Criterion for Selection of Turbines for Hydroelectric Power Project

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ABSTRACT
The hydro-turbines are used in hydropower plants to convert the hydraulic energy into mechanical energy. There are different types of turbines, mainly Pelton, Kaplan, and Francis. Further, there are some variants of each type of turbine. The hydraulic parameters, power grid requirement geological conditions etc. differ from one site to another which makes each hydropower project, a unique. Hence, selection of turbine to suit a specific site is a specialized job and need utmost considerations. The selection criterion of hydro turbine are discussed in this paper.

Keywords- Hydro turbines Peloton turbine, Kalplan Turbine, Francis Turbine

I INTRODUCTION

Hydraulic turbines are the highest efficiency prime movers used for power generation. They convert hydraulic energy contained in water to mechanical energy. A turbine is coupled to the generator which converts mechanical energy into electrical energy. The hydropower projects are generally multi-purpose for use in irrigation, water supply, flood control, fisheries etc. In some projects it is used only for power generation. A typical layout of a hydro power Plant is shown in Figure 1.

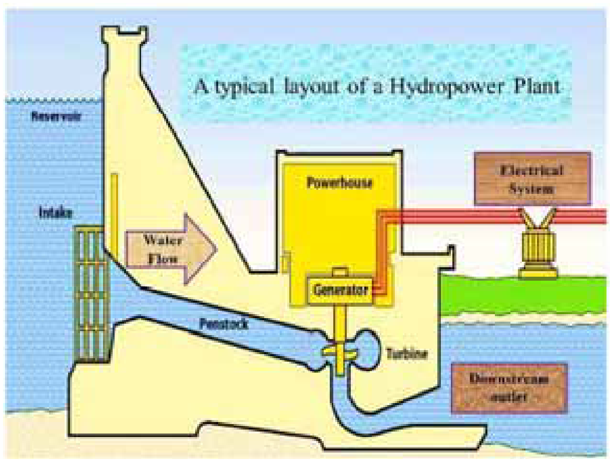

Fig No. 1: Typical layout of a hydro power plant [1]

II CLASSIFICATION OF TURBINES

The conversion of energy in a turbine takes place on the principle of impulse or reaction and hence, the hydro turbines are broadly classified as impulse and reaction types. Pelton turbine is an impulse type turbine whereas Francis and Kaplan turbines are reaction type.

The hydro turbines and their variants are given below:
Impulse: Pelton type tangential flow turbine
Pelton turbine
Turgo impulse turbine
Cross flow turbine
Reaction: Francis type mixed flow turbine
Francis turbine (adjustable guide vanes)
Deriaz turbine
Pumped storage (reversible) pump-turbine (adjustable guide vanes)
Reaction: Kaplan type axial flow turbine
Kaplan: Vertical & horizontal (adjustable blades & adjustable GV)
Propeller: Vertical & horizontal (fixed runner blades and adjustable GV)
Semi-Kaplan: Vertical and horizontal (adjustable runner blades but fixed GV)
Tubular (S-type): Horizontal (Kaplan or semi Kaplan or propeller)
Bulb: Horizontal (Kaplan or semi-Kaplan or propeller)
Straflo: Horizontal (Kaplan or semi-Kaplan or propeller)

(a) **Orientation of turbines** -The hydro turbines are horizontal or vertical axis type. Inclined axis turbines are also offered by some suppliers. The vertical axis arrangement of generating unit i.e. turbine and generator is generally suitable for higher rating turbines whereas horizontal axis arrangement suits low rating turbines, say up to 1 to 2 MW. However, there are some exceptions also. Some large rating hydro turbines with horizontal axis orientation are in operation, e.g. 4×12.65 MW Ramam HEP in West Bengal. A horizontal axis Pelton and vertical axis Francis & Kaplan turbines are shown in Figure 2.

In general higher capacity horizontal units are provided with Pelton turbines. The centre line of large capacity reaction turbines is set invariably below minimum tail water level. Therefore, power plants with reaction turbines mostly have vertical configuration, mainly due to economic reasons.

