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Design Aspects of Small-Hydropower Plant

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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ABSTRACT

Presently, however, Hydroelectric is a source of power that can prove to be available to all, regardless of conditions such as weather. As history showed, a lot of development, as well as alterations, were made to this efficient supply of energy. Hydropower is a positive alternative energy source that nature provides, therefore, its effective usage is not prohibited. Although there are many disadvantages associated with the design and construction of a hydroelectric power plant, the advantageous features are even more enormous. This paper deals with construction and design aspects for the implementation of the small hydroelectric power station. The main parameters can be collected from the site. Then the turbine type and dimensions can be specified. The generator specifications,which is the main part in the system, for hydro-power stations can be obtained from the determination of turbine output power. These specifications involve mainly the rated power in KVA, the type of system, system frequency, the type of stator winding connection, rated load voltage, rated load current, load power factor, generator speed, method of the system cooling, and the generator type of excitation.

Keywords: Small-hydroelectric power station; hydro-turbine; hydroelectric-generator.

1. INTRODUCTION

A hydropower station is a resource of renewable energy, which generates electricity by the flow of water to produce electrical energy from the potential energy of water. When waterfalls by the gravity force, its stored potential energy is converted into the kinetic type of energy. This

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energy of the flowing water rotates the blades of the turbine, and the type of energy is changed into rotational energy. The generator shaft connected to the turbine rotor changes this rotational energy into electrical energy [1-7].

Small hydroelectric power stations are one of the alternative sources of power generation. From (5) to (100) kilowatts of power can be generated when set across streams. The benefits of a small hydroelectric power station compared to the conventional power station are [4-6]:

- It can produce power close to what is needed, minimizing power losses during transportation.
- It can high economically handle varying demand at peak load, while conventional power plants can only provide baseload, due to the long starting times.

Small hydroelectric power stations are less costly, small in size, and constructed to serve the small and isolated community, and they are installing more conveniently. A part of the stream water is divided during a penstock or conduit to a hydraulic turbine that installs across the river, as shown in Fig. (1). Therefore, there is a band to harness the potential of a small hydroelectric power plant through proper siting and optimal design [8-11].

2. TYPES OF HYDRO-TURBINES

The energy stored in the water is changed into rotational energy in the turbine, by the following basic methods:

A- The pressure of water is changed into kinetic energy before coming to the turbine shaft. The kinetic type of energy is in the form of a very fast-speed hitting the buckets, fixed on the runner's circumference. The turbines that run in this method are called pulse turbines. Since the water after hitting the buckets drops into the tailwater with less energy left, the casing is light and serves the aim of avoiding splashing. Pulsed-turbines can be classified into three kinds as follows [3]:

1- Pelton-type turbine [4]: This type is called "impulse turbine" where jets hit a wheel carrying a large number of buckets around it. The jet is emitted during a nozzle fitted with an adjustable valve to govern the water as shown in Fig. (2).

