International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-2 Issue-5, June 2013

Design of Micro - Hydro - Electric Power Station

Bilal Abdullah Nasir

Abstract: ***Micro-hydro-electric power is both an efficient and reliable formof clean source of renewable energy. It can be an excellent method of harnessing renewable energy from small rivers and streams. The micro-hydro project designed to be a run -of-river type, because it requires very little or no reservoir in order to power the turbine. The water will run straight through the turbine and back into the river or stream to use it for the other purposes. This has a minimal environmental impact on the local ecosystem.The design procedure of micro-hydro power plant was implemented by a Matlab Simulink computer program to calculate all the design parameters. The choice of the turbine type depending mainly on the site head and flow rate. The turbine power and speed were directly proportional with the site head, but there were specific points for maximum turbine power and speed with the variation of the site water flow rate. The head losses in the penstock could range from 5 to 10 percent of the gross head, depending on the length of the penstock, quantity of water flow rate and its velocity. The turbine efficiency could range from 80 to 95 percent depending on the turbine type, and the generator efficiency about 90 percent. The design study showed that construction of micro-hydro-electric project was feasible in the project site and there were no major problems apparent at the design and implementation stages of the micro-hydro-electric power plant.***

Keywords: ***micro-hydro-electric power plant, design and implementation, hydro-turbines.***

I. INTRODUCTION

Energy is one of the most fundamental elements of our universe. It is inevitability for survival and indispensable for development activities to promote education, health, transportation and infrastructure for attaining a reasonable standard of living and is also a critical factor for economic development and employment [1].

In the last decade, problems related to energy crisis such as oil crisis, climatic change, electrical demand and restrictions of whole sale markets have a risen world-wide. These difficulties are continuously increasing, which suggestthe need of technological alternatives to assure their solution. One of these technological alternatives is generating electricity as near as possible of the consumption site, using the renewable energy sources, that do not cause environmental pollutions, such as wind, solar, tidal and hydro-electric power plants [2, 3]. Hydro-electric power is a form of renewable energy resource, which comes from the flowing water. To generate electricity, water must be in motion. When the water is falling by the force of gravity, its potential energy converts into kinetic energy. This kinetic energy of the flowing water turns blades or vanes in a hydraulic turbines, the form of energy is changed to mechanical energy. The turbine turns the generator rotor which then converts this mechanical energy into electrical energy [4].

Manuscript published on 30 June 2013.

***** Correspondence Author (s)
Bilal Abdullah Nasir, Hawijah Technical Institute, Kirkuk, Iraq

The power generated from falling water has been harnessed in various applications such as milling grains, sawing wood and pumping water for irrigation. The slow-moving water wheels were used to harness the mechanical power from flowing water. The design and efficiency improvements made to these early water wheels led to the rise of the hydro-electric turbines. The first hydro-electric power systems were developed in the 1880's. According to the international energy agency (IEA), large-scale hydro-electric plants currently supply 16% of the world's electricity. However, such kind of projects requires tremendous amounts of land impoundment, dams and flood control, and often they produce environmental impacts [5]. Micro-hydro-electric power plants are one of an alternative source of energy generation. They are the smallest type of hydro-electric energy systems. They generate between (5) and (100) Kilowatt of power when they are installed across rivers and streams. The advantages of micro-hydro-electric power plant has over the fossil and nuclear power plant are [4, 6]:

- It has ability to generate power near when its needed, reducing the power inevitably lost during transmission.
- It can deal more economically with varying peak load demand, while the fossil-fuel or nuclear power plants can provide the base load only, due to their operational requirements and their long start-up times.
- It is able to start-up quickly and make rapid adjustments in output power.
- It does not cause pollution of air or water.
- It has low failure rate, low operating cost and is reliable.
- It acts much like a battery, storing power in the form of water.

In particular, the advantages that micro-hydro-electric power plant has over the same size wind, wave and solar power plants are:

- 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) [7]. So, there is a scope for harnessing the micro-hydro-electric power plant potentiality by identifying proper site and designing appropriate power generation systems.

Properly designed micro-hydro-electric power plant causes minimum environmental disruption to the river or stream and can coexist with the native ecology.

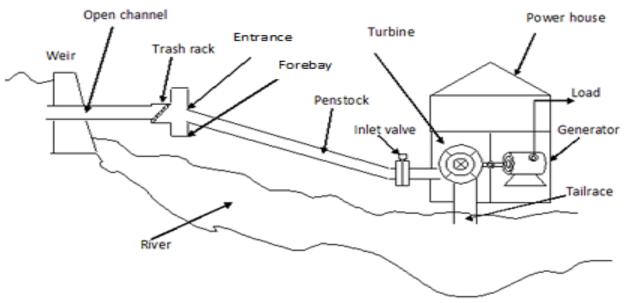

Figure (1) Schematic diagram of micro-hydro-electric power plant

This paper reports on the design in Matlab Simulink procedure and implementation of micro-hydro-electric power plant taking into account a lot of design considerations such as site survey, measuring of head and water flow rate, civil work components (weir–trashrack – intake – channel - penstock), selection of hydraulic turbine type and dimensions and specifications of electrical power generator.