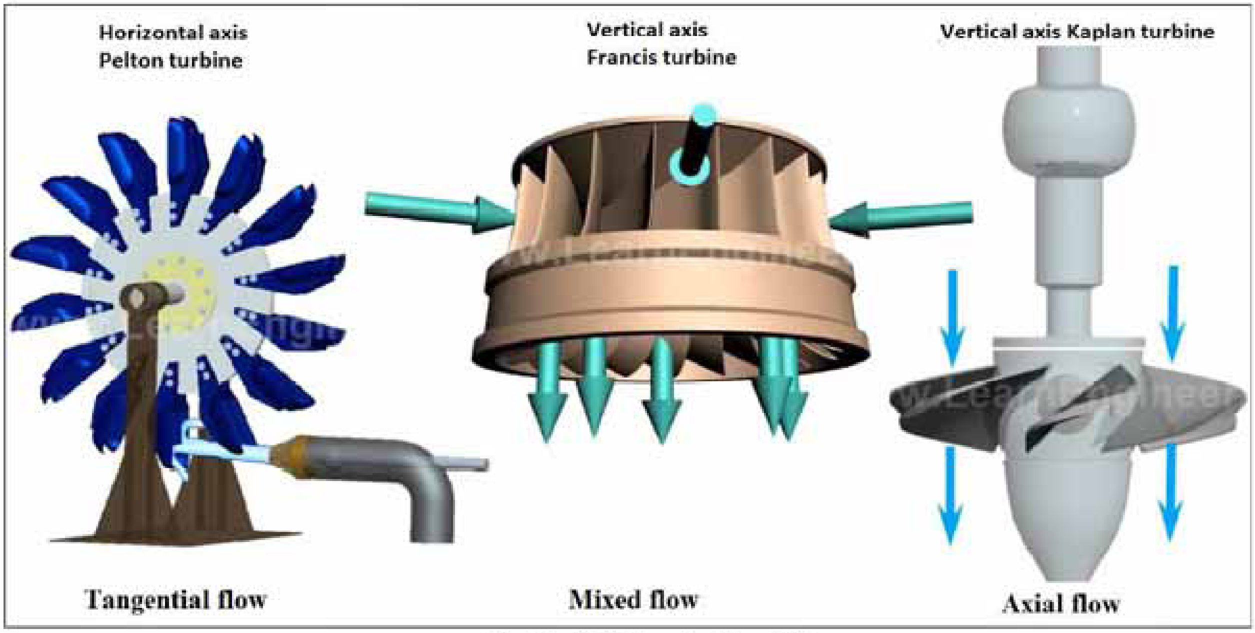

Fig No. 2: Hydro turbines [2]

The decision on the orientation of turbine depends mainly on the recommendation of turbine supplier and cost economics. In general, vertical axis large Francis and Kaplan turbines make the best use of head and space which makes the project economically viable.

(b) Impulse and reaction turbines: A comparison

The salient features of impulse and reaction turbines are compared in Table 1. **Comparison between impulse and reaction turbines**

Table No. 1

Impulse turbine	Reaction turbine
The potential energy of water is converted into kinetic energy by nozzle that forms a free jet	A part of potential energy in water is converted into kinetic energy before water enters the runner
The jet is at atmospheric pressure while passing through the runner and thereafter	The pressurized (with pressure almost equal to the pressure created by the head prevailing at a moment) water enters the runner and then both the velocity and pressure change as water passes through the runner and draft tube
The buckets are in action only when they are in front of the nozzle	Blades are in action all the time.
Runner is partially filled with water	Runner is fully submerged in water
Casing has no hydraulic function to perform as it only prevents splashing and guides water to the tail race	Pressure at inlet to the turbine is much higher than pressure at outlet. The unit has to be sealed from surroundings and therefore, casing is a must
Turbine runner is installed above the tail race	Turbine runner is submerged in water below the tail race elevation
When water glides over the moving buckets, its relative velocity either remains constant or reduces slightly due to friction	There is continuous drop in pressure while water flows through the blades.
No cavitation due to free flow of water from jets to runner and runner to tail race	Cavitation due to the flow of water in closed system

III CRITERION FOR SELECTION OF TURBINES

The hydraulic parameters, power grid requirement geological conditions etc. are to be taken care of in the development of a hydroelectric power project. Hence, the hydro power projects are tailor made i.e. specifications, design, layout, construction etc. of no two projects are identical. The selection of hydro turbine is project specific and their selection criterions are discussed next.

