Suitable Selection of Components for the Micro-Hydro-Electric Power Plant

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Abstract The micro-hydro-electric power plant is a renewable energy plant which has many advantages over the same size of wind and solar renewable energy plants. It has a high efficiency (up to 90%), high capacity factor (up to 60%) and slow rate of change (due to the water flow varies gradually from time to time). This paper deals with a suitable selection of the micro-hydro-electric power plant components such as the turbine type, which is the main part in the plant and generator size and capacity, which is the second main part component in the power station. Also a procedure is developed for calculation of transmission line voltage drop during the transmission of power to the load site, and to specify the transformer size and its protection facilities.

Keywords Micro-hydro-electric Power Plant, Design of Components, Hydro-Turbine, Generator, Line Voltage Drop

1. Introduction

The advantages that micro-hydro-electric power plant has over the same size of wind, wave and solar power plants of renewable energies are[1,2,3]:
- High efficiency (70-90%), by far the best of all energy technologies.
- High capacity factors (> 50%) compared with 10% for solar and 30% for wind power plant.
- Slow rate of change; the output power varies only gradually from day to day not from minute to minute.
- The output power is maximum in winter.

Comparative study between small-hydro-electric power plants (up to 10 MW capacity) and micro-hydro-electric power plants (up to 100 KW capacity) reveals that the former one is more capital intensive and involves major political decisions causing difficulties in different implementation phases. On the other hand micro-hydro-electric power plants are low cost, small sized and can be installed to serve a small community making its implementation more appropriate in the socio-political context. Many of these systems are "run-of-river" which does not require an impoundment. Instead, a fraction of the water stream is diverted through a pipe or channel to a small turbine that sits across the stream, as shown in figure (1).

So, there is a scope for harnessing the micro-hydro-electric power plant potentiality by identifying proper site and designing appropriate power generation systems specially the selection of the turbine, which is the first important part in the generating station, the generator which is the second important part in the station and the components of the power transmission line. Properly designed micro-hydro-electric power plant causes maximum power output and minimum environmental disruption to the river or stream and can coexist with the native ecology [4].

Figure 1. Schematic diagram of micro-hydro-electric power plant

2. Classification of Hydraulic Turbines

The potential energy in the water is converted into mechanical energy in the turbine, by one of two fundamental and basically different mechanisms:
A. The water pressure is converted into kinetic energy before entering the turbine runner. The kinetic energy is in the form of high-speed jet that strikes the buckets, mounted on the periphery of the runner. Turbines those operate in this way are called impulse turbines. As the water after striking the buckets falls into the tail water with little remaining energy, the casing can be
light and serves the purpose of preventing splashing. The impulse turbines can be divided into two types as [3]:

i.
Pelton turbines [4]: They are impulse turbines where one or more jets impinge on a wheel carrying on its periphery a large number of buckets. Each jet issues through a nozzle with a needle valve to control the flow. They are only used for relatively high heads. The axis of the nozzles is in the plane of the runner. To stop the turbine the jet may be deflected by a plate so that it does not impinge on the buckets. The needle valve can be closed very slowly, so that over pressure surge in the pipe line is kept to an acceptable minimum. Any kinetic energy leaving the runner is lost and so the buckets are designed to keep exit velocities to a minimum.

ii.
Cross-flow (Banki-Michell) turbine [5,6]: Banki turbine is an atmospheric radial flow wheel which derives its power from the kinetic energy of the water jet. It consists of two parts:

1. Nozzle.
2. Runner, which is built up of two parallel circular disks joined together at the rim with a series of curved blades. The water flow enters the wheel at an angle of (16°) to the tangent of the periphery of the wheel. Maximum efficiency occurs at practically a constant speed for all gate opening at constant head.

B. The water pressure can apply a force on the face of the runner blades, which decreases as it proceeds through the turbine. Turbines those operate in this way are called reaction turbines. The turbine casing, with the runner fully immersed in water, must be strong enough to withstand the operating pressure. To reduce the kinetic energy still remaining in water leaving the runner, a draft tube or diffuser stands between the turbine and the tailrace. The function of the draft tube is to reconvert the kinetic energy into flow energy by a gradual expansion of the flow cross section. The reaction turbines can be classified into two main types as [5,6,7]:

i.
Francis turbines: They are radial flow reaction turbines, with fixed runner blades and adjustable guide vanes, used for medium head. They can be set in an open flume or attached to a penstock. For small heads and power, open flumes are commonly employed. Steel spiral casings are used for higher heads.

ii.
Kaplan turbines: They are axial-flow reaction turbines, generally used for low heads. It has adjustable runner blades and may or may not have adjustable guide vanes. If both blades and guide vanes are adjustable, it is described as double-regulated. If the guide vanes are fixed, it is single regulated.

