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Design of Pico Hydropower Plants for Rural Electrification

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Abstract. Pico hydro power stations include all hydropower systems with output of up to 5 kW. These systems have proven themselves to provide a reliable source of electricity for rural areas. Apart from rural area electrification, pico hydro power stations are convenient for utilizing the hydropower potential of water supply systems. This paper shows the calculation procedure and the selection criteria for basic components of a pico hydropower station based on a Pelton turbine. The paper provides an example of calculation procedure as well as the possibility of using them in Bosnia and Herzegovina.

Keywords: Hydropower · Pico hydropower plants · Pelton turbine
Rural electrification

Nomenclature

c_1 - absolute velocity of water jet [m/s]
D - pitch circle diameter [m]
d - optimal jet diameter [m]
D_a - runner outside diameter [m]
d_N - nozzle diameter [m]
d_u - inside diameter of the penstock [m]
s - wall thickness [m]
g - gravitational constant (g = 9,81) [m/s^2]
h - bucket height [m]
Hn - net head [m]
i - transmission ratio [-]
k_c - nozzle coefficient [-]
k_u - coefficient [-]
n_G - rotational speed [min^{-1}]
P - power output [kW]
Q - installed flow [m^3/s]
t - bucket depth [m]
u_1 - optimal peripheral velocity [m/s]
z - approximate number of buckets [-]
η - efficiency [-]
ψ_D - jet contraction coefficient [-]

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1 Introduction

In this paper, there will be presented the possibility of producing electricity in the pico hydropower plants. Pico hydropower plants include all hydropower systems up to 5 kW. In the last 20 years, pico hydropower plants found their highest use in the electrification of rural areas, replacing aggregates with fossil fuel, photovoltaic systems and wind power plants. Pico hydropower plants are most used today in the countries of South America and Southeast Asia. In addition to the hydrologic wealth of these areas, the main reason for the dominance of the picohydroelectric systems in the electrification of rural areas is low cost and negligible operating costs.

2 Low-Power Hydropower Plants – Pico Hydropower Plants and Their Use

In most literature, hydropower systems of up to 50 kW are classified as "micro hydropower systems" [1], but it is not uncommon for systems of power from 5 to 50 kW to be classified as "micro hydropower systems", and those of up to 5 kW classified as "pico hydropower systems" [2]. In this paper, systems of power up to 5 kW will be classified as "pico hydropower systems" in order to make a difference between them and micro hydropower plants, which according to the current law in the Republic of Srpska and Bosnia and Herzegovina are all hydropower plants up to 500 kW. Low-power hydropower systems (up to 5 kW) have proven to be a very stable source of electricity for the electrification of rural areas [3]. Their highest advantage is a long lifetime and a small number of components.

In this paper, there will be presented the guidelines for the selection of components and the design of a turbine wheel of a pico hydropower plant based on the Pelton turbine are presented. Input parameters for design are: installed flow Q [m^3/s], and gross head H [m]. Also, here will be considered only systems up to 5 kW. The design principle of the turbine and all components is the same for both 5 and 50 kW, with more rigorous safety requirements, precise manufacturing of components, material selection, etc.

2.1 The Use of Pico Hydropower Plants in the Electrification of Rural Area

Hydropower systems with power up to 5 kW have a very important role in the electrification of rural areas. These systems are suitable for the supply of individual households with electricity. For example, it is estimated that there are between 60,000 and 100,000 picohydropower plants only in rural parts of the state of Laos (Laos People's Democratic Republic) [4].

The first country that began to use the picohydropower plant for rural electrification is Nepal. In 1990, more than 600 picohydropower plants were installed in this country. Of all turbines, the highest use had Crossflow and Pelton turbines. The reason for this is the greatest adaptability to the parameters of the net head and flow, and the lowest cost of production [8].

The basic precondition for using picohydropower plants in the electrification of rural areas is the existence of a widespread hydrological network of water sources. For this reason, the pico hydropower plants found their greatest use in the countries of South America and Southeast Asia.

