposite reaction force, adding to the torque on the turbine runner.

Francis turbine

- Most important part of Francis turbine is its runner.
- It is fitted with a collection of complex shaped blades

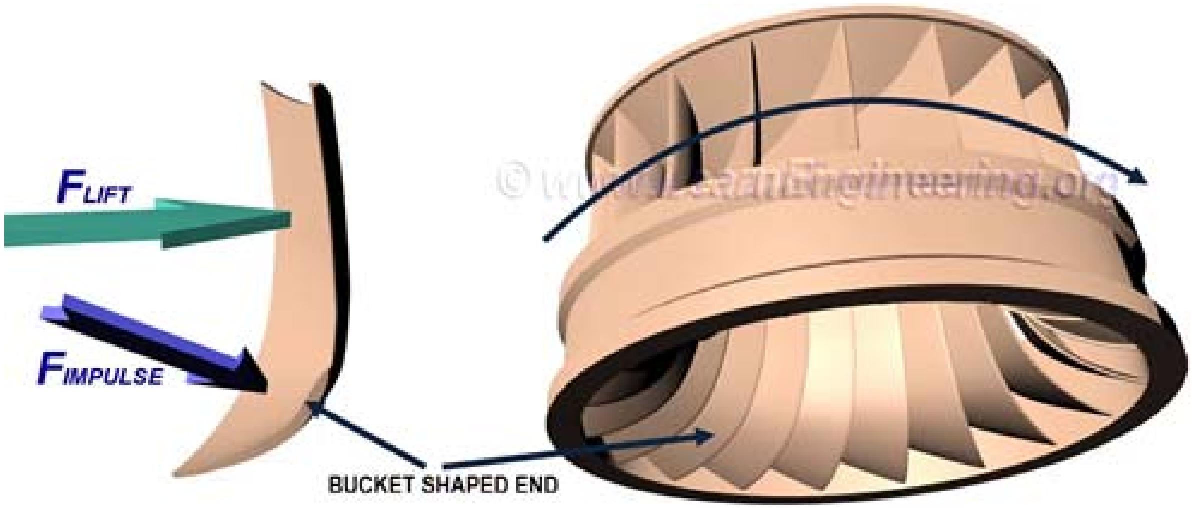


- In runner water enters radially, and leaves axially.
- During the course of flow, water glides over runner blades.

Francis turbine

- Blades of Francis turbine are specially shaped.
- The shape of blade cross-section is of thin airfoils.
- So when water flows over it, low pressure will be induced on one side, and high pressure on the other side.
- This will result in a lift force.

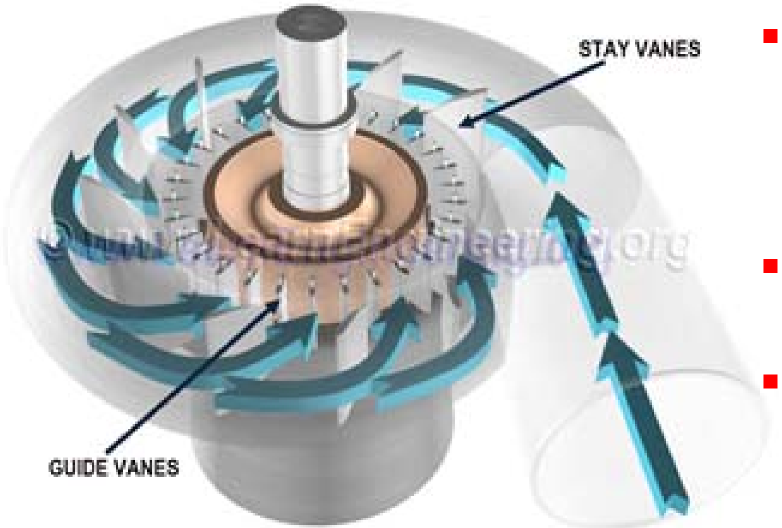
Francis turbine



- Note also that it has a bucket kind of shape towards the outlet.
- So water will hit and produce an impulse force before leaving the runner.
- Both impulse force and lift force will make the runner rotate.

