Determination of operating parameters of turbines for micro hydroelectric power plants for optimal use of hydropower

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Abstract. Energy trends have been mostly focused on renewable energy sources in recent years. In the world, about 20% of electricity is produced using energy of water flows, i.e. hydropower with a total installed power of 720 GW. The production of hydroelectric power has a number of advantages from fossil fuels or nuclear energy and the greatest is that it does not pollute the environment. In mountainous areas, small and micro hydro power plants are often used, which can be installed on small rivers or streams with little or negligible impact on the environment. The choice of the type of turbine is influenced by a number of parameters, which should be determined before the complete project of the micro hydroelectric power plant. For turbines that are most commonly used in micro hydroelectric power plants, the process of determining operating parameters for optimal utilization of available hydro power is presented in the paper.

1. Introduction

The basic function of the turbine is the transformation of the kinetic energy of the water into the mechanical energy of the rotating parts of the turbine. The operating conditions of the turbine depend on a large number of influencing parameters such as field configuration, possible flow and fall combinations, etc. Many different types of turbines have been developed to cover a wide range of working conditions. It can be said that turbines used in small hydropower plants are a reduced version of turbines used in conventional large hydroelectric power plants.

According to the qualification of the turbines according to the delivered electricity of the micro hydro power plants, they include a power range of 5 to 100 kW.

Considering that in the case of micro-flow hydroelectric power plants, the flow of water varies widely, which is why water turbines are chosen that work efficiently at wide flow limits. Based on the diagram in Fig. 1 in micro hydroelectric applications Pelton, Francis, Kaplan, and crossflow turbines are applied.

2. Parameters of micro hydro power plants

2.1. Operational parameter

Today, technically defined and available to engineers a larger number of turbines, which can be applied to mini and micro hydro power plants. For this reason it is first necessary to show the most important components of a mini hydro power plant with their operating parameters. Figure 2 shows the layout of the most important components and devices as well as the parameters of small and micro hydro power plants.
Figure 1. Selection of turbine from the aspect of power, flow and height of the fall.

Figure 2. Profile of micro hydro power plant with components and devices.

| WF – water accumulation | Tu – turbine | Ek – kinetic energy |
|-------------------------|-------------|-------------------|
| SF – crossing           | Ge – generator | E_0 – potential energy |
| Ka – channel            | 0 – ref. point of accumulation | p – pressure |
| Re – grille             | 1 – ref. point at the entrance to the turbine | H – gross height drop |
| EB – input workspace    | 2 – ref. point at the exit from the turbine | H_0 – net height drop |
| DL – input line         | 3 – ref. point of the drainage channel | H_L – hydraulic energy losses |
| AO – input body of the turbine | E – energy line |

The most important parameters of the hydroelectric power plant are:

- Flow - the amount of water that passes through the turbine in the Q unit [m³ / s].
• Gross height drop - height difference between the water level in the accumulation (point 0) and the level of water at the exit from the turbine (point 3) \( H [m] \).
• Net height drop - which represents the available potential energy of the turbine \( H_n [m] \)
• Hydraulic energy losses expressed through altitude difference represent losses in flow of water through grilles, channels, pipelines and turbine \( H_v [m] \). Determined according to:

\[
H_v = A \cdot Q^2
\]  
(1)

• Hydraulic power of the turbine is determined according to [W]:

\[
P_{hyd} = \rho \cdot Q \cdot g \cdot H_n
\]  
(2)

• Mechanical power on the shaft of the turbine [W]:

\[
P_{mech} = T \cdot \omega = T \cdot \frac{\pi \cdot n}{30} = \frac{T \cdot n}{9.549}
\]  
(3)

• Efficiency of the turbine is determined as the ratio between the mechanical and hydraulic power of the turbine

\[
\eta_t = \frac{P_{mech}}{P_{hyd}}
\]  
(4)

2.2. Specific parameters

Different types of turbines can be classified according to characteristic sizes that include the most important operating parameters. The most commonly used are the following sizes.

1. The specific speed from the aspect of power \( n_s \)

It is defined as the number of rotations of the turbine \( n_s \) in min\(^{-1}\), where 1 kW power level is obtained for a height drop of 1 m.

\[
n_s = n \cdot \sqrt[4]{\frac{P}{H_n}}
\]  
(5)

This term has the advantage that the utilization rate is encompassed by the power \( P \).

2. The specific speed from the aspect of flow \( n_q \)

It is defined as the rotational speed of the turbine \( n_q \) in min\(^{-1}\) at a height drop of 1 m and a flow of 1 m\(^3\)/s.

\[
n_q = n \cdot \sqrt[4]{\frac{Q}{H_n}}
\]  
(6)

Corelation between \( n_s \) and \( n_q \):

\[
n_s = 3.65 \cdot \sqrt[4]{\eta} \cdot n_q
\]  
(7)

\[\begin{align*}
D & - \text{nominal diameter of the turbine circuits \([m]\)} \\
A & - \text{coefficient} \\
g & - \text{acceleration due to gravity: } g=9.81 \text{ \([m/s^2]\)} \\
\rho & - \text{water density } \rho=1000 \text{ \([kg/m^3]\)} \\
n & - \text{working speed of the impeller \([min^{-1}]\)} \\
P & - \text{turbine power \([kW]\)} \\
\omega & - \text{angular velocity \([rad/s]\)}
\end{align*}\]
3. Operating parameters of turbines for application to micro power plants

3.1. Pelton turbine
The basic geometric dimensions of the Pelton turbines are (Fig. 3) the mean diameter of the impeller \( D_0 \) and the diameter of the jet \( D_2 \). The flow of water per nozzle is:

\[
Q_i = 0,97 \cdot \frac{\pi}{4} \cdot D_i^2 \cdot \sqrt{2g \cdot H_n} \quad [m^3/s]
\]  

(8)

For the number of nozzles \( z_i \), the total flow of water is

\[
Q = z_i \cdot Q_i \quad [m^3/s]
\]  

(9)

The diameter of the water jet

\[
D_2 = 0,545 \cdot \frac{\sqrt{Q_i}}{\sqrt{H_n}} \quad [m]
\]  

(10)

The middle diameter of the impeller \( D_1 \) where the resulting force of the jet of water is operating is determined according to:

\[
D_1 = (37...41) \cdot \frac{\sqrt{H_n}}{n} \quad [m]
\]  

(11)

\( H_n \) - net height drop [m]
\( n \) - speed of the impeller [min\(^{-1}\)]

Depending on the specific speed, empirically it can be taken

\[
\frac{D_1}{D_i} = 1/7 \ldots 1/30
\]  

(12)

Figure 3. Principal scheme of the Pelton turbine.
3.2. Crossflow turbine

Crossflow turbines are pulse turbines in which water passes twice over the blades of the impeller. It has a simple construction with three main components (fig.4):

- Rectangular introductory device, which directs the flow of water over two profiled blades placed side by side.
- Impeller drum with arched profiled shovels.
- Enclosures that, in accordance with the flow of water, surround the impeller and on which the impeller of the impeller is clamped.

![Figure 4. Principal diagram of the crossflow turbine.](image)

The flow of water through the flow turbines is determined according to:

\[
Q = 0.25 \cdot \alpha \cdot \frac{D \cdot B}{2} \cdot \sqrt{2g \cdot H_n} = (0.2 \ldots 0.3) \cdot D \cdot B \cdot \sqrt{2g \cdot H_n} \quad \text{[m}^3/\text{s]}\]  

(13)

and

\[
B \cdot D = (1.13 \ldots 0.75) \cdot \frac{Q}{\sqrt{H_n}}
\]

(14)

\[D\] - turbine wheel diameter [m]
\[B\] - width of the turbine circuits [m]
\[H_n\] - net height drop [m]
\[\alpha\] - angle of water flow [rad]