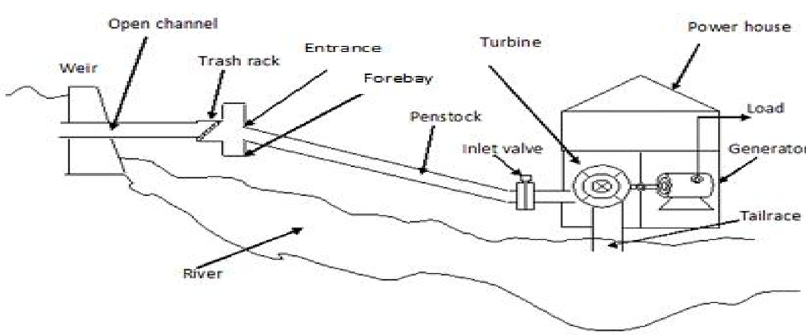

Fig. 1. Small-hydro- power plant

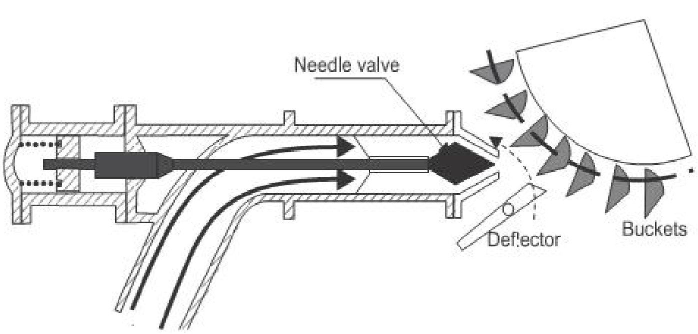

Fig. 2. Pelton turbine

2- Torgo- turbines: They can rotate in a head range between 30 to 300 meters. It is an impulse turbine, but the flow of water hits the surface of its runner at an angle (20 degrees). Turgo has a high runner speed (double the Pelton runner), which leads the coupling of the generator with the turbine directly to improve the overall system efficiency and reduce the maintenance cost.

3- Cross-flow- turbine: It is a radial flow runner that generates the shaft power from the stored energy in the water of a jet as shown in Fig. 3. It is made up of two parts: the nozzle and the runner. The runner consists of two circular discs connected in parallel at the edge by arced blades.

B- Pressure of the potential energy in the water can generate a force on the blades, which reduces as they lead during the turbine. The turbine that rotates by this method is named ‘reaction turbine”. The turbine- housing, in which the buckets are completely submerged in water, must resist the rotating pressure. To minimize the residual energy of movement in the water leaving the runner, an intake diffuser is located between the turbine and the tail. These turbines can be divided into two kinds as follows [1], [2], [3]:

1- Francis turbines: These are vertical water flow turbines, with constant blades and controllable vanes, utilized for the medium-head. Fig. 4 shows a horizontal axis of a Francis turbine. It can be placed in an open duct. For heads and small power, open-air ducts are used.

2- Kaplan-type turbines: These types are horizontal water flow reaction turbines utilized in small heads. They have controllable blades and may have controllable steering vanes. If the blades and vanes are controllable, it is specified as “double-regulated” as shown in Fig. 5.

