Theory of Hydropower Plant Technology

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Abstract: ***The Hydropower technology is the most reliable and cost - effective renewable energy generation technology to date. The early developed hydropower technology was around 17 century and it was broadly used for activities related to milling and especially grain and lumber, but also in other areas it was used for pumping irrigation water. The technology was based on a water wheel on which the power of water used to rotate the wheel and in turn use the mechanical shaft power to drive mechanical systems. This development in hydropower resulted in the introduction of hydroelectric generation stations. The early development on hydropower began around 1870 in England when the first hydro - electric power plant was installed at Cragside. But the actual commercial use hydropower generation station started around 1880 in the USA, with a dynamo driven by a water turbine and at that time it was only producing 12.5 kW of power that can be equated to 250 lights. This invention made several countries in the world to adopt to the technology and 120 years later in the 1990s almost 300 hydroelectric plants were developed around the world.***

Keywords: Hydropower, Waterwheel, Potential Energy, Kinetic Energy, Penstock, Turbine

1. Introduction

In early days before the development of hydropower, the idea of harnessing water energy was started by using the potential energy of falling water to rotate a waterwheel. The waterwheel is attached with a pulley and belt to create a rotational mechanism for different machines like grinding mills, sledge hammers, textile machines, sawmills and in some areas the rotational mechanism is used to pumping water for irrigation purposes [1]. The waterwheel technology on the other hand uses the potential or kinetic energy of the water flow to rotate the waterwheel which cause rotational motion on the pulley and belt section. Waterwheel consists of a large circular rotating wheel/drum which is made of wooden or metallic material that consists of several blades/buckets which are installed tangentially outside the wheel rim as shown in Figure 1 below.

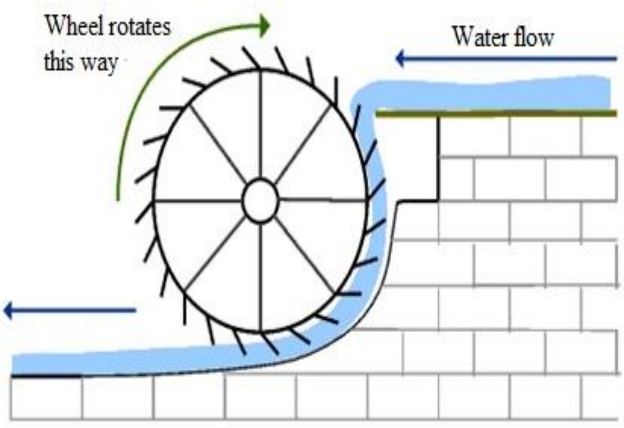

Figure 1: Waterwheel layout [2]

The technology of waterwheel was substituted by the development of hydropower in the early 1820's [3] due to their poor flexibility during variations of water flow discharge and this made waterwheels less efficient as compared to the current hydro turbines [4]. Due to their less application in today's water power technologies and poor system efficiency, water wheels will not be discussed further in this research paper.

2. Methods and Materials

2.1 Methodology

The hydro - power which is also known as water power is the type of technology at which the energy produced by the falling water is extracted by the turbine - generator system at a site to produce electrical power. In this system, the turbine is the type of machine that uses the power of falling water to gain potential energy which is converted to kinetic energy under pressure to gain rotational speed of the turbine wheel. This rotational energy produces mechanical power at the turbine output shaft which is then connected to the generator system to produce electrical power [5]. In the hydropower technology, the potential energy is created by the mass (m) of the falling water from a particular height (H) while the converted kinetic energy that creates rotational speed is also created by the mass (m) and velocity (U) of the flowing water using the following formula:

$$PE = mgH \tag{1}$$

$$KE = \frac{1}{2}mU^2 \tag{2}$$

where; PE = potential energy, KE =kinetic energy, m = mass, g = gravity, H = head (height) and U = water flow velocity.

When considering the hydropower system, the maximum potential energy is obtained at the water entry to the penstock pipe (point 1) with the pressure p_1 and head H_1. The water from the reservoir is conveyed to the turbine through a penstock pipe and the maximum kinetic energy of the water is obtained at the water exit (point 2) with pressure p_2 and head H_2 as shown in Figure 2 below.

