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Mat lab Simulation Procedure for Design of Micro -Hydro-Electric Power Plant

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Abstract: *The design procedure of micro-hydro power plant was implemented by Matlab Simulink computer program to calculate all the power plant parameters. The choice of turbine type was depending mainly on the site head and rate of flow. 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, intake channel, trash rack specifications and gate valves type. The turbine efficiency could range from 80 to 95 percent depending on the turbine type. The choice of generator power and its specifications depends on the turbine output power and speed. The generator efficiency was 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 except of turbine manufacturing and the generator type in case of low site head and low flow quantity.
Keywords:*micro-hydro-electric power plant, design and Mat-Lab, hydro-turbines, induction generator.*

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I. Introduction

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 have over the fossil and nuclear power plant are [1- 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 makes rapid adjustments in output power.
- It does not cause pollution of air or water.
- 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 isa maximumin 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[7]. 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. 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[8,9].

AIDGroup [10]have been presented a detailed design procedure of Pelton turbine for (16) KW micro-hydro power plant. No theoretical or practical results are shown in the report of the project for the performance of the installed plant. Dan BasarabGuzun and, et al.[11] have been described one micro-hydro-power plant prevented from the initial design to generate electric energy and to educate the students to prepare the Master or Ph.D. degree.The power plant was installed on the Dambovita river crossing the Bucharest city near the Politechnica University in Bucharest.The plant consists of three units with the same Kaplan turbine type, but different electrical generator. There are no design calculations for the units except the power and turbine speed equations. Felix Mtalo and, et al. [12] have been developed a cross-flow hydro turbine which can be produced locally at low cost and used in the implementation of micro-hydro power plants. A physical prototype model has been fabricated and tested in a laboratory but not implemented as a part of micro-hydro power plant, to show the realistic values for the turbine in the field. Javed, A. C. and et al. [13] have been designed a cross-flow turbine for micro-hydro-electric power applications, and a typical site has been selected for installing the micro-hydro power station. A detailed design procedure for the turbine is presented, the results of the runner dimension calculation are completely anomaly due to a mistake in the transformation of units from British to metric (SI), results in a mistake mathematical equations. Okonkwo, G. N. and Ezeonu, S.O. [14] have been implemented a practical mini- hydro -electric power plant using a storage tank as a reservoir (dam) and plastic pipe as a Penstock. The theory of electrical generation is presented but there are no design calculations for the plant components. Veneesh, V. and Selvakumar, A. I. [15] have been simulated in Matlab the turbine and synchronous generator of a micro-hydro-power system. There are no results to improve the validity of the turbine simulation. Loice,G. and Madanhire ,I. [16] have been stated a general recommendations to consider investing in processes that produce Pelton and Cross-flow turbines with higher efficiencies to improve the power output of micro-hydro plants while keeping the overall project cost with acceptable range.

The following sections involve the design procedure in Matlab Simulink and implementation of a run-of-river micro-hydro-electric power plant on a small river taking into account a lot of design considerations such as site survey, measuring of head and water flow rate, civil work components (fore-bay tank– trash-rack – penstock-gatevalve–tailrace channel), vorticity and cavitation phenomena, selection of speed increaser, selection and design of hydraulic turbinetype and dimensions,selectionof electrical power generator specifications and selection of power transmission line type and specifications.

II. Design Steps of Micro-Hydro-Electric Power Plants

A- Turbine power [6]:

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

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 is always above the downstream 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. Figure (6) shows the efficiency characteristic for several types of turbine.

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.

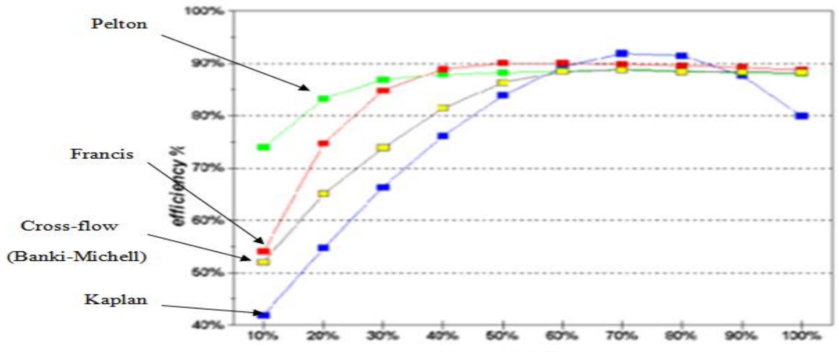


Figure (1) Efficiency-flow rate characteristics for different types of turbines

B- Turbine speed [6**]:**

To ensure the control of the turbine speed by regulating the water flow rate, certain inertia of rotating components is required. Addition inertia can be provided by a flywheel on the turbine or generator shaft. When the load is disconnected, the power excess accelerates the flywheel, later, when the load is reconnected, deceleration of the addition inertia supplies additional power that helps to minimize speed variation. The basic equation of the rotating system is: $\frac{dw}{dt} = \frac{1}{J*w} * (P_t - P_l - B * w^2)$(2)

