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Wrocław University of Technology

Renewable Energy Systems

Piotr Stawski, Kazimierz Herlender
Władysław Bobrowicz

WATER POWER PLANTS

Wrocław 2011

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1. INTRODUCTION

Hydroelectricity, **hydroelectric power**, is a form of hydropower (the use of energy released by water falling, flowing downhill, moving tidally, or moving in some other way) to produce electricity. The mechanical energy of the moving water is converted into electrical energy by a water turbine driving an generator. Most hydroelectric power is currently generated from water flowing downhill. Recently some concepts and technology are developed for exploiting power from the tide. Hydroelectric power is usually generated at dams or other places where water descends from a height. Hydroelectricity is a renewable energy source, since the water that flows in rivers has come from precipitation such as rain or snow, and tides are driven by the rotation of the earth.

1.1. CLASSIFICATION OF HYDROPOWER

The hydroelectric power plants are classified in various ways like quantity of water available in the dam, total head of water in the reservoir and the nature of electrical load on them [1].

1.1.1. HYDROELECTRIC POWER PLANTS BASED ON THE QUANTITY OF WATER

There are three types of the hydroelectric power plants resulting from the quantity of water available in the dam. These are:

Run-off river hydroelectric plants without pond

In the run-off river type of hydroelectric power plants the running water of the river is used for the generation of electricity. There is no facility for storing the water. Whenever the water is available the hydroelectric power plant generates electricity and when there is no water no power is generated. During rainy seasons when there is maximum flow of water available in the rivers, they produce maximum power. These types of hydroelectric power plants produce the power continuously only as long as flowing water is available.

Run-off river hydroelectric plants with pond

These types of run-off river hydroelectric power plants usually produce the power during peak loads. During the day-time and off-peak periods they don’t produce power and water is stored in large pond. At night and during peak load the stored water is used to generate electricity. This is possible because it is easy to start and stop the hydroelectric power plants, hence they can be used as peak load power plants. The pond in the run-off river plants facilitates the production of electricity at any time since it does not depend on the continuous flow of water.

Reservoir hydroelectric power plants

The reservoir in the hydroelectric power plants has the capacity to store extremely large quantities of water that can be used throughout the whole season. The reservoir usually gets filled during the raining season and the water lasts for the whole year till the next summer season. In these hydroelectric power plants large reservoir is constructed behind the dam wall. Water from the reservoir is released to the power generation unit via penstock. The flow of water to penstock is controlled by the gates. The reservoir hydroelectric power plants can be used as peak load plant or base load plant. They produce electricity throughout the year. Most of the hydroelectric power plants are the reservoir type of plants.

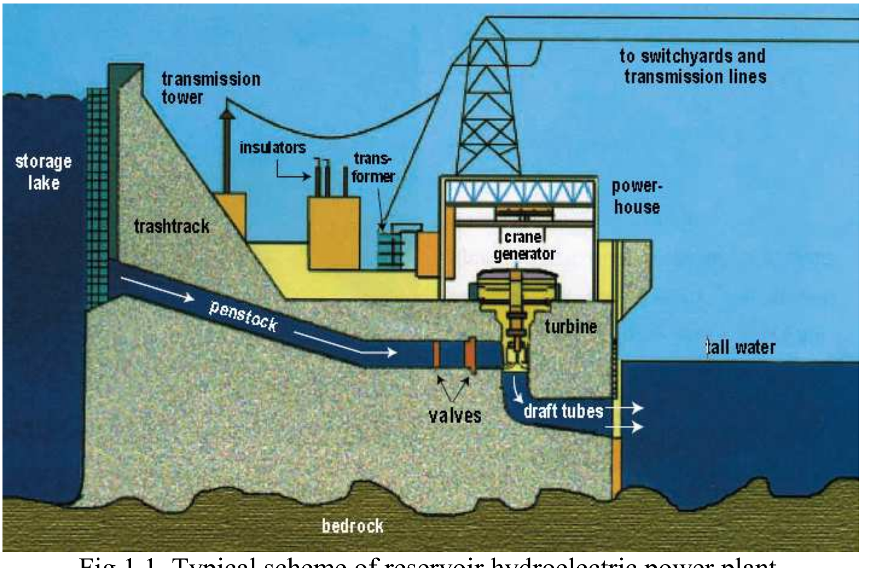

Fig.1.1. Typical scheme of reservoir hydroelectric power plant.

1.1.2. HYDROELECTRIC POWER PLANTS BASED ON THE WATER HEAD

Low head hydroelectric power plants

The low head hydroelectric power plants are the ones in which the available water head is less than 30 meters. The dam in this type of power plants is of very small head and may be even of few meters only. In certain cases weir is used and in other cases there is no dam at all and merely flowing water in the river is used for electricity generation. The low head types of hydroelectric power plants cannot store water and electricity is produced only when sufficient flow of water is available in the river.

Thus they produce electricity only during particular seasons when abundant flow of water is available. Since the head of water is very small in these hydroelectric power plants, they have lesser power production capacity.

Medium head hydroelectric power plants

The hydroelectric power plants in which the working head of water is more than 30 meters but less than 300 meters are called medium head hydroelectric power plants. These hydroelectric power plant are usually located in the mountainous regions where the rivers flows at high heights, thus obtaining the high head of the water in dam becomes possible. In medium head hydroelectric plants dams are constructed behind water reservoir.

High head hydroelectric power plants

In the high head hydroelectric power plants the head of water available for producing electricity is more than 300 meters and it can extend even up to 1000 meters. These are the most commonly constructed hydroelectric power plants. In the high head hydroelectric power plants huge dams are constructed across the rivers. There is large reservoir of water in the dams that can store water at very high heads. Water is mainly stored during the rainy seasons and it can be used throughout the year. Thus the high head hydroelectric power plants can generate electricity throughout the year. When constructing the high head types of hydroelectric power plants a number of factors especially those related to the environment and natural ecosystem of the land and water should be considered. The total height of the dam depends upon a number of factors like quantity of available water, power to be generated, surrounding areas, natural ecosystem, etc.

1.1.3. HYDROELECTRIC POWER PLANTS BASED ON THE NATURE OF LOAD

Base load hydroelectric power plants

The base load type of hydroelectric power plants produce power constantly irrespective of the total load in the national grid. They keep on producing power throughout the day and during all the times of the year. They will stop producing power only during breakdown of maintenance. Usually these types of hydroelectric power plants have standby power generation unit to ensure continuous production of power even in case of failure of one of the power generation unit. The generation of power from base load power plants is cheaper therefore so they can be run continuously.

The total generated power within the national grid includes the power generated by the base load type of hydroelectric power plant. The power output from the base load plants is constant and it does not usually vary in the normal working conditions. The total capacity of the national grid includes the power produced by the base power plant. The majority of the power in the national grid it supplied by the base power plants.

All the base plants within the national grid are allotted specific amount of base-load to handle constantly depending upon their power generation capacity. If there are fluctuations or peak demands like during the nighttime, these are handled by the other smaller plants that can be started and stopped easily. The thermal and nuclear power plants are the base plants, but there are many hydroelectric plants that are used as the base load power plants.

Peak load hydroelectric power plants

Most of the normal power demand is fulfilled by the base load hydroelectric power plants. During peak load periods small power plants are started that add to the total power generated in the grid by base load plants. The peak load plants are not run continuously because of high production cost. The hydroelectric power plants can be used as the peak load plants since they can be started and stopped easily.

1.2. SMALL HYDRO POWER STATION

1.2.1. DEFINITION OF SMALL HYDRO POWER STATION

In the European Union do not exists uniform classification criteria of small hydro power station (SHP). As a rule the installed power capacity is main criterion of classification. According to ESHA (European Small Hydro Association), European Commission and UNIPEDE (International Union of Producers and Distributors of Electricity), to SHP belong units up to 10 MW. This limit in Italy is at the level of 3 MW, France 8 MW, in UK 5 MW [2].

Often the subgroup of Mini-hydro is distinguished. To this group belong units between 100 kW and 1 MW. Sometimes to Mini-hydro group belong units of 100÷300 kW feeding local loads not connected to distribution network, located usually in rural areas.

1.2.2. EUROPEAN DRIVERS OF SHP DEVELOPMENT

European Commission (EC) supports the development of renewable resources, including hydropower and SHP, publishing suitable directives and recommendations. In 1997 EC published document “Energy for the Future: Renewable Sources of Energy”, (White Paper) [3]. Creation of suitable circumstances for the development of renewable generation was the main target of this document. In 2001 EU Parliament adopted 2001/77/EC Directive (RES-e) concerning „the promotion of electricity produced from renewable energy sources in the internal electricity market”. One of the indicatives in this document is the 22,1 % share of electricity produced from renewable energy sources in total Community electricity consumption by 2010. After

EU extension, for EU-25 countries, this indicative is estimated now at the level of 21%.

The main aims of RES development are:

- reduction of the community development negatives on the environment,
- increase of the security of the power supply,
- creation of the sustainable energy systems.

Building of the large hydropower station needs as the rule large interference in the environment with later consequences. These problems almost do not appear in the case of SHP, to 10 MW. SHP can be generally easier built in local ecosystems. Small hydro power stations should be well equipped in dedicated installation to meet the high requirements dealing with energy generation efficiency, simplicity, environment protection.

In Europe there are about 18000 of SHP in 26 countries, about 14000 in EU-15 and 2800 in in newly admitted EU-10 countries [1]. The total capacity reches level of 11.5 GW, including 10 GW in EU-10, 9820 MW in EU-15, 600 MW – EU-CC (candidate countries). The annual production is at the level of 44 TWh (40-EU-10, 2,3 – EU15, 1,4 – EU-CC). It is 1,7% of the total energy production in these countries and about 9,7% of energy production of all hydro power stations.

Average installed power of hydropower station is about 0.7 MW in EU-15 countries and 0.3 MW in EU-10. In total SHP installed capacity reaches 9820 MW. Production adequately is of 40TWh/a in EU-15 and 2,3 TWh/a in new EU-10. Average price in EU-15 vary from 5 to 15 Eucent/kWh (2003r) [4].

According to EUROSTAT[1] the production of electrical energy from hydro station was 343768 GWh in 2007 and 359185 GWh in 2008. (357147 GWh in 2004) – figure 1.2.

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[1] http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&plugin=1&language=en&pcode=ten00092

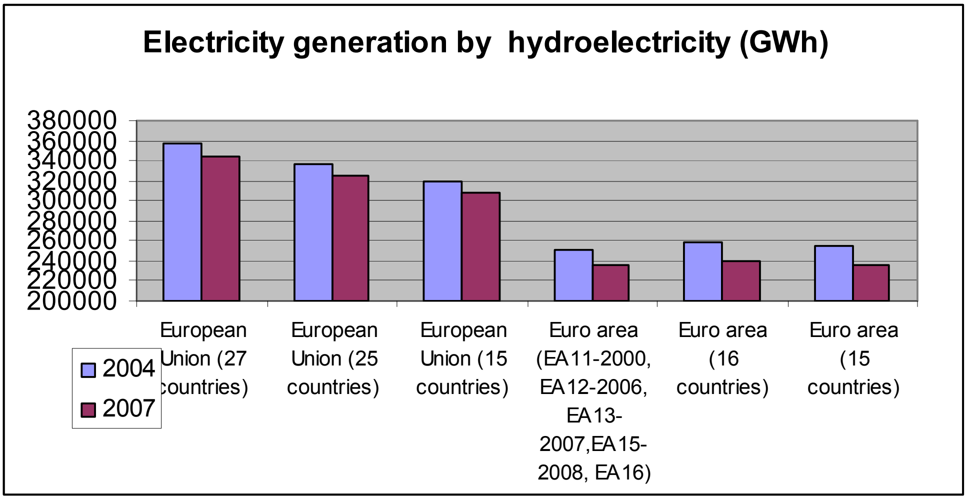

Fig. 1.2. Production of electrical energy from hydro station.

One of the main aims of the EU is to achieve the level of 14 GW of installed capacity and 55 TWh/a of electrical energy production before year 2010 (White Paper).

Potential of SHP is concentrated mainly in Italy - 21% of EU-25 potential, France – 17% and Spain - 16%. New SHP resources are mainly in Norway and Swiss [6,7].

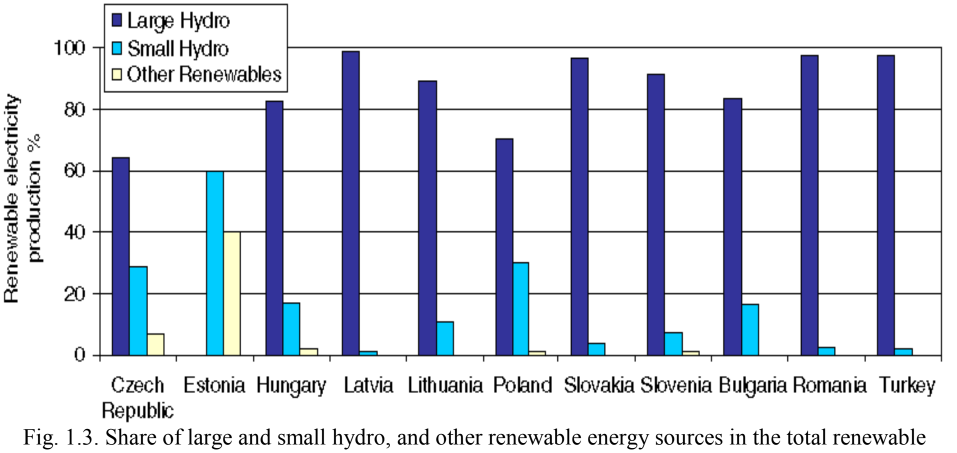

Fig. 1.3. Share of large and small hydro, and other renewable energy sources in the total renewable electricity generation.

The special attention one applies to the modernization of existing installations. It is estimated that more than 70% of installations are older then 40 years.

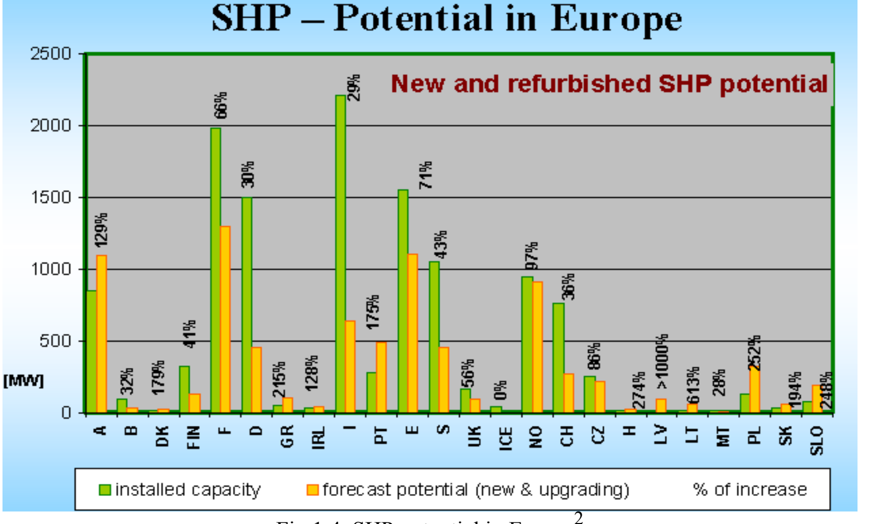

Fig 1.4. SHP potential in Europe[2]

The ranking hydropower capacity by the end of 2008 – the total small hydraulic capacity (<10 MW) in MW is shown in table on figure 1.5.

Ranking:	Country:	Amount:	Bar Graph:
1	Italy	2595	
2	France	2061	
3	Spain	1882	
4	Germany	1756	
5	Austria	1201	
6	Sweden	962	
7	Portugal	371	
8	Romania	325	
9	Finland	316	
10	Czech Rep.	277	
11	Poland	250	
12	Bulgaira	225	
13	United Kingdom	167	
14	Slovenia	155	

[2] www.esha.be

15	Greece	116	
16	Slovakia	63	
17	Belgium	57	
	Total EU	**12932**	

Fig 1.5. SHP potential in Europe[3]

The European Small Hydropower Association (ESHA) is the representative of sector business.

1.2.3. WHY SHP

There are many reasons for the big interest in mini hydropower. The weight of arguments is relative to type and scale of the benefits. One of the more important for the investor – producer are stable incomes and relative high rate of return. These conditions are fulfilled by adequate support mechanism, e.g. green certificates. From the environmental point of view the reduction of CO2 as well as participation in preservation of catchment area are very important. Very often not working dams are resituated and some micro retention objects are renewed. In the result some wetness conditions on nearest water basins areas are improved. SHP growth can be valuable part of so called region sustainable development policy widely supported by EU. The main aim of this policy is secure supply of energy upon the preservation the energy quality parameters with public accepted prices and environment protection. Small hydropower production may also have a positive impact on the development of local communities. The possibility of supplementary income from local electricity production with possibility to start small industry could be the goal for small hydro development.

Realisation of SHP cannot be charged overall cost of the new dam and hydrologic equipment. Such financial outlays could strike out the economical efficiency of entire project. Extra benefits from the SHP growing can be achieved as a result of synergy efforts on local, national and European levels. The adequate financial streams should be the effect of this.

To assure the rent-ability, every potential investor should correctly qualify basic parameters of the investment, first of all the range of the investment, potential problems, potential sources of the habilitation, the rate of return from the capital, basic categories of costs, taking into account operating costs. Therefore initially one should prepare the simplified feasibility study of the project containing the balance of costs and expected advantages. A base of such preliminary analysis is first of all the correct estimation of hydro-technical parameters at the seating of the power station. Hence the data measurement of suitable hydrological services should be used. In the case of the

[3] http://www.energy.eu/#renewable

lack of measurements- the estimation (the interpolation) of flows is possible on the basis of measurement in other points of the catchment area. The investor can perform his own measurements, what can however be too expensive. One of the elements of estimation of the hydro-power potential is determination of the Flow Duration Curve. Also important is the perusal with condition of the connecting to the grid, estimation of the realization time-limits and exploitation conditions of the investment. The effect of the preliminary analysis should be the obtaining of the answer to questions: Does the investment fulfil my expectations? Is it good investment?

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[6] ***Small hydropower – A proven technology for a cleaned sustainable energy future*** , http://www.erec-renewables.org/

[7] ESHA, www.esha.be/BlueAge.pdf

[8] ***Strategic Study for Development of SHP in EU_2008***, www.erec.org

2. WATER AND ENERGY POTENTIAL

Potential and kinetic energy of mass of water flowing down from higher point to beneath seated places can be converted into electrical energy. Hydrological potential of the water is determined by two parameters head **H** and flow **Q**. Quantity of head is crucial, especially for SHP. Rapidity of water flow have no such importance.

Head **H** (brutto) is the maximal difference of levels of water falling. Current head of turbine is diminished due to losses caused by friction onto construction elements and the internal friction (the stickiness of liquid). Depending on head quantity, heads are classified as the:

- „low head", for H <10 m,
- „medium head", for H of the range 10 ÷ 50 m,
- „high head", for H >50 m.

Flow (Q) in the given cross-section of the water stream determines the volume of flowing water through this section in chosen time in m3/s.

2.1. ELECTRICAL POWER AND ENERGY

Energy is equal to work carried out in a fixed interval of time. Turbine changes energy of water pressure to the mechanical energy of turbine shaft which drives generator producing electrical energy. Energy unit is Joule [J]. Electrical energy unit is kilowatt-hour [kWh], 1 kWh = 3600 J. Power determines the quantity of the energy in unit interval of time. Electrical power of generator can be defined by expression

$$P = \eta \rho g Q H \qquad (2.1)$$

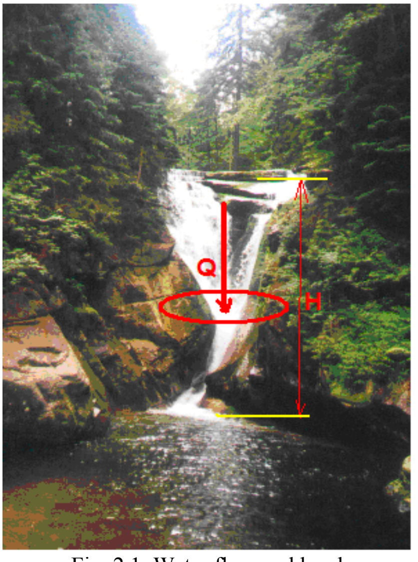

Fig. 2.1. Water flow and head

where:
P – electrical power in [W],
η - hydraulic efficiency of turbine,
ρ - water density, ρ=1000 kg/m^3,
g – acceleration of gravity of the earth, g=9.81m/s^2,
Q – flow – volume of water flowing across turbine in unit time, [m^3/s],
H – head – effective pressure of water flowing in turbine [m].

Turbine technology is mature technology and is characterised by relatively high efficiency. Efficiency of large hydropower units reaches level 80 ÷ 90 %. Efficiency of smaller hydro units (<100kW) is less about 10÷20 %. For the estimation of power of small hydro units, e.g. microturbines, turbine efficiency is usually equal η = 70÷75%. Electrical power can be roughly estimated by expression:

$$P \approx 7 \div 8 \cdot QH \tag{2.2}$$

P - [kW], Q - [m^3/s], H – [m]. For roughly calculation of energy one can accept 4500 of working hours with the power output defined by (2.2):

$$E \approx 4500 \cdot P \tag{2.3}$$

where E – energy [kWh].

2.2. FLOW DURATION CURVE

The flow duration curves (FDC) can be used for more precisely estimation of energy hydrologic potential at the seat place of power station. FDC are plotted from long term annually registered flows (hydrograph). FDC curves replies the question: „What amount of energy can be generate annually?”. FDC curves should be determined for the year of medium water conditions as well as for the wet and dry years. These curves are graphical representation of flows data: flow quantity, amount of days at fixed flow and the percentile portion of such days yearly, ordered by flow quantity. Simplified example of such flow data are presented in Table 2.1.

Table 2.1. Example of flow data

Flow Q [m3/s] >	*Number of days*	*Total*	*% in year*
8	20	20	5,48
7	25	45	12,33
6	50	95	26,03
5	60	155	42,47
4	90	245	67,12
3	120	365	100,00
Total	365	365	

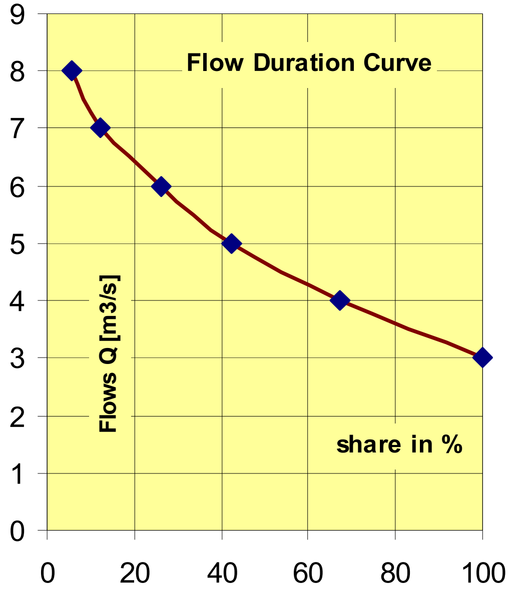

Fig. 2.2. Flow Duration Curve (probability of flows ...)

Energy is a measure of power duration at fixed level in particular time interval. Hence FDC curve determines probability of the event *„In how many days given level of flow will be achieved*".

Field beneath the FDC curve is the measure of the quantity of the generated energy. This field should be as large as possible.

Good flow systems are characterised by rather flat curve high above X axis. It corresponds to stable and uniform flows in all days of the year.

2.3. ANALYSIS OF WATER RESOURCES AND HYDRAULIC ENGINEERING

The basic knowledge of the liquids mechanics and engineering of hydraulic devices is useful for the estimation of the water potential. In hydropower, hydraulic engineering is applied to:

- optimise of waterways performers to reduce energy losses,
- design spillways and structure for flood prevention,
- design adequate energy dissipation works downstream of spillways,
- erosion control and manage silt transportation.

The energy of the water jet flowing through the pipe is specified by the Bernoulli's rule for so-called laminar flow. Without details: energy of the water defined by Bernoulli's rule summarize potential energy described by head, energy of a pressure, kinetic energy. Under some assumptions the Bernoulli's rule can be written if form:

$$H_1 = h_1 + \frac{P_1}{\gamma} + \frac{V_1^{\ 2}}{2g} \qquad (2.4)$$

Where:

H_1 –the total energy head [m]
h_1 – the elevation above some specified datum plane [m]
P_1 – the pressure [Pa]
γ - the specified weight of water [kg/m^3],
V_1 – the water velocity [m/s]
g - the gravitational acceleration [m/s3].

For an open channel the term p/γ replaced may be replaced by d - the water depth.

According to this equation, the total energy head at point 1 is then the algebraic sum of the potential energy h1, the pressure energy P1/γ, and the kinetic energy V12/2g, commonly known as the "Velocity head". In the slow, laminar (layers) flow, water leaks through the pipe like in a series of thin walled concentric pipes. The outer virtual pipe adheres to the wall of the real pipe, while each of the inner ones moves at a slightly higher speed, which reaches a maximum value near the centre of the pipe. The velocity distribution has the form of a parabola and the average velocity (figure 2.3) is 50% of the maximum centre line velocity.

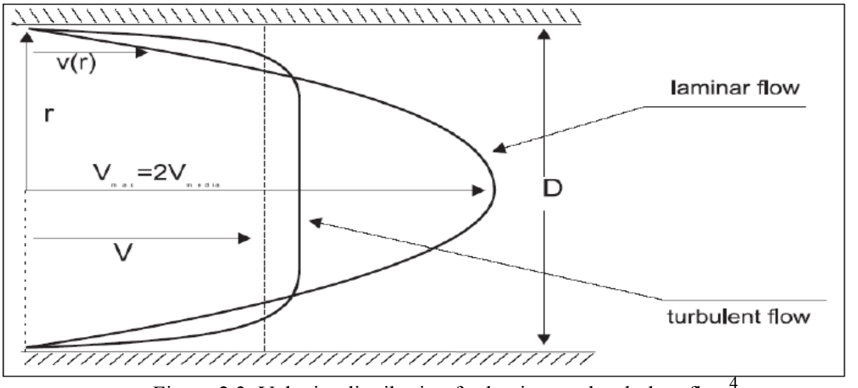

Figure 2.3. Velocity distribution for laminar and turbulent flow[4].

If the flow rate is gradually increased, a point is reached when the laminar flow suddenly breaks up and mixes with the surrounding water. The particles close to the wall mix up with the ones in the midstream, moving at a higher speed, and slow them. At that moment the flow becomes turbulent, and the velocity distribution curve is much flatter. Experiments carried out by Osborne Reynolds, near the end of the 19th century, found that the transition from laminar flow to turbulent flow depends, not only on the velocity, but also on the pipe diameter and on the viscosity of the fluid, and is a ratio of the inertia force to the viscous force. This ratio is known as the Reynolds number and can be expressed, in the case of a circular pipe, by the equation:

$$R_e = D \cdot V / \upsilon \quad (2.5)$$

where:

D (m) is the pipe diameter

V is the average water velocity (m/s),

υ is the kinematic viscosity of the fluid (m^2/s).

From experimentation it has been found that for flows in circular pipes the critical Reynolds number is about 2000.

Example

Pipe of 50mm diameter, temperature of water in the pipe 20°C.

Calculate the largest flow-rate for which the flow would be laminar.

The kinematic viscosity of water at 20oC is u = 1 x 10-6 m2/s.

Assuming a conservative value for Re = 2000

V = 2000 / (106x0.05) = 0.04 m/s

[4] ESHA- Guide how to developed small hydropower

$Q = AV = \pi/4 \text{x } 0.05^2 \text{ x } 0.04 = 7.85 \text{ x } 10^{-4} \text{ m}^3/\text{s} = 0.785 \text{ l/s}.$

Water energy losses as it flows through a pipe, fundamentally due to:

1. friction against the pipe wall
2. viscosities dissipation as a consequence of the internal friction of flow.

The energy losses increase with the Reynolds number and with the wall pipe roughness. For water flowing between two sections, a certain amount of the head of energy h_f is lost.

$$\frac{V_1^2}{2g} + \frac{P_1}{\gamma} + h_1 = \frac{V_2^2}{2g} + \frac{P_2}{\gamma} + (h_2 + h_f) \qquad (2.6)$$

In practice during the flow some losses of the energy occur due to the friction for walls of the channel and specific internal friction determined by the stickiness of liquid.

Loss of fluid energy flowing by the pipe can be estimated by the equation (Darcy and Weisbach):

$$h_f = f_f\left(\frac{L}{D}\right)\cdot\frac{V^2}{2g} \qquad (2.7)$$

where

f_f = friction factor, a dimensionless number,
L = the length of the pipe in m
D = the pipe diameter in m
V = the average velocity in m/s, g- the gravitational acceleration (9.81 m/s2).

In a laminar flow f_f can be calculated from the equation:

$$f_f = \frac{64\upsilon}{V \cdot D} = \frac{64}{R_e} \qquad (2.8)$$

For the laminar flows and tubular draught of inlet water, these losses are in proportion to the speed and inversely proportional to square of the profile diameter of the pipe. Material quality of the channel walls is of big importance (friction coefficient).

Substituting f_f from equation (2.8) into (2.7), gives:

$$h_f = \frac{64\upsilon}{V \cdot D} \cdot \frac{L}{D} \cdot \frac{V^2}{2g} = \frac{32\upsilon LV}{gD^2} \tag{2.9}$$

In laminar flow, head loss is proportional to V and inversely proportional to D^2. When the flow is practically turbulent (Re>2000), the friction factor becomes less dependent on the Reynolds number and more dependent on the relative roughness height e/D, where "e" represents the average roughness height of irregularities on the pipe wall and D the pipe diameter. Some values, according to [SHP Guide][5] of the roughness height are provided in Table 2.2.

