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Research Article

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A Bizarre Design and Engineering physics of small/micro and Pico/family hydro-electric power plants/farms

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Abstract The bizarre design and engineering physics of two kinds of small/medium/pico/family hydro-electric power generating plants/farms have been analysed. One utilizes a stream/river with a dam constructed so that the water falls from a height and turn a turbine while, the other maximizes the energy of a falling mass of water from a reservior at a particular height to also turn a turbine. The latter, in addition uses a solar pump to raise the water from a receptacle at the ground level back to the elevated reservior and it can also make use of a public water supply, running at high pressure to raise water to the reservior. Also, employing the relevant engineering physics, a mini power plant/farm has been designed with calculations on how to generate about then thousand watt (10000W) of electricity.

Keywords Design, Engineering physics, Small/medium, Pico/family, hydro-electric power plant/farm.

Introduction

There are many sources of energy that are renewable and considered to be environmentally friendly and harness natural processes. These sources of energy provide an alternative cleaner source of energy that is not hazardous or harmful to the ecosystem. These power generation techniques are described as renewable since they are not depleting any resource to create their energy. While there are many large-scale renewable energy projects and production, renewable technologies are also suited to small off-grid applications, sometimes in rural and remote areas, where energy is often crucial in human development [1].

Some of these energy sources that are renewable are: tidal energy, wave power, photovoltaic (PV), solar power, wind power, hydroelectricity, radiant energy, geothermal power, Biomass, Compressed Natural, Gas, Nuclear Power. However, nuclear power, Gas, Compressed natural gas and geothermal power are not clean sources [2].

In the world today, there is a climatic change resulting in an unfriendly globe due to some harmful human activities. More so, now more than ever before there is a greater demand for power. Nearly every technological apparatus requires power for its optimal performance. Old harmful/hardazous/ecoenemy power technologies today are folding up due to their devastating byproducts e.g. nuclear power, geothermal and gas power generating technologies.

Today, friends of the globe are seeking renewable, safe and even low cost efficient technologies to generate power. Every hour new power technologies are innovated in our scientific universe. Most of these technologies are for small or medium power production, to solve perenial power problem.

One of the renewable and safest technologies of producing power is the hydroelectric power generation technology. This technology as well is facing a lot of roadblocks due to to the present global climatic changes. Some streams or rivers for the technology are running low or dry; affecting outputs. More so, seasonal changes in water level is also a heavier barrier. Worth mentioning as well is that its establishment is capital consuming.

Nigeria today is at the summit of a power crisis. Even with eco-enemy technologies like geothermal/gas plants, our power generating capacity is below four (4) Giga Watt (GW). This energy supply is far below our national power demand. So much volume of money is poured into transportation (transmision) of power several kilometers through the national grid before distribution: an economic waste, in a dark hour of the global economy.

Nigeria sits in an ocean of power fountains (sources), but we thirst for it. Perenial power problems have struck a huge force on our engine/machinery of civilization. Some governments in the country have nursed the idea of opening a nuclear power farm, even when more technologically advanced nations in Europe and the Americas are closing theirs up.

The purpose of this research paper is to design a small/medium scale, safe and cost effective power generation plant using any flowing stream/river or a public water supply.

Basics of Hydro-electric power generation

Hydroelectricity is the term referring to electricity generated by hydropower; the production of electrical power through the use of the gravitational force of falling or flowing water. It is the most widely used form of renewable energy, accounting for about 16 percent of global electricity generation [3].

A mass of water moving down a height difference contains energy which can be harvested using some waterwheel or turbine. The moving water drives the waterwheel and this rotation either drives machinery directly (e.g. mill, pump, hammer, thresher etc.) is coupled with a generator which produces electric power [4].

Hydro power is probably the first form of automated power production which is not human / animal driven. Moving a grind stone for milling first, developed into the driving of an electrical generator. Next to steam it was for long the main power source for electricity. Its continual availability does not require any power storage (unlike wind / solar power). It is mainly mechanical hardware. This makes it relative easy to understand and repair-/maintainable. In smaller units its environmental impact becomes neglect-able [4].