3. Turbine Power

All hydro-electric generation depends on falling water. Stream flow is the fuel of a hydro-power plant and without it generation ceases.

Regardless of the water path through an open channel or penstock, the power generated in a turbine (lost from water potential energy) is given as [4]:

\[ P_t = \rho \cdot g \cdot H_n \cdot Q \cdot \eta_t \text{ (watt)} \]  

Where \( P_t \) = power in watt generated in the turbine shaft.
\( \rho = \) water density (1000 Kg/m^3).
\( H_n = \) net head (m).
\( Q = \) water flow rate (m^3/s).
\( g = \) gravity acceleration constant (9.8 m/s^2).
\( \eta_t = \) turbine efficiency (normally 80-90%).

The turbine efficiency (\( \eta_t \)) is defined as the ratio of power supplied by the turbine (mechanical power transmitted by the turbine shaft) to the absorbed power (hydraulic power equivalent to the measured discharge under the net head).

It is noted that for impulse turbines, the head is measured at the point of impact of the jet, which is always above the down-stream water level. This amounts to reduction of the head. The difference is not negligible for low head schemes, when comparing the performance of impulse turbines with those of reaction turbines that use the entire available head.

To estimate the overall efficiency of the micro-hydro-power plant, the turbine efficiency must be multiplied by the efficiencies of the speed increaser (if any) and the alternator.

4. Turbine Speed

To ensure the control of the turbine speed by regulating the water flow rate, certain inertia of rotating components is required. Addition inertia can be provided by a flywheel on the turbine or generator shaft. When the load is disconnected, the power excess accelerates the flywheel, later, when the load is reconnected, deceleration of the addition inertia supplies additional power that helps to minimize speed variation. The basic equation of the rotating system is:

\[ \frac{dw}{dt} = \frac{1}{J \cdot \omega} (P_t - P_l - B \cdot w^2) \]  

Where \( w = \) turbine speed in (rad. /sec.).
\( P_t = \) turbine power (watt).
\( P_l = \) load power (watt).
\( B = \) turbine and generator friction torque coefficient (N.m/(rad./sec.)).
\( J = \) moment of inertia of the whole rotating system (Kg.m^2).

When \( P_t = P_t + B \cdot w^2 \), \( dw/dt = 0 \) and \( w = \) constant. So operation is steady. When \( P_t \) is greater or smaller than \( P_t + B \cdot w^2 \), the speed is not constant and the governor must intervene so that the turbine output power matches the generator output power. The motion equation of the whole system is a first-order differential equation and it can be solved numerically by MATLAB. The turbine speed depends on the head, turbine specific speed and turbine
power.

5. Turbine Specific Speed

The basic for comparison of the characteristics of hydraulic turbines is the specific speed (Ns), or the speed at which a turbine would run if the runner were reduced to a size which would develop (1) KW power under (1) meter head. This speed is proportional to the square root of the power and inversely proportional to the (5/4) power of the head, i.e.:

\[ N_s = \frac{N \sqrt{P_t}}{H^{5/4}} \]  

(3)

Where N = actual speed of rotation (r.p.m).
Pt = turbine power in (KW).
H = water head in (m).

In general, the higher the specific speed for a given head and turbine power output, the lower is the cost of the installation as a whole.

6. Turbine Selection

Once the turbine power, specific speed and net head are known, the turbine type, the turbine fundamental dimensions and the height or elevation above the tailrace water surface that the turbine should be installed to avoid cavitations phenomenon, can be calculated. In case of Kaplan or Francis turbine type, the head loss due to cavitations, the net head and the turbine power must be recalculated[8,9].

The turbine type can be estimated by comparing the calculated net head and specific speed with those given in table (1) and table (2).

<table>
<thead>
<tr>
<th>Turbine type</th>
<th>Range of head (meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaplan and propeller</td>
<td>2 &lt;Hn&lt; 40</td>
</tr>
<tr>
<td>Francis</td>
<td>10 &lt;Hn&lt; 350</td>
</tr>
<tr>
<td>Pelton</td>
<td>50 &lt;Hn&lt; 1300</td>
</tr>
<tr>
<td>Cross-flow (Banki-Michell)</td>
<td>3 &lt;Hn&lt;200</td>
</tr>
</tbody>
</table>