Table 2.2. Roughness height for various commercial pipes

Pipe material	e (mm)
Polyethylene	0.003
Fiberglass with epoxy	0.003
Seamless commercial steel (new)	0.025
Seamless commercial steel (light rust)	0.250
Seamless commercial steel (galvanised)	0.150
Welded steel	0.600
Cast iron (enamel coated)	0.120
Asbestos cement	0.025
Wood stave	0.600
Concrete (steel forms, with smooth joints)	0.180

In a hydraulically smooth pipe flow, the friction factor f is not affected by the surface roughness of the pipe, and for this case Von Karman, developed the following equation for the friction factor f_f:

$$\frac{1}{\sqrt{f_f}} = 2\log_{10}\left(\frac{R_e\sqrt{f_f}}{2{,}51}\right) \tag{2.10}$$

For high Reynolds numbers, the friction factor f_f becomes independent of Re and depends only on the relative roughness height. In this case the pipe is a hydraulically rough pipe. The friction factor f can be calculated from the formula:

$$\frac{1}{\sqrt{f_f}} = 2\log_{10}\left(3{,}7\frac{D}{e}\right) \tag{2.11}$$

5

Guide on How to Develop a Small Hydropower Plant, www.esha.be

Between these two extreme cases, the following equation is valid (Colebrook and White):

$$\frac{1}{\sqrt{f_f}} = -2\log_{10}\left(\frac{e/D}{3.7} + \frac{2.51}{R_e\sqrt{f_f}}\right) \tag{2.12}$$

For this situation pipe behaves neither completely smooth nor completely rough. The average velocity U can be expressed:

$$V = -\sqrt{2gD\cdot {}^{h_f}\!/_{L}}\,\log\left(\frac{e/D}{3.7} + \frac{2.51\nu}{D\sqrt{2gD\cdot {}^{h_f}\!/_{L}}}\right) \tag{2.13}$$

The friction coefficient for the energy losses in the water can be calculated from the Moody's graph ("Friction factors for pipe flow").

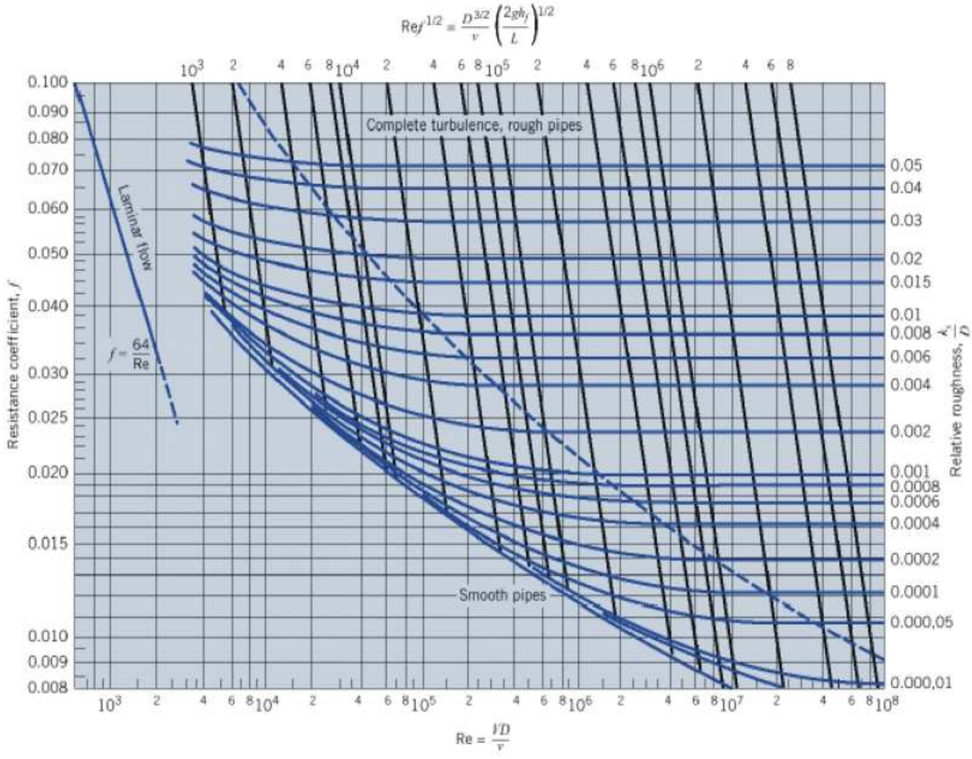

Fig. 2.4. Moddy's Diagram

Looking at the chart, four different flow zones are shown:

1. A laminar flow zone where f is a linear function of R (equation 2.8);
2. A badly defined critical zone;
3. A transition zone, starting with the smooth pipes (equation 2.10) and finishing in the dashed line where, in between, f depends both of R_e and e/D (equation 2.12);
4. A developed turbulence zone where f depends exclusively of e/D (equation 2.11).

Example

Calculate, using the Moody chart, the friction loss in a 900-mm diameter welded steel pipe along a length of 500 m, conveying a flow of 2.3 m3/s.

The average water velocity is 4Q /(π D2)= (4*2.3/(3.14*(0.9)2)=3.615 m/s

From the table 2.2,
e = 0.6 mm and therefore e/D = 0.6/900 = 0.000617.
Re =DV / u = (0.9 x 3.615)/ 1.31x 10^6= 2.48x10^6 (u = 1.31 10 -6).
In the Moody chart for e/D = 0.00062 and Re = 2.48*10^6 we find f_f=0.019

From equation (2.7):

$$h_f = f_f(\frac{L}{D}) \cdot \frac{V^2}{2g} = 0.019 \cdot \frac{500}{0.9} \cdot \frac{3.615^2}{2 \cdot 9.81} = 7{,}03\,\mathrm{m}$$

In engineering practice the Colebrook-White formula (2.12) and the Moody diagram can be used to solve the following typical problems with flows in closed pipes:

1. Given U (or Q), D and e, compute h_f;
2. Given U (or Q), h_f and e, compute D;
3. Given D, h_f and e, compute U (or Q);
4. Given U (or Q), D, h_f, compute e.

Foregoing problems 3 and 4 can be solved directly by using formula (2.13), whereas the remaining problems require an iterative solution. The Moody's diagram provides a direct solution for the 1st and 4th problem.

The energy losses for the canals with the walls made of from wood can be significant. The energy losses can be greater for different kind bends and clapper. For the first case some profiles should be modified, e.g. some greater profiles can be used.

Knowledge about the places of arising losses and about possibilities of their reduction, taking into account local condition in place of the plant seat, is one of the valid determinants of project optimisation.

2.4. WATER FLOWS IN THE OPEN CANALS

For the purpose of the water flow analysis and right estimation of the flow quantity Q in the canal, determination of the medium water velocity is very important.

Distribution of the water velocity depends on flow profile. Examples of different profile shapes are shown in figure 2.5.

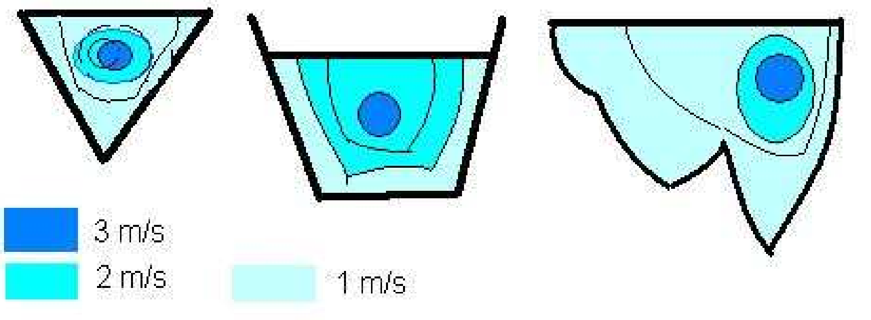

Fig.2.5. Distribution of the water velocity for different flow profiles (iso-velocity lines).

For the steady flows, e.g. for which deep, cross-section, velocity do not change in given place, velocity of the flow can be calculated using more or less complicated mathematical formulas, e.g. from Manning's formula [ESHA Guide]. This velocity depends on canal roughness parameters, shapes (hydraulic radius) and slope of the canal.

One of the important problems is the selection of parameters of the canal, e.g. its depth, level of the water in the canal.

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3. TYPES AND CHARACTERISTICS OF THE SHP

3.1. CLASSICAL SHP

3.1.1. TYPES OF SHP

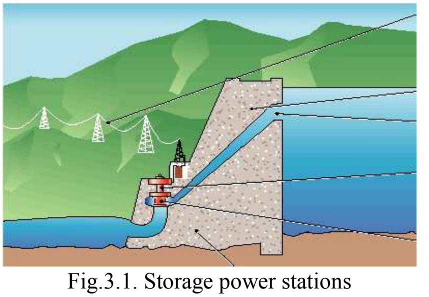


Fig.3.1. Storage power stations

Storage power stations use a dam to store river water in a reservoir. The water may be released either to meet changing electricity needs or to maintain a constant reservoir level.

Fig.3.2. Run of river power stations

Run of River plants

(Flowing water power stations) utilizes the flow of water within the natural range of the river.

Peaking with Hydropower - Pumped storage facility

Water can be stored overnight in a reservoir, and then released through turbines to generate power during the day.

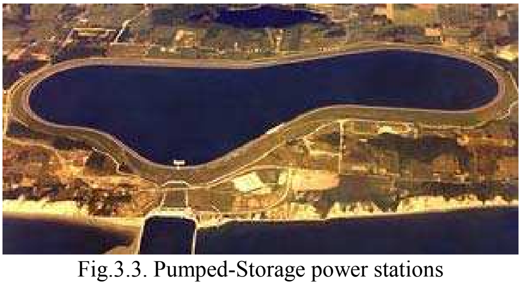
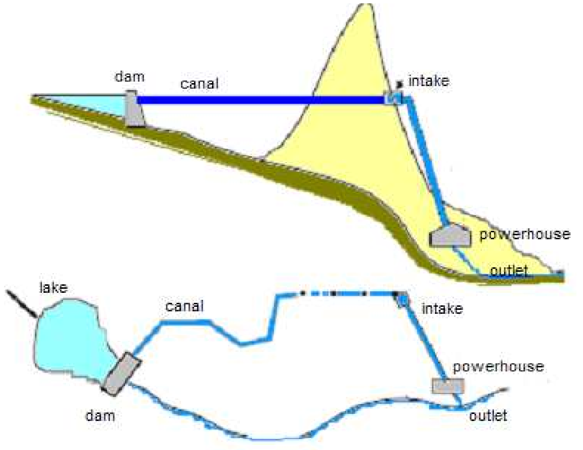


Fig.3.3. Pumped-Storage power stations

One of the most important parameters of hydro power station is head which describes difference in meters between the level of inlet water, e.g. useful water, and the level of outlet water ("highness of the head" classification in the chapter 1.1.2). The schema of the hydro power station with the high head is shown in figure 3.4.



Construction of power station depends on head profile and geomorphology of localisation. The type and power output of turbines, theirs number and configuration depend on these parameters.

Fig. 3.4. Schema of hydropower station with high head.

A good example of such construction is shown in figure 3.5.

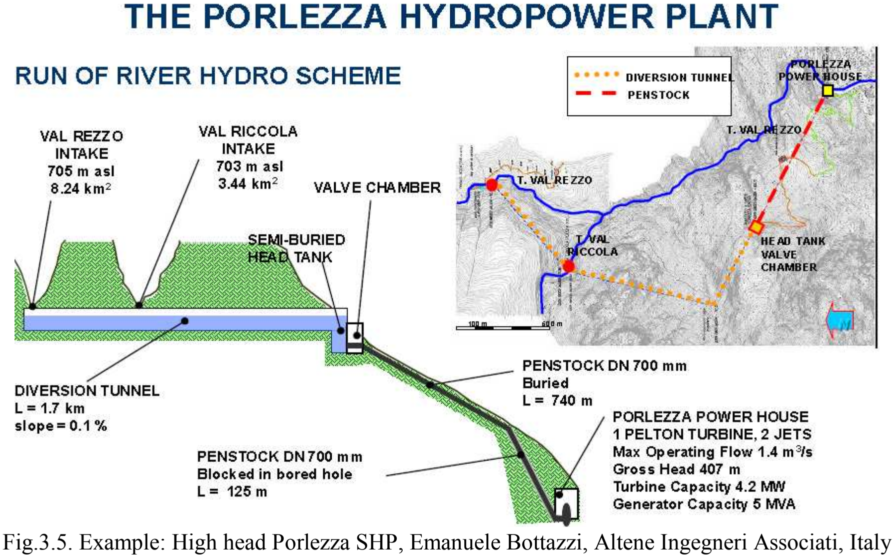
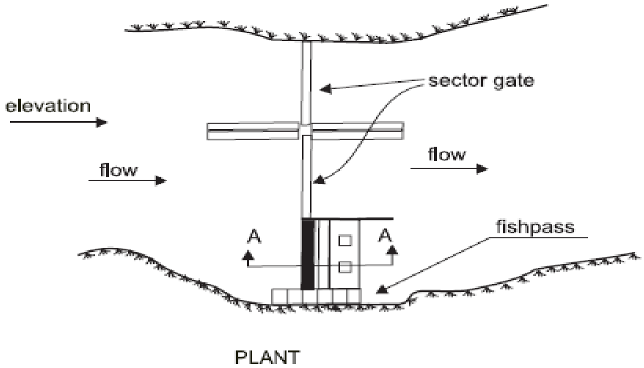


Fig.3.5. Example: High head Porlezza SHP, Emanuele Bottazzi, Altene Ingegneri Associati, Italy

Schema of small head hydropower station is shown on figure 3.6. and 3.7.



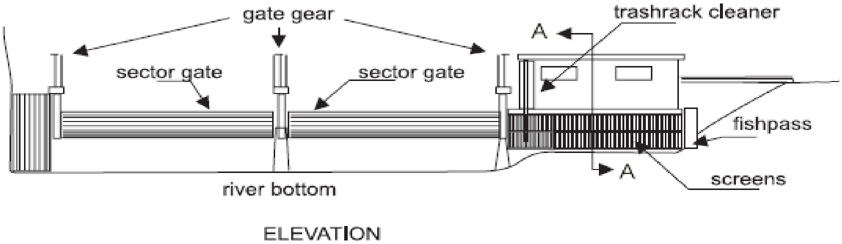


Fig.3.6. General schema of small head hydropower station.

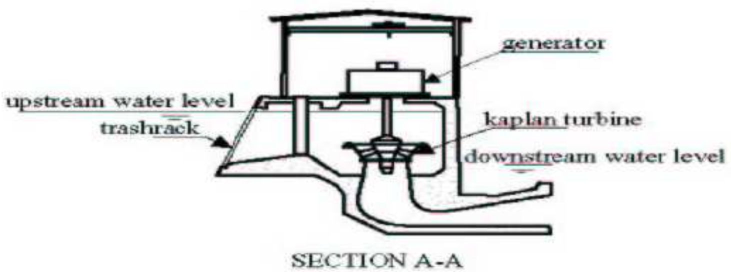


Fig.3.7. Cross-section of small head hydropower station.

Depending on the way of lead-in of the water to hydro station, and on location of the hydro technical objects, the hydropower station can be classified to three groups:

- near dam,
- with canal derivation,
- with pipe derivation.

Small investors are on the rule interested in the near dam power station or in the station with derivative pipe. Hydropower station with canal derivation are rather interested for institutional investors. Near-weir SHP are usually built in the lowland where natural head is rather small. They are often functioning as the damming element. In near-weir hydropower station, turbines are often installed in the dam pillars. Such solution enables saving some building materials. Turbines can be built in dam construction – in this case the horizontal axis turbines are often mounted.

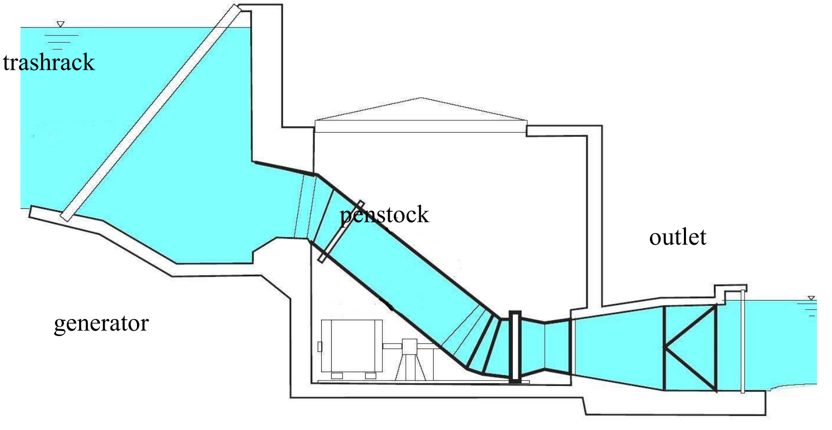


Fig. 3.2. Schema of hydropower station with feeding pipe and horizontal axis turbine.

In the case of hydropower station with small head, the two schemas of turbine positioning and water feeding are typically used: with short feeding pipe as in the figure 3.2 or with small causey and vertical axis turbine as in figure 3.3.

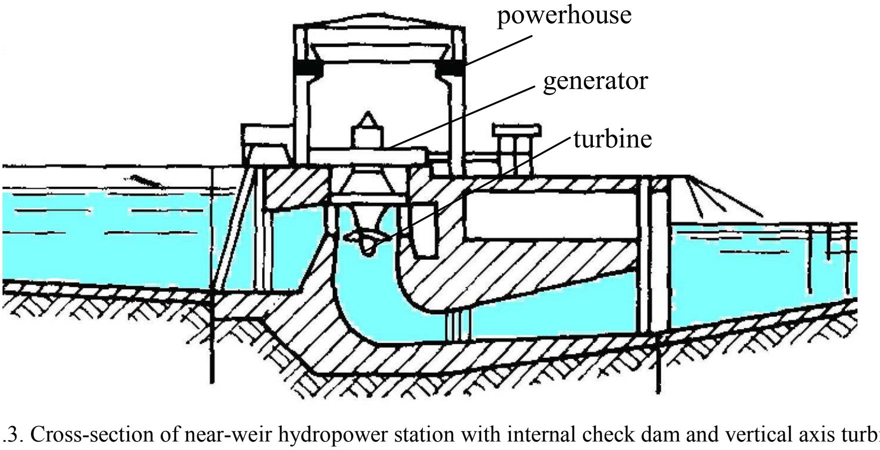


Fig. 3.3. Cross-section of near-weir hydropower station with internal check dam and vertical axis turbine.

Canal derivation is often used on the river bend places as in the figure 3.4. The canal can shorten the natural river passage and allows obtaining greater head. Characteristic feature of such system is upper inlet and tailwater canals. Tailwater canal downtakes water to the river bed.

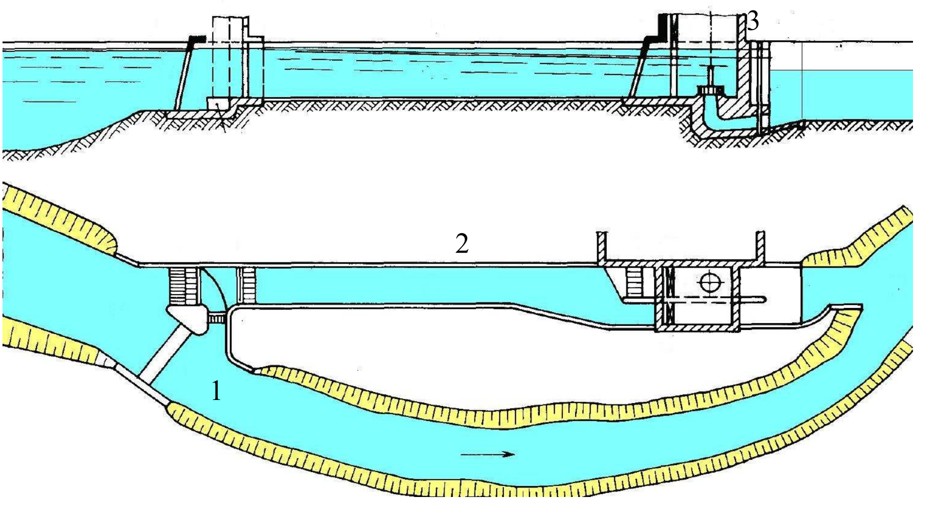


Fig. 3.4. Hydropower station with canal derivation: 1-weir, 2 – canal, 3 - powerhouse

Pipe derivation with pressure pipe is used in the cases where head is greater then 20-30m and when the powerhouse is far-away from water inlet like in figure 3.5.

Ability to turbine control depends on length of the pipeline. There should be fulfilled condition that sum of products of length and speed of flows in the pipes should not be greater then value of twenty five times head of hydropower station.

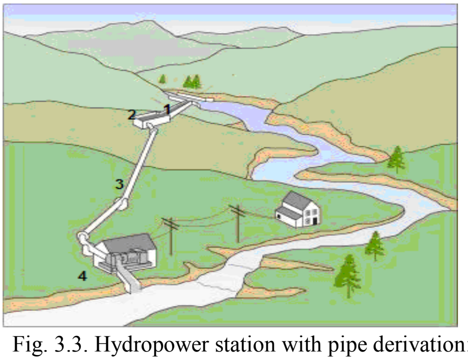


Fig. 3.3. Hydropower station with pipe derivation: 1- canal, 2 - intake, 3 - penstock, 4 - powerhouse

Fig. 3.4. Feeding pipes of SHP.

Near-dam hydropower stations

Fig. 3.5. Schema of near-dam hydropower station.

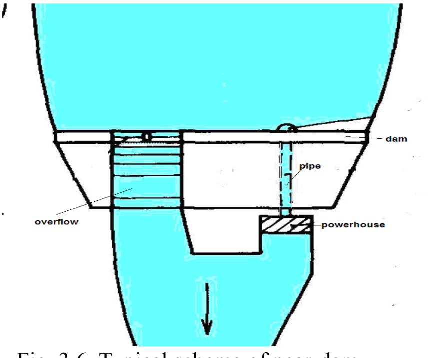


Fig. 3.6. Typical schema of near-dam hydropower station

In the case of large heads, from 30 to 100 m, the near-dam hydropower station schemas can be considered. They are often put into a composition of dam construction and create common integral complex. Pipes are as a rule arranged in reinforced concrete gallery.

3.1.2. HYDRAULIC STRUCTURES

A hydropower development includes a number of structures, the design of which will be dependent upon the type of scheme, local conditions, access to construction material and also local building traditions in the country or region. The following structures are common in a hydro scheme:

- ✓ **Diversion structure**
  - Dam
  - Spillway
  - Energy dissipation arrangement
  - Fish pass
  - Residual flow arrangements
- ✓ **Water conveyance system**
  - Intake
  - Canals
  - Tunnels
  - Penstocks
  - Power house

Dam types:

✓ **Embankment Dams**

- Homogeneous dams,
- Zoned embankment dams,
- Embankment dams with membrane.

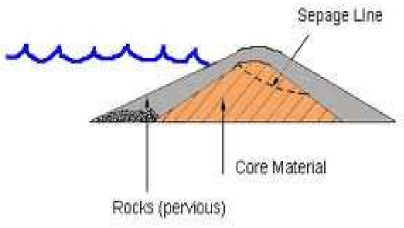


Fig. 6.7. Embankment dams

✓ **Concrete Dams**

- Gravity dams,
    - Concrete Faced Rockfill Dam (CFRD)
    - Roller Compacted Concrete Dams (RCC)
- Buttress dams,
- Arch and Cupola dams.

Fig.3.8. Gravity (RCC) dam

These are dependent on their own mass for stability. Their cross-section is basically triangular in order to provide adequate stability and stress distribution across the foundation plane. The upper part is normally rectangular in order to provide adequate crest width for installation and transportation.

✓ **Other dam types**

- Inflatable (rubber weir),
- Spillway dam
- Masonry dam,
- Timber dams.

Inflatable (rubber) weir

A rubber dam is a rubber membrane filled with water or air, attached to the concrete sill. In the upright – full position it serves as a barrier which impounds water. Cross-section of such weir is shown in figure 3.9.

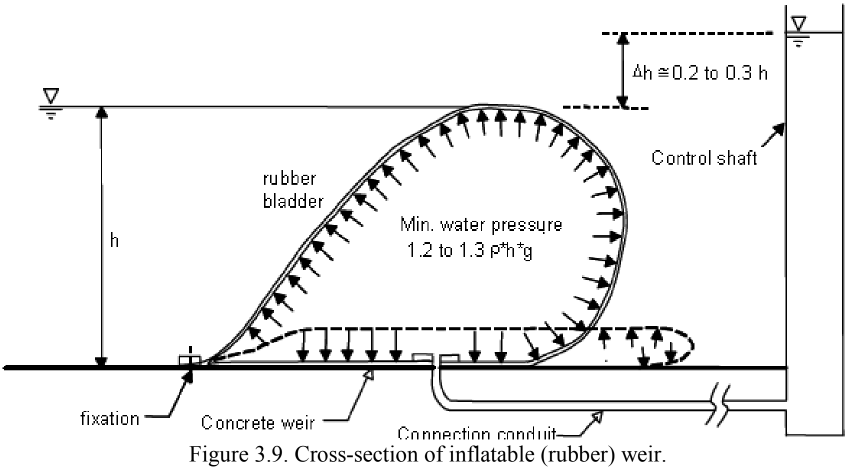


Figure 3.9. Cross-section of inflatable (rubber) weir.

Figure 3.10. Illustration of inflatable (rubber) weir.

The advantages of use of a rubber dam:

- The increase of power of a hydroelectric power plant
- A rubber dam restrains very fine sand and deposits which could damage the turbine.
- If water gets to high, the rubber weir reacts quickly by lowering and enabling high water to pass. In this way it prevents damage and possible flooding to the engine room of the plant.
- No rusting, no maintenance necessary (painting, lubrication etc.).
- Relatively easy – low-priced adjustment of the height of the weir.
- The possibility of automated functioning without electric power.
- Due to its flexibility it withstands also very high waters.
- High life expectancy. A rubber dam can be used for 20 years and more.

Channels design

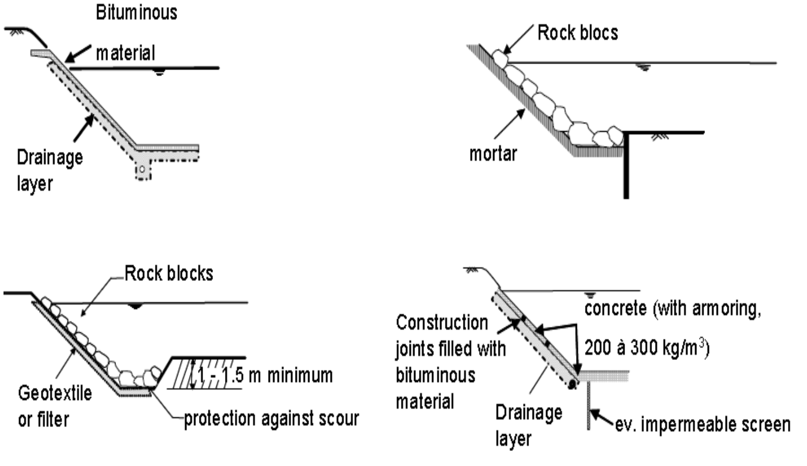


Figure 3.11. Elements of channel design.

Penstocks

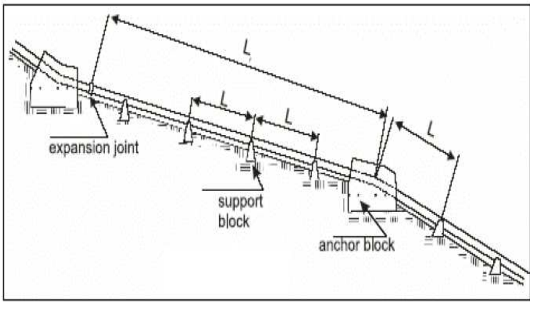


Figure 3.12. Penstocks design.

3.2. HYDROKINETIC ENERGY CONVERSION SYSTEMS

The process of hydrokinetic energy conversion implies utilization of kinetic energy contained in river streams or tidal currents for generation of electricity [2]. The kinetic energy of the flowing water is converted to electrical energy – potential energy as the consequence of the head is small in this case. The good feature of such solution is that it does not need any additional canals and greater hydro-technical works – they are constructed without significantly altering the natural pathway of the water stream. It is in contrast to conventional hydroelectric plants, which use artificial water-head created using dams or penstocks. For setting such hydropower station the existing hydro-technical construction are useful like bridges, dams, wears, canals. Typically they are more environmentally friendly and have attractive features of modularity and scalability.

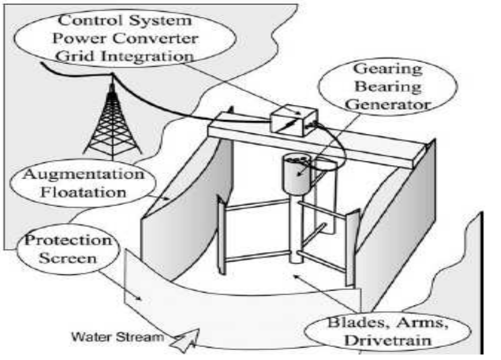


Fig. 13. Outline of a hydrokinetic energy converter system

There are two main classes of such energy converters: turbine and non-turbine systems. The turbine systems can be classified as follows:

a) Axial (Horizontal): Rotational axis of rotor is parallel to the incoming water stream (employing lift or drag type blades) [3].
b) Vertical: Rotational axis of rotor is vertical to the water surface and also orthogonal to the incoming water stream (employing lift or drag type blades) [4] –figure . 3.15


Fig.3.14 Free flow axial turbine [treehugger.com]

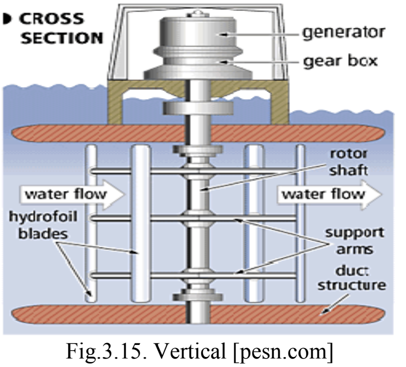


Fig.3.15. Vertical [pesn.com]

c) Cross-flow: Rotational axis of rotor is parallel to the water surface but orthogonal to the incoming water stream (employing lift or drag type blades) [5].

d) Venturi: Accelerated water resulting from a choke system (that creates pressure gradient) is used to run an in-built or on-shore turbine [6].

e) Gravitational vortex: Artificially induced vortex effect is used in driving a vertical turbine [7].

c) Cross-flow, tripod.com

d) Submerged tidal, engineerlive.com

e) Gravitational vortex

Fig.3.16. Hydrokinetic turbine of type c)÷e): cross-flow, Venturi, vortex.

To the second class of non-turbine systems belong Flutter Vane [8], piezoelectric [9], vortex induced vibration [9], oscillating hydrofoil [10] and sails systems [11]. Hydrokinetic devices for power generation purposes are used in two main areas - tidal current and river stream. In order to achieve economies of scale, tidal current turbines are currently being designed with larger capacity (several MW). River turbines on the other hand, are being considered in the range of few kW to several hundred kW. From all of developed kinetic technologies axial (horizontal and vertical) are the most popular and valid – about 75% of all applications in this group. A general classification of these turbines based on their physical arrangements is given in figure 3.17

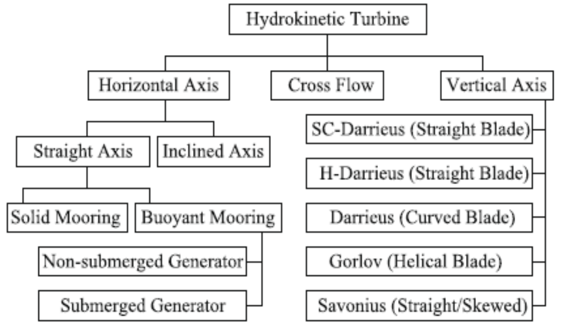


Fig. 3.17. Classification of turbine rotors.[12]

The horizontal axis turbines have usually axes parallel to the fluid flow and employ propeller type rotors. Most of these devices were tested in river streams but practical, commercial solutions are of limited scales.

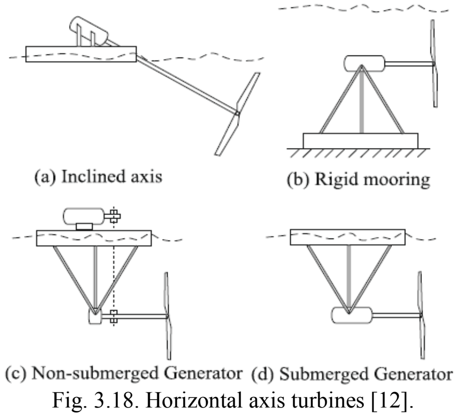


Fig. 3.18. Horizontal axis turbines [12].

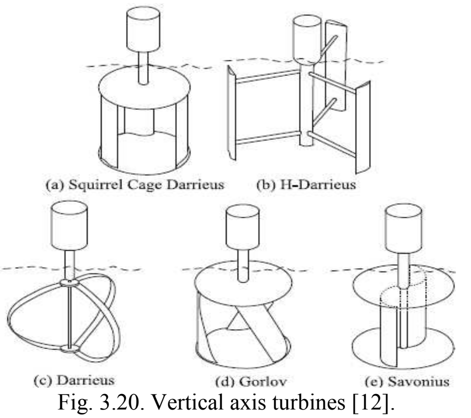


Fig. 3.20. Vertical axis turbines [12].

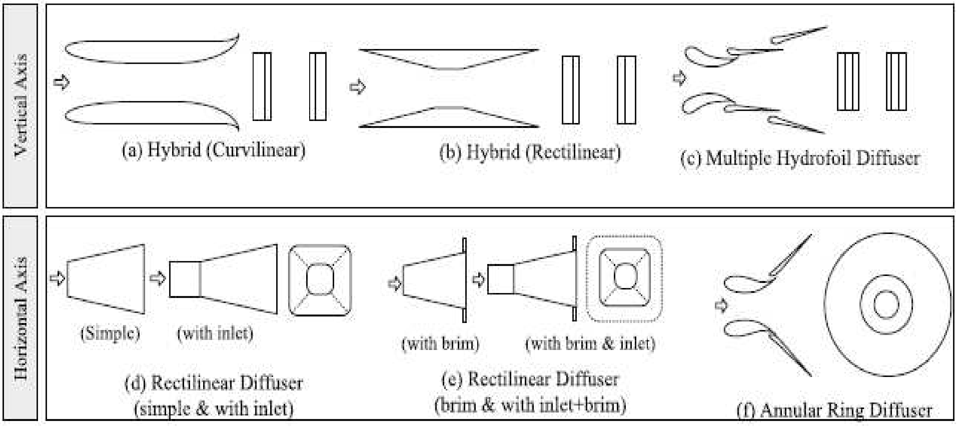


Figure 3.20. Channels shapes and diffuser solutions [20]

In [13], it has been shown that a power coefficient as high as 1.69 is possible, exceeding the Betz limit of 0.59. It can be stated that hydrokinetic energy technologies are emerging as a viable solutions for renewable power generation but they are at the beginning of commercialization – some significant research and development should be done before realizing true commercial success in this sector. Hydrokinetic energy systems are deeply developed in USA. There is a big application potential of such equipments on see as well as at the mouth of rivers. The Electric Power Research Institute (EPRI) conservatively indicated that marine and hydrokinetic power (exclusive of ocean thermal energy resources) could provide an additional 23,000 megawatts (MW) of capacity by 2025 and nearly 100,000 MW by 2050 [14]. The list of projects and technologies is published in internet [15].

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4. BASIC TYPES OF TURBINES

The aim of a hydraulic turbine is to transform the water potential energy to mechanical rotational energy. It is done by one of two fundamental and basically different mechanisms

1. The water pressure can **apply a force on the face of the runner blades**, which decreases as it proceeds through the turbine. Turbines that operate in this way are called <u>**reaction turbines**</u>. The turbine casing, with the runner fully immersed in water, must be strong enough to withstand the operating pressure. Francis and Kaplan turbines belong to this category.
2. **The water pressure is converted into kinetic energy before entering the runner**. The kinetic energy is in the form of a high-speed jet that strikes the buckets, mounted on the periphery of the runner. Turbines that operate in this way are called <u>**impulse turbines**</u>. The most usual impulse turbine is the Pelton.

Selection of suitable type of turbine in dependence on local circumstances is one of the keys of success. This selection depends mainly on the values of head and flow of the water stream. Other important parameters taken into account in the process of turbine selection are accepted speed of the turbine and ability of work in the states of lower flows. Because of large differences of conversion energy processes in the turbines ones can distinguish acting turbines taking advantage of speed water energy and reactive turbines taking mainly advantage of energy of the pressure.

4.1. ENERGY PARAMETERS OF TURBINE

State of the movement of turbine is determined mainly by the following energy parameters: head H [m], turbine flow Q [m3/s], power Pt [kW], rotational speed of turbine ω[rotation/min]. Ones can distinguish levelling (gross) head H_n and usable (net) head H_u. Gross head is the maximum available vertical fall in the water, from the upstream level to the downstream level. Net head defines the difference of energy between intake and tailwater.

Turbine flow *Q* defines volume of water leading into turbine in the unit of time, including all leakages and water taking into the system decreasing the pressure on the axis.

Theoretical turbine power P_t depends on the net head and flow

$$P_t = 9.81 Q_t H_u \text{ [kW]} \qquad (4.1)$$

Available power of the turbine P_u is the power on the turbine shaft and depends on the theoretical power and the efficiency of the turbine η and is defined by expression 4.1.

Efficiency of the turbine is the ratio of available power to net power. This efficiency is the multiplication of volume efficiency η_v, hydraulic efficiency η_h and mechanic efficiency η_m

$$\eta_t = \eta_v \eta_h \eta_m \tag{4.2}$$

The volume efficiency depends on the losses of volume water caused by some aperture leaks and leaks in the construction of the rotor depletion. The water losses cause striking of the water on the turbine blades, whirling around some outlet edge and during flowing across blade canals and as a result influent strongly on the hydraulic efficiency.

One of the capital elements of productivity estimation of SHP are proper calculation of power on the turbine shaft. Power depends on head, water speed at the lower basin and sum of losses from water flows across hydraulic equipment and leaks.

The expression 4.1 can be used to the initial, simplified calculation.

Mechanical losses are caused mainly by friction of the shaft in the turbine bearings and in gland as well as friction of rotation elements in the water. Hydraulic efficiency as the rule assign values η_h=0,88÷0,95, whereas mechanical efficiency of the turbine is from the range of η_m=0,98÷0,99. Generator efficiency can be estimated meanly at η_g=0,94÷0,97, and system of power output η_u=0,98÷0,99.

The specific hydraulic energy of machine is defined as follows:

$$E = gH = \frac{1}{\rho}(p_1 - p_2) + \frac{1}{2}(c_1^2 - c_2^2) + g(z_1 - z_2) \tag{4.3}$$

gH = specific hydraulic energy of machine [J/kg]
px = pressure in section x [Pa]
cx = water velocity in section x [m/s]
zx = elevation of the section x [m].

The subscripts 1 and 2 define the upstream and downstream measurement section of the turbine.

The net head is defined by

$$H_n = \frac{E}{g} \tag{4.4}$$

4.2. TURBINE TYPES

Vital factors of turbine type choice are values of head and flow at the SHP seating place. Additional factors taking into account in the process of turbine type choice are as follows:

- depth of the turbine seating in the hydro-technical construction of SHP,
- efficiency,
- costs.

Pelton turbines

Impulsive turbines use speed of the water to shaft movement and unload water pressure to atmospheric pressure value. In this type of turbine one or more jets impinge on a wheel carrying on its periphery a large number of buckets. Each jet issues water through a nozzle with a needle valve to control the flow – Fig. 4.1b). The turbine vane consists of blades in the shapes of buckets mounted on the wheel.

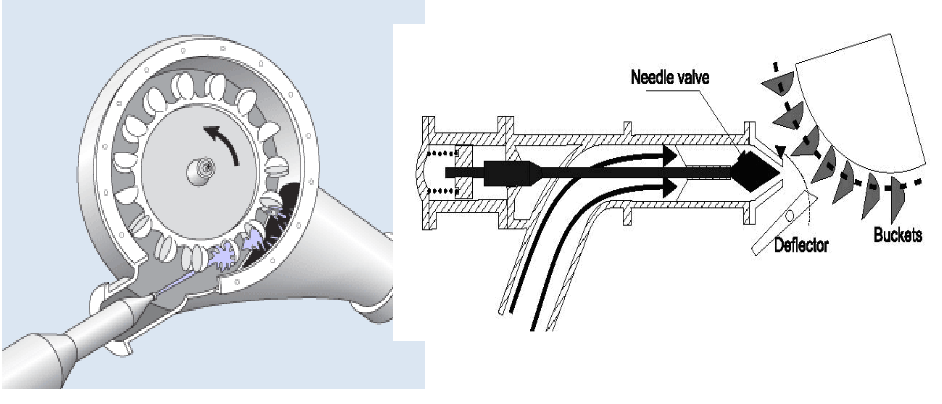

Fig. 4.1. Pelton turbine : a) idea of operation, b) needle valve

Impulse turbines are mainly used at the high heads. The representative of that group is Pelton turbine. Pelton turbine is mainly used in the palaces of high heads, from 30 to 400 m. These turbines can be mounted both on the horizontal and vertical shafts. There are differences in the solutions of some elements like so called wheel and number of discharge jets. As the rule these turbines can work in the wide range of flows from 5 to 100 %.

Some modification of Pelton turbine is Turgo turbine. A Turgo turbine can be used when the flow varies strongly or in case of long penstocks, as the deflector allows avoidance of runaway speed in the case of load rejection and the resulting water hammer.

Banki-Michell’s Turbines

Flow turbine usually is of cylinder shape with the blades set in a chamber or directly in derivation canal. Construction of the blades often enables double effective flow through the blades. Such solution improves efficiency of turbine. Banki-Michella turbine is representative of this group.

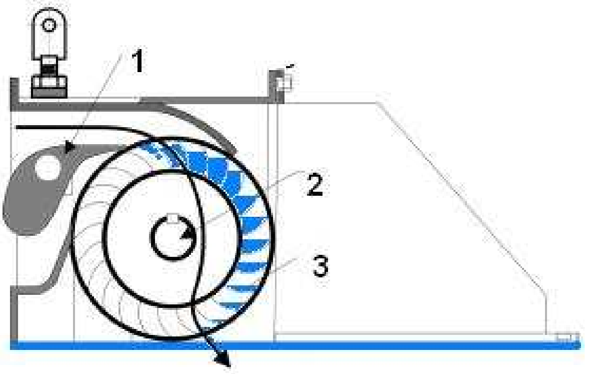

Fig. 4.2. Cross-section of Banki-Michell turbine: 1- distributor, 2 – runner, 3 – blades.

This simple design of Banki-Michella turbine makes it cheap and easy to repair in case of runner brakes due to the important mechanical stresses. The Cross-flow turbines have lower efficiency compared to other turbines. The important loss of head due to the clearance between the runner and the downstream level should be taken into consideration when dealing with low and medium heads. It is an interesting alternative when one has enough water, defined power needs and low investment possibilities, such as for rural electrification programs. This turbine can have discharge capacity from 20 l/s to 10m^3/s and is used at the head in the range from 1 to 200m.

Kaplan Turbine

Reactive turbines give power using both pressure and movement of the water. The driving mechanism is submerged in the water. Water stream flows over the blades, do not strike them directly. **Reactive turbines are generally used at the seats with small head and greater flow in comparison to impulse turbines.** To this class belong propeller turbines.

Propeller turbines have driven element equipped in three or six blades which have uniform contact with water. Angle of attack of the blades can be adjustable.

Fig 4.3. Propeller of the Kaplan turbine
Source: www.wissen-mit-spass.de

Kaplan turbine is the typical represent of the propeller turbine class. Both blades and gaps are adjustable. The Kaplan turbine has adjustable runner blades and may or may not have adjustable guide-vanes. If both blades and guide-vanes are adjustable it is referred to as "double-regulated". If the guide-vanes are fixed it is "single-regulated".

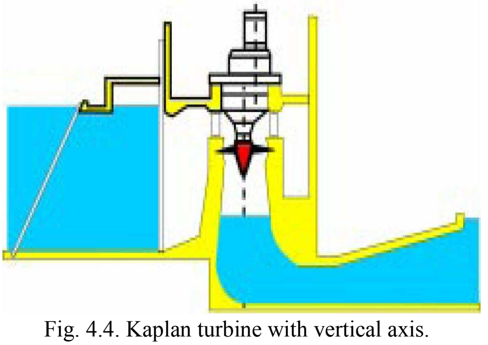

Fig. 4.4. Kaplan turbine with vertical axis.

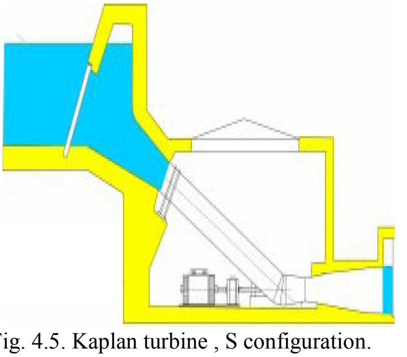

Fig. 4.5. Kaplan turbine , S configuration.

Fixed runner blade Kaplan turbines are called propeller turbines. They are used when both flow and head remain practically constant. This is a feature that makes them practically useless in small hydropower schemes. They are generally used for low heads from 2 to 40 m.

Different systems of turbine positioning are used in practice: with horizontal axis, vertical axis, S configuration and other. The examples of two solutions are shown in figures 4.4 and 4.5. The speed increaser configuration permits the use of a standard generator usually rotating at 750 or 1 000 rpm, and is also reliable, compact and cheap. The S configuration is becoming very popular, however disadvantage is that the turbine axis has to cross either the entrance or the outlet pipe with consequent head losses. It is mainly used for medium heads and/or hydropower schemes with penstock.

Francis turbine

The overflow element of Francis turbine consists of wheel, rotor, feeding pipe and encasement with supplying water elements, mostly in the shape of spiral. The wheel ensures the water supply and adequate form of stream. In the rotor the energy of the water is converted to mechanical energy. The direction of the flow is also changed from radial to axcial at the water outlet. The shape of the rotor and its blades depends on the head magnitude.

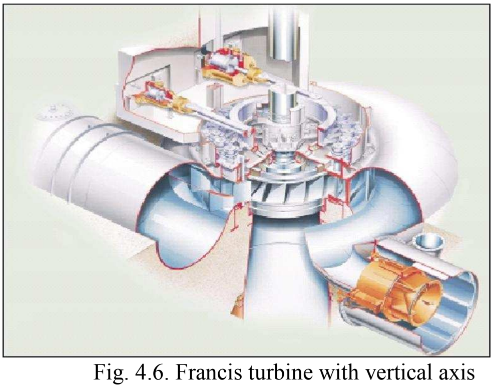

Fig. 4.6. Francis turbine with vertical axis

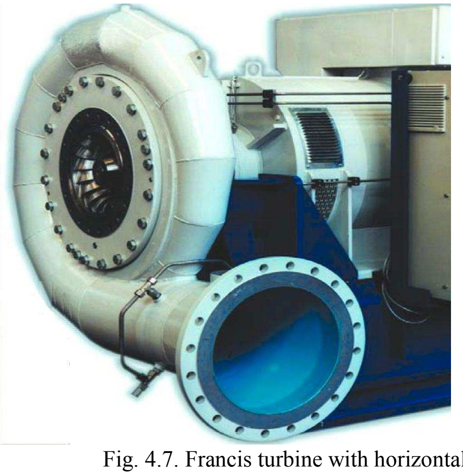

Fig. 4.7. Francis turbine with horizontal axis

Basic advantage of Francis turbine is the possibility of production in different construction solutions. This feature enables optimal turbine choice, i.e. optimal parameterization to the local circumstances, hydrotechical equipment, powerhouse, etc. Francis turbines with vertical axis located in open chamber are mostly used, especially in SHP up to 5 MW. Turbines with vertical axis in scroll, including multiimpeller are used in SHP as well.

Table 4.1. Classification of turbines in dependence on high-speed and head

Type of Turbine		Range of running [circles/min]	Range of heads [m]
Kaplana	L	350÷500	30÷40
	M	501÷750	10÷30
	F	751÷1100	≤10
Francisa	L	50÷150	110÷300
	M	151÷251	50÷110
	F	251÷450	≤50
Peltona	L	2÷15	1000÷1300
	M	16÷25	700÷1000
	F	26÷50	100÷700
Banki-Michella		30÷200	5÷100

L- low speed turbine ,
M – medium speed turbine,
F – fast-speed turbine.

To appropriate selection of turbine in dependence on highness of head and the flows, the diagram are used as depicted in the figure 4.8.

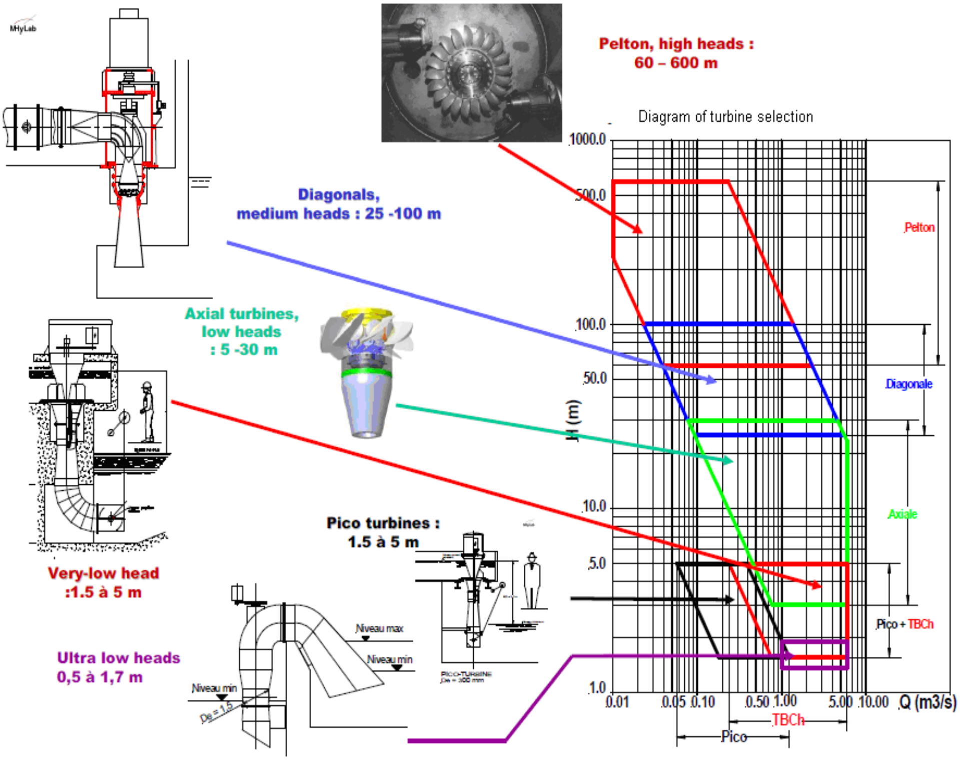

Fig. 4.8. The diagram of turbine selection in dependence on highness of head and the flows.

4.3. SPECIFIC SIMILITUDE PARAMETERS

In planning hydraulic structures of hydro power plant it is necessary to compare designed elements and their functionality to some preliminary models. The behavior of these models is based on the principles of hydraulic similitude, including dimensional analysis; the analysis of the physical quantities engaged in the static and dynamic behavior of water flow in a hydraulic structure. For the aim of comparison analysis (similarity) the models should be scaled.

It is particularly important to notice that model tests and laboratory developments are the only way to guarantee the industrial turbines efficiency and hydraulic behavior. All the similitude rules are strictly defined in international IEC standards 60193 and 60041.

According to these standards, the specific speed of a turbine is defined as:

$$n_{QE} = \frac{n\sqrt{Q}}{E^{3/4}} \qquad (4.5)$$

Where:

Q = Discharge [m^3/s]
E = specific hydraulic energy of machine [J/kg]
n = rotational speed of the turbine [t/s]

n_{QE} is known as specific speed. These parameters characterise any turbine. In general turbine manufacturers denote the specific speed of their turbines. The statistical studies formulas of the correlation of the specific speed and the net head for each type of turbine are included in the Table 4.2.:

Table 4.2. Formulas of the specific speed and the net head for chosen type of turbine

Type of turbine	**Formulae**	**Range**	**Number**
Pelton (1 nozzle)	$n_{QE} = \frac{0.0859}{H^{0.243}}$	$0.005 \leq n_{QE} \leq 0.025$	(4.6)
Francis	$n_{QE} = \frac{1.924}{H^{0.512}}$	$0.05 \leq n_{QE} \leq 0.33$	(4.7)
Kaplan	$n_{QE} = \frac{2.294}{H^{0.486}}$	$0.19 \leq n_{QE} \leq 1.55$	(4.8)
Propeler	$n_{QE} = \frac{2.716}{H^{0.5}}$	$0.19 \leq n_{QE} \leq 1.55$	(4.9)
Bulb	$n_{QE} = \frac{2.716}{H^{0.5}}$	$0.19 \leq n_{QE} \leq 1.55$	(4.10)

Some of the correlation formulae are graphically represented in figure 4.9.

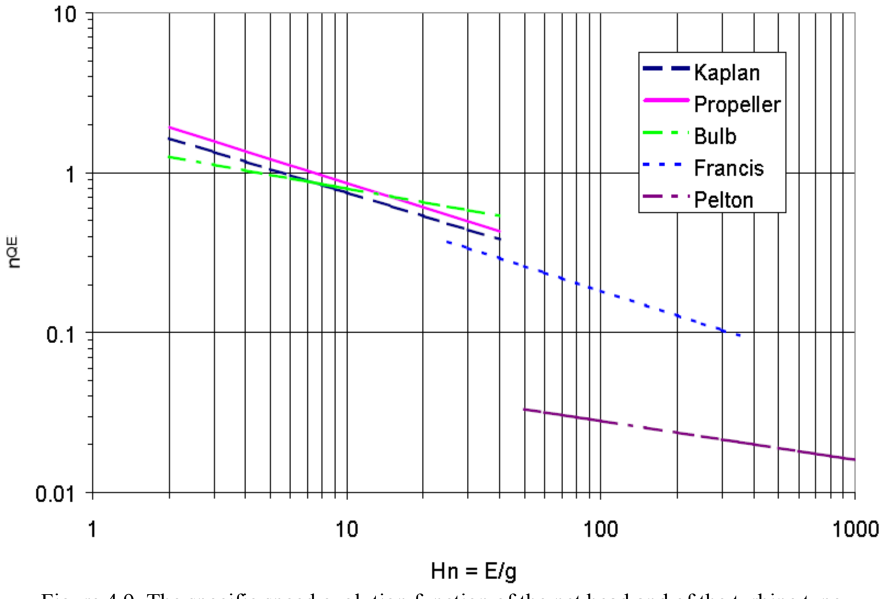

Figure 4.9. The specific speed evolution function of the net head and of the turbine type.

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5. GENERATORS AND ELECTRICAL EQUIPMENT

Hydro Power Plant (HPP) have different parameters correlated with water reservoirs and kind of construction. Big fluctuations of water stream, especially for free water flows, with small upper reservoir or in the river, can be observed resulting in big volatility of energy parameters. One of the essential factors affecting power grid operations is the connection of the generator. Generator/connection operations can cause fluctuations of frequency, voltage asymmetry, flickering, drop or over-voltages.

In HPP two main types of generators are used:

- synchronic generator – with the possibility of reactive power control produced or consumed by field circuits,
- asynchronous generator.

5.1. SYNCHRONIC GENERATOR

5.1.1. MAIN SCHEMES OF CONNECTION TO THE GRID

Most synchronic generators work in mode of production of inductive reactive power – most receivers have inductive character. The power coefficient of such a generator is in the range 0,9÷0,95. In the case of "islanding" control systems should be equipped with devices of valves setting and adjustable turbine blades for the control of rotational speed of generator. In island mode it is necessary to control the voltage frequency of generated power. It is realized by controlling field current which is responsible for the voltage in point of connection of supplied network. Synchronization of generator with the network deals with short-lived floating currents of small energy. One of good features of synchronic generators is smoothing the asymmetry and voltage deformation. Problem is to smooth regulation of rotational speed of generator. In such cases the power electronic converters or generators with permanent magnet are used.

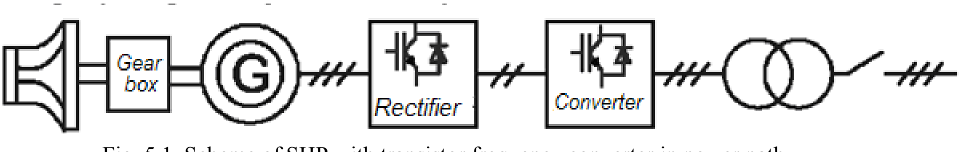

Fig. 5.1. Scheme of SHP with transistor frequency converter in power path.

Especially power electronic converters enable to achieve good quality parameters of electrical energy. The level of converter complexity increases with the increasing of the output power – power transistors in such devices have some limitations. In the cases of large power generation the thyristor systems are used. The currents in such systems, as in figure 5.2, can be distorted and have reactive component.

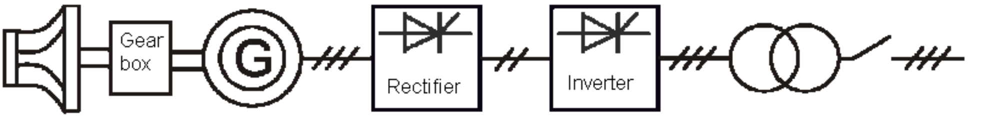

Fig. 5.2 Scheme of SHP with thyristor frequency inverter in power path.

The quality of output current can be improved by using multi-pulse systems. Schemes of such systems are illustrated in figure 5.3. Using such systems makes it possible to decrease current distortion coefficient THDi – with 24-p inverter even to 4-6%.

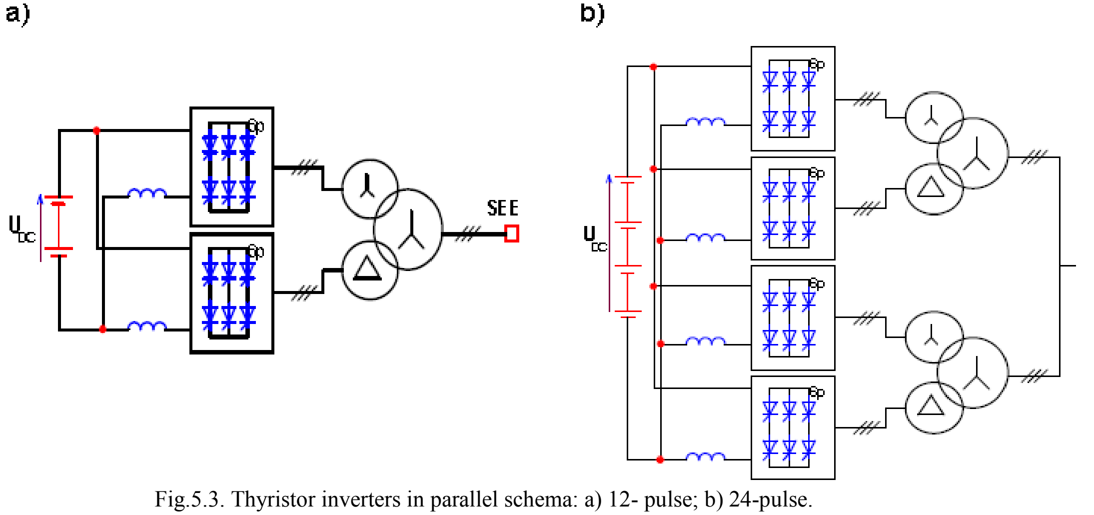

Fig.5.3. Thyristor inverters in parallel schema: a) 12- pulse; b) 24-pulse.