(a) Preliminary selection - A preliminary idea of a turbine output for different heads and discharge can be obtained from Figure 3.

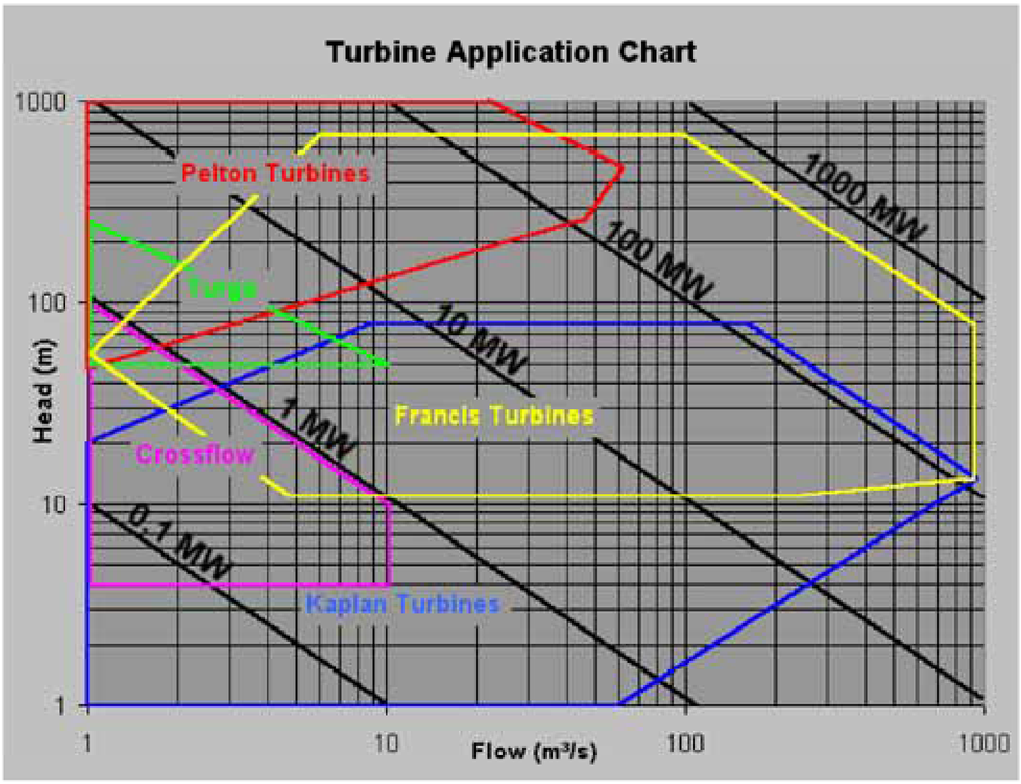

Fig No. 3: Relationship of turbine output with head and discharge [3]

In Figure 3, it is observed that there are some overlapping areas. For example, a discharge of 20 m^3/s and head of 300 m fall in the range of Pelton as well as Francis turbine. Such cases need detailed analysis for optimum selection of appropriate turbine.

(b) Specific speed

Hydraulic turbines are the highest efficiency prime movers used for power generation. They convert hydraulic energy contained in flowing water to the mechanical energy. A turbine is coupled to the generator which converts mechanical energy into electrical energy. The hydro turbines are basically categorised as impulse and reaction.

