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PERFORMANCE EVALUATION OF HYDROKINETIC ROTORS USING CUSTOM MADE ON-SITE TESTING SYSTEM

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Abstract: *The paper presents the performance evaluation of two hydrokinetic rotors with geometric similarity using a specially developed on-site testing system. The necessity of this system derives from the need to effectively measure the power output produced by a hydrokinetic turbine during design stage. For an adequate characterisation and performance evaluation, similar models on a progressive scale were used. The increased diameters that can supply significant power require larger models which cannot be tested on testing benches in laboratory conditions. Therefore, testing should be performed on-site in real operating conditions of the river or channel where potential problems might be encountered such as the variation of the water level, turbine anchoring and electrical insulation of the generator and power output cables. In this regard, there was developed a dedicated and portable testing stand able to test hydrokinetic rotors of up to 1 m diameter with a generated effective torque of up to 20 Nm. The testing system was designed so that the electronic and electric components are placed outside the water and requires low power supply that can be provided from batteries when used in remote areas. The system operation only requires a laptop, a DC current source for the electromagnetic brake and a battery assembly. The system can achieve measurement of characteristic parameters such as power, mechanical torque or power coefficient for hydrokinetic rotors. The first measuring campaign focused on the performance evaluation of two hydrokinetic rotors: a small one with a diameter of 200 mm surrounded by a diffuser and a larger one with a 700 mm diameter without shroud on. Two different sites with increased water velocity were assessed. The torque and rotational speed parameters were registered using a torque transducer linked to a compatible software application, which allows data acquisition, real time monitoring and further analysis of the results.*

Keywords: *Hydrokinetic turbine, on-site testing, power output, data acquisition and analysis.*

1. Introduction

Hydrokinetic turbines use the kinetic energy of the water for producing ecological electricity without impacting the surrounding environment, with minimal influence on the river natural flow conditions without using a dam or diversion head works. The kinetic energy is available on most rivers although the power density represents an important obstacle for large-scale development. In contrast to conventional water turbines which operate based on a certain head and flow, the hydrokinetic turbines operate with reduced efficiency based on the similar principle as wind turbines. Thus, the maximum power coefficient (C_p) is usually below 0.45 and the only way to increase the power extracted is to increase the water velocity or to provide a shroud or diffuser around the rotor. Thus, the flow is concentrated from a larger surface which locally increases the velocity. The design of the rotor blades is a very complex process due to the fact that the performance of these turbines depends on various parameters like number of blades, tip speed ratio, air foil type, blade pitch, chord length and twist angle along the blade. Specific design methods are required in order to address certain issues related to performance, operational optimization, feasibility and environmental impact [1]. Among the advantages of hydrokinetic turbines, there is worth mentioning that these are easy to install, their operation being simple, while the maintenance costs are affordable.
The most convenient method to study them is to use small scale models driven in closed circuit testing stand or using towing tanks. The limitation of this approach is that larger rotors cannot be tested due to their size limitation and the proximity to the testing channel walls which determines the so-called blockage effect.
If the blades rotate near the channel walls, then the turbine performance in a partially blocked flow needs correction in order to reflect the operation in unbounded free stream conditions [2, 3].

Therefore, on-site testing can represent a solution at hand for performing rotors evaluation while ensuring constant water depth and velocity during measurements. The research aimed the on-site evaluation of the hydrokinetic turbines performance by using an improved rotor design which has been previously tested [4, 5] in order to identify if the power output is according to the results of the reduced scale model tested in a closed channel circuit.

Several papers and studies addressed various aspects regarding the operation of hydrokinetic turbines suitable to tidal currents [6] or to high velocities rivers [7]. Although these studies have addressed the characteristic determination of the hydraulic parameters, providing some important knowledge on related fluid mechanics phenomena, the information is not sufficient for a quantitative characterization and power estimations for such water turbines.

The issue of adapting and using the characteristics of experimental rotor models on a different scale was also addressed [2]. According to some literature recommendations, it is possible to adapt the power coefficient vs. tip speed ratio (TSR) curve in order to achieve correct power estimations. In some cases, the scale difference exceeds 1:30. Thereby, it is clear that an assessment is difficult to achieve.