The angular velocity, or the speed of the turbine impeller, is determined according to:

\[
\omega = 0.45 \cdot \frac{2}{D} \cdot \sqrt{2g \cdot H_n} = 0.9 \cdot \frac{\sqrt{2g \cdot H_n}}{D} \quad \text{[rad/s];} \quad n = \frac{30}{\pi} \cdot \omega \quad \text{[min}^{-1}]\]

(15)

For \[\alpha=120\ldots90^\circ\]:

\[\]
Depending on the height of the drop $H_n$ and the load of the material of the impeller, the ratio of width and diameter moves within the limits $B/D = 0.3 \ldots 4$. The number of blades of the impeller moves within the limits $z_r = 24 \ldots 32$.

\[
D = 38 \cdot \frac{\sqrt[3]{H_n}}{n}; \quad B = (0.02 \ldots 0.03) \cdot \frac{Q \cdot n}{H_n}
\]  

Figure 5. Principal scheme of Francis turbine.

3.3. Francis turbine

With the Francis turbine, the introducer device is a fixed wheel, where the introductory blades are located. The blades are articulated so that the turbine operation can be controlled. The water is fed by a circular channel and directs it to the impeller via the opening blades. The impeller is connected to a shaft that is clamped over the main bearing of the turbine and connected to the gear and generator. Selection of the turbine is made according to the specific speed $n_q$ (Fig.5).

Depending on the flow $Q$ and the speed rpm, the outer diameter of the impeller is determined according to:

\[
D_{z_r} = 4.44 \cdot \left(\frac{Q}{n}\right)^{1/3}
\]  

The internal diameter depends on the height of the drop $H_n$ and the speed rpm of the impeller, and can be roughly determined according to:

\[
D_{l_i} = 64.4 \cdot \frac{\sqrt{H_n}}{n}
\]  

3.4. Kaplan turbine

The Kaplan turbine impeller is similar to a propeller. It is primarily intended for low altitude falls, where it has a good degree of efficiency. The blades of the impeller at Kaplan's turbine are attached to the hub so that their position can be adjusted. The impeller is most often placed in the spiral housing so that the water flows radially through the input device and radially through the impeller. A complete turbine can be integrated into the pipeline, which enables a compact construction.

The oscillatory dimensions of the Kaplan turbine are shown in Fig.6. The outer diameter of the impeller $D_e$ can be approximately determined by
The velocity coefficient depends on the specific speed \( n_q \).

| \( c_{ue} \) | 1.2 | 1.4 | 1.51 | 1.65 | 1.75 | 1.85 | 1.95 |
|---|---|---|---|---|---|---|---|
| \( n_q \) | 100 | 125 | 150 | 175 | 200 | 225 | 250 |

4. Determination of operating parameters for selecting the turbine of the micro power plant

Based on the expressions given in items 2 and 3, as well as the nomograms in Fig. 1, turbines for micro hydroelectric power plants can be selected. For the purpose of further analysis, the operating parameters for power of 50 kW (4 variants) and 100 kW (4 variants) were determined for Pelton, throughput, Francis and Kaplan turbines. The results are shown in Tables 1 to 4.
Table 1. Pelton turbine parameters with 1 nozzle.

| H [m] | Q [m³/s] | η [-] | P [kW] | n_q [min⁻¹] | n_s [min⁻¹] | n [min⁻¹] | D₁ [m] |
|-------|---------|-------|--------|------------|-------------|-----------|--------|
| 100   | 0.06    | 0.9   | 50.00  | 8.00       | 27.70       | 1238.85   | 0.31   |
| 90    | 0.06    | 0.9   | 50.00  | 6.00       | 20.78       | 814.49    | 0.44   |
| 80    | 0.07    | 0.9   | 50.00  | 4.00       | 13.85       | 468.65    | 0.73   |
| 70    | 0.08    | 0.9   | 50.00  | 2.00       | 6.93        | 198.30    | 1.60   |
| 100   | 0.11    | 0.9   | 100.00 | 8.00       | 27.70       | 876.00    | 0.43   |
| 90    | 0.13    | 0.9   | 100.00 | 6.00       | 20.78       | 575.93    | 0.63   |
| 80    | 0.14    | 0.9   | 100.00 | 4.00       | 13.85       | 331.39    | 1.03   |
| 70    | 0.16    | 0.9   | 100.00 | 2.00       | 6.93        | 140.22    | 2.27   |