The selection of an appropriate turbine is important for ensuring its optimum performance. The characteristics of a turbine runner are embodied in 'specific speed'. It is defined as the speed at which the turbine would run at its designed efficiency when reduced to scale, so as to produce unit power at unit head. It forms a uniform basis for comparison of different types of turbines. A model developed for a specified specific speed is used for wide range of output with same geometrical shape i.e. homologous reproduction, differing only in size. All such turbines would have the same specific speed. The specific speed (rpm) is given by the following equation:

Specific speed $$n_s = \frac{n\sqrt{P}}{H_n^{5/4}} \qquad (1)$$

where,

n	=	Speed, rpm
P	=	Turbine output, kW
H_n	=	Net head, m

The concepts of specific speed and hydraulic similarity are applicable to all the types of turbines. The mechanical design considerations, tendency of cavitation, vibration, drop in peak efficiency and increased ratio of runaway speed to normal speed impose limitations on the specific speed of hydro turbines. These limiting factors are being progressively overcome with the technological advancements such as better understanding of the hydraulic profiles with the help of computational fluid dynamics (CFD) software in respect of pressure & velocity distribution; reasonably accurate prediction through model testing by adopting precision measurement techniques etc. The modern trend aims to attain higher specific speed which makes the turbine economical.

For example, the initial three Francis turbines for Grand Coulee Dam-III, USA were 600 MW, 86.9 m head and 72 rpm with a specific speed of 213 rpm. Later, three more Francis turbines installed were 700 MW and 85.7 rpm had a specific speed of 274 rpm.

(i) **Specific speed and heads** - The specific speed and head are interlinked with each other. Higher specific speed of a turbine results in smaller size of generating equipment and smaller dimensions of a power house. The maximum net head acting on a turbine is one of the criteria for selection of a turbine for a specific site. The normal ranges of specific speed and head for various turbines are given in Table 2. **Specific speed and head range of turbines [4]**

Table No. 2

Type of Turbine	Specific Speed (rpm)	Head Range (m)	Remarks
Pelton	15-60	> 200	High heads
Francis	70-400	30-600	Medium heads
Deriaz	200-400	50-150	Medium heads
Pumped storage-reversible	70-400	30-600	Wide head range
Kaplan	300-800	10-80	Low heads
Bulb/Tubular	600-1200	3-25	Very low heads

In the overlapping head ranges, an elaborate techno-economic analysis becomes necessary. The variation in turbine model efficiency with specific speed is shown in Figure 4.

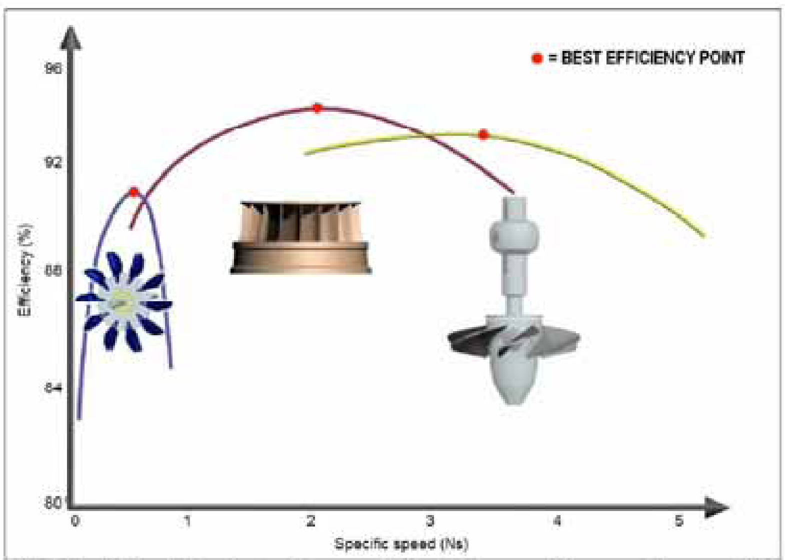

Fig No. 4 Variation in turbine model efficiency with specific speed [2]

(ii) **Specific speed and setting** - The setting of centre line of runner depends on specific speed. The operating speed of a turbine is proportional to specific speed. Selection of higher specific speed turbine results in high speed generator which reduces generator cost and also the size of power house.