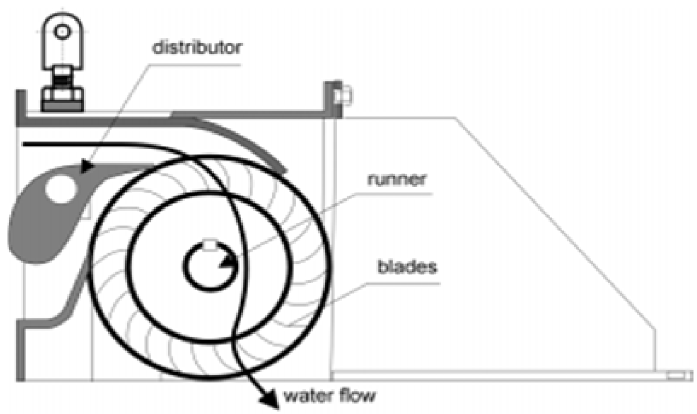

Fig. 3. Cross-flow turbine

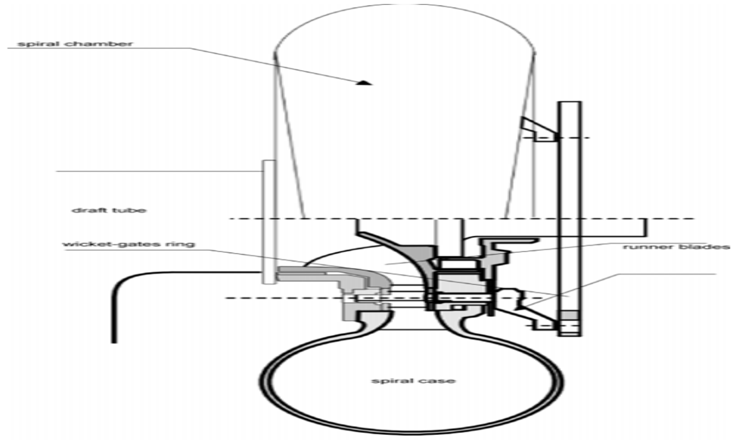

Fig. 4. Francis turbine

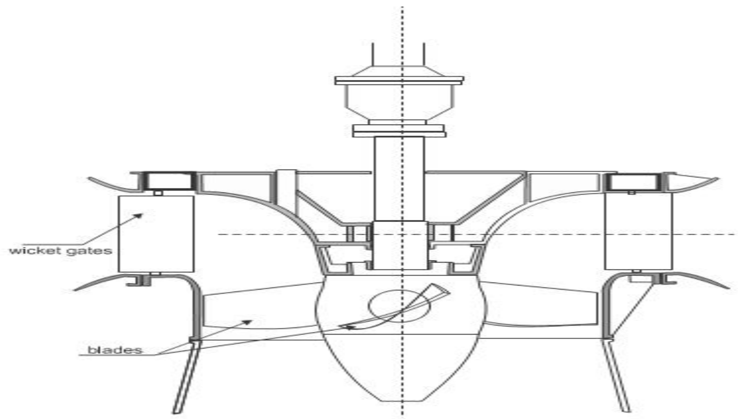

Fig. 5. Kaplan turbine with double-regulated guide vanes

3. DESIGN ASPECTS

For the design of small stations of hydroelectric power, several aspects must be considered into account in the design procedure. All hydropower production depends on dropping water. The flowing water is the fuel for a hydroelectric power station and without water flowing, the production stops. The power generated in the turbine is obtained as [4]:

$$P_t = \rho * g * H_n * Q * \eta_t \ (watt) \quad (1)$$

P_t is the power of the turbine shaft.
ρ is the density of water (1000 Kg/m^3).
H_n is the final head (*m*).
Q is the rate of water flow (m^3/s).
g is the constant of gravity (9.8 m/s^2).
η_t is the efficiency of the turbine (80-90%).

The efficiency of the turbine (ηt) is classified as the ratio of the power out by the turbine shaft to the power input. For a pulse turbine, the height is measured at the point of the jet, which is always over the level of water downstream. Fig. (6) shows the efficiency characteristic of several types of turbines.

The average speed of the whole rotating system is [4-6]:

$$\frac{dw}{dt} = \frac{1}{J*w}(P_t - P_l - B * w^2) \quad (2)$$

where *w* is the system speed in (*rad./sec.*).
P_t is the power of the whole system (*watt*).
P_l is the power of the load (*watt*).
B is the friction coefficient of the whole system (*N.m/*(*rad./sec.*)).
J is the inertia of the whole rotating system (Kg/m^2).

The motion differential equation (2) of the system is first-order and solved numerically in MATLAB. The kind of the turbine is determined by comparing the determined head and turbine specific speed with those obtained in Tables (1-2).

The turbine must be fixed at least over the tailrace-water level by a distance (Z) to avoid the phenomenon of cavitation. The distance (z) can be obtained by the equation [7]:

$$Z = H_{atm} - H_{vap} - \delta_T - H_n + \frac{V_e^2}{2g} + H_{DT} \quad (3)$$

Z is the distance above the tailrace (meters).
H_{atm} is the head of the pressure of the atmosphere in (meters).
H_{vap} is the head of the pressure of the vapor of water in (meters).
δ_T is The sigma-coefficient of Thomas.
H_n is the net-head of the site in (meters).
V_e is the velocity of the draft tube (*m/s*).
H_{DT} is the head loss of the draft tube in (meters).
g is the accelaration constant (9.81 m/s^2).

The load factor is defined as [4]:

$$LF = \frac{Energy\ produced\ in\ year\ (KWH/year)}{Total\ capacity\ (KW)*8760} \quad (4)$$

The energy produced per year (KWH) is determined as:

$$E = \rho * g * Q * H_n * \eta_{turbine} * \eta_{generator} * \eta_{gear\ box} * \eta_{transformor} * n$$

Where g is the constant of gravity (9.8 m/s^2).
ρ is the density of water (1000 kg/m^3).
Q is the rate of water flow (m^3/s).
H_n is the final head (m).
$\eta_{turbine}$ is the efficiency of the turbine.
$\eta_{generator}$ is the efficiency of the generator.
$\eta_{gear\ box}$ is the efficiency of the gearbox.
$\eta_{transformer}$ is the efficiency of the transformer.
n is the total hours in a year for which the quantity of water flow occurs.