Computational design optimization tools such as the Rotor Optimization Algorithm tested by Sale et al. [8] may be used for hydrokinetic turbine designs. The algorithm includes 15 defined variables in 5 control points, namely the blade hub, blade tip, and even spaced points in between. Afterwards, a Genetic Algorithm (GA) uses constraints and dependencies in order to determine the optimal shape of the blades. Optimizing a rotor for maximum hydrodynamic efficiency does not necessarily result in a turbine generating the highest annual energy production, but is rather related to maximizing the turbine efficiency (increasing approach angle/velocity) [9]. A possible reason for a low power coefficient of several solutions is represented by massive flow separation on the hub surface due to high adverse pressure gradient inside the diffuser, resulting on low mass flow capture and, hence, poor performance [10]. Riglin et. al [11] tested a hydrokinetic turbine prototype for river applications that was built for experimental testing in the circulating water channel at the Naval Surface Warfare Center, US. The prototype was designed based on numerous blade characterization and optimization analyses conducted using computational fluid dynamics (CFD) simulations. Testing was conducted for channel flow speeds ranging from 1.0 m/s to 1.7 m/s. The shrouded turbine with a tip diameter of 0.68 m, 3 blades and diffuser area ratio of 1.31 tested at 1.5m/s had a peak power coefficient of 0.37 at a tip speed ratio of 2.50.

Many of the applications developed for improving the operation of hydrokinetic turbines [12,13] have represented short-term testing installations. Thus, the evaluation of long-term functioning of these units is difficult to predict, although these short-term applications do provide insights on attainable power outputs. The research aims to continuously improve a certain rotor design by collecting more specific data regarding its operation in order to draw a more accurate prediction curve. The experimental data can be used for the achievement of correlations between rotor size, water velocity and mechanical power output and can lead to the efficiency estimation of other rotor designs just by scale model laboratory testing. If a large rotor is envisaged to be tested, the on-site system is another useful tool suitable to characterize a rotor design from model to large scale. Moreover, by using the data obtained in real operating conditions, a specific electric generator with a certain torque and rotational speed can be developed given that these turbines require custom made electric generators for increased efficiency.

2. Development of the hydrokinetic rotors and on-site testing system

The design of the hydrokinetic rotors used for testing was developed in other previous projects regarding the optimization of hydrokinetic turbines [14]. The optimum chord length calculation was performed for each section along the rotor blade and the most appropriate airfoil type was chosen. Simulations performed with Qblade software revealed the effect of the chord length for each section. The software generates specific curves when one of the input parameters varies in the given range (attack angle, velocity, rotational speed). It has been shown that changes in chord length along the blades and variation of the twist angle have a significant impact regarding the power output. The blade design and airfoil type are presented in Figure 1.

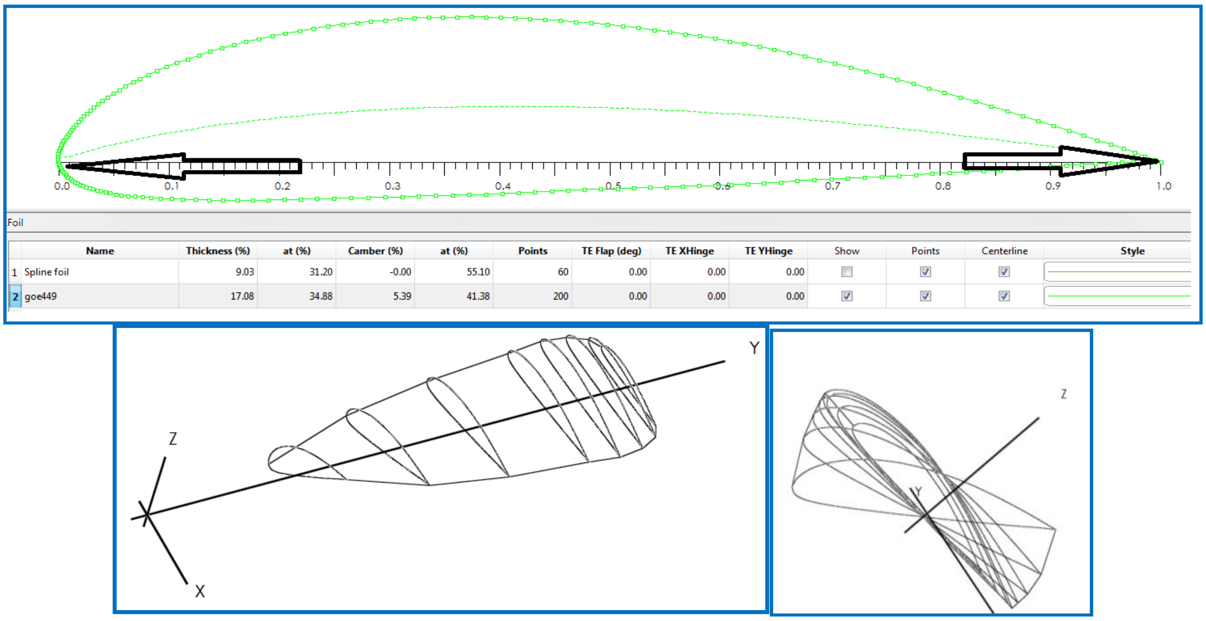

Fig. 1. Improvements of the rotor blades structure achieved for the determination of the optimal geometry [8]

