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Hardware-in-the-Loop emulator for a hydrokinetic turbine

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Abstract. Hydroelectric power has proven to be an efficient and reliable form of renewable energy, but its impact on the environment has long been a source of concern. Hydrokinetic turbines are an emerging class of renewable energy technology designed for deployment in small rivers and streams with minimal environmental impact on the local ecosystem. Hydrokinetic technology represents a truly clean source of energy, having the potential to become a highly efficient method of harvesting renewable energy. However, in order to achieve this goal, extensive research is necessary. This paper presents a Hardware-in-the-Loop emulator for a run-of-the-river type hydrokinetic turbine. The HIL system uses an ABB ACS800 drive to control an induction machine as a significant means of replicating the behavior of the real turbine. The induction machine is coupled to a permanent magnet synchronous generator and the corresponding load. The ACS800 drive is controlled through the software system, which comprises of the hydrokinetic turbine real-time simulation through mathematical modeling in the LabVIEW programming environment running on a NI CompactRIO (cRIO) platform. The advantages of this method are that it can provide a means for testing many control configurations without requiring the presence of the real turbine. This paper contains the basic principles of a hydrokinetic turbine, particularly the run-of-the-river configurations along with the experimental results obtained from the HIL system.

1. Introduction

The difficulties related to the global energy crisis during the past decade have pushed the boundaries of science and technology and have forced researchers to find new and innovative ways of dealing with this ever-increasing problem. The main challenge is not only extracting more energy, but doing it in a more economic and environmentally friendly fashion. One of these is generating electricity as near as possible of the consumption site, which is usually part of the urban environment and through this reducing the power inevitably lost during transmission. This solution cannot be applied for large-scale power plants due to the environmental impact and the disheartening financial investment involved. Therefore small-scale renewable energy sources can be used instead [1], [2].

Micro-hydropower plants that generate between 5 and 100 kW of power constitute such a source. These plants are reliable; low cost; small sized and can be installed to power remote areas or stand-alone loads harnessing energy from small rivers or streams nearby. Compared to other renewable energy sources, micro-hydropower plants have certain advantages such as higher efficiency and slower change rates. One such hydropower source is the hydrokinetic turbine, the study of which constitutes the object of this paper [1].

Hydrokinetic conversion systems represent an emerging class of hydropower technology that are used in free-flowing/zero-head hydro streams. The process of hydrokinetic energy conversion implies

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utilization of kinetic energy contained in river streams, tidal currents, or other man-made waterways for generation of electricity without significantly altering the natural pathway of the stream [3]. In this paper, we considered the hydrokinetic turbine as being in run-of-the-river configuration. This represents one of the most cost effective and environment friendly technologies, partly due to the fact that it uses no dam or water storage [4]. River turbines operate under the influence of varying volumetric flow, but have the advantage of higher resource predictability. Also, the flow of the river is unidirectional and this eliminates the requirement for rotor yawing and the complicated mechanics that goes with it [3].

However issues such as the limited energy contained in the natural flow of many rivers, the frequent presence of floating and submerged debris, the possible destruction during flash flood and corrosion make the task of implementing a functional water turbine a complicated one [5].

2. Hydrokinetic energy

The hydrokinetic method of extracting energy from flows captures the kinetic energy of the flow as it passes across a rotating device. The device is connected through a mechanical shaft to a generator either directly or through a gearbox, in a manner similar to wind turbines. The rotor turns with the current, creating rotational energy that is converted into electricity by a generator. This ensemble constitutes a hydrokinetic energy conversion system (HKECS) [6].

Although a number of novel concepts have emerged recently, hydrokinetic energy conversion has mostly seen advancements in the domain of axial (horizontal) and vertical axis turbine systems. Horizontal axis hydrokinetic turbines have rotor blades which rotate in a plane perpendicