Hydrokinetic Energy Harnessing for River Application

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***Abstract*—Hydrokinetic Energy Conversion System (HECS) is the electromechanical devices that able to harness the electricity from river current, tidal stream or man-made water irrigation system. In this work, design considerations of vertical-axis hydrokinetics turbine for Pahang river have been initiated. Double multiple streamtube (DMS) algorithm in QBlade software has been used to determine the rotor performance. In this design, NACA 0015 hydrofoils, and three blade rotor configurations with 0.25m chord length has been identified. Based on simulation design, the H-Darriuse turbine able to harness 200W output power at 0.582m/s water velocity with 5.5m^2 swept area.**

***Index Terms*—H-Darrieuse; Hydrokinetic; QBlade; Vertical Axis.**

I. Introduction

The necessity of new energy sources has received considerable interest due to concerns about CO_2 gas emissions, greenhouse effects and environment problems. Nevertheless, the increasing of energy demand and running out reserves of fossil fuels is also one of the major factor. Electricity generation from sustainable energy sources and environmentally friendly method are being considered. One of the sources is from kinetic energy stored in moving water such as river and tidal currents. The hydrokinetic energy conversion systems are the devices that able to convert the kinetic energy of river streams, tidal current or man-made water channels into useful energy. The systems also require no special head and any physical structure to operate [1].

The advantages of hydrokinetics system over the conventional hydropower is that the system requires minimum civil works [2]. This means, the system not required to construct a water storage system or reservoir to accumulate the water. Compared to a conventional hydroelectric system which is required the reservoirs and penstocks to extract the potential energy of falling water. Besides, the system has minimal impact on biodiversities, such as people relocation or destruction of flora and fauna. In addition, this type of energy harvesting systems provides a good choice of electrification for off-grid remote communities which is transmission lines do not exist [1]. Although the hydrokinetic system can harness a small amount of energy, the amount of energy harnessing can be increased by installing in multi-unit arrays system such a wind turbine farm [3]. The system can also be predicted especially for river streams and tidal currents. As a result, the hydrokinetic system is more valuable and predictable energy compared to the wind and solar energy system [4]. In terms of electrical hardware, turbine, concept of operation and variable speed generator, both hydrokinetic and wind turbine has a close similarity for optimal energy extraction [5]. However, compared to a similar rate of a wind turbine, the hydrokinetic system can produce four times, energy extraction at the rated speed of 2-3m/s [6]. This is because of fluid density in water is 800 times denser than air, hence the hydrokinetics turbines are able to extract the energy even at low speed [7].

Like the others energy production method, hydrokinetic also has several drawbacks. The turbine system has a lower power coefficient and relatively suitable for small-scale power production. The maximum efficiency of the hydrokinetic turbine system can reach 59.3 %, which also known as Betz limit [1]. Cavitation is also one of the biggest constraints of hydrokinetic turbines because it able to damage the turbine. This phenomenon occurred as the formation of water bubbles or voids when the local pressure falls below the vapor pressure [1]. The harsh marine environment can also damage the hydrokinetic system. The design of energy conversion devices must strongly withstand the high and irregular water loads [1]. Besides, the installation of hydrokinetic systems in the river and sea can block the navigation and fishing. Moreover, the turbine parts, chemical agents, noise and vibration can badly affect the water habitat in the river [1]. In this paper, a design consideration for straight blade H-Darrieuse for Pahang River has been initiated. The turbine design is expected to generate 200 W output power at 0.582 m/s water velocity. In this work, streamtube modeling of the H-Darrieus is carried out to analyze the turbine performance.

II. Survey of Technological Progress

Based on the formal literature, the first river current turbine was developed and field tested is attributed to Peter Garman [8]. Garman turbines were used for water pumping, irrigation and to harness electricity in remote areas. The system was developed by the Intermediate Technology Development Group (ITDG) in 1978. An assessment of various river resources in the United States (US) was carried out by Environment Inc. under the US Department of Energy’s ultra-low-head hydro program during the early 80s [9]. In the project, a free rotor turbine with 15kW at 3.87 m/s water velocity were carried and successfully installed.

In 1995, Gorlov Helical Turbine(GHT) was designed by

Alexander M. Gorlov at the Northeastern University, Boston, USA. Gorlov turbine employs twisted blades with the helical curvature structure. The designed gained significant attention for both river and tidal applications. The turbine design has been claimed for better modularity, scalability and more economics [2].