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

When $P_t = P_l + B * w^2$, $dw/dt = 0$ 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:

$$w = \sqrt{\frac{(P_t - P_l)}{B}\left(1 - e^{\frac{-2B}{J}t}\right) + w_\circ^2 * e^{\frac{-2B}{J}t}} \quad (3)$$

Then the turbine speed in r.p.m. can be determined as: $N = \frac{60*w}{2\pi} \quad (r.p.m)$ (4)

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

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 constitutes 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. In case of speed increasers between turbine and generator,these should be synthetic belts (flat,toothed and V-belts). Gearboxes are acceptable under special circumstances only (high gearing ratio). High quality flat belts are recommended for the full power range (5- 100 KW). Standard V-belts are accepted for outputs below 30 KW.

C- 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 recalculatedThe turbine type can be estimated by comparing the calculated net head and specific speed with those given in tables (1) and (2) respectively.

Table (1) Range of head

Turbine type	Head range (meter)
Kaplan and propeller	$2 < H_n < 40$
Francis	$10 < H_n < 350$
Pelton	$50 < H_n < 1300$
Cross-flow (Banki-michell)	$3 < H_n < 200$

Table (2) Range of specific speed

Turbine type	Range of specific speed (r.p.m)
Pelton one nozzle	$5 \le N_s \le 25$
Pelton two nozzles	$7 \le N_s \le 35$
Pelton four nozzles	$10 \le N_s \le 50$
Cross-flow (Banki-michell)	$20 \le N_s \le 200$
Francis	$50 \le N_s \le 350$
Kaplan and propeller	$200 \le N_s \le 1550$

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 (2 m) and up to (50 *m*), also the cross-flow impulse turbine can be used.

The cross-flow turbine is selected, designed, constructed and implemented in this research project.Once the turbine type is known, the fundamental dimensions of the turbine can be easily estimated.

D- Cavitation phenomenon [24**]:**When the hydro-dynamic pressure in a flow liquid falls below the vapor pressure of the liquid, there is a formation of the vapor 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 vapor 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 installat least at a height over the tailrace water level (Z) giving by the equation:$Z = H_{atm} - H_{vap} - \delta_T - H_n + \frac{V_e^2}{2g} + H_{DT}$ (6)

Where Z = the elevation above the tailrace (meters), H_{atm} = the atmospheric pressure head in (meters), H_{vap} = the water vapor 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, $\delta_T = 6.4 * 10^{-5} * (N_s)^{\wedge 1.46}$

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 it is under the downstream level and the turbine setting (installing) requiring an excavation.

To avoidcavitation, the following criterion must be satisfied in the design of the micro-hydro power plant:

$\frac{N_s}{995} \leq 0.686 * (\delta_T)^{0.5882}$	(7)

E- Generator selection [25**]:**

The hydro generators are an essential part of the system and their performance effect the overall micro-hydro power plant efficiency. The direct coupling turbine generator at the same mechanical speed will increase the system efficiency, save space in the hydro-power station, cancel the gear-box or pulley and belt, limit the lubricant utilization in the hydro-power station and reduce the system cost.The basic parameters to be considered in the selection of a suitable type of electrical generator are;

Type of desired output:A.C. or D.C, constant frequency or variable frequency.Hydraulic turbine operations mode.

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

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

In addition to this consideration, there is the economy that can be effect by choosing hydro-units of equal size, from the point of view of hydraulic equipment, penstock, draft-tube and construction details. The generator specifications for micro-hydro station can be obtained from the calculation of turbine output power. These specifications include mainly the rated power in Kilowatts, Kilovolt-ampere capacity, number of phases, frequency, connection of stator winding, voltage, current, power factor, speed, method of cooling, temperature rise, type of excitation, excitation voltage and machine reactance.

Run-of-river micro-hydro generators are low speed machines of salient-pole type, having a large number of poles, a large diameter and a short-rotor. The power factor for which the generator is designed up to (0.95) lagging. The generator speed is limited by the turbine speed, which depends on the specific speed of the particular type of the turbine. The main dimensions of the generator are the diameter, the air-gap and the length of the stator core. The output of the generator in (KVA) depends on these main dimensions and the speed of the machine. The general expression for the generator output power in (KVA) can be derived as:

$$f = {P * n}/{2}\ (H_z) \quad (8)$$

The generator frequency can be given as: Where P = number of magnetic poles, n = generator speed in (r.p.s)

The voltage per phase can be given as:$E_{ph} = 4.44 * K_w f N_{ph} \Phi_m \quad (volts)$ (9)