The generator shaft is coupled to the shaft of the turbine via gear, so when the turbine rotates the generator rotates as well, converting rotational energy into electrical energy. Generators in renewable energy like hydroelectric power stations work just as generators in other types of conventional power plants. Fig. 7 shows an interior view of a typical generator, used to receive power from a hydroelectric power station.

The hydro-generator is the main part of the system and its performance effect the overall hydropower plant efficiency. The direct coupling of the turbine-generator set with the same speed will increase the efficiency of the whole system, cancel the gear-box or pulley, and reduce the system cost. The basic variables to be taken in the selection of an electrical generator size are [8]:

i. The generated output power: alternating or direct current system, constant or variable frequency.
ii. Turbine mode of operation.
iii. Type of load connected to the generator.

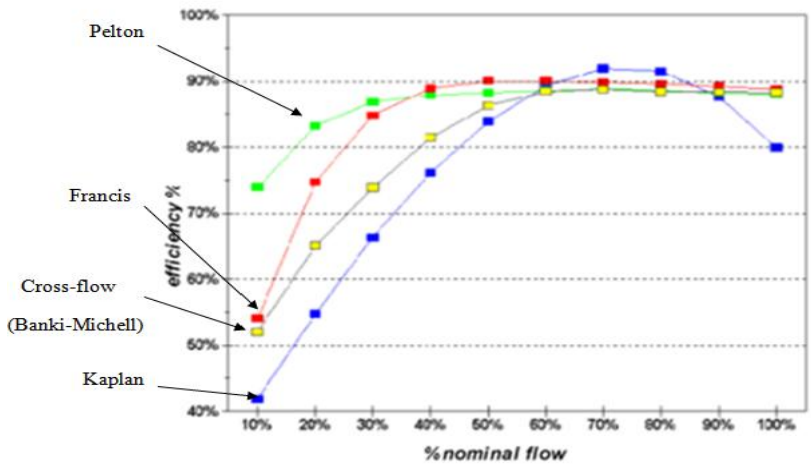

Fig. 6. Efficiency versus flow rate characteristics for different types of turbine

Table 1. Head range [3],[4]

Turbine specification	range of head (meter)
Kaplan	5 <H_n< 30
Francis	20 <H_n< 200
Pelton	40 <H_n< 100
Cross-flow	3 <H_n< 20

Table 2. Specific speed [3],[4]

Turbine specification	range of specific speed (meter)
Type Pelton (1- nozzle)	5≤N_s≤ 30
Type Pelton (2-nozzles)	8≤N_s≤ 40
Type Pelton(4- nozzles)	12≤N_s≤ 60
Type Cross-flow	20≤N_s≤150
Type Francis	40 ≤N_s≤ 300
Type Kaplan	100 ≤N_s≤ 1500

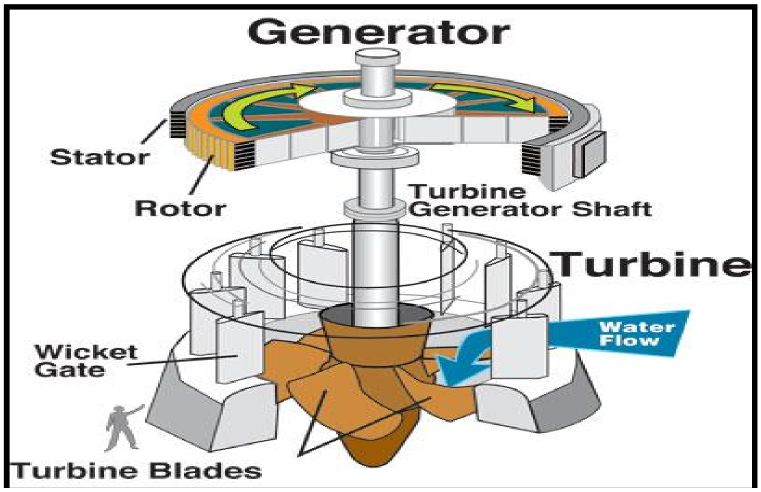

Fig. 7. Typical generator, used in a hydroelectric power plant

The generator specifications for hydro-power stations can be obtained from the determination of turbine output power. These specifications involve the rated power in KVA, the number of phases, the system frequency, the connection type of winding, rated load voltage, rated load current, load power factor, generator speed, method of the system-cooling, and excitation type of the generator. The main components of the generator are the stator diameter, the air-gap distance, and the distance of the stator-core. The generated output power in (KVA) depends on these components and the generator speed. The main expression of the output power of the generator in (KVA) is obtained as [8]:

The frequency of the generated voltage is obtained as:

$$f = {P * n}/{2} \ (H_z) \quad (5)$$

Where P is the number of machine magnetic poles. n is the shaft-speed in (r.p.s)
The phase voltage is given as:

$$E_{ph} = 4.44 * K_w f N_{ph} \Phi_m \ (volts) \quad (6)$$

Where K_w is the factor of winding. N_{ph} is the series of turns per phase.
Φ_m is the maximum magnetic flux per pole (weber).

For asynchronous generator, the winding-factor is taken between (0.95-0.97), and the magnetic flux per pole is obtained as[6]:

$$\Phi_m = B * (\pi * D/P) * L \ (weber) \quad (7)$$

B is the average density of the magnetic flux in the air-gap (weber/m^2), D is the length of stator-diameter (m). L is stator core-length (m)

The load phase current is obtained as:

$$I_{ph} = {(\pi * D * A_c)}/{(6 * N_{ph})} \ (amperes) \quad (8)$$

Where A_c is the ampere-conductors of the generator per meter of stator core-periphery.
Also, the output power of the generator is given as:

$$S = 3 * E_{ph} * I_{ph} * 10^{-3} \ (KVA) \quad (9)$$

Substituting equations (6 - 8) into (9) to obtain:

$$S = 10.4 * B * D^2 * L * n * A_c * 10^{-3} \ (KVA) \quad (10)$$

For the small power generator, the factor (A_c) is considered between the range (20000-40000) ampere-conductor per meter of generator stator core-periphery, and the magnetic flux density (B) is considered between (0.6-0.8) weber/m^2. When the generator ampere-conductor per meter and magnetic flux density has been selected, the result of (D^2*L) for a specific output generated power can be determined by equation (10). The length L of the generator-stator core is considered as:

$$L = 1.2 * \lambda \ (m) \quad (11)$$

Where λ is the magnetic pole-pitch of the stator winding. Then, substitute equations (11) into (10) to determine the length of stator core diameter

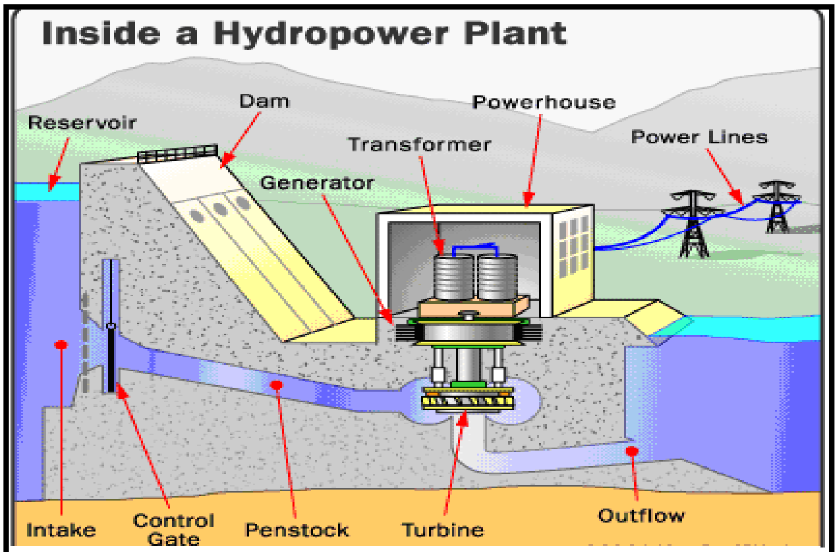

Fig. 8. Complete hydroelectric power plant

(D). The generator dimensions must be calculated to overcome the complete run-away speed of the system under the highest head and water flow rate.

The voltage drop of the transmission line system is determined as[9]:

$$V_d = I * (R * \cos(\theta) + X * \sin(\theta))\ (volts) \quad (12)$$

Where: $R = \rho * LL/A\ (\Omega)$ per phase resistance of the transmission line.

