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Improvement of the efficiency of water pumping systems by adding a device for recovering the potential energy of stored water to produce electric current

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ABSTRACT

Decentralized power generation around the world has been growing rapidly in recent decades. The technology is also constantly improving. In the field of photovoltaic pumping, the cost is still very high despite the studies already conducted for its optimization where several branches have been explored. In order to make a contribution, this work proposes an improvement of the efficiency of water pumping systems by adding a device for recovering the potential energy of the stored water. A synoptic representation of the recovery and conversion system allowed studying its different blocks by determining the speed of the waterfall, its hydraulic power, the mechanical power of the generator and its output current. By neglecting its losses, this system is able to produce a power of the order of 375 W starting from a generator of 24V driven by a wheel. This generator is able to supply a load absorbing a current of 15.63A.

This power depends on the height of the waterfall of the castle, the volume of water and the section of the pipe.

Key words: pumping systems, efficiency, addition, potential energy

INTRODUCTION

Several studies have been conducted for improving the performance of solar pumping systems, in particular by proper sizing of the pumping installation [1], by the sizing of the water tank [2] or by the use of a MPPT controller [3] and many other researchers.

However, we noticed that the exploitation of the potential energy of the stored water remains inexistent. Therefore, the objective of this work is to study a device that can be attached to the domestic supply pipe of the system to exploit the potential energy of water for the production of electricity. Depending on the height of the tank, the possibility of adding several of these devices is also considered. Finally, it is also important to check whether the device alters the quality of the water.

1. REVIEW OF THE LITERATURE

1.1. Photovoltaic pumping systems

Pumping water through a photovoltaic system is very common nowadays. There is a correlation between energy availability and water demand. When the demand for water increases during hot periods, the radiation intensity is high and the output of the solar panels is maximum. When the water demand decreases due to cooler weather, the sunlight is less intense.

The advantages of using water pumps powered by photovoltaic systems include minimum maintenance, ease of installation, good reliability and a match between generator power and water use requirements. In addition, water tanks can be used instead of batteries in photovoltaic pumping systems.

The elements of a photovoltaic water pumping system are [4]:

- The solar panels to provide the power supply for the motor pump. This supply can be in direct current as well as in alternating current, obtained by converting direct current into alternating current;

- A power control unit, consisting of a charge controller;

- A battery and a command and control unit, consisting of a charge controller, a battery and an inverter, capable of ensuring voltages with adjustable amplitudes and frequencies according to the available power of the solar generator.

- A submerged electro pump group, consisting of an asynchronous motor (or direct current) and a centrifugal pump.

- An electrical wiring, through which the energy from the generator to the motor is transmitted, and the information related to the safety controls.

- A hydraulic infrastructure (water storage tank, piping...) that conducts the water from the well to the distribution points.

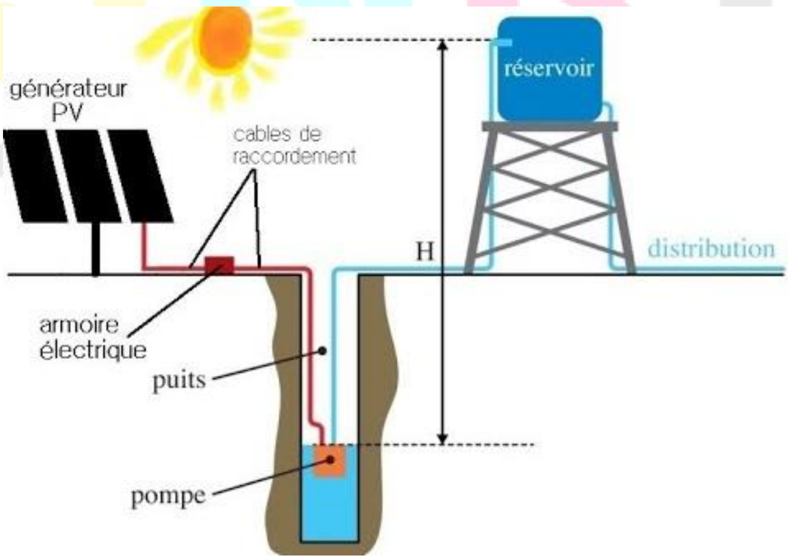

Figure 1: Solar pumping system [5].