Table 2. Parameters of crossflow turbines.

| H [m] | Q [m³/s] | η [-] | P [kW] | n_q [min⁻¹] | D [m] | B [m] | n [min⁻¹] | n_s [min⁻¹] |
|-------|---------|-------|--------|------------|-------|-------|-----------|-------------|
| 24    | 0.25    | 0.84  | 50.00  | 65         | 0.11  | 0.23  | 1639.69   | 218.26      |
| 20    | 0.30    | 0.84  | 50.00  | 57         | 0.15  | 0.30  | 1138.67   | 190.37      |
| 12    | 0.51    | 0.84  | 50.00  | 39         | 0.32  | 0.64  | 409.92    | 129.78      |
| 10    | 0.61    | 0.84  | 50.00  | 34         | 0.42  | 0.84  | 284.67    | 113.19      |
| 24    | 0.51    | 0.84  | 100.00 | 46         | 0.23  | 0.45  | 819.84    | 154.34      |
| 20    | 0.61    | 0.84  | 100.00 | 40         | 0.30  | 0.60  | 569.34    | 134.61      |
| 12    | 1.01    | 0.84  | 100.00 | 27         | 0.64  | 1.28  | 204.96    | 91.77       |
| 10    | 1.21    | 0.84  | 100.00 | 24         | 0.84  | 1.69  | 142.33    | 80.04       |

Table 3. Parameters of the Francis turbine.

| H [m] | Q [m³/s] | η [-] | P [kW] | n_q [min⁻¹] | n_s [min⁻¹] | n [min⁻¹] | D₁ [m] | D₂ [m] |
|-------|---------|-------|--------|------------|-------------|-----------|--------|--------|
| 30    | 0.19    | 0.9   | 50.00  | 35.00      | 121.19      | 1203.37   | 0.29   | 0.24   |
| 20    | 0.28    | 0.9   | 50.00  | 30.00      | 103.88      | 621.35    | 0.46   | 0.34   |
| 14    | 0.40    | 0.9   | 50.00  | 25.00      | 86.57       | 331.53    | 0.73   | 0.47   |
| 10    | 0.57    | 0.9   | 50.00  | 20.00      | 69.25       | 174.16    | 1.17   | 0.66   |
| 30    | 0.38    | 0.9   | 100.00 | 55.00      | 190.45      | 1337.14   | 0.26   | 0.29   |
| 20    | 0.57    | 0.9   | 100.00 | 40.00      | 138.51      | 585.82    | 0.49   | 0.44   |
| 14    | 0.81    | 0.9   | 100.00 | 30.00      | 103.88      | 281.32    | 0.86   | 0.63   |
| 10    | 1.13    | 0.9   | 100.00 | 24.00      | 83.10       | 147.78    | 1.38   | 0.88   |

Selection of turbine is significantly influenced by the available flow and its change during the year. In this regard, the following cases should be distinguished:

- Constant flow - a turbine with a fixed hole is selected at the input of the propeller turbine (Kaplan's with fixed inlet blades) and Pelton to a constant diameter of the nozzles.
- Small change of flow - turbine is relatively little exposed to variable flow. A Francis or Kaplan turbine is selected with a fixed fixed hole at the inlet for maximum efficiency.
- A large change in flow - turbine very often does not have enough water. Despite the reduced efficiency, it is recommended to use a flow turbine or a Francis turbine. Pelton turbines with multiple nozzles, as well as Kaplan turbines with 2 degrees, can be used as they can be adjusted according to the flow.
Table 4. Kaplan turbine parameters.

