Electric Power Generation Modeling for an Experimental Biomimetic Turbine with Permanent Magnets in Places with Low Water Flow in the Mantaro Valley - Perú

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Abstract. The paper presents a methodology for the design of propeller and generator of a biomimetic hydraulic turbine, as well as an estimate of the electrical power generated for places with low-flow water inflows in the Mantaro Valley, Junín - Perú. The objective was to model the power generated by the biomimetic turbine when it is installed in irrigation channels of 0.8 x 0.8 m², as a proposal for a micro-hydroelectric plant, an alternative generation with renewable energy, where the flow is at least 4 m³/s. For the verification of the design, a simulator of real conditions such as Computational Fluid Dynamics was used to predict the capacity the amount of force that acts on the movement axis based on the Finite Element Method, to verify the structural unity of the design. The design methodology is based on biomimetic technology, continuity equations, Reynolds Averaged Navier-Stokes Equations, equations applied to determine power, through computational simulation of the turbine, obtaining data such as shaft speed and torque, through the percentage of pressure that exists in each hood, the power generated in the entire system was determined, by means of mathematical modeling a permanent magnet generator was developed as an alternative generator for this type of turbine.

1. Introduction
The proposed hydraulic turbine is an innovation in renewable energy technology as a consequence of a design adapted to the needs and characteristics of the Mantaro Valley region, where, according to the project for the identification and diagnosis of irrigation projects with water treated wastewater from the city of Huancayo ANA [1], is supplied by the left bank irrigation canal CIMIR, capturing the waters of the left bank of the Mantaro river. This type of electrical generation is used as a partial solution to provide electrical service to areas without electrical supply, which, according to Agudelo & others [2], in microgenerators there is no design methodology to estimate an efficient model to validate models of turbines of regular hydroelectric plants.

Developing new industrial designs establishes guidelines for progress in what is considered sustainable development. Collado-Ruano [3], He concludes, that the capacity of creative dimension in human formation to face the prevailing unsustainability is necessary for the present and the future, being only possible reorient our biotic models within the biophysical limits of nature; Develop models, methods, techniques, designs, prototypes, etc. The rotors were elaborated by means of a modeling based on biomimetic technology, which, is carried out by means of the Fibonacci sequence, the quotient of any term in the sequence and its antecedent, generates a number close to Φ. These designs
have a mathematical extrapolation where the spirals are systems of mechanical models that have the power dissipation capacity as an intrinsic characteristic of the system, and going deeper, it refers to the natural frequency of developing and returning to a state of rest after the alterations [4]. Riechman [5], considers that systems inspired by life and highly hospitable and compatible with people should be made. Most of the industrial sectors carry out an adequate innovation in terms of technical engineering and methods, adapted to designs of characteristics and principles, being a potential facilitator for regenerative and efficient designs [6]. The rotor was idealized to the modern infinite helical Archimedean screw, complemented by the natural imitation of the “Zantedeschia aethiopica”. The new forms of design are focused on neural networks that determine the best solution in design, neural networks as well as biomimicry allow adapting the changes that have undergone a natural structure to improve fundamental activities of living beings [7]; While neural networks allow defining which conditions should not be used, biomimetics as natural design defined the living conditions to survive or adapt to certain conditions, biomimetics is a natural technique of intelligence in design.

Currently, many models, forms, and methods are being developed to design, evaluate, simulate and build hydraulic and wind turbines, the case of Simpson & Williams [8], establishes that the use of a fluid-dynamic computational analysis allows to parameterize the generation capacity that It is about to develop the turbine, it allows to evaluate design without first building them, on a large scale it saves time and money in unnecessary construction, so much so that it would be desirable that there be some manual and design method for micro or pico centrals based on fluid dynamic analysis. Garcia, Jaramillo & Velasco [9], determined that the simulation software validates the design with a precision in the results similar to a real experiment, with a difference of 12% of comparison. Ramos, Simão & Kenov [10], computational analyzes can help researchers and equipment manufacturers to improve and understand the phenomena associated with hydrodynamics and the computer-aided design of different turbines as well, similar experiments have been achieved. Chica, Agudelo & Sierra [11] to obtain efficient results in the project, they establish as properties of the design, the geometry of the rotor, while the conditions of the collection system depend on the height and discharge.