In case of an underground power house, the selection of high specific speed turbine results in compact generator which reduces the size of power house and excavation. On the other hand, high specific speed necessitates deep setting of centerline of turbine which increases excavation. However, there is overall economy as the quantum of excavation for the power house reduces due the reduction of power house dimensions. Further, as compared to gross excavation of complete project, the power house excavation is around 25%. Thus, even deep setting does not matter. In fact, it marginally reduces the excavation which leads to overall economy. The 2 x 80 MW Pench hydro electric projects, near Nagpur, is an example of underground project.

(c) Turbine efficiency - Amongst various sources of energy, the hydropower generating units are the most efficient. The efficiency depends mainly on the type of turbine. The efficiencies of a higher rating turbine are also higher. The general range of efficiency of large and small capacity turbines are given in Table 3. Efficiencies of large and small capacity turbines

Table No. 3

Type of turbine	Efficiency (%)		
	Large capacity	Small capacity	Remarks
Pelton	93	92	
Turgo	---	90	
Cross flow	---	60	
Francis	96	94	
Deriaz	94	93	
Pumped storage-Reversible	94	92	Turbine mode
	Reversible unit operates at its peak efficiency point		Pumping mode
Kaplan	95	94	
Bulb/tubular	95	94	

(d) Part load operation - Allowable minimum part load operation in view of the cavitation and vibrations depends on type of turbine. Normally, the turbine manufacturers do not recommend operation of turbine below the minimum output limit. However, they specify minimum time allowed for operation below minimum load for which cavitation guarantee has been given. The general limits of minimum turbine loading are given in Table 4. **Part load operation of turbines [4]**

Table No. 4

Type of turbine	Minimum output (% of full load)	Remarks
Pelton	50	with alternate half the jets on, i.e. 2/3
	25	with total 4/6 jets
Francis	40-50	
Deriaz	40	
Pumped storage-reversible	up to 50	Turbine mode
	-------	Pump is operated at the maximum efficiency point.
Kaplan	25-40	
Bulb/Tubular	25-40	

(e) Cavitation and centreline setting of turbine - Recovery of head in the draft tube results in lowering of pressure immediately under the runner of reaction turbines. The absolute pressure at runner discharge is a function of draft tube suction, the relative levels of runner, tailrace and barometric pressure. The only factor which may readily be adjusted at design stage is the difference between the levels of runner centreline and tail race, called suction head. The suction head is decided from the consideration of cavitation. The Pelton runner is installed above the maximum tail water level and hence the excavation requirement from the cavitation point of view is not applicable.

(f) Transient parameters - The fast changes in pressure and speed are of transient nature which happens due to sudden change in the loading of a generating unit. In high head units, the higher pressure rise in penstock increases the cost of penstock and associated civil works. The higher speed rise increases the vibrations and pressure fluctuations in draft tube. A very long water conductor system results in high pressure rise in penstock in case of Francis and Kaplan turbines. The pressure rise in pen stock is restricted to a reasonable level (generally as specified in the contract) by providing pressure relief valve or surge tank to relieve water pressure. Pelton turbine does not require pressure relief valve or surge tank due to the provision of jet deflectors. Pressure rise and speed rise are low in Pelton turbines. The general range of pressure rise and speed rise for various turbines are given in Table 5. **Transient parameters of different turbines [4]**

Table No. 5

Type of turbine	Pressure rise (%)	Speed rise (%)
Pelton	15 - 30	20 – 45
Turgo	15 - 30	20 – 45
Francis	30 - 40	35 – 60
Deriaz	30 – 40	35 – 60
Pumped storage-reversible	10-25 (turbine)	20-35 (turbine)
	Not applicable for pump	
Kaplan	30 – 50	35 – 65
Bulb/Tubular	30 – 50	35 - 90

(g) Transportation Limitations - The transport limitations define the constraints in the design of major components of a generating unit. Normally, runner is the most important component which is desired in one piece from cost, reliability, maintenance , vibrations and cavitation point of view, considerations Further assembly, welding, fine finishing is very difficult to done at site, if runner is to be sent in two or more segments. The problem of transport in large Kaplan runner is much less due to an option to assemble the blades at site. It is preferred to design the runner of a Francis turbine within transportation limits of weight and dimensions. The large runners may have to be manufactured in two parts or cast fabricated for welding at site which may increase the cost of turbine. The runners of Pelton turbines are small and made in one piece only.