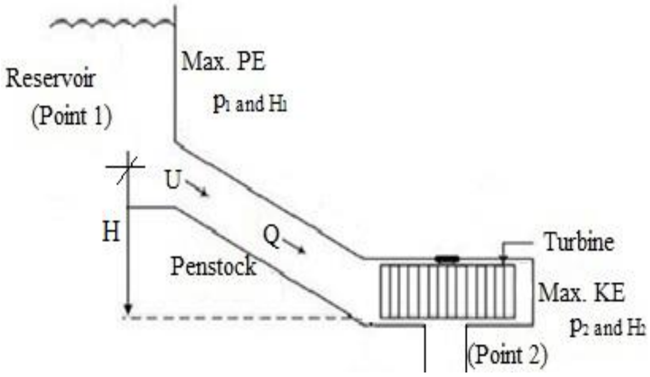

Figure 2: Water energy conversion to produce hydro power

By considering the water flowing from point 1 (penstock entry) with the following values, pressure p_1, head H_1 and velocity U_1 to point 2 (penstock exit) with the following values, pressure p_2, head H_2 and velocity U_2. The energy equation for hydropower system is determined using the Bernoulli equation as follows:

$$p_1 + \frac{1}{2}\rho U_1^2 + \rho g H_1 = \rho_2 + \frac{1}{2}\rho U_2^2 + \rho g H_2 \qquad (3)$$

In hydropower system the water flow velocity, U in the penstock pipe with the same cross - section area is maintained at a constant value from the entry (point 1) to the exit (point 2) so, in this case $U_1 = U_2$ = constant as shown in Figure 3 below.

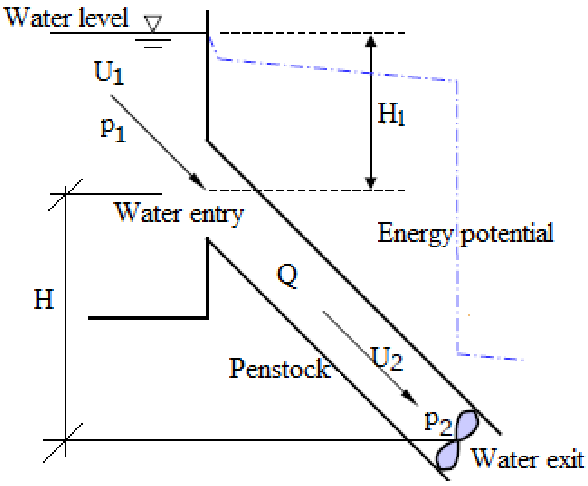

Figure 3: Penstock pipe layout

Simplifying and re - arranging the equation 3 gives the following relation:

$$\Delta p = \rho g \Delta H \qquad (4)$$

where; Δp = changes in pressure ($p_1 - p_2$), ρ = density of water, g = gravity and ΔH = changes in head ($H_1 - H_2$).

But in the penstock pipe with uniform diameter, the pressure, p is given by the following equation:

$$\text{Pressure}, \Delta p = \frac{\text{Force (F)}}{\text{Area (A)}} \qquad (5)$$

where; F = force in N and A = area in m^2

The pressure value is acting on the entire span of the penstock pipe so, when introducing the length factor, L on both the numerator and denominator for the above equation 3.5 gives the following pressure relation:

$$\Delta p = \frac{F \ x \ L}{A \ x \ L} = \frac{Work \ Done}{Volume} = \frac{Energy \ (J)}{Volume \ (m^3)}$$

$$\Delta p = \frac{E}{v} \qquad (6)$$

$\Delta H = H$ and υ = volume (m^3)
Note: 1 Joule = 1 N.m.

Substituting the pressure value, Δp from the above equation 6 to the equation 4 gives the following energy equation:

$$E = \rho g v H \qquad (7)$$

But all hydro turbines produce power and not energy, so using the power and energy relation:

$$Energy = Power \ x \ time \qquad (8)$$

This gives the following power equation for the hydropower systems:

$$Power = \rho g \frac{v}{t} H$$

$$P_{HP} = \rho g Q H \qquad (9)$$

Where; P_{HP} = power output for the hydropower system in kW, Q = water flow discharge in m^3/s and H = site head in m.