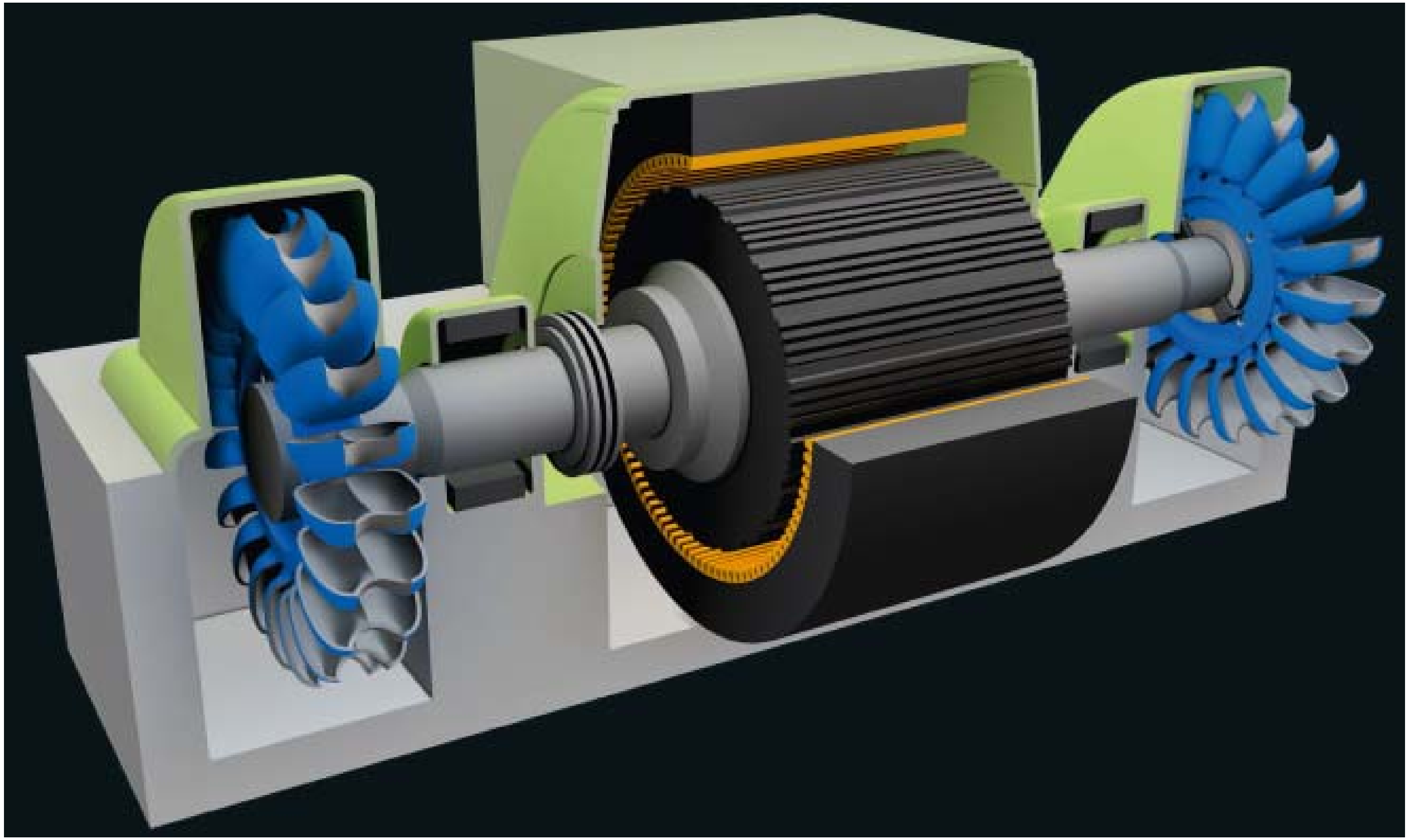
Use of Spiral Casing

- Runner is fitted, inside a spiral casing. Water enters via an inlet nozzle.
- Flow rate of water will get reduced along length of casing, since water is drawn into the runner.
- But decreasing area of spiral casing will make sure that, flow is entered to runner region almost at uniform velocity.

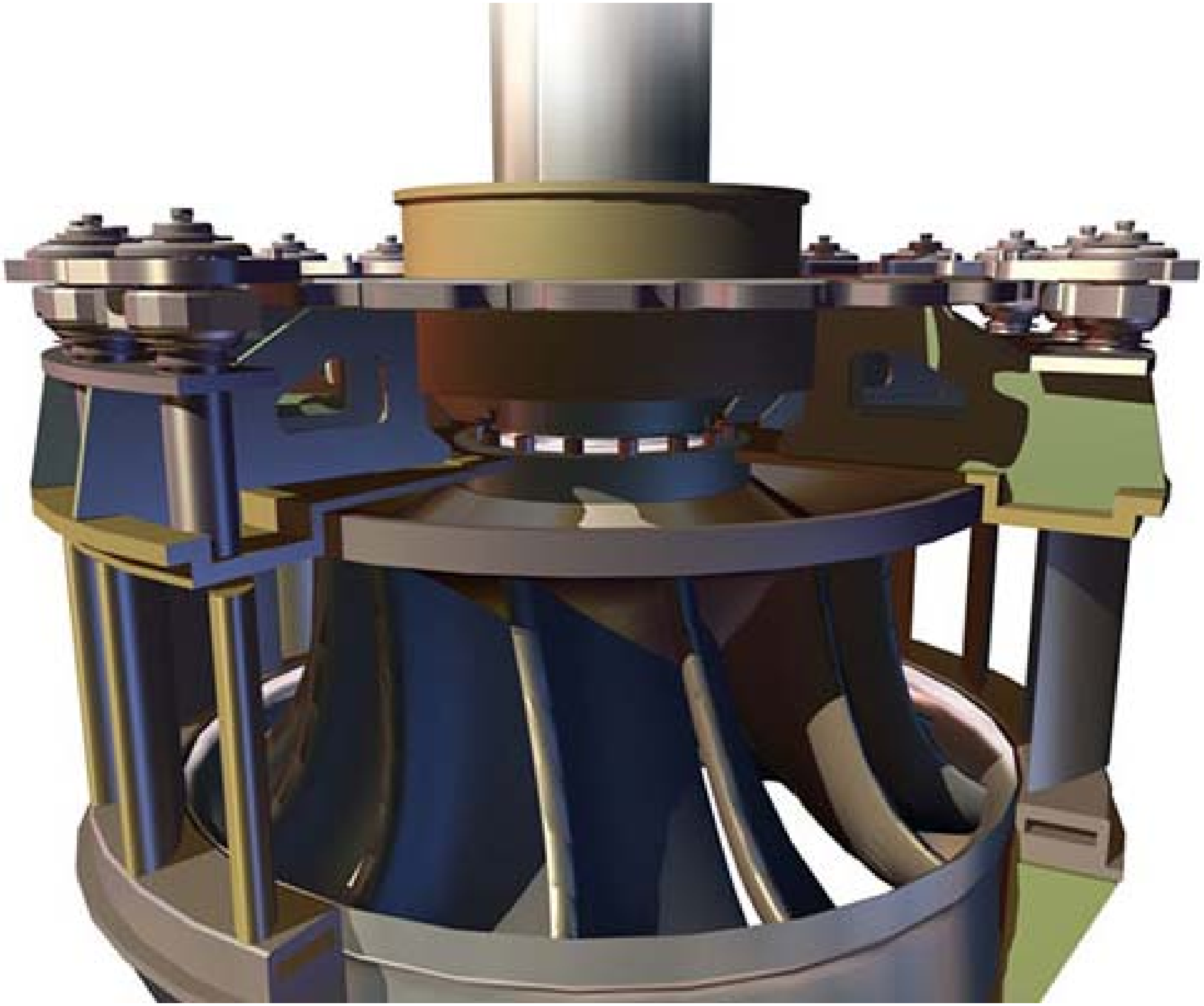


- Stay vanes and guide vanes are fitted at entrance of runner. Stay vanes are fixed; steer the flow towards the runner section thus reducing swirl of inlet flow.
- The guide vane mechanism is used to control water flow rate.
- Also control flow angle to inlet portion of runner blade; thus making sure that inlet flow angle is at optimum angle of attack for maximum power extraction from water

Generator



375-MW Alstom Francis turbine for GERD



Power plants in Ethiopia

Finchaa

- Head 590 m
- 4 x 33 MW **Pelton turbines**

Gilgel Gibe I

- One underground power house
- 3 x 61.3 MW **Francis turbines**

Gilgel Gibe II

- penstock 500 m long
- 4 x 107 MW **Pelton turbines**
- Each turbine is 3.5 m in diameter.

