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# Introductory Chapter - Aspects of Renewable Hydroelectric Power Generation

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Additional information is available at the end of the chapter

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## 1. Introduction

For many years, hydroelectric power has been considered as one of the most efficient and magnificent sources of power generation. It played an essential role in the development of humanity. It is a conventional renewable energy source for generating electricity in small- and large-scale production. The power generation from hydroelectric power plants can exceed 10 GW. Hydroelectric power is also the most desirable and has a long and successful track record. Hydropower is the power derived from the energy of falling water (as in waterfalls) or fast running water (as in rivers or long water streams). A schematic showing a cross-section of a typical hydroelectric power facility is shown in **Figure 1**. In this figure, water (the working fluid) is collected in a reservoir just behind a dam. The water accumulation behind the dam is normally dependent on several factors such as the intensity, distribution, and duration of rainfalls; the field moisture capacity of the basin or reservoir soil; and the direct evaporation, transpiration, and ground infiltration. The working fluid is then transported through large pipes (called penstock) to the inlet of one or more hydroturbines at the base of the dam. The hydroenergy available from conversion to mechanical shaft work is the potential energy of the water in the main reservoir. The water makes the hydroturbine rotate by action of the available hydroenergy contained in the water. Nowadays, hydroturbines are made more compact and usually operate at high rates of rotation and with high mechanical efficiency. The mechanical shaft work is then converted into electricity using the electric generator coupled with the hydroturbine shaft in the powerhouse. The power is then regulated using electric transformers before being transmitted through powerlines to the main electric grid.

This book provides a unique collection of recent research topics related to hydropower technology. The topics cover the following important aspects: diagnosability of soft fault in hydropower systems, hydropower impacts and implications with application to a case study, prospects of
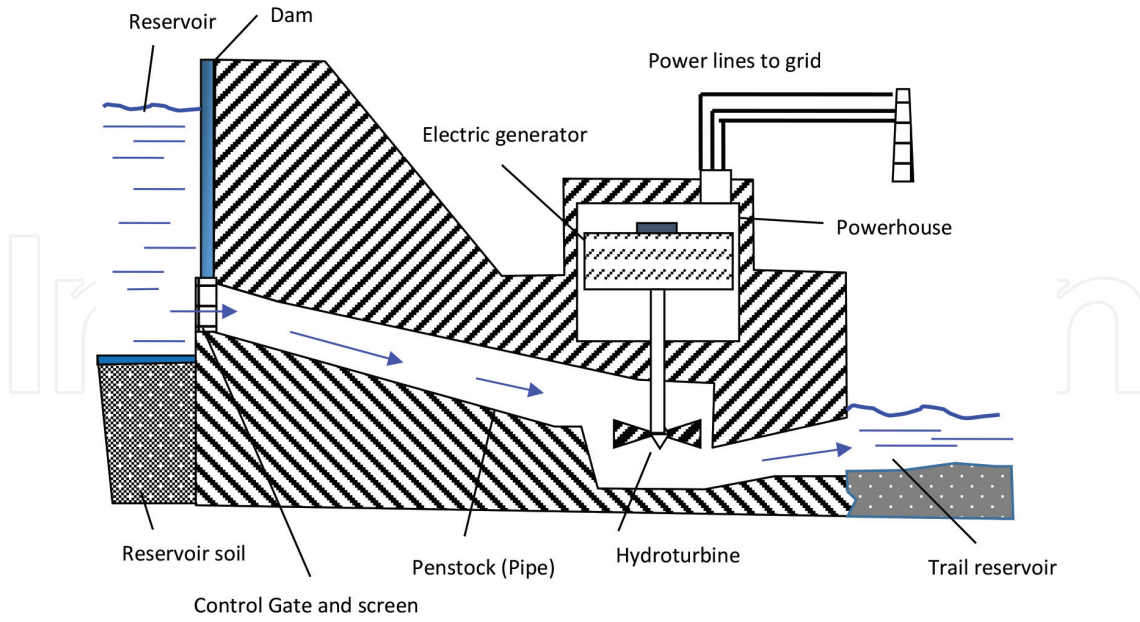
**Figure 1.** A schematic showing a cross-section of a typical hydroelectric power facility.

hydropower technology, planning of hydropower production under resources and system knowledge uncertainty, and design of zero-head hydroturbines for power generation. Before these practical topics are presented in the following subsequent chapters, it would be useful to provide some introductory energy conversion fundamentals and present brief aspects of concepts of hydroelectric power generation. This is presented in this introductory chapter.

# 2. Hydropower principles

## 2.1. The available hydropower

There are two significant operating parameters for hydroelectric power generation potential: (1) the amount of water volumetric flow rate ($\dot{\forall}_w$) and (2) the elevation head that water can be made to fall ($h$). It should be noted that the elevation head may be attributed to the naturally existing site topography or it may be made artificially by constructing a dam.