1.2. Hydroelectric dams

1.2.1. High head power plant

They are characterized by a dam located in the mountains connected by a feeder tunnel that can measure about ten kilometers to a penstock. The difference in level or head is between 200 and 2000 meters, so the speed of the water in the pipe and the pressure are high. The turbine used is of the Pelton type and operates on the kinetic energy of the water [6].

The energy production in the power plant is controlled by the foot valve and the turbine injectors. A system of gates allows water to be pumped from the valley into the dam to use the excess energy on the power grid. The pump is connected to the electrical machine which then functions as a motor.

1.2.2. Medium-head power plant

In this type of installation, the power plant is located at the foot of the dam and the head is therefore much lower. Still, high power can be obtained with a larger flow. Because of the lower head, the velocity is lower and the Francis turbine uses the kinetic and pressure energy of the water. The water injection device on the turbine rotor and the shape of the rotor are such that the water enters the turbine at a reduced speed corresponding to a fraction of the speed the waterfall is capable of at that point. The Francis turbine is suitable for falls between 20 and 350 meters. A Francis turbine is also used as a pump when the head is low (200 - 300 m) and can reach 500 m [7].

1.2.3. Run-of-river power plants

In this case, the head is very low (between 5 and 30 meters) but the flow is enormous. The Kaplan turbine with adjustable blades is used. Because of the low head of water, the Kaplan turbine and its generator rotate very slowly [6].

2. MATERIALS AND METHODS

2.1. Material

2.1.1. Software

Matlab Simulink version R2019a.

2.1.2. Tools

To carry out our study, we needed the characteristics of a solar pumping system already dimensioned. For this we have taken the results of the work of BAKRI from the Centre for Renewable energy Development (CDER) in Morocco [9] who carried out a case study of a village water supply project, with the following characteristics:

- Nature of the project (circular well, operating flow rate 3l/s);
- General data (50 families (500 inhabitants), 300 heads of livestock (sheep), 100 heads of cattle);
- Hydraulic infrastructure data (Total depth: 30m, Static level: 15m, Dynamic level: 20m, tank height: 5m, Drop: 2m)

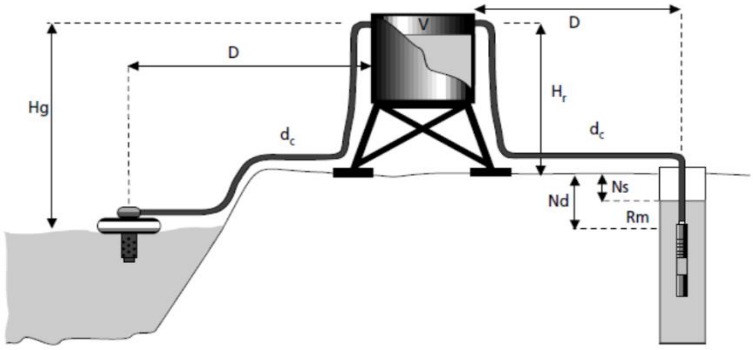

Figure 2: Synchronous machine used in single-phase or three-phase

i. Different parts

- The total head (THR) of a pump is the pressure difference in meters of water column between the suction and discharge ports.

- Hr : Geometric height from ground to top of tank (m);

- Ls : Static water level (at rest);

- Ld : Dynamic level of the water table (for an average flow)

- Dm : Maximum drawdown before stopping the pump (Ld - Ls)

THR = Hr + Ld + Pressure drop = Hr + Ls + Dm + Pressure drop

ii. Pressure drops

Pressure drops produced by the friction of water on the pipe walls. These losses are a function of the length of the pipes (D), their diameter (dc) and the flow rate of the pump (Q). They are expressed in meters of water column (mWC) [9]. The diameter of the pipes is calculated so that these head losses correspond to no more than 10% of the head (THR).

iii. Different heights

- Static level (Ls) of a well or borehole is the distance from the ground to the water surface before pumping.