For reactive power compensation the active filter can be used. The scheme of such system is illustrated in figure 5.4. Distortion of current is very small and reactive component practically does not exist.

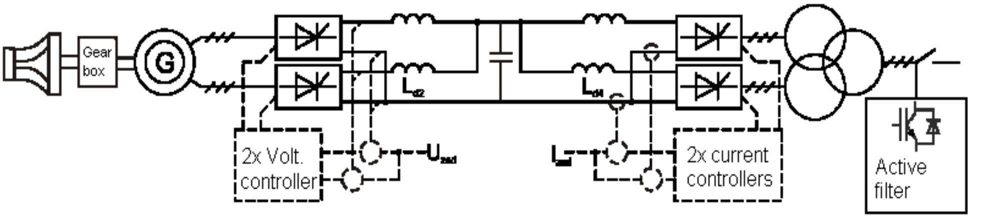

Fig. 5.4. Scheme of SHP with thyristor voltage inverter and active filter.

5.2. ASYNCHRONOUS GENERATOR

5.2.1. MAIN SCHEMES OF CONNECTION TO THE GRID

The valid feature of asynchronous generator is low costs of investment and maintenance. There is no need to install exciter, frequency voltage and reactive power controllers. It does not allow to work on island system. It consumes inductive reactive power. Such power should be compensated, mostly by using battery of condensers. This battery is switched of together with switching generator. Switching on of asynchronous generator can cause flows of impulse start-up currents of large values (up to 8 times in relation to nominal) and voltage cut down. To reduce this effect the systems related to as soft start are used. Such scheme is illustrated on figure 5.5.

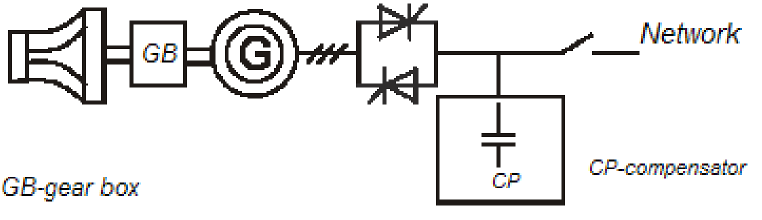

Fig.5.5. Scheme of SHP with soft-start and reactive power compensator

In the state of energy production, the shaft speed of the cage asynchronous generator should be greater then the nominal speed. In the states of low water the work of such generator is often impossible. Solution with double-feed generator, figure 5.6, can improve such cases.

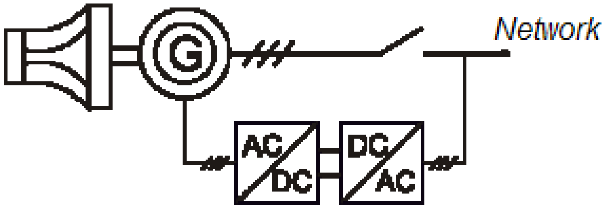

Fig.5.6. Scheme of SHP with double-feed asynchronous generator.

Double-feed generator enables soft control of turbine speed (in some range) and reactive power control.

5.2.2. BASIC CHARACTERISTICS OF ASYNCHRONOUS GENERATOR

Asynchronous generator is very popular in SHP. It has many advantages and some disadvantages in relation to synchronous generator – table 5.1.

Table 5.1. Features of application of asynchronous generators

Advantages	Disadvantages
1. lower price (the machine neither has slip-rings nor brushes - it requires low maintenance, has a long service life and a robust design), a high efficiency can be achieved at a very favourable price, 2. lack of necessity of synchronization with the network, 3. simple protection and control systems, 4. the current status of inverter technology offers the possibility of network cooperation in alert states or on isolated island.	1. consumption of reactive energy from the network, 2. using battery of capacitors for reactive power compensation, 3. difficulties in working on isolated network island.

An active power is applied to the mains, when the fed mechanical power is higher than the machine losses. The speed is over-synchronous. After the speed equalizing, the slip is of a similar size like at motor operation with the same power, only with a negative sign:

$s = (n_{syn} - n) / n_{syn}$ (Motor operation: $n < n_{syn}$, $s > 0$

(Generator operation: n > nsyn, s < 0)

$\mathbf{n_{syn} = 120\ f / 2\ p}$

s =slip, n_{syn} = synchronous speed of the machine (1/min), n = rated speed (1/min)
f = frequency (Hz), 2 p = number of poles.

The asynchronous machine needs "reactive power" to build up the magnetic field. It is known that the reactive power is an apparent power not contributing to the direct energy conversion. The current associated with it, which means the reactive current, causes losses in supply and in the machine. The higher the reactive current content in the overall current is, the lower is the power factor „cosφ“. The power factor can be optimized by an adequate machine design. Since the asynchronous machine is not "excited" as in case of the synchronous machine it takes the reactive power from the mains. This applies to both motor and generator operation. Growth of slip correspond to the growth of active power generated to the network.

Generator operation of the asynchronous machine is normally not possible without the existing ("rigid") three-phase mains. In that case reactive power sources would be required, for example a capacitor bank making available the reactive power for the generator and the load at the respective operating point.

Therefore an asynchronous machine can not be so easily used e.g. as an emergency generating unit, e.g. in "Isolated operation” mode.

REACTIVE POWER COMPENSATION AND SELF-EXCITATION

One of a few disadvantages of the asynchronous generator is that the required reactive power is to be taken from the mains. A part of the required reactive power can be compensated by capacitors which are parallel connected to the motor or generator. It must be noticed that the self-excitation limit may be exceeded. It means that the generator produces a voltage even at disconnected system. It is a certain extent running at "Isolated operation mode". This self-excitation process is explained in figure 5.7.

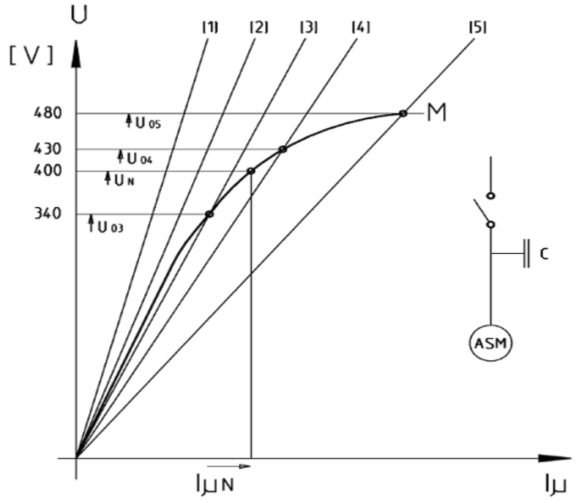

Figure 5.7. Reactive power and excitation process. M - magnetisation characteristic, (1)-(5) capacitors straight lines [4].

The magnetization characteristic M is obtained from the chart U= f(I_μ). For U= U_N the magnetizing current $I_{\mu N}$ flows to provide the required magnetization. The straight lines (1)- (5) show the so-called capacitor straight lines of the compensating capacitors for different capacitor sizes (capacities):

$$X_c = 1/(\omega C) = 1/(6.28\ f\ C)$$

$$I_c = U / X_c = U\ 6.28\ f\ C$$

I_c [A] - capacitor current, U [V] - (terminal)voltage f [Hz] – frequency,

C [Farad] - capacity of the capacitor bank.

Self-excitation occurs when the capacitor straight line is intersecting the magnetization characteristic. This is not the case for the capacitor straight lines (1) and (2), but for (3), (4) and (5) is possible.

On the terminals of the unloaded asynchronous machine which is disconnected from the rigid mains the voltages U_3 or U_4 or U_5 are to be measured as long as the capacitors (3), (4), (5) are parallel connected to it and the speed (frequency) is assumed to be constant. Without three-phase mains the speed and also the frequency are increasing at the generator terminals of the unloaded machine. However at an increasing frequency the required magnetization of the asynchronous machine and consequently also the magnetizing current decrease. This is because the machine is quasi operated in the field-weakening range. This means that the magnetization characteristic M inclines to the left (it is ascending). On the other hand the capacitor straight lines incline to the right, are descending, because according to the above formula the capacitor reactance X_c decreases and consequently the capacitor current I_c

increases. By practical experience a degree of compensation of about 0.9 times the no-load reactive power of the generator or a compensation to cosφ ≤ 0.96 at rated operation have proven to be acceptable.

Calculation of the required compensating power Q is possible according to the following formula:

$$Q[kVar] = P_{GEN}(\tan\phi_{actual} - \tan\phi_{specified})$$

e.g.:

Generator power = 50 kW, $\cos\varphi_{actual} = 0.84$, $\cos\varphi_{specified} = 0.96$,
U= 400 V, f= 50 Hz
$\cos\varphi_{actual} = 0.84$, $\varphi = 32.8°$; $\tan\varphi_{actual} = 0.646$
$\cos\varphi_{specified} = 0.96$; $\varphi = 16.3°$; $\tan\varphi_{specified} = 0{,}292$
Q = 50 (0.646 – 0.292) = 17.7 kVAr
Selected is a compensating facility of 18 kVAr, consisting of 3 single capacitors each of 6 kVAr.

5.3. OPERATION OF ASYNCHRONOUS MACHINE

OPERATION OF THE ASYNCHRONOUS MACHINE TO THE POWER SUPPLY

The asynchronous machine starts and accelerates the turbine in motor operation up to almost the no-load speed. The turbine is pressurized which causes that a speed increases above the no-load speed. The energy flow reverses and supplies electric power into the mains. When the rated torque is reached the rated data are finally set. Since adequately dimensioned machines have the corresponding breakdown torque, the turbine cannot cause the asynchronous machine to become unstable, even at overloading (e.g. higher water availability). It is almost acting like a spring converting the given (mechanical) shaft output into electric energy in a very wide range and without any regulation. If the sudden torque changes occurring at the above mentioned simple connection cannot be accepted considering the coupling, gearbox etc.

SMOOTH COUPLING OF GENERATOR TO THE GRID

- **Connection at synchronous operation**.
  If the turbine regulator keeps the machine unit operating at no load at the synchronous speed of the asynchronous generator the starting current and the impulse torque are lower than for the connection at non-synchronous speed. Compared to the synchronous machine it is not necessary to consider the phase position.

- **Connection via electric soft starters or via starting transformers**.
  Both devices are functioning according to the principle of a slow voltage rise in the generator winding. The soft starter regulates the terminal voltage rise at an adjustable "rate" and thus allows a continuous "pulling into synchronism" of the already running machine unit or the motor-operated soft start.
- **Connection via starting resistors.**
  The resistors connected in series to the stator winding are (e.g.) reduced step by step. In this way impulse torques and starting current impulses can mostly be avoided as well.
- **Star-delta-connection.**
  It is known that the star-delta-starting reduces both the starting current and the starting torque to approx. 1/3 compared to direct starting. However it must be pointed out to the fact that at changing to the delta step a momentarily occurring impulse torque is possible which depending on the machine and the instant of switching can be at least as high as this one at direct starting.
- **Use of a frequency inverter.**
  As regards the price of the inverter, this solution is only chosen when the input speed must be variable at constant mains frequency. Or if it is e.g. essentially low then a high-speed generator which supplies into the mains via a frequency inverter is a better solution than the low-speed generator. The advantage of a connection without current impulses results in common at inverters application.

5.4. ELECTRICAL SCHEMA, AUTOMATION AND PROTECTION

Electrical grid of the hydropower station usually consists of own loads circuits and connection to the bus-bar. Bus-bar through transformer and power output line are usually connected to the electric power system. The following devices are basic own loads of the hydropower station:

- control of position of wheel apparatus,
- control of main water cut-off,
- automation and protection,
- lighting and network of electric connectors.

Electrical switching station can be equipped with the measurement system to measure load and output power, system of hydro-generator control and reactive power compensation system. Battery of capacitors should be switched on-off automatically according to the switch on-off of the main circuit breaker.

Hydropower station can be fully automated with full control of hydrogenerator in dependence on amount of water in disposal to maximise the electrical energy production.

In the case of working on the isolated island, the control of flow through the turbine is carried out to stabilize rotation of the generator. The speed controller is used in this case which in SHP uses centrifugal sensor of rotational speed. In the case of grid connection the power controller is used which co-operates with sensor of high water sensor. Frequency in this case is supported by electrical grid and the aim of the controller is stabilisation of the high water level.

Automation of hydropower station should concern:

- hydro generator break down in the emergency,
- monitoring of the hydro generator work states and signalising of the emergency states,
- control of the opening degree of wheel blades in the function of high water level,
- automatic reconnection of hydro-generator to the grid.

Great part of SHP is equipped not only in simple and absolutely necessary automatic and protection systems. This situation is improved because the new microprocessor control devices and relatively cheap automation systems are available on the market. More investors appreciate the need of installation of modern and efficient control systems. SHP are often built in the solitude areas. It is one of the reasons focussing the attention of investors on the remote control systems. It is expected that such system should be able to continuous optimization of generation process, without any staff intervention. This enables the maximisation of profits. Factors of direct increasing of the economical efficiency of hydropower station which show the necessity of application the modern control systems are among other things:

- decreasing of idly hours after emergency shutdown of HP (e.g. as the result of voltage collapse in the electrical grid) through automatic start of machine and connection of the generator to the grid,
- continuous maintenance of the nominal high water level through changing of the turbine opening and simultaneously maximization of the water for each inlet,
- monitoring of work parameters of hydro turbine set for identification and early reaction of emergency states and in the result extension of failure-free working time of hydro power station.

Necessity of maximization of efforts in the aim of available resources utilization, and development of technology from the second hand, enables accepted return rate of invested capitals. Time of return of capital on the investment in automatic and control systems is shorter in the case of greater power station and longer for smaller hydro power station.

Protection automation of network, system and devices of SHP is installed rather in the minimum to indispensable requirements defined in connection order and to essential normal work of the hydro power station.

SHP EXAMPLE – ILLUSTRATION OF MAIN CIRCUITS OF PLANT

Good example of small SHP station was described in [9]. This SHP is of flow type with head H=1,8 m and flow Q=6,3 m3/s – figure 5.8. It is equipped with three Kaplan turbines and three induction generators of 30 kW. This example enables to illustrate all basic circuits of SHP.

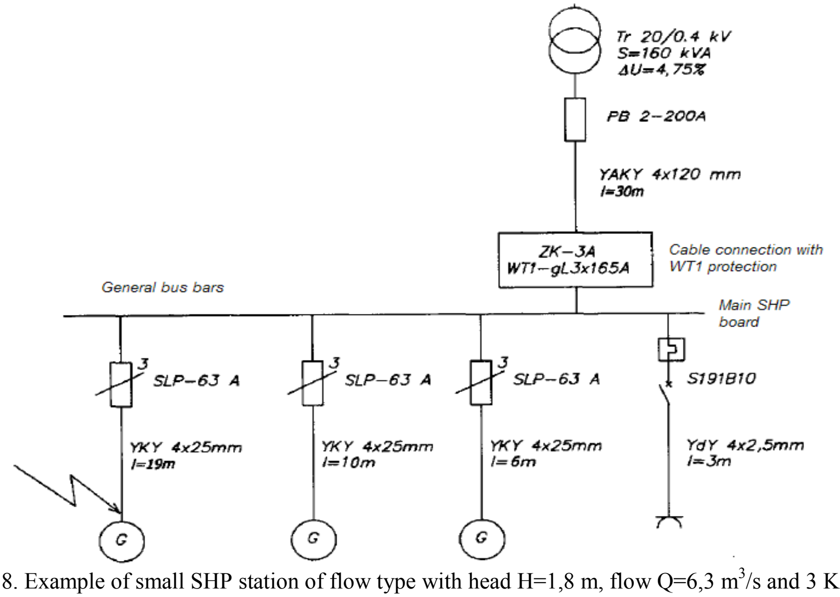

Fig.5.8. Example of small SHP station of flow type with head H=1,8 m, flow Q=6,3 m^3/s and 3 Kaplan turbines [9].

ELECTRICAL SCHEMA OF SHP

SHP is connected to electrical system via transformer and power line. The auxiliary circuit supply the following equipments:

− control of vane closing – circuit of 12 V direct current,

− control of inlet lock,

− automation and protection,

− lighting and outlets circuits.

Power switchgear can be equipped with semi-indirect measurement system which assures measure power (in both directions), control of turbine generator set and equipment for reactive power compensation. Capacitor unit can be switched on-off automatically together with main switcher.

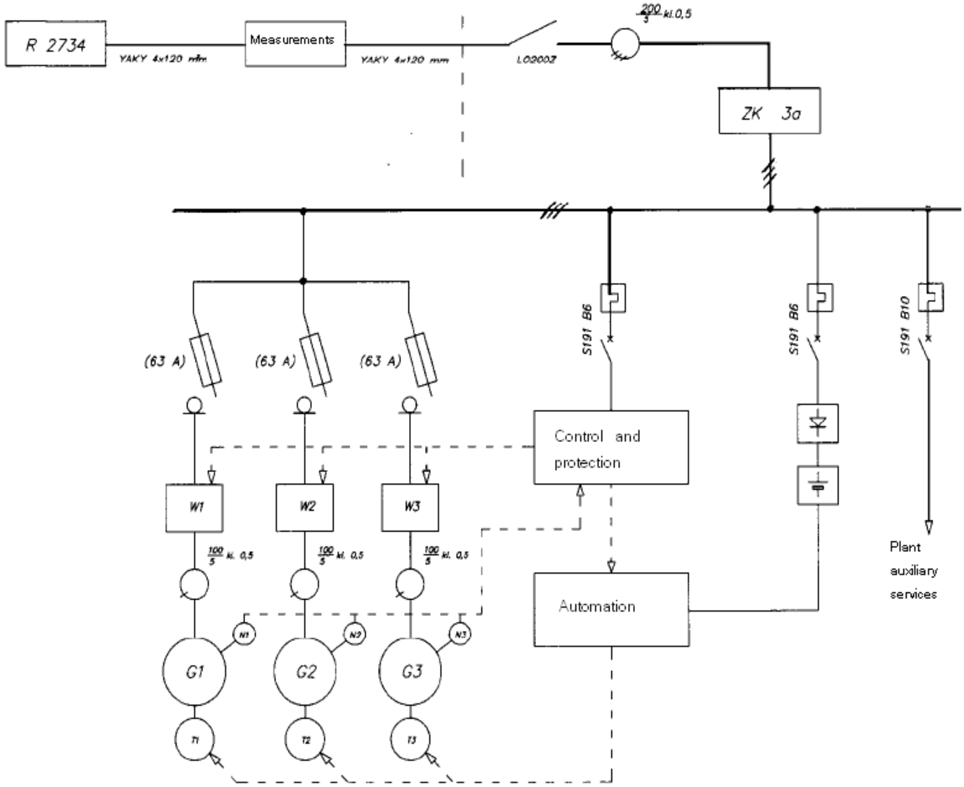

Fig.5.9. Supply structure diagram of the hydroelectric power station [9].

DESCRIPTION OF GENERATOR WORK

Network connection

In the case of small power station typically it is connected to low voltage electric network. In such case (network 0,4 kV) currents flowing by load lines can be at the level of a few hundred amperes. So high value currents can cause the necessity of increasing conductor cross-section and resulting in additional costs. Similarly cross-section of generator wiring should not be large. A generator for higher voltage, e.g. 3 kV, (SHP Marszowice) or 10 kV (SHP Wrocław), should be used in such case with transformer. 3/20 kV. For technological reasons, 10 kV is maximal voltage level of wiring. In the case of 10, 15, 20 kV line the block transformer should be used. The deep difference between solution for LV and MV are construction of protections and measurements. For MV level protection and measurement equipments work in indirect system by current or voltage transformers.

Switching on the generator to electric network successively brings it up to a synchronous speed. It is necessary to smooth network currents after load switch of power disjunctor. Rotational speed is controlled by the programmable speed measurement unit which prevents switch off load power disjunctor when rotational speed is incorrect.

The level of rotational speed can be calculated using simulation tools, e.g. TCAD[6] software with model of 30 kW asynchronous cage motor. Typically the best situation is when rotational speed of generator is in the range of +/– 5% of nominal speed. In such a case after two network cycles, current does not exceed nominal value.

Generator, after switching on to the network, is loaded automatically or manually by maintenance service by the way of control of turbine flow capacity.

WORK OF GENERATOR

Cooperation of generator with electrical network is supervised be electrical protection devices which protect network from incorrect states and unfavorable parameters of generated energy. If generator is taking energy from the network- it is shutdown by appropriate protection device. This protection should be active at the level +/– 0,05 of nominal power and be blocked in the case of start up process. Protection in the field of line branch should switch off all generator units in the case of unacceptable parameters of generated energy.

GENERATOR SWITCH OFF

Generator switch off is done manually by maintenance service or automatically in the situation of electrical or mechanical perturbances.

Manual switching off is preceded by earlier switch-over of the automatics to manual control, put off the load and activation of the power disjunctor. It results in the hydro unit coming to stop. In the case of the protection activating, the stopping process is done automatically. For turbines with electrically controlled inlet guide vanes the process of stopping if harmonized with inlet vanes closing and coupled with mechanical breaker. For the siphon turbine this function is realized by ventilating inlet valve coupled with mechanical breaker. In both cases shutdown of hydro-generator unit is independent of supply of auxiliaries. Inlet guide vane valve is closed using 12V dc motor fed from battery. For the pipe turbines, the tripping solenoid activating ventilation valve is done as a clearance which in de-energized state take the valve open.

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6. CONTROL AND SIMULATION OF HYDRO POWER PLANTS

6.1. INTRODUCTION

Control schemes are roughly classified as follows:

1. **Manual Control:-**Whereby each item in the chain of the pre-starting checks starting, synchronizing, loading and stopping. The sequence is selected and performed in turn by hand whether mechanically or by push buttons
2. **Semi- Automatic Control:-**Whereby from a single manual starting impulse a unit may be brought to the ready to synchronize condition by the automatic selection, performance, and providing of a sequence of controls. Likewise a similar stopping impulse completely shutdown the unit. Synchronizing and loading as well as running control remain manual functions from the local and remote control points.
3. **Fully Automatic Control:-** Whereby means are provided for running up, automatic synchronizing and loading up to a predetermined quantity on receipt of a single starting impulse. Subsequent manual variations of loading and excitation may be provided as a remote control function. The corresponding stopping impulse will cause the load to be reduced, the unit to be disconnected from the bus bars and the turbine to be shutdown.
4. **Offsite Supervisory Control:-** Starting, stopping, switch closing or opening and other functions initiated from a remote point, together with indications of successful operations of voltage and load control and of the repetition of alarm conditions at the remote control point. The equipment is ancillary to either semi-automatic or fully automatic unit control.

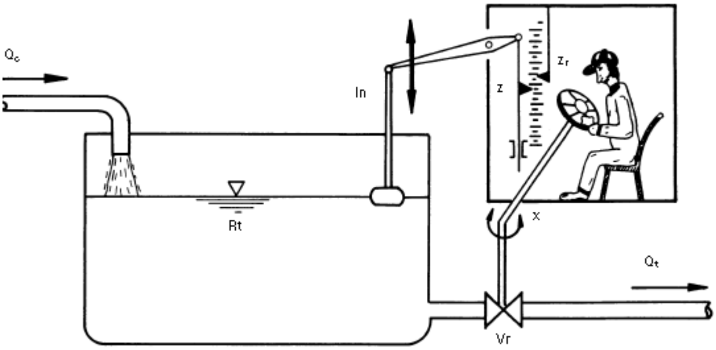


Fig. 6.1. Illustration of water level in reservoir

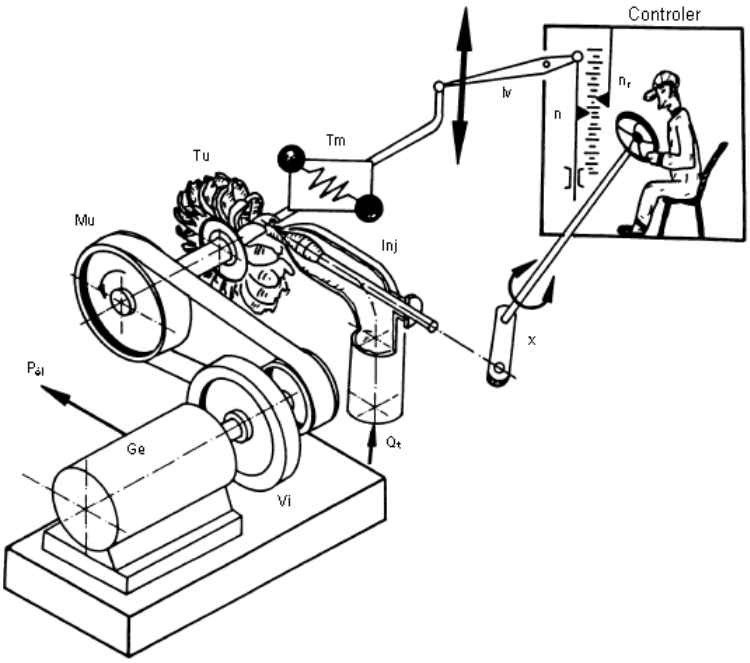


Fig. 6.2. Illustration of water turbine control – hydraulic controller [11].

The main control and automation system in a hydroelectric power plant are associated with start and stop sequence for the unit and optimum running control of power (real and reactive), voltage and frequency. Data acquisition and retrieval is used to cover such operations as relaying plant operating status, instantaneous system efficiency, or monthly plant factor, to the operators and managers. Type of control equipment and levels of control to be applied to a hydro plant are affected by such factors as number, size and type of turbines and generators. The control equipment for a hydro power plant includes control circuits/logic, control devices, indication, instrumentation, protection and annunciation at the main control board and at the unit control board for generation, conversion and transmission operation including grid interconnected operation of hydro stations including small hydro stations.

The large diversification in behaviour of nonlinear plants across their operating points requires different control objectives and thus different control actions to be taken for each variation in operating point. The nonlinear dynamic characteristics of hydro plant largely depend on internal and external disturbances, set point changes, leading to shift from its optimum operating point. The schematic of hydropower plant is illustrated in Fig. 4. A key item of any hydro power plant is the governor. This governing system provides a means of controlling power and frequency. The speed governor includes all those elements, which are directly responsive to speed and position or influence the action of other elements of the speed governing system. The speed control mechanism includes equipment such as relays, servomotors, pressure or power amplifying devices, levers and linkages between the speed governor and governor-controlled gates/vanes. The speed governor normally actuates the governor-controlled gates/vanes that regulate the water input to the turbine through the speed control mechanism.

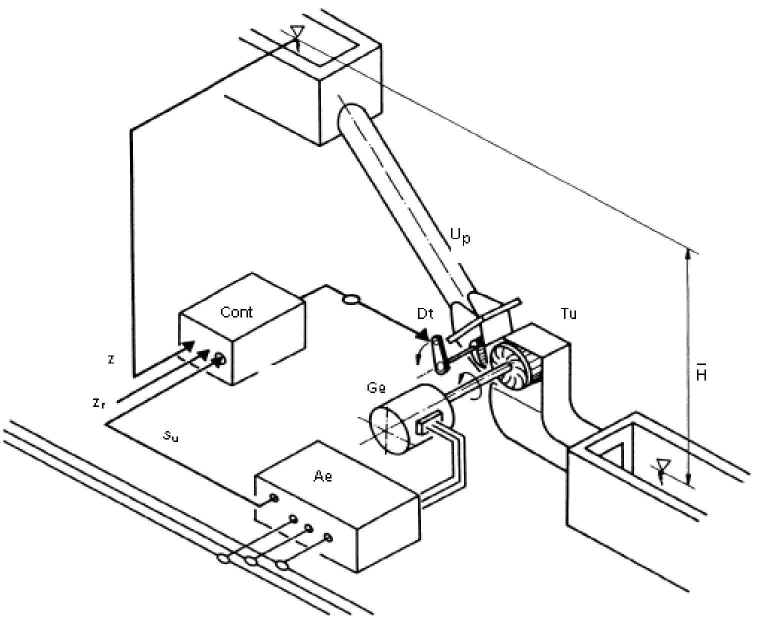


Fig. 6.3. Illustration of water turbine control – electronic controller, Ae –energoelectronic equipment [11].

Conventionally, hydraulic-mechanical governor and electro-hydraulic type with PID controllers are popular in use. The technologies of these governors have developed considerably over the past years. In recent years, digital governors have gradually replaced these analog controllers. Recent developments in the field of control technologies impose a new approach in the turbine control systems with application of artificial intelligence (AI) [3]. One of the most discussed applications of artificial intelligence in turbine governing is the replacement of a standard Electro-hydraulic governor with fuzzy logic or neural network or hybrid controller - fuzzy logic and neural network.