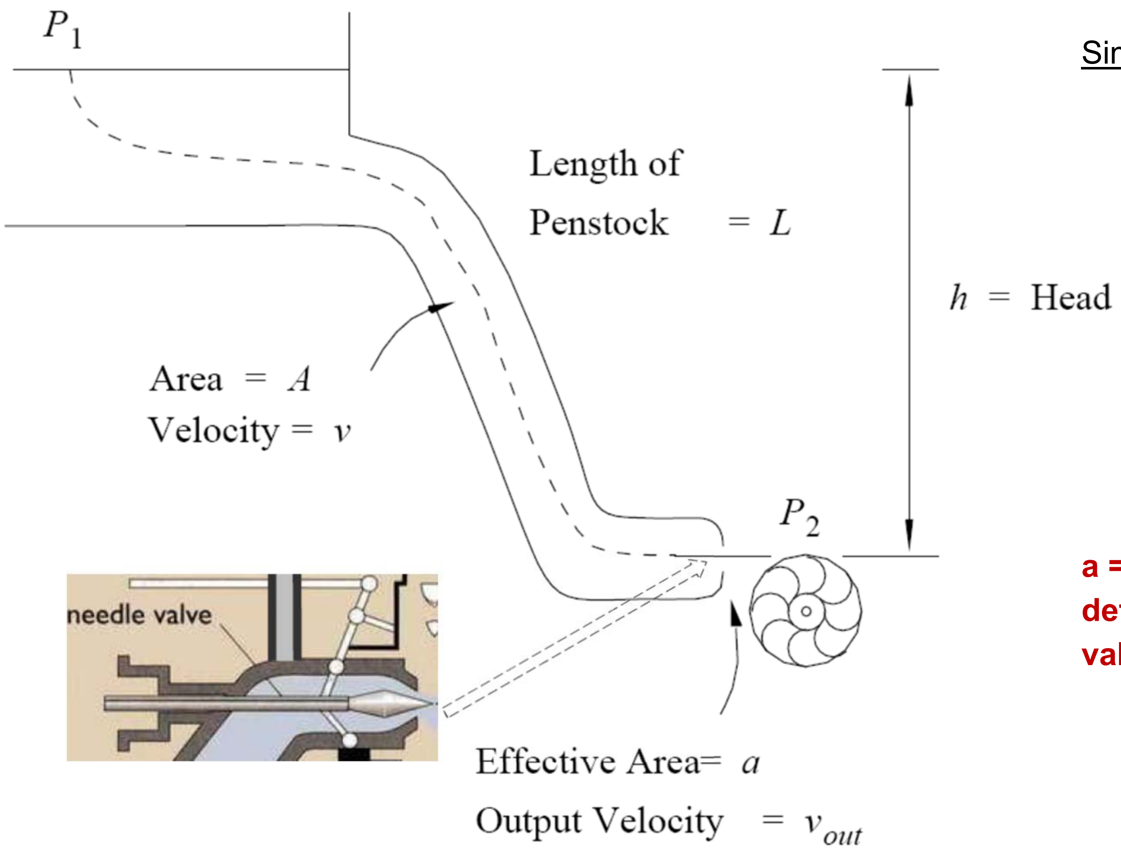
Gilgel Gibe III

- two penstocks; each branches into five separate tunnels for each individual turbine.
- 10 x 187 MW **Francis turbines** for a total installed capacity of 1,870 MW

GERD

- 2 power stations, 1 on the right bank and 1 on the left bank at the foot of the main dam
- Right bank: 10 x 375 MW **Francis turbines**
- Left bank: 6 x 375 MW **Francis turbines**

Hydraulic Turbines and Governors



Simplified version of Bernoulli's Equation:

$$L\frac{dv}{dt}+\frac{1}{2}\cdot v_{out}^2-gh=0$$

$$v_{out}=\frac{A}{a}\cdot v$$

$$\frac{dv}{dt}=\frac{1}{L}\cdot gh-\frac{1}{2L}\cdot\left(\frac{A}{a}\cdot v\right)^2$$

a = the effective opening of penstock is determined by the position of the control valve

The maximum available power at the turbine is:

$$P=\frac{1}{2}\cdot\rho\cdot a\cdot v_{out}^3=\frac{1}{2}\cdot\rho\cdot\frac{A^3\cdot v^3}{a^2}$$

$$\left(P=\frac{dW}{dt}=\frac{d}{dt}\left(\frac{1}{2}.m.v^2\right)=\frac{1}{2}.\frac{v.dt.a.\rho}{dt}.v^2=\frac{1}{2}.a.\rho.v^3\right)$$

System equation in a state – space form

Definitions:

$$x = v$$

$$u = \frac{a}{A}$$

$$y = P$$

(x = state variable, u = control signal, and y = output signal)

The system equations:

$$L\frac{dv}{dt} + \frac{1}{2} \cdot v_{out}^2 - gh = 0 \qquad P = \frac{1}{2} \cdot \rho \cdot a \cdot v_{out}^3 = \frac{1}{2} \cdot \rho \cdot \frac{A^3 \cdot v^3}{a^2} \qquad v_{out} = \frac{A}{a} \cdot v$$