2.2 The Use of Pico Hydropower Plants in the Water Supply Systems

Except the use in the electrification of rural areas, the pico hydropower plants can also be used for the exploitation of hydropower potential in water supply systems. If there is a sufficient height difference between the two values on the transport pipeline, it is justified to invest the installation of the turbine and the generator on the already existing pipeline. [6] When installing the hydropower plant on the transport pipeline, the costs of the water intake and the supply pipeline are eliminated. The biggest lack of these systems is variability of flow due to different consumption during the day. Therefore, the turbine and the generator must be dimensioned so that they can work in both increased and reduced loads. This will lead to a reduction in the efficiency coefficient at nominal parameters, but will allow the system to operate throughout the year.

3 Design of a Pico Hydropower Plants

The first step in designing a pico hydropower plant is to estimate the hydropower potential of the water source. This is done by measuring the gross head and the water discharge. After dimensioning of the supply pipeline, the net head is calculated, and it, together with the flow, represents the hydropower potential of the hydropower plant. After determining the net head and water discharge, approach to designing a system is used to make the most of this potential. According to some analyzes, for the optimal diameter of the pipeline, the diameter for which the hydraulic losses are 5–15% of the gross head is taken [3]. After previously selection of the diameter of the supply pipeline, we approach to estimate of the net head. In this paper there will be not describe of the calculation of the net head, but it will be approached to the estimate of the Pelton's turbine with known parameters of the watercourse (flow, gross and net head).

In the electrification of rural areas, the largest use found action-type turbines. The reason for this is that action turbines can work efficiently with much less installed flow. In such small systems, Crossflow turbines were first used. The reason for this is their simple production. The Pelton turbine can work with a smaller flow from the Crossflow turbine and to operate at a significantly higher net loss.

3.1 Design of Pelton Turbine

There are three main principles in designing of the turbine:

- calculation of optimal jet diameter,
- calculation of turbine wheel diameter, and
- calculation of turbine buckets dimensions.

3.1.1 Calculation of the Nozzle

Nozzle is an inlet pipe of Pelton turbine. On account of pressure loss, kinetic energy is increasing, so velocity of water jet is very high:

$$c_1 = k_c \cdot \sqrt{2 \cdot g \cdot H_n} \tag{1}$$

For absolute velocity of water jet, calculation needs to be calculated optimal jet diameter:

$$d = \sqrt{\frac{4 \cdot Q}{\pi \cdot c_1}} \tag{2}$$

By instructions given in [8], water jet diameter should not be smaller than 4 mm. Number of buckets depend on water jet diameter. Also, if number of buckets is not at least possible in calculation $(z = 16)$, there needs to be increased number of nozzles in it and calculation have to be done again. There are two main construction implementations of nozzles: Nozzles with variable cross section and nozzles with constant cross section. In variable ones, width of water jet is regulated by position of regulation spear. Adjustment of that can be done manually or automatically.

In calculating of nozzle's diameter, jet contraction coefficient must be considered. This coefficient represents relation between nozzle's diameter and water jet diameter:

$$\psi_D = \frac{d_N}{d} \tag{3}$$

Jet contraction coefficient ψ_D is in amplitude of 1,6 for holes with sharp edges till 1,05 for ideally rounded edges.

Beside nozzles with an option of regulation of the cross section, it is possible to use even nozzles with the constant cross section. The only advantage of it is lower price and better lasting than first ones.

