A STUDY OF POWER GENERATION FROM A LOW-COST HYDROKINETIC ENERGY SYSTEM

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The kinetic energy in river streams, tidal currents, or other artificial water channels has been used as a feasible source of renewable power through different conversion systems. Thus, hydrokinetic energy conversion systems are attracting worldwide interest as another form of distributed alternative energy. Because these systems are still in early stages of development, the basic approaches need significant research. The main challenges are not only to have efficient systems, but also to convert energy more economically so that the cost-benefit analysis drives the growth of this alternative energy form. One way to view this analysis is in terms of the energy conversion efficiency per unit cost. This study presents a detailed assessment of a prototype hydrokinetic energy system along with power output costs. This experimental study was performed using commercial low-cost blades of 20 in diameter inside a tank with water flow speed up to 1.3 m/s. The work was divided into two stages: (a) a fixed-pitch blade configuration, using a radial permanent magnet generator (PMG), and (b) the same hydrokinetic turbine, with a variable-pitch blade and an axial-flux PMG. The results indicate that even though the efficiency of a simple blade configuration is not high, the power coefficient is in the range of other, more complicated designs/prototypes. Additionally, the low manufacturing and operation costs of this system offer an option for low-cost distributed power applications.
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**NOMENCLATURE**

<table>
<thead>
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<th>Description</th>
</tr>
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<tr>
<td>AFPAG</td>
<td>Axial-flux permanent magnet generators</td>
</tr>
<tr>
<td>CEPoS</td>
<td>Cost of the electricity production of the system</td>
</tr>
<tr>
<td>HES</td>
<td>Hydrokinetic energy system</td>
</tr>
<tr>
<td>HKT</td>
<td>Hydrokinetic turbine</td>
</tr>
<tr>
<td>HAHT</td>
<td>Horizontal-axis hydrokinetic turbines</td>
</tr>
<tr>
<td>NdFeB</td>
<td>Neodymium-iron- boron</td>
</tr>
<tr>
<td>N</td>
<td>Grade of the magnets</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite element method</td>
</tr>
<tr>
<td>PMG</td>
<td>Permanent magnet generator</td>
</tr>
<tr>
<td>ROI</td>
<td>Return on Investment</td>
</tr>
<tr>
<td>RPM</td>
<td>Revolutions per minute</td>
</tr>
<tr>
<td>TSR</td>
<td>Tip speed ratio</td>
</tr>
<tr>
<td>CFD</td>
<td>Computer fluid dynamics</td>
</tr>
<tr>
<td>D.C.</td>
<td>Direct current</td>
</tr>
<tr>
<td>A.C.</td>
<td>Alternating current</td>
</tr>
<tr>
<td>VDC</td>
<td>Volts of direct current</td>
</tr>
<tr>
<td>LabVIEW</td>
<td>Laboratory virtual instrument engineering workbench</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Coefficient of power</td>
</tr>
<tr>
<td>$P_{available}$</td>
<td>Mechanical output power</td>
</tr>
<tr>
<td>$P_{output}$</td>
<td>Electrical output power</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>Water density</td>
</tr>
</tbody>
</table>
\( v \)  
Water flow velocity

\( A \)  
Rotor swept area

\( d \)  
Rotor diameter

\( \beta \)  
Pitch angle

\( \omega \)  
Rotor rotation rate

\( I \)  
Phase current

\( V \)  
Rectified output voltage

\( T \)  
Torque

\( \Omega \)  
Electrical resistance

\( p \)  
Number of pairs of poles

\( n \)  
Number of revolutions per minute

\( \sigma \)  
Standard deviation
The focus on alternative energy systems has grown very fast due to environmental concerns and the decrease of fossil fuels. Alternative energies “are derived from replenishable natural resources that do not use up natural resources or harm the environment”\(^1\). They have been considered a viable and non-polluting source of renewable power, thus new methods have been developed for the generation of electricity.

In the last several years, sustainable energy technologies have been increasing significantly and have become more cost-effective. A good example is the development of hydrokinetic systems, devices which extract and convert the energy produced from the movement of water in rivers, streams, and tidal currents into electricity. In general, hydrokinetic systems can be classified as electro-mechanical systems where there are electrical devices and electronics, moving and stationary mechanical components.

Hydrokinetic energy is currently the second largest source of alternative systems, and it also provides the cheapest way of electrical generation [2]. The low investment costs and maintenance fees make hydrokinetic systems more cost-effective in comparison with other renewable technologies.

Furthermore, small-scale hydrokinetic systems represent a solution for power supply in remote areas. The configuration of the system requires a technical design and a study of the economical factors. Some of the work that has been developed is associated with applications for free-flowing rivers, and it depends on the axis of the turbine, number of the blades, and water flow velocity.

---

\(^1\) Concise OED Alternative Energy. [Accessed 19 May 13].
The turbine unit can be placed inclined or straight (horizontal or vertical); these configurations define the pitch of the blades that sets the position of the blades with respect to the direction of the rotor rotation to optimize the angle of attack, which is the direction of the incoming water flow through the blades. Some designs include variable pitch, meaning the blades can be changed automatically, or their angle could be manually adjusted to multiple positions depending on the water income such as Squirrel Cage Darrieus or H-Darrius [3]. Other options include fixed pitch; in this type of array the blades have a defined angle and cannot be changed to the desired pitch. Darrius, Gorlov, and Savonius turbines have this type of configuration [3].

The number of the blades determines the solidity. More blades represent higher solidity because there is more surface area, but they represent more manufacturing costs; several examples are related with a fewer number of blades such as the SeaFlow turbine [4]. This turbine consists of two blades with full-span control; the SeaGen turbine has a twin rotor with two blades mounted on a monopole structure; the SMD-Hydrovision TidEl system has two H-axial counter-rotating rotors, each one has two blades [4]. The 3-blades configuration represents the optimum balance between solidity, costs, efficiency, and power extraction. Some of the developments are the Verdant Power with different capacities, the Free Flow turbine, the WPI Turbine from Water Power, and the HydroVenturi [4]; all of them have airfoil profiles on their blades. Moreover, there are turbine systems with multiple numbers of blades such as the Kobold with high starting torque and variable pitch; the EnCurrent Hydro Turbine, a vertical-axis system with ducted or non-ducted installation; the Atlantisstrom, the Neo-Aerodynamic; and the CycloTurbine, from a paddle wheel with articulated blades to orient themselves at the desired blade pitch [3].
Finally, duct augmentation designs are included on the turbines to increase the water flow velocity. Some examples with a diffuser are the Lunar Energy Rotech Tidal Turbine, which has a symmetrical duct that does not need a gearbox or control system [4]; the Underwater Electric Kite, a twin axial system that contains a double-shroud duct with a rear augmenter that creates low pressure areas behind the turbine; and the Blue Energy tidal turbine with a cross-flow duct [4]. Other applications that use diffusers can be found on the Tidal Turbine Generator, which has a bi-directional duct that works as a speed increaser; the Hydrohelix Energy Turbines, which have several turbines aligned on the same axis, and each one has its own diffuser [5]; the Kirke’s diffuser-augmented water turbine; and the Self-Regulated Vertical-Axial Hydroturbine, which is integrated with a flow speed amplifier [5].

All the previous work depicts the current progresses of the hydrokinetic energy systems. However, since it is still in the early stages of development, there is significant research to do for solving the need for energy conversion in a more economical way, so that the cost-effectiveness analysis drives the growth of this form of alternative energy. One way to view this analysis is in the terms of the energy conversion efficiency per unit of cost, i.e. Watts/$. Improving the conversion efficiency is the basis of this study, which consists of a detailed study of design, development, and performance of a hydrokinetic energy system (HES). It is related to the power generation and cost from a horizontal-axis hydrokinetic turbine (HAHT), as another form of distributed energy.

The HES involves the electro-mechanical design as well as its development. The work was divided into two stages: (a) a HAHT with fixed-pitch blade configuration, using a radial permanent magnet generator (PMG), and (b) the same hydrokinetic turbine (HKT), with a variable-pitch blade. Also, for this second phase, an axial-flux PMG for low RPM was built.
This experimental study used commercial low-cost blades consisting of two different diameters and/or blade numbers inside a tank with water flow velocity up to 1.3 m/s. Power, torque, voltage, current, and rotor rotation rate were measured to analyze the capacity and the cost of the hydrokinetic energy system for both stages, by varying the electrical resistance placed on their respective generators.

The first part is related to a detailed assessment of the hydrokinetic prototype energy system along with power output costs. In this phase, the HKT had a fixed-pitch blade of 22°, a 0.50 m diameter of the swept area with a simple transmission shaft and the radial PMG. This configuration gave an output of ~47 W at 350 RPM, and the coefficient of power was ~0.22.

The radial PMG can only generate higher levels of power above 800 RPM, and the maximum rotation rate measured in the first stage of the testing was only 400 RPM. Thus for the second stage, a coreless axial-flux permanent magnet generator with a larger diameter was constructed. This sandwiched generator can increase the energy production at a lower RPM, so the cost of the energy from the hydrokinetic system can be reduced. To test the total potential output of the generator, a big drill press machine was used; here, the axial-flux PMG was able to produce ~350 W at 175 RPM. Moreover, the generator was tested on the HES, where it could only generate ~80 W at 250 RPM due to other factors that will be explained later.

In addition, for this second phase of the experiment, a HAHT of 0.48 m diameter with variable-fixed pitch was designed. The pitch of the blade was varied manually from 20° to 45°, but it was fixed inside the tank. In addition, a gearbox was used this time to measure directly the mechanical torque produced from the HKT. A new frame for the vertical configuration of the axial-flux generator was built to give more support and to avoid bending problems due to the high torque produced. With this array, the power output was almost two times greater compared
to that of the first configuration using 6 blades, and the maximum rotor rotation rate stayed constant; it also achieved 500 RPM when no load was placed. On the other hand, the cost of the system was reduced, but there are still some design parameters that might need to be changed; however, the power coefficient rose to 0.36.

The results indicate that the cost-effectiveness of the HES using a simple blade configuration is in the range of other more complicated designs. Additionally, the manufacturing and operation costs of these systems are low compared to those of other prototypes, and this represents an option for low-cost distributed power applications. Nonetheless, the co-existence of corrosion demands stringent material selection procedures and high performance materials.

Finally, the work is organized as follows. Chapter 2 presents the first configuration of power generation using the low-cost blade set with fixed-pitch, as well as its hydrodynamic performance of the hydrokinetic energy system. Chapter 3 provides detailed information regarding the construction process of the axial-flux permanent magnet generator for this work, with primary focus on the electrical design and the manufacturing process. Chapter 4 discusses the results obtained from the second configuration of the hydrokinetic energy system with a variable-pitch blade and using the axial-flux PMG. This configuration was compared with the existing experimental results from Chapter 2, followed by further analysis considering individual effects on the variables discussed previously. In conclusion, Chapter 5 analyzes the findings from both configurations and provides the implications of water turbines’ performance using low-cost blades under given operating conditions. Also future work is projected.
CHAPTER 2
A STUDY OF POWER GENERATION USING A LOW-COST FIXED-PITCH BLADE FOR A HYDROKINETIC ENERGY SYSTEM

Introduction

Hydrokinetics turbines or water current turbines are an emerging non-polluting alternative energy source. They produce electricity directly from the water flowing in a river or a stream with a velocity higher than 0.8 m/s, where no dam is needed [6, 7]. This natural form of power for electricity production has been of interest for quite some time. Thus, such hydropower technology has led to substantial variations as different ideas are developed. Factors such as weather conditions, variable water flow, and other artificial incidences influence the design of these systems and should be considered for their correct operation. Even though a number of concepts have emerged recently, axial (horizontal) and vertical axis turbines have been considered as primary choices for hydrokinetic energy schemes, and they represent 43% and 33%, respectively of the total systems [3]. Turbine concepts and designs including cross-flow, Venturi, gravitational vortex and other non-turbine systems are also being developed [4].

In addition to turbine concepts and designs, an important aspect of hydrokinetic technology is the relationship among design simplicity, reliability and system cost, since they represent significant differences compared to other renewable technologies. Most of the previous research has not included any extensive analysis about hydrokinetic turbine performance at low cost. The profiles of the blades are considered important, and the turbine blade profiles in the hydrokinetic energy systems are often derived from wind turbine blades. Such designs lead to higher efficiencies, but also have significantly higher manufacturing costs associated with 3D machining or forming. An alternative approach would be to consider a simpler blade design that
is less expensive to manufacture. The framework for such an approach would then consider system efficiency per unit cost.

The cost-benefit analysis then would center on the loss of energy capture or conversion efficiency and reduction in manufacturing cost. The choice between a vertical axis turbine and horizontal axis turbine again centers on balancing performance and design complexities. The generator coupling is more complicated for a horizontal axis system. Although vertical axis systems emit less noise than horizontal turbines, the vertical systems have low starting torque, more vibrations, non-uniform forces and lower efficiency, all of which may require special electromechanical arrangements. Additional factors include cavitation and fatigue loading due to unsteady hydrodynamics of the vertical axis turbines. Most of these factors are eliminated in the axial flow turbines [3, 8]. Early designs had vertical configurations, but now the trend is to horizontal arrangements because of the advantages associated with this configuration [9].

Therefore, the current study focuses on a horizontal hydrokinetic energy system. Similar systems have been created to generate electricity for 50W-100W range applications, but the cost varies depending on their manufacturing process. For example, a commercially submerged 3-blade water turbine developed by the Ampair Company (model UW100) is 12.2 inches in diameter and generates about 50 Watts in a 2.3 m/s flow. The generator output could be selected to be 12, 24 or 48 volts DC, and the price is around $1500 [10]. Another example is the Scott, a homemade waterwheel made from a cage fan of 20 inches diameter; this turbine generates 20 W, the gear ratio is 3:1, but it has very low RPM. This system charges 2 amps into a 12 V battery, 24 hours a day [11]. An experimental water turbine of 10 inches diameter with 50 W power output in a stream with a flow speed of 2 m/s exhibited efficiency of 35% [12].
Most of the present sustainable energy sector is focused on developing new storage technologies and how they can be used in a power source [13]. Thus the capacity for renewable power production is changing. Hydropower systems are increasingly cost-competitive because they represent the most economic option for off-grid electrification [2]. To work at high power levels, the designs need to be 1.5 to 4.0 m diameter, and operate at higher velocities and in deeper levels. For instance, the water current horizontal turbines from Thropton Energy Services go up to 2kW at 240 V, and their velocity varies in accordance with diameter size; whereas the small Darrieus cross-axis turbines reach 750 W at 1m/s; or the axial Submerged Hydro Unit produces 1-5 kW above 0.5 m/s [6, 14]. All of these systems include a permanent magnet D.C. generator with higher capacity, which constitutes a major cost component for the smaller systems.

On the other hand, most studies applied to the cost of the turbines are oriented to wind energy and are related to blade performance [15, 16]. An example was a study using a commercial low cost wind turbine (model MG4520) [17]. Hydrokinetics studies are oriented to hydrodynamic performance [8, 18] or increased efficiency through enhanced coefficient of power ($c_p$) [19-21]. As stated earlier, such approaches involve complex blade designs, and higher manufacturing cost. The final outcome for wind turbines then depends on balancing the coefficient of power with manufacturing costs. Similar research on the cost-performance analysis of hydrokinetic energy production is needed. This study is in part an overall effort towards cost-performance analysis of hydropower generation for small-scale applications. The front-end process of hydrodynamic-to-mechanical power conversion is the first step towards developing a comprehensive understanding. Therefore, this work reports on measuring power output generated from a fixed pitch, three-blade horizontal hydrokinetic energy prototype turbine.
Experimental Method

Testing Setup

The hydrokinetic energy conversion system used in this study consists of four subsystems: (a) the hydrokinetic-mechanical energy convertor device including the blades and shaft-chain arrangement; (b) the support structure; (c) the electrical power converter including the generator and the power control system; and (d) the steel tank with water flow system. Figure 1 shows the overall layout of the hydrokinetic energy system.

![Diagram of hydrokinetic energy system](image)

Fig. 1. An overall depiction of the first configuration of the hydrokinetic energy system.

The steel tank dimensions were $3 \, \text{m} \times 1 \, \text{m} \times 1.2 \, \text{m}$, and it is shaped to avoid any reflection waves getting into the test section; at the top it also incorporates an aluminum mounting frame. Inside the tank, was an acrylic tunnel, $0.60 \, \text{m} \times 0.60 \, \text{m} \times 2.5 \, \text{m}$ that works as a simple duct augmentation to provide a unidirectional flow. The volume flow rate for the system is determined by the product of the cross-sectional area of the tunnel to the average water
velocity (1.0 m/s). This system is able to move 372 l/s, which represents ~10% of the tank capacity (3400 l).

The key part for this testing is the turbine blades. The blades were commercially available fan blades made of aluminum sheets. Individual blades had constant chord length and the same cross section over the 0.175 m length. The blades were purchased for $20 in pre-mounted configuration with fixed pitch (Fig. 2). The specifications of this turbine are given in Table 1. The power transmission shaft is integrated with the electrical generator by a chain and a 4:1 sprocket ratio. This configuration was chosen for lower cost and simpler design for the placement of the generator and can achieve rotation rates up to 500 RPM. This system can vary water velocity up to 2 m/s at the front of the set-up; however, the maximum average velocity measured around the blades is only 1.3 m/s. The output of the turbine was rectified with a commercial permanent magnet D.C. generator (48V output).

![Fig. 2. The preassembled three-blade configuration used in this hydrokinetic energy prototype.](image)

**Electrical Configuration of the System**

In this work, only the energy extracted from the PMG, $P_{output}$, was computed. This power was dissipated by load resistors, as the purpose was only to measure the power capacity of the system and not to store. To provide a reference of this power output, it was compared to the
power in the free-water stream which flows through the area $A$ of the turbine, without mechanical power being extracted from it. This power is directly related to the flow velocity and is defined by [22]:

Equation 1. Power available

$$P_{available} = \frac{1}{2} \varphi v^3 A$$

The electrical power output is reported as the product of the measured voltage and current output from the generator as follows:

Equation 2. Power output

$$P_{output} = Voltage \cdot Current$$

Different sensors for monitoring and recording output power and rotation rate of the generator were also implemented. This power was dissipated by applying electrical load resistance on the PMG at the same time, which means there is no storage source as shown in (Fig. 3). The voltage and current were recorded with transducers over the electrical resistance from 5 $\Omega$ to 75 $\Omega$ and open circuit. The RPM were measured using a proximity sensor attached to the generator, and the incoming water velocity was measured by flow watch meter. LabView was used to acquire and process all the data. Power, torque, tip speed ratio (TSR) and coefficient of power were computed at water velocities of 0.5 m/s, 0.7 m/s, 1.0 m/s and 1.3 m/s. All these parameters had already been defined by [23, 24].

Equation 3. Torque

$$Torque = \frac{P_{output}}{Rotor\; Rotation\; Rate\; (\omega)}$$
Fig. 3. Block diagram on the first stage of the hydrokinetic energy system.

Table 1. Characteristics of the hydrokinetic energy system using a fixed-pitch blade.

<table>
<thead>
<tr>
<th>No. of blades</th>
<th>3</th>
</tr>
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<tbody>
<tr>
<td>Hydrofoil</td>
<td>N/A</td>
</tr>
<tr>
<td>Rotor diameter (d)</td>
<td>~0.5 m</td>
</tr>
<tr>
<td>Chord length</td>
<td>0.175 m</td>
</tr>
<tr>
<td>Blade pitch (β)</td>
<td>fixed at 22°</td>
</tr>
<tr>
<td>Cost of the blades</td>
<td>$20</td>
</tr>
<tr>
<td>Water density (ρ)</td>
<td>1000 kg/m$^3$</td>
</tr>
<tr>
<td>Rotor swept area (A)</td>
<td>$A = 0.2027 \text{ m}^2$</td>
</tr>
<tr>
<td>Rated output power ($P_{\text{output}}$)</td>
<td>~47 W</td>
</tr>
<tr>
<td>Maximum allowable output of the system ($P_{\text{available}}$)</td>
<td>220 W</td>
</tr>
<tr>
<td>Maximum water velocity ($v_{\text{max}}$)</td>
<td>1.3 m/s</td>
</tr>
<tr>
<td>Cut-in water flow velocity</td>
<td>~0.5 m/s</td>
</tr>
<tr>
<td>Radial Permanent Magnet Generator</td>
<td>D.C. (48 V)</td>
</tr>
<tr>
<td>Maximum Rotor Rotation Rate (ω)</td>
<td>500 RPM</td>
</tr>
</tbody>
</table>

Cost of the Power from a Hydrokinetic Energy System

The cost-performance-reliability analysis was carried out considering design simplicity of the turbine and cost of the current hydrokinetic system. This was then used to discuss scale-up
and projection of the associated return on investment (ROI). The cost of electricity depends on both location and pattern of use. For alternative energy systems, it is also determined by the percentage of operated hours at the maximum capacity in a given time period. The load factor for hydrokinetic energy is ~100 percent, since the water flow in the river is predictable and can have year-round flow for a suitable location. Thus, the system can be assumed to operate 24 hours a day for 355 days/year (assumption of downtime only for maintenance and possible technical repairs). This relation is expressed as:

Equation 4. Total operated hours

\[ \text{Total operated hours} = \text{load factor} \cdot 24\text{hours} / \text{day} \cdot \text{number of the business days/year}. \]

So, the cost of the power can be written as:

Equation 5. Cost of electricity

\[ $\text{Cost of electricity produced} = Wattage_{output} \cdot \frac{\text{hour used}}{1000} \cdot \frac{\text{Price}}{\text{kw}}. \] (5)

Figure 4 depicts an overview layout of linkages in energy conversion steps and elements that lead to the final cost of energy produced from the current type of hydrokinetic system. It lays out the basic factors that influence the cost of electricity from a hydrokinetic turbine.

Experimental Results

Power Output

This section presents data generated from this simplified version of a hydrokinetic system. Equation (1) was used to compute the theoretical power available in the projected cross-section of a ~0.5 m system at the highest flow velocity (1.3 m/s) available in the system. The maximum computed power is ~ 220 W.

Figure 5 shows the voltage and current variation with the water velocity for various electrical resistance values. The electrical load placed on the generator was varied in the range of
5 to 75 Ω and was measured for infinite load (open circuit). The highest current was measured to be ~1.5 A at the lowest resistance of 5 Ω (Fig. 5(a)). While the peak current varies systematically with resistance, some of the curves overlap because of the variation in measurement. The highest voltage measured was ~60 V at 75 Ω, which is the maximum load on the generator (Fig. 5(b)). Both parameters were measured between the cut-in speed of ~0.5 m/s and the maximum velocity of 1.3 m/s. The open circuit potential shows the maximum voltage that can be produced from this generator at a given water velocity.

![Diagram of hydrokinetic energy system](image)

**Fig. 4.** Overall layout of the costs to generate electricity from a hydrokinetic energy system.

![Variation of current and voltage](image)

**Fig. 5.** Variation of (a) current and (b) voltage with the water velocity for various electrical load resistances.
The voltage and current produced from the generator reflect how much kinetic energy from the river stream is converted via the blades depending on load resistance and rotor speed. For these experiments, the electrical load is the only parameter that can be changed directly. Thus current and voltage are inversely or directly proportional, respectively. When no load is placed on the D.C generator, it runs without resistance so the current stays at zero; on the other hand, voltage output is determined by the electrical load and how fast the generator is rotating at different water flow velocities (Fig. 6(a) and 6(b)).

As was mentioned earlier, current is directly affected by electrical resistance. So the rotation rate of the turbine affects current and voltage output differently. Figures 7(a) and 7(b) show the variation of current and voltage with respect to rotor rotation rate. This has implications for the maximum power that can be generated from the turbine. The resistance used for these plots was 55 \( \Omega \) at 1.3 m/s, where the maximum achievable output occurred for this system.

When resistivity decreases, more current can flow, and the load on the generator shaft increases; in other words, the system experiences higher torque and the rotor rotation rate decreases. Thus the minimum and maximum angular velocities occur at the smallest and largest...
resistances, respectively; they represent the two limits of the short and open circuit. For short circuit, the resistance is almost zero.

![Graph showing variation of current and voltage with rotor rotation rate.](image)

Fig. 7. Variation of (a) current and (voltage) with rotor rotation rate, at the maximum power output.

This causes a very low voltage potential between the transducers and the generator, which results in the minimum non-zero rotor angular velocity. Then for the case of the open circuit, the resistance can be considered to be extremely large, and thus no electrical energy dissipation exists. Under this condition, the power generated is balanced only by power losses, and the rotor runs without encountering any additional torque, which finally results in maximum rotor rotation rate.

Maximum power output of the system was ~47 W, as shown in Figure 8(a). This is only ~25 percent of the theoretical energy in the cross-section of water flowing through the system. It also shows the range of rotor rotation rate over which power can be produced. The electrical power increases after 100 RPM and reaches the maximum value at ~350 RPM. Because the pitch of the blade set is fixed, different power curves of the turbine at various electrical resistances loads and different water flow velocities were compared (Fig. 8(b)). The comparison started from the cut-in speed of ~0.5 m/s, continued 0.7 m/s where no much power was produced, then...
at 1.0 m/s, the average speed along the tank, and finally 1.3 m/s, the maximum water flow velocity.

Fig. 8. (a) Total power extracted from the generator as a function of rotor rotation rate. (b) Power output at different water flow velocities as a function of the electrical resistance.

**Torque**

Since the mechanical configuration of this system does not have space for a torque sensor, the torque of the blades could not be measured directly. Thus, the power output of the generator enabled obtaining the torque supplied by the blades using Equation (3), (Fig. 9(a)). The angular velocity at maximum power is larger than that at maximum torque. Power production starts at the cut-in speed of ~50 RPM where the torque is ~0.2 Nm. The maximum torque was obtained at ~250 RPM and then it started to drop; torque intersected to the power curve at ~300 RPM and ~1.4 N·m, but the power output continued increasing with rotor rotation rate. The variation of torque for various flow velocities as a function of rotation rate is shown in Figure 9(b). The values of the torque are small because the solidity of the blades is only 0.382.

**Power Coefficient**

To quantify the power coefficient of the system, the ratio between the electrical power extracted from the generator and the power available in the flowing stream was calculated, using
Equation (6).

**Equation 6. Coefficient of power**

\[ c_p = \frac{P_{\text{output}}}{P_{\text{available}}} \]

---

Fig. 9. (a) Torque and power from the turbine. (b) The variation of torque of the turbine, as a function of the rotor rotation rate respectively.

The peak \( c_p \) for this hydrokinetic turbine was \( \sim 0.225 \). For further understanding, the tip speed ratio (TSR) was calculated. The variation of \( c_p \) with TSR is shown in (Fig. 10). The maximum \( c_p \) is obtained around TSR of \( \sim 7 \) at the water flow velocity of 1.3 m/s.

---

Fig. 10. Variation of the power coefficient of this hydrokinetic energy system with the tip speed ratio (TSR).
The cost of energy production was determined by energy conversion processes until the generation of electricity as shown in (Fig. 11). The total cost for these hydrokinetic system components (generator, connectors, blades, transmission-shaft and the mounting frame) was valued at $770 and the State of Texas was taken as the place of operation, where the grid electricity cost to consumers oscillates between $7.74 - 8.68 ¢/kWh [25].

The purpose is to highlight the cost elements; further discussion is provided in [26-28]. The cost per month of the electricity production of the system (CEPoS) was calculated as a function of the product of the total electrical energy produced by the system (~50 W) multiplied
by the total hours operated per month (720 hours) and the cost of electricity in Texas (8.0¢). That gave the value of the electrical output \( \sim 2.88 \) $/month. Thus the ratio between the total cost of the system by the cost of electricity production per month indicated that the payback period is more than 20 years. This highlights that the return on investment for renewable energy takes longer than other types of energy production. Of course this prototype was designed for small amounts of energy production, and the calculations are for illustrative purposes. Time of the ROI, could be reduced in three ways: (a) increase the size for same \( c_p \), (b) increase the \( c_p \), and (c) augment the channel design to increase water flow velocity. If the size is increased to 1.15 m to extract \( \sim 1000 \) W, the return on investment can be recovered in one year if all the other cost elements are same. Another choice could be to increase the efficiency of the system, since it is able to extract 220 W with 0.5 m sweep area; if the \( c_p \) were doubled to \( \sim 0.5 \); the cost would be recovered in ten years.

**Discussion**

This study was focused on the cost of power generation from a hydrokinetic system with a simpler design. Because of a simple blade set, the efficiency obtained was only \( \sim 24\% \), which represents a feasible value that is in the range for other, more complicated or expensive designs. For example, the current system can produce more than twice the power as compared to the design in reference [11], which is also a simple design that uses a fan as an electro-mechanical convertor with the same diameter. Another comparison is with the work of Sharkh et al. [13], in which the system has 35 percent efficiency but the level of power generation is similar. The maximum coefficient of power for the current flat blades is 0.25 at a tip speed ratio of approximately \( \sim 7.4 \). Optimum values for TSR for three-blade configuration has been reported to be between 5-6 [22, 29]. The present TSR results of 6-8 for variable water speeds (0.5 to 1.3 m/s)
are consistent with the literature. The blade profile is non-optimal in that it does not taper towards the tip. The coefficient of power can be enhanced by simple modification to the profile from root to tip, and this will be explored in future research. Such a design will not add to the manufacturing cost of the flat blades, as production will still be a sheet metal stamping operation. Another aspect for future redesign would be the angle of attack.

The current system also had loss of efficiency from other electrical and mechanical considerations. The generator used in the current study is more efficient at rotation rates above ~800 RPM; whereas measurements in this study were conducted below 400 RPM. On the other hand, mechanical losses came mostly from frictional losses among the bearings, sprockets and the chain, all of which contributed to reduction in the rotor rotational rate. Improvements in these can be made without increasing system cost. A mechanical option is to use a gearbox to eliminate some of the frictional losses; however, that is likely to increase the overall cost. The number of blades also determines the coefficient of power; but in this study that was not an option, as low-cost manufactured blade sets available in the market typically have three blades. In the current design the solidity of the turbine was high because of the wider blades.

The discussion on scale-up involves increase in the sweep area, and that has the best possibility of increasing the power output per unit cost. Another design aspect for a larger system would be the use of a diffusor in the system to increase the flow velocity, since power output scales with the cube of water flow velocity. The cost of a simple sheet metal diffuser would need to be balanced with the increase in power output. The present approach of simple design of the whole hydrokinetic system kept the cost relatively low, because this design involves minimum manufacturing processes in contrast to other designs such as [10]. Further research is needed to develop this cost-centric approach to viability of alternative energy.
Conclusions

This research establishes a baseline power generation using a simple, low-cost blade set. The configuration of the system had limitations because of the simple design and the fixed pitch blade but does demonstrate the feasibility of achieving a reasonable coefficient of power. The design can be enhanced by reducing the mechanical and electrical losses with minimal cost penalty. The change in blade profile and angle are also design features that will improve system efficiency without increasing cost. An important aspect is to consider alternative energy production efficiency normalized by the system and operational costs. Such an approach to system development will enhance the prospect of alternative energy implementation both economically and competitively.
CHAPTER 3
DESIGN AND CONSTRUCTION OF A LOW RPM AXIAL FLUX PERMANENT MAGNET GENERATOR

Introduction

Axial-flux permanent magnet generators (AFPAG) have been employed as directly driven for wind and water turbines since they do not need a gearbox. This advantage leads to less wear, losses, and costs at higher efficiency. In addition, this type of generator can have huge power output possible at very low rotation rate compared to the traditional generators that need to revolve above 1500 RPM for generating significant power [30], thus there is a lower cost per watt of output.

Other benefits associated with low RPM generators in terms of performance are reliability and long life. In small energy applications, coreless axial-flux generators are characterized to have large diameters to enhance the match between power output and rotational rate of the turbine and then increase the power production. Also, the use of larger diameters augments the torque [31]. Thus more of the construction process of this type of generator is related to their efficiency, but this parameter led to more complicated electrical designs.

Furthermore, plenty of analogous generators have been built; the designs mainly differ on the number of magnets and the number of the coils to increase their electrical output and efficiency. The size, grade, and shape of the magnets determine the power output and cost; larger magnets and higher grade produce a more powerful alternator design. N40, N42, N48, N50, and N52 of Neodymium-Iron-Boron (NdFeB) are the most commercial and strongest grades for permanent magnets [32]. According to [33] round magnets are more powerful than rectangular but more expensive.
Most of the literature has been focused on wind turbines for greater amounts of electrical power production. In [30], there is a development of a wind generator with capacities above 100 kW. On the other hand, the size and the shape of the coils also define the efficiency, as well as the cost of the system. For instance, in [34], there is an array of 20 pole pairs with 15 coils, using a diameter of 238.26 mm, and can generate 3 kW above 300 RPM. In [31], there is a relatively small axial-flux generator of 120 mm in diameter within 12 pole pairs, and 6 trapezoidal coils; this performance achieved 390 W at 3000 RPM; in both designs, (NdFeB) rectangular permanent magnets were used. Another electrical configuration with an overall diameter of 495 mm, using the same type of magnets but now with a round shape, can be found in [35]. It has 32 magnets and 12 coils that were winding 276 times; this generator was able to produce 1 kW at 300 RPM and 2000 W at 500 RPM. The variety is extensive: [36, 37] presented more complicated geometries for axial flux generators, and [38-40] included a three-dimensional finite element method (FEM) for more accurate and efficient designs.

In this chapter, as a part of the prototype hydrokinetic energy system, the construction of a 400 mm diameter axial-flux three-phase coreless permanent magnet generator in a “sandwich” configuration (N-S type) was performed for a relative higher level of power production and cost-benefit at lower RPM, and the manufacturing process was similar to [34, 41].

This work was done primarily because the electrical power produced from the previous permanent magnet generator used in the first hydrokinetic energy system was small, so using the axial-flux configuration, the power output is enhanced. This generator consisted of two magnet disc rotors made from steel with 12 rectangular 48 NdFeB magnets on each disc, and the stator had nine trapezoidal copper coils of 12 mm thickness.
A drill press machine was used as an infinite source of power to test the total power capacity and torque production of this axial-flux generator. During the experimental testing, voltage, current, and torque were measured at different rotational rates. The output was purely dissipated with variable resistors that were connected to three bridge rectifiers to invert the A.C. signal into D.C. and estimated the power output.

Finally, a projection is presented for higher rotor rotation rates at the maximum output for future designs to improve their cost-effectiveness and increase their energy capacity of production.

Experimental Method

Electrical Design

An axial-flux PMG was designed for a water turbine that operates between water flow velocities of 0.5 m/s to 1.3 m/s. The electrical characteristics of the generator were calculated for 48 V output. The voltage output was rectified through a three-wave D.C. diode bridge rectifier, but in the current configuration the power will only be dissipated by different electrical loads, and there is no provision for battery storage or grid connection, (Fig. 12).

The number of pairs of poles, \( p \) is computed from the nominal frequency at a certain RPM of the generator, then the total number of magnets is calculated by the number of pairs of poles times two, and number of the coils is given by Eq. (7), [32]. The electrical design of [33] is as follows:

\[
\text{Equation 7. Number of coils:} \\
\frac{\text{Number of coils}}{\text{Number of the phases}} = \frac{\text{Pair of poles}}{2} \cdot \frac{\text{Number of the phases}}{2} \\
12 \text{ poles pairs} \times 2 = 24 \text{ magnets and} \\
\frac{12 \text{ pair poles}}{2} \times \frac{3 \text{ phase}}{2} = 9 \text{ coils}
\]
Furthermore, the axial-flux PMG has a sandwiched configuration: two rotor discs reside on both sides of the stator, and each one has twelve permanent magnets. Where each magnet faces its opposite pole on the other magnet rotor, the north magnetic poles of every other magnet on one rotor are aligned with all the alternative south faces on the other rotor and vice versa. This type of electrical configuration produces sinusoidal waveforms, (Fig. 13).

In Figure 13, an overview of all the dimensions between the stator and the two rotor magnets is presented. The air gap is the distance between the magnets’ faces; the mechanical gap
is the space between the stator and the magnets, where the thickness of the magnets is proportional to the thickness of the coils, and the inner area of the coils should be the same size of the magnets.