Can be written as:

$$\dot{x} = \frac{g.h}{L} - x^2 . \frac{1}{2.L.u^2}$$

$$y = \rho . A . \frac{x^3}{2.u^2}$$

Model of a hydro turbine

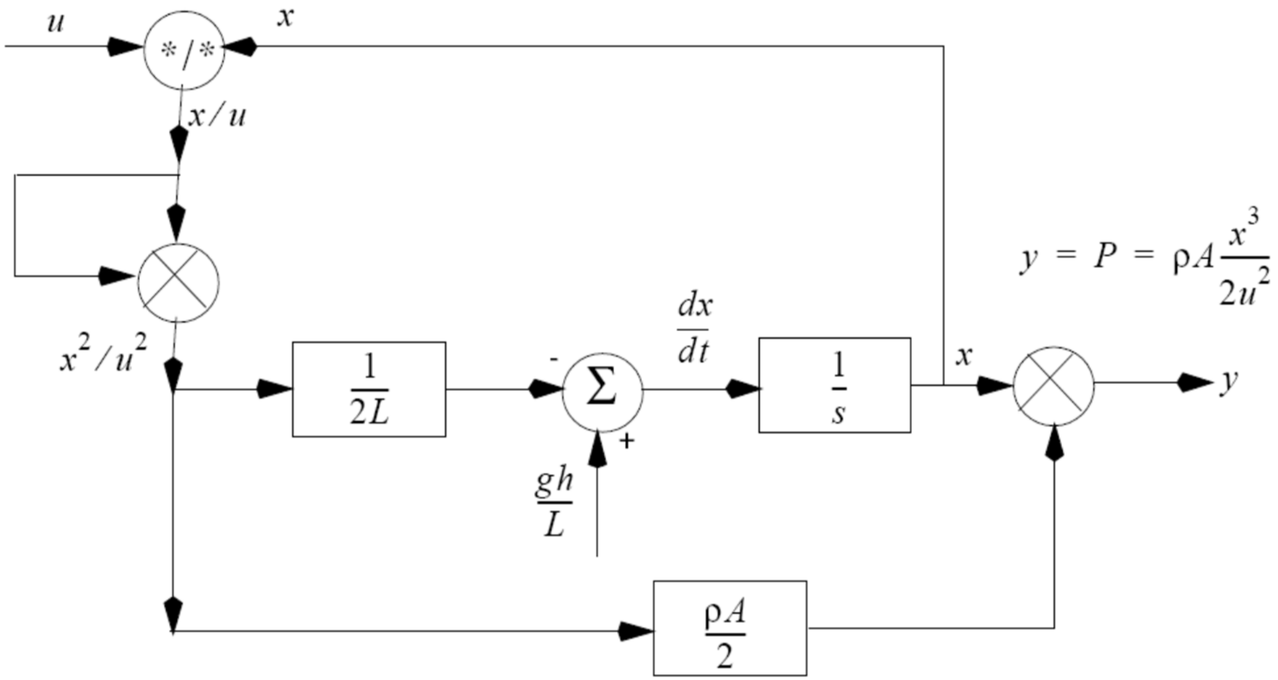
$$\dot{x} = \frac{g.h}{L} - x^2.\frac{1}{2.L.u^2}$$

$$y = \rho.A.\frac{x^3}{2.u^2}$$

$x = v$ — x = state variable

$u = \frac{a}{A}$ — u = control signal

$y = P$ — y = output signal



Steady state response

In steady state:

The state is determined by x_0, u_0, and y_0

From:

$$\dot{x} = \frac{g.h}{L} - x^2.\frac{1}{2.L.u^2} = 0 \rightarrow \quad x_0 = u_0.\sqrt{2.g.h}$$

$$y = \rho.A.\frac{x^3}{2.u^2} \quad \rightarrow \quad y_0 = \rho.A.\frac{x_0^3}{2.u_0^2}$$

Small deviations Δx, Δu, and Δy around the operating point satisfy:

$$\Delta x = x - x_0 \rightarrow \quad \Delta\dot{x} = \dot{x} = \frac{g.h}{L} - (\Delta x + x_0)^2.\frac{1}{2.L.(\Delta u + u_0)^2} \rightarrow$$

$$\Delta\dot{x} = \frac{g.h}{L} - (x_0^2 + 2\Delta x.x_0).\frac{1}{2.L.\left(u_0^2 + 2\Delta u.u_0\right)^2}$$

Steady state response

In steady state: $\dot{x} = \frac{g.h}{L} - x^2.\frac{1}{2.L.u^2}$ = 0

The state is determined by x_0, u_0, and y_0

$$x_0 = u_{0.}\sqrt{2.g.h}$$

From: $y = \rho.A.\frac{x^3}{2.u^2}$ $\rightarrow$

$$y_0 = \rho.A.\frac{x_0^3}{2.u_0^2}$$

$$\Delta\dot{x} = \frac{g.h}{L} - \frac{\left(x_0^2+2\Delta x.x_0\right)}{2.L.\left(u_0^2+2\Delta u.u_0\right)^2} = -\frac{\sqrt{g.h}}{u_0.L}.\Delta x + \frac{2.g.h}{u_0.L}.\Delta u$$

$$\Delta y = \Delta x.\frac{\partial y}{\partial x}\Big]_{x=x_0} + \Delta u.\frac{\partial y}{\partial u}\Big]_{u=u_0} = \frac{3.y_0}{u_0.\sqrt{2.g.h}}.\Delta x - \frac{2.y_0}{u_0}.\Delta u$$

Steady state response

$$\Delta\dot{x} = -\frac{\sqrt{g.h}}{u_0.L}.\Delta x + \frac{2.g.h}{u_0.L}.\Delta u$$

$$\Delta y = \frac{3.y_0}{u_0.\sqrt{2.g.h}}.\Delta x - \frac{2.y_0}{u_0}.\Delta u$$

$T = L / \sqrt{2gh}$

- the time it takes for the water to flow through the penstock when a = A

$$\Delta\dot{x} = -\frac{\sqrt{g.h}}{u_0.L}.\Delta x + \frac{2.g.h}{u_0.L}.\Delta u \rightarrow$$

$$\Delta x = \frac{L/T}{1+s.u_0.T}.\Delta u$$

Steady state response

$$\Delta x = \frac{L/T}{1+s.u_0.T}.\Delta u$$

Substitute in: $$\Delta y = \frac{3.y_0}{u_0.\sqrt{2.g.h}}.\Delta x - \frac{2.y_0}{u_0}.\Delta u$$