Based on the calculation methods suggested in [15] as well as the results obtained by successive simulations, the optimum rotor geometry allowing the increase of the conversion efficiency was achieved. A first rotor model with a diameter of 200 mm was built using 3D printer and tested in a closed-circuit testing bench designed for axial hydraulic turbines [4]. The experimental testing of the model showed that the best results were obtained for a pitch angle of 40° when the supplied power reaches a maximum value of 4.2 W at a water velocity of 0.9 m/s. In the following stage, the design was improved by printing the rotor model in a single part with rounded hub and fixed blade position [16]. The rotor design presented in Figure 2 has four twisted blades with GOE 449 profile and variable chord length.

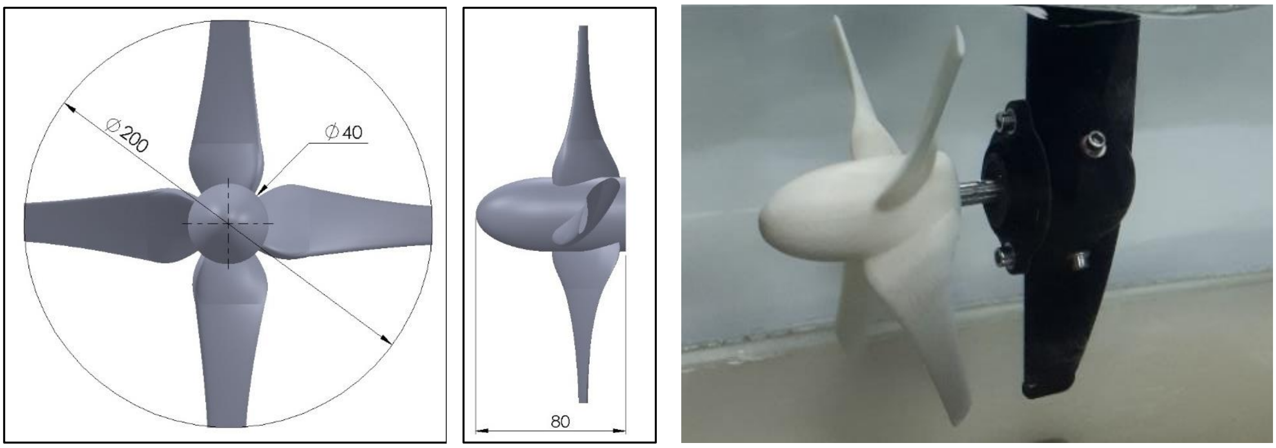

Fig. 2. 200 mm hydrokinetic rotor – 3D view and printed object prepared for testing [10]

The same design was also used for the second rotor which was manufactured at a larger scale respecting the geometric similarity. This was developed by several parts joined together by screws. The resulting diameter of the rotor was 700 mm. The rotor comprises four blades including their support and the central hub as presented in Figure 3. The geometric similarity will provide conditions for comparison between progressive scale rotors.

Fig. 3. 3D printed 700 mm rotor

For on-site testing of the rotors and better understanding of their behaviour in real operating conditions, a special system was developed. It is based on mechanical transmission with bevel gear and positioning system on boat, pontoon or bridge. The movement of the rotor is transmitted through an inner shaft at the top of the installation, where a torque and speed measuring system is placed within a specially constructed enclosure. The enclosure comprises an assembly of elastic couplings, torque transducer and electromagnetic brake, capable of performing torque measurements up to 20 Nm and speeds up to 4000 rpm. It has a simple and robust design in order to ensure a quick assembly and facilitate easy maintenance and further adjustments. The system shown schematically in Figure 4 is modular and allows the transducer or brake to be replaced or inspected without significant operations.