Various rivers and tidal energy converters have been emerging since the early 1990s in the commercial domain. UEK Corporation in the United States was developed diffuser augmented solid pontoon for river/tidal turbines under the brand name Underwater Electric Kite [2]. Table 1 shown the various companies and associated technologies in the hydrokinetic system.

Table1
List of Companies and Associated Technologies [10]

Manufacturer	Device name	Power Output
Lucid Energy Pty. Ltd (USA)	Gorlov Helical Turbine	Up to 20 kW
Thropton Energy Services (UK)	Water current turbine	Up to 2 kW at 240 V
Tidal Energy Pty. Ltd (Australia)	Davidson-Hill Venturi (DHV) Turbine	From 4.6 kW
Seabell Int. Co., Ltd. (Japan)	Stream	0.5-10 kW
New Energy Corporation Inc. (Canada)	EnCurrent Hydro Turbine	5 kW (and 10 kW)
Eclectic Energy Ltd. (UK)	DuoGen-3	8 Amps at 3.09 m/s
Alternative Hydro Solutions Ltd. (Canada)	Free Stream Darrieuse Water Turbine	Up to 2-3 kW
Energy Alliance Ltd. (Russia)	Sub-merged Hydro Unit	1-5 kW (and >10 kW)

A. Hydrokinetic Energy Conversion

Figure 1 shows a complete hydrokinetic energy conversion system. The system consists of the turbine rotor, gearing and bearing, permanent magnet synchronous generator (PMSG), electronic power converter and DC load. The hydrokinetic system basically has a turbine with two or more blades rotating around horizontal and vertical shaft mounting on the generator. The concept is based on the effects of the hydrodynamic forces generated by the free stream. The blades rotate with the torque that is produced by the lift or drag force. Selecting a high-performance hydrofoil with the largest lift/drag ratio is important in the design process due to this reason.

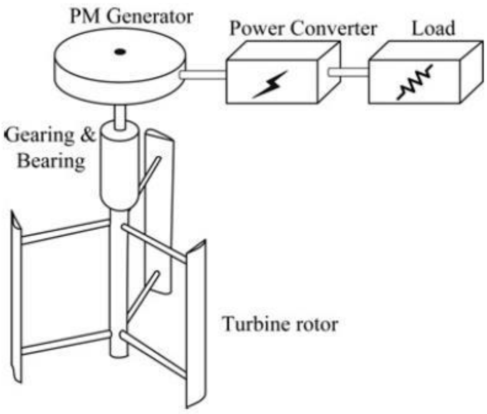


Figure 1: Vertical Axis Hydrokinetic System [11]

B. Basic Principle and Operation

Blade Element Momentum (BEM) and Double Multiple Streamtube (DMS) algorithm are the main principles to model the rotating hydrokinetic turbines. The algorithm provides a details turbine design procedure, including the lift and drag forces over a different angle of attack (AoA), thrust and power coefficient, rotational speed, twist and pitch angle distributions [1].

The angle of Attack (AoA) is the angle between the relative velocity and the blade section's chord line. Figure 2 shows the resultant loads on the blade section or hydrofoil with an optimum angle of attack (AoA). The extracted power is proportional to the relative velocity (V_{rel}) which is the sum of vector axial and tangential velocities. The angle of attack (α), varies from hub to tip with the effect of the tangential velocity [1].

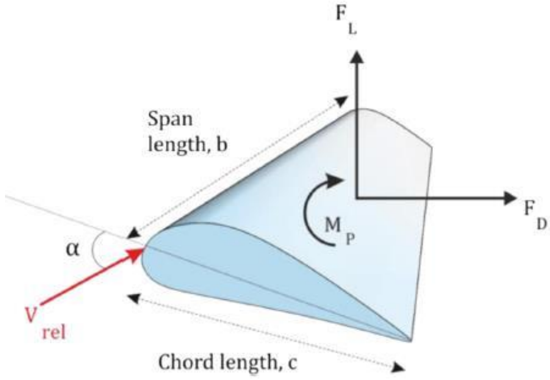


Figure 2: The resultant load on typical blade section [1].