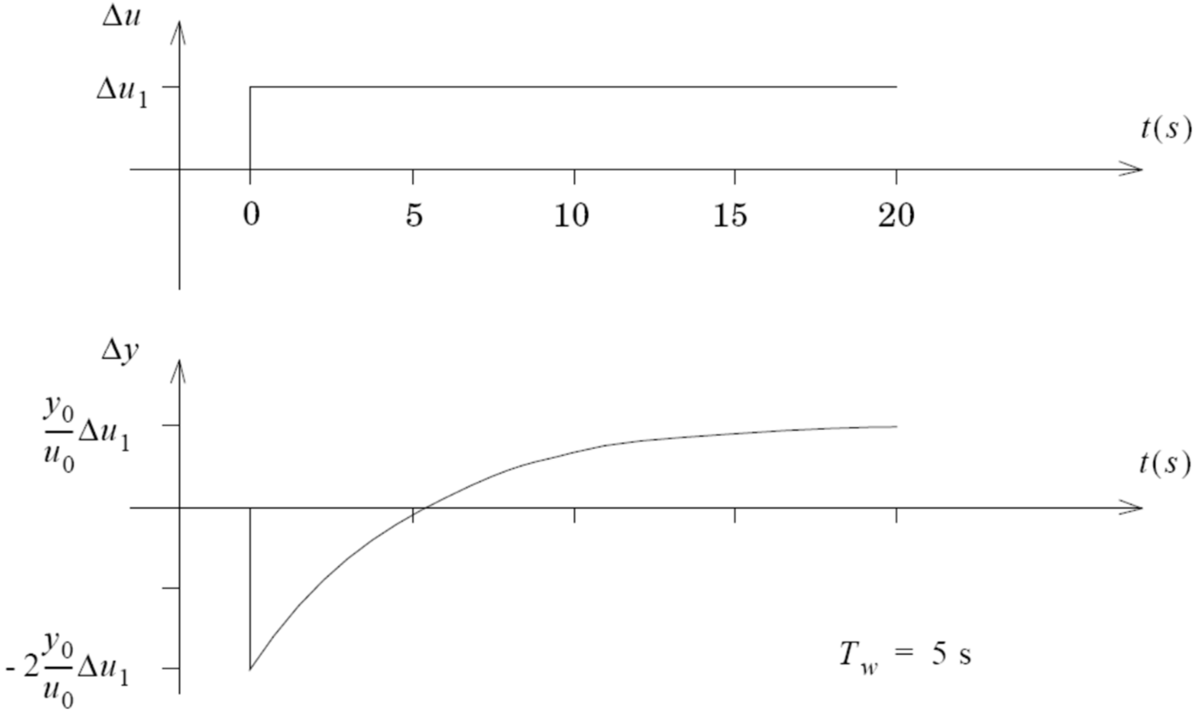
$$\Delta y = \frac{y_0}{u_0}\frac{1-2.u_0.T.s}{1+u_0.T.s}.\Delta u$$

$$T_w = u_0.T = \frac{a_0.T}{A} = \frac{a_0}{A}.\frac{L}{\sqrt{2.g.h}}$$

$$\Delta y = \frac{y_0}{u_0}\frac{1-2.s.T_w}{1+s.T_w}.\Delta u$$

- Tw is referred to as the **water starting time**. It represents the time required for a head h to accelerate the water in the penstock from standstill to the velocity v = $\sqrt{2.g.h}$. It should be noted that Tw varies with load. Typically, Tw at full load lies between 0.5 s and 4.0 s.

Step response

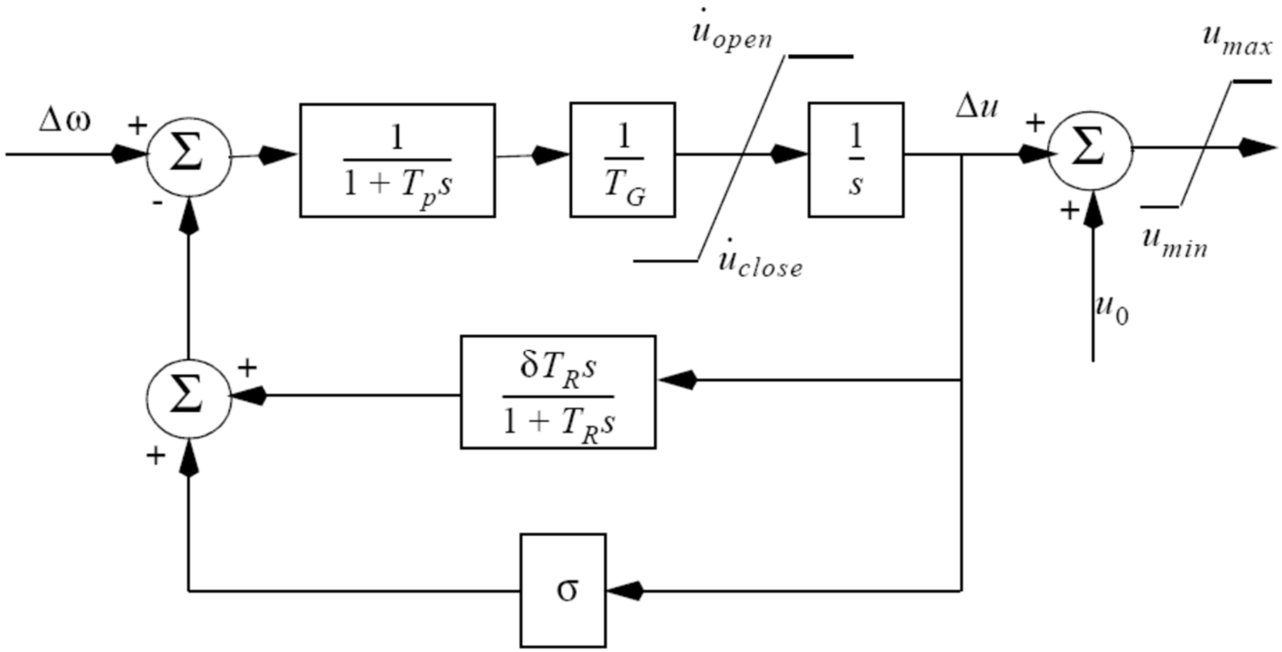


The variation of power produced, Δy, after a step change in the control valve

Step response

- The system has the peculiar property of giving a lower power just after the opening of the control valve before the desired increased power generation is reached.
- This is because, when the gate is suddenly opened, the flow does not change immediately due to water inertia; however, the pressure across the turbine is reduced causing the power to reduce. Once the water accelerates, the generated power increases as a consequence of the increased flow.
- This property of water turbines places certain demands on the design of the control system for the turbines.