The above equation 9 represent the theoretical output power for the hydropower system, but in obtaining actual power output for the hydropower plant, the theoretical output power from equation 9 needs to be multiplied by the total efficiency (η_{total}) due to losses during the power conversion in order to obtain the electrical power output from the generator system as follows:

$$P_{HP} = \rho g Q H \eta_{total} \quad \text{[kW]} \qquad (10)$$

where; η_{total} = system efficiency which is given as turbine efficiency (η_t) x generator efficiency (η_g)

Thus, from the above equation 10 it is noted that the power capacity generated by the hydropower system depends upon the density of water (ρ), gravitational force (g), water flow discharge (Q), elevation head (H) and total efficiency of the hydropower system (η_{total}). Among the above parameters for hydro power output determination, only two parameters of water flow discharge and elevation head are usually obtained from site measurement of river volumetric flow (Q) and site elevation head (H) respectively.

2.2 Parts of a hydropower system

The main parts of a hydropower system from the intake to the power house may be classified into two main groups as follows:

a) The hydraulic system components
b) The power and control system components

2.2.1 Hydraulic system components

The hydraulic system components in a hydropower system consists of all the main water handling sections from the water intake to the penstock area. The main components in this section include diversion weir and intake, canal or conduit, settling basin, forebay and penstock pipe

2.2.1.1 Weir and intake

The weir is the concrete wall structure that is used to create enough upstream water depth for a water intake. It is usually installed across the river section at the intake area and in large or small hydropower system it creates a dam or reservoir wall structure while in mini and micro hydropower system which are mostly run - of - river system it creates a small water pondage in order to get enough water flow discharge to the canal.

On the other hand, literature have shown that there are many types of weir structures but the main types that are commonly used include concrete weir, masonry block weir, rock fill weir, gabion weir etc as shown in Figure 4 below.

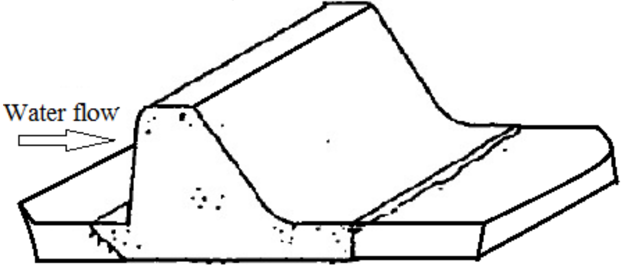

Figure 4: Concrete weir

To determine the size of the weir structure, the minimum water flow discharge and environmental flow, needs to be determined using the following equation [6]:

$$Q_D = \frac{1}{2} C_d \; x \; g(n_w - 0.2\Delta h_n)\Delta h_n^{1.5} \tag{11}$$

$$Q_E = 2.5(n_w - 0.2\Delta h_n)\Delta h_n^{1.5} \tag{12}$$

Where; Q_D= water flow discharge, Q_E = environmental flow, C_d = coefficient of discharge, g = gravity, n_w = weir notch width, Δh = notch head difference

When the amount of water flow volume is accumulated at the weir structure, the required water flow discharge is directed to the intake structure. There are two types of intake structures that conveyed water flow discharge to the canal from the weir which include side intake or bottom intake types as shown in Figure 5 below.

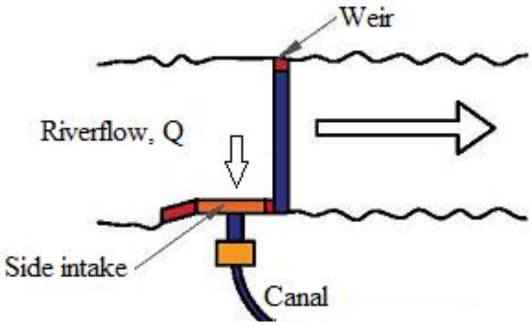

Figure 5: Side intake

The size of the intake in a hydropower plant is usually determined by the amount of water flow discharge that is required to be conveyed to the turbine unit. In this case the main determining parameters are the water flow velocity which is maintained at a constant value and the cross - sectional area of the intake using the following equation:

$$Q = A \; x \; U \tag{13}$$

where; Q = flow discharge (m^3/s), A = intake cross - sectional area (m^2) and U = water flow velocity (m/s).