Table 2. Range of specific speed

<table>
<thead>
<tr>
<th>Turbine type</th>
<th>Specific speed range (meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelton one nozzle</td>
<td>5≤N≤25</td>
</tr>
<tr>
<td>Pelton two nozzles</td>
<td>7≤N≤35</td>
</tr>
<tr>
<td>Pelton four nozzles</td>
<td>10≤N≤50</td>
</tr>
<tr>
<td>Cross-flow (Banki-michell)</td>
<td>20≤N≤200</td>
</tr>
<tr>
<td>Francis</td>
<td>50 ≤N≤ 350</td>
</tr>
<tr>
<td>Kaplan and propeller</td>
<td>200 ≤N≤ 1550</td>
</tr>
</tbody>
</table>

In general, the Pelton turbines cover the high pressure domain down to (50 m) for micro-hydro. The Francis types of turbine cover the largest range of head below the Pelton turbine domain with some over-lapping and down to (10 m) head for micro-hydro. The lowest domain of head below (10 m) is covered by Kaplan type of turbine with fixed or movable blades. For low heads and up to (50 m), also the cross-flow impulse turbine can be used.

Once the turbine type is known, the fundamental dimensions of the turbine can be easily estimated.

To obtain constant frequency from a generator driven by a water turbine, it must run at a constant speed and drive the generator through a fixed gear-ratio. The speed of the water turbine is controlled by a governor which opens or closes a valve or gate to hold the speed constant as the load changes. Both mechanical and electrical hydraulic governors are used to control the flow of water through the turbine by adjusting the gate position [10].

7. Penstock selection

Penstocks (pipes) are used for conveying water from the intake to the power house. They can be installed over or under the ground, depending on factors such as the nature of the ground itself, the penstock materials, the ambient temperature and the environmental requirements. The internal penstock diameter (Dp) can be estimated from the flow rate, pipe length and gross head as [4, 8]:

\[ D_p = 2.69 \times \left( \frac{n_p^2 \times Q^2 \times L_p}{H_g} \right)^{0.1875} \]  

(4)

Where \( n_p \) = Manning's coefficient of the penstock material type.
\( L_p \) = penstock length in (m).
\( H_g \) = gross head in (m).

The wall thickness of the penstock depends on the pipe materials, its tensile strength, pipe diameter and the operating pressure. The minimum wall thickness is recommended as:

\[ t_p = \frac{D_p + 508}{400} + 1.2 \ (mm) \]  

(5)

Where \( D_p \) = penstock diameter in (mm).
\( t_p \) = minimum penstock thickness in (mm).
The pipe should be rigid enough to be handled without danger of deformation in the field.

8. Generator Selection

The basic parameters to be considered in the selection of a suitable type of electrical generator are:

i. Type of desired output: A.C. or D.C. constant frequency or variable frequency.

ii. Hydraulic turbine operations mode.

iii. Type of electrical load: Interconnection with the national grid, storage in batteries or an isolated system supplying variety of household or industrial loads.

For an isolated micro-hydro station supplying all the
power to the load, the number and size units are chosen considering the load curve of the power system to be supplied and should represent the best compromise between the plant capacity factor and the plant load factor.

In addition to this consideration, there is the economy that can be effected by choosing hydro-units of equal size, from the point of view of hydraulic equipment, penstock, draft tube and construction details.

The generator specifications for micro-hydro station include mainly the output power in Kilowatts, Kilovolt-ampere capacity, number of phases, frequency, connection of stator winding, voltage, current, power factor, speed, method of cooling, temperature rise, type of excitation, excitation voltage and machine reactance.

Micro-hydro generators are low speed machines of salient-pole type, having a large number of poles, a large diameter and a short-rotor. The power factor for which the generator is designed up to (0.95) lagging. The generator output power in (KVA) can be derived as [11, 12]:

\[ P = \frac{9.44 \times B \times \phi_m \times n}{\pi \times D \times \rho} \]

Where \( P \) = output powers in (KVA)
\( n \) = generator speed in (r.p.s)
\( B \) = average flux density in air-gap (weber/m²)
\( \phi_m \) = maximum magnetic flux per pole (weber).
\( D \) = stator diameter at the air-gap (m)
\( \rho \) = resistivity of the conductor material type (Ω.m).

The main dimensions of the generator are the diameter, the air-gap and the length of the stator core. The output of the generator in (KVA) depends on these main dimensions and the speed of the machine -stator diameter (D). the generator must be designed to withstand the full runaway speed of turbine under the maximum permissible head and water flow rate.

9. Power Transmission and Distribution Lines

The measurements have been made in the distribution network from the micro-hydro power station to the isolated houses of the national grid of electricity. These measurements take into account the difficulty in creating a distribution network when houses are located at a considerable distance from each other. The voltage drop calculation for 3-phase distribution system is as follow [11]:

\[ V_d = \sqrt{3} \times I \times R \times L/CM (volts) \]

Where \( R = (12.9 \Omega \text{ for copper wire}) \) or \( (21.2 \Omega \text{ for aluminum wire}) \) resistance constant for a conductor that is \( 1 \) circular mill in diameter and \( 1 \) foot long at an operating temperature of \( 75 ^\circ \text{C} \).