II. DESIGN CONSIDERATIONS OF MICRO-HYDRO-ELECTRIC POWER PLANTS

To design a micro-hydro-electric power plant, there are many considerations to be prepared and taken into account in the design procedure. These considerations are:

a- Flow duration curve (FDC) [6]:

The choice of turbine type, size and speed is based on the net head and maximum water flow rate, which must be determined by the river or stream where the turbine shall be installed. Because of micro-hydro-electric power plants are normally built as run of the river plants, the maximum water flow capacity of the turbine must be determined by mean of the flow duration curve for the river or stream.

A way for organizing discharge data is by plotting a flow duration curve, that shows for a particular point on a river the proportion of time during which the discharge there equal or exceeds certain values. It can be obtained from the hydro-graph by organizing the data by magnitude instead of chronologically.

The mean annual flow gives an idea of a stream's power potential. FDC can be produced for particular periods of time as well as for particular years.

b- Flow rate measurement [4]:

To measure the water flow rate (discharge) several methods are available. The velocity-area method is a conventional method for medium to large rivers, involving the measurement of the cross-sectional area of the river and the mean velocity of the water through it. It is a useful approach for determining the stream flow with a minimum effort. The river should have a uniform width and the area well defined.

i- Measuring the cross sectional area (Ar):

To compute the cross-sectional area of a natural water course, it should be divided into a series of trapezoids. Measuring the trapezoid sides, marked rules, the cross-section would be given by:

$$A_r = \frac{(a+b)}{2} * \frac{h_1+h_2+h_3+\cdots+h_k}{k} \quad (m^2) \qquad (1)$$

Where a = width of top river (m)

b = width of bottom river (m)

$\frac{h_1+h_2+h_3+\cdots+h_k}{k}$= average height of water in the river (m).

ii- Measuring the velocity (Vr):

Since the velocity both across the flow and vertically through it is not constant, it is necessary to measure the water velocity at a number of points to obtain a main value.

The velocity can be measured by a floating object, which is located in the center of stream flow. The time (t) in seconds elapsed to traverse a certain length (L) in meter is recorded. The surface speed (m/s) is given as:

$$Vrs = L / t \quad (m / s) \qquad (2)$$

To estimate the average flow speed (Vr), the above value must be multiplied by a correction factor, that may vary between (0.6) and (0.85), depending on the water course depth and their bottom and river bank roughness (0.75 is a well-accepted value).

$$Vr = 0.75 * Vrs \quad (m / s) \qquad (3)$$

Then, the flow rate can be calculated as:

$$Q = Ar * Vr \quad (m^3 / s) \qquad (4)$$

Where Q = water flow rate (discharge) of the river or stream.

c- Weir and open channel [4]:

In case of low discharge rivers (less than $4\ m^3/s$), it may be possible to build a Weir. It is a low wall or dam across the stream to be gauged with a notch through which all the water may be channeled. A simple linear measurement of the difference in level between the up-stream water surface and the bottom of the notch is sufficient to quantify the flow rate (discharge). Several types of notch can be used such as rectangular, Vee or trapezoidal. The actual notch may be metal plate or hard wood with sharp edges,the flow rate through it can be given as [4]:

$$Q = 1.8 * (W - 0.2\,h) * h^{1.5} \quad (m^3 / s) \qquad (5)$$

Where W = Weir width (m)

h = Weir height (m)

If $w = 3h$ then the Weir dimensions can be calculated. The most important thing to consider while constructing the headrace open channel to make slope of channel only slightly elevated because higher slope can lead to higher velocity of water which can then cause erosion in the channel surface.

In open channel foundation two requirements must be satisfied:

- The stability: channel is a rigid structure and do not permit deformations
- Channel does not support thrust or up lift pressure. The flow of water in open channel is considered uniform when:
- The water depth, area and velocity in every cross-section of the channel are constant.

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- The energy gradient line, surface line and bottom channel line are parallel to each other.

Based on these concepts Manning found that [4]:

$$Q = ({}^{1}/_{n_{ch}}) * Sf * S_{ch}^{\frac{1}{2}} \quad (m^3 / s) \tag{6}$$

Where Q = flow rate of water in uniform open channel.
n_{ch} = Manning factor.
Sf = section factor .
S_{ch} = channel bottom line slope (hydraulic gradient) which normally is the bed slope.

$$S_{ch} = \left[{}^{Q * n_{ch}}/_{Ach.Rch^{2}/_{3}} \right]^2 \tag{7}$$

Where $A_{ch} = (W * h)$ (m^2) open channel cross-sectional area. (8)

$R_{ch} = {}^{A_{ch}}/_{(W + 2h)}$ (m) hydraulic radius of the section area. (9)

The open channel velocity (V_{ch}) can be calculated as:

$$V_{ch} = {}^{Q}/_{A_{ch}} \tag{10}$$

d- Intake location [4]:

The water-intake usually located at the end of the water channel. In small hydro-power schemes, even in high head ones, water-intakes are horizontal, followed by a curve to an inclined or vertical penstock.

The location of the intake depends on a number of factors, such as submergence, geotechnical conditions, environmental considerations and ice formation. Several components need to be considered:

- Approach walls to the trash rack designed to minimize flow separation and head losses.
- Transition from rectangular cross-section to a circular one to meet the entrance to the penstock.
- Piers to support mechanical equipment including trash racks and service gates.
- Vortex suppression devices.