The turbine model considered in the design of the governor plays an important role. A great deal of attention has been done towards linearized modelling. A linear model

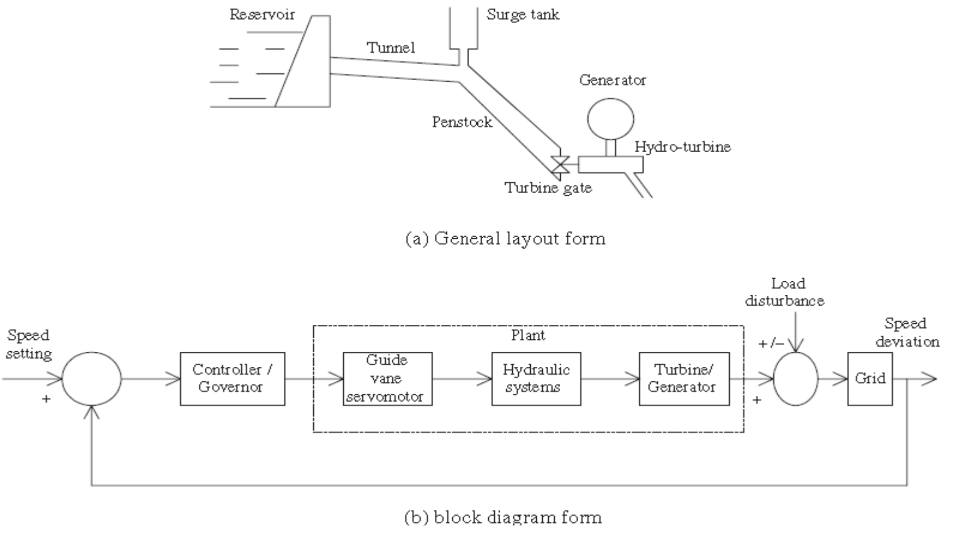


Fig. 6.4. Schematic of hydropower plant with its structures and components (a) general layout form (b) block diagram form [6]

representation of the turbine system is important in governor tuning using classical techniques (frequency response, root locus, etc.), which is valid only for small signal performance study (load disturbance of ≤10% rated value or frequency deviation of ≤1% rated value). This makes model an over simplified and realistic issues not being discussed. Such a linearized model is inadequate for large variations in power output (>±25% rated load) and frequency study (>±8% rated value) [6]. As the hydraulic turbine exhibits highly nonlinear characteristics that vary significantly with the unpredictable load on the unit, this requires controller gain scheduling at different gate positions and speed error. In practice they are designed on a linearized turbine model at rated condition, **the controller is then de-tuned for worst operating conditions**. Such a design approach does not perform optimally. Nonlinear models are required when speed and power changes are large during an islanding, load rejection and system restoration conditions. A nonlinear model should include the effect of water compressibility i.e. inclusion of transmission-line-like reflections which occur in the elastic-walled pipe carrying compressible fluid. This modelling is more important in a system with long penstock. An interesting area for control theory and application is in the study of a penstock-turbine model with elastic water column effect. To gain economic merits, determination of transfer function limits and operating limits have gained an importance in recent years, specially, in case of common penstock model. A hydraulic coupling between the units of the plant [3,4] gives an opportunity to investigate models of the hydro plant and turbine control existing in different plant layout/configurations.

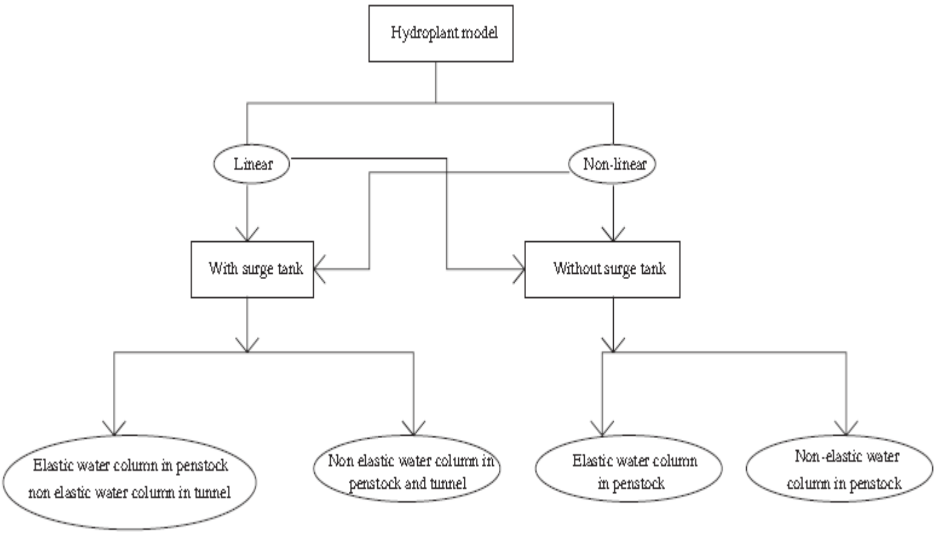


Fig. 6.5. Overview of hydropower plant models

The classical PID is the most common form of controller used in governing. The structure of the PID controller is simple. The three terms of the controller treat the current control error (P), past control error (I), and predicted future control error (D). Its use ensures faster speed response by providing both transient gain reduction/transient gain increase. The derivative term in the control action is important in case of isolated operation. Its use results in excessive oscillation in interconnected system. The transfer function of PID without derivative effect in action is equivalent to that of the hydraulic-mechanical governor. **The design is based on linear control theory at one load condition and then de-tuned for worst operating conditions.**

This controller design does not guarantee the close loop system to remain stable at all operating conditions.

6.1.1. DIGITAL GOVERNOR

Advancement in digital technology has resulted in tremendous reduction in digital component's cost and improvement in reliability. This in important alternative to analog circuitry PID controlled governor. A digital governor can be designed to offer:

- Speed control of the turbine;
- Operate sensitively and respond to errors ±15 Hz to restore the normal condition;
- Parallel operation in multi-machine system;
- A minimum dead band;
- Good dynamic response on load throw-off and during static frequency condition.
- Steep droop characteristics;
- Load control based on load reference and line frequency using feed back control
- loops;
- A self-regulating feature to stabilize the system.

6.1.2. MODERN APPROACH

Many methods are used in hydro plant control [6] These methods use:

- Adaptive control, self-tuning; such controller scheme offers on-line adjustment of controller parameters. The design also includes tracking of plant parameters as the operating parameters change, to provide optimal performance over the wide operating range.
- Genetic algorithm (GA) optimization approach for optimal governor tuning. GA may be one of possible means of adaptively optimizing the gains of proportional-plus-integral governors.
- Development of the intelligent tuning of PID controller - the use of adaptive and learning control scheme, which is neural network techniques. The PID gains are tuned adaptively by fusing both self-tuning control technique and neural networks.
- Neural network (NN) coordinated control for both exciter as well as governor for low head power plant. Their design is based on self organization and the predictive estimation capabilities of NN implemented through the cluster-wise segmented associative memory scheme [13]. The developed NN based

controller whose control signals are adjusted using the on-line measurements can offer better damping effects for generator oscillations over a wide range of operating conditions than conventional controllers.

- Fuzzy set theory and NN coordinated stabilizing control for the exciter and governor. The controller is said to be real time operating. In the design, for a non-linear system model, a linearized approximation is obtained for optimal linear regulators to serve as benchmark.
- In [74] intelligent integral strategy is realized by fuzzy logic. The output of fuzzy logic algorithm modifies the integral gain of PID regulator. This makes the response robust and adaptive.
- Intelligent fuzzy PID controller for regulating the turbine. The designed fuzzy logic compensator (FLC) improves the performance of conventional PID controller. The fuzzy PID controller offers a self-tuned control gains with proportional, integral and derivative gains as non-linear functions of the input signals.

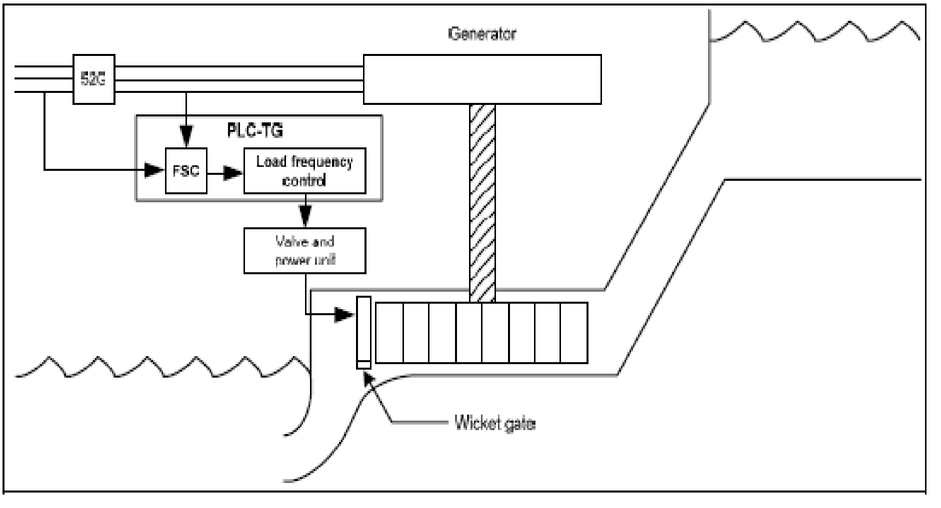


Fig. 6.6. Illustration of speed governor of hydro turbine PLC-TG - hydraulic turbine speed governor, FSC - -frequency signal converter.

6.2. CLASSIFICATION OF HYDROELECTRIC SYSTEM MODELS

6.2.1. PARAMETERS AND VARIABLES

Table 6.1. Parameters and variables [12]

Variable	Meaning
$A_{(c,p,s)}$	Cross section area of conduit in [m^2] (p: penstock; c: tunnel, s: surge tank).
$L_{(c,p)}$	Length of the conduit in [m] (p: penstock; c: tunnel).
a	Wave velocity in [m/s].
g	Acceleration of gravity [m^2/s].
α	$\alpha = \rho \cdot g(1/\kappa + \phi / f \cdot E)$.
ρ	Density of water [kg/m^3].
κ	Bulk modulus of compression of water [$kg/(m \cdot s^2)$]
ϕ	Internal conduit diameter [m].
f	Thickness of pipe wall [m].
E	Young's modulus of elasticity of pipe material
$T_{\overline{W}}$	Water starting time at any load in [s].
$T_{WP,WC}$	Water starting time at rated or base load in [s] (WP: penstock; WC: tunnel).
C_s	Storage constant of surge tank in [s].
$T_{e,ep,ec}$	Elastic time in [s] (e: conduit, ep: penstock, ec: tunnel).
T_p	Pilot valve and servomotor time constant in [s].
T_g	Main servo time constant in [s].
T	Surge tank natural period in [s].

$f_{p1,p2,0}$	Head loss coefficients in [pu] (p1: penstock, p2: tunnel, 0: surge chamber orifice).
$\Phi_{p,c}$	Friction coefficient in [pu] (p: penstock, c: tunnel).
k_f	Head losses constant due to friction in [pu].
A_t	Turine gain in pu.
$Z_{(p,c,n)}$	Hydraulic surge impedance of conduit (p: penstock, c: tunnel, n: normalized).
D_l	Turbine damping in [pu/pu].
$\overline{H}_{(t,r,l,l2,0,w)}$	Head in [pu] (t: turbine, r: riser of the surge tank; l: loss in penstock, l2: loss in tunnel, 0: reservoir, w: reservoir).
$\overline{U}_{(t,p,c,s,0,NL)}$	Velocity of the water in the conduit or flow in [pu] (t: turbine, p: penstock; c: tunnel, s: surge tank, 0: initial value, L: no load).
$\overline{H}_{(tcs,css)}$	Head in steady state[pu] (tss: turbine, css: tunnel).
$\overline{U}_{(tcs,css)}$	Velocity of the water in the conduit in steady state in [pu] (tss: turbine, css: tunnel).
$U \mid U_{(rated)}$	Velocity of the water in the conduit in steady state in [m/s] (rated: normalised)
$Q_{(base,rated)}$	Flow in the conduit in [m^3] (base, rated: turbine flow rate with gates fully open and head at the turbine equal to $H_{(base)}$).
$H \mid H_{(base)}$	Head in [m] (base value of head, i.e. total available static head).
$\overline{G} \mid \Delta\overline{G}$	Gate opening in [pu]. | Deviation of the gate opening in

	[pu]
$\overline{P} \mid \Delta\overline{P}$	Turbine mechanical power [pu] | Deviation of the mechanical power [pu]
$\Delta\overline{\varpi}$	Deviation of the rotor speed in [pu].

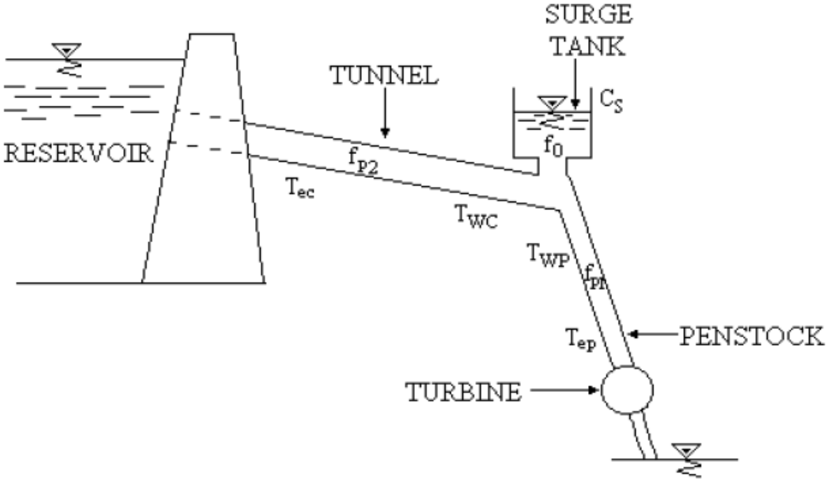


Fig.6.7. Distribution parameters in hydro power plant

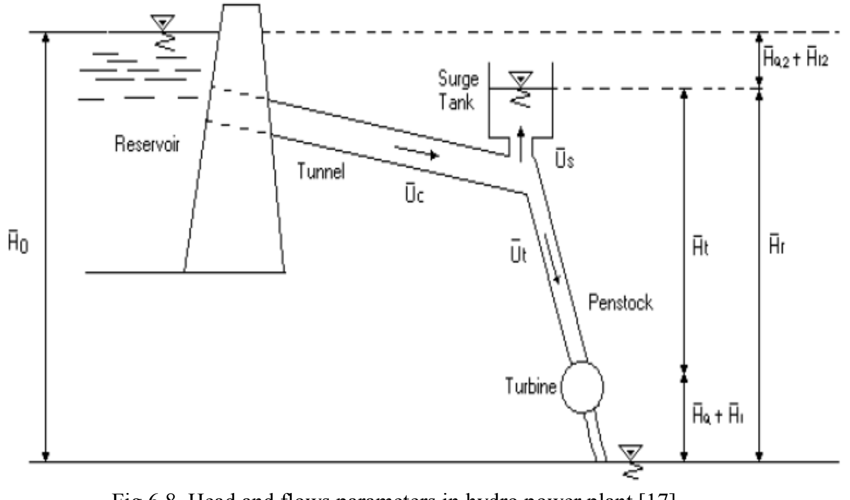


Fig.6.8. Head and flows parameters in hydro power plant [17]

6.2.2. MOST IMPORTANT DEFINITIONS AND PARAMETERS

- Elastic time:

$$T_{e(p,c)} = L_{(p,c)} / a = L_{(p,c)} / \sqrt{g / \alpha}$$

- Hydraulic surge impedance of the conduit:

$$Z_{(p,c)} = 1/(A_{(p,c)} \cdot \sqrt{g \cdot \alpha}$$

T_w – the water starting time , is defined as the time required to accelerate the flow from zero to rated (base) flow (Q_{base}) under the base head (H_{base}).

- Water starting time in penstock:

$$T_{WP} = \frac{L_p}{A_p \cdot g} \cdot \frac{Q_{base}}{H_{base}} = z_p \cdot T_{ep}$$

- Water starting time in tunnel:

$$T_{WC} = \frac{L_c}{A_c \cdot g} \cdot \frac{Q_{base}}{H_{base}} = z_c \cdot T_{ec}$$

- Storage constant of surge tank:

$$C_s = \frac{A_s \cdot H_{base}}{Q_{base}}$$

- Surge tank natural period:

$$T = 2\pi \sqrt{T_{WC} \cdot C_s}$$

- Relationship between flow and velocity of water in the conduit (tunnel or penstock):

$$Q = A \cdot U$$

- Relationship between the normalised flow and the normalised water velocity in the conduit (tunnel or penstock):

$$\frac{Q}{Q_{rated}} = \frac{A \cdot U}{A \cdot U_{rated}} \Rightarrow \overline{Q} = \overline{U}$$

6.2.3. BASIC EQUATIONS

The general equations of the hydroelectric system dynamics[7]:

- Flow Equation (water velocity) in the penstock:

$$U_t = \overline{G} \cdot \sqrt{H_t} \tag{6.1}$$

- Mechanical Power Equation

$$\overline{P}_{mechanical} = \overline{U} \cdot \overline{H} \tag{6.2}$$

$$\overline{P}_{mechanical} = (\overline{U}_t - \overline{U}_{NL}) \cdot \overline{H}_t \tag{6.3}$$

  $\overline{U}_{NL}$ considers the no load flow or the minimal flow needed to make the turbine deliver useful power.

- Newton's second law:

$$\frac{\partial U}{\partial t} = -g \cdot \frac{\partial H}{\partial x} \tag{6.4}$$

- Continuity equation:

$$\frac{\partial U}{\partial x} = -\alpha \cdot \frac{\partial H}{\partial t} \tag{6.5}$$

  where x – distance between two points.

The solutions of these equations (in per units) in the Laplace domain are given by:

$$\overline{U}_1 = \overline{U}_2 \cdot \cosh(T_e \cdot s) + 1/z_n \cdot \overline{H}_2 \sinh(T_e \cdot s) \tag{6.6}$$

$$\overline{H}_2 = \overline{H}_1 \cdot \sec h(T_e \cdot s) - z_n \cdot \overline{U}_2 \tanh(T_e \cdot s) - k_f \overline{U}_2 \cdot |\overline{U}_2| \tag{6.7}$$

The subscripts 1 and 2 refer to the conditions at the upstream and downstream ends of the conduit, respectively, e.g. when the surge tank-penstock-turbine hydraulic circuit is considered, the subscript 2 indicates downstream water (turbine) and subscript 1 indicates upstream water (surge tank).

6.2.4. LINEARIZED EQUATIONS

Linearizing equation (6.1) and (6.2) at operating point leads to:
Equation of the flow in the penstock (velocity of water):

[7] P. Kundur, „Power System Stability and Control" Mc Graw-Hill, New York,1994.

$$\Delta\overline{U} = \frac{\partial\overline{U}}{\partial\overline{H}}\Delta\overline{H} + \frac{\overline{\partial}U}{\partial\overline{G}}\Delta\overline{G} = a_{11}\Delta\overline{H} + a_{13}\Delta\overline{G} \tag{6.8}$$

Equation of the mechanical power:

$$\Delta\overline{P}_m = \frac{\partial\overline{P}_m}{\partial\overline{H}}\Delta\overline{H} + \frac{\partial\overline{P}_m}{\partial\overline{U}}\Delta\overline{U} = a_{21}\Delta\overline{H} + a_{23}\Delta\overline{G} \tag{6.9}$$

The partial derivatives a_{11}, a_{13}, a_{23} and a_{24} depend on kind of turbine and on the operating point, e.g. for the Francis turbine optimal values of these parameters should be:

a_{11}=0,5; a_{13}=1; a_{21} =1,5 and a_{24}=1 [Oldenburger and Donelson] [14].

6.2.5. CLASSIFICATION OF THE MODELS

The models can be classified into two basic groups:

- Nonlinear Models.
- Linear Models.

6.3 NONLINEAR MODELS

Nonlinear models of turbine control systems are useful in the cases where large turbine velocity and power changes exists, e.g. in isolated power stations, when a load rejection happens or in process of system restoration.

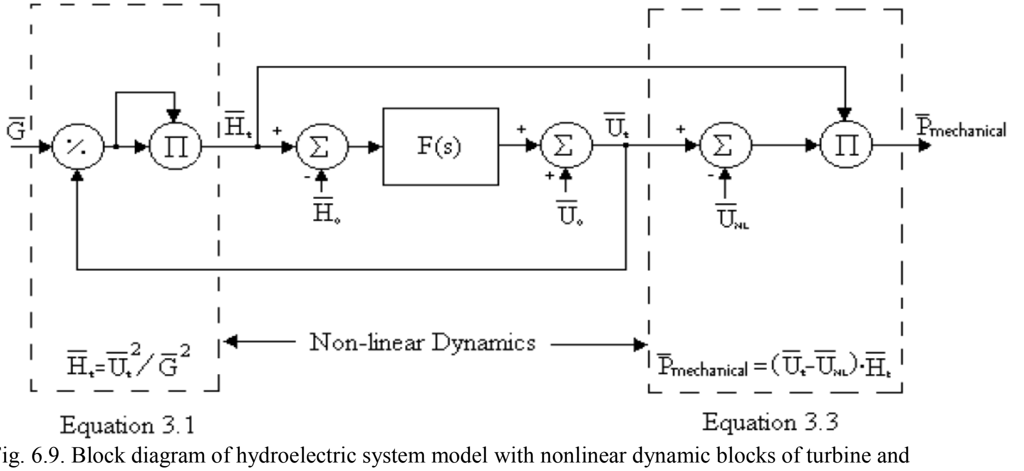
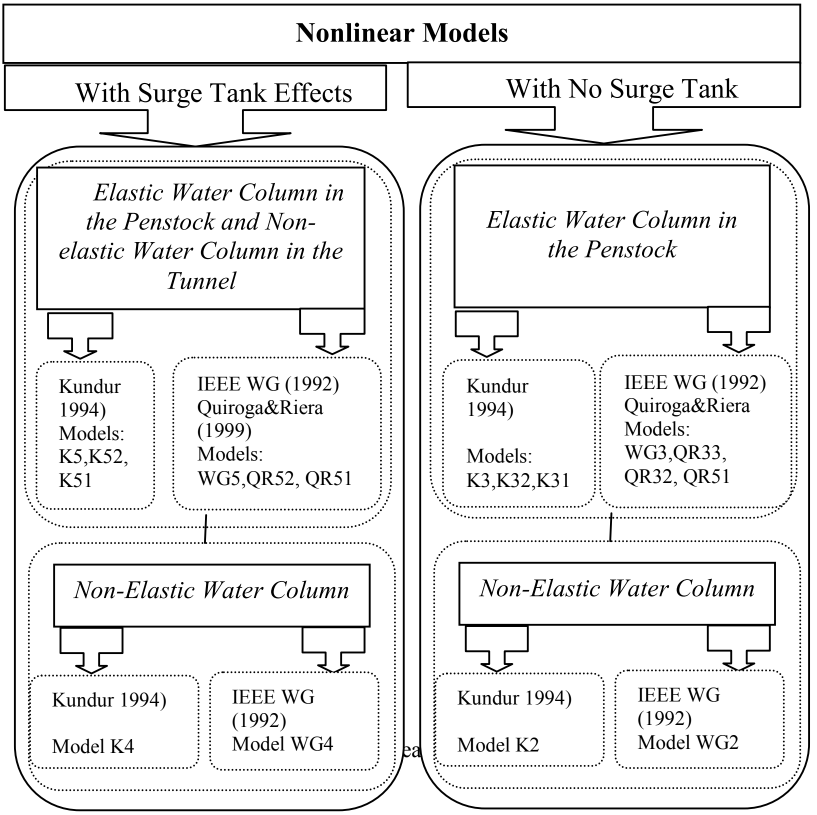


Fig. 6.9. Block diagram of hydroelectric system model with nonlinear dynamic blocks of turbine and mechanical power (models of Kundur).

Table in figure 6.10 summarizes the classification of nonlinear models with *surge tank effect* and *no surge tank effect*. In the first group of models elastic or non-elastic water columns can be considered. In the second group equation of continuity can be modified or non-modified.



6.3.1. MODELS WITH SURGE TANK EFFECTS

The main function of the surge tank is to hydraulically isolate the turbine from deviations generated in the head by transients in the conduits. Models with the surge tank take into account an undulatory phenomenon whose time period is T.

6.3.1.1. Model with an elastic water column in the penstock and a non-elastic water column in the tunnel.

The model K5 is the most complete. It includes surge tank effects and considers an elastic water column in the penstock, non-elastic water column in the tunnel, and the complete continuity equation.

Firstly, the relationship between the head and the flow in the turbine should be calculated. Equations (6.6) and (6.7) should be used in the following hydraulic circuits:

1. Reservoir-Tunnel Surge Tank,
2. Surge Tank-Penstock-Turbine.

By combining conveniently both relationship, a transfer function is obtained, which connects the turbine flow and its head:

$$F(s) = \frac{\overline{U}_t - \overline{U}_0}{\overline{H}_t - \overline{H}_0} = -\frac{1 + \dfrac{G(s)}{z_p} \cdot \tanh(sT_{ep})}{\Phi_p + G(s) + z_p \cdot \tanh(sT_{ep})} \tag{6.10}$$

According to Oldenburger and Donelson (1962), G(s) is

$$G(s) = \frac{\overline{H}_0 - \overline{H}_s}{\overline{U}_p - \overline{U}_0} = -\frac{\Phi_c + z_c \cdot \tanh(sT_{ep})}{1 + sC_s \cdot \Phi_c + z_c \cdot \tanh(sT_{ep}) \cdot sC_s} \tag{6.11}$$

The hyperbolic tangent function is given by

$$\tanh(sT_{ep}) = \frac{1 - e^{-2T_{ep} \cdot s}}{1 + e^{-2T_{ep} \cdot s}} - \frac{sT_{ep} \cdot \prod_{n=1}^{\infty} (1 + (\frac{sT_{ep}}{n\pi})^2)}{\prod_{n=1}^{\infty} (1 + (\frac{2sT_{ep}}{(2n-1)\pi})^2)} \tag{6.12}$$

Kundur (1994) considers for the hydraulic circuit reservoir-tunnel-surge tank the expansion with n=0, so that $\tanh(T_{ec} \cdot s) \approx T_{ec} \cdot s$. The physical meaning is that reservoir water level is considered constant.

The reservoir water level is considered constant. By replacing this result in (6.11), G(s) becomes

$$G(s) = \frac{\overline{H}_s - \overline{H}_0}{\overline{U}_p - \overline{U}_0} = -\frac{\Phi_c + sT_{WC}}{1 + sC_s \cdot \Phi_c + s^2 T_{WC} \cdot C_s} \tag{6.13}$$

The models K52 and K51 are obtained by considering in (6.10) the approximations n=2 and n=1 of equation (6.12). Finally, the models K52 and K51 are completed by combining equations (6.1), (6.3), (6.10) and (6.13), as is shown in figure 6.6.

6.3.1.2. Model with an elastic water column in the penstock and a non-elastic water column in the tunnel.

(IEEE Working Group, 1992; Quiroga and Rivera, 1999)

Models WG5, QR52, QR51

The solution of continuity equation (6.6) for these models is given by

$$\overline{U}_t = \overline{U}_c - \overline{U}_s \tag{6.14}$$

By applying this last equation in (6.7), the dynamic equations of the hydraulic circuit 1 and circuit 2, can e expressed as follows:

- Dynamics of the Tunnel:

$$\overline{H}_r = 1.0 - \overline{H}_{12} - \overline{H}_{Q2} \tag{6.15}$$

$$\overline{H}_{12} = f_{p2} - \overline{U}_c - |\,\overline{U}_c\,| \tag{6.16}$$

$$\overline{H}_{Q2} = T_{WC} \cdot \frac{d\overline{U}_c}{dt} \tag{6.17}$$

- Dynamics of the Surge Tank:

$$\overline{H}_r = \frac{1}{C_s} \cdot \int \overline{U}_s dt - f_0 \cdot \overline{U}_s \cdot |\,\overline{U}_s\,| \tag{6.18}$$

- Dynamics of the Penstock:

$$\overline{H}_1 = f_{p1} - \overline{U}_c^2 \tag{6.19}$$

$$\overline{H}_Q = z_p \tanh(T_{ep} \cdot s) \cdot \overline{U}_t \tag{6.20}$$

$$\overline{H}_t = \overline{H}_r - \overline{H}_1 - z_p \tanh(T_{ep} \cdot s) \cdot \overline{U}_t = \overline{H}_r - \overline{H}_1 - \overline{H}_Q \tag{6.21}$$

- Mechanical Power:

$$\overline{P}_{mechanical} = A_t \overline{H}_t (\overline{U}_t - \overline{U}_{NL}) - \overline{P}_{damping} \tag{6.22}$$

$$\overline{P}_{damping} = D_1 \overline{G} \Delta \varpi \tag{6.23}$$

The last expression represents the damping effect due to friction and it is proportional to the rotor speed deviation and to the gate opening. It is indispensable to include equation (6.1) that represents the relation among turbine flow, the turbine head and the gate opening.