F_L and F_D are lift and drag coefficient of the airfoil blade respectively. These two parameters solely depend on the blade shape and Reynolds Number (R_e) under a given operating condition. While Reynolds Number is an index of turbulence created by body placed in fluid [12]. R_e can be expressed as:

$$R_e = \frac{V.d}{v} \tag{1}$$

where, v is the kinetic viscosity of the water equivalent to 1.1x 10^{-6}, rotor diameter (d) and water velocity (V). Then, the estimation of R_e can be found. Basically, the value of R_e is big enough to reduce the cavitation. The aspect ratio (AR) of the blade is a measure of its length and slenderness. The (AR) can be expressed as;

$$AR = \frac{h}{c} \tag{2}$$

where h=height and c=chord length.

The dimension of rotor turbine diameter (d), number of blades (N) and blade chord length (c) is interrelated through solidity information. The solidarity (σ) can be expressed as;

$$\sigma = \frac{N.c}{d} \tag{3}$$

River/tidal turbines have a higher solidity compared to wind turbines. The solidity values may range between 0.15 to 1.6. Lower solidity implies better hydrodynamic performance, while higher values of solidity generally allow stronger mechanical structure. As a result, the induced torque will be increased [12]. The maximum efficiency for an ideal turbine can reach is knows as Betz Limit. Betz law proposed that the theoretical maximum power coefficient for rotating turbine in the fluid stream and wind turbines is 0.593 [1]. However, this efficiency can be applied to hydrokinetic turbines working in a free stream without augmentation. By using the augmentation channels or ducts around the turbines this theoretical limit may increase. This is because the concentration of incoming water velocity toward the rotor turbine [12]. Figure 3 shows the power coefficient (C_p) comparison for a different type of turbines.

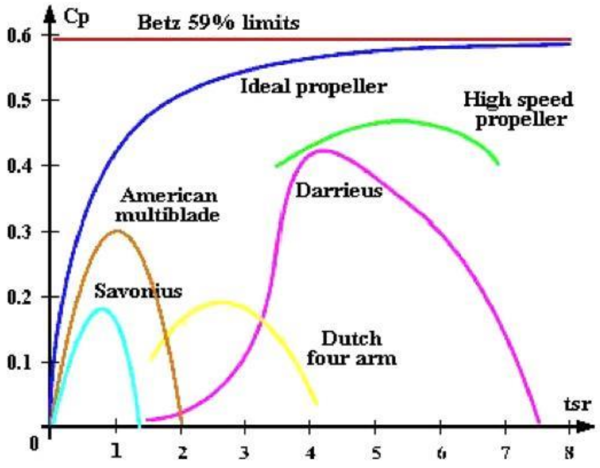
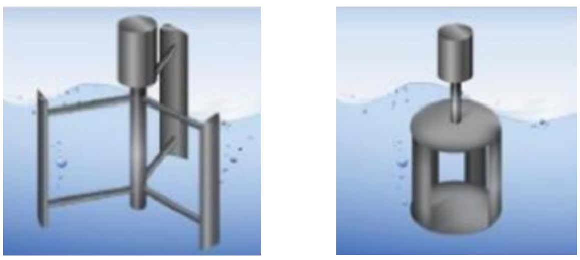


Figure 3: Comparison of Cp- λ performance curves [13].

III. H-DARRIUES DESIGN CONSIDERATION

Darrieus rotor configuration has gained significant attention because of unique performance, operational and design features. This turbine design was invented by G.J.M Darrieus, who is French inventor. The turbine was patented in 1931 with the U.S Patent Office [12]. Figure 4 shows the vertical axis straight blades H-Darrieus and Squirrel cage Darrieus turbines.



(a) H-Darriuse (b) Squirrel Cage Darriuse

Figure 4: Darriuse turbine [13]

A. Turbine Sizing

Turbine sizing design starts by estimating the power required by the remote home. Alternating current (AC) in the range of 200 W is considered sufficient for a single remote home [14]. The available hydrokinetic power of a water turbine can be computed from the water flow and the turbine dimension as:

$$P = \frac{1}{2}\rho A V^3 C_p C_n \quad (4)$$

where: P = Power (Watt)
ρ = water density
A = Cross section area
C_p = power coefficient
C_n =Drive train (generator,gearing, etc)efficiency