The available steady-state ideal hydropower can be estimated using:

$$P_{H,ava,i} = \gamma_w \dot{\forall}_w \, h \tag{1}$$

where $P_{H,ava,i}$ is the available ideal hydropower (W or kW), $\gamma_W$ is the specific weight for water ($\cong 9180$ N/m³), $\dot{\forall}_w$ is the available flow of a watercourse (m³/s), and $h$ is the water elevation head measured between the main and trail reservoirs ($m$) of the hydropower site.

The available steady-state actual hydropower can be estimated using

$$P_{H, ava, a} = P_{H, ava, i} - P_{HL} \tag{2}$$

where $P_{HL}$ is the hydraulic frictional losses in the piping system (W or kW). These losses can be estimated using

$$P_{HL} = \rho \dot{\forall}_w g \sum H_L \tag{3}$$

where $\sum H_L$ represents the total head losses in the piping system (i.e., penstock) in $m$. The parameters $\rho$ and $g$ are the density of water and gravitational constant (9.81 m/s$^2$), respectively. In general, the total head losses are given by:

$$\sum H_L = \underbrace{\sum H_L}_{Major\ losses} + \underbrace{\sum H_L}_{Minor\ losses} \tag{4}$$

and

$$\underbrace{\sum H_L}_{Major\ losses} = \sum_{m=1}^{M} f_m \frac{L_m}{D_m} \left( \frac{V_m^2}{2g} \right) \tag{5}$$

In Eq. (5), $f_m$ is the friction coefficient, and $L_m$ and $D_m$ are the length and internal diameter, respectively, for a given pipe segment $m$ of the long pipe that could have different pipe segments. The flow velocity $V$ can be calculated using

$$V = \frac{\dot{\forall}_w}{A_c} \tag{6}$$

The parameter $A_c$ is the cross-sectional area of the pipe. Substituting Eq. (6) in Eq. (5) and considering a circular pipe yields:

$$\underbrace{\sum H_L}_{Major\ losses} = \sum_{m=1}^{M} \left( 8 f_m \frac{L_m \dot{\forall}_w^2}{g\ \pi^2 D_m^5} \right) \tag{7}$$

The friction coefficient $f_m$ can be estimated depending on the type of flow regime in the pipe, which is characterized by Reynolds number $Re$. For laminar flow, it is determined using:

$$(f_m)_{Lam} = \frac{64}{Re} \tag{8}$$

and for turbulent flow, it can be estimated using:

$$(f_m)_{Turb} = \frac{0.3086}{\left\{ log \left[ \left( \frac{\varepsilon}{3.7 D_m} \right)^{1.11} + \frac{6.9}{Re} \right] \right\}^2} \tag{9}$$

where $\varepsilon$ is the roughness of the inner pipe surface and Reynolds number is defined as:

$$Re = \frac{\rho\,V\,D}{\mu} \tag{10}$$

The minor losses are due to any fittings that might be part of the piping system. It might be given by:

$$\sum_{Minor\ losses} H_L = \sum_{n=1}^{N} K_n \left( \frac{V_n^2}{2g} \right) \tag{11}$$

where $K_n$ is the fitting friction coefficient for a component $n$ in the piping system.

## 2.2. The hydroelectric power output

The output (produced or generated) of the hydropower depends on the hydroturbine conversion efficiency, the electric generator efficiency, and the electric transformer efficiency. This is given by:

$$P_{H,out} = \eta_{HT}\eta_{EG}\eta_{ET}P_{H,ava,a} \tag{12}$$

where $P_{H,out}$ is the produced (output) hydropower (W or kW), $\eta_{HT}$ is the hydroturbine energy conversion efficiency, $\eta_{EG}$ is the electric generator efficiency, and $\eta_{ET}$ is the electric transformer efficiency. The three types of efficiencies in Eq. (2) can be combined to represent the overall hydropower plant efficiency, $\eta_{HPP}$, so that Eq. (2) becomes

$$P_{H,out} = \eta_{HPP}P_{H,ava,a} \tag{13}$$

The total power losses from the plant can be determined using

$$P_{TL} = P_{H,ava,i} - P_{H,out} \tag{14}$$

or using

$$P_{TL} = (1 - \eta_{HPP})P_{H,ava,a} + P_{HL} \tag{15}$$

*Illustrative example A*

As an illustrative numerical example, consider a hydroelectric power facility that has a rated electrical capacity of 210 MW. The operating elevation head in this facility is 60 m, and the water flow rate into the hydroturbine is estimated at 510 m³/s. Estimate (1) the overall efficiency of the hydropower facility and (2) the total power losses from this facility. It can be assumed that the hydraulic frictional losses are negligible compared to other power losses.