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

For 3-phase synchronous machine, the winding factor may be taken as (0.95), and the flux per pole is given by:

$\Phi_m = B * (\pi * D/P) * L(weber)$(10)

Where B = average flux density in air-gap (weber/m^2), D = stator diameter at the air-gap (m), L = core length (m)

The current per phase is given by: $I_{ph} = (\pi * D * a_c) / (6 * N_{ph}) \ (amperes)$(11)

Where a_c = number of ampere-conductors per meter of stator periphery.
Also, the output power of the 3-phase, A. C generator is given by: $S = 3 * E_{ph} * I_{ph} * 10^{-3} (KVA)$ (12)
Substituting equations (9-11) into (12) to obtain: $S = 10.4 * B * D^2 * L * n * a_c * 10^{-3} (KVA)$ (13)
For the micro-hydro power generator, the factor (a_c) is taken between (30000-43000) ampere-conductor per meter of stator periphery, and the air-gap flux density (B) is taken between (0.54-0.7) weber/m^2. When the ampereconductor per meter and flux density in air-gap have been chosen, the value of (D^2*L) for a given output power can be found from equation (13). The length L of the generator core can be taken as:

$L = 1.2 * \lambda(m)$ (14)

Where λ = pole pitch of the machine winding =$(\pi * D/P)(m)$ (15)

Then, substitute equations (14-15) into (13) to calculate the machine-stator diameter (D). The generator must be designed to withstand the full runaway speed of turbine under the maximum permissible head and water flow rate.In this research project, due to a low side head(about 2 meters) and Cross-flow turbine is used with 150 r.p.m output speed,the 3-phase 380 V,10 KW,750 r.p.m induction generator is used.The difficulty in obtaining a low speed standard 3-phase synchronous generator,which requires a special manufacturing.The power can be transmitted from the turbine to the generator by a gear-box or pulley and belt. Because of low cost and power loss,the pulley and belt are used as a speed increaser.

F-Power transmission and distribution lines [26]:

The measurements have been made in the distribution network from the micro-hydro power station to the isolated houses of the national grid of electricity. These measurements take into account the difficulty in creating a distribution network when houses are located at a considerable distance from each other. The voltage drop calculation for 3-phase distribution system is as follow: $V_d = \sqrt{3} * I * R * L / CM \ (volts)$(16)
Where R = (12.9 Ω for copper wire) or (21.2 Ω for aluminum wire) resistance constant for a conductor that is (1) circular mill in diameter and (1) foot long at an operating temperature of (75 ℃), L = length of the distribution line from the micro-hydro power station to the load site in (feet), I = load current in amperes, CM = conductor wire size in Circular-Mills.
Or the voltage drop of the 3-phase distribution system can be calculated as: $V_d = I * (R * \cos(\theta) + I * X * \sin\theta volts$ (17)

Where: $R = \rho * L/A$ (Ω)resistance of the line, ρ = resistivity of the conductor material type (Ω.m), A = conductor cross-sectional area (m^2), L = length of the distribution line (m), and x is inductive – reactance of the line and can be calculated as: $X = 0.145 * \log_{10}\left(\frac{GMD}{GMR}\right) * L(\Omega)$
In case of medium voltage lines (11 KV), this reactance must be considered, while in low voltage lines (220 / 400 V), this reactance can be neglected.

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

Over-head transmission/distribution lines shall be of ACSR or Aerial Bundled Cables with pole height sufficient to observe (5) meters minimum ground clearance. Armored cables are required for under-ground transmission lines with at least (0.5) meter depth of burial along the land.
The surge arrestor should be mounted on the first transmission line pole and may be connected to the power house earth system. The earth system conductor must be at least (25) mm^2 cross-sectional area of copper wire. Under all loading conditions,as far as the input power is sufficient to meet the active load connected to the generator, the voltage regulator (AVR) shall maintain steady state voltage deviation within -5% and +5% of nominal value.

In this project,due to a short over-head transmission line is implemented and the calculated voltage drop of the line is within the permissible range,the project is not required a step-up power transformer. The transformer will increase the line losses and the project cost. The 3-wires of the line consist of aluminum alloy with 70 mm^2 cross – sectional - area and the fourth wire for neutral with 50 mm^2 cross-sectional-area.

G- Power house [27**]:**

Power house shall be located at an elevation well above any known flood water level of the stream.Dueto the presence of large and heavy equipment units, the power house stability must completely secure. 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 is turbine, electrical generator,electrical board control and drive systems.

H- Speed increaser [4, 17**]:**

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.
Turbine manufacturers 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. In this project,the 3-phase,(750) r.p.m.,induction generator is selected. Comparing of a gear-box with the pulley and belt for transmitting of power,the gear-box has high cost and power loss. Pulley and belt are used as a speed increaser to transfer the rotation from the turbine to the generator and to increase the speed abovethe synchronous speed.