The velocity of water along the intake may vary from 0.8-1 m/s through the trash rack to 3-5 m/s in the penstock. A good profile will achieve a uniform acceleration of the flow, minimizing the head losses. The best design is that of a compact intake with a sloping roof and converging wall.

e- Trash rack design [4]:

To prevent the trash from getting entry into the entrance flume, bars at certain spacing (called trash rack) are placed in a slanting position (at an angle 60° to 80° with horizontal). The maximum possible spacing between the bars is generally specific by the turbine manufacturers. Typical value are (20-30 mm) for Pelton turbines, (40-50 mm) for Francis turbines and (80- 100 mm) for Kaplan turbines. A screen or grill is always nearly at the entrance of both pressure pipes and intakes to avoid the entrance of floating debris. The flow of water through the rack also gives rise to a head loss. The trash rack coefficient (K_{tr}) depends on the bar shape and may be vary from (0.8) to (2.4).

f- Gates and valves [4]:

In low head schemes with integral intake and power house, the best way to increase the head without risking up stream flooding, is the sector gate. A hydraulic system or an electric motor opens the gate, so that the water passes underneath. In case of maintenance or repair, a gate is used to avoid the runways speed on a shut down turbine. A sliding gates of cast iron, steel, plastic or timber are suited to the intake small and micro-hydro systems. The loss of head produced by the water flowing through an open valve or gate depends on the type and manufacture of the valve.

g- Forebay [6]:

The water carried by the power channel is distributed to various penstocks leading to the turbines through the forebay. It also known as the head pond. Water is temporarily stored in the forebay in the event of a rejection of load by the turbine and there is withdrawal from it when the load is increased. Also the forebay acts as a sort of regulating reservoir.

h- Vorticity [6]:

Vorticity can appear for low-head pressurized intakes (power intakes) and should be avoided because it interferes with good performance of turbines. Vorticity may produce non-uniform flow conditions, introduce air into the flow with bad results on the turbine and draw trash into the intake. Lack of sufficient submergence and not symmetrical approach seem to be the most common causes of vortex formation. The minimum value of submersion (h_s) is given by [4]:

$$h_s \geq D_h * \left[1 + 2.3 \frac{V_{en}}{\sqrt{g * D_h}} \right] \tag{11}$$

Where D_h = hydraulic diameter of the down stream conduit (m).
V_{en} = entrance velocity (m/s).
g = gravitational constant (9.8 m/s^2).

i- Penstock design:

Penstocks (pipes) are used to 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 (D_p) can be estimated from the flow rate, pipe length and gross head as [4]:

$$D_p = 2.69 * \left({}^{n_p^2 * Q^2 * L_p}/_{H_g} \right)^{0.1875} \quad (m) \tag{12}$$

Where n_p = Manning's coefficient .
Q = water flow rate (m^3/s).
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:

$$t_p = \frac{D_p + 508}{400} + 1.2 \quad (mm) \tag{13}$$

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.

j- Saddles [4]:

The saddles are designed to support the weight of penstock full of water. The vertical component of the weight to be supported, in KN, has value of [4]:

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$$F = \left(W_p + W_w\right) * L_{ms} * \cos(\theta) \qquad (14)$$

Where W_p = weight of penstock per meter (*KN/m*).
W_w = weight of water per meter (*KN/m*).
L_{ms} = Length of penstock between mid-points of each span (*m*).
θ = angle of pipe with horizontal.

Maximum length between supports is given by [4]:

$$L_{mms} = 182.61 \frac{\sqrt[3]{(D_p + 0.0147)^4 - D_p^4}}{P_w} \qquad (15)$$

Where D_p = internal diameter of penstock (*m*).
P_w = unit weight of the penstock full of water (*Kg/m*).

k- Tailrace [6]:

After passing through the turbine, the water returns to the river through a short canal called tailrace. Impulse turbines can have relatively high exit velocities, so the tailrace should be designed to ensure that the power house would not be undermined. Protection with rock riprap or concrete aprons should be provided between the power house and the stream. The design should also ensure that during relatively high flows the water tailrace does not rise so far that it interferes with the turbine runner. With a reaction turbine the level of the water in the tailrace influences the operation of the turbine and more specifically the onset of cavitation.

The level above the tailrace also determines the available net head and in low head systems may have a decisive influence on the economic results.

l- Head measurement [4]:

The gross head (H_g) is the vertical distance between the water surface level at the intake and at the tailrace for the reaction turbines (such as Francis and Kaplan turbines) and the nozzle level for the impulse turbines (such as Pelton, Turgo and cross-flow turbines). The modern electronic digital levels provide an automatic display of height and distance with about (4) seconds with measurement accuracy of (0.4 *mm*). Surveying byGlobal Positioning Systems (GPS) is already practiced and handheld GPS receiver is ideal for field positioning and rough mapping. Once the gross head is known, the net head (H_n) can be computed by simply subtracting the losses along its path, such as open channel loss, trash rack loss, intake or inlet to penstock loss, gate or valve loss and penstock friction loss.

m- Turbine power [5]:

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, 5]:

$$P_t = \rho * g * H_n * Q * \eta_t \quad (watt) \qquad (16)$$

Where P_t = power in watt generated in the turbine shaft.
ρ = 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).
η_t = turbine efficiency (normally 80-90%).