The water to wire efficiency (C_pC_n) is assumed equal to 21%. A typical value small turbine for an electric generation due to C_p and drive train efficiency is equal to 35% and 60% respectively [14].The power coefficient (C_p) is a non-linear function of the Tip Speed Ratio (*TSR*) and pitch angle (β). However, for a hydrokinetic turbine with fixed pitch angle, the C_p is only determined by the *TSR* [10]. The tip speed ratio (*TSR*) is expressed as;

$$\lambda = \frac{\omega . r}{V} \quad (5)$$

where: λ = Tip Speed Ratio
ω = Angular velocity of turbine
r = Turbine radius
V = Water velocity

B. Blade Design

After basic dimensioning is complete, the subsequent step is to select a set of blades with a certain shape and solidity. The H-Darriues turbine is the lift coefficient type airfoil and the tangential forces induced in the blades are the prime movers of the rotor. Basically, a standardize airfoils from National Advisory Committee for Aeronautics (NACA) has been used in wind turbine and hydrokinetics blades system. The most common blade profiles used in Darriues turbines are NACA 0012, NACA 0015, NACA 0018 and NACA 63-018.

C. Site Assessment

Pahang River is the longest river in Peninsular Malaysia with 459 km length. The upstream source of the river is located in the main range of Titiwangsa [15]. The river basin has an annual rainfall of about 2170mm. A large proportion of rain occurs during the North-East Monsoon between mid-October and mid-January. The Pahang river's having the width more than 100 m and the depth could be reached more than 10 m [15]. Based on hydrologic sampling study on January 2010, the water velocity at Pahang River ranged from 0.308 ms^{-1} to 0.582 ms^{-1}.

IV. METHODOLOGY

Figure 5 shows the flowchart of the hydrokinetics design process. There are several constraints need to consider in the hydrokinetic system design. This includes the desired rate power, number of blades and water current velocity. In this design, the rated power chosen by the author is 200 W. In addition, NACA 0015 has been used as blade airfoil. Streamtube analysis was carried -out to analyze the rotor performance. Equation (4) has been used to calculate the size of the turbine. The radius and the length of the turbine blades can be calculated as below;

$$A = \frac{P}{0.5\rho V^3 C_p C_n}$$

where: P = 200 W
ρ = 1022 kgm^{-3}
V = 0.582 ms^{-1}
C_p = 0.45
C_n = 0.8

Based on the calculation, the value of A is equal to 5.515m^2. However, the effective area encountered by the vertical axis turbine is a rectangle, expressed as;

$$A = h.d \tag{6}$$

where: A= Area
h= height
d=diameter

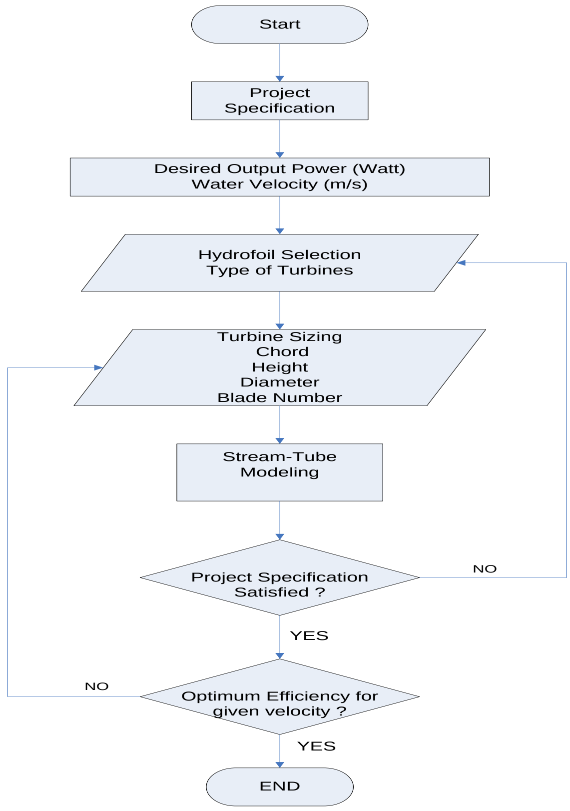


Figure 5: Design turbine flowchart

There are several issues need to compensate in turbine design. An increase in the diameter (d) cause decrease in turbine height (h). This measure eventually reduces the output power since the airfoils shaped blades are present in vertical spacing [12]. While the turbine with the higher diameter can reduce the mutual effect due to turbulence. A trade-off needs to be reached between the rotor efficiency and the power output when deciding the height-diameter ratio [12].