| H [m] | Q [m³/s] | η [-] | P [kW] | n_q [min⁻¹] | n_s [min⁻¹] | n [min⁻¹] | D₀ [m] |
|-------|---------|------|-------|-------------|-------------|---------|-------|
| 9     | 0.63    | 0.9  | 50.00 | 120.00      | 415.52      | 916.04  | 0.39  |
| 7     | 0.81    | 0.9  | 50.00 | 105.00      | 363.58      | 585.45  | 0.54  |
| 5     | 1.13    | 0.9  | 50.00 | 90.00       | 311.64      | 329.52  | 0.80  |
| 3     | 1.89    | 0.9  | 50.00 | 75.00       | 259.70      | 145.01  | 1.41  |
| 9     | 1.26    | 0.9  | 100.00| 120.00      | 415.52      | 647.74  | 0.55  |
| 7     | 1.62    | 0.9  | 100.00| 105.00      | 363.58      | 413.98  | 0.76  |
| 5     | 2.27    | 0.9  | 100.00| 90.00       | 311.64      | 233.01  | 1.14  |
| 3     | 3.78    | 0.9  | 100.00| 75.00       | 259.70      | 102.54  | 2.00  |

From the aspect of optimal exploitation of the available hydroelectric power plant, it is necessary, in accordance with hydrological conditions, to harmonize the choice of the turbine itself, its construction parameters with the parameters of the machine plant or the generator itself. It should be noted that the working speeds of the turbine circuits are not fixed and can be changed within certain limits by changing the design parameters of the turbine.

The current generator is connected to a network having a constant network frequency of 50 Hz. Therefore, it is necessary that the number of revolutions of the generator does not change and that it is harmonized with the other parameters of the hydroelectric power plant. The following should be taken into account:

- With the increase in the speed, the centrifugal force increases significantly, and therefore the mechanical mapping of the machine group, and therefore the nominal speed is limited to 1500 min⁻¹.
- When applying a generator with a rotational speed below 600 min⁻¹, the overall dimensions and therefore the specific price of the generator are growing, while at the same time reducing the energy efficiency due to magnetic losses.
- It is therefore recommended that, with turbine speeds below 750 min⁻¹, using a multiplexer power transmission, the rpm rises to 1500 min⁻¹ or 1000 min⁻¹ and optimally exploits available hydropower.

5. Conclusion

The energy efficiency of small hydropower plants depends on a number of influencing parameters: flow, altitude, selected turbine plant, variation of flow and height drop during the year, terrain configurations, etc. The problem that arises when choosing a type of micro-hydroelectric turbine is to determine the influencing parameters for the correct turbine precipitation with the optimum use of available hydro power. For the most commonly used turbines of micro hydroelectric, Pelton, flow, Fransis and Kaplan, the process of determining operating parameters, based on which it is possible to make the choice of the type of turbine, is presented in the paper.

Changing hydrological conditions mostly reflect the available flow and its change during the year. It is easiest to choose the type of turbine for ideal conditions when the flow rate is constant. It is then recommended for a smaller altitude drop of Kaplan turbine with fixed inlet blades, and for Pelton turbine higher altitude drops to constant nozzle diameter. In case of a small change in flow, it is recommended in accordance with the altitude drop of the Fransis or Kaplan turbine with the tuned opening at the inlet for the maximum degree of efficiency. In case of large flow changes, one of the flow turbines or Fransis turbines is recommended. Pelton turbines with multiple nozzles, as well as Kaplan turbines with 2 degrees, can be used as they can be adjusted according to the flow.

From the aspect of optimal use of the available hydroelectric power plant, it is necessary, in accordance with hydrological conditions, to harmonize the choice of the turbine itself, its construction
parameters with the parameters of the machine plant or the electricity generator itself. In this regard, the application of the generator with the numbers of revolutions of 1500 min⁻¹ or 1000 min⁻¹ is purposeful, with adequate harmonization with the speeds of the turbine circuits with the use of a power transmission - multiplexer.

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