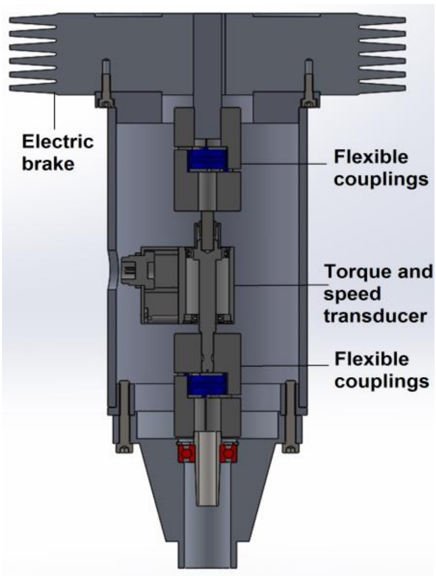

Fig. 4. Torque and speed measurement unit

Since field testing was considered, the components were chosen in order to be easily transported and installed, with low power consumption provided by batteries without grid connection. Therefore, a torque transducer was used with data transmission via USB port, powered at 5 V, with a required maximum current of 500 mA. A dedicated USB amplified extension cable with a length of 20 m provides the connection to a laptop running the data acquisition software for recording the measured values. The DR-3003 transducer model, manufactured by Lorenz Messtehnik Gmbh is characterized by an accuracy class of 0.1% of the full scale. The sensor is linked through VS3 interface ensuring that analog sensor signals will be digitized with up to 16-bit resolution. By the measuring rate of 5000 measurements/s per measuring channel, high-dynamic measurements can be achieved. Another critical component of the testing system is the electromagnetic brake which ensures the load of the turbine similar to an electric generator. The advantage over a conventional electric generator is that torque and speed values can vary significantly, the power adjustment being determined by the gradual loading of the brake until the rotor stops. An electromagnetic brake with a maximum torque of 35 Nm, FRAT 350 model, produced by Mobac Gmbh, was chosen. The final enclosure of torque and speed measurement unit is presented in Figure 5a. Figure 5b indicates the content of the enclosure which consists of torque transducer and related flexible couplings.

Fig. 5a. Enclosure of the torque and speed measurement unit

Fig. 5b. Torque transducer and flexible couplings

The torque and speed measurement unit was assembled with a mechanical transmission of the testing installation fitted with bevel gear at the end which transmits the movement from the immersed horizontal rotor to vertical plane, resulting the assembly in Figure 6. A fastening system is provided in the upper part of the assembly. It facilitates the fixed grip to the pontoon or bridge.

Fig. 6. On-site testing system with a 700 mm rotor ready for testing

The mechanical transmission connects the hydrokinetic turbine to the test system and has a length of 720 mm from the rotor axis to the torque and speed measuring system, allowing to test hydrokinetic turbines with diameters up to 1 m. The use of this system generates mechanical losses, which cannot be determined by using the torque transducer and have to be determined separately. Therefore, the torque loss due to friction caused by the bearings was previously rated at 0.24 Nm. This value will be subtracted from the result of the useful torque measurements at the turbine shaft because it cannot be determined directly with the torque transducer, placed behind the transmission chain. A stiffening rod is added to the assembly to avoid bending the drive shaft when large rotors are tested in high velocity water.

3. On-site hydrokinetic rotors testing

Testing was performed in two sites with water velocities above 1 m/s. The 700 mm rotor was tested in the tailrace channel of Mihăilești hydroelectric plant, Giurgiu County, Romania. In order to achieve the experiments, a pontoon was designed and built in the frame of a previous project related to low head hydrokinetic turbines suitable to natural or artificial water courses. The pontoon shown in Figure 7 was positioned in the middle of the channel, being anchored on both banks. At the upstream side of the pontoon, the testing system was deployed using a retractable support. The median water velocity can reach 1.6 m/s in the channel, when all the water turbines of the hydroelectric power plant operate at full potential. Testing was performed at 1.45 m/s at a depth measured from the tip of the upper blade of around 50 mm. Experimental testing imaging of the 700 mm rotor are presented in Figure 7.

Fig. 7. 700 mm rotor testing

Figure 7 shows the system in upright position aligned and prepared for testing. Also, there are indicated the downward position, when the rotor is submerged in water as well as the devices and equipment used for operating the system. Several trials were performed and the resulted data was stored for further analysis and interpretation. During the tests, the water turbines of the hydroelectric power plants were set to operate at maximum capacity in order to maximize the water flow rate in the tailrace channel so to obtain a velocity of 1.45 m/s in the immersion area of the rotor. The water velocity was measured by using SonTek 3D Doppler Velocimeter equipment - Micro ADV (Acoustic Doppler Velocimeter) which operates in the range of 0.001 to 4.5 m/s.
The 250 mm hydrokinetic turbine was tested on a channel through which the excess water from the Roșu Treatment Plant reaches Morii Lake located in Bucharest, Romania.