\( L \) = length of the distribution line from the micro-hydro power station to the load site in (feet).
\( I \) = load current in amperes
\( CM \) = conductor wire size in Circular-Mills.

Or the voltage drop of the 3-phase distribution system can be calculated as:

\[ V_d = I \times (R \times \cos(\theta) + X \times \sin(\theta)) (volts) \]

Where \( R = \rho \times L/A \) (Ω) resistance of the line.
\( \rho \) = resistivity of the conductor material type (Ω.m).
\( A \) = conductor cross-sectional area (m²).

\( L \) = length of the distribution line (m).
\( X = 0.145 \times \log_{10} \left( \frac{L}{GMD} \right) \times L (\Omega) \) inductive reactance of the line.

In case of medium voltage lines (11 KV), this reactance must be considered, while in low voltage lines (220 / 400 V), this reactance can be neglected.

\[ GMD = \text{Geometric main distance between the line conductors in (meter).} \]
\[ GMR = \text{Geometric main radius of the line conductor in (meter).} \]
\[ \theta = \text{power factor angle of the load.} \]
For the distribution line, at first the voltage drop at farthest house-holder area shall be calculated, and a low tension line (400 / 220 V) can be applied if the voltage drop is within 10%. If the voltage drop by the low tension line becomes more than 10%, a medium tension distribution line (11KV) should be applied for the power supply, with step-up and step-down transformers and some protection facilities such as fuses, circuit breakers and lightning arrestors may be required.

Over-head transmission/distribution lines shall be of ACSR or Aerial Bundled Cables with pole height sufficient to observe (5) meters minimum ground clearance. Armoured cables are required for under-ground transmission lines with at least (0.5) meter depth of burial along the land.

The surge arrestor should be mounted on the first transmission line pole and may be connected to the power house earthing system. The earthing system conductor must be at least (25) mm² cross-sectional area of copper wire. Under all loading conditions, as far as the input power is sufficient to meet the active load connected to the generator, the voltage regulator (AVR) shall maintain steady state voltage deviation within -5% and +5% of nominal value.

10. Results

The results were taken by Matlab software computer program. After introducing the site measurements and calculations as input data to the computer program, the turbine type, turbine size, turbine power, turbine speed, turbine efficiency, generator specifications, generator dimensions and generator speed are calculated.

Figure (2) shows the variation of turbine type, turbine power and turbine dimensions with head at different values of water flow rate. The Cross-Flow turbine was used for low head and low flow rate (up to 0.8 m³/s), while Kaplan turbine was used for medium head and flow rate. Figure (3) shows the variation of turbine power with head for Pelton turbine. Pelton turbine was used for high head and very low flow rate. Figure (4) shows the variation of generator power with generator diameter at different values of speed. It can be shown that the generator – stator diameter was inversely proportional with the generator speed.

11. Conclusions

In general, the Pelton turbines cover the high pressure domain down to (50 m) for micro-hydro. The Francis types of turbine cover the largest range of head below the Pelton turbine domain with some over-lapping and down to (10 m) head for micro-hydro. The lowest domain of head below (10 m) is covered by Kaplan type of turbine with fixed or movable blades. For low heads and up to (50 m), also the cross-flow impulse turbine can be used.
Once the turbine type is known, the fundamental dimensions of the turbine can be easily estimated.

The speed of a hydro-electric generator depends on the speed of the turbine driving it, which in turn depends on the specific speed of the particular type of turbine. Thus, there is a limitation in the choice of speed in addition to the frequency requirement. Also the weight multiplied by the square of the radius of gyration ($WR^2$) is an important consideration in hydro-generators. The $WR^2$ should be sufficient to ensure satisfactory speed regulation under sudden load changes. This can improve the water hammer effect and decrease the runaway speed.

It is noted that slow-speed generator require a large ($D^2*L$) for a given generator power. They are typically shaped like a disk (large diameter and small axial or stator core length). From the electrical viewpoint, slow-speed machines are considered to have lower internal reactance, high short circuit currents, small angular change in rotor position can cause large power swings and requiring good protection against faults occurring near the machine terminals.

For the distribution line, at first the voltage drop at farthest house-holder area shall be calculated, and a low tension line (400 / 220 V) can be applied if the voltage drop is within 10%. If the voltage drop by the low tension line becomes more than 10%, a medium tension distribution line (11KV) should be applied for the power supply, with step-up and step-down transformers and some protection facilities such as fuses, circuit breakers and lightning arrestors may be required.

REFERENCES