Since the value of flow velocity for the intake structures is kept at a constant rate, then the determining factor for the intake sizing is the area of the intake opening called orifice which is used to allow water to pass through it in order to convey water to the canal. Most of the orifice structures are constructed in a rectangular or square shape with the width (w) and height (h) as shown in Figure 6 below on which the corresponding cross - sectional area is given as follows:

$$A = w \; x \; h = \frac{Q}{U} \tag{14}$$

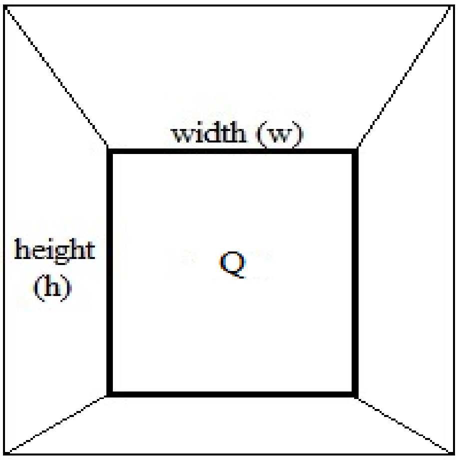

Figure 3.6: Side intake with rectangular orifice

2.2.1.2 Headrace canal/conduit

When water flow discharge is collected at the intake it must be conveyed to the turbine unit. The structure that is used to transport this flow discharge is called canal or conduit and it link the intake to the subsequent water conveying structures. The size of the canal structure is determined by the amount of water flow discharge that need to be transported. In this structure the water flow velocity is maintained at a constant value, hence using the equation 13 the size determining factor is the area of the canal given by equation 14. Most canal structures are made up of either concrete, cement mortal blocks or stone masonry materials. There are three main types of canal structures based on shapes that are commonly used in small hydropower plants. This include rectangular/square shape, round shape or trapezoidal shape as shown in Figure 7 below.

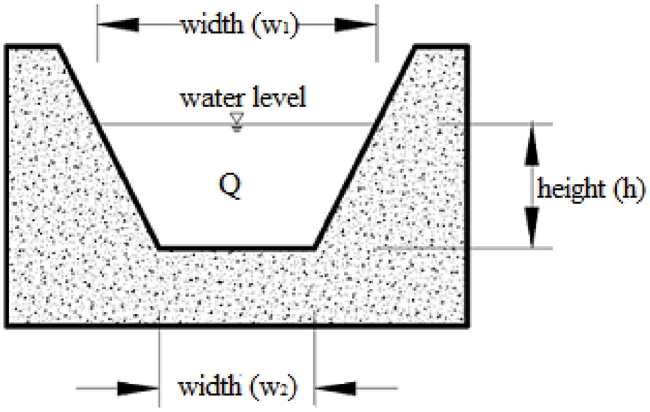

Figure 7: Trapezoidal shape canal

For the trapezoidal shape which is the mostly applicable type of canal structure, the cross - sectional area of the canal system is given by the following formula:

$$A = \frac{1}{2}\ x\ (w_1 + w_2)\ x\ h = \frac{Q}{U} \quad (15)$$

2.2.1.3 Settling basin and forebay

(a) Settling basin

The amount of water flow discharge conveyed by the canal is transported across the settling basin to the forebay tank. Most of the water flowing from the canal are not clean and they contain some debris and sand particles which must be removed before the water enters to the forebay. The function of the settling basin is to settle and remove the sand and debris that have entered to the canal from the intake. It has a gentle slope that allow sand and debris to be trapped and removed. In additional to that, settling basin structures also contain other features such as spillway that removes excess water flow that enters the intake during floods and exceed the required flow discharge needs to be spilled away in order to minimize structure collapse. The other feature that is incorporated in the spillway structure is the flushing gate which is used to flush/remove bottom settled sand at the basin. To determine the dimensions of the spillway structure, the following formula is used [7]:

$$L_{spillway} = \frac{(Q_{flood} - Q_{design})}{C_w\,(H_{flood} - H_{spillway})^{1.5}} \quad (16)$$

where; $L_{spillway}$ = spillway length (m), C_w = crested weir coefficient for a round edges profile which is 1.6 [8], Q_{flood}= flood flow discharge (m^3/s), Q_{design} = design flow discharge (m^3/s), H_{flood} = flood level height (m), $H_{spillway}$ = spillway crest height (m), $H_{flood} – H_{spillway} = H_{overtop}$