Through this channel, the water from Argeș river supplements the Morii Lake volume.
The location was chosen considering the channel has significant water velocity and is provided with a pedestrian bridge which allows the immersion of the testing rig. During experimenting, a water current meter was also immersed to measure the median water velocity. To increase the rotor speed as well as the output power, a hydrodynamic profiled diffuser was mounted. This shroud facilitates the power increase by creating a high pressure area inside. A divergent diffuser with an output diameter of 250 mm was used. Measurements images are shown in Figure 8.

Fig. 8. Experimental testing of the 250 mm shrouded rotor

During tests, shaft torque and rotational speed values were recorded by progressive loading of the electromagnetic brake powered by an adjustable DC source. The source was powered by a 1kVA inverter connected to a 12V battery able to supply at least 3 hours of continuous measurements. The data was saved by the torque transducer application in csv file format and exported subsequently for further processing.

4. Results and interpretations

Given the registered torque and rotational speed values *n*, other specific parameters were calculated, as follows: the mechanical power available at the turbine shaft - *P*, the power coefficient - C_p, tip speed ratio – *TSR* representing the ratio between the peripheral speed and the velocity of the considered fluid. These determined values lead to the characteristic curves $C_p = f(TSR)$ and $P=f(n)$ can be drawn. The power output *P* can be calculated by using the formula:

$$P = M\omega \tag{1}$$

where *M* – is the torque, and *ω* the angular speed, which can be determined as:

$$\omega = \pi n/30 \tag{2}$$

In order to determine the $C_p = f\ (TSR)$ curve, it is necessary to determine TSR by the formula:

$$TSR = v_{per.}/v \tag{3}$$

where $v_{per.}$ represents the rotational speed at the periphery of the rotor and *v* the upstream median water velocity, which can be determined as follows:

$$v_{per.} = \omega R \tag{4}$$

Where *R* is the radius of the tested rotor.

The power coefficient represents the ratio between the determined mechanical power P and the theoretical power $P_{th.}$ which is given by the following relation:

$$P_{th.} = 1/2 \cdot \rho A v^3 \tag{5}$$

where A is the equivalent area of the rotor and ρ the water density.

In the case of the 700 mm diameter rotor, the characteristic curves determined at 1.45 m/s velocity are shown below in Figure 9 – Power curve and Figure 10 – Power coefficient curve.

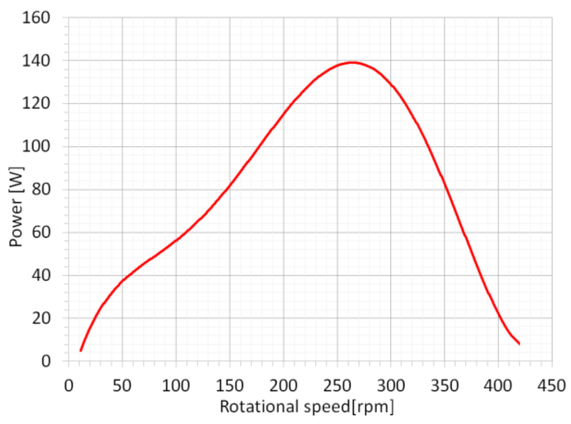

Fig. 9. Power curve for the 700 mm rotor

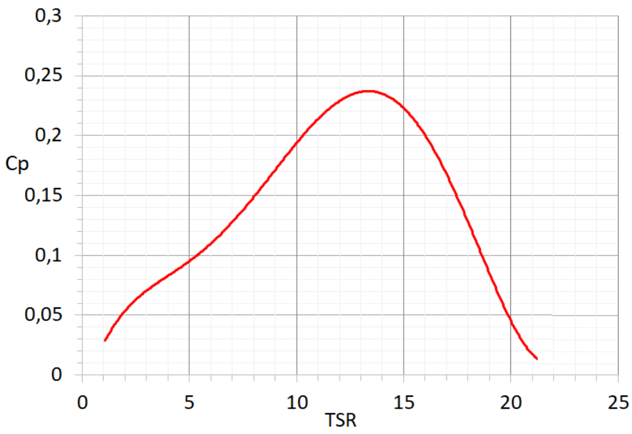

Fig. 10. Power coefficient curve for the 700 mm rotor

For the 200 mm rotor, the characteristic curves determined at 1.42 m/s velocity are shown in Figure 11 – Power curve and in Figure 12 – Power coefficient curve.