The evaluation of the turbine was by means of an experimental model of the biomimetic turbine integrated with an electric generator of permanent magnets. The simulations through the computer packages allow us to evaluate the rotational speed conditions for small hydropower plants; and consider that both the design of the stator and the turbine rotor were designed separately to estimate the losses in each system. According to Borkowsky, & others, performing an analysis of a complete turbine system must be performed in parts and using fluid dynamic computational analysis software [12].

2. Biomimetic Design Methodology for Turbine Propeller

2.1. Identify
In the present investigation, different natural elements were observed, whose functional parts are better adapted to an aquatic environment; From these systems, data such as the contact area of its elements, the shape it had, the composition and quantity of its parts were obtained. Many natural elements have a spiral and numerical modeling that of mollusk shells as a three-dimensional integrated volume [13].

2.2. Interpret
The parts of the natural elements in which they were in contact with water that are developed were analyzed in order to obtain water for their vital needs to obtain the necessary amount of water for their growth, therefore, the outstanding characteristic was that its leaves extended wide at the beginning and moderately conical at the distance from the axis that the branch projects, having less area in the lower part of the petal.

2.3. Discover
The elements that had these characteristics were the rose and the water lily, some differences were found between these elements, the first was that the water lily, had the shape of its petals more open at the beginning, whereas the rose has the petals closest to their pistils; The rose has a large number of petals, in addition to the way it develops, it does not allow the passage of water, on the other hand, in the water lily it is the opposite.

2.4. Summarize
The parts of the elements that were identified to adapt, outstanding geometric possessions, such as the arrangement of their petals, observed from the ground, is determined by a geometric progression described as the Fibonacci sequence, it is considered that this is characteristic of an interesting shape of natural design, due to the fact that many elements have this form of growth, such as: the shells of snails, the petals of roses, the geometry of the solar system, as shown in Figure 1.

2.5. Emulate
In this part of the design methodology, it was understood that differentiating the design factors was necessary to develop an adequate turbine, that is why it was described that the turbine would be designed based on the variation of the number of blades, the amount of hoods and shaft type,

2.6. Evaluate
After evaluating the different turbines, through the experimental design 2 different functional qualities could be found in each type of turbine, in which the most outstanding were the type of shaft and the number of blades. This type of turbine is considered suitable for low flow rates, due to the results obtained in the simulation, although indications were also found that this type of turbine is also suitable for high velocities of water inflows, as shown in the table 1.

3. Permanent Magnet Generator Design Methodology

3.1. Determination of the power in each “bell”
The simulation under CFD is a fundamental tool for the optimization of turbomachines, it allows us to carry out a detailed analysis of the phenomena that occur in each part of the system [14]. The mathematical models used by the CFD software are continuity equations and Navier-Stokes equations, the modeling is carried out using meshes, which are rectangular, straight or curvilinear triangular areas, they adapt to the design geometry to analyze the vertices of the triangles or rectangles, in this way the speed, pressure and torque of the propeller are determined in simulation, it was necessary to determine the mechanical power of the propeller to know the electrical power, in this way the permanent magnet generator would be designed [15].

Continuity equation:
\[ \frac{\partial p}{\partial t} + \frac{\partial}{\partial x_i} \left( \rho u_i \right) + \frac{\partial}{\partial x_j} \left( \rho u_j \right) + \frac{\partial}{\partial x_k} \left( \rho u_k \right) = 0 \]  

Reynolds Averaged Navier-Stokes Equations (RANS):
\[ \frac{\partial}{\partial t} \left( \rho u_i \right) + \frac{\partial}{\partial x_j} \left( \rho u_i u_j \right) = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_l}{\partial x_l} \right) \right) + \frac{\partial}{\partial x_k} \left( - \rho u_i' \bar{u}_j \right) \]  
\[ \frac{\partial}{\partial t} \left( \rho u_j \right) + \frac{\partial}{\partial x_k} \left( \rho u_j u_k \right) = - \frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_k} \left( \mu \left( \frac{\partial u_j}{\partial x_k} + \frac{\partial u_k}{\partial x_j} - \frac{2}{3} \delta_{jk} \frac{\partial u_l}{\partial x_l} \right) \right) + \frac{\partial}{\partial x_i} \left( - \rho u_j' \bar{u}_k \right) \]  
\[ \frac{\partial}{\partial t} \left( \rho u_k \right) + \frac{\partial}{\partial x_i} \left( \rho u_k u_i \right) = - \frac{\partial p}{\partial x_k} + \frac{\partial}{\partial x_i} \left( \mu \left( \frac{\partial u_k}{\partial x_i} + \frac{\partial u_i}{\partial x_k} - \frac{2}{3} \delta_{ki} \frac{\partial u_l}{\partial x_l} \right) \right) + \frac{\partial}{\partial x_j} \left( - \rho u_k' \bar{u}_i \right) \]  