The longitudinal and cross - section structure of the spillway with design parameters is shown in Figure 8 and Figure 9 below [9]:

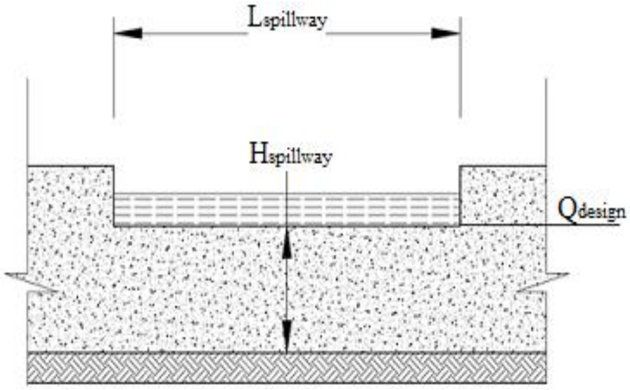

Figure 8: Longitudinal section of a spillway

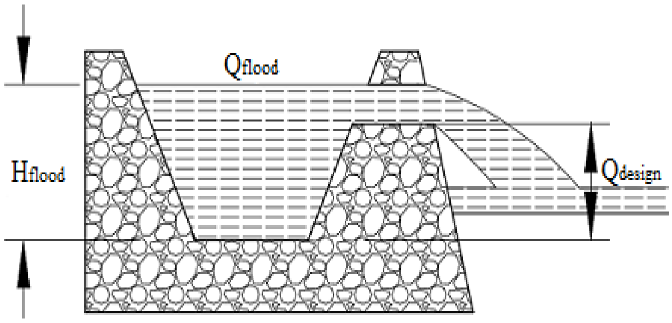

Figure 9: Cross - section of a spillway

(b) Fore - bay (Head tank)

The forebay is the civil structure that is used as a head tank to retain the required amount of water flow before allow it to enter the penstock pipe. It is usually located at the end of the headrace canal just after the settling basin. The structure has an air vent that is used to release trapped air by the water entering the penstock pipe. The operation head of the hydropower scheme is usually determined by the water level at the head tank. In the fore - bay structure there is also a small overflow that maintain the required volumetric water flow by spilling excess water during floods. The water flow velocity at the fore - bay is much slower than in the headrace canal which allow the sediments to get settled down. For the safe removal of the sediments the flushing gate or pipe is also required at the fore - bay structure. The penstock pipe is usually connected at the end point of the fore - bay as shown in Figure 10 below.

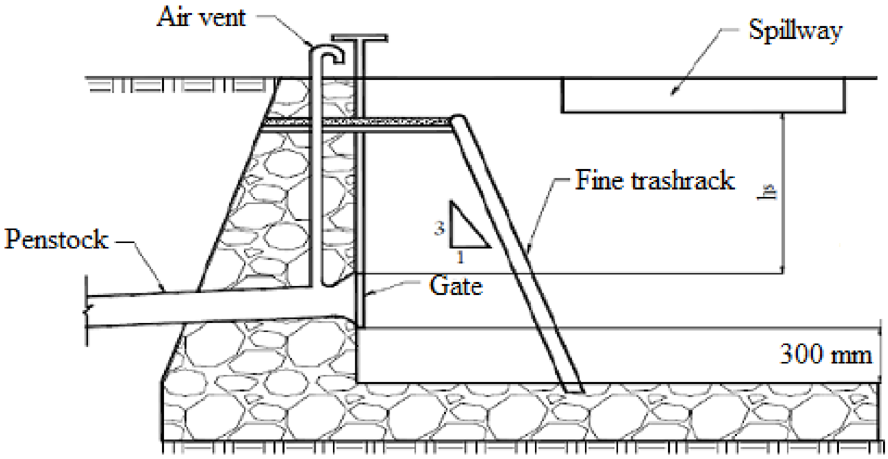

Figure 10: Fore - bay layout [9]

(c) Penstock pipe

The penstock is the pipe material that conveyed the required water flow discharge from the fore - bay/dam structure to the turbine unit. It is usually made up from different materials and the commonly used materials are mild steel and HDPE pipes. At higher heads or large water volume, steel pipes are better suited due to their resistance to higher water pressure values while at lower heads or small - scale hydropower plants HDPE pipes are commonly used due their relatively low cost and easy to join and repair. Other materials for the penstock pipes include uPVC, concrete and ductile Iron as shown in the following Table 1.