**Analysis:**

The first part of this example can be determined using Eq. (13). Here, $P_{H,out}$=210 MW and $P_{H,ava,a}$ can be estimated using Eqs. (1) and (2):

$$P_{H,ava,a} = 9810 \times 510 \times 60 \times 10^{-6} - 0 \cong 300 \text{ MW} \tag{16}$$

Using Eq. (13):

$\eta_{HPP} = \frac{210}{300} = 0.7$, that is, the hydropower plant is 70% efficient.

The steady-state total power losses from this facility can be estimated using either Eq. (14) or Eq. (15). Using Eq. (14), gives:

$$P_{HL} = 300 - 210 = 90 \text{ MW} \tag{17}$$

*Illustrative example B*

Consider a microhydropower facility with an available elevation head of 23 m and a pipe of a total length of 350 m and diameter 30 cm. The available discharge of watercourse from the hydro resource is 0.25 m$^3$/s. Properties of water (taken at standard temperature of 20$^\circ$C) are $\rho$=1000 kg/m$^3$ and $\mu$=0.00114 Pa. s. The hydroturbine efficiency is 85% and the electrical generator and transformer have 100%. The hydropower that could be delivered from this facility is estimated.

**Analysis:**

Using Eq. (1), $P_{H,ava,i}$ is calculated to be ~56.4 kW, and using Eq. (9), $f$ is estimated to be 0.01411. Applying Eq. (3), $P_{HL}$ = 25.7 kW so that Eq. (2) gives $P_{H,ava,a}$=30.7 kW. Finally, substituting back in Eq. (12) yields $P_{H,out}$=26.1 kW. This means that the microhydroelectric facility is capable of supplying ~26 kW under the given steady-state operating conditions.

## 3. Some important aspects of hydropower

There are many practical aspects related to renewable hydropower technologies, for example, aspects for consideration in supplying electric power for rural populations in developing countries using small hydropower systems, hydroturbine design aspects, planning hydropower production of small reservoirs under resources and system knowledge uncertainty, impacts and implications of hydropower in economically poor countries, and fault diagnosis and control of operating parameters for optimizing production of hydropower systems. Brief description of these aspects is presented here and more details are covered in the subsequent chapters of this book.

Small hydropower technology is one of the commonly used technologies for electricity generation supplied in rural population in both developed and developing countries. Small hydroelectric power plants contribute to meeting the needs of regions where there is no major technological development, and they are able to improve the population's quality of life with the creation of jobs, increase of the local economy, and enhancement of the region.

The design and innovation of hydroturbines in hydropower systems constitute a major part in the success of this technology. The blades represent a vital component of any hydrokinetic

turbine due to their complexity, cost, and significant effect on the operating efficiency. During its lifetime, a hydrokinetic turbine blade is subjected to different types of loads such as hydrodynamic, inertial, and gravitational forces. The hydrodynamic design provided the blade external shape, that is, the chord and twist angle distributions along the blade, which resulted in optimal performance of the hydrokinetic turbine over its lifetime. The blade element method (BEM) could be used for the hydrodynamic design of the rotor of a horizontal axis hydrokinetic turbine of mini power production.

Planning hydropower production of small reservoirs under resources and system knowledge uncertainty is another important practical aspect that should also be considered. Available energy from water varies widely from season to season, depending on precipitation and streamflows, especially in small catchments. In addition, the reservoir operation problem is associated with the inability of operators to formulate crisp boundary conditions due to uncertainty in knowledge. In this chapter, an approach for planning the operation of small multipurpose reservoir systems for hydropower generation and flood control under consideration of the stochastic nature of inflows and initial storage levels that allow formulation of constraints with some range of uncertainty will be presented. The approach is based on a joint chance that is constrained and fuzzy programming, which addresses the problem of including risk directly in the optimization. Besides the optimal reservoir release strategy, this approach also determines the optimal reliabilities of satisfying hydropower demand and flood control storage requirements. Therefore, this tool has some advantages in planning the operations of reservoirs in extreme hydrological events such as floods and droughts. A case study could be considered in using this practical approach.

The impacts and implications of hydropower in economically poor countries are other insightful aspects. Despite the high potential of hydropower, a country's low economy and slow GDP growth rate in combination with environmental and socio-economic constraints, effective implementation of existing policy, and political stability may be supportive to reach the sustainable development goals of this country.

The diagnosability of soft fault in hydropower systems. In a hydropower system, the operating hydroturbine speed is one of the critical variables that requires monitoring and optimization for efficient control of the frequency and output voltage from the electrical generator coupled with the turbine. Diagnoses and control aspects in a hydropower system.

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