I- Rotational and runaway speed [22**]:**

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. Table (3) shows this ratio for various turbines. The cost of generator and gear box may be increased when the runaway speed is higher, since they must be designed to withstand it.

Table (3) ratio of runaway speed for different turbines

Turbine type	Normal speed (*r.p.m*)	Runaway speed (N_{max}/N)
Kaplan single regulated	75-100	2-2.4
Kaplan double regulated	75-150	2.8-3.2
Francis	500-1500	1.8-2.2
Pelton	500-1500	1.8-2.0
Cross-flow	60-1000	1.8-2.0
Turgo	600-1000	2

J- 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:$t_r = {Wt * r^2 * N^2}/{(91270 * P_t)}$ (sec.)(18)

Where Wt = weight of all the rotating parts (*Kg*), r = radius of gyration (*m*), N = turbine speed (*r.p.m*), and 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:

$$t_w = {(L_p * V_p)}/{(g * H_g)} \quad (sec.) \tag{19}$$

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

To achieve good regulation, it is necessary that $t_r/t_w > 4$. The water starting time is not exceeded (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 improve the water hummer effect and decrease the runaway speed.

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

$$Loadfactor = \frac{Energygeneratedperyear\ (KWH/year)}{Installedcapacity(KW) * 8760} \quad (20)$$

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

$$E = \rho * g * Q * H_n * \eta_{turbine} * \eta_{generator} * \eta_{gearbox} * \eta_{transformer} * n \quad (21)$$

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, and n = number of hours in year for which the specified flow occurs.
Table (4) shows the variation of the load factor with the designed water flow rate (Q).

Table (4) Variationofthe load factor with the designed water flow- rate

Design flow (Q)	Load factor
100% Q	40%
0.75 * Q	50%
0.5 * Q	60%
0.33 * Q	70%

III. DesignstepsandMat lab Simulinkflow-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- Riverorstreamarea (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_w) in (Kg/m^3).p- Gravity constant (g) 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(B) ($N.m/(rad./sec.)$).
2- Calculation of water flow rate (Q) in (m^3/s).
3- Calculation of rectangular weir and open channel dimensions (width (w) and height (h) in (m)) .
4- Calculation of an open channel bottom line slope (S_{ch}).
5- Calculation of an open channel hydraulic radius (Rch).
6- Calculation of an open channel water flow velocity (V_{ch}) in (m/s).
7- Calculation of penstock inlet velocity (V_p) in (m/s) from the following formula:

$$V_p = \frac{Q}{A_p} = \frac{4 * Q}{\pi D_p^2} \quad (m/s) \quad (22)$$

Where A_p = penstock area (m^2), and D_p = penstock diameter in (m).

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

$$H_n = H_g - (H_{ch} + H_{tr} + H_{en} + H_v + H_p) \quad (23)$$

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

$$H_{ch} = \left[\frac{Q * n_{ch}}{A_{ch} Rch^{2/3}}\right]^2 * L_{ch} \text{ open channel loss in } (m) \quad (24)$$

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

$H_{tr} = K_{tr} * \left(\frac{t}{b}\right)^{4/3} * \frac{V_{ch}^2}{2g} * Sin(\alpha)$ trash rack loss in (m)	(25)
$H_{en} = K_{en} * \frac{V_p^2}{2g}$ entrance loss in (m)	(26)
$H_v = K_v * \frac{V_p^2}{2g}$ valve gate loss in (m)	(27)
$H_p = \frac{10.29 * n_p^2 * Q^2}{D_p^{5.33}} * L_p$ penstock friction head loss in (m)	(28)

9- Calculation of the turbine power in (watt) from equation (1).
10- Calculation of turbine speed (N) in ($r.p.m$) from the solution of motional differential equation (2).
11- Calculation of specific speed (N_s) in ($r.p.m$) from equation (5).
12- Selection of turbine type from the comparison of calculated specific speed (N_s) and net head (H_n) with those given in tables (1) and (2).
13- Calculation of turbine dimensions according to the type of turbine which obtained from the previous step.
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 (23).
Then steps (9) to (13) will be repeated to take the effect of cavitation into account.
The flowchart of the whole Matlab Simulink program including the design steps is prepared in figure (2).
15- Calculation of generator dimensions from equations (8) to (15).
16- Calculation of transmission line voltage drop from equation (16) or (17).