Model of hydro turbine governor



u = gate opening

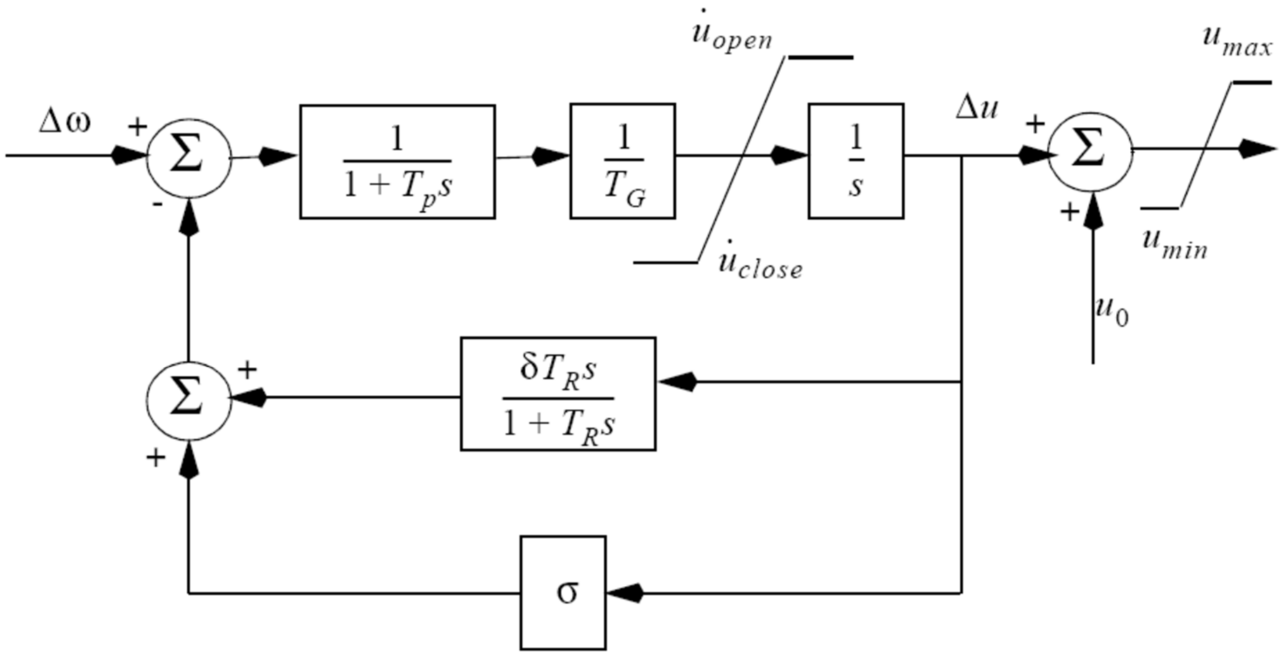
- The control servo is represented by a delay with a time constant T_p.
- The main servo (the guide vane) is represented by an integrator with the time constant T_G.
- Limits for opening and closing speed as well as for the largest and smallest opening of the control valve are also given

Model of hydro turbine governor

Requirement for a Transient Droop

- **Hydro turbines have a peculiar response due to water inertia: a change in gate position produces an initial turbine power change which is opposite to that sought.**
- **For stable control performance, a large transient (temporary) droop with a long resetting time is therefore required.**
- **This is accomplished by the provision of a rate feedback or transient gain reduction compensation as shown**
- The rate feedback retards or limits the gate movement until the water flow and power output have time to catch up
- The result is a governor which exhibits a high droop (low gain) for fast speed deviations, and the normal low droop (high gain) in the steady state

Model of hydro turbine governor

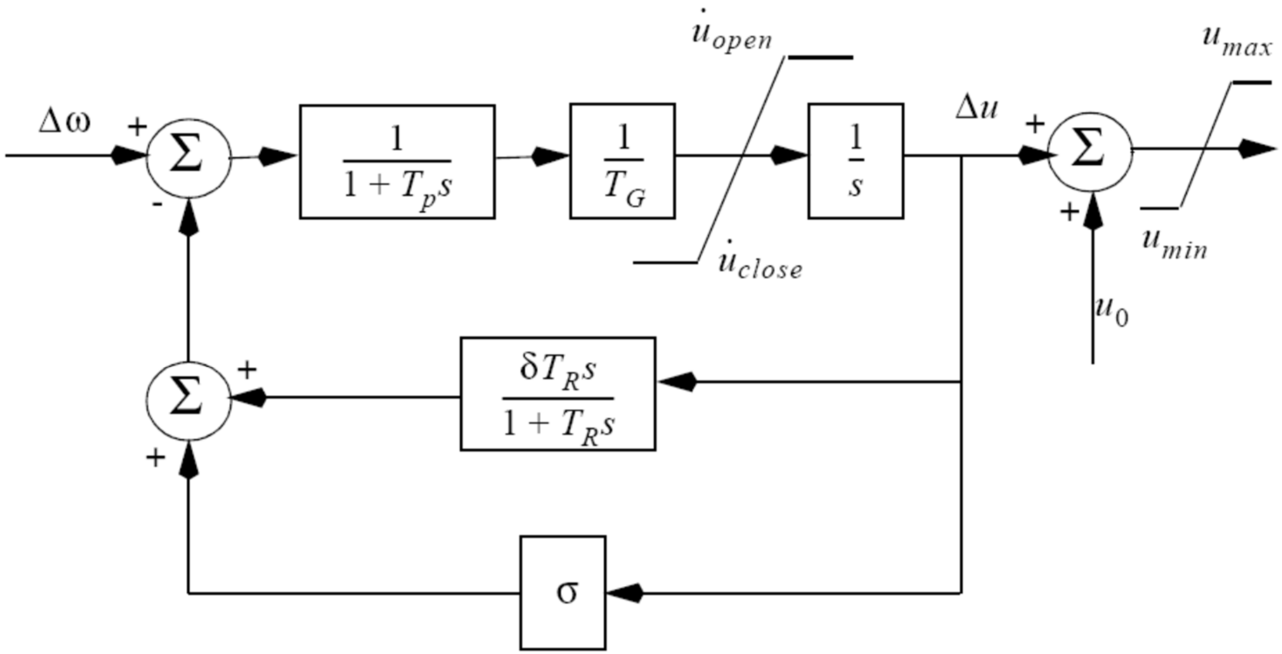


u = gate opening

- The controller has two feedback loops, a transient feedback loop and a static feedback loop.
- The transient feedback loop has the amplification for high frequencies. Thus, the total feedback after a frequency change is -(δ+σ).
- In steady state, the transient feedback is zero, and the ratio between the frequency deviation and the change in the control valve is given by:

$$\Delta u = \frac{1}{\sigma} \Delta \omega$$

Model of hydro turbine governor



u = gate opening

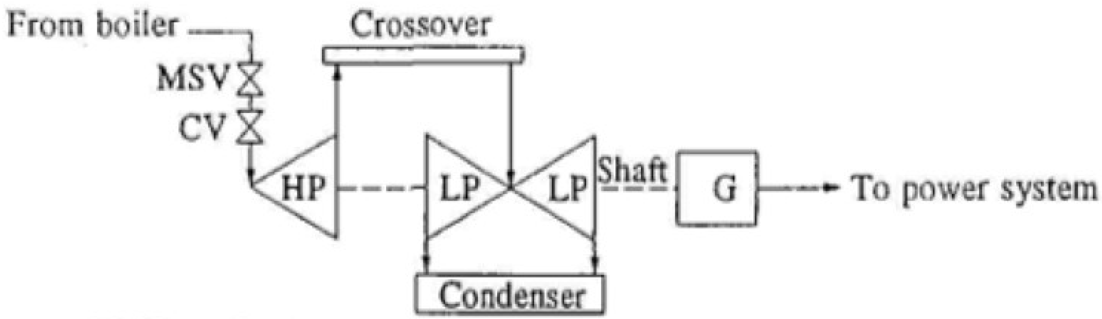
Typical values for the Parameters of hydro turbine:

Parameter	Typical Values
T_R	2.5 – 7.5 s
T_G	0.2 – 0.4 s
T_p	0.03 – 0.06 s
δ	0.2 – 1
σ	0.03 – 0.06

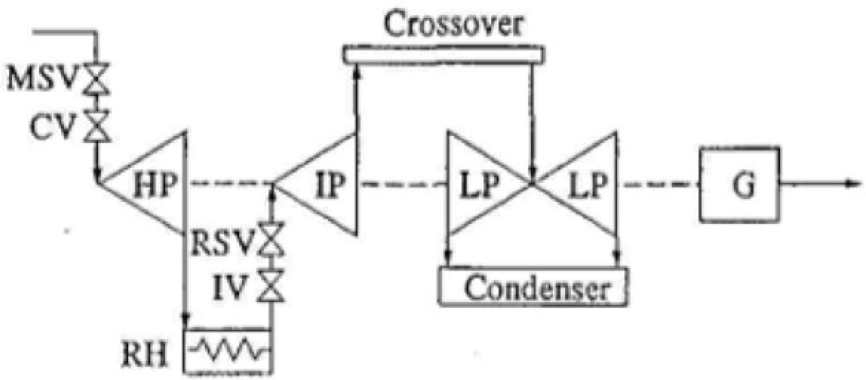
Steam turbine governing systems

- **A steam turbine converts stored energy of high pressure and high temperature steam into rotating energy**
  - the heat source may be a nuclear reactor or a fossil fired boiler
- **Steam turbines with a variety of configurations have been built depending on unit size and steam conditions**
  - normally consist of two or more turbine sections or cylinders coupled in series
- **A turbine with multiple sections may be**
  - *tandem-compound:* sections are all on one shaft with a single generator, or
  - *cross-compound:* sections are on two shafts, each with a generator; operated as a single unit
- **Fossil-fuelled units can be of tandem-compound or cross-compound design**
  - may be of reheat or non-reheat type