3.1.2 Calculation of Pelton Wheel Dimensions

After calculation of the absolute velocity and water jet diameter, now is the turn of calculation of the wheel turbine. Geometric characteristics of turbine buckets are calculating based on water jet diameter, most important of which are (Fig. 1):

- bucket width - b [m]

$$b = (2,5 \div 3,2) \cdot d \tag{4}$$

- bucket height - h [m]

$$h = (2,1 \div 2,7) \cdot d \tag{5}$$

- bucket depth - t [m]

$$t \approx 0,9 \cdot d \tag{6}$$

For net head amount, extensive optimal peripheral velocity is calculated:

$$u_1 = k_u \cdot \sqrt{2 \cdot g \cdot H_n} \tag{7}$$

$$k_u = \frac{u_1}{c_1} = 0,45 \div 0,49 \tag{8}$$

Beside coefficient of nozzle usage and hydraulic losses, coefficient k_u highly affects on coefficient of Pelton turbine usage. Relying on extensive velocity of the turbine wheel and designed number of generator's rotational speed, pitch circle diameter is calculated by this form:

$$D = \frac{60 \cdot u_1 \cdot i}{\pi \cdot n_G} \tag{9}$$

In the case of the pico Pelton turbine, processed in this paper, transmission ratio will have the value i = 1, because the turbine and the generator are directly connected, which means there is no change rotational speed. Figure 1 shows the main dimensions of the Pelton turbine buckets.

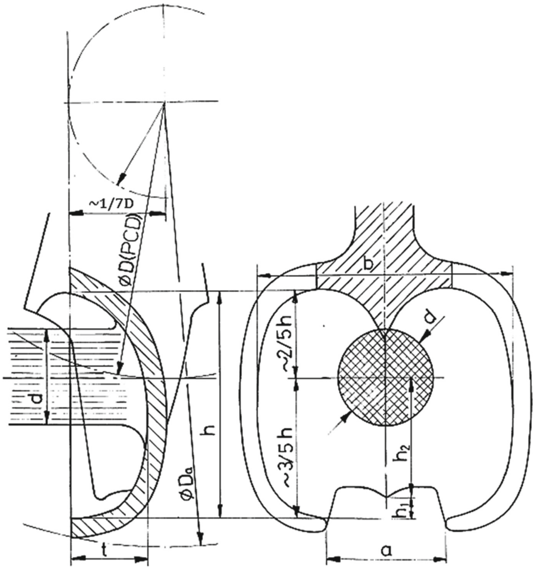

Fig. 1. Main dimensions of Pelton buckets [8]

In some cases, it is possible to install a turbine with larger buckets of calculated ones. Small increase in dimensions slightly affect the reduction of the useful efficiency coefficient. Increasing the dimensions obtained from the calculation is justified if an already existing turbine is used, or if the reduction in dimensions would lead to changes in production, thereby affecting the increase in production costs.

Depending on the pitch circle diameter and the height buckets, the runner outside diameter is calculated:

$$D_a = D + 1{,}2 \cdot h \tag{10}$$

On the efficiency of the Pelton turbine, a big influence has the number of buckets adopted. Optimal number of Pelton turbine buckets depend on the pitch circle diameter and water jet diameter [7]:

$$z = \frac{D \cdot \pi}{2 \cdot d} \tag{11}$$

According to the same author, the number of buckets not be less than 16. Various authors give different formulas for calculating the optimal number of buckets. In principle, any cutting of a water jet on the bucket causes a disruption in the flow. Therefore, the unnecessary increase in the number of buckets reduces the efficiency of the turbine. On the other hand, insufficient number of buckets causes volumetric losses in turbine wheel.

4 Calculation Example

In this chapter will be displayed calculation of pico hydropower plants, using the following parameters:

- installed flow – $Q = 0{,}005\ \mathrm{m^3/s}$;
- gross head – $H = 50$ m;
- the length of the supply pipeline – $l = 200$ m;

The first step in the calculation is the previous choice of the diameter of the supply pipeline. A high density polyethylene pipe (HDPE pipe), a nominal operating pressure of 10 bar (PN 10) and an absolute roughness coefficient, k = 0.002 mm was selected for the supply pipeline.

Respecting the recommendation on the choice of the optimal diameter of the supply pipeline referred to in Sect. 3, the order of standard pipe sizes, the pipe DN 110 NP 10 is selected, with the following parameters:

- inside diameter – $d_u = 93{,}8$ mm;
- wall thickness – $s = 8{,}1$ mm;
- pressure nominal – 10 bar.