Table 2. The axial dimensions of the axial-flux PMG.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of the rotor discs, ( h_r )</td>
<td>5/8 in = 16 mm</td>
</tr>
<tr>
<td>Thickness of the back steel discs, ( h_s )</td>
<td>¼ in = 6.3 mm</td>
</tr>
<tr>
<td>Thickness of the magnets, ( h_m )</td>
<td>½ in = 12.7 mm</td>
</tr>
<tr>
<td>Mechanical clearance gap, ( g )</td>
<td>1/8 in = 3 mm</td>
</tr>
<tr>
<td>Thickness of the stator, ( h_s )</td>
<td>½ in = 12.7 mm</td>
</tr>
<tr>
<td>Thickness of the coils, ( h_c )</td>
<td>½ in = 12.7 mm</td>
</tr>
<tr>
<td>Air gap</td>
<td>3/4 in = 19.4 mm</td>
</tr>
<tr>
<td>Outer diameter of the rotor, ( d_{or} )</td>
<td>12 in = 0.3 m</td>
</tr>
<tr>
<td>Inner diameter of the rotor, ( d_{ir} )</td>
<td>2.5 in = 63.5 mm</td>
</tr>
<tr>
<td>Outer diameter of the stator, ( d_{os} )</td>
<td>16 in = 0.406 m</td>
</tr>
<tr>
<td>Inner diameter of the stator, ( d_{is} )</td>
<td>2.5 in = 63.5 mm</td>
</tr>
<tr>
<td>Diameter of the wire copper, ( d_w )</td>
<td>0.053 in = 1.35 mm</td>
</tr>
<tr>
<td>Inner area of the coil, ( A_c )</td>
<td>1.29 ( in^2 = 8.3 \ cm^2 )</td>
</tr>
</tbody>
</table>

Also (Fig. 14) depicts the electric circuit of the 3-phase generator. It starts at the A.C. signal from the 3-phase of the 9 coils-set in series to the electrical resistance between them. After passing through the two diodes of each bridge rectifier, the current was transformed into D.C. output, which finally led to the voltage output for the power production from the generator.

Fig. 14. Full bridge rectifier circuit from 3-phase A.C. to D.C. output.
Construction Process of the Generator

This axial-flux permanent magnet generator has a simple design, which makes it relatively easy to construct, and lower cost per unit of power. This section captures some of the steps involved and the tools needed for building this generator, according to the dimensions of the parameters defined in Table 2.

Mold building: Two re-usable plywood molds were built for the stator and the pair of magnet rotors, which were subsequently cast in resin for strength and protection from the other elements, (Fig. 15).

Coil winder: In Figure 16, a simple spool was constructed for making nine trapezoidal coils. The spool of the coil winder was mounted on a lathe machine. This setup gave tightly-wound and consistent coils every time; each coil had 130 windings. This number of turns gave an inner area proportional to the thickness and size of the magnets.

Fig. 15. Completed molds for the stator and rotor respectively.

Fig. 16. The coil winder, the RPM sensor, and the final bobbin-wound coil.
**Magnet rotor:** In the bottom part, they were integrated on ¼ inch thick steel discs, and the top had 12 rectangular (1 inch by 2 inch by ½ inch) N48, neodymium-iron-boron (NdFeB) magnets.

**Placing the magnets:** An aluminum template was used for placing the magnets on the steel discs (Fig. 17), and then they were glued at all the edges for firm attachment.

![Fig. 17. Placing the magnets and testing their polarity; also the final rotor before casting.](image)

**Stator:** The stationary component of the generator consists of nine coils of wire across which the magnets spin. The coils are trapezoidal and equally spaced around a circle (Fig. 18). This shape produces more flux density, which leads to a better usage of the generator’s volume and increases the efficiency. The wiring was done before casting, so each phase will consist of three coils in series, with a “star” connection and wired in three-phase configuration, thus for a 12 poles rotor there are 4 poles for every 3 coils.

![Fig. 18. All nine coils placed in the stator before the casting.](image)
Casting the stator and rotors: The winding was done and the coils were connected. They were cast along with the magnets with resin and fiber glass in their respective molds. The resin places them in a fixed space and prevents corrosion. Figure 19 shows the stator and the rotor after the resin dried.

![Fig. 19. Final stator and rotor discs.](image1)

After building all the components for the generator, the assembly of the hub, shaft, frame, and steel base were done. For this last step, the two magnet rotors must be perfectly aligned with the stator. Fig. 20 shows two views of the final generator, where the coreless stator is mounted onto the steel base and the magnet rotors to the hub, forming the sandwiched configuration.

![Fig. 20. Side and front view of the assemble components of the axial-flux generator.](image2)

Experimental Results

Afterward the construction of the axial-flux permanent magnet generator, the performance of the generator was experimentally measured on a drill press machine with clockwise rotation. The axial flux generator was mounted with the drill press in order to obtain
the baseline performance curves and to get an estimate of total energy that it can produce. The testing was done at different rotational rates at a lower end (50, 70, 90 and 130 RPM). First, it was tested with no electrical load placed on the generator (open circuit) and then with varying resistivity, which was decreasing from 30 Ω, 12 Ω, 6 Ω until 3.5 Ω. The D.C. output was obtained from the simple uncontrolled diodes that were connected to the generator. The power was calculated from the product of the voltage and current output. To measure the torque, a shaft- to-shaft rotatory torque sensor (TRS 300) of 100 Nm, 10 VDC of capacity was mounted on the spindle of the drill press. Then a transmission shaft between the generator and the spindle was built using a chain and a 1:1 sprocket ratio (Fig. 21). The general results of the output measured from the generator are summarized in Table 3 along with some additional information.

![Fig. 21. Testing facilities: (drill machine, generator, and controller).](image)

Table 3. General characteristics of the axial-flux generator.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Power</td>
<td>~350 W</td>
</tr>
<tr>
<td>Nominal Frequency</td>
<td>17.5 Hz</td>
</tr>
<tr>
<td>Maximum Voltage</td>
<td>65 V</td>
</tr>
<tr>
<td>Maximum Current</td>
<td>8 A</td>
</tr>
<tr>
<td>Maximum Rotational Rate</td>
<td>175 RPM</td>
</tr>
</tbody>
</table>
Pole pair number 12  
Dimensions of the magnets 2 x ½ x 1  
Coil number 9  
Number of turns 130  
Conductor size #16 gage, 1.36 mm diameter  
Number of phases 3  
Total Cost $400 USD  
Total mass 15 kg  
Efficiency <90 %  

The frequency of the axial-flux generator was calculated from Equation (8), [42]; \( n \) is the number of revolutions per minute from the generator, and \( p \) the number of pairs of poles. The maximum frequency was 17.5 Hz at the highest rotational rate of 175 RPM.

Equation 8. Frequency of the axial-flux generator

\[
Frequency = \frac{n \cdot p}{120}
\]

Power Output

Fig. 22(a) and 22(b) show the voltage and current produced from this generator. The maximum outputs are \(~65\) V and \(~8\) A, respectively, at 175 RPM and with the smallest load of \(3.5\) \(\Omega\). Note that when the RPM was doubled, the power output quadrupled. In this setup, the power output was limited to relatively low RPM.

Fig. 22. Variation of (a) current and (b) voltage with the rotational rate for various electrical load resistances.
Table 4 presents the values of the voltage and power dropped from the rectifiers at the different rotational rates using two scenarios: (a) with no load (open circuit), and (b) when the generator is submitted under the highest electrical resistance of 30 Ω.

Table 4. Voltage and power output from the drill machine.

<table>
<thead>
<tr>
<th>Rotational Rate (RPM)</th>
<th>Voltage (open circuit) (V)</th>
<th>Power output (W)</th>
<th>Voltage (full load, 30 Ω) (V)</th>
<th>Power output (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>18.7</td>
<td>0</td>
<td>16.4</td>
<td>8.85</td>
</tr>
<tr>
<td>70</td>
<td>25.2</td>
<td>0</td>
<td>22.55</td>
<td>16.91</td>
</tr>
<tr>
<td>95</td>
<td>35</td>
<td>0</td>
<td>31.2</td>
<td>31.2</td>
</tr>
<tr>
<td>130</td>
<td>48</td>
<td>0</td>
<td>43.5</td>
<td>65.25</td>
</tr>
<tr>
<td>175</td>
<td>65</td>
<td>0</td>
<td>59.5</td>
<td>113.05</td>
</tr>
</tbody>
</table>

In Fig. 23, it is observed that the maximum rotational rate tested was only 175 RPM, and ~350 W of power was produced using 3.5 Ω. Thus as the resistance decreased, more power was produced when RPM increased. However, this is not the total power that can be generated; the curves can grow more until they reach their maximum output at an optimum rotation rate.

Fig. 23. Power extracted from the generator versus rotational rate as a function of the electrical resistance.

Torque

Also, at the highest rotation rate, ~30 Nm at 3.5 Ω was the maximum mechanical torque produced from the generator (Fig. 24(a)). It can be observed that as rotation rate increases, less
rotational torque is needed to produce the same amount of power.

On the other hand, the torque produced from the generator was also measured using Equation (3) over each rotational rate and at every load resistance. For this approach, the maximum torque was \( \sim 20 \text{ Nm} \) at 175 RPM using the lowest resistor (Fig. 24(b)). Thus torque varies as a function of the electrical load placed on the generator, and it is directly proportional to its electrical current.

![Fig. 24. (a) Mechanical and (b) electrical torque versus the rotational rates at variable electrical resistances.](image)

Due to the high torque produced, the axial flux generator could be tested only until 175 RPM. Because of this, an extrapolation was done to determine the total energy production of this system. The same electrical resistors of the testing were used, but at higher rotational rates. In (Fig. 25(a) and 25(b)), the power and torque projections are plotted until 450 RPM. At this rate it is expected that the axial-flux generator will be able to generate 1000 W with a torque of 80 Nm using the smallest resistance of 3.5 \( \Omega \); therefore, only 30 % of the generator capacity was measured on the drill machine.
Fig. 25. (a) Power and (b) Torque projections from the generator at higher rotation rates.