The turbine efficiency (η_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 isalways 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.

n- Turbine speed [4]:

To ensure the control of the turbine speed by regulating the water flow rate, a 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:

$$\frac{dw}{dt} = \frac{1}{J * w}\left(P_t - P_l - B * w^2\right) \qquad (17)$$

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 $P_t = P_l + B * w^2$, $dw/dt = 0$ and w = constant. So operation is steady. When P_t is greater or smaller than ($P_l + B * w^2$), 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 Matlabsoftware or MatlabSimulink or closed form solution as:

$$w = \sqrt{\frac{(P_t - P_l)}{B}\left(1 - e^{\frac{-2B}{J}t}\right) + w_\circ^2 * e^{\frac{-2B}{J}t}} \qquad (18)$$

Then the turbine speed in r.p.m. can be determined as:

$$N = \frac{60 * w}{2\pi} \quad (r.p.m) \qquad (19)$$

Any turbine, with identical geometric proportions, even if the sizes are different, will have the same specific speed (N_s). The specific speed is defined as [4]:

$$N_s = \frac{N * \sqrt{P_t}}{H_n^{5/4}} \quad (r.p.m) \qquad (20)$$

Where N = turbine speed in (*r.p.m*) which can be calculated from the solution of motional equation.
H_n = net head in (meter).
P_t = turbine power in (*Kw*).

The specific speed constitute a reliable criterion for the selection of turbine type and dimension.

After determination of turbine speed (N), the gear box ratio and the generator type can be selected.

o- Turbine selection [4, 6]:

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 cavitation phenomenon, can be calculated. In case of Kaplan or Francis turbine type, the head loss due to cavitation, the net head and the turbine power must be recalculated.

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 as [6]:

i- For Pelton turbine:

If the runner speed (*N*), the net head and water flow rate (*Q*) are known, the dimensions of the Pelton turbine can be estimated from the following equations [6]:

$D_1 = 40.8 * \frac{\sqrt{H_n}}{N}$ diameter of circle describing the buckets center line in meters. (21)

$B_2 = 1.68 * \sqrt{\frac{Q}{K} * \frac{1}{\sqrt{H_n}}}$ bucket width in meters. (22)

Where *K* = number of nozzles.

$D_e = 1.178 \sqrt{\frac{Q}{K} \frac{1}{\sqrt{g * H_n}}}$ nozzle diameter in meters. (23)

$D_j = 0.54 * \sqrt{Q / \sqrt{H_n}}$ jet diameter in meters. (24)

$V_{jet} = 0.97 * \sqrt{2 * g * H_n}$ jet velocity (*m/s*). (25)

The ratio D_1/B_2 must be always greater than (2.7). if this is not the case, then a new calculations with more nozzles number has to be carried out. If the turbine is Turgo at the same power of Pelton, the specific speed is double of that Pelton and the diameter is halfed.

ii- For Francis turbine:

It covers a wide range of specific speed, going from (50) to (350) corresponding to high head and low head respectively.Themain dimensions can be estimated as [6]:

$D_3 = 84.5(0.31 + 2.49 \frac{N_s}{995}) \frac{\sqrt{H_n}}{N}$ exit diameter in meters (26)

$D_1 = \left(0.4 + \frac{94.5}{N_s}\right) * D_3$ inletrunner diameter in meters (27)

$D_2 = \frac{D_3}{(0.96 + 3.8 * 10^{-4} * N_s)}$ inlet diameter in meters (28)

If $N_s < 163$ then $D_1 = D_2$

iii- For Kaplan turbine:

$D_e = 84.5(0.79 + 1.6 * 10^{-3} N_s) \frac{\sqrt{H_n}}{N}$ therunner exit (outer) diameter in meters (29)

$D_i = \left(0.25 + \frac{94.5}{N_s}\right) * D_e$ the runner hub (inlet) diameter in meters (30)

iv- For cross-flow turbine:

$D_r = \frac{40 * \sqrt{H_n}}{N}$ runner diameter in meters (31)

$L_r = \frac{0.81 * Q}{D_r * \sqrt{H_n}}$ runner length in meters (32)

$t_j = \frac{0.233 * Q}{L_r * \sqrt{H_n}}$ jet thickness or nozzle width in meters (33)

p- Cavitation phenomenon [12]:

When the hydro-dynamic pressure in a flow liquid falls below the vapour pressure of the liquid, there is a formation of the vapour pockets. This induces the formation of small individual bubbles that are carried out of the low pressure region by the flow and collapse in regions of higher pressure. The formation process of these bubbles and their subsequent collapse is called cavitation. If the vapour bubbles are near or in contact with a solid boundary when they collapse, the forces exerted by the liquid rushing into cavities create very high localized pressures that cause pitting of the solid surface. This phenomenon is accompanied by noise and vibration that resemble those of gravel going through a centrifugal pump.