Where \( \rho \) is the density of the fluid, \( p \) represents the pressure, \( \delta_{ij} \) is the Kronecker delta; and \( u_i, u_j \) and \( u_k \) are the average velocities in \( x_i, x_j \) and \( x_k \) directions. While the last term, \( \frac{\partial}{\partial x_j} \left( - \rho u_i' \bar{u}_j \right) \), Reynolds stress, represents the effects of turbulence, the simulation using finite elements in CFD based on the equations shown, it shows in Figure 1.
3.2. Estimated power generated

To find the Useful Power that this machine will have, it is done by means of the following equation:

\[ P_{\text{util}(u)} = \omega u_1 \cdot M \] (5)

Where:
- \( M \): Torque (N-m)
- \( \omega \): Angular velocity (rad/s)

The power for a speed, height and torque [16] is given by:
- \( P \): Torque (N-m)
- \( n \): Speed (m/s)
- \( H \): Net height (m)
- \( \eta_{\text{gen}} \): Generator efficiency

\[ \frac{n_2}{n_1} = \left( \frac{H_2}{H_1} \right)^{1/2} \cdot \frac{P_2}{P_1} = \left( \frac{H_2}{H_1} \right)^{3/2} \] (6)

According to [17] the generator efficiency level \( \eta_{\text{Gen}} \) is \( 0.95 < \eta_{\text{Gen}} < 0.98 \). Finally,

\[ P_{\text{Elec}(u)} = P_{\text{mech}} \cdot \eta_{\text{Gen}} \] (7)

3.3. Design of the generator with permanent magnets

The initial design power is:

\[ P = \pi \cdot B \cdot K \cdot R_m^2 \cdot \Delta r \cdot \omega \cdot \cos \phi \] (8)

where:
- \( P \): Power (Watts)
- \( B \): Magnetic Induction (Teslas)
- \( K \): Specific Linear Load (A / cm)
- \( \Delta r \): Diameter of magnets (meter)
- \( \omega \): Angular Speed (RPM)
Finally, to determine the power effective:

\[ P = 3 \cdot E_{ph} \cdot l \]  

(9)

Power in copper:

\[ P_{cu} = n_{colt} \cdot R_{colt} \cdot I^2 \]  

(10)

The efficiency will be:

\[ \eta = \frac{P}{P + P_{cu}} \cdot 100 \]  

(11)

4. Results

4.1. Biomimetic design for the turbine propeller

Table 1: Data in the table of the Methodology for the Experimental design

| Observations model | DATA OF THE RESULTS WITH THE COMBINATION OF THE DIMENSIONS INCLUDING THE REPLICAS |
|--------------------|----------------------------------------------------------------------------------|
|                    | DEPENDENT VARIABLE                                                             |
|                    | INDEPENDENT VARIABLE                                                            |
|                    | Iterations                                                                      |
|                    | Propeller configuration                                                         |
|                    | Combination of the treatments                                                   |
| Number of blades   | Number of "bells"                                                                |
| Units              | Units                                                                           |
| Shaft type         | Peculiarity                                                                     |
| Electric power generation | Energy                                                                  |
| Torque N-m         |                                                                                  |

|                | A1                         | C1 | E1 | A1-C1-E1 | 1.3959 |
|                |                            |    |    |          |       |
|                |                            |    |    | A1-C1-E2 | 6.3221 |
|                |                            |    |    | A1-C2-E1 | 0.8050 |
|                |                            |    |    | A1-C2-E2 | 12.8274|
|                |                            |    |    | A2-C1-E1 | 0.5779 |
|                |                            |    |    | A2-C1-E2 | 5.0133 |
|                |                            |    |    | A2-C2-E1 | 0.6791 |
|                |                            |    |    | A2-C2-E2 | 12.0989|

To evaluate the design, experimental tests were carried out on the combinations of the factors for the possible turbine. In the first instant, the propeller, which is the main element of any turbine, was designed, based on biomimetic methodology. Under the modality of the solution design, the one with the best performance was evaluated from the list of many turbines, being the A1-C2-E2 turbine the ones that offered the best conditions, being 3 blades with 4 bells and biomimetic axis, as a show in the table 1.