Table 1: Commonly used penstock materials [10]

Material	Pressure resistance	Corrosion resistance	Weight	Easy of joining	Friction loss	Cost
Mild Steel	Excellent	Average	Average	Good	Average	Good
HDPE	Good	Excellent	Excellent	Poor	Excellent	Average
uPVC	Good	Good	Excellent	Good	Excellent	Good
Concrete	Poor	Excellent	Poor	Average	Poor	Average
Ductile Iron	Good	Good	Poor	Excellent	Good	Poor
Asbestos cement	Poor	Good	Good	Average	Average	Average

When water flow in the penstock pipe, the conversion of potential energy of water at the penstock entry into kinetic energy at the penstock exit is usually taking place as explained in section 2.1and shown in Figure 11 below. The recommended water flow velocity in the penstock pipe is usually kept at a constant value between 2 – 3 m/s in order to reduce the energy loss when water velocity is much lower or higher which will make the hydropower scheme un - economical in the power production [11].

To determine the amount of water flow discharge through the penstock pipe, its diameter need to be determined using the following equation [12]:

$$d_p = \left(\frac{m_c^2 \ x \ Q_p^2 \ x \ L_p}{H} \right) \qquad (17)$$

where; d = diameter of the penstock pipe (m), m_c = manning coefficient (0.012 for mild steel pipes), Q_p = water flow discharge in the penstock pipe (m^3/s) and L_p= length of the penstock pipe (m) and H = head (m) as shown in Figure 11 below

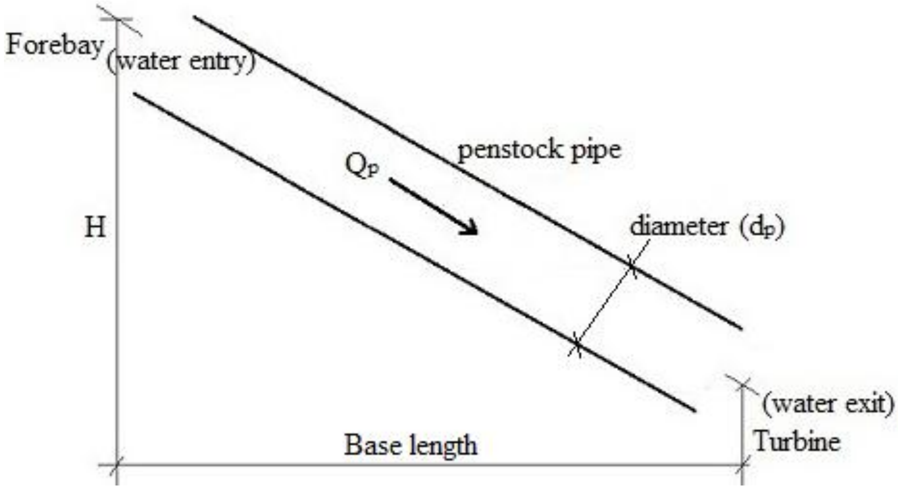

Figure 11: Penstock pipe layout

2.2.2 The power and control system components

The power and control system in the hydropower system consists of the turbine unit, generator unit and control system. The turbine system is the prime mover that utilize the energy of the water flow conveyed by the penstock pipe to rotate the turbine runner and produce mechanical power at the turbine shaft. The amount of mechanical power produced by the hydro turbine depends on the main three parameters of water flow discharge (Q), head value (H) and efficiency of the turbine as explained in detail in section 2.1. On the other hand, this mechanical power from the turbine unit is used to drive the generator system to produce the electrical power. The power conversion from mechanical to electrical is determined by the conversion efficiency as shown in equation 10. To maintain smooth power output, the turbine and generators system need to be controlled. For the turbine system, the control action is done by the governor that regulate the amount of water flow discharge (Q) to the turbine unit. The common types of control governors that are widely used in hydropower plants are the hydraulic - mechanical governor and electro - hydraulic (PID) governor (digital governor). During the control action, the amount power produced by the turbine unit (P_m) is direct proportional to the water flow discharge conveyed by the penstock pipe (Q) and the pressure head (H) as shown in Figure 12 below.