For the models QR52 and QR51 equations (6.1), (6.14) ÷ (6.20) (6.22) ÷ (6.23) are valid. Putting approximations n=2,1 of (6.12) in (6.21), yields

$$\overline{H}_t = \overline{H}_r - \overline{H}_1 - z_p \tanh(T_{ep} \cdot s)\,|_{n=1,2} \cdot \overline{U}_t \tag{6.24}$$

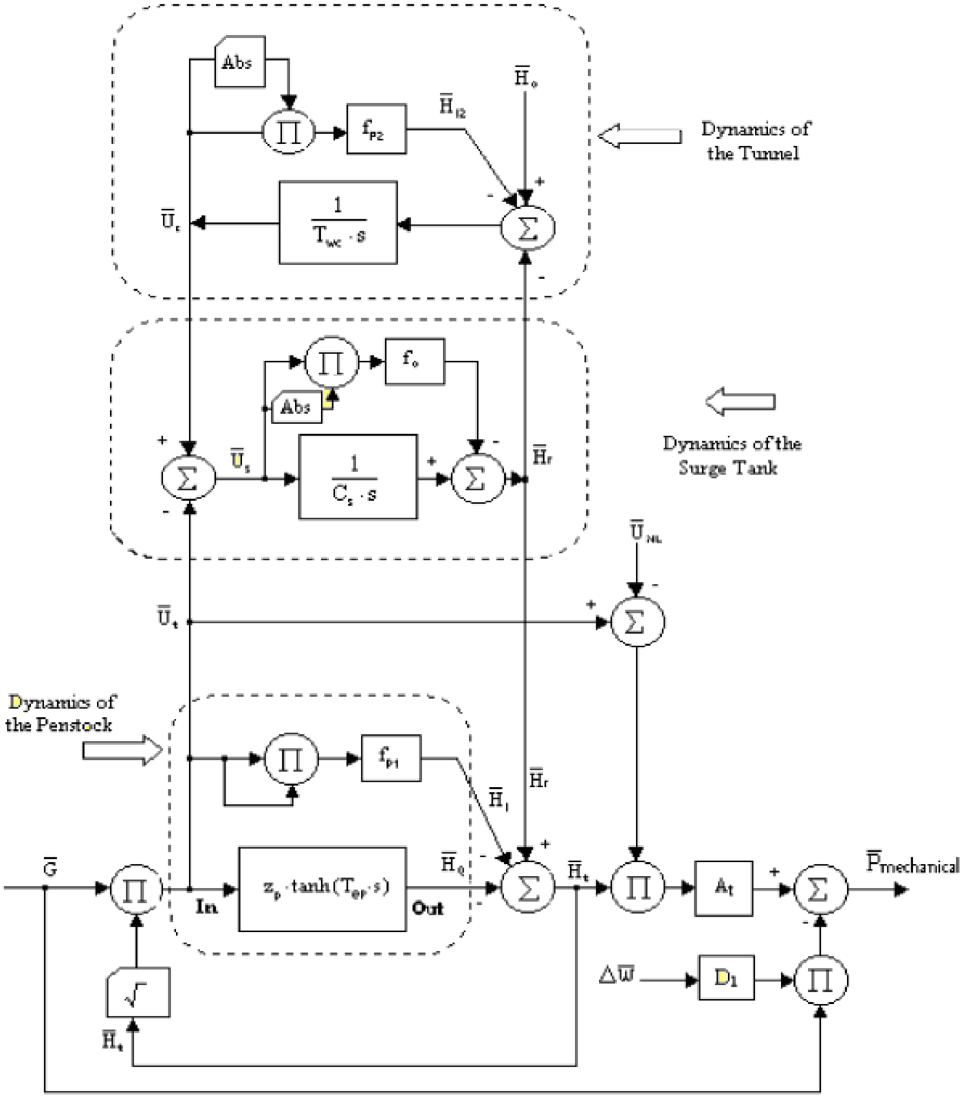


Fig. 6.11. Functional diagram of model WG5 from the IEEE Working Group (1992) including associated dynamics [17].

6.3.1.3. Model with non-elastic water columns. Model K4 (Kundur)

Water columns in this model are seen as rigid conduits. For the penstock $\tanh(T_{ep}\cdot s)\approx T_{ep}\cdot s$. Hence equation (6.10) becomes

$$F(s) = \frac{\overline{U}_t - \overline{U}_0}{\overline{H}_t - \overline{H}_0} = -\frac{1 + \dfrac{G(s)}{z_p}\cdot sT_{ep}}{\Phi_p + G(s) + z_p \cdot sT_{ep}} \qquad (6.25)$$

where G(s) for this equation comes from (6.13).

To obtain the complete model, equation (6.25) must be combined with equations (6.1) and (6.3).

6.3.1.4. Model with non-elastic water columns. Model WG4 (IEEE Working Group, 1992)

This model is based on equations (6.14)÷(6.19) and (6.23). With adopted approximations: $\tanh(T_{ec}\cdot s)= T_{ec}\cdot s$ and $\tanh(T_{ep}\cdot s)= T_{ep}\cdot s$. The equation of the penstock dynamics for this case is given by

$$\frac{d\overline{U}_t}{dt} = \frac{\overline{H}_r - \overline{H}_t - \overline{H}_1}{T_{Wp}} \qquad (6.26)$$

6.3.1.5. Comparison between the models with an elastic water in the penstock and non-elastic water columns

The comparison between models requires the analysis of the flow and head in the hydraulic circuit reservoir-tunnel-surge tank and the analysis of the equation of the dynamics of the surge tank.

Analysis of the Heads

In the model K5 using of equation (6.7) to the reservoir tunnel surge tank hydraulic circuit leads to

$$\overline{H}'_w = \overline{H}_r + z_c \tanh(T_{ec}\cdot s)\cdot \overline{U}_c + \Phi_c \cdot \overline{U}_c$$

$$\overline{H}'_w = \overline{H}_r + T_{WC}\cdot (d\overline{U}_c / dt) + \overline{H}_{12} = \overline{H}_r + \overline{H}_{Q2} + \overline{H}_{12} \qquad (6.27)$$

where

$$\overline{H}'_w = \overline{H}_w \cdot \sec h(T_{ec}\cdot s) \qquad (6.28)$$

The reservoir head $\overline{H}'_w$ is a function of s (s=σ+jω) and T_{ec}. If the reservoir level is considered constant it means that the reservoir has considerably large dimension. In this case $\tanh(T_{ec}\, s)\approx T_{ec}\, s$ and $\sec(T_{ec}\, s)\approx 1$. Therefore, $\overline{H}'_w = \overline{H}_w$, and then

$$\overline{H}_w = \overline{H}_r + \overline{H}_{Q2} + \overline{H}_{12} \tag{6.29}$$

In model WG5, applying equation (6.15) to the reservoir tunnel surge tank hydraulic circuit leads to

$$\overline{H}_0 = \overline{H}_r + T_{WC} \cdot (d\overline{U}_c / dt) + \overline{H}_{12} = \overline{H}_r + \overline{H}_{Q2} + \overline{H}_{12} \tag{6.30}$$

where $\overline{H}_0 = \overline{H}_w = 1.0$. This last equation is similar to the equation of the heads of the model K5 (6.29).

Analysis of Flows

Applying equation (6.6) in the model K5 leads to

$$\overline{U}_c = (\overline{U}_s + \overline{U}_t) \cdot \cosh(T_{ec} \cdot s) + 1 / z_c \cdot \overline{H}_r \cdot \sinh(T_{ec} \cdot s) \tag{6.31}$$

According to the approximation tanh(T_{ec}·s)≈ T_{ec}·s, cos(T_{ec}·s)≈1 and sinh(T_{ec}·s) ≈T_{ec}·s, the continuity equation takes the following form

$$\overline{U}_c = (\overline{U}_s + \overline{U}_t) + 1 / z_c \cdot \overline{H}_r \cdot (T_{ec} \cdot s) \tag{6.32}$$

In accordance with equation (6.14), the model WG5 uses the following modified continuity equation (Figure 6.8)

$$\overline{U}_c = \overline{U}_s + \overline{U}_t \,.$$

This equation implies that impedance of tunnel (z_c) is quite large and is called by the [17] the modified continuity equation in order to differentiate from continuity equation (3.31).

Analysis of the dynamic equation of the surge tank

In model K5 equation of the surge tank without considering the riser has the following expression

$$\overline{H}_r = \frac{1}{C_s} \cdot \int \overline{U}_s dt \tag{6.33}$$

In model WG this dynamics is given by (6.18). Therefore, the difference between both models is that K5 does not consider the surge chamber orifice head loss coefficient. Thus, models consider different surge tanks.

6.3.1.6. Comparison between the models with non-elastic water columns in the penstock and non-elastic water columns (6.3.1.3 and 6.3.1.4)

Analysis of the Heads

The surge tank-penstock-turbine hydraulic circuit takes the approximation n=0 for hyperbolic tangent function, or $\tanh(T_{ep}\cdot s) \approx T_{ep}\cdot s$ (non-elastic water column in penstock). This also means that $\operatorname{sech}(T_{ep}\cdot s) \approx 1$.

By applying equation (6.7) to the surge tank-penstock-turbine hydraulic circuit

$$\overline{H}_t = \overline{H}'_r + z_p \tanh(T_{ep}\cdot s)\cdot\overline{U}_t + \Phi_p\cdot\overline{U}_t$$

$$\overline{H}_t = \overline{H}'_r - \overline{H}_Q - \overline{H}_1$$

Where $\overline{H}'_r = \overline{H}_r \sec h(T_{ep}\cdot s)$, so $\overline{H}'_r = \overline{H}_r$ and

$$\overline{H}_t = \overline{H}'_r - \overline{H}_Q - \overline{H}_1 \qquad (6.34)$$

In model WG4 the relationship of heads is deduced from equation (6.21), which is similar to equation (6.34), as can be seen in figure (6.7). This means that there are no differences in heads between the models K4 and WG4.

6.3.2. MODELS WITH NO-SURGE TANK EFFECTS

6.3.2.1 Models with an elastic water column in the penstock (Kundur – K3,K32,K31)

In the model K3, transient function of the hydraulic circuit (reservoir-penstock-turbine) is as follows

$$F(s) = \frac{\overline{U}_t - \overline{U}_0}{\overline{H}_t - \overline{H}_0} = -\frac{1}{\Phi_p + z_p\cdot\tanh(sT_{ep})} \qquad (6.35)$$

Where approximation n=2 and n=1 (6.12) leads to model K32 and K31.

6.3.2.2 Models with an elastic water column in the penstock (WG3,QR33,QR32,QR31)

The equation of the dynamic of the penstock is given by formula:

$$\overline{H}_t = (\overline{H}_0/\overline{H}_0) - \overline{H}_1 - z_p \tanh(T_{ep}\cdot s)\cdot\overline{U}_t = 1.0 - \overline{H}_1 - \overline{H}_Q \qquad (6.36)$$

where $$\overline{H}_Q = z_p \tanh(T_{ep}\cdot s)\cdot\overline{U}_t$$

Taking approximation n=2 and n=1 of the hiperbolic tangent (6.12), gives models QR31 and QR32

$$\overline{H}_t = 1.0 - \overline{H}_1 - z_p \tanh(T_{ep} \cdot s)\,|_{n=1,2} \cdot \overline{U}_t \tag{6.37}$$

6.3.2.3 Models with non-elastic water column in the penstock – model K2

Transfer function is given by equation (from 6.3) putting $\tanh(T_{ep}\ s) \approx T_{ep}\ s$ and friction coefficient in penstock $\Phi_p=0$

$$F(s) = \frac{\overline{U}_t - \overline{U}_0}{\overline{H}_t - \overline{H}_0} = -\frac{1}{sT_{WP}} \tag{6.38}$$

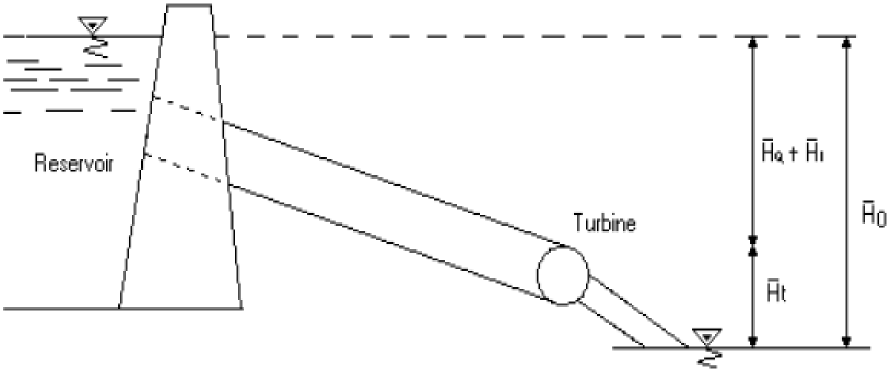


Fig 6.12. Diagram of heads and flows distribution in models WG3,QR33,QR32,QR31 and WG2

6.4 LINEARIZED MODELS

Linearizing the mechanical power model equation (6.2) and flow equation (6.1) leads to linearized models useful in cases of small signal stability and frequency response studies (IEEE Working Group, 1992, Kundur, 1994). These methods are classified in

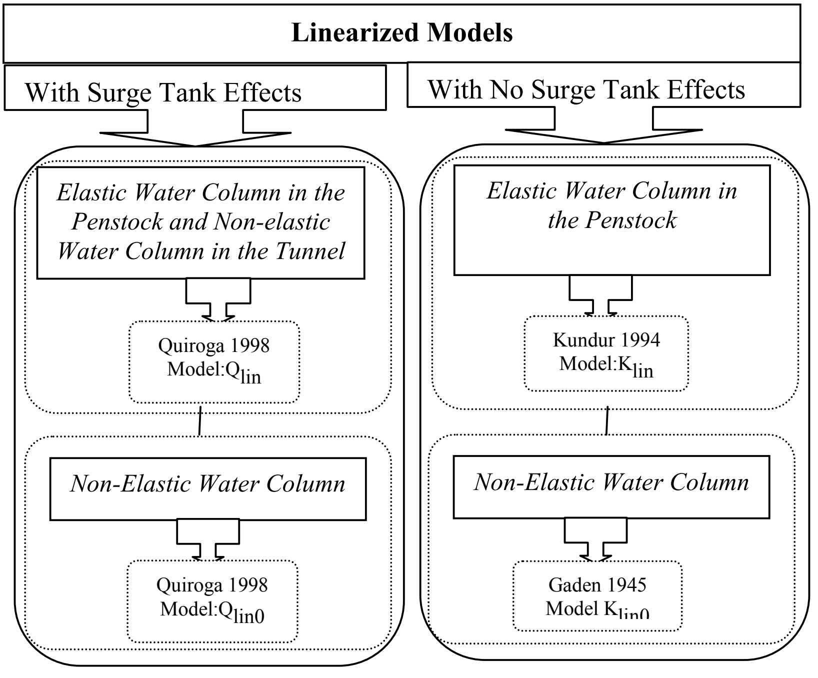


Fig. 6.13. Classification of the linear methods [17]

6.4.1. MODELS WITH SURGE TANK EFFECTS

6.4.1.1 Models with an elastic water column in the penstock and non-elastic water column in the tunnel – model Q_{lin}.

$$\frac{\Delta \overline{P}_m}{\Delta \overline{G}} = \frac{1 - \Phi_p + z_p \cdot \tanh(sT_{ep}) + \dfrac{G(s)}{z_p}\tanh(sT_{ep}) - G(s)}{1 + 0.5\Phi_p + 0.5 z_p T_{ep} s + 0.5 G(s) \cdot \dfrac{G(s)}{z_p}\tanh(sT_{ep})} \qquad (6.39)$$

This model may be interesting when a frequency response study is necessary, in particular, when stability studies are required.

6.4.1.2 Models with non-elastic water column– model Q_{lin0}.

The model Q_{lin0} is the simplification of model Q_{lin0} for the hyperbolic tangent (n=0), which means a non-elastic water column in the penstock is taken into account. Equation (6.39) leads to the following form

$$\frac{\Delta\overline{P}_m}{\Delta\overline{G}} = \frac{1-\Phi_p + z_p\cdot\tanh(sT_{ep}) + \dfrac{G(s)}{z_p}\cdot sT_{ep} - G(s)}{1+0.5\Phi_p + 0.5z_pT_{ep}s + 0.5G(s)\cdot\dfrac{G(s)}{z_p}\cdot T_{ep}s} \tag{6.40}$$

6.4.2. MODELS WITH NO-SURGE TANK EFFECTS

6.4.2.1 Models with an elastic water column in the penstock– model K_{lin}.

The model result from equation (6.8.), (6.9) and (6.35) with assumption elastic water column in the penstock:

$$\frac{\Delta\overline{P}_m}{\Delta\overline{G}} = \frac{1-\Phi_p - z_p\cdot\tanh(sT_{ep})}{1+0.5\Phi_p + 0.5z_pT_{ep}s} \tag{6.41}$$

6.4.2.2 Models with non-elastic water column in the penstock– model G_{lin0}.

The model results from equation (6.8.), (6.9) and (6.38). The transfer function F(s) considers non-elastic water column in the penstock and the penstock head loss coefficient is equalled to zero. Transfer function has form

$$\frac{\Delta\overline{P}_m}{\Delta\overline{G}} = \frac{1-z_p\cdot sT_{ep}}{1+0.5z_pT_{ep}s} = \frac{1-T_{WP}\cdot s}{1+0.5T_{WP}\cdot s} \tag{6.42}$$

6.5 TIME DOMAIN ANALYSIS

Time domain analysis of models 6.3 and 6.4 can be checked using SIMULINK toolbox of the MATLAB. Such deep analysis, with comparison of models is done in [Quiroga]. In the figure 6.14 is shown a chart of P_{mech} for models WG2, QR31, QR32, QR33 and WG3 as the example is shown. It was obtained for data of chosen hydro power plant.

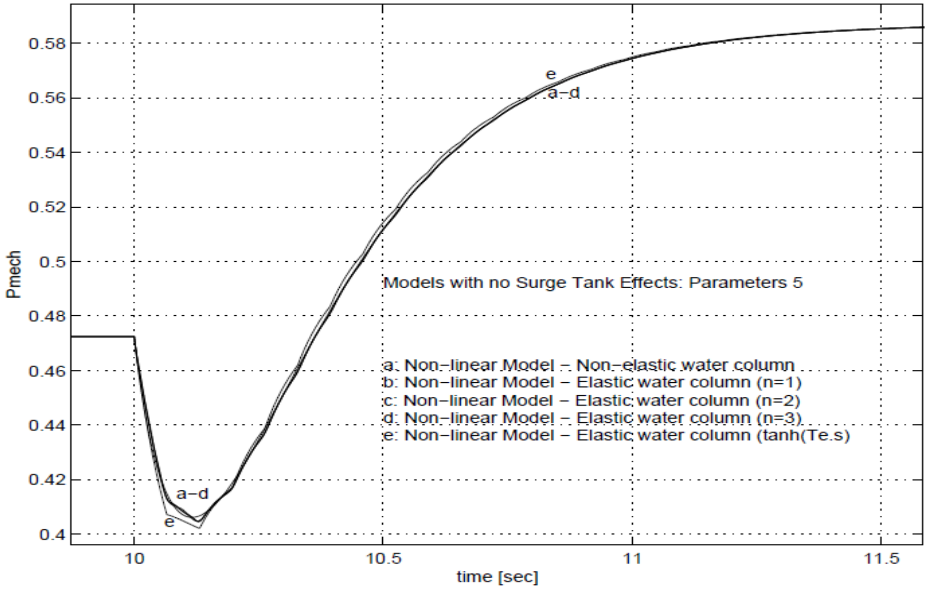


Figure 6.14. Comparison among the models WG2, QR31, QR32, QR33 and WG3.

A large number of control models enables to adjust one of them to real construction and technical solutions of real hydro power plants. According to [Quiroga] the following features of these methods are interesting:

1. The model WG5 allows the best approximation since it represents all the phenomena in detail. It can show non-minimal phase behaviour for a step input but may be inconvenient or complex for application. Therefore, when a control must be designed, instead of WG5, it is necessary to take the lumped approximations of this function and the model is turned into QR2, QR51 or WG4.
2. Models of Kundur are interesting in the analysis of the hydroelectric plant in a general sense but not for the design of a speed control.
3. Linearized models are interesting when a frequency response analysis is necessary for stability studies. Only the simplest model can be used since these models are unstable for lumped approximations greater than n=0.
4. For models with no surge tank effects, K3, K32, K31 models are interesting for performance analysis and for controllers design.
5. Models K_{lin} and G_{lin} are useful in cases when small-signal stability studies are required (Kundur, 1994).

6.6 NONLINEAR CONTROLLERS

General control scheme showing relationship between parts of hydroelectric control system is shown in figure 6.15. It includes speed control and generation control. The frequency of hydroelectric system depends on the balance of active power. If a change in active power demand occurs and a power balance is affected, the speed of turbine and the frequency of the synchronous generator are also affected. In order to control the active power both control loops should be used.

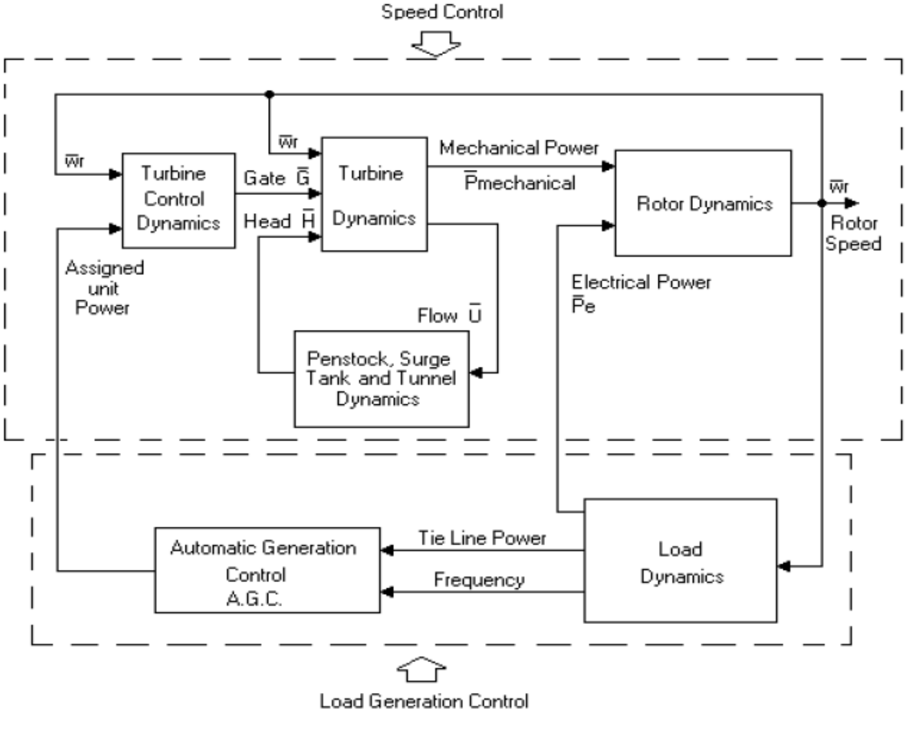


Figure 6.15. General scheme of hydroelectric control system [17].

General speed control scheme for a hydropower plant supplying an isolated load is shown in figure 6.16.

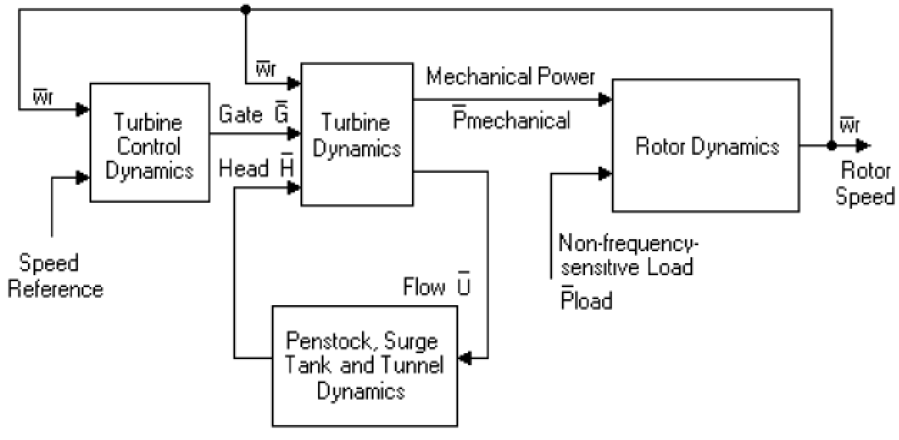


Fig.6.16. General speed control scheme for hydropower plant

Controllers of dhe different structure may be applied. Among them the PID, PI-PD, Gain Scheduling PID and Gain Scheduling PI-PD may be the typically used. The standard PID controller is shown in figure 6.17.

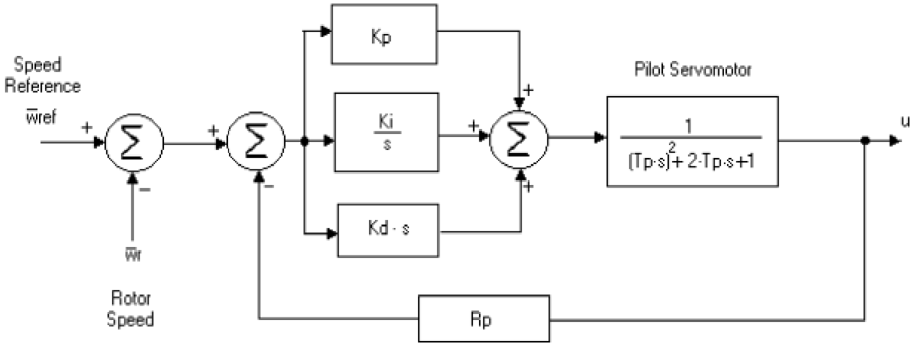


Figure 6.17.Scheme of standard PID controller.

6.7. EXAMPLES OF CONTROL REALISATIONS

Example of real, simplified control system, for SHP described in section 4, is shown in figure 6.18.

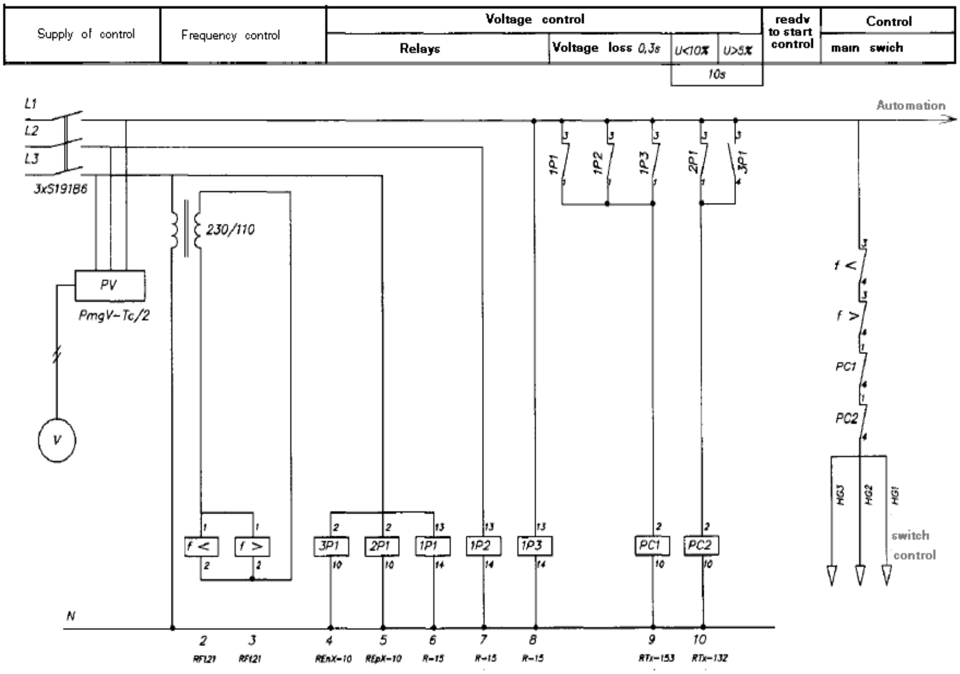


Fig.6.18. General diagram of the hydroelectric power station control system [15]

Equipment control

The scheme of turbine gate opening control is shown in figure 6.19 and control of breakers in figure 6.20.

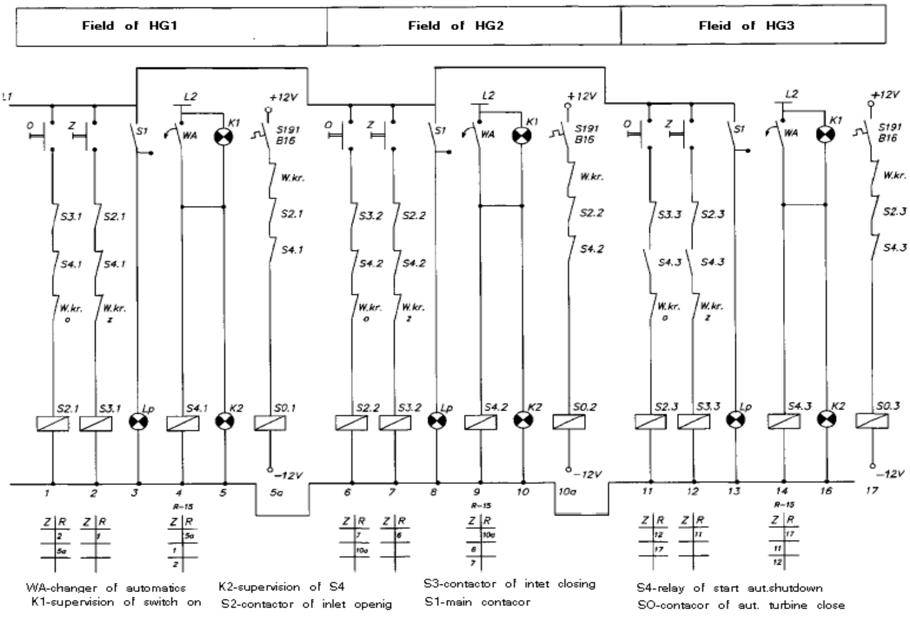


Fig. 6.19. Diagram of turbine capacity opening control [15].