The cost of hydroelectricity is relatively low, making it a competitive source of renewable electricity. The average cost of electricity from a hydro station larger than 10 megawatts is 3 to 5 U.S. cents per kilowatt-hour. It is also a flexible source of electricity since the amount produced by the station can be changed up or down very quickly to adapt to changing energy demands. However, damming interrupts the flow of rivers and can harm local ecosystems, and building large dams and reservoirs often involves displacing people and wildlife. Once a hydroelectric complex is constructed, the project produces no direct waste, and has a considerably lower output level of the greenhouse gas carbon dioxide (CO_2) than fossil fuel powered energy plants; hence it is eco-friendly [3].

Types of hydro power plant/farm in regard to capacity

The following are the various classification of hydro power plant/farm in regard to their generation capacity.

Large hydro: these are hydroelectric power stations that are more commonly seen as the largest power producing facilities in the world, with some hydroelectric facilities capable of generating more than double the installed capacities of the current largest nuclear power stations. Although no official definition exists for the capacity range of large hydroelectric power stations, facilities from over a few hundred megawatts are generally considered large hydroelectric facilities [3].

Small hydro: this is the development of hydroelectric power on a scale serving a small community or industrial plant. The definition of a small hydro project varies but a generating capacity of up to 10 megawatts (MW) is generally accepted as the upper limit of what can be termed small hydro. Small hydro stations may be connected to conventional electrical distribution networks as a source of low-cost renewable energy. Alternatively, small hydro projects may be built in isolated areas that would be uneconomic to serve from a network, or in areas where there is no national electrical distribution network. Since small hydro projects usually have minimal reservoirs and civil construction work, they are seen as having a relatively low environmental impact compared to large hydro [3].

Micro hydro: this is a term used for hydroelectric power installations that typically produce up to 100 kW of power. These installations can provide power to an isolated home or small community, or are sometimes connected to electric power networks. There are many of these installations around the world, particularly in developing nations as they can provide an economical source of energy without purchase of fuel. Micro hydro systems complement photovoltaic solar energy systems because in many areas, water flow, and thus available hydro power, is highest in the winter when solar energy is at a minimum [3].

Pico hydro: this is a term used for hydroelectric power generation of under 5 kW. It is useful in small, remote communities that require only a small amount of electricity, for example, to power one or two fluorescent light bulbs and a TV or radio for a few homes. Even smaller turbines of 200-300W may power a single home in a developing country with a drop of only 1 m (3 ft). A Pico-hydro setup is typically run-of-the-river, meaning that dams are not used, but rather pipes divert some of the flow, drop this down a gradient, and through the turbine before returning it to the stream [3].

Family hydro: this is a term for hydro power generation of less than 1 kW. It uses single households/clusters connection, often locally handmade solutions and professional equipment [4].

Design of the small/micro and Pico/family hydro plants/farms

The Figs. 1 and 2 below show the diagram of small/micro and Pico/family hydro plants/farms respectively. The difference in the designs is based on some factors that include the power generation capacities, cost and availability of river/stream and in addition to the afore-mentioned; head/flow of river/stream. Also figs. 3 and 4 show a 3-d design of the hydro power plants'/farms' turbine and a water splash guard with the turbine inside respectively.