To avoid cavitation, the turbine should installed at least at a height over the tailrace water level (Z) giving by the equation [12]:

$$Z = H_{atm} - H_{vap} - \delta_T - H_n + \frac{V_e^2}{2g} + H_{DT} \qquad (34)$$

Where *Z* = the elevation above the tailrace (meters).
H_{atm} = the atmospheric pressure head in (meters).
H_{vap} = the water vapour pressure head in (meters).
δ_T = Thoma's sigma coefficient.
H_n = the net head of the scheme in (meters).
V_e = draft tube velocity (*m/s*).
H_{DT} = draft tube head loss in (meters).
g = gravitational constant (9.8 m/s^2).

Also the Thoma's sigma coefficient for Francis and Kaplan turbines can be given in a function of turbine specific speed (N_s) as [4]:

For Francis turbine, $\delta_T = 7.54 * 10^{-5} * (N_s)^{1.41}$
For Kaplan turbine, $\delta_T = 6.4 * 10^{-5} * (N_s)^{1.46}$

A positive value of the suction head (*Z*), means that the turbine runner is over the down- stream level, a negative value of (*Z*), that is under the down-stream level and the turbine setting (installing) requiring an excavation.

To avoid cavitation the following criterion must be satisfied in the design of the micro-hydro power plant [12]:

$$\frac{N_s}{995} \le 0.686 * (\delta_T)^{0.5882} \qquad (35)$$

q- Power house [4]:

Due to the presence of large and heavy equipment units, the power house stability must completely secured. Settlements cannot be accepted in the power house. If the power house is founded on rock, the excavation work will eliminate the superficial weathered layer, leaving a sound rock foundation. If the power house is to be located on fluvial terraces near the river banks which do not offer a good foundation then the ground must be reconditioned. The equipment of the power house are turbine, electrical generator and drive systems.

r- Speed increaser [4, 13]:

When the turbine and generator operate at the same speed and can be placed so that their shafts are in line, direct coupling is the right solution. Virtually no power losses are incurred and maintenance is minimal.

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Turbine manufactures will recommend the type of coupling to be used, either rigid or flexible although a flexible coupling that can tolerate certain misalignment is usually recommended. In the lowest power range, turbines run at less than (400) *r.p.m*, requiring a speed increaser to meet (1500) *r.p.m* of standard alternator. In the range of powers contemplated in small and micro-hydro schemes, this solution is always more economic than the use of a custom alternator.

s- Rotational and runaway speed [4, 14]:

The rotational speed of a turbine is a function of its power and net head. In the small and micro-hydro schemes, standard generators should be installed when possible, so in the turbine selection, it must be borne in mind that the turbine, either coupled directly or through a speed increaser (gear box) to reach the synchronous speed.

Each runner profile is characterized by a maximum runaway speed. This is the speed, which the unit can theoretically attain when the turbine power is at its maximum and the electrical load has become disconnected. Depending on the type of turbine, it can attain 2→3 times the nominal speed. The cost of generator and gear box may be increased when the runway speed is higher, since they must be designed to withstand it.

t- Speed governor [6]:

A governor is a combination of devices and mechanisms, which detect speed deviation and convert it into a change in servomotor position. Several types of governors are available. The purely mechanical governor is used which fairly small turbines. In modern electric-hydraulic governor, a sensor located on the generator shaft to sense the turbine speed. The turbine speed is compared with reference speed. The error signal is amplified and sent to the servomotor to act in the required sense.

To ensure the control of the turbine speed by regulating the water flow, certain inertia of rotating components is required. Additional inertia can be provided by a flywheel, on the turbine, or generator shaft. The flywheel effect of the rotating components is stabilizing whereas the water column effect is destabilizing. The start-up time of the rotating system (t_r) is given as [6]:

$$t_r = Wt * r^2 * N^2 \Big/ (91270 * P_t) \quad (sec.) \qquad (36)$$

Where Wt = weight of all the rotating parts (Kg).
r = radius of gyration (m).
N = turbine speed ($r.p.m$).
P_t = turbine power (KW).

The water starting-up time (t_w) needed to accelerate the water column for zero to penstock water velocity is given as [6]:

$$t_w = L_p * V_p \Big/ (g * H_g) \quad (sec.) \qquad (37)$$

Where l_p = length of penstock (m).
V_p = penstock water velocity (m/s).
H_g = gross head (m).
g = gravity acceleration constant (9.8 m/s^2).

To achieve good regulation, it is necessary that $t_r/t_w > 4$. The water starting time is not exceed (2.5) seconds. If it is larger, a modification of the water conduit must be considered, either by decreasing the velocity or the length of the penstock. The possibility of adding a flywheel to the generator to increase the inertia of the rotating parts can also be considered. This can improves the water hummer effect and decrease the runaway speed.

u- Bypass [6, 15]:

A bypass of the turbine may be required to guarantee the primary function of the existing micro-hydro-electric power plant at any time. It can be used when the turbine is not operating due, for example, to a too low discharge or to maintenance needs. It can also be used when the discharge needed for the existing scheme is higher than the turbine nominal one. In such situation, the turbine uses its maximal discharge, whereas the surplus flows through the bypass.