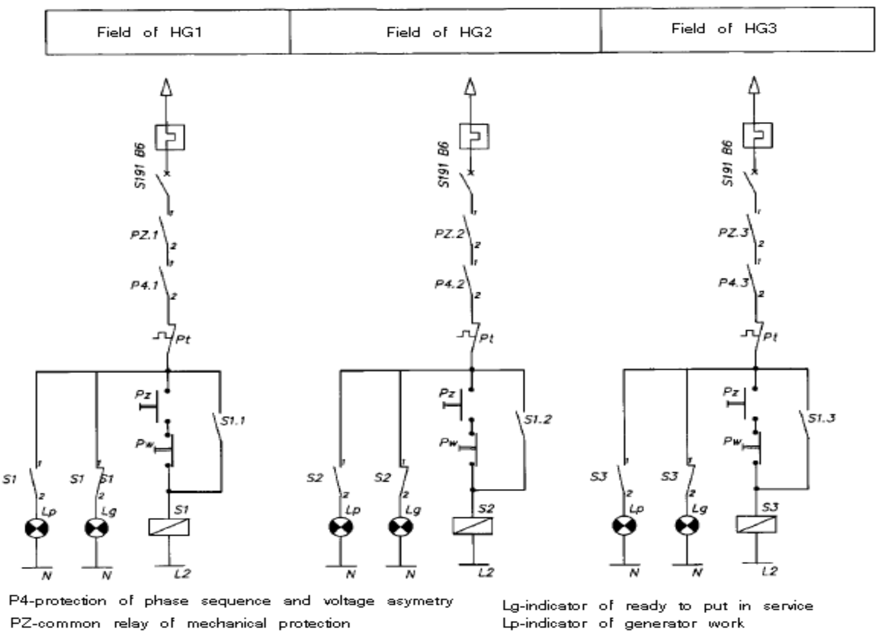


Fig.6.20. Diagram of switches control [15].

COMPUTER BASED CONTROL OF HYDRO ELECTRIC STATION

The hierarchy of computer control hierarchy is shown in table 6.2.

Table 6.2. Summary of control hierarchy

CONTROL CATEGORY	SUBCATEGORY	REMARKS
Location	Local	Control is local at the controlled equipment or within sight of the equipment
	Centralized	Control is remote from the controlled equipment, but within the plant
	Offsite	Control location is remote from the project
Mode	Manual	Each operation needs a separate and discrete initiation;
	Automatic	Several operations are precipitated by a single initiation;
Operation supervision	Attended	Operator is available at all times to initiate control action
	Unattended	Operation staff is normally not available at the project site

6.3.1. CONTROL OF UNIT OPERATION

Synchronizing, loading and stopping from a central control room are based on control of unit operation and type of control schemes of pre start checks of starting. Starting of the unit may be performed by means of a sequence master controller (MC) switch installed on the control panel of each unit:

1. generally the main inlet valve is opened and unit auxiliaries are started,
2. the turbine is started and brought up to speed at no load and field breaker is closed,
3. the paralleling of the unit is carried out and unit is synchronized with the generator bus by closing generator breaker.

4. the loading of the unit to a preset value is carried out. MC switch is used in a similar way for controlled action shutdown. Starting, synchronizing and loading automatically on receipt of single starting impulse is provided in automated hydro stations.

The control system receives input signals from main equipment such as the turbine or the generator and from various other accessory equipment, such as the governor, exciter, and automatic synchronizer. Status inputs are obtained from control switches and level and function switches indicative of pressure, position, etc. throughout the plant.

The proper combination of these inputs to the control system logic will provide outputs to the governor, the exciter, and other equipment to start or shutdown the unit. Any abnormalities in the inputs must prevent the unit's start up, or if already on-line, provide an alarm or initiate its shutdown.

Generator Control –excitation control of synchronous generator

The excitation is an integral part of a synchronous generator which is used to regulate the operation of the generator. The main functions of excitation system of a synchronous generator are:

- Voltage control in case of isolated operation and synchronising,
- Reactive power or power factor control in case of interconnected operation.

Reactive Power and Voltage Control - synchronous generator

When the unit is serving isolated load, its terminal voltage is held to a scheduled value by means of **continuously acting automatic voltage regulator**. The reactive power requirements of the load connected to it are adjusted **by excitation control called power factor control**. When unit is connected to a large power system, the system voltage and any change in its excitation results only in changing its kilovar loading and its power factor.

Generally, the unit is operated at rated kilovar load. The maximum and minimum excitation applied to the generator is dependent upon the **reactive power capability of the unit**. Limitations:

- on the high side – results from field and armature overheating,
- on the low side - results from stability and loading power factors.

6.3.2. PLC BASED CONTROL

Control systems based on PLC technology take advantage of their inherent properties:

- Extremely **reliable**, industrially hardened with no moving parts;
- **Flexible**, a single PLC can control multiple machines;

- **Modular**, components can be easily added to operate new equipment;
- "Off the shelf" components are widely stocked;
- Simple to program using traditional ladder-logic;
- Program can be easily modified, changes can be made in the field;
- Service can be performed by local technicians;
- Visual program operation makes troubleshooting quick and simple;

Compatible with a wide range of communication networks;

Allows remote access to operation, information transfer, troubleshooting, and program modification.

Plant PLC and GSM- or PTT-modem

The simplest remote controlling or monitoring implementation requires only GSM- or PTT-modem. This applies to one directional data transfer, usually a SMS message that alarms or just informs the personnel. If a PLC program can handle the most usual abnormal situations this kind of an implementation can reduce the service costs delivering the necessary information about the failure or alarm. Based on this information it can be determined whether the service visit is required or not.

In pilot hydro plants, the typical messages are loss of mains or return of mains. The investment costs of this type of system are approximately 1000€. This type of implementation can also receive SMS messages.

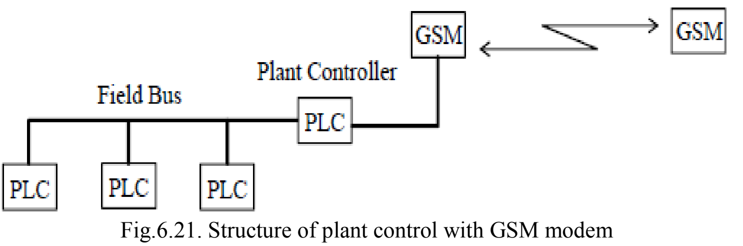
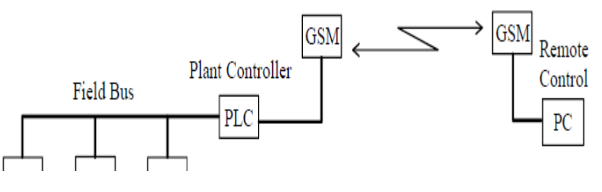


Fig.6.21. Structure of plant control with GSM modem

Plant PLC and GSM- or PTT-modem

A more sophisticated monitoring and remote control is accomplished by using a computer instead of a GSM telephone and very simple field bus protocol through a modem.



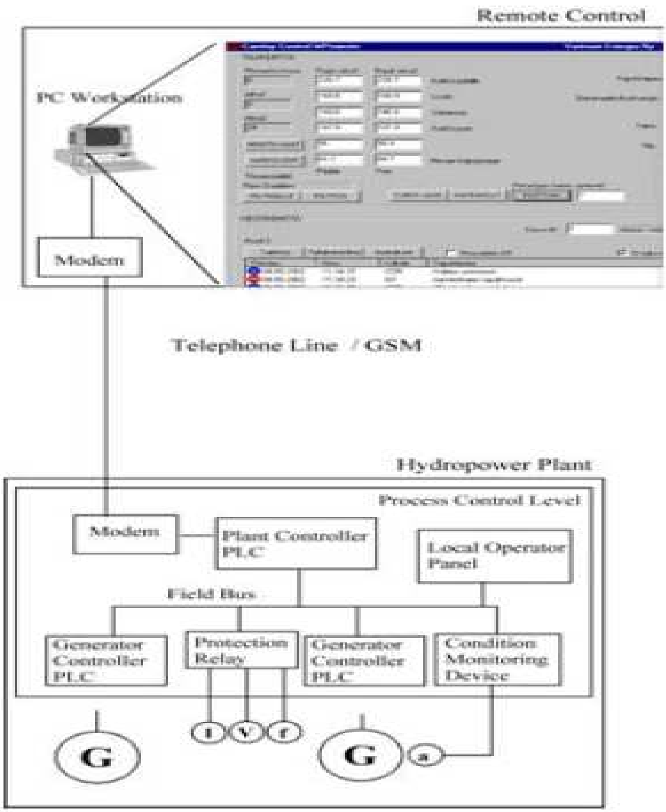


Fig.6.23. Example of application: Idea of plant GSM remote control

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7. PROTECTION

The designer must balance the expense of applying a particular relay against the consequences of losing a generator. The total loss of generator may not be catastrophic if it represents a small percentage of the investment in an installation. However, the impact on service reliability and upset supplied loads must be considered. Damage to equipment and loss of product in continuous processes can be dominating concern rather than generating unit. Accordingly there is no standard solution based on MW-rating. However, it is rather expected that a 200 kW, low voltage hydro machine will have less protection compared to 20 MW base load hydro electric machine.

With increasing complexity of in power system, utility regulation, stress on cost reduction and trends towards automation, generating unit protection has become a high focus area. State of the art of a micro controller based protection schemes offer a range of economical, efficient and reliable solution to address the basic protection and control requirements depending upon the size and specific requirement of the plant.

To basic types of protection used in SHP the following ones can be of the most importance:

- Over-frequency protection activated when frequency exceed the upper-frequency limit.
- Under-frequency protection activated when frequency exceed the lower-frequency limit.
- Over-voltage protection.
- Under-voltage protection.
- Protection against the voltage dips on the low voltage bus-bar.

7.1. PROTECTION OF TURBINE

Two level protection is recommended by IEC 1116. Elements to be considered are:

(a) Speed rotation

(b) Oil levels in bearing

(c) Circulation of lubricants

(d) Oil level of the governing system

(e) Oil level of speed increaser (if provided)

(f) Bearing temperatures

(g) Oil temperature of governing system

(h) Oil temperatures of speed increasers

(i) Oil pressure of governing system

(j) Pressure of cooling water

Immediate tripping is required for a, c, i, and j, whereas for item b, d, e, f, g and h only alarm and annunciation is required to alert the operator and take corrective action, but in case corrective action is not taken, tripping will eventually follow. Brakes are applied at a particular [8]speed (30% of full speed) for time reduction in achieving stand still position of machine.

It is recommended to use two independent devices must to shut down over speed on larger machines.

7.2. PROTECTION OF GENERATOR

7.2.1 REQUIREMENTS FOR PROTECTION OF GENERATOR

Elements to be considered normally are:

a. Stator temperature,
b. Over current (stator and rotor),
c. Earth fault with current limits (stators & rotor),
d. Maximum and minimum voltage,
e. Power reversal,
f. Over/ under frequency,
g. Oil level in bearing sumps,
h. Pad & oil temperature of bearings,
i. Cooling air temperature.

Immediate tripping is required for items b, c, d, e & f while for items a, g, h and i first alarm and annunciation is required for taking correcting measure and then tripping if correcting measure is not taken within permissible time. It is advisable to provide heating arrangement to prevent condensation in generator.

In view of the economy and plant requirements generator protection for small hydropower stations is categorized as follows:

• Generator size less than 300 kVA,
• Generator size 300 to 1000 kVA,
• Generator size 1 MVA to 10 MVA,
• Generator size above 10 MVA.

[8] Guidelines For Monitoring Control And Protection of SHP Stations, Alternate Hydro Energy Centre Indian Institute Of Technology, Roorkee

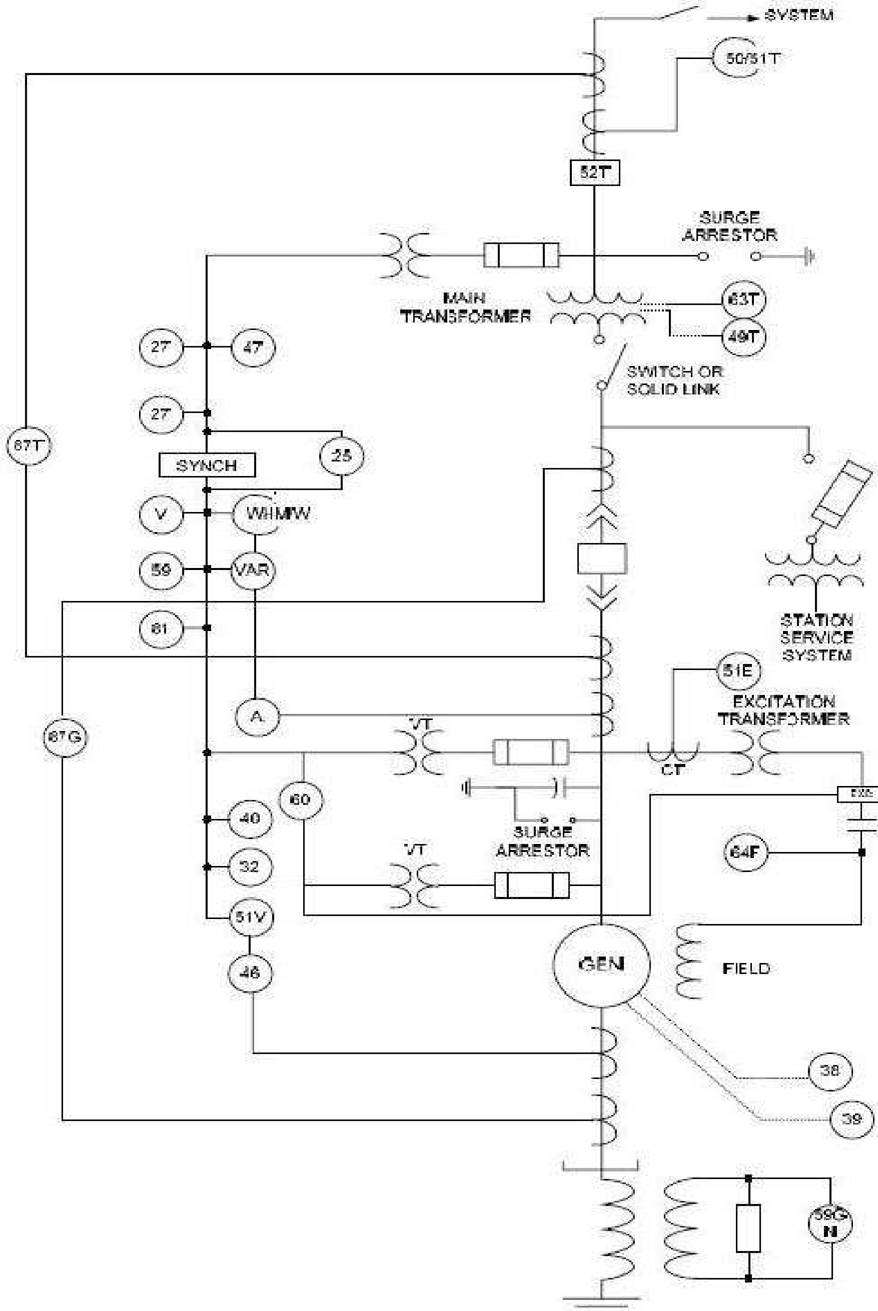

Fig.7.1.Diagram of typical protection diagram for small hydro unit

Where:

Basic Package
21 Distance
24 Over excitation
27 Under voltage
27TN Third harmonic under voltage
32 Reverse power
40 Loss-of-excitation
46 Current unbalance (negative sequence)
51GN Ground over current (backup to 64G)
51V Voltage-restrained over current
59 Over voltage
60V VT fuse failure detection
64G Stator ground
64F Ground (field)-I
87G Percentage differential
50/27 Accidental energisation protection
95 Trip circuit monitoring
86G Lockout auxiliary relay
12 Over speed relay
Options
21G System backup distance relay (in place of 51V)
49R Stator over temperature relay (RTD)
60V2 Voltage ground relay-II
78 Out-off step relay.
81L/H Under/ Over frequency.

Example

For the SHP described in chapter 5, the following protections are used:

1. Overfrequency protection (activating if frequency exceeds upper limits). Parameters of overfrequency relays: f set at 51 Hz, and their time unit set on 0,5 s.
2. Underfrequency protection (activating if frequency exceeds lower limits). Parameters of overfrequency relays: f set at 49 Hz, and their time unit set on 0,5 s.
3. Overvoltage protection (activating if phase voltage of network exceeds upper limits). Parameters of overvoltage relays: U set at 253 V (110% of 230 V), and their time unit set on 10 s.

4. Overvoltage protection (activating if phase voltage of network exceeds lower limits). Parameters of overvoltage relays: U set at 207 V (90% of 230V), and their time unit set on 10 s.
5. Protection from loss of electricity on nn buses. Parameters of relays U set on 0,8*U_N and their time unit set on 0,3 s.
6. Separate protection unit in area of each generator tripping protected generator:
   a. Thermal (overload) protection of generator. Responding to active power overload. Setting depend on turbine power of generator rating.
   b. Protection .responding to direction of field wiring and load asymmetry. It is activated in the case of asymmetry of stator currents. Negative sequence current component can cause flow of additional current in the rotor circuit and overheating of its winding.
   c. Protection against taking energy from the network by generator. It is directional-power protection type.
   d. Protection controlling speed of rotation preventing interlock. It responds when rotational speed is incorrect and interlock the generator switch on.
   e. Mechanical protection in the generator bay acting on generator switch off:
      - protection from belt break; acting on engage the clutch turbine-generator unit;
      - protection of open-close state of turbine gate; it is double limit switch;
      - protection to close and break the turbine after acting the main switch;
      - protection against increasing of rotation speed of turbine; it is inertia protection.
7. Electrical protection in the bay of feed line common for all generators. It initiates circuit breaker opening and locks the turning on.

Auxiliary circuits

The safety and continuity of output of a generating plant largely depend on the reliability of the electrical supplies to the auxiliaries. Hence careful consideration should be given to the design of the electrical auxiliary distribution system.

Switchgear equipment

Switchgear must be installed to control the generators and to interface them with the grid or with an isolated load. It must provide protection for the generators, main transformer and station service transformer. The generator breaker, either air, magnetic or vacuum operated, is used to connect or disconnect the generator from the power grid. Instrument transformers, both power transformers (PTs) and current transformers (CTs) are used to transform high voltages and currents down to more manageable levels for metering. The generator control equipment is used to control the generator voltage, power factor and circuit breakers.

Plant service transformer

Electrical consumption including lighting and station mechanical auxiliaries may require from 1 to 3 percent of the plant capacity; the higher percentage applies to micro hydro (less than 500 kW). The service transformer must be designed to take these intermittent loads into account. If possible, two alternative supplies, with automatic changeover, should be used to ensure service in an unattended plant.

DC control circuits

It is generally recommended that remotely controlled plants are equipped with an emergency 24 V DC back-up power supply from a battery in order to allow plant control for shutdown after a grid failure and communication with the system at any time. The ampere-hour capacity must be such that, on loss of charging current, full control is ensured for as long time as it may be required to take corrective action.

Headwater and tailwater recorders

In a hydro plant, provisions should be made to record both the headwater and tailwater. The simplest way is to fix, securely in the stream, a board marked with meters and centimetres in the style of a levelling staff, however someone must physically observe and record the measurements. In powerhouses provided with automatic control the best solution is to use transducers connected to the computer via the data acquisition equipment.

Outdoor substation

The so-called water-to-wire system usually includes the substation. A line breaker must separate the plant including the step-up transformer from the grid in case of faults in the power plant. PTs and CTs for energy (KWh) and power (kW) metering are normally mounted at the substation, at the connecting link between the plant-out conductors and the take-off line to the grid. In areas with very high environmental sensitivity the substation is enclosed in the powerhouse, and the transmission cables, leave it along the penstock. Lightning arresters for protection against line surges or lightning strikes in the nearby grid are usually mounted in the substation structure.

For turbine-generators the one of the important auxiliary circuits is one to control **main inlet valves**. Typically the main control is done by hydraulic opening of the valve with gravity closing. It is an important item because main inlet valve closure is usually a part of the turbine-generator set shut-down sequence.

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8. DETAILS OF PROJECT ANALYSIS

Initial part of project analysis of SHP project should cover three capital areas: determination of available water resources, including annually energy for different yearly average states of stream, i.e. for wet, medium and dry years.

- determination of the investment range, acquiring suitable permissions and licences from competent water service, local or regional administration, environment protection.
- determination of electrical parameters: loads, connection, cooperation with the grid.

The project should determine also the basic economic indicators including balance of costs and incomes, ways of financing and environmental interaction. In the technical part of project the following parameters should be defined:

- levels of water (high, medium and low),
- water head, so called gross head,
- flow in the stream for fixed cross-section of dam,
- installed gullet of turbine, i.e. maximal volume of water flowing across turbine in unit of time (on the base of medium yearly flow),
- nominal power of hydro power station,
- turbine and mechanical gear parameters,
- parameters of generator,
- structure and type of electrical switching station,
- control systems, automatic systems and protection,
- parameters of the lines and transformer of hydro power substation connection with the electrical grid,
- quantity of the energy production in the year estimated taking into account knowledge about volatility of the water flow,
- time of power utilization from the power station.

8.1. ANALYSIS OF HYDROLOGICAL POTENTIAL OF THE SEAT

One of the data categories which should be obtained from adequate hydro-meteorology services are characteristic flows. These quantities should be determined on the basis of long term statistics, or in some cases of lack of data, be interpolated from other places statistics of river. To the group of characteristic flows belong:

HOF – highest observed flow,
MOMaxF –medium from observed maximal flows,
MOTF – medium from observation time,
MOMinF —medium from observed minimal flow,
LOF – lowest observed flow.

The next group of data determines maximal flows with the fixed probability of availability level – Flow Duration Curve (FDC)– table 4.1. One of important calculation is determination of maximal flows with probability levels of appearance equal to 0.1%, 0.3%, 1%, 10%, 50%. These quantities should be used for determination of FDC curves, like on the figure 4.2. For determination of flow estimation errors FDC curves should be determined at least for wet, medium and dry year.

8.2. SCHEMA AND LOCALISATION OF PLANNED SHP

Planning of localization and schema of SHP is complicated iterative process. In such a process the influence of environment and different technological options are taken into account from point of view of economical efficiency. Particularly in the document „Feasibility study" the following problems should be described:

- topography and geomorphology of the SHP seat,
- choice of localization place and schema of exploitation of water resources,
- basic solutions of hydro-technical equipment and power house,
- estimation of economical efficiency of the project and financing possibilities,
- discussion of administrative procedures relative to suitable permissions and licences.

The important element, particularly in designing completely new hydrotechical infrastructure of hydro power station, is choice of supply way of turbine and in consequence choice of whole turbine. Investment in the hydro-technical equipment can compose the most essential cost component and decide about the success of investment. The vital point is selection of shapes and parameters of the canals, pipes and penstock, water basins, construction of dam and gullet. Knowledge of parameters of such equipment is the key of correct estimation of power productivity. Hydrotechnical constructions in the SHP seat should enable to maintain parameters of the water stream according to environmental requirements and obtained licenses. One of such parameters is inviolable flow, i.e. minimum amount of water which should be hold in fixed cross-section of the water stream because of biological and social affairs. Values of this parameter can influent the estimation of productivity of power station. Quantity of the inviolable flow is strongly related to quantity of the overflow above fixed weir. Maintenance of overflows on the required levels is mostly administrative requirement implicit from environmental requirements. In the case of small inflows the overflow can be minimal or even nonexistent. Overflow control can significantly influence power plant production level because feeding canals can be closed and generator cut down in case at small overflow.

Sluices and fish ways

Building, construction and exploiting of the fish ways depend individually on local circumstances and is one of the important environmental requirements. Similar problems are with maintenance of continuous flow across fish way. Flow across fish way depends on value of medium flow in the water stream.

Next elements which should be taken into account in some solutions are sluices. In this case of sluice analysis valid element is number crossing through the sluice, if such crossing exist, and turnover of sectors (up, down). Sluice crossing can considerably decrease quantity of energy production because of water level variation and possibility of shutdown the machines, e.g. with the minimal water levels.

8.3. TURBINE CHOICE

Choice of the turbine type, its parameters: size, rotational speed, suction depends on flow and head parameters in the seat of a power station. For the flow hydro power station it mainly depends on maximal and medium flows and FDC curves. On this stage ones should take into account some elements of cost-price effectiveness. The optimization of costs related to kWh in the function of turbine power should be carried out. This stage of analysis is illustrated in the figure 8.1.

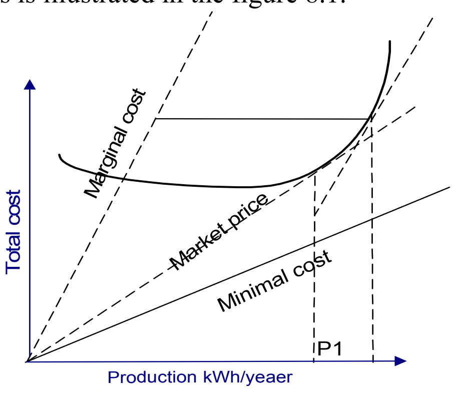

Fig. 8.1. Costs optimization in the turbine power. P1 determines the point of the return from the investment.

Initial choice of type and size of turbine can be done using suitable diagrams of turbine efficiency. Example of such diagram is presented in figure 8.2. From the analysis of such diagrams one implies that at high heads Pelton's turbines can be

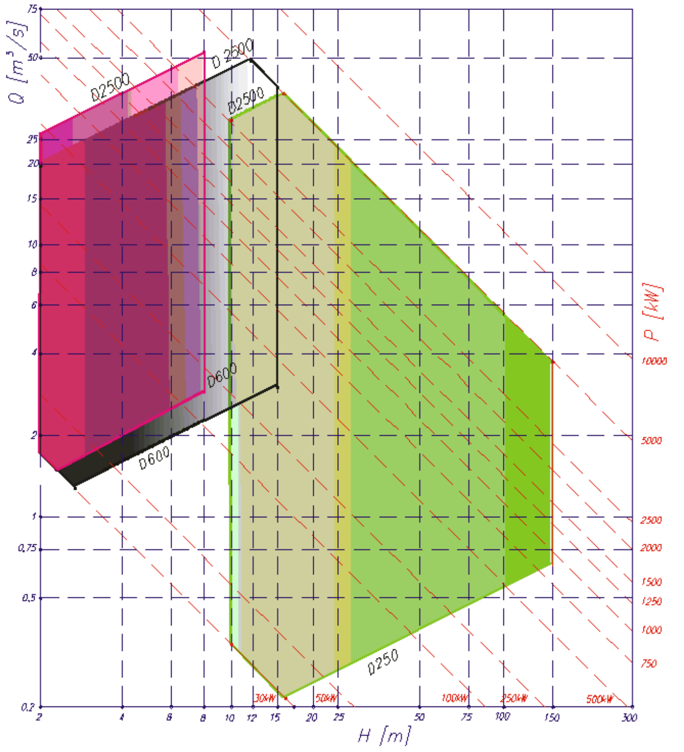

Fig. 8.2. Diagram of turbine efficiency: colours:
red – Kaplan turbine, grey – Francis,
green – Pelton.

used whereas at high flows and small heads - Kaplan turbines. Detailed characteristics, as on figure 8.2, are prepared by turbine producers.

Variability of the flow is important parameter of big influence on the decision of turbine choice. This impact is illustrated in figure 8.3.

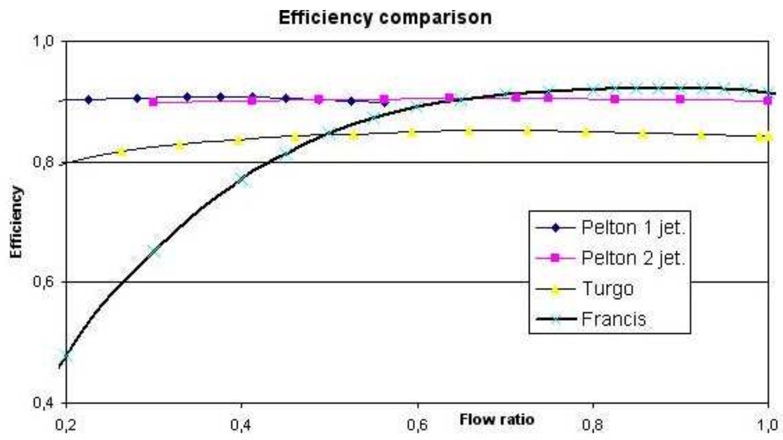

Fig.8.3. Efficiency of different types of turbines.

For chosen type of turbine the size of the turbine should be fixed in the next step. For this aim the high-speed discriminator should be determined, i.e. parameter of rotational speed of the turbine geometrically similar, for so called reduced head. Higher value of this parameter means that it is possible to achieve more power using turbine with the smaller diameter of impeller. In the next step the diameter of impeller should be set using suitable formulas valid for adequate turbine class and size. Generally the choice of turbine is quite complicated problem. Fault on this step can decrease cost efficiency of the project, e.g. because of not quite full utilisation of hydrological potential of the water stream.

8.4. SELECTION OF GENERATOR

In SHP the asynchronous generators are used as the rule for economical reasons – the lower investment costs. The construction is simpler in comparison to synchronic generators, are lighter, cheaper and do not need the synchronisation and voltage control. Asynchronous engines are used for the generation work. In this case attention should be focused on the following problems:

- ♦ **reactive power compensation** (greater induction of reactive power, then greater costs of compensation),
- ♦ **profile of current paths** (the necessity of using greater dimension profiles)
- ♦ **loads of generators** (work in lower power range, higher temperature work of generators)
- ♦ **necessity of rebuilding of power output.**

These problems can increase capital and exploitative costs. In small hydro power station synchronic generators, like 3-phase synchronic generators with permanent magnet may be used as well. These generators have high efficiency (up to 97%), much more higher then asynchronous generators or generators of direct current.