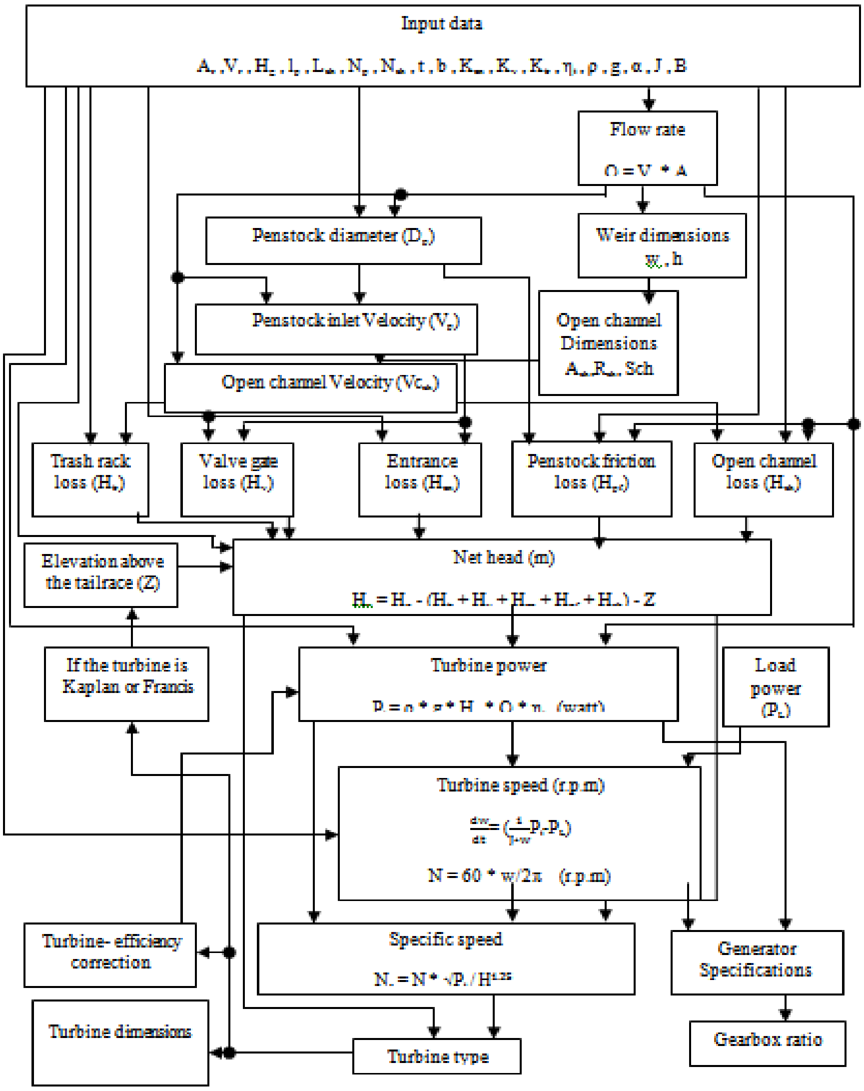


Figure (2) Flow-chart of the Matlab Simulink Program

IV. Experimental Rig

To verify the theoretical design procedure of micro-hydro-electric power station an experimental rig was designed and installed across small river. Sited data and specifications of the micro-hydro power station components were given as follow:

Site head = 2 m,water flow = 0.5 m^3,concrete channel length = 20 m,water density =1000 Kg/m^3, penstock length= 15 m, penstock diameter = 50 Cm, turbine type = Cross-flow (Banki-Michell) with the following specifications; outer diameter =35 Cm,inner diameter =23Cm, speed at maximum efficiency = 150 r.p.m , runner length = 1.2 m ,number of blades =18 ,nozzle width(water jet thickness) =10 Cm.

The 3-phase self-excited stand-alone induction generator is used in this project with the following specifications; 10 KW,380 V,21 A, 750 r.p.m, Y-connected,capacitor bank with 120 micro-faradcapacitance for self-excitation.

The induction generator is a type of A.C. electrical generators that uses the principles of induction motor to produce an active power. A prime mover(micro-hydro-turbine) drives the rotor above the synchronous speed. The presence of residual magnetism produces a stator flux. A relative motion between the rotor and stator flux is achieved. The stator flux induces current in the rotor conductors which gives rise to the rotor flux. The rotor flux cuts the stator coils, an active current is produced in stator coils and the machine now operates as a generator. However, a source of excitation current for magnetizing flux (reactive power) for stator is still required to induce rotor current[28].

A capacitor bank is used to supply the reactive power to the generator when it used as self-reactive power that the machine normally draws when it operates as a motor. The terminal voltage will increase with the capacitance, but it is limited by the iron saturation.

Since the induction generator is actually an induction motor being driven by a prime-mover, it has several advantages when is compared with the synchronous generator as:

It is less expensive and more readily available than a synchronous generator.

It does not require a D.C. field excitation voltage.

Its control is simpler and less expensive.

It is robustand brushless construction.

It is ruggedness, ease of maintenance, absence of D.C. power supply for excitation.

It is better transient performance, self – protection against short – circuits and large over – load.