The basic process for designing the bypass is to calculate the intake during floods. Then the maximum height of the water level in the canal during a flood should be calculated followed by the dimensions for the crest of the bypass. The dimensions of the bypass are given as [15]:

$$L_{bypass} = (Q_{flood} - Q_{design}) \Big/ \left[1.6 * (H_{flood} - H_{sp})^{1.5}\right] \qquad (38)$$

Where L_{bypass} = length of bypass (m).
Q_{flood} = flood flow via intake (m^3/s).
Q_{design} = design flow in headrace (intake) canal (m^3/s).
H_{flood} = height of flood level in the canal (m).
H_{sp} = height of the bypass crest from canal bed (m).

$$H_{overtop} = H_{flood} - H_{sp} \qquad (39)$$

v- Load factor [4]:

The load factor is a ratio of summarizing how hard a turbine is working, expressed as [4]:

$$Load\ factor = \frac{Energy\ generated\ per\ year\ (KWH/year)}{Installed\ capacity(KW) * 8760} \qquad (40)$$

The energy generated per year (KWH) can be calculated as:

$$E = \rho * g * Q * H_n * \eta_{turbine} * \eta_{generator} * \eta_{gear\ box} * \eta_{transformor} * n \qquad (41)$$

Where g = gravitational constant (9.8 m/s^2).
ρ = water density (1000 kg/m^3).
Q = flow rate (m^3/s).
H_n = net head (m).
$\eta_{turbine}$ = turbine efficiency.
$\eta_{generator}$ = generator efficiency.
$\eta_{gear\ box}$ = gear box efficiency.
$\eta_{transformer}$ = transformer efficiency.
n = number of hours in year for which the specified flow occurs.

III. DESIGN STEPS AND MATLAB SIMULINK FLOW-CHART

The design procedure involves the following steps:

1- preparing the input data and parameters of the micro-hydro-electric power plant to the computer program. These parameters are:

a- River or stream area (A_r) in (m^2).
b- River or stream flow velocity (V_r) in (m/s).
c- Length of an open channel (L_{ch}) in (m).
d- Length of penstock (L_p) in (m).
e- Manning factor of penstock (n_p) .
f- Manning factor of an open channel (n_{ch}) .
g- Gross head (H_g) of water flow through the turbine in (m).
h- Inclined angle (α) with horizontal for trash rack.

i- Bar thickness (*t*) in (*mm*) of trash rack screen.
j- Bar width (*b*) in (*mm*) of trash rack screen.
k- Entrance factor (K_{en}).
l- Screen factor (K_{tr}) of trash rack.
m- Valve gate factor (K_v).
n- Turbine efficiency(η_t).
o- Water density (ρ) in (Kg/m^3).
p- Gravity constant in (m/s^2).
q- Moment of inertia of the whole system (*J*) in ($Kg.m^2$).
r- Friction torque coefficient of the whole system (*N.m/(rad./sec.)*).

2- Calculation of water flow rate (*Q*) in (m^3/s) from equation (4).

3- Calculation of rectangular weir and open channel dimensions (width (*w*) and height (*h*) in (*m*)) from equation (5).

4- Calculation of an open channel bottom line slope (S_{ch}) from equation (7).

5- Calculation of an open channel hydraulic radius (*R*ch) from equation (9).

6- Calculation of an open channel water flow velocity (V_{ch}) in (*m/s*) from equation (10).

7- Calculation of penstock inlet velocity (V_p) in (*m/s*) from the following formula [4]:

$$V_p = \frac{Q}{A_p} = \frac{4 * Q}{\pi D_p^2} \quad (m/s) \qquad (42)$$

Where A_p = penstock area (m^2).

D_p = penstock diameter in (*m*), which can be calculated from equation (12).

8- Calculation of the net head of the power plant from the following relation:

$$H_n = H_g - (H_{ch} + H_{tr} + H_{en} + H_v + H_p) \qquad (43)$$

Where H_n = the net head of power plant in (*m*).

$$H_{ch} = \left[\frac{Q*n_{ch}}{A_{ch}Rch^{2/3}}\right]^2 * L_{ch} \text{ open channel loss in } (m). \qquad (44)$$

Where A_{ch} = open channel area (*W*h*) in (m^2).

$$H_{tr} = K_{tr} * \left(\frac{t}{b}\right)^{4/3} * \frac{V_{ch}^2}{2g} * Sin(\alpha) \text{ trash rack loss in } (m). \qquad (45)$$

$$H_{en} = K_{en} * \frac{V_p^2}{2g} \text{ entrance loss in } (m). \qquad (46)$$

$$H_v = K_v * \frac{V_p^2}{2g} \text{ valve gate loss in } (m). \qquad (47)$$

$$H_p = \frac{10.29 * n_p^2 * Q^2}{D_p^{5.33}} * L_p \text{ penstock friction head loss in } (m). \qquad (48)$$

9- Calculation of turbine power in (watt) from equation (16).

10- Calculation of turbine speed (*N*) in (*r.p.m*) from the solution of motional differential equation (17).

11- Calculation of specific speed (N_s) in (*r.p.m*) from equation (20).

12- Selection of turbine type from the comparison of calculated specific speed (N_s) and net head (H_n) with those given in standard specifications.