In this work, the software QBlade has been used to design the turbine. Figure 6 shows the software module in QBlade that consists of Xfoils, polar extrapolation blade design and turbine analysis. The XFoils analysis has been used to require the lift and drag coefficient over the different angle of attack (AoA).

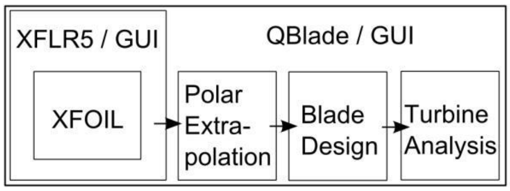


Figure 6: Software module in QBlade [16]

The Polar extrapolation module has been used to ensure the smooth operation of the Blade Element Momentum (BEM) and Double Multiple Streamtube (DMS). This module able to generate and import airfoil polars that need to be extrapolated to the full range of 360^o angle of attack. The aerodynamic simulation module for Vertical Axis Wind Turbine (VAWT) in QBlade is based on DMS algorithm as developed by Paraschivoiu [16]. In DMS analysis, a series of equal streamtubes are assumed to past through the rotor. The momentum equation for each tube is computed. Then the effects of all the streamtubes are integrated to determine the forces acting on the rotor blade [12].

V. RESULT AND DISCUSSION

The most important part in rotor configuration is solidity. Since the solidity has great impacts on power coefficient (Cp). The weight and manufacturing costs will be increased with the higher solidity. The greater the solidity causes the TSR range will be lower and leads to the decrease of the power coefficient (C_p). However, lower solidity implies the better hydrodynamic performance of hydrokinetic turbines. Besides, the higher values generally allow stronger mechanical structure and increased the induced torque. The values of solidity may range from 0.16 to 1.6 [12]. Figure 7 shows the multiple streamtube analysis for different solidity.

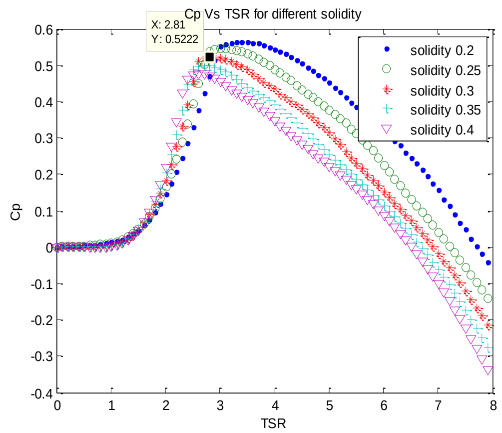


Figure 7: Power Coefficient at different solidity

The solidity values around 0.3 seem more suitable for the given blade shape (NACA0015) as seen in the plot. The value of Cp is equal to 0.52 while TSR is equal to 2.81. Based on this observation, the blade rotor chord can be determined by equation (3). In addition, the rotor speed can be calculated using equation (5). Based on performance plot, the blade design procedure for Pahang River can be initiated. In this design, the turbine has been decided to use 3 blades (N=3). The chord length of each blade is equal to 0.25m at solidity σ = 0.3. Table 2 shows the parameter consideration for H-Darrieuse straight blade for energy harnessing at Pahang River.

Table 2
H-Darrieuse Design Configuration

Parameter	Details
Chord	0.25m
Height	2.2m
Radius	1.25m
Hydrofoils	NACA0015
Number of Blade	3
Swept Area	$5.5m^2$
Speed	25RPM
Pitch Angle	Fix

Figure 8 shows the pressure distribution on the NACA 0015 airfoils. Computations were performed using the open-source code in QBlade. Through this analysis, lift and drag coefficient can be determined.

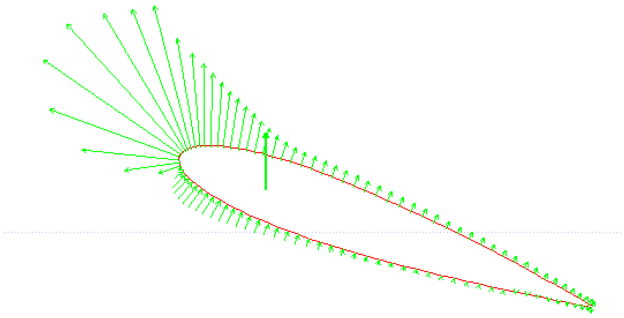


Figure 8: NACA0015 XFOIL analysis

Figure 9 and Figure 10 shows the lift and drag coefficient of the airfoil blade. These two parameters totally depend on the blade shape and Reynolds number (R_e). Basically, high Reynolds number is necessary to reduce the turbulence effect in the water.

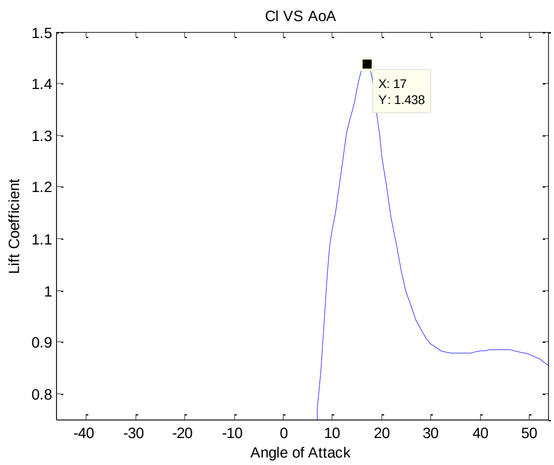


Figure 9: Lift Coefficient of NACA 0015

As seen in the plot (Figure 9 and Figure 10), for well-designed system the drag force generated during the process is typically smaller than the lift component. This is necessary because the H-Darrieuse turbine rotates with the torque produced by the lift force. Figure 11 shows the front & top view of straight blade H-Darrieuse turbine.

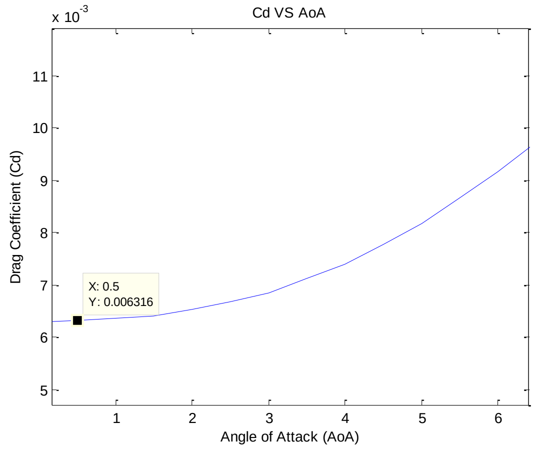
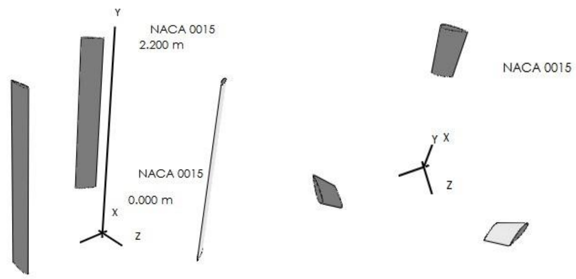


Figure 10: Drag coefficient of NACA 0015



(a) Front View (b) Top View

Figure 11: Straight Blade H-Darriuse

Figure 12 shows the energy harnessing at different water velocity. As seen in the plot, this turbine able to generate 214 W output power at 0.61 m/s water velocity.

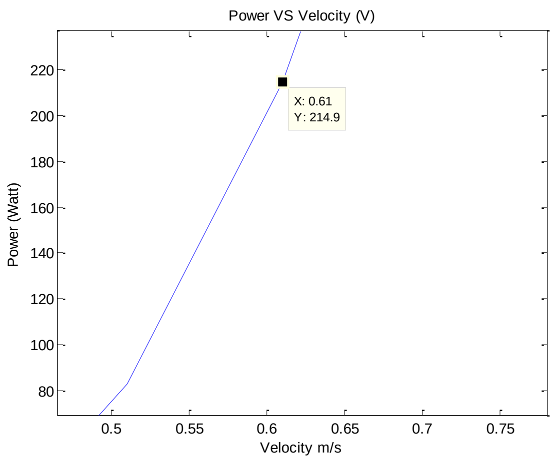


Figure 12: Power vs. Water Velocity

VI. CONCLUSION

In this work, design configuration for straight blades, H-Darriuse turbine in river application has been presented. The simulation indicates that the turbine can harness 200 W energy at 0.582 m/s water velocity. The blade design is very important in hydrokinetics system because the well-designed turbine will increase the energy harnessing.

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