- Dynamic level (Ld) of a well or borehole is the distance from the ground to the water surface when pumping at a given rate. For the calculation of the THR, the dynamic level is calculated for an average flow rate.

- The total head (THR) of the pumping is the sum of the static head and the dynamic head.

THR = Hs + Hd

2.2 Methods

2.2.1. Setting up the mechanism

Our device will consist of a toothed wheel immersed in the pipe which under the impulse of the potential energy of the water will cause its rotation. At one of the ends of the pipe, the wheel is connected by its axis to a DC machine which will transform the mechanical energy received into electric energy. The synoptic diagram of the system is:

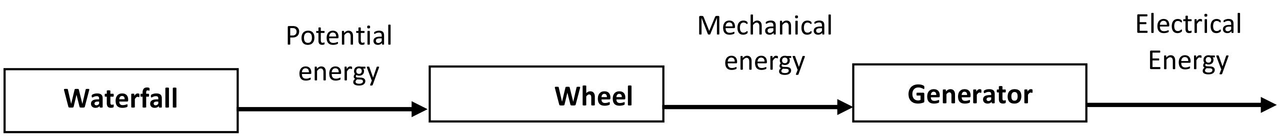

Figure 3: Block diagram of the system

The waterfall, which by a vertical translation movement provides potential energy to the gear wheel (buckets or blades) thus, causes its rotation in the pipe. In hydraulics, which is the study of flows, there are two types:

- The loaded flows, in which the water fills completely the pipe, it is the case in particular of the drinking water networks;
- Free surface flows (interface between water and air), which is the case of rivers and sewerage systems.

In flow under load, the regime of a flow is characterized by the temporal fluctuation of velocities and pressures within the liquid stream. When the velocity is low, we generally speak about laminar flow, and when the velocity is high, we speak about turbulent flow which is manifested by the appearance of eddies of various sizes.

The distribution of velocities in a straight pipe depending on the flow regime (laminar or turbulent) the forces in the flow are different. This results in a distribution of the time-averaged point velocity (called time-averaged velocity) inside the pipe which is different depending on the flow regime. Knowing the velocity profile in a pipe allows calculating the flow rate. Most of the network sensors measure the temporal average velocity in some points and reconstitute the complete profile of the velocity to deduce the flow. It is found that the maximum velocity is at the center of the pipe [10]. On the other hand, the turbulent velocity profile varies much more than in laminar flow near the wall. This zone of strong velocity gradient is called the boundary layer.

According to the work of J. VAZQUEZ [11], we note that the maximum velocity is generally found in the center of straight and circular pipes whatever the type of movement. It is advantageous for a laminar flow regime. Thus, the motion of the waterfall is a potential energy that attacks the impeller.

2.2.2. The wheel

In view of the turbine design, the Pelton type is very well suited for large hydraulic heads and small flows. In addition, they have a good efficiency for small and medium powers and are relatively easy to realize locally [12]. In such a turbine, the torque is generated by the force exerted by a jet of water coming from an injector on a set of buckets that can be compared to a kind of spoon fixed on a rotor. The buckets are shaped to obtain maximum efficiency while allowing water to escape on the sides of the wheel. They have an indentation that ensures optimal progressive penetration of the jet into the trough. These machines can have one or two jets per wheel in cases where the rotor axis is horizontal. It is even possible to have up to six jets in the case of a vertical axis turbine. The injector is designed to produce a cylindrical jet as homogeneous as possible with a minimum of dispersion. The flow rate is adjustable by means of a movable needle inside the injector, which is moved by a hydraulic or electric servomotor. This needle is controlled by the turbine regulation.