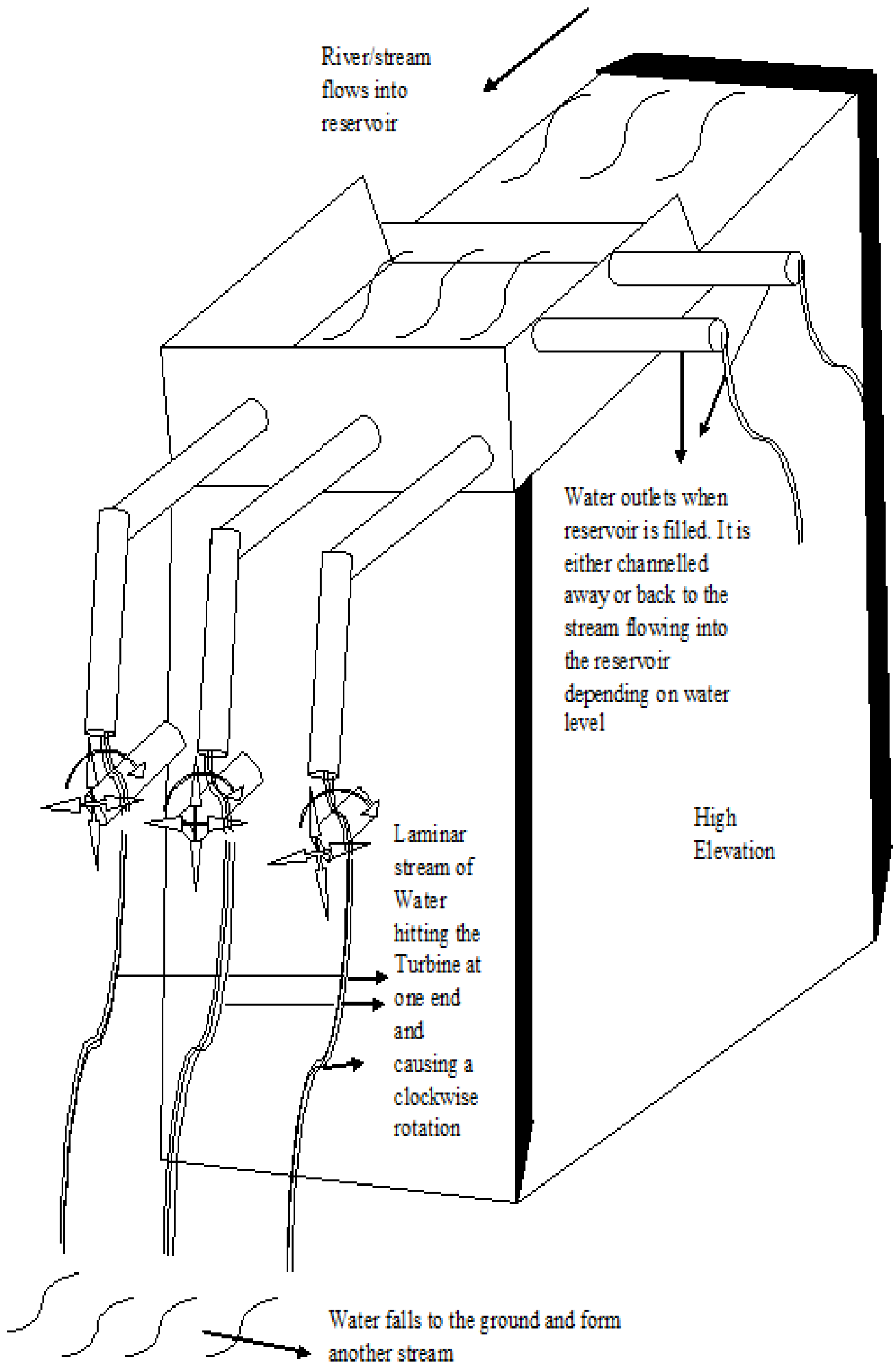

Figure 1: Diagram of the design of a small/mini hydro power plant/farm

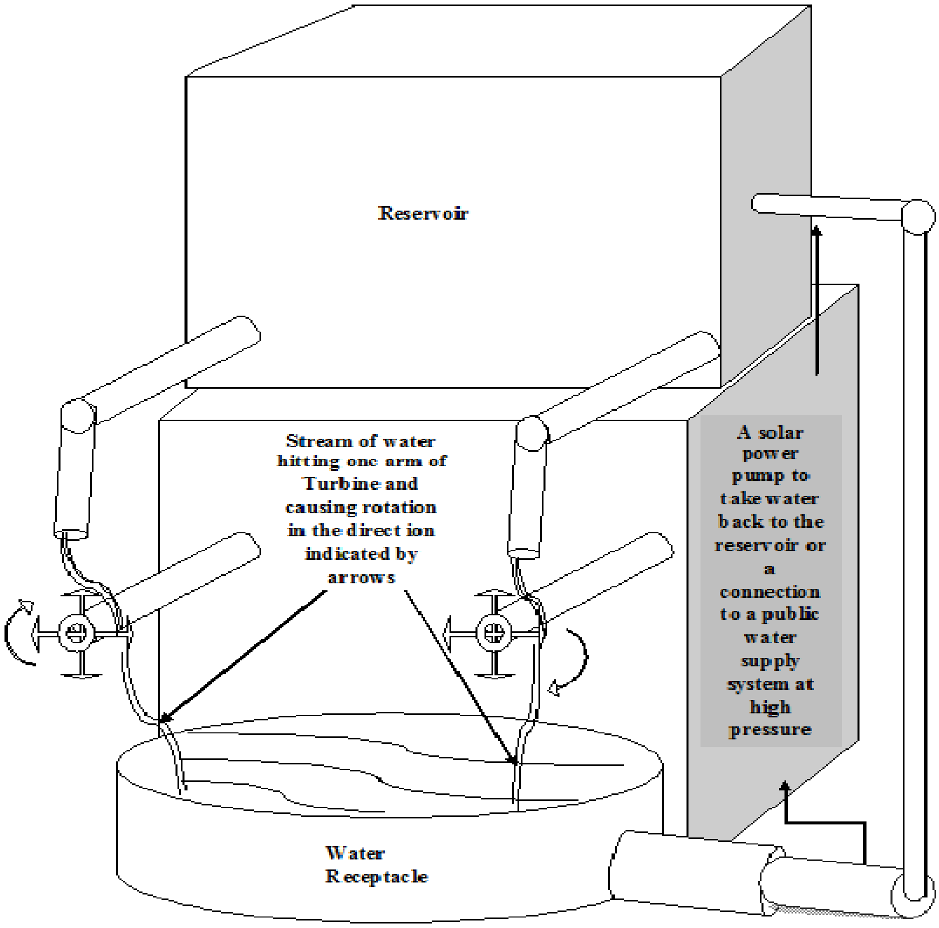

Figure 2: Diagram of a Pico/family hydro power generation design

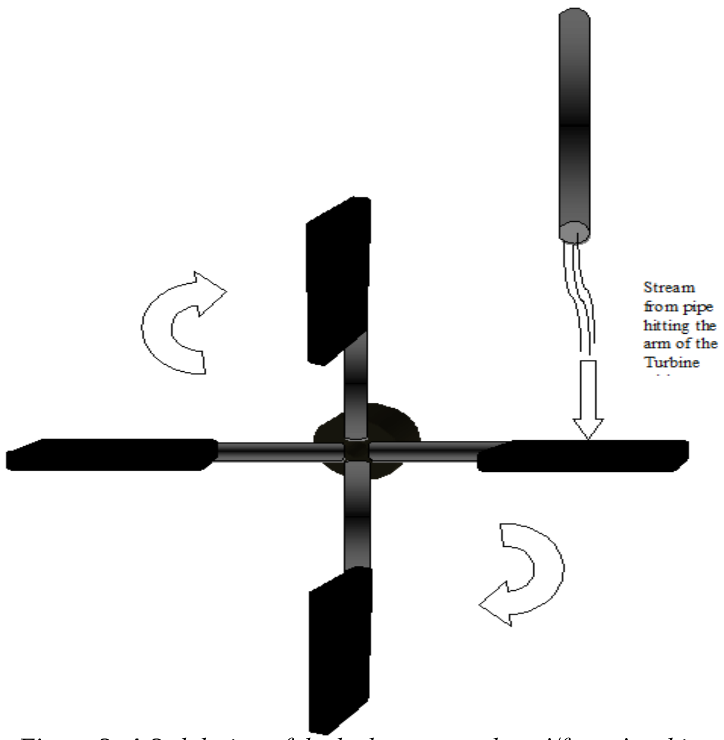

Figure 3: A 3-d design of the hydro power plants'/farms' turbine

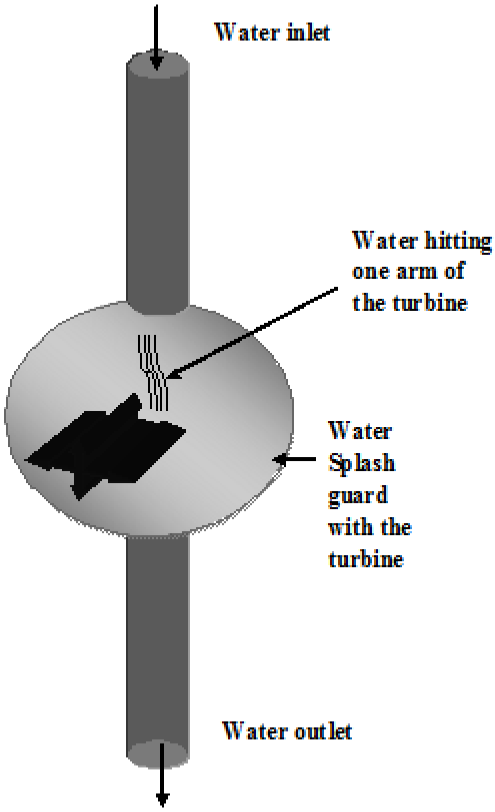

Figure 4: A water splash guard with the turbine inside

The working principle of the designed hydro power plants/farms

In Fig. 1, the river/stream flows into a reservoir and it is channelled by pipes to the turbine. As the water falls from a high elevation, the gravitational force from the water hits the turbine and causes a rotational motion by virtue of the torque created by the arms of the turbine. The mechanical energy/power generated is harnessed and converted to electrical energy/power with the aid of a generator. The process is continuous as the river/stream flows at a sufficient speed.

In Fig. 2, the water from the reservoir falls through the channels at a particular height. The falling mass of water is channelled by a pipe to strike an arm of the turbine with a force. The force generates a torque that turns the turbine. The mechanical energy/power generated is harnessed and converted to electrical energy/power with a generator. The process is continuous as longs as the water does not run dry in the reservoir. The turbine is domiciled in a guard to prevent the mass of falling water striking the turbine to be lost through splashes. The design of the guard is a shown in Fig. 4. The major challenge here is how to raise the water collected by the receptacle to the reservoir. A solar pump may be used to power the lifting of the water back to the reservoir any time it runs low/dry. Also, water from a public water supply system, running at a very high pressure can be channelled to the reservoir. In this case, whenever, the water is used in by consumers, the turbine turns and generates electricity. Since the flow of water in this case may not be continuous, energy from other sources may be used to supplement power generation capacities and an AC to DC converter (rectifier) is employed so that the excess energy at a particular moment could be saved and conserved for use when needed. However this technology is not really efficient.