13- Calculation of turbine dimensions according to the type of turbine which obtained from the previous step, using the relations given in equations (21) to (33).

14- If the turbine type is Francis or Kaplan, the net head in step (8) is corrected by introducing the head loss due to elevation above the tailrace using equation (34).

Then steps (9) to (13) will be repeated to take the effect of cavitation into account.

The flow-chart of the whole Matlab Simulink program including the design steps is prepared in figure (2).

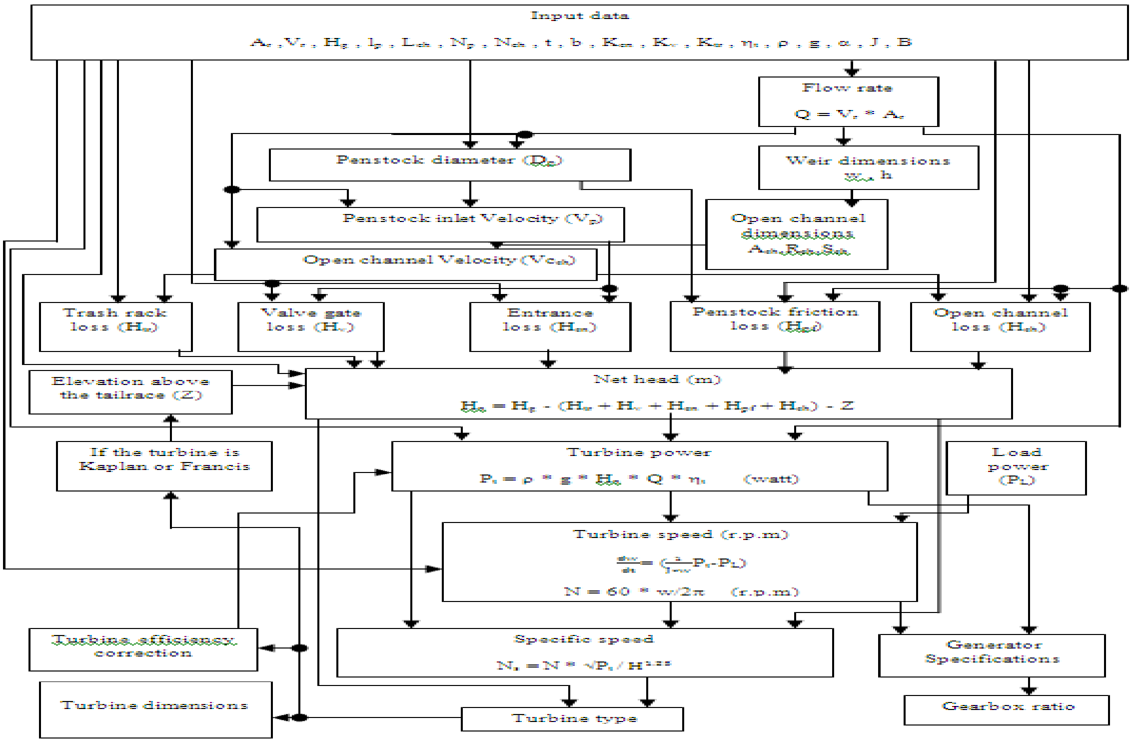


Figure (2) Flow-chart of the MatlabSimulink Program

IV. RESULTS

The design procedure of micro-hydro-electric power plant was implemented by Matlab Simulink computer program. After introducing the site measurements and calculations as input data to the computer program, the weir dimensions, open channel dimensions, penstock dimensions, turbine type, turbine size, turbine power, turbine speed, turbine efficiency, generator specifications and gear box ratio were determined.

Figures (3, 4) show the relation between turbine power and speed with gross head at different values of water flow rate. Figures (5, 6) show the variation of turbine power and speed with water flow rate at different values of site head. From these results, the turbine power and speed were directly proportional with the gross head, but there were specific points for maximum power and maximum speed in case of water flow variation.

Figures (7, 8) show the variation of head loss with the gross head and water flow rate. It can be shown that the head loss was increased very high with increasing the water flow rate than that with increasing the gross head.

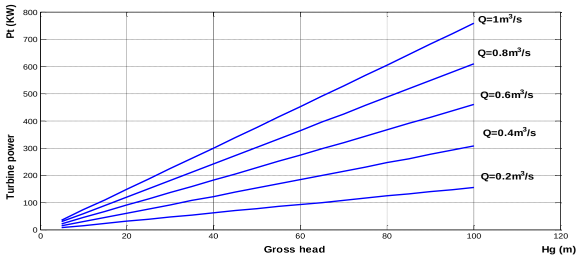


Figure (3) Variation of turbine power with gross head at different values of water flow rate

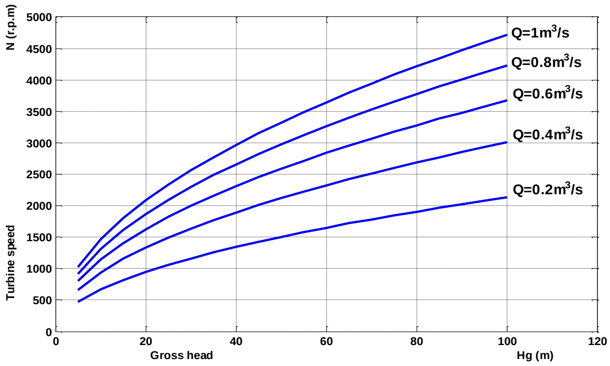


Figure (4)Variation of turbine speed with gross head at different valuesof water flow rate