It operates as autonomous generator from a renewable energy source such as hydro-turbine to supply for ordinary growing energy demand loads in mainly rural areas owing to many economically advantages.

For self-excitation to be occurs, the following conditions must be satisfied:

The rotor of the machine should have sufficient residual magnetism.

The 3-phase capacitor bank should be of a sufficient value. The minimum capacitance value. The minimum capacitance value can be calculated as[29]:

C_{min} = 1/ (W_r ^2*Lm).(29)

Where W_r = rotor speed of the generatorin electrical radian per second,Lm = magnetizing inductance of the machine and can be calculated from the no-load test of the machine.

A precise calculation of the capacitance required to generate a given voltage under a specific load is only possible with knowledge of the electrical parameters of the induction machine in question. These parameters can be obtained by means of a number of standard tests. In practice it is sufficient to calculate an approximate value of excitation capacitance and adjust the hydro turbine speed until the required system voltage is obtained. This will mean that the operating frequency may differ from the rated frequency of the induction machine, which is acceptable provided that the frequency is kept within reasonable limits.

A simple method for an approximate calculation of the required excitation capacitance uses manufacturer's data from the machine plate can be calculated as:

$S = \sqrt{3} * V_l * I_l$ Total power of the machine (30)

P = S*cos(θ) Active power of the machine (31)

Q = $\sqrt{S^2 - P^2}$ Reactive power of the machine (32)

Qph= Q/ 3 Reactive power per phase (33)

Iph= Qph / Vph Reactive phase current (34)

The necessary capacitance per phase can be calculated as:

Cph= Iph / (Wr * Vph) (35)

$Vph = V_l/\sqrt{3}$ For star connection machine (36)

$Vph = V_l$ For delta connection machine (37)

V. 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(9) shows the variation of turbine type, turbine power and turbine dimensions with head at different values of water flow rate. The Cross-Flow turbine was used for low head and low flow rate(up to-0.8m^3/s),while Kaplan turbine was used for medium head and flow rate. Figure (10) shows the variation of turbine power with head for Pelton turbine. Pelton turbine was used for high head and very low flow rate. Figure (11) shows the variation of generator power with generator diameter at different values of speed.It can be shown that the generator –stator diameter was inversely proportional with the generator speed.

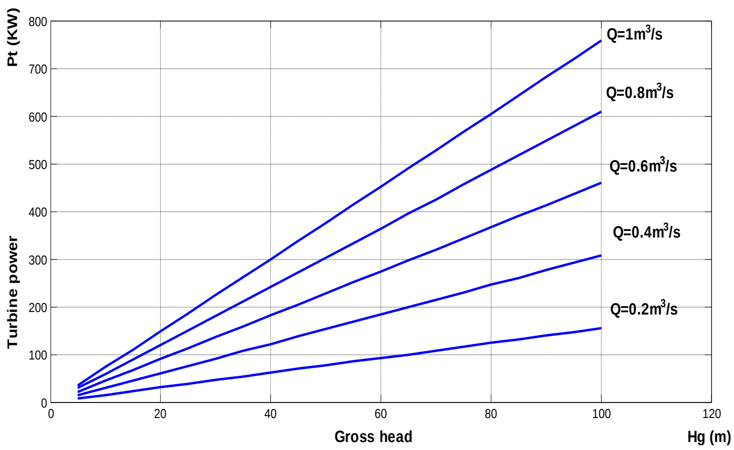


Figure (3) Variation of turbine power with gross head at different values of water flow rate

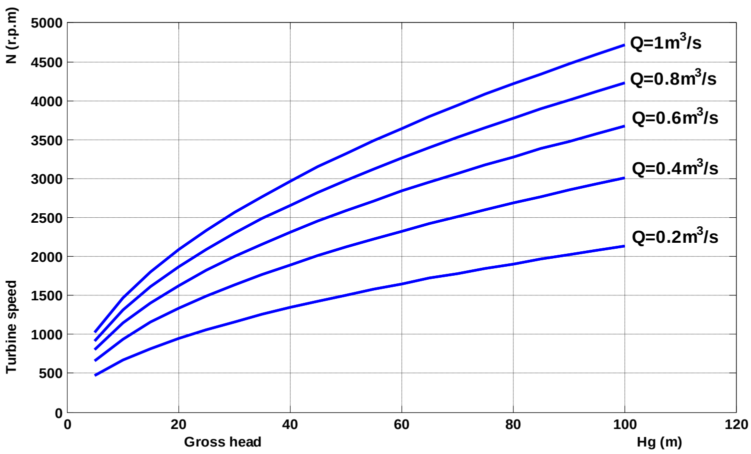


Figure (4) Variation of turbine speed with gross head at different values of water flow rate