The Engineering physics of a small/mini and Pico/family hydro plants/farms

The water falling from the tank has a pressure $P = \rho gh$

Where ρ = Density of the water

g = Acceleration due to gravity and

h = Height/length of the pipe channelling water to the turbine

However, P = F/A

Where F = Force of the water hitting the arms of the turbine and

A = Area of the pipe

Hence, the force of water hitting the arm of the turbine to cause the torque

$F = PA = \rho ghA$
The torque generated $T = rF\sin\Theta$ [5]
Where F = Force of the water hitting the arm of the turbine
r = Radius of the turbine (Distance of one arm of the turbine to the centre).
Since Ө is changing with time as the force of water impacts any arm of the water. For a four arm turbine as seen in the design shown in Fig. 3, the angle Ө varies from about 45^0 to 135^0 before the impact between the mass of water and arm of the turbine ceases (partially inelastic collision). Hence, the torque as well varies with time.
Therefore: $dT/dt = rF\, d\sin\Theta/dt$
Therefore $dT/dt = rF \cos\Theta d\Theta/dt$: but $d\Theta/dt = \omega$
Hence $dT/dt = rF\omega \cos\Theta$: $dT = rf\omega \cos\Theta dt$, but $\Theta = \omega t$
Therefore Average $T = rF\omega \int_{45}^{135} \cos\omega t dt$ Hence Average $T_{avg} = rF\omega\ (1/\omega)\, [\sin\Theta]_{45}^{135}$ = rF[sin 135 – 45] = 0.76253484 rF
But Power $P = 2\Pi T_{avg}\, \omega = 2\Pi m\omega^2 r\, \Theta r/t$ [i.e. Fs/t: s = length of the arc = Өr and t = time = Ө/ ω]
This implies, $P = 2\Pi\ T_{avg}\, \omega = 2\Pi\ m\omega^2 r\ \Theta r \times \omega/\ \Theta = 2\Pi\ m\omega^3 r^2$
Where T_{avg} = Average Torque
ω = Angular velocity (rad/s or rev/s)
m = Mass of one arm of the turbine
From the equation above, an increase in the radius of the arm of the turbine in other to increase the torque will reduce the angular velocity and hence the power.
Also power P = Workdone/time = Fh/t = mgh/t
Where m = Mass of the water hitting the arm of the turbine
t = Time of impact of the mass of water
Hence, $P = \rho vgh/t$, since $m = \rho v$
And $P = \rho Qgh$, since $Q = v/t$
Where v = volume of the water in the pipe
Q = Quantity of the flowing water
The velocity of the flowing water can be determined from the law of conservation of mechanical energy.
Potential energy (P.E) per unit volume = Kinetic energy (K.E) if no loss of energy by the water in course of running through the pipe per unit volume
Thence, $\rho gz = 0.5\rho V^2$ and $V = \sqrt{(2gh)}$
Where h = The height of the pipe
But since it is flowing through a pipe, it experiences some loss in velocity, thence the equation above is $V = C_{vl} \sqrt{(2gh)}$ [5]
Where C_{vl} = The coefficient of loss through the pipe (friction and bending pipe).
But the mass of water hitting the arm of the turbine $m = F/g = \rho ghA/g = \rho hA$ where hA = v
Hence, the mass of water hitting the arm of the turbine depends on the height of the pipe and the area of the pipe channelling the water to the turbine.
From Newton's second law
Impact/impulse = $F\Delta t_{im} = m\Delta V$
Therefore the time of impact/impulse with the arm/arms of the turbine $t_{im} = \Delta t = m\Delta V/F$, since $\Delta t_{im} = t_f - t_i$ and $t_i = 0$; but $\Delta V = V - \omega r$. Where ω = Angular velocity of the turbine and r = Radius of the circumference formed by the arms of the turbine.
$t_{im} = \rho hA \times ((C_{vl}\sqrt{2gh}) - \omega r)/\rho ghA = ((C_{vl}\sqrt{2gh}) - \omega r)/g$
Also the impact time t_{im} between the angles 45^0 to 135^0 where the water hits one arm of the turbine before switching to the subsequent arm is $t = \Delta\Theta/\omega$ but $\Delta\Theta = \Theta = s/r$
Where s = Length of the arc the end of the turbine travels
r = Distance from one arm of the turbine to the centre
Hence $t_{im} = s/r\omega$
The power loss in the course of change from the linear motion of water to rotational motion of the turbine $P_{loss} = \Delta P = \rho Qgh - T_{avg}\, \omega$
The efficiency of the turbine $E = T_{avg}\, \omega/(\rho Qgh) \times 100\%$
In the generator, the magnitude of the emf generated $E = d\phi/dt = d(NAB\cos\Theta)/dt$
Where N = Number of turns of the coil
ϕ = Flux through the coil of the generator
A = Area of coil
B = Magnetic field strength (proportional to the size of the magnet).