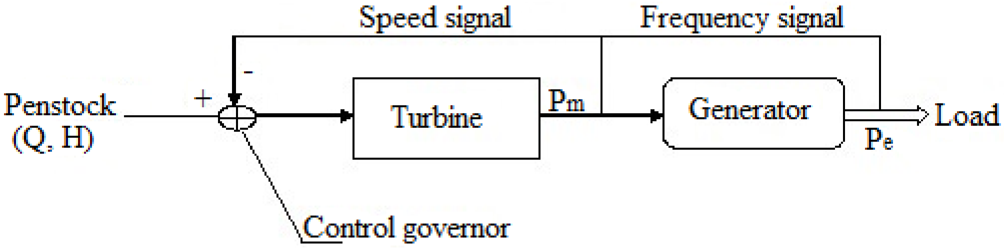

Figure 12: Turbine - generator power and control system layout

From the diagram above it is noted that the turbine shaft power (P_m) is directly connected to the generator unit and this causes the generator to spin and hence produce electrical power (P_e) that is supplied to consumer load. In the turbine - generator system the speed (RPM) and frequency (Hz) needs to be maintained at the rated value, so in this case the speed signal from the turbine and frequency signal from the generator is fed back to the control governor to regulate the amount of water flow discharge (Q) in order to maintain the required turbine speed and also synchronized generator frequency.

2.3 Advantages of hydropower plants

Most hydropower plants are used to generate electricity and supply it to the consumer load demand. In large hydropower plants, the produced electrical power is usually connected to the national grid and distributed to the entire nation. Hydropower plants have a lot of advantages and some of them include:

(a) Low operating and maintenance costs: - The cost of running a hydropower plant is relatively low due to the low in labour cost because of few operators during the normal operation. Also, most parts of the hydropower plants have higher life time which have resulted to the reduction in the maintenance cost.
(b) Energy storage: - Large hydropower plants with pumped hydro storage are used to store water energy during off - peak hours by pumping it to the upper reservoir and used to produce additional power during high peak demand hours.
(c) No fuel cost involved: - Hydropower plants does not require any fuel to produce electrical power like most of other conversional power plants. This has resulted into low electricity cost as compared to other power plants which makes hydropower as one of the cheapest source of energy.
(d) No air pollution: - Hydropower is the energy source with no pollution and hence when used in a big scale it saves the environment by reducing the greenhouse gas emissions and other forms of pollution.
(e) Reliability: - Hydropower is a very reliable technology because it is a source of electricity that stay for many years in their service life. A typical hydropower plant can last for a very long time if well maintained and have high load factor.
(f) Small size development is possible: - Hydropower plants can be scaled down to small sizes that are mostly applicable to small rivers and streams. The small sizes ranges from mini, micro or pico hydropower scale and these kinds of small - scale hydropower plants are more economical and thus can be applicable to rural and off - grid areas for village - based electrification.

3. Conclusion

The hydropower system uses the energy of the water flow to rotate the turbine wheel to produce mechanical power at the turbine shaft which is attached to the generator system to produce the electrical power. From the river flow, the water is collected at the intake canal after being accumulated at the dam/reservoir by the intake weir structure. The water is then transported by the canal/conduit structure from the intake through the settling basin to the head tank (forebay). At the end of the forebay structure the penstock pipe that conveyed water flow discharge to the turbine unit is connected. At the penstock entry, the maximum potential energy (PE_{max}) is obtained due to the presence of maximum water pressure column (H_1) in the forebay. This potential energy is then converted to maximum kinetic energy (KE_{max}) at the turbine nozzle/jets due to the presence of maximum water flow velocity (U_{max}). This causes the turbine wheel to spin and produce mechanical power (P_m) that drives the generator system to generate electrical power (P_e) that is supplied to the load demand (consumers) or connected to the national grid.

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