ρ is the resistivity of the wire material type (Ω.m). A is the wire cross-sectional area (m^2).

LL is the length of the distance of the transmission line (m).

$X = 0.145 * \log_{10}\left(\frac{MD}{MR}\right) * L\ (\Omega)$ = the line inductive reactance.

This reactance must be considered in medium and long transmission lines while in short lines (220 / 400 V), this reactance may be neglected. MD = the average distance between the transmission line wires in (meter). MR is the average radius of the line wire in (meter). θ is the power factor angle of the load.

The transformer takes alternating current (AC) and converts it into high alternating voltage. From each power station comes four wires - the three lines of power are simultaneously produced plus a neutral or ground common to the three. Outgoing water is carried through pipelines, which are called tailraces, and enters back into the riverbed. Fig. 8 below shows the completion of the hydroelectric power station.

4. RESULTS AND DISCUSSION

4.1 The design Procedure Consists of the Following Points

1- Providing the input variables of the small and micro power stations to the Matlab software program.

These data are:

a- Area of the river (A_r) in (m^2). b- Velocity of water flow of the river (V_r) in (m/s). c- Distance of the channel (L_{ch}) in (m).
d- Distance of penstock (L_p) in (m). e- Penstock factor. f- Channel factor.
g- Total-head (H_g) of water entering the turbine in (m). h- Angle (α) of trash rack with horizontal.
i- Screen bar-thickness (t) in (mm). j- Screen bar-width (b) in (mm). k- Entry-factor (K_{en}).
l- Trash-rack factor (K_{tr}). m- Main valve factor (K_v). n- Efficiency of the turbine (η_t) .o- Density of the water (ρ) in (Kg/m^3).
p- Accelaration-constant in (m/s^2).q- Inertia of the whole- system (J) in ($Kg.m^2$). r- Friction coefficient of the whole- system ($N.m/(rad./sec.)$).
2- Determination of the rate of the river water flow (Q) in (m^3/s).

3- Determination of the weir of rectangular type and dimensions of the water-channel (width (*w*) and height (*h*) in (*m*)).
4- Determination of an open-channel bottom line slope (S_{ch}).
5- Determination of an open-channel hydraulic radius (*Rch*).
6- Determination of the channel river water velocity (V_{ch}) in (*m/s*).
7- Determination of penstock-entry velocity (V_p) in (*m/s*).
8- Determination of the net-head of the power plant site.
9- Determination of the power of the turbine in (watt).
10- Determination of the speed of turbine shaft (*N*) in (*r.p.m*) from equation (2).
11- Determination of specific-speed (N_s) in (*r.p.m*).
12- Choosing of turbine type.
13- Determination of turbine dimensions according to the turbine type.
14- Repeating points (9) to (13) to take the cavitation effect into account.
15- Determination of generator type and specifications.
16- Determination of transformer and transmission line specifications.

5. CONCLUSION

The use of this type of an energy-source requires the change of energy from one form to another. The mechanical energy is obtained by direct moving water. The energy available in moving water is calculated by the flow of river water. Water- flows quickly in a large river and carries a large amount of energy in the flow. So, with the water run rapidly from a very high point. Hydropower is an ideal fuel for electricity generation because it is almost free, there is no loss, and hydropower does not pollute the water or the environment.

However, various methods have been used to fix the problem of changing the environment, involving the construction of "fish-ladders" that help fish ascend the dam to their upstream spawning grounds. As the defects widen, there are increasingly recommended solutions to these problems. Therefore, it has become an indispensable basis for obtaining electrical energy from hydropower stations.

The hydro-generator is the main part of the system and its performance effect the overall hydropower plant efficiency. The direct coupling of the turbine-generator at the same speed will increase the system efficiency, cancel the gear-box or pulley, and reduce the whole system cost.

The generator specifications for hydro-power stations can be obtained from the determination of turbine output power. These specifications involve mainly the rated power in KVA, the type of system, system frequency, the type of stator winding connection, rated load voltage, rated load current, load power factor, generator speed, method of the system cooling, and the generator type of excitation.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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