It implies emf = NAB d(cosϴ)/dt = NABsinϴdϴ/dt but dϴ/dt = ω
Therefore emf = NABωsinϴ but ω = ϴ/t, but ϴ = ωt
Hence magnitude of emf generated is NABωsin ωt
This equation shows that the performance of the generator is a function of the angular velocity of the turbine, number of turns of coil, magnetic field intensity (proportional to the size of the magnet) and area of the coil.
But from ohms law, emf = I_0sinϴ R = RI_0sinϴ
Where R = Resistance of the coil
I_0 = Peak value of current
Recall ϴ = ωt
Hence: emf generated = RI_0sinωt
Therefore the peak value of current generated is I_0 = emf/(R sinωt)
The frequency of the wave generated is gotten from F = ω/2Π. The frequency of the output can be adjusted. It is a function of the angular velocity.
Power output by the generator = $(emf)^2$/R = $(I_0)^2$R$\sin^2$ϴ
The overall power gain or loss of the system is P_{og} or P_{0l} = $(I_0)^2$R$\sin^2$ϴ - ρQgh
When $(I_0)^2$R$\sin^2$ϴ > ρQgh; the system gained power
But, when $(I_0)^2$R$\sin^2$ϴ < ρQgh; the system lost power
The overall efficiency of the system is P_{og} or P_{0l}/ (ρQgh) × 100%
A point of note is: when efficiency is beyond 100%, the there is a power gain by the system.
Also, The power gain or loss between the turbine and generator is P_g or P_l = $(I_0)^2$R$\sin^2$ϴ - 2 ΠT_{avg} ω.
Similarly: when $(I_0)^2$R$\sin^2$ϴ > 2 ΠT_{avg} ω; there is a power gain by the generator
But, when $(I_0)^2$R$\sin^2$ϴ < 2 ΠT_{avg} ω; there is a power loss by the generator
Hence: the efficiency between the turbine and generator is P_g or P_l/ 2 ΠT_{avg} ω × 100%.

Other important Engineering Physics worthy of note in the Design
For the hydro plant/farm utilizing a river: from continuity equation
$A_1 V_1 = A_2 V_2$
Where A_1 = Cross-sectional area of the pipe
A_2 = Cross-sectional area of the face of the reservoir supplying water to the pipe
V_1 = Velocity of the water through the pipe
V_2 = Velocity of the flow in the reservoir from the river
Hence: A_1 = Πr^2 where r is the radius of the pipe
A_2 = B h_{wt} where B is breath of the reservoir's face and h_{wt} is the height of the water in the reservoir.
Thence, Πr^2 V_1= B h_{wt} V_2: Therefore; V_1 = B $h_{wt}V_2$/ Πr^2
The above equation shows that the speed of the water flowing through the pipe depends on the height of the water in the reservoir and breath of the reservoir.
From the law of conservation of linear momentum
The collision between the water and turbine is partially inelastic [6].
$M_t U_t + M_w U_w = V_{tw} (M_t + M_w)$
Assuming initially, the velocity of the turbine U_t is zero
Hence $V_{tw} = M_w U_w/(M_t + M_w)$: but $V_{tw} = \omega r$
Therefore $\omega = M_w U_w/(M_t + M_w) \times 1/r$
The point worthy of note is that to increase the angular velocityω, the speed of the water in the pipe must be increased, but the mass and radius of the turbine must be reduced.
Also, as in Fig. 1, there are three outlets channelling water from the reservoir to the turbine. From the continuity equation, it can be derived that:
$AV = A_1V_1 + A_2V_2 + A_3V_3$
Where: A is the Cross-sectional area of the face of the reservoir supplying water to the pipe
V is the Velocity of the flow in the reservoir from the river
A_1, A_2 and A_3 are the Cross-sectional areas of the pipes (either of similar or different radius).
V_1, V_2 and V_3 are the velocities of water in the pipes
Hence; an increase in the number of pipes channelling water from the reservoir leads to a decrease in the velocity of the water flowing through the pipes, assuming the cross-sectional areas are constant.