Discussion

The original electrical design of the current axial-flux generator was applied on a wind turbine of 10 ft. diameter, where it could produce 1000 W at 450 RPM. Thus for this work, the same electrical configuration was built to generate ~300 W, but on a hydrokinetic water turbine with a smaller diameter, and with a maximum rotation rate of 400 RPM.

The experimental work on a drill machine revealed that this generator can achieve ~350 W at 175 RPM. However, the mechanical rigidity of the setup limited the measurements, so it was not possible to test the total power capacity of the axial-flux PMG due to problems on the transmission shaft between the generator and the spindle caused by high torque production; if the testing had continued above this rotation rate, or smaller resistances were placed on the generator, serious bending problems would have taken place on the generator, or the coils could have burnt. To find out the total capacity of the generator, the testing requires higher rotation rates, a stronger mechanical setup between the spindle of the drill press machine and the generator, and a cooling system for huge power production.

According to the projection that was made, only 35% of the total electrical power production was measured when the drill machine was used. The results indicate that this
electrical design starts to generate significant power above 300 RPM. Also, the projection showed that the torque sensor will work for future experimental work at higher RPM without problems.

On the other hand, the output of the PMG was improved compared to similar designs. For example in reference [31] also used 12 pole pairs, and that generator produced 390 W at 3000 RPM; whereas this axial-flux can produce 400 W, but using only 200 RPM. Another comparison can be done with the work of Bumby et al. [34], in which the generator can produce 1000 W at 300 RPM. For this work, the current generator takes higher RPM to produce the same amount of power, but using less number of magnets and coils, which means less materials and costs for the same power production. Thus with a fewer number of pole pairs, the cost of the axial-flux generator is reduced; however, the efficiency will be affected.

The axial-flux generator offers low cost per watt of output and high efficiency. The cost is around $400 USD; this price includes the core components (magnets, copper wire, stator, rotor discs, shaft, and hub). However, the set of 24 magnets used in this electrical design is still the single most expensive component of the generator; it represents the half of the cost. Nonetheless, there are still some changes needed to increase the cost benefit of the electricity production. An option could be reducing the number of magnets and the number of coils, but winding them more turns and using a smaller gauge for the copper wire, or keeping the same size and grade of the magnets, but increasing the number of magnets and coils, so the price will double but the power will be at least four times greater.

Finally, this generator will be mounted on the hydrokinetic energy system and tested. In this case, the generator needs only to produce 300 W from the hydrokinetic turbine; the purpose is to generate greater amounts of power at lower RPM.
Conclusions

Simple low-cost manufacturing techniques were developed to design and construct an axial-flux generator. The power production of the axial-flux generator depends on the efficiency, which is determined by its electrical design, size, grade, and the shape of the magnets. The larger magnetic field they have, the more power they can produce, but the cost will rise proportionally to these parameters. This generator, for low rotational rates, is an ideal choice for a reliable power source at an affordable price.

During the testing on the drill machine, the amount of energy generated was substantial, and there were no heating problems inside the bobbins. These experiments have consistently shown that this low-cost generator is a powerful and cost-effective solution for applications smaller than 1000 W.

The present generator will be tested on the hydrokinetic energy system, but a new setup will be built for the mechanical transmission between the blade-set and the generator to test it at higher RPM than those used on the drill press. With this new generator coupled with a hydrokinetic energy system, more power generation is expected due to the increase of the rotor rotation rates.
CHAPTER 4
PERFORMANCE OF POWER GENERATION FROM VARIABLE-FIXED-PITCH OF A HYDROKINETIC TURBINE USING AN AXIAL-FLUX PMG

Introduction

Hydrokinetic systems are attracting significant attention to generate energy from the movement of water. These non-polluted machines and/or devices are still in their development stage, but they have been growing as a sustainable source of new electric power generation.

The improvement of the design on hydrokinetic systems of power generation is increasing fast in the recent years due to the serious ecological concerns from the fossil fuels. At present, they are not economically competitive with conventional electrical energy production methods. However, the technological advancements and system level optimization are expected to elevate the hydrokinetic technology to a level where it becomes a viable source without any government push for this technology. These systems are gaining more interest around the world, since the conventional hydroelectric systems have significant environmental impact that has caused their production to decrease more than 10 percent from 2009 [27].

The mechanical and electrical schemes for hydrokinetic energy systems are extensive [3, 4], but most of the prototypes are developed from wind turbines. Conventional studies are focused on the number of the blades as it directly influences the solidity of the system [8, 19]. However, a recent focus in the literature is about variable-pitch blades to speed up the starting torque to reduce the vibration and thus increase the efficiency [43-45], but that means adding an electrical controller and raising the cost of the system. In addition, most of the pitch controllers that have been developed are also derived from wind energy. The simple pitch controllers are
used to optimize the operation of the wind turbines [46-48]. Moreover, the pitch angle controllers have been developed for variable wind speeds [49, 50].

Similarly, there have also been studies related to variable pitch for hydrokinetic turbines, but most of them are related to computer simulations. For instance, Lazauskas and Kirke [51] predict how variable pitch maximizes the performance of a Darrieus turbine. Sheng et al. [52] have performed a hydrodynamic analysis of a vertical axial tidal turbine with fixed and variable pitch using CFD simulations. In a recent study, Hu et al. [53] have reported a reliability analysis for composite hydrokinetic turbine blades with variable pitch.

Additionally, the performance of the pitch angle is also related to the electrical design of the generator [54], especially when there are low rotor rotational rates. Thus axial-flux permanent magnets generators have been employed particularly in wind turbines with variable-pitch for small-scale applications [55, 56], since they can reduce the cost of the electrical power production and increase the energy captured at a relatively low RPM after the energy transformation.

Because self-sustainability of commercial technologies depends mainly on economic viability, this chapter presents the second phase of the study of power generation and performance of a horizontal-axis hydrokinetic turbine (HAHT). In this stage, a variable-pitch blade configuration was designed for the same low-cost blades. The axial-flux generator (see Chapter 3), was mounted in a horizontal configuration into the hydrokinetic energy system. A new frame was built for the assembly of the generator, and all the components of the transmission shaft. Also, in this phase, a gearbox was used to have 1:1 ratio of the rotor rates, so mechanical torque can be monitored through a direct driven torque sensor as in references [57, 58].
In this chapter, the variable pitch angle of a water turbine is analyzed using simple blades. In particular, it is related to the extraction of their maximum available energy, torque production, and the final power output. The experimental test was conducted by a simple controller, the pitch of the blades was varied from 20º to 40º, and the generator was operated at a variable electrical load from 20 Ω to 100 Ω and infinite load (open circuit). Voltage, current, torque, rotor rotation rate, and coefficient of power were computed in LabView.

The results show high performances for all the variables compared to those of the first configuration of the hydrokinetic energy system, especially when the number of blades increased. Also, using the axial flux generator, power output was enhanced compared to that from the radial generator, but the output is still less than 100 W; the reasons will be discussed later. Torque increased significantly, and the rotor rotation rate was above 500 RPM for infinite load. Moreover, for the second phase, similar amounts of power were produced at a lower RPM, the coefficient of power rose to 0.25.

This second configuration highlighted what is the optimum pitch for a 19 in diameter blade with simple geometry in a flow water speed of 1.3 m/s. The addition of the axial flux generator enhanced the performance of the system; however, there are still other factors that decreased its efficiency. Therefore, new components are necessary to perform the output of the system and reduce the mechanical stresses on the shaft, as well as on the structure of the turbine, due to the energy losses.

Experimental Method

Testing Setup

For the second phase, another electro-mechanical configuration from the hydrokinetic energy system described in Chapter 1 was developed to improve the power output and its cost-
The new hydrokinetic system consists of the same four subsystems, but their components are different or have been modified: (a) the hydrokinetic energy converter device still includes the same untwisted, uniform cross-section, and low-cost blades, but a gearbox is added between the shaft of the rotor and the shaft of the generator; (b) the support structure is attached to a different transmission shaft that is placed horizontally; (c) the electrical power converter for the new array included the axial-flux PMG, and a torque sensor was added to the system; (d) the steel tank with water flow system remains unchanged. Figure 26 provides an overall view of the new configuration of the hydrokinetic energy system.

![Fig. 26. An overall depiction of the second phase of the hydrokinetic energy system.](image)

The main characteristics of the new hydrokinetic system are the rotor assembly, the addition of the gearbox, and the construction of the axial-flux generator. In this new phase, the core part is still the same aluminum set-blade that was tested in Chapter 2, but it is now using a variable-fixed pitch. This assembly is integrated by (a) a blade mount pivot, (b) the blade mount,
and (c) the blade hub (Fig. 27). All these components are made of stainless steel, and plasma cutting was used for easier manufacturing of their geometries.

![Components of the variable-fixed-pitch, before the blades were welded and the hub was completed manufactured.](image)

**Fig. 27.** Components of the variable-fixed-pitch, before the blades were welded and the hub was completed manufactured.