The manufacturers make best efforts to dispatch various assemblies/sub-assemblies factory assembled to the extent possible. Generally, the stator frame and core assembly with partial stator is shipped in segments to site. However, it may not be possible to do so in case of very large and/or heavy assemblies. Indira Sagar Hydroelectric Project is equipped with 8 x 125 MW, 115.4 rpm Francis turbines and 11 kV, 0.9 power factor, 50 Hz hydrogenerators. The lower specific speed of turbine has resulted in the slow speed, large size and heavy generator. The wound stator assembly weighs 230 t. In view of the permissible transport limits, the stator frame was shipped is 6 segments. The core building and winding was done in erection bay of power house. During the installation, the wound stator assemblies were lifted by tandem operation of 2 x 200 t overhead cranes and lowered in the generator pit.

In small hydro power projects, the probability of constraints in transportation is quite low. However, in the hilly terrain, sometimes the transport limitations may pose problem due to old, small and low capacity of bridges, culverts, steep slopes/bends etc. In some areas, the road traffic is blocked for several months due to heavy rainfall. Zojila pass in J&K is one such example which remains closed for several months during winter. In Leh-Laddakh, two projects of NHPC Ltd. were installed, namely 3 × 15 MW Nimmo Bajgo and 4 × 11 MW Chutak in Kargil in which several consignments had to be air lifted to avoid erection hold-ups.

(h) Maintenance of equipment - The maintenance of turbine, generator, auxiliaries, control/protection systems, cranes etc. as per the schedule provided by their manufactures plays key role in the performance of the generating unit. The guide vanes, guide bearing, runner in reaction turbine, nozzles/buckets in Pelton turbine etc are the critical components which are susceptible to damage by cavitation and silt erosion and they necessitate regular maintenance. In a hydropower project, even a 10 to 20 MW generating unit may have quite a large size components in case of low speed reaction turbines. In large Kaplan or Francis vertical axis turbines, provision may be made for bottom removal of runners and other under water parts without dismantling of a generator. Large Kaplan turbines may be designed to enable replacement of the runner blades without dismantling the generator and turbine top cover. The damages due to cavitation and silt erosion are relatively difficult to maintain and repair. They need more time for maintenance in reaction turbines as compared to Pelton turbines in which major and vital parts are easily accessible being in open. Replacement of spears and nozzles of Pelton turbines are much quicker and easier than replacement of guide vanes of reaction turbines.

In generator, windings and thrust/guide bearings need special care and attention in monitoring and maintenance.

IV CONCLUSION

The turbine is selected from techno-economic considerations which include the cost of civil works and associated benefits. It is really a difficult decision to select appropriate turbine as far as reaction turbine is concerned. Sometimes, depending on proven model testing and operation of prototype turbine, selection of turbine of lower specific speed may also be preferred.

Depending upon unit capacity, number of units, total energy generation, exhaustive studies, model test etc. are required to be done before final selection, as it relates to the cost of generator, its size, weight etc. which in turn relates to the sizing of the power house, crane capacity etc.

It is always intended to enhance the specific speed of turbines as can be noted from various papers published in leading national and international journals. On the basis of data of number of turbines manufactured during last several decades, analysis is carried out that shows the preference for higher and higher specific speeds for high heads. The objective is to economize on overall dimensions of power house which depend mainly on runner diameter. Several researches and experiments aim to improve metallurgy, profile of turbine blades etc. to minimize cavitation, erosion due to hard particles, silt etc. Though initially it increases cost of a turbine but over the useful life of a turbine, the additional cost incurred is paid back due to the reduced maintenance and increased availability of unit for operation. Thus, the optimum selection of hydro turbines to suit site parameters is very important.

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