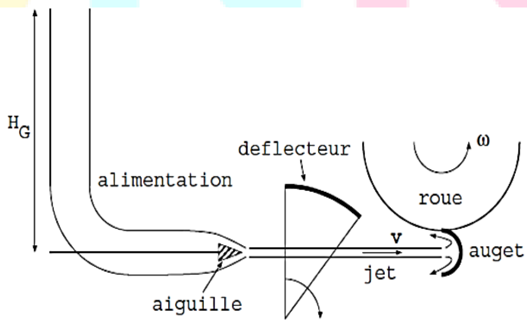

Figure 4: Schematic diagram of a Pelton turbine

2.2.3. The Electrical Generator

The generator converts mechanical energy into electrical energy. They operate either in alternating or continuous. There are three types of generators [13]:

- Direct current generators,

- Alternating current generators,

- The direct current generators, brushless, electronically switched (Brushless permanent magnetic DC Motors)[14].

The criteria to lightly choose a generator are:

- Good efficiency.

- Flexibility of operation.

- Robustness of the material in order to limit to the maximum the maintenance and the risks of breakdowns.

- Reliability and autonomy of the installation.

Our choice will mainly be a direct current machine, working as a generator. It converts mechanical energy into electrical energy via magnetism. By rotating a magnet around a copper coil, an induced current appears. It has a flexibility of operation, it does not require too much maintenance and less robust.

For this study, characteristics of the generator are following: DC: 24V/5 A; P=110 W; rpm: 800tr/min; η=85.

2.2.4. Piping

Piping plays a particularly important role in hydraulic equipment. They carry the power transmitted by the water. The choice of type of pipe depends on many criteria. This will be based on the advantage of flexible pipes where mobility is possible between the connected points and their ability to slightly dampen pressure pulsations. On the other hand, certain fragility over time can be observed. Rigid pipes have good resistance to aging and easy routing, but transmit mechanical vibrations [15].

2.2.4.1. Determination of pipe diameter

The internal diameter of the different pipes of a hydraulic circuit is defined by the maximum flow velocity and the admissible pressure drops.

Table 1: Common flow velocities

Operating pressure	Suction	Discharge	Return
$<$ 150 b	0,8 to 1 m/s	3 to 4 m/s	2 to 3 m/s
$<$2 50 b	0,8 to 1 m/s	4 to 5 m/s	
$>$250 b	0.5 to 0.8 m/s	5 to 7 m/s	

The inner diameter of the tube is calculated from the flow velocities in the table above:

$$d=\sqrt{\frac{21,2\times Q}{v}}$$

2.2.4.2. Theoretical approach to head loss in a pipe

The common approach is to evaluate the linear pressure losses. These losses are proportional to the length of pipe to be traveled.

$$\Delta P = \lambda \times \frac{1}{d} \times 5 \times \rho V^2 \times L$$

The friction coefficient λ depends on the Reynolds number:

$$R_e = \frac{V \times d}{\upsilon} \times 1000$$

The Reynolds number characterizes a flow, and in particular the nature of its regime (laminar, transient, turbulent etc. ...). We can thus calculate the friction coefficient λ [16]:

- If $Re < 2000$, the regime will be laminar and we shall use the POISEUILLE formula: $\lambda = \frac{64}{\mathrm{Re}}$;
- If $2000 < Re > 2000$, the regime will be turbulent smooth and we shall use the Balsius formula: $\lambda = \frac{0{,}316}{\sqrt[4]{\mathrm{Re}}}$;

The choice of the internal diameter of a pipe is thus a particularly delicate compromise to arbitrate and the consequences of a bad choice can be felt on the cost of the installation, the performance and sometimes on malfunctions.

3. RESULTS AND DISCUSSION

For this study, consider that:

- Losses in the pipes are considered nil;
- The wheel of the device has no degree of reaction, therefore no pressure variation;
- The fluid used is water which is considered incompressible.
- The photovoltaic pumping system: Q=3l/s; h=5m
- A 1000l tank (ϕ=1100mm, H=1260mm);
- The valve is fully open and the orifice has a diameter ϕ=25mm

3.1. Installation of the device for recovering the potential energy of the water

The wheel model of the Pelton turbine has a shape that is easy to adapt. Given that the displacement of the potential energy of water is vertical and that the speed of the flow is maximal at the center of straight for circular piping, the impeller will be directly connected to the generator shaft.