The blade mount pivot will allow the blades to rotate at the desired pitch. It will be manually turned and fixed, so it will not vary inside the tank. Thus the pivot needs to be changed every time for a different position during the testing, and the maximum angle of attack can be obtained easier as compared to that of other designs [45, 51]. The blades are welded to each component, but they can be removed from the hub. In Figure 28, a transition from the original set-blade to the variable-fixed-pitch blade is shown. The hub was completed in the redesign to change the pitch of the blades, and its cone geometry allows the water to flow easier through the blades.

![Fixed-pitch blade set and disassembly blades of the variable-fixed-pitch.](image)

**Fig. 28.** Fixed-pitch blade set and disassembly blades of the variable-fixed-pitch.
Furthermore, Figure 29 shows the gearbox that was added to measure the mechanical torque produced from the rotor shaft. This mechanical component gives the rotor rotational rate a ratio of 1:1 between the shaft of the water turbine and the shaft of torque sensor. Also, two couplings were attached on both ends of the gearbox and two others were connected between to the torque sensor and the transmission shaft.

![Gearbox Diagram](image)

**Fig. 29.** Side view of the gearbox attached to the water turbine with variable-fixed-pitch.

Finally, because of the high torque values of the axial flux PMG that were measured on the drill machine (see Chapter 3); an additional assembly was built into the original mounting frame to support the entire transmission shaft, which is integrated by a chain, a 4:1 sprocket ratio, and the torque sensor. This new array leads to the electrical generator, gives a stronger support, and avoids possible bending problems between the generator and the shafts-chain-sprockets arrangement; thus the system will be able to rotate at higher rotational rates without any problems. A proximity sensor is attached to the frame to count the RPM of the axial-flux PMG (Fig. 30).
Electrical Configuration of the System

Figure 31 provides a 2D side view of all the mechanical and electrical components of the present hydrokinetic energy system. For the new design, a shaft-to-shaft rotatory torque sensor will be included to measure the torque at the rotor shaft. It has a 100 Nm, 10 VDC of capacity, and two couplings connected: one to the shaft of the gearbox and the other to the shaft of the larger sprocket.

Another important component is the source of electricity, the D.C. axial-flux permanent magnet generator. It is a simple and cost-competitive generator that was constructed to increase the power production from this hydrokinetic energy system, since the former configuration only went up to 400 RPM and produced 47 W. The generator is placed horizontally above the level of the water that makes it more accessible; the turbine is oriented in a horizontal axis so it can directly drive the generator through the transmission shaft, which is attached to the generator.

The current axial-flux generator has a larger diameter because with this characteristic, it needs less turns or lower rotational rates to generate a higher amount of power. It is expected to increase the power output compared to the power that was generated using the previous generator through the current variable-fixed-pitch blade at a relatively low RPM. The axial-flux PMA is integrated by the stator that has nine rectangular coils and two rotor discs that reside on
both sides of the stator and have twelve permanent magnets on each rotor, which is known as “sandwich array” [33]. More details of the construction process and its properties can be found in Chapter 3.

![Block diagram of the components of the hydrokinetic energy system with variable-pitch blade.](image)

Fig. 31. Block diagram of the components of the hydrokinetic energy system with variable-pitch blade.

Regarding the electrical control of the system, the simple controller that was established in Chapter 1 will be maintained for regulating the torque, power output, and pitch of blades. The power was measured through Eq. (2), using the same voltage and current transducers from the first phase of this work; this parameter was also dissipated by different electrical load resistors of 3.5, 6, 12, 30 Ω, and open circuit (infinite load); the pitch blade was varied from 20º to 40º, where maximum energy was extracted.

The variable parameters for testing will be the electrical resistance and the pitch blade of the water turbine. They will define the maximum power and torque output of the system.
Although the hydraulic impeller and the power unit produce different water speeds, the measurements will be taken only for 1.3 m/s, which is the highest inflow velocity, so it will be considered a constant value. The turbine and generator rotational rates will be measured through a proximity sensor that works as a counter and is attached to the generator.

Finally, LabView software for the hydrokinetic turbine data analysis has been used to perform the power analysis and the coefficient of power was measured as a function of the power output and the power available Eq. (6), at variable pitch-blade.

Experimental Results

This section summarizes the results obtained using the variable-pitch blade to compare the performance of the power output and torque from a low-cost blade set, and enhance the cost-benefit of the energy conversion of the hydrokinetic system. To do this, the obtained coefficient of power of the first configuration was compared with the measurements of the coefficient of power of this second configuration. The measurements were performed for 3, 5, and 6 blades at a constant flow velocity of 1.3 m/s. All the plots depicted the average value of the testing for five runs with their respective standard deviation (σ). The general characteristics of the experimental water turbine for three blades are summarized in Table 5.

Table 5. Hydrokinetic turbine characteristics.

<table>
<thead>
<tr>
<th>Number of blades</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum pitch</td>
<td>25°</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>0.48 m</td>
</tr>
<tr>
<td>Rated power</td>
<td>55 W</td>
</tr>
<tr>
<td>Rated torque</td>
<td>13 Nm</td>
</tr>
<tr>
<td>Nominal rotor rate</td>
<td>235 RPM</td>
</tr>
<tr>
<td>Water speed</td>
<td>1.3 m/s</td>
</tr>
</tbody>
</table>

*Power Output at a Variable-Pitch Blade*

The power output values of the water turbine with variable pitch are computed for both
configurations. The first group of values belongs to the array of the hydrokinetic system with the radial generator (see Chapter 2); the pitch blade was varied from 15° to 45°. These results showed that 22° is the optimum angle for maximum power output of ~47 W at 420 RPM, (Fig. 32 (a)). Also, it is observed that as the angle decreases, the rotational rates are greater, but power production is reduced, and smaller pitch angles need smaller cut-in velocities. Figure 32(b) exposed the power output at an angle of 35° for 3 and 5 blades. The results showed that the production increased when more blades were added due to more solidity, but this happened at a higher RPM.

Fig. 32. Power output at variable pitch (a) 3-blade set and (b) 3-5-blade sets, versus rotor rotation rate on the first phase.

The second group represents the values for the second configuration, when the axial flux generator was used. For this array, the pitch of the blade was changed from 20° to 45°; in between this range, most of the power was computed. Figure 33(a) illustrates the best performances of the power output at different values of the pitch angle within a water inflow of 1.3 m/s, using variable electrical resistance (20 Ω to 100 Ω, and open circuit), where 100 Ω was the resistor for the maximum power extracted. Also, in Figure 33(b) ~55 W is the maximum power produced at 25°; moreover, at the open circuit, there was no power production for any
pitch, but the rotor rotation rate was the highest because there was no load applied on the generator.

Fig. 33. Power output at variable pitch versus (a) variable resistance and (b) rotor rotation rate for the second phase.

Figure 34(a) and 34(b) present the current and voltage output, respectively, of this second configuration. As it was expected, voltage increased with electrical resistance, thus RPM also augmented, whereas current was reduced. Table 6 shows the results obtained for voltage, current, and power for this second design using 3 blades with the largest resistors of infinite load and 100 Ω.

Fig. 34. Variation of (a) current and (b) voltage with various electrical load resistances at variable pitch in the second phase.
Table 6. Current, voltage, and power for variable pitch at open circuit and 100 Ω.

<table>
<thead>
<tr>
<th>Blade-pitch</th>
<th>Rotor Rotation Rate</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open 100 Ω</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45º</td>
<td>257 168</td>
<td>54.42</td>
<td>0.54</td>
</tr>
<tr>
<td>40º</td>
<td>293 183</td>
<td>59.18</td>
<td>0.59</td>
</tr>
<tr>
<td>35º</td>
<td>345 203</td>
<td>65.83</td>
<td>0.65</td>
</tr>
<tr>
<td>30º</td>
<td>420 227</td>
<td>74.12</td>
<td>0.73</td>
</tr>
<tr>
<td>25º</td>
<td>470 235</td>
<td>75.21</td>
<td>0.74</td>
</tr>
<tr>
<td>22.5º</td>
<td>506 226</td>
<td>76.19</td>
<td>0.77</td>
</tr>
<tr>
<td>20º</td>
<td>475 192</td>
<td>74.019</td>
<td>0.80</td>
</tr>
</tbody>
</table>

Furthermore, the experiments were running for different numbers of the blades: 3-5 and 3-6 at angle of 35º and 22.5º, respectively. Also in this configuration, power increased when more blades were used as it occurred for the first array. From Figure 35(a), a comparison can be made with 3 and 5 blades: power rose from ~43 W to ~48 W. On the other hand, in Fig. 35(b), the amount of power produced increased significantly when 6 blades were tested as compared to 3 blades: the power went from ~53 W to ~80 W. For both scenarios, more blades need slightly higher rotational rates to enhance the power production.

![Graphs showing power output at variable pitch](image)

Fig. 35. Power output at variable pitch (a) for 3-5-blade set and (b) 3-6-blade set, versus rotor rotation rate on the second phase.

**Torque at the Rotor-Shaft**

The shaft-to-shaft sensor measured the torque produced from the rotor shaft at variable
pitch. Figure 36(a) shows the torque obtained from this sensor: the output data highlighted an average value of 13 Nm for all the pitch-blade measurements at the maximum water speed of 1.3 m/s. Since torque is directly proportional to current, the highest torque was produced when the smallest resistor was placed on the generator. Figure 36(b) illustrates that torque also increased with the number of blades; however the values were similar to those obtained for 3, 5, and 6 blades.