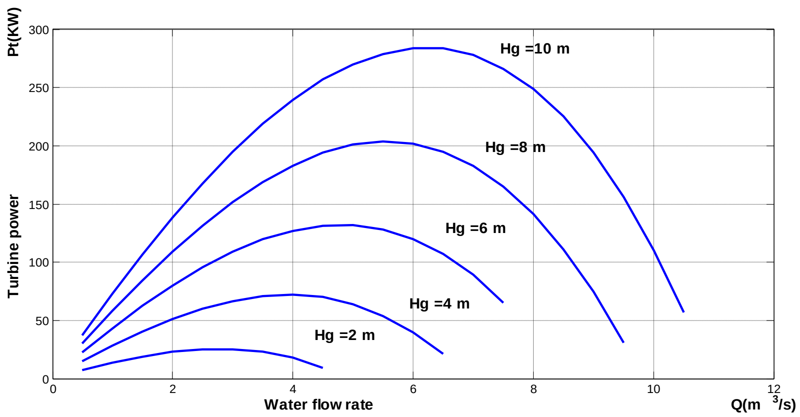


Figure (5)Variation of turbine power with water flow rate at different values of gross head

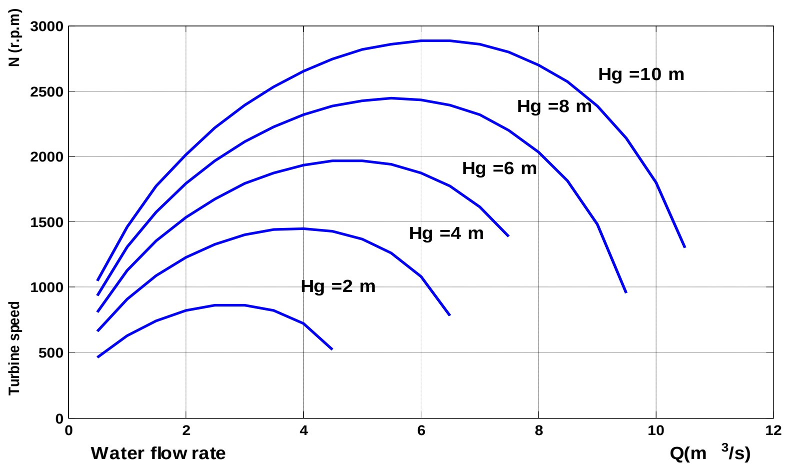


Figure (6) Variation of turbine speed with water flow rate at different values of gross head

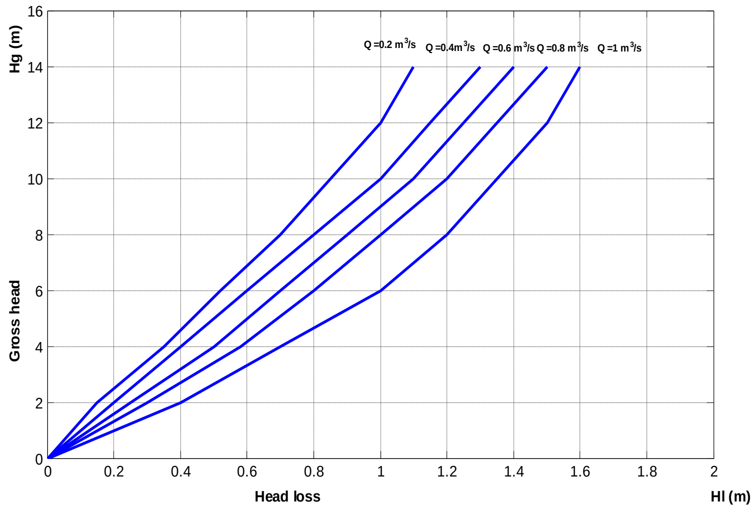
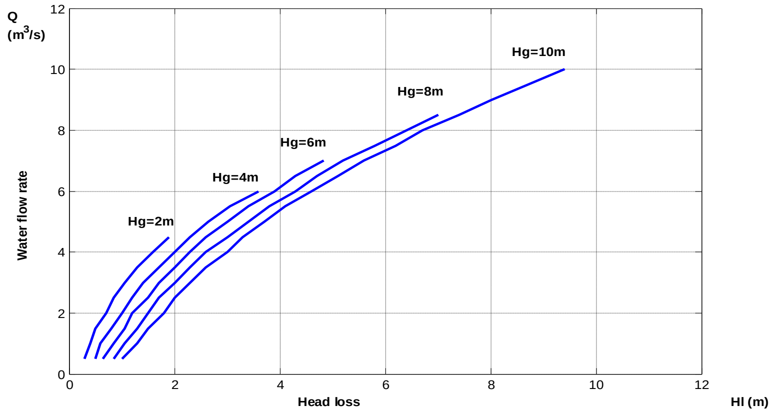
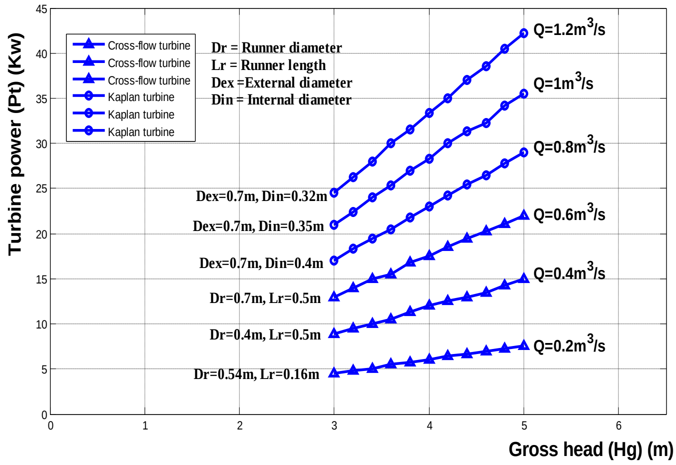