Single /non-reheat

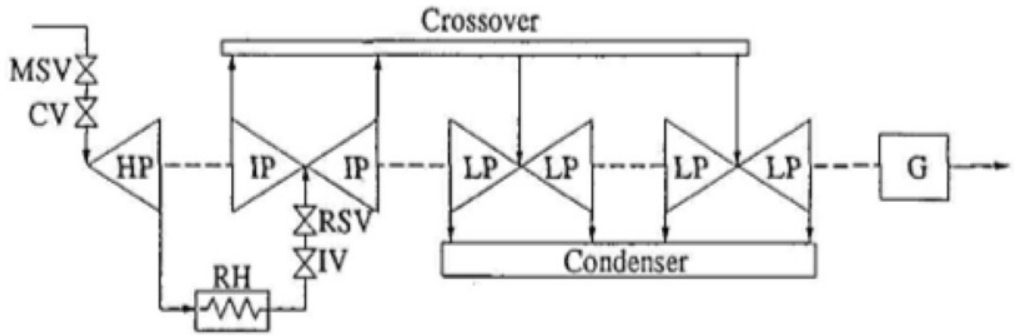


(a) Non-reheat

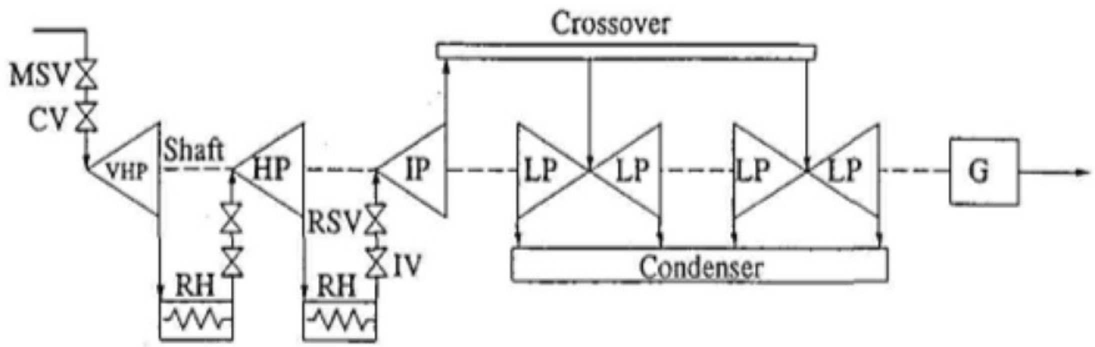


(b) Single reheat

Single / double reheat

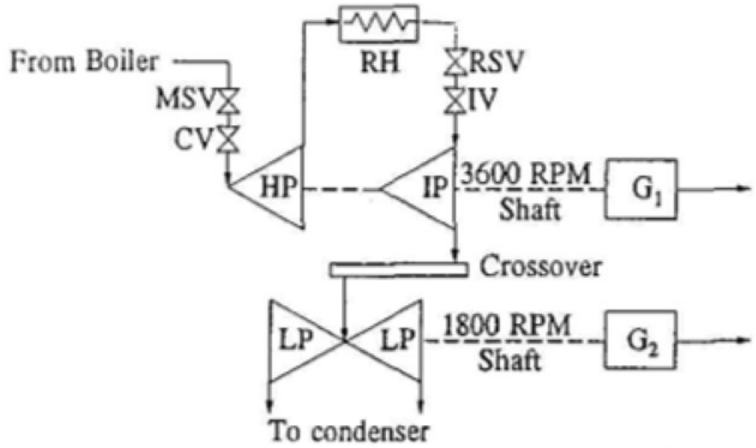


(c) Single reheat

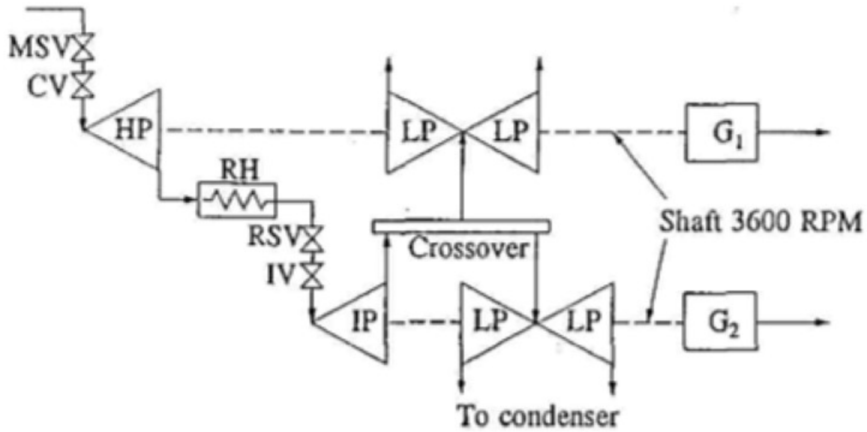


(d) Double reheat

Cross-compound

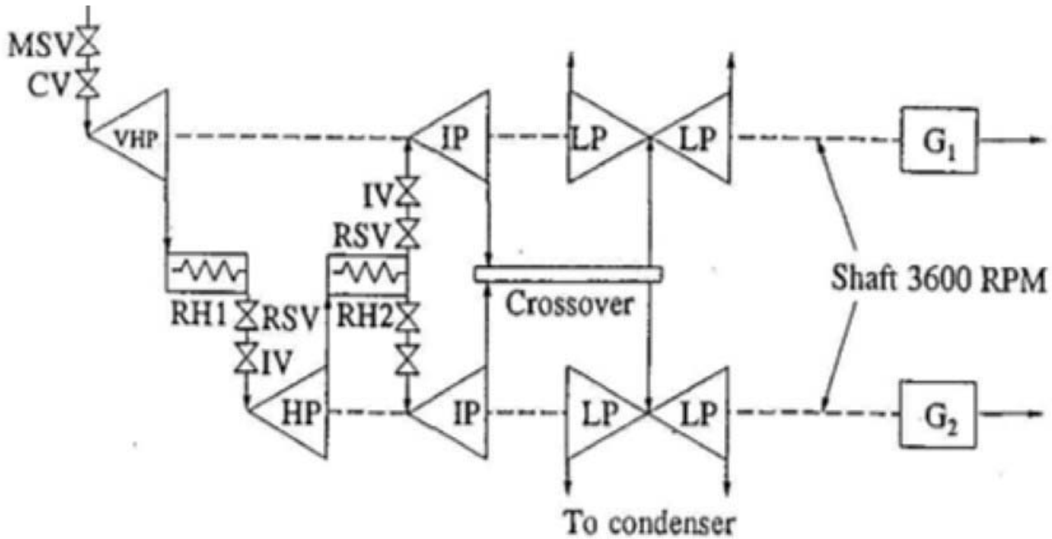


(a) Single reheat, 3600/1800 RPM shaft speeds



(b) Single reheat, 3600/3600 RPM shaft speeds

Steam turbine governing systems



(c) Double reheat, 3600/3600 RPM shaft speeds

Figure 9.17: Examples of cross-compound steam turbine configurations

Steam turbine governing systems

- **Nuclear units usually have tandem-compound turbines**

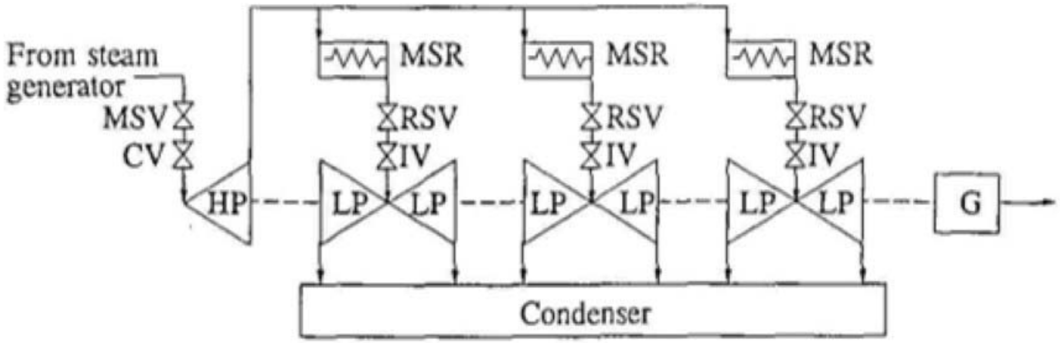


Figure 9.18: An example of nuclear unit turbine configuration

- moisture separator reheater (MSR) reduces moisture content, thereby reducing moisture losses and erosion rates

Steam turbine governing systems

- **Large steam turbines for fossil-fuelled or nuclear units are equipped with <u>four sets of valves</u>**
  - main inlet stop valves (MSV)
  - main inlet control (governor) valves (CV)
  - reheater stop valves (RSV)
  - reheater intercept valves (IV)
- **The stop valves (MSV and RSV) are primarily <u>emergency</u> trip valves.**
- **The CVs modulate steam flow during <u>normal</u> operation.**
- **The CVs as well as the IVs <u>limit overspeed</u>.**

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