The power found is for a fluid velocity of 7 m³/s, because the fluid velocity in the Mantaro valley areas is at least 4 m³/s, the useful and electrical power must be found for these conditions. so, useful power is \( P_{util(6,25)} = 6770.5 \text{ W} \), and electric power generated by the turbine is \( P_{Elec(6,25)} = 6431.8 \text{ W} \).

The fluid dynamics of the pressure and the velocity of the axis were evaluated, considering as front-end variables the initial velocity of 10.93 m / s, which is the speed of the torque determined in the flow rate of 7 m³/s in an area of 0.8x0.8 m², having a speed in the turbine of 10.83 m / s. The torque for these effects reached 321.68 N-m (32.79 kg-m). In the investigation, the useful power of a turbine was
determined by the percentage of pressure that each turbine has and the useful power of the first bell, as a show in the table 2.

The angular velocity of the turbine is given by:

\[ \omega = \frac{10.83}{0.2169} = 49.93 \text{ rad/s} \]

Finally:

| Item | pressure (%) | Mechanical Power (W) | Total, Power (W) |
|------|--------------|----------------------|-----------------|
| Bell₁ | 100%         | 16061.5W             |                 |
| Bell₂ | 30.08%       | 4831.3W              | 35226W          |
| Bell₃ | 26.34%       | 4230.6W              |                 |
| Bell₄ | 62.9%        | 10102.7W             |                 |

*Bell: Coupling of three or four propellers of the basic design unit on the shaft*  

### 4.2. Design of the permanent magnet generator

| Models |  |  |  | N | 1 coil (m) | Rph (Ω) | Xph (Ω) | I (A) | Pow. Gen. (W) | Lost Joule (W) | Efficiency % |
|--------|-----------------|-----------------|-----------------|-----|------------|---------|---------|-------|-----------------|---------------|---------------|
| 1      | 0.00004         | 0.00007         | 0.000103        | 574 | 4.7414     | 0.16029 | 2.9912  | 14.97 | 4940.259        | 3167.685      | 60.93%        |
| 2      | 0.00029         | 0.00035         | 0.000424        | 116 | 2.2216     | 0.02082 | 3.7613  | 19.46 | 6420.054        | 2522.568      | 71.79%        |
| 3      | 0.00019         | 0.00035         | 0.000565        | 111 | 2.1259     | 0.01218 | 9.2024  | 10.91 | 3599.403        | 758.737       | 82.59%        |
| 4      | 0.00039         | 0.00068         | 0.000989        | 61  | 1.669      | 0.00479 | 13.845  | 7.68  | 253.327         | 295.301       | 89.56%        |

5kW was considered as initial design power, because it is a smaller amount than the electrical power found in item B, so when developing the design, the power generated, for a magnet of magnets permanent will be lower, than found with generator efficiency. For the possibility of configuration of table 2, where the speed is 275 rpm and 110 V for phase voltage, it has a maximum power of 6420,054 W with an efficiency of 71.79%, where the combination of Di and Do correspond to 3 cm and 4 cm respectively.

Finally, the permanent magnet generator for this turbine will have the following characteristics:

- The speed of 275 rpm will be maintained. The length of the coils will be 2.1 cm. Each coil will have 116 turns. The frequency will be 73.33 Hz. The generator will have 32 pair of poles. The generator will be a three-phase system. The magnets will be neodymium. There will be 8 coils per phase. The average diameter of the generator will be 52.4 cm.

### 5. CONCLUSIONS

Eight hydraulic turbines were designed for micro-hydroelectric plants, with combinations of characteristics of blade, bell and type of shaft, with 2 levels each, from this the equations that could indicate the minimum amount of generation are shown, being the useful power for the minimum flow velocity 6.25 m/s, generating 6770.5 W; the electrical power it could generate was 6431.8 W for a 0.95 efficiency generator.

The disposition of the factors, influence the generation of energy. The angle when it is coupled has a significant influence on the result of the torque generated and, therefore, on the electrical generation obtained. In the results found it is shown that the turbines of greater torque generated are as many as 4 blades. This could have happened at the time of assembling the pieces, and not considering an angle of separation between each blade.

The turbine will generate a useful power of 6770.5 W, determined by torque, angular velocity and efficiencies. A minimum efficiency of 95% generation was applied according to the generators of the hydroelectric plants in which a capacity of 6431.8 W was obtained. Through a theoretical simulation the design of a permanent magnet generator for the turbine A1-C2-E2 was developed and a power of
6420.054 W was obtained with a generator efficiency of 73.06%.

6. References

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