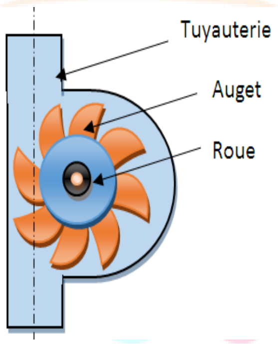

Figure 5: Water kinetic energy harvesting device

- Piping: it houses the wheel and serves as a bearing for it.

- Bucket: organs facilitating the rotation of the wheel. It has a circular and slightly hollow shape to better store the liquid.

- Wheel: component allowing the generator to be driven in rotation through its shaft

In general, in a Pelton turbine, the number of buckets placed on a wheel is between 18 and 24. However, it is important to determine this value carefully to avoid any problem of creeping. This phenomenon appears when part of the incident jet fails to interact with any bucket. This portion of the jet threads its way between the buckets to end its course against the frame of the turbine. Sneaking is, therefore, very detrimental to the performance of the machine since the energy contained in the portion of the jet that sneaks is simply lost.

3.2. Determination of characteristic quantities

3.2.1. Piping or pipes

Piping plays a particularly important role in hydraulic equipment. They carry the power transmitted by the water. The choice of type of pipe depends on many criteria. We relied on the advantage of flexible pipes where mobility is possible between the connected points and their ability to slightly dampen pressure pulsations in addition to being on the local market. We choose a pipe with a diameter of ϕ=25mm which is the most used.

3.2.2. Waterfall

The waterfall which, by a vertical translational movement, supplies potential energy to the toothed wheel (buckets or fins) thus causing it to rotate in the piping. We consider that the flow is laminar.

i. **Determination of the fluid velocity at the outlet of the orifice (B)**

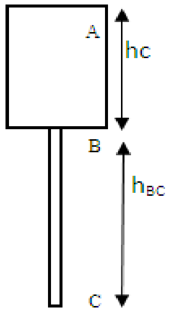

Figure 6: presentation of the tank and the water pipe

According to Torricelli's Theorem considering that our tank is a container with a hole (B) at the distance h below the free surface of the incompressible liquid. At t = 0, it is assumed that a tank valve (located at B) opens. Initially the height of water in the reservoir is h_0 and it is noted h(t) at t time.

Once the valve is open, we assume the one-dimensional flow at the interface air-water in the tank with $\vec{v}(M,t) = -V(t)\overrightarrow{u_z} = -\dot{h}\overrightarrow{u_z}$ and in the horizontal tube where $\vec{v}(M,t) = v(x,t)\overrightarrow{u_x}$.

We therefore have by conservation of the volume flow:

$$v(x,t) = \frac{S}{s}V(t) = -\frac{S}{s}\frac{dh}{dt}$$

This allows with $s \ll S$ to neglect V(t) in front of v(t) in the whole sequence.

We place ourselves in the approximation of quasi-stationary regimes: we will be able to apply Bernoulli's theorem stationary. This amounts to neglecting the local acceleration in front of $\overrightarrow{grat}\frac{1}{2}v^2$.

We therefore find $\mu g z_A = \mu\frac{1}{2}v^2 + \pi g z_B$

Finally, the velocity at point B is: $v = \sqrt{2gh}$

With g= 9.81N /Kg and hc (the height of the tank) = 1.26m.

Simulating in MATLAB the linear speed as a function of the height, we obtain:

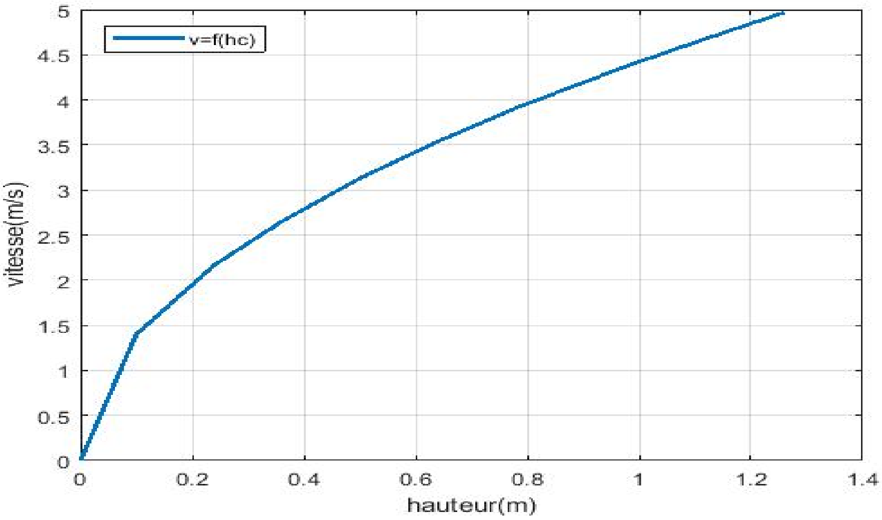

Figure 7: Evolution of speed as a function of height

Interpretation: it can be seen that the linear velocity of the water at the outlet of point B (at the outlet of the tank) is maximal and decreases as the water level drops in the tank.

ii. Determination of angular velocity

The water, under the effect of gravity, makes a free fall in the conduit arrives on the bucket of the wheel which impels it with an angular speed. Starting from the elementary equation of the relation linking the linear speed to the angular speed $\omega = \frac{v}{R}$, we obtain the following curve:

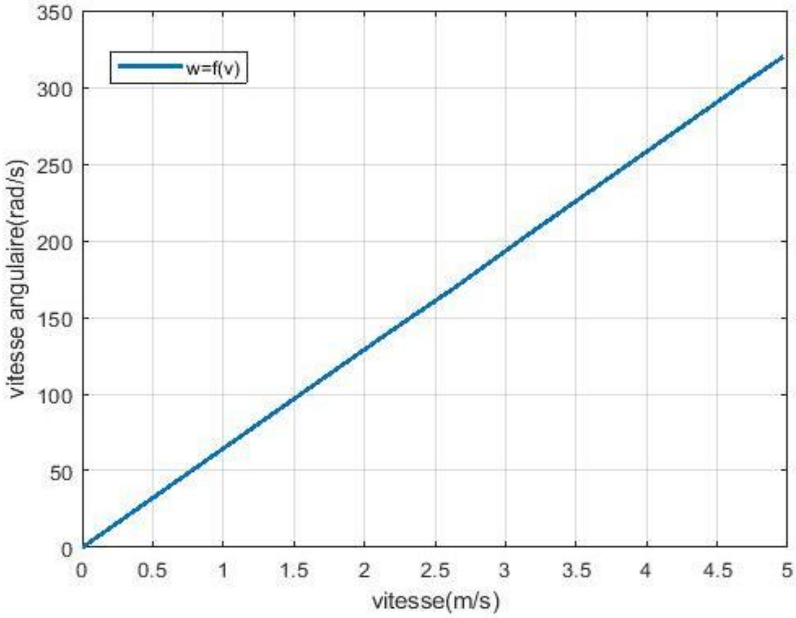

Figure 8: Angular Velocity Curve

Interpretation: The angular velocity increases linearly as a function of the linear velocity which depends on the height of the tank.

iii. Determination of the speed of rotation

The classic relationship between angular velocity and rotational velocity is: $= \frac{2\pi n}{60} =\gg n = \frac{30w}{\pi}$. We get the following curve:

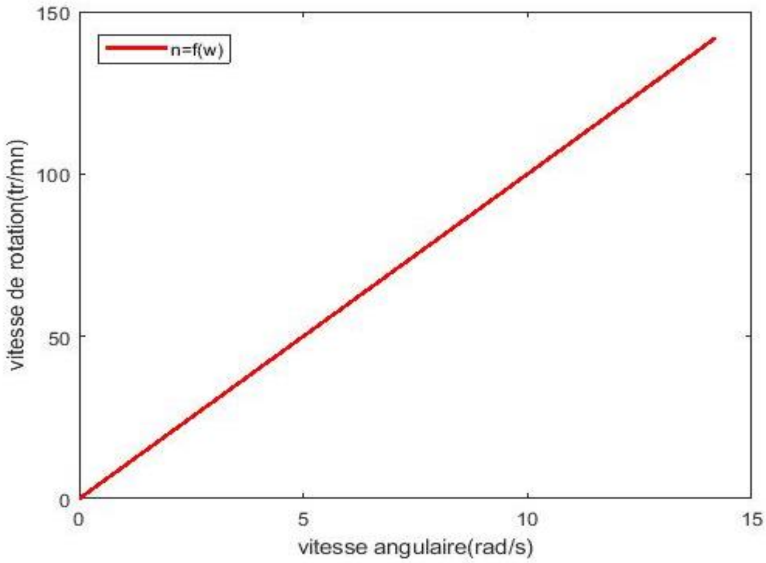

Figure 9: rotational speed curve

Interpretation: We find that the rotational speed increases with the angular velocity. That made us believes that our water potential energy harvesting device can rotate at a maximal speed of 903 rpm up to 3200 rpm. Hydraulic power calculation Hydraulic power is the power supplied to the wheel by the water that feeds it. The falling water gives hydraulic power to the wheel [17] which is:

$$P_{h_{BC}} = \rho Q g h_{BC}$$
$$P_{h_{BC}} = 1000 \times 3.10^3 \times 9{,}81 \times 5 = 441{,}4\ \mathrm{W}$$

iv. Determination of mechanical torque

Since the wheel is directly connected to the generator shaft, we assume no losses. Therefore $P_{h_{BC}} = P_m = 441{,}4\ \mathrm{W}$

By considering $C = \frac{P_m}{W}$, the mechanical couple according to the mechanical power has the following curve:

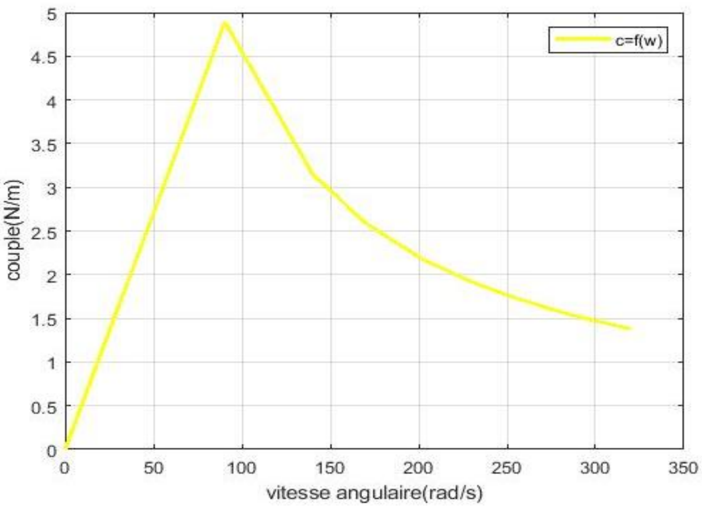

Figure 10: Evolution of torque

Interpretation: it can be seen that the torque increases linearly with the angular velocity and reaches a peak of 4.9 N.m at 75 rad/s before gradually decreasing and remaining at 1.37.

3.2.Determination of generator current

The main objective being to verify if our device is capable of driving a rotating generator and producing a current, we consider a permanent magnet generator with an efficiency of 85% and an output voltage of 24V. We know that $P_U = UI$ soit $I = \frac{P_U}{U}$

While $P_U = \eta P_a$

Thus: $I = \frac{\eta P_a}{U} = \frac{0{,}85 \times 441{,}4}{24} = 15{,}63A$

The generator driven in rotation by our wheel is capable of supplying a 24V load absorbing a current of 15.63A.

CONCLUSION

This work focused on the improvement of the performance of water pumping systems by adding a device for recovering the potential energy of the stored water where the objectives were to study a system that can be attached to the piping of domestic water supply system in order to exploit the potential energy of the water for the production of electricity. That subsequently, depends on the height of the tank. Possibility of fixing several devices has been noted and the study checked that those devices do not alter the quality of the water. We set up a synoptic diagram of optimization of the potential energy through an analysis of each compartment of the waterfall. Observation showed that there is an electric current produced. The generator power can supply a load of 24V/15A. This can contribute at least to the lighting of the site of the photovoltaic pumping system.

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