For selected pipe DN 110, approaches to a detailed calculation of Pelton turbine parameters.

Table 1. Results of the Pelton turbine calculation for different rotational speed

Quantity	Symbol	Unit	Calculation		
Rotational speed	n_G	[min^{-1}]	650	1000	1200
Net head	H_n	[m]	47,2		
Power output for efficiency coefficient 55%	P	[kW]	1,27		
Absolute velocity of water jet	c_1	[m/s]	29,22		
Optimal jet diameter	d	[mm]	14,76		
Nozzle diameter	d_n	[mm]	18,45		
Optimal peripheral velocity	u_1	[m/s]	13,70		
Pitch circle diameter	D	[mm]	402,45	261	218
Optimal number of buckets	z	[-]	43	28	23
Bucket width	b	[mm]	47,23		
Bucket height	h	[mm]	39,85		
Helpful sizes	h_1	[mm]	5,16		
	h_2	[mm]	22,14		
	a	[mm]	17,71		
Runner outside diameter	D_a	[mm]	450	309	266
Bucket depth	t	[mm]	13,28		

The calculation is done for different rotational speed. The results of the calculations are shown in Table 1.

As can be seen from Table 1, for different rotational speed of the turbine, the different pitch circle diameter and number of buckets are obtained. Other values do not depend on the projected rotational speed, but only on the parameters of the projected flow. The turbine parameter calculation process is calculated for available rotational speed of the generator. For this turbine, 1200 min^{-1} is chosen. For the given number of turns, the generator 145STK2 M, manufacturer ALXION, is selected, the characteristics shown in Fig. 2:

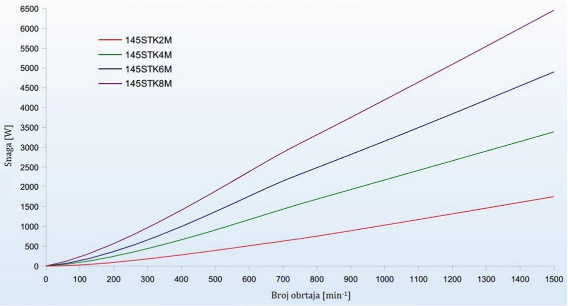

Fig. 2. Nominal power output of generator depending of rotational speed [5]

A flange ball valve must be installed before the regulating nozzle, so that the supply pipeline should not discharge due to possible repairs on the nozzle, turbine or housing. Figure 3 shows the system of concrete pico hydropower plants.

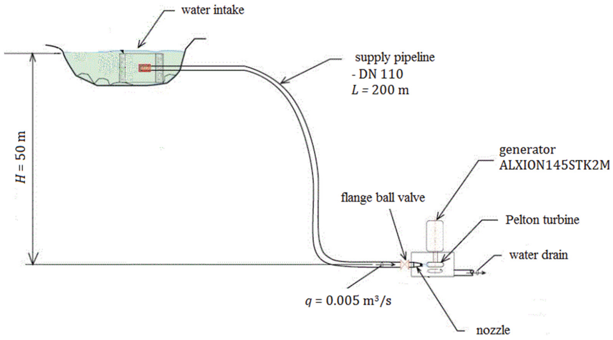

Fig. 3. Concrete pico hydropower plant

5 Conclusion

Pico hydropower plants proved to be a stable source of energy for the electrification of rural areas. Apart from lower investments comparing to the solar systems, wind power plants and aggregates on fossil fuels, the advantage of the pico hydropower plant is the simplicity of construction, easy assembly and disassembly, low operating costs, as well as greater resistance to weather conditions.

Pico hydropower plants, so far, are not specifically defined by the laws of the RepublikaSrpska and BiH. By resolving the legislation for the pico hydroelectric power plants, the conditions for further progress in this area would be met.

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