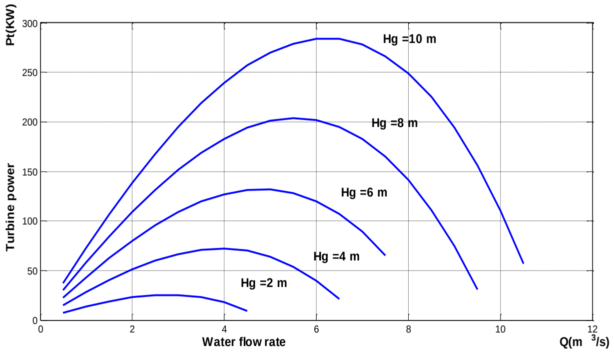


Figure (5)Variation of turbine power with water flow rate at different valuesof gross head

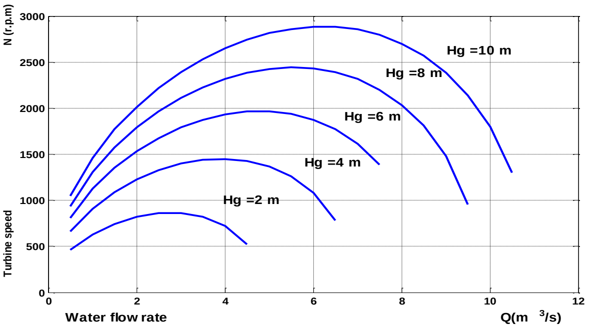


Figure (6) Variation of turbine speed with water flow rate at different values of gross head

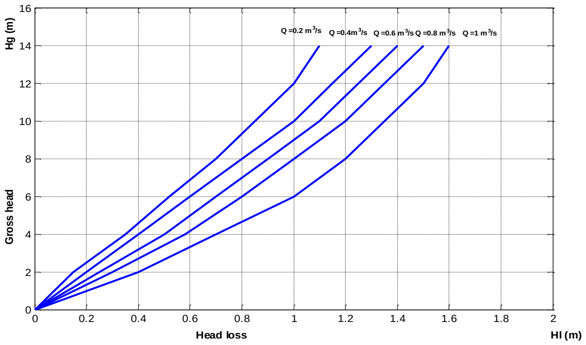
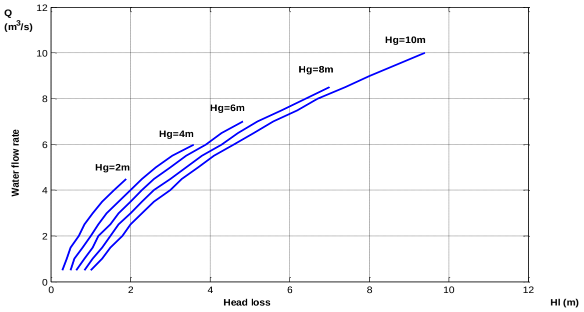


Figure (7)Variation of gross head with head loss at different values of water flow rate



Figure(8)Variation of water flow rate with head loss at different values of gross head

V. CONCLUSIONS

i- Micro-hydro power continues to grow around the world, it is important to show the public how feasible micro-hydro systems actually are in a suitable site. The only requirements for micro-hydro power are water sources, turbines, generators, proper design and installation, which not only helps each individual person but also helps the world and environment as a whole.

ii- Run-of-river micro-hydro turbine schemes generate electricity when the water is available and provided by the river. When the river dries-up and the flow falls below predetermined amount or the minimum technical flow for the turbine, generation will ceases.

iii- Medium and high head schemes use Weirs to divert water to the intake, it is then conveyed to the turbines via a pressure pipe or penstock. Penstocks are expensive and the design is usually uneconomic due to the high penstock friction head loss. An alternative is to convey the water by a low-slope canal, running a long side the river to the pressure intake or forebay and then in a short penstock to the turbine.

iv- The choice of turbine will depend mainly on the pressure head available and the water flow rate. There are two basic modes of operation for hydro power turbines: Impulse and reaction. Impulse turbines are driven by a jet of water and they are suitable for high heads and low flow rates. Reaction turbines run filled with water and use both angular and linear momentum of the flowing water to run the rotor and they are used for medium and low heads and high flow rate.

v- Regulated turbines can move their inlet guide vanes or runner blades in order to increase or reduce the amount of flow they draw. Cross-flow turbines are considered best for micro-hydro projects with a head of (5) meters or less and water flow rate (1.0) m^3/s or less.

vi- Micro-hydro power installations are usually run-of-river systems, which do not require a dam, and are installed on the water flow available on a year round basis. An intake structure with trash rack channels water via a pipe (Penstock) or conduit down to a turbine before the water released down- stream. In a high head (greater than 50 m) and low water flow (less than 0.5 m^3/s), the turbine is typically Pelton type connected directly to a generator with control valve to regulate the flow of water and turbine speed.

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