8.5. AUTOMATICS AND PROTECTION

Choice of suitable automatics and protection is one of the important decisions in the SHP design selection. Function of automation and control depend on construction, runtime mode, e.g. supplying the island, necessity of remote control. The main goal should be maximisation of electric energy generation. The basic function of SHP automation is assurance of secure work, e.g. emergency shutdown of generator or control in dependence on varying water conditions.

Increasingly greater number of investors appreciates the need for installation of modern control systems. SHP are often built in the solitude spots. It is one factors focusing attention of investors on remote systems.

Continuous optimisation of generation, without intervention of the staff, is the most important expectation for such a system – for profit maximisation.

Protection of electrical grid

Protection requirements are defined by the owner of the local electric network (distribution company) to which the SHP is connected. SHP protection devices are mostly inbuilt in minimal arrangement specified by network operator, despite of the fact that participation of protection devices cost in the total investment costs is small. Endless improvement of requirements referring to network security and connected customer equipment contributes to installing more modern and reliable protection.

The basic network protections:

- frequency protection
- voltage protection.

8.6. DOCUMENTATION

8.6.1. STRUCTURE AND PROJECT PREPARATION

Project documentation should contain rationale of investment and its profitability. Positive balance of costs and profits as well as rentability is the base of acquirement of indispensable investment funds and bank credits.

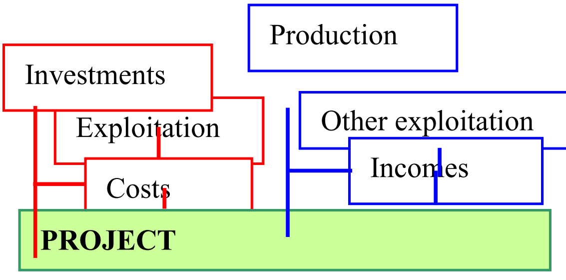

Fig. 8.4. Preparation of project: analysis of costs and incomes

Methodology and procedures

For chosen profiles of pipes, passages, sluices and canals the water flows, the following action and parameters should be determined, among other things:

- depth and speed of the water flow in the canal,
- height of the flow control structures, e.g. dams, weirs, places of potential overflows,
- analyze return flows and influence of the dam on such flows,
- height and width of transport canals,
- determination if the flow will be subcritical or overcritical; it enables to forecast the level of flow stability and irregularity,
- determination of slope of the canal to minimise turbulences,
- settlement of optimal canal parameters from the costs point of view, i.e. determination of the best dimensions for maintenance the required level of flow,
- required smooth of the canal; reduce costs by using suitable material for canal formwork which should assure maximal levels of depth,
- determination of the pipe diameter to avoiding increased pressure flows,
- comparison of different shapes without changes of inlet levels.

Project documentation and its realisation should be prepared and carried out according to suitable standards and requirements.

Because of UE requirements implemented for project practice, the preparation and realisation of investment should be carried out according to planning guidelines given by UNIDO, like in figure 8.5.

8.6.2. ADMINISTRATIVE LICENSES OF WATER USE

RES Directive of European Parliament defines general requirements concerning administrative actions for the promotion energy from renewable sources. Statements of this Directive oblige administrative to reduction of all barrier limited energy production from the renewable sources.[9]

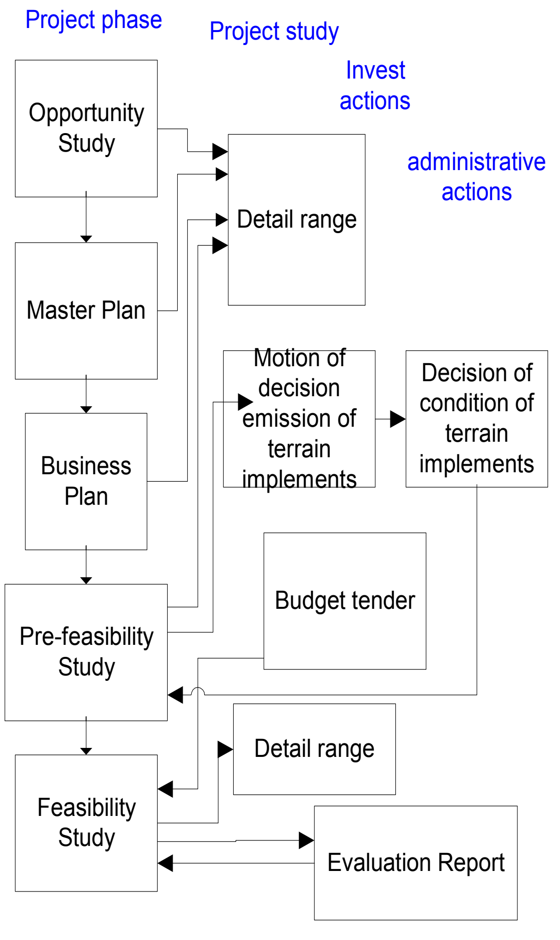

Fig. 8.5 Diagram of preparation phases of feasibility study project.

Rules of SHP investment preparation are similar in almost all EU countries. Everywhere the licenses concerning terrain and environment using are required. The way of environment using as the rule is consulted with specialized agencies and local community, especially in case of large projects. Suitable allowances are known as the licenses. Content of these documents is defined by appropriate low regulations e.g. Water low. Superior regulations are defined in so called Water Directive (WFD)[10] of European Parliament. In

Norway where the almost all energy is produced from hydro power station, licenses are agreeable to law act Water Regulation Act i Energy Act. Procedure of a license acquisition is quite complicated and prolonged. It is consulted on the many stages of the project. Time of this procedure for SHP is equal from 1 to 5 years, medium 2÷3

9 DIRECTIVE 2001/77/EC of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market

10 DIRECTIVE 2000/60/EC of 23 October 2000 establishing a framework for Community action in the field of water policy

years[11]. This process needs communal acceptance. The intervention in project shape, e.g. its range can be limited. Final license is issued by the proper ministry (MPE).
In Greece the acquisition of suitable licenses needs social consultation and is quite complicated. Licenses are authorised by Ministry of Development after earlier acceptance by energy commission - RAE (Regularity Authority for Energy). Procedure takes mostly from 6 to 12 months.

In Austria, the energy market is fully open12. Suitable licenses are issued by administrative of province authority, but for SHP to 500kW, such licenses are not required[13].. Certain obstruction is lack of the obligation of energy purchasing by local distribution company. Sale is done using market prices. In Swiss the certification of SHP is in accordance with greenhydro standards[14]. According to them SHP project has to fulfil environmental standards. For SHP some wide simplification are used in procedures of acquiring licenses and certifications, e.g. there are some SHP types for which the licenses are not necessary or are strong simplified.

In UK adequate licenses are following:

- *Abstraction Licence* , for hydro station with derivation canals,
- *Impoundment Licence*, for all hydrotechnical constructions affected on water relations,
- *Land Drainage Consent*, in the case of works in main runway of the water stream, *Section 158 Agreement*, different additional requirements[12].

In Poland use of water resources is regulated by „Water Law". This regulation defines administrative authorities adequate to water administration. These bodies issue needed licenses. In the license the aim and range of water usage and additional requirements; environmental, social and economy are included. The details of requirements are included in additional document "Waterlaw operat". It contains:

- characteristics of the water span in the license,
- determination of influence of water management on surface and underground water,
- the way of proceeding in the some operational cases, accidents, etc,
- plan of the water equipment and functional schema.

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11 The Licensing Procedures for Hydropower Development in Norway, http://www.nve.no

12 The Energy Liberalization Act – "Energieliberalisierungsgesetz" (BGBl I 2000/121; in the following "ELG")

13 The Transposition of Directive 96/62/EC on the Internal Market in Electricity into Austrian Law, http://www.dbj.at

14 Standard for environmentally compatible hydropower, EAWAG Switzerland.

8.6.3. Summary –essential requirements and threats

Initial stage (befor realisation)	
Question:.What have to do!	Cautions
determinations of expectations concerning SHP: financial, realisations, exploitations, familiarization with conditions: electrical energy turnover formal-law, technical financial analysis of investment	- thesis „myth of flowing water" which is only the source of incomes should be opposed to solid analysis of expectations which should be fulfilled on each stage of the project realisation
if answer of the question „ IS THIS INVESTMENT FOR ME ?" will be positive :	
- determination on the base of historical data potential locations and initial conditions: head, flow	- errors in determination of initial parameters are transferred into next stages and are difficult to be improved
- obtainment of initial co-ordination, agreements concerning SHP location, water management, grid connection, power output	- not always chosen place is good, respect to law, technical affairs, security, environment, financial
- determination of water requirements, acquire suitable licenses	- determine full range of requirements concerning water exploiting
- realisation of technical projects of water step, inlet, pipes, outlet, powerhouse, turbines, electrical connections, automation	- choice of types and number of turbines in dependence of flow is base of energy potential using and optimisation of electric energy production
-business plan, feasibility study, financial guarantee and resources	-correct determination of costs of each part of project is the guarantee of achievement of set technical level of SHP
-realisation of investment	-before start of the project realisation it is proper to consult project in wider group of specialists in each area taking into account high costs
-technical acceptance, admission for operation	-essential is fulfilment of requirements concerning security of exploitation, grid protection, meters and control system, especially in the storm flood,
- contract of electric energy sale and reception	-market analysis, contracts preparation, fulfilment of energy turnover
-exploitation	-requirements: -formal and lawful concerning turnover of energy, -technical, connected with exploitation and environment, -financial, connected with exploitive costs, taxes, etc

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9. ECONOMY

The background of each investment project is economy analysis which contributes all costs, expenses and forecasted incomes and enables tocompare the different possible alternatives to allow the choice of the most advantageous or to abandon the project. For the purposes of preliminary analysis very useful may be the RETScreen Pre-feasibility Analysis Software - a generic, freely available software package. It enables users to prepare a preliminary evaluation of the annual energy production, costs and financial viability of projects.

9.1. COST OF INVESTMENT

Costs of SHP investment depend on:

- type of SHP(cross-flow, basinal),
- installed power and number of hydrogenerators,
- useful slope,
- capacity of the water basin,
- local circumstances (terrain configuration, length and height of eventual embankment of basin , hydrological conditions, costs of terrain using, etc.),

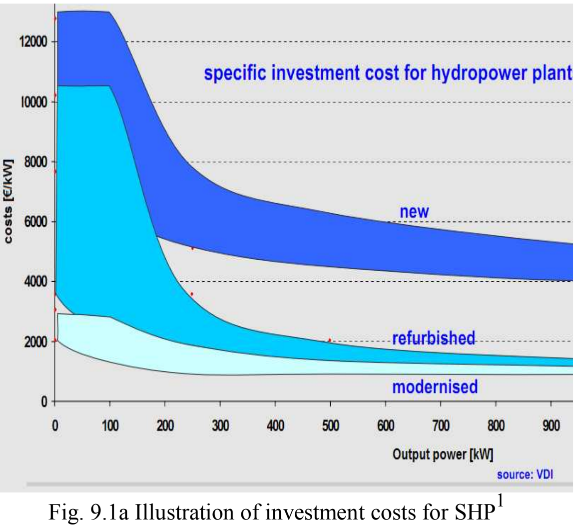

Fig. 9.1a Illustration of investment costs for SHP[1]

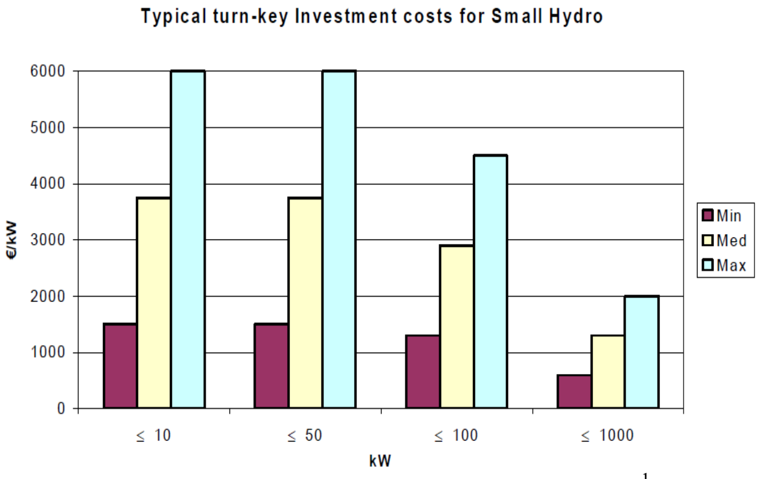

Fig. 9.1b Illustration of min-max investment costs for SHP[1]

General presentation of costs level of SHP build-up is very difficult because projects are not unified and comparable. In each investment the local environmental condition caused that the individual solutions are chosen, including hydro-technical construction, turbines and electrical equipments.

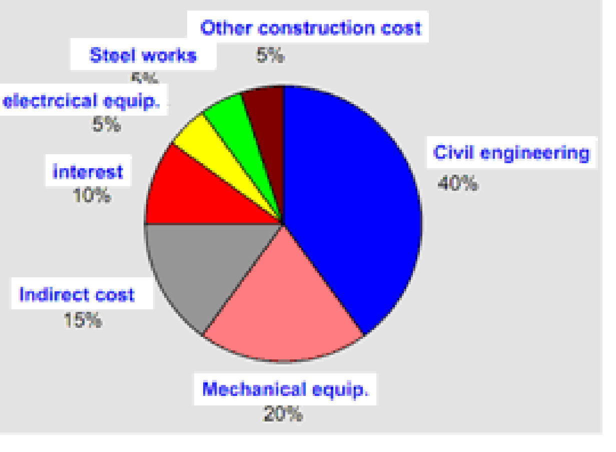

Fig.9.2. Structure of unit investment costs for new SHP

Structure of unit investment costs for new SHP (data from German market) is illustrated in figure 9.2. For real investments cost structure may be different, e.g. participation of civil engineering vary from 30 to 60%.

9.2. BASIC INDEXES

Present Value

The present value (PV) of a future amount of money or future value (FV), discounted at a given interest rate "r" (also called discounted rate), for a number of years "n", the following formula is used:

$$PV_0 = \frac{FV_n}{(1+r)^n} = \frac{1}{(1+r)^n} FV_n \tag{9.1}$$

The term 1/(1+r)n is called "present value factor" (PVF). Therefore, for a discounting rate r, the cost C_n (or the benefit B_n), disbursed or received in the year n, is discounted to the year zero by the equation:

$$C_0 = \frac{1}{(1+r)^n} C_n \tag{9.2}$$

To find the comparable value of a given sum of money if it were received, or disbursed, at a different time, the above formula may be used.

For instance, if the investor's opportunity earning potential were 8%, then €10 000 received in 5 years from now, would be equivalent to a present value of:

$$\frac{1}{(1+0.08)^n} 10000 = 6808{,}83$$

With the concept of present value for a future payment, investors can calculate the present value of the future sales price of a SHP plant. The formula is useful in understanding that an investment today has to be sold at a much higher price in the future if the investment is to be interesting from an economic point of view.

An annuity is a series of equal payments over a certain period of time. The present value of an annuity over n years, with an annual payment C_n (starting at the end of the first year) will be the result of multiplying C by a factor, a_n, equal to the sum of present value factors, PVF's (v):

$$a_n = v^1 + v^2 .... + v^n = \frac{1-(1+r)^{-n}}{r} \tag{9.3}$$

$$PVA_n = C\left[\sum_{t=1}^{n} \frac{1}{(1+r)^t}\right] = C \cdot \frac{1-(1+r)^{-n}}{r} = C \cdot a_n \tag{9.4}$$

The concept of present value of an annuity allows the evaluation of how much the annual sales revenue from the SHP plant electricity is worth to the investor.

Example:
Incomes of 1000 € annually in 10 years for a required return of 8% for the investor are valuated to investors as:

$$PVA_{10} = 1000 \frac{1 - \frac{1}{(1+0.08)^{10}}}{0.08} = 1000 \cdot 6.7101 = 6701{,}10\,€.$$

Payback period

$$\text{Payback period} = \frac{\text{investment cost}}{\text{net annual revenue}}$$

Return on Investment method (ROI)

The return on investment calculates average annual benefits, net of yearly costs, such as depreciation, as a percentage of the original book value of the investment. The calculation is as follows:

$$\text{ROI} = \frac{\text{net annual revenue - depreciation}}{\text{investment cost}} \times 100$$

$$\text{Depreciation} = \frac{\text{cost - salvage value}}{\text{operational life}} \times 100$$

Using ROI can give you a quick estimate of the project's net profits, and can provide a basis for comparing several different projects, but it completely ignores the time value of money.

Net Present Value (NPV) method

NPV is a method of ranking investment proposals. The net present value is equal to the present value of future returns, discounted at the marginal cost of capital, minus the present value of the cost of the investment. The calculation PV is summarised by the following steps:

1. Calculation of expected free cash flows (often per year) that result out of the investment
2. Subtract /discount for the cost of capital (an interest rate to adjust for time and risk) giving the Present Value
3. Subtract the initial investments giving the Net Present Value (NPV).

The net present value is an amount that expresses how much value an investment will result in, in today's monetary terms. Measuring all cash flows over time back towards the present time does this. A project should only be considered if the NPV results in a positive amount.

The formula for calculating NPV, assuming that the cash flows occur at equal time intervals and that the first cash flows occur at the end of the first period, and subsequent cash flow occurs at the ends of subsequent periods, is as follows:

$$\mathrm{PVA_n} = \sum_{i=1}^{n} \frac{\mathrm{R_i} - (\mathrm{I_i} + \mathrm{O_i} + \mathrm{M_i})}{(1+\mathrm{r})^{\mathrm{i}}} + \mathrm{V_r} \tag{9.5}$$

I_i – investment in period i,
R_i – revenues in period i,
O_i – operating costs in period i,
M_i – maintenance costs in period i,
V_r - residual value of the investment over its lifetime, where equipment lifetime exceeds the plant working life,
r – periodic discount rate,
n – number of lifetime periods e.g. years, quarters, month.

Different projects may be classified in order of decreasing NPV. Projects where NPV is negative will be rejected, since that means their discounted benefits during the lifetime of the project are insufficient to cover the initial costs. Among projects with positive NPV, the best ones will be those with greater NPV.

Benefit-Cost ratio

The benefit-cost method compares the present value of the plant benefits and investment on a ratio basis. It compares the revenue flows with the expenses flow. Projects with a ratio of less than 1 are generally discarded. Mathematically the $R_{b/c}$ is as follows:

$$RB/C = \frac{\sum_{i=1}^{n} \frac{R_i}{(1+r)^i}}{\sum_{i=1}^{n} \frac{(I_i + O_i + M_i)}{(1+r)^i}} \tag{9.6}$$

Table 9.1. Financial analysis of real schemes in Europe

Country		Germany	France	Ireland	Portugal	Spain
Rated discharge	m3/s	0.3	0.6	15	2	104
Gross head	m	47	400	3.5	117	5
Type of Turbine		Francis	Pelton	Kaplan	Francis	Kaplan
Installed capacity	kW	110	1900	430	1630	5000
Investment cost	€	486 500	1297 400	541 400	1148 000	5578 928
Working hours		8 209	4 105	8 400	4 012	3 150
Annual production	MWh	903	7800	3612	6540	15750
Tariff	€/MWh	76.13	53.65	23.23	53.54	63.82
Revenue	€/Yr	68 745	418 443	83 907	350 128	1005 165
O&M	€/Yr	19 850	51 984	25 176	22 960	157 751
O&M	%	4.08	4.01	4.65	2.00	2.83
Gross Profit	€/Yr	48 895	366 459	58 731	327 168	847 414

Economic Analysis						
Capital cost	€/kW	4 423	683	1 259	704	1 116
Capital cost	€/MWh	539	166	150	176	354
Simple payback period	Yr.	9.95	3.54	9.22	3.51	6.58
NPV	€	63 374	2 649 850	115 910	2 375 270	3 739 862
IRR	%	9.37	28.23	10.33	28.49	14.99
B/C		1.15	2.72	1.16	2.82	1.64

The figures have been calculated using a discount rate of 8% over a lifetime of 30 years.

9.3. RETSCREEN SOFTWARE

RETScreen is useful, free software for pre-feasibility study. Apart other, it covers the analysis of potential small hydro projects. All economic parameters, including NPV and IRR are there calculated. Details one can find on producer pages.[15].

[15] www.retscreen.net

Table 9.2. Example of table in RETScreen.

Rose Blanche Hydroelectric Development, Newfoundland, Canada

RETScreenfi Formula Costing Method				Detailed Project Costs	Variance
			(1)	(2)	(1)/(2)
Initial Costs (Formula Method)	Cost (local currency)	Adjustment Factor	Amount (local currency)	Amount (local currency)	
Feasibility Study	$ 504,000	1.00	$ **504,000**	$ -	
Development	$ 529,000	1.00	$ 529,000	$ 463,500	114%
Land rights			$ -	$ -	
Development Sub-total:			$ **529,000**	$ **463,500**	114%
Engineering	$ 537,000	1.00	$ **537,000**	$ **875,500**	61%
Energy Equipment	$ 3,032,000	1.00	$ **3 032,000**	$ **2,729,500**	111%
Balance of Plant					
Access road	$ 1,096,000	1.00	$ 1,096,000	$ 957,900	114%
Transmission line	$ 217,000	1.00	$ 217,000	$ 372,860	58%
Substation and transformer	$ 175,000	1.00	$ 175,000	$ 539,720	32%
Penstock	$ 1,831,000	1.00	$ 1,831,000	$ 3,090 000	59%
Canal	$ -	1.00	$ -	$ -	
Tunnel	$ -	1.00	$ -	$ -	
Civil works (other)	$ 6,326,000	1.00	$ 6,326,000	$ 4,351,750	145%
Balance of Plant Sub-total:	$ 9,645,000		$ **9,645,000**	$ **9,312,230**	104%
Miscellaneous	$ 2,015,000	1.00	$ 2,015,000	$ 821,940	245%
GHG baseline study and MP	Cost	$ -	$ -	$ -	
GHG validation and registration	Cost	$ -	$ -	$ -	
Miscellaneous Sub-total:			$ **2,015,000**	$ **821,940**	245%
Initial Costs - Total (Formula Method)	$ 16,262,000		$ **16,262,000**	$ **14,202,670**	**114%**

9.4. FINANCING

Financing sources

Financing of SHP projects is written into the mechanisms of supporting and financing of RES. Effect of RES supporting are suitable UE Directives and as the result national development plans. Finance support for RES is given both from private and public sources. The range of finance changes from macro to micro scale in dependence on project size, like in the case of near home and micro hydro stations. Recently more and more banks are interested in financing of RES seen as the good business area. Important role have public banks. In EU European Investment Bank, the European Bank for Reconstruction and Development (EBRD) is good example bank of such kind. Significant possibilities of financial support have different kind organisations and government agencies, e.g. German Development Finance Group (KfW). In 2004 KfW disposed fund about 180 millions euro for the RES development. In this case German government assign for KfW disposal of about 500 millions euro for RSE support in the developing countries. In the case of smaller investments, some financial support of RES can be expected from different nongovernment organisations, e.g. industrial networks, private foundations. A good example is network RENv21 Renewable Energy Policy Network. Important are also such financial instruments as grants, subsidies, preferences, facilities and taxes. For these instruments the local or regional conditions are possible.

In Poland, one of the most important financing sources of RES, including SHP, is National Found of Environment Protection and Water Economy (Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej). Among banks Bank of Environment Protection (Bank Ochrony Środowiska S.A,) gives preferential credits for investment in the area of environment protection.

Conditions of financing

Creating financial plan of SHP, the following assumption are often accepted:

- large costs of hydro technical infrastructure ,
- project life time of SHP is longer then time of capital return.

In the case of SHP, the preparation of project documentation and feasibility study the can be serious cost component - it can achieve even 50% of overall costs. In the project the cheap and typical solution should be applied. The executor of the project is valid side seriously cost influent. It has to have all authorizations. Credits for the project usually amount 60÷80%, and in such a level are mostly from government institutions. Project is often co-financed by the local institutions, industry, financial institutions interested in long-term financing.

Many investors mostly have no sufficient resources for project investment. With high risk of the project cost of acquired capital can be expensive. It can be additionally gained from several sources which can also increase costs. Banks can require additional expected insurance of capital or require special supervising of the realisation process when high risk is estimated. In some cases the consumer credit is also possible. Time of capital return is estimated from 10 to 20 years, and 10 years for commercial banks. Good preparation of the process with correct estimation of future incomes is guarantee of success.

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10. ENVIRONMENT

Electricity production in small hydro plants does not produce carbon dioxide or liquid pollutants. The fact is that due to their location in sensitive areas local impacts are not always negligible. A small hydropower scheme producing impacts that usually can be mitigated is considered at lower administrative levels, where the influence of pressure groups - angling associations, ecologists, etc. The implementation of the Water Framework Directive introduces severe additional demands in ecological terms. The significant cost implications or even the viability reduction of SHP have fulfilling of ecological aims such as the construction of fish bypass systems or the reduction of water through increased reserved flow have. The achievement of environmental goals is not dependent on the ideological resistance of the developer of the site but on his economical restrictions. The most important impacts during the construction and operation are listed in tables 10.1 and 10.2.

Table 10.1. The most important impacts on environment during the construction

Events during construction	Persons or things affected	Impact	Priority
Existing Vegetation Cutting	Forestry	Alteration of habitat	Medium
Enlargement of Existing Roads	General public	Creation of opportunities, alteration of habitat	Medium
Embankment Realisation	Aquatic life, site hydro-morphology	Alteration of river hydraulic	Medium
Water Courses Dredging	Aquatic ecosystem	Alteration of habitat	Medium
Temporary Diversion of Rivers	Aquatic ecosystem	Alteration of habitat	High
Use of Excavators, Trucks, Helicopters, Cars for the Personnel, Blondins	Wildlife, general public	Noise	High

Table 10.2. The most important impacts on environment during the operation

Events during operation	Persons or things affected	Impact	Priority
Renewable Energy Production	General public	Reduction of Pollutants	High
Water courses Damming	Aquatic ecosystem	Modification of habitat	High
Permanent Works in the Riverbed	Aquatic ecosystem	Modification of habitat	High
Diversion of Watercourses	Aquatic ecosystem	Modification of habitat	High
Penstocks	Wildlife	Visual intrusion	Medium
Flow Rate modification	Fish	Modification of habitat	High
	Plants	Modification of habitat	Medium
Removal of material from streambed	Aquatic life, General public	Improvement of water quality	high

One of the very important is biological impact. This usually deals with calculation of reserved flow. There are many formulas for estimate reserved flow but no one has a good universally valid solution. A complete survey on methods for calculating reserved flow can be found in the document prepared by ESHA within the Thematic Network on Small Hydroelectric Plants and is available at (www.esha.be). Generally there are three groups of methods:

- referring to the average flow rate (MQ) of the river at a given cross section. Typically, a figure of 10 % of the average flow is used for reserved flow,
- referring to the minimum mean flow (MNQ) in the river. The reserved flow calculated when applying these methods varies from 20% to 100% of MNQ.
- referring to the prefixed values on the Flow Duration Curve (FDC).

Fish protection

One of the basic problems of SHP investors is fish protection. SHP have to be equipped wthi hydrotechnical equipment designed for these purposes. The following elements belong to such equipment the:

- fish-passes, sluices, lifts for fish,
- canals,
- screen plates, coverer bars.

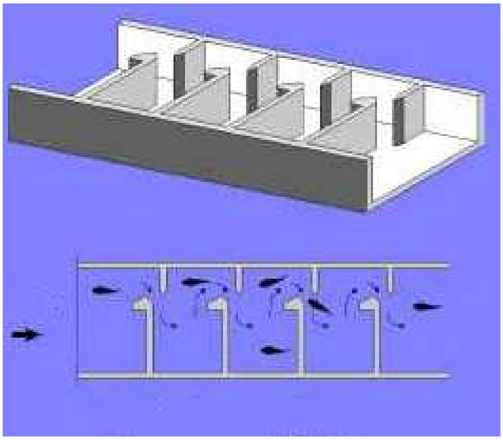
Fig.10.1. Fish-pass – canal with chambers

Fish-passes can have different constructions.

There are often built in the form of multi chamber, cascade canal. Canal with cell cover all head, from high to low water level. It may be used to limit the water speed in the case of quick flow. Such solution is presented in figure10.1.

In the simplified form the solution as in the figure 10.2 can be used.


fis

Of ... of ... n water ... ba ... e of adeq... fa...

Recommended speed of the water near the bars should be at the level of 0.30÷0,40 m/s. Fixed screens from bars should stop the fishes and direct them to opposite bank or on the surface. Apart of fixed screens the screen in the shape of rotated net gates are mounted also.

Sometimes the not standard solutions are used, as in figure 10.3.

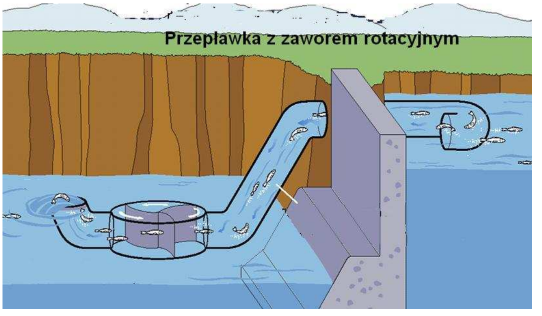

Fig. 10.3. Fish-pass with rotational valve for fish crossing.

There can be also used behavioural barriers, e.g. sound, lighting, curtains of air-bubbles.

Limitation of emission

For production of 1 MWh of electrical energy about 500 kg of coal is needed. As a result 850 kg CO_2, 11 kg CO, 10 kg SO_2, 4 kg NO_x is emitted to atmosphere.

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