Because the chord length of the blades is relatively small, the solidity decreased; thus there was not a very high starting torque, especially as the pitch blade was increased. This mechanical configuration generates low loads because of the small capacity of the power available in the system. In other words, the hydraulic impeller- and blade-set arrangement is a small source of energy, compared to the amount of energy that can be produced from the axial-flux generator. Due to this, small torque was produced, and it did not exceed the capacity of the hydrokinetic energy system.

Fig. 36. Mechanical torque versus rotor rotation rates for variable pitch.

Power Coefficient

The plots from Figure 37 show the coefficient of power for the first stage using 3 blades and the $c_p$ computed for the second stage of the HES with 3 and 6 blades. The design with the
variable pitch caused a higher starting torque for small pitch blades, thus the efficiency of the system was improved when more blades were used. The maximum $c_p$ on the first configuration was 0.225, whereas the second system went to 0.25 using the same number of blades, and for 6 blades, it rose up to 0.36. All these values were calculated through Equation (6) at a maximum water flow of 1.3 m/s. The maximum values of power, torque, and $c_p$ at 100 Ω are showed in Table 7 for a 3-blade set.

![Figure 37](image)

**Fig. 37.** Coefficient of power from both configurations of the hydrokinetic energy systems for 3 and 6 blades.

**Table 7. Values of the performance parameters as a function of the blade-pitch.**

<table>
<thead>
<tr>
<th>Pitch-blade at 100 Ω</th>
<th>Power (W)</th>
<th>Torque (Nm)</th>
<th>$c_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>45°</td>
<td>29.8</td>
<td>8.0</td>
<td>0.14</td>
</tr>
<tr>
<td>40°</td>
<td>34.9</td>
<td>8.5</td>
<td>0.16</td>
</tr>
<tr>
<td>35°</td>
<td>43.3</td>
<td>9.0</td>
<td>0.20</td>
</tr>
<tr>
<td>30°</td>
<td>50.2</td>
<td>10.0</td>
<td>0.23</td>
</tr>
<tr>
<td>25°</td>
<td>55.7</td>
<td>11.5</td>
<td>0.25</td>
</tr>
<tr>
<td>22°</td>
<td>53.0</td>
<td>12.0</td>
<td>0.24</td>
</tr>
<tr>
<td>20°</td>
<td>50.3</td>
<td>13.5</td>
<td>0.22</td>
</tr>
</tbody>
</table>

The cost-benefit of the system is determined by the cost of electricity production of the system (CEPoS) as it was calculated for the first configuration (see Chapter 2). In this case, 80
W was the maximum power output, thus the electricity cost from the second configuration and the time to recover this investment is shown as follows:

\[ CEP = \frac{80 \text{ W} \times 720 \text{ hours/month}}{1000 \times 8 \text{ ¢/kWh}} = \$4.61/\text{month} \]

The return on investment is equal to the ratio between the total cost of the system, which is $700 and the cost of electricity per month, $4.61, and then divided by 12 months. Therefore, 12.5 years are needed to pay back the cost of this configuration, and the annual output corresponds to the product of the power output in kW units times the total business hours, which gives a production of 610 kWh/year.

**Discussion**

The fact of adding a simple low-cost, variable-pitch design and axial-flux generator in a horizontal configuration to the system achieved higher starting torque and high efficiency compared to those of the first configuration. The results showed that the proposed design with the axial-flux generator allows the water turbine to generate more power than the first configuration, above all when 6 blades were used. The maximum output was reached with the largest electrical resistance of 100 \(\Omega\); this power was purely dissipated.

On the other hand, there was constant drive shaft torsion because torque was affected directly by current, thus rotation rates were reduced depending on the size of the resistor. In essence, Figure 38 describes the phenomenon that occurred between the torque produced from the water turbine and the axial-flux generator. This figure illustrates only the behavior of current and rotation rate using the 100 \(\Omega\) resistor; it started from open circuit, where maximum rotor rotation rate is achieved, so as current started to increase, RPM went down simultaneously or vice versa. This performance caused a dampened oscillation response in the generator, until both of them reached a stable state, so at this point measurements were made, each resistor became a
partial break to the current until they reached the equilibrium. In general, as electrical resistance decreased, current went up, thus torque and power augmented, whereas voltage and RPM were reduced.

Fig. 38. A dampened oscillation response of the axial-flux generator.

Moreover, the pitch of the blade set and the effect of the electrical loads control the behavior of the power output. This new configuration produced 80 W, but at lower rotor rotation rates compared to those from the first configuration. With this array, vibration problems were reduced because there was more power production per revolution. Also, this simple variable-fixed pitch design can theoretically achieve any desired angle of attack to enhance maximum efficiency. The plots showed that the power and efficiency could increase, when more blades were added; however, the addition of the blades did not affect the torque.

The cost-benefit of the system depends on the performance of the $c_p$. The highest water speed, low torque, and a relatively low solidity have achieved a power coefficient that rose from 0.22 to 0.25 for 3 blades and to 0.36 with 6 blades in this second scenario. Thus as $c_p$ increases, there is a higher energy production per month, and that means a smaller period to recover the investment. In general terms, the cost of the system is relatively low compared to other reported
designs [10-13]; however, the generator represented the most expensive component because of the rare-earth magnets.

While the simplicity of the blades remains the primary focus of this work, the efficiency of the system is limited due to the low cost of the blades. More of the energy losses occurred there because of their geometry, especially when torque increased. So when more blades were used the harnessed energy increased because more water was passing through the blades, and more energy was captured.

Since the axial-flux PMG is already able to produce more power than the system capacity, improvements upon the mechanical system are the only way to increase system performance. To produce greater mechanical power, the number of the blades, the rotor diameter, and the water flow velocity can be amplified. Alternatively to increase the power output and efficiency of the current hydrokinetic energy system a round shroud-diffusor can be utilized to increase the water velocities and eliminate energy losses on the blades, thus more water can be exploited and higher torque will be produced. Figure 39 illustrates the possible future designs for these components.

Fig. 39. Round shroud-diffusor for the hydrokinetic energy system.

Conclusions

An improvement of the current hydrokinetic system was developed using a new electro-mechanical array allowing for more power extraction. It has been shown that the configuration of the low-cost, variable-pitch blades and the axial-flux generator can develop higher starting
torque and efficiency compared to those obtained using the first configuration of the system, and the output can be higher if more blades are added. Also, it has been determined that there is an optimum pitch dependent on the number of the blades.

The axial-flux PMG was able to improve a different number of parameters: minimum maintenance, no heat problems inside the bobbins, double the power production at lower RPM, and the cost of electricity production was enhanced compared to that reached at the first stage of this work.

The current configuration has been found to produce more power, operate with greater efficiency, and require less maintenance for small-scale applications. The arrangements for this new design of the hydrokinetic energy system show increased performance with unsophisticated controllers and components, but improvements are still needed to further optimize the designs; in Chapter 5 some of the future work is introduced.
CHAPTER 5
CONCLUSIONS AND FUTURE WORK

Conclusions

The trends for energy production are changing, but hydropower is still the cheapest way to generate electricity. In this work, a river-based hydrokinetic energy system was studied and discussed in terms of energy conversion efficiency, so that the cost-benefit analysis drives the growth of this alternative energy form. Characteristics of hydrokinetic turbine power are focused on the simplicity of the blades; the experiments were conducted for different numbers of blades operating at fixed and variable pitch conditions for maximum power extraction.

A complete electro-mechanical design for a hydrokinetic energy system was developed. This prototype analyzed the power output associated to the torque produced from the blades using a simple controller. No power was stored; it was purely dissipated with electrical load resistances that were placed on the generator.

Based on the capacity of the hydrokinetic turbine system, an axial-flux generator was used to implement and perform the power output of this system, because flux generation is a unique way to harness power from the low rotational rates. The development of the axial-flux generator in the HES is similar to that of wind energy applications. The assembly’s experimental results reflected the performance of the proposed system. The efficiency of the hydrokinetic energy system is limited by its design and the energy conversion process; both factors reduce the overall output and determine the cost-benefit of the system. However, this study highlighted the idea for larger-scale systems that can have cost effectiveness in small periods of time when they are placed in similar conditions.
This research reveals the value of an effective, unsophisticated, and low-cost hydrokinetic setting. It also looks for areas where changes could be made to improve significantly the system operation and its energy production for small applications. It is recommended to improve the economics of energy efficiency, increase the cost benefit, and reduce the time interval to recover the capital investment for simple blade profiles. The blades for hydrokinetic production should be designed to generate large amounts of energy. They need to consider light weight, ease of assembly, and utilization of readily available materials or low-cost components which saves money. However, there is still a need to continuously improve the blade designs, materials, and optimize their associated manufacturing processes.

Future Work

Since hydropower generation is one of the predominant resources used to satisfy electricity demands due the high water availability, it is expected to be a preeminent form of energy for future years, but lowering the capital costs and accelerating the payback period are needed. Thus for the future of this hydrokinetic system, mechanical improvements are possible, such as increasing the size of the turbines; adding more blades with variable pitch for higher power extraction, but keeping their simplicity; and using larger ratio on the transmission shaft for higher rotational rates. Also, a simple form of shroud and diffuser with a removable turbine chamber can be included on the system to reduce energy losses and obtain greater influx of water flow velocities. Nevertheless, CFD is needed for reliable operation and validation for higher power coefficients to optimize the electro-mechanical design. This computational tool will provide crucial information for maximizing power output and saving costs, thus the cost-benefit will increase.
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