The design of a 10 KW mini plant
Power output by the generator = $(emf)^2$/R = 10000 W
Hence emf = $\sqrt{10000R}$ = 100$\sqrt{R}$
But emf = NABωsin ωt = 100$\sqrt{R}$

Assuming N = 100 Turns: B = 1 Tesla and the resistance of the coil is 25 Ohms
Also, assuming we are considering the peak value of the emf, when $\omega t = 90^0$
Also; if the radius of the coil is 0.2 m then $A = \Pi r^2 = 0.04\Pi\ m^2 = 0.13\ m^2$
Therefore to get an output of 10000 W with the above measured parameters;
ω must be equal to $100\sqrt{R}$ / NAB = $100 \times \sqrt{25} /100 \times 0.13 \times 1 = 38.46$ rads/sec
At equilibrium: assuming no loss of force in the course of translation from gravitational force to centripetal force; $F = m_w g = \rho hAg = m_t \omega^2 r$
Assuming the mass of one arm of the turbine m_t is 0.5 kg; the height of the pipe channelling the water to the turbine is 10 m and radius of the pipe is 0.01 m: hence $A = \Pi r^2 = 0.000314\, m^2$
Also, if the density of the water is 1000 kg/m^3
Therefore; the Force turning the turbine, i.e. the centripetal force = $\rho hAg = m_t \omega^2 r$
Hence; $1000 \times 10 \times 3.14 \text{ x } 10^{-4} \times 10 = 0.5 \times 38.46^2 \times r$
That implies, the radius of our turbine must be r = 0.0425 m
But; Impulse/impact $Ft = m\Delta V$ and $F = \rho hAg$ and $m = \rho v = \rho hA$
Impact t_i = time = $\Delta\Theta / \omega$, where $\Delta\Theta = 135^0 – 45^0 = 90^0 = \Pi/2$ but $\omega = 38.46$ rads/sec
Hence $t_i = \Pi/2 \times 1/38.46 = 0.041$ sec

Also: $t_i = s/r\omega = 0.067/(4.25 \text{ x } 10^{-2} \times 38.46) = 0.041$ sec

s = Length of the arc formed by the arm of the turbine = 0.067 m (from $s = \Theta r$)

$\Delta V = Ft_i/m = \rho hAgt/\rho hA = gt_i = 10 \text{ x } 0.041 = 0.41$ m/s
Therefore: $\Delta V = V – \omega r = 0.41$ m/s: Where $V = C_{vl} \sqrt{(2gh)}$ and C_{vl} = The coefficient of loss through the pipe (friction, turbulence, bending pipe).
V is the velocity of the flowing water in the pipe. It plays a significant role in determining the impulse or impact.

Conclusion

One of the renewable and safest technologies of producing power is that of hydroelectric power generation. Hydroelectricity is the term referring to electricity generated by hydropower: i.e. the production of electrical power through the use of the gravitational force of falling or flowing water. It is the most widely used form of renewable energy, accounting for about 16 percent of global electricity generation.
This technology as well is facing a lot of roadblocks due to to the present global climatic changes. Some streams or rivers for the technology are running low or dry; affecting outputs. More so, seasonal changes in water level is also a heavier barrier. Worth mentioning as well is that its establishment is capital consuming.
The small/micro and Pico/family hydro plants/farms are a solution to the aforementioned roadblocks, since the technology behind the plants/farms is not capital consuming and it utilizes and maximizes hydro resources.
The engineering physics behind it is the conversion of potential energy to kinetic energy as a mass of water falls from a height in a dam or reservoir to mechanical energy and finally to electrical energy with the help of a generator.

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