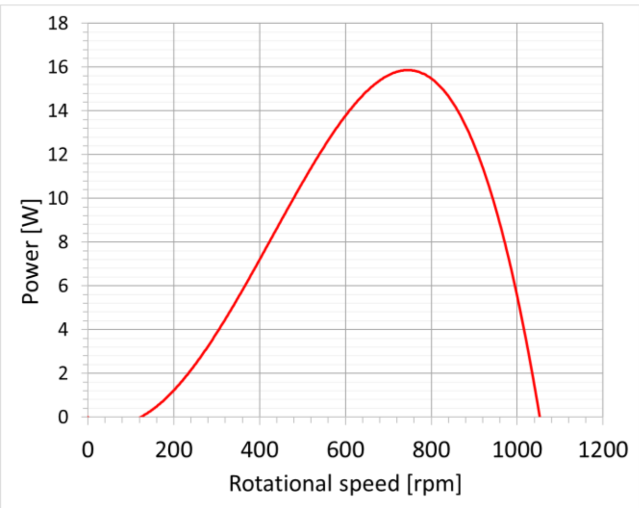

Fig. 11. Power curve for the 200 mm rotor with shroud

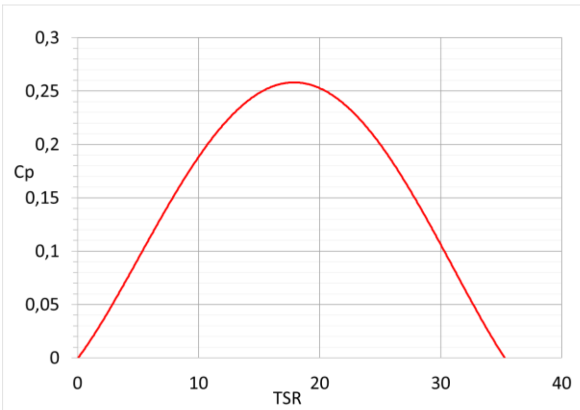

Fig. 12. Power coefficient curve for the 200 mm rotor with shroud

As depicted in Figure 12, the increased value of the power coefficient C_p is obtained in the case of a lower TSR value given the increased size of the rotor. Larger rotors determine reduced rotational speeds and according to relation (3) the TSR reduces accordingly. The power coefficient for the both rotors was approximately 0.25 while the shrouded rotor is characterized by slightly increased values. Prediction curve could not be drawn given that one of the rotors was tested with a diffuser which locally increased the rotational speed of the rotor.

The diffuser was used in the scope of increasing the starting torque of the 200 mm rotor which is difficult to drive due to reduced size and residual torque of the brake and the bevel gear. Thereby, it improves the power output of the rotor, but reduces the operating range with increased efficiency as can be seen in Figure 11. Thus, the diffuser influences the registered parameters compared to bare rotor. A comparison at different scale is possible only if the studied rotors are the same type, either with or without shroud. The registered parameters using the installation allow to further design an electrical generator suitable to be used in the determined range of rotational speed and torque. The evaluation of the rotor specific parameters allows the determination of the generator's efficiency and its related devices like controllers and inverters. Nevertheless, the on-site testing system proved useful for the evaluation of a considered rotor with or without diffuser in terms of rotational speed and generated power.

5. Conclusions

The paper presents a tool which is useful for the continuous development of hydrokinetic rotors by identifying the power produced at certain rotational speed values. The determined parameters are critical for designing an electric generator, another important component of the turbine. In this regard, a dedicated and portable testing stand was developed which was able to test two similar hydrokinetic rotors at different scale: a small one with 200 mm diameter surrounded by a diffuser and a larger one with 700 mm diameter without shroud. The two impellers were tested on two different sites with available increased water velocity. The developed system can achieve measurement of characteristic parameters such as power, mechanical torque or power coefficient for hydrokinetic rotors. The torque and rotational speed parameters were registered using a torque transducer linked to a compatible software application, which allows data acquisition, real time monitoring and further analysis of the results. Testing procedures showed that the on-site testing system can achieve the performance evaluation in terms of torque, power and rotational speed of rotors tested in channels with water velocity around 1.5 m/s. Future work considers testing different rotor designs and identification of other suitable rivers or channel where hydrokinetic turbines can be installed successfully.

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