Figure (7)Variation of gross head with head loss at different values of water flow rate



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



Figure(9) Variation of turbine power with head for Cross-Flow and Kaplan turbines at different values of dimensions and water flow rate

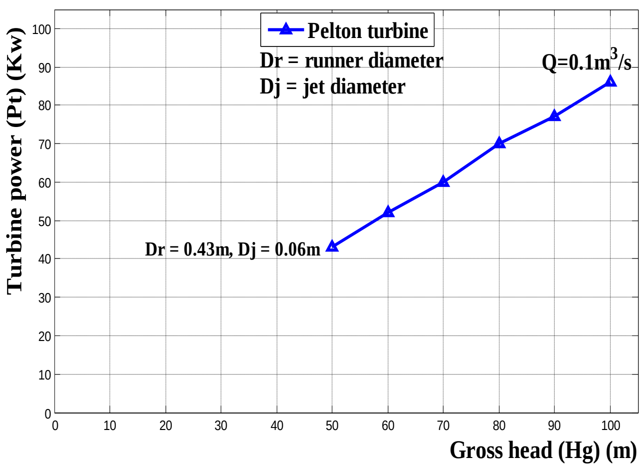


Figure (10) Variation of turbine power with head for Pelton turbine

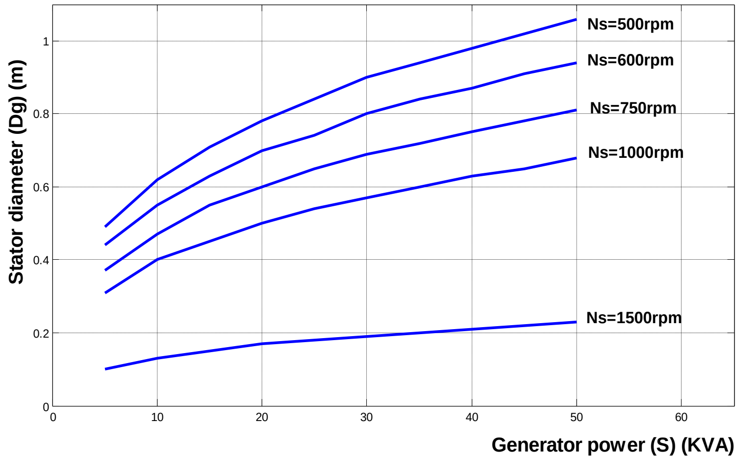


Figure (11) Variation of generator – stator diameter with power for different generator speeds.

VI. Conclusions and Outcomes

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 cease.

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. 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. An alternative is to convey the water by a low-slope canal, running a long side the river to the pressure intake or fore-bay 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- 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.

VI- 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.

VII- 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 downstream. In a high head (greater than 50 m) and low water flow (lessthan-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.

VIII- 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.

IX- The cross-flow turbine is suitable for installing small hydro-electric power plants in case of low head and flow rate. A complete design of such turbines has been presented in this paper. The maximum efficiency was found to be 88% constant for different values of head and water flow rate. The complete design parameters such as runner diameter, runner length,water-jet thickness, blade spacingradius of blade curvature, turbinepower,turbinespeed and number ofbladeswere determinedat maximumturbineefficiency.

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

XI- It is noted that slow–speed generator requires a large (D^2*L) for a given generator power. They are typically shaped like a disk (large diameter and small axial or stator core length). From the electrical view point, slow-speed machines are considered to have lower internal reactance, high short circuit currents, small angular change in rotor position can cause large power swings and requiring good protection against faults occurring near the machineterminals.Due to a difficult in manufacturing low speed synchronous generator to be used in the project site, the standard (400 V, 8-poles,50 Hz,750 r.p.m.) inductionmachine is used as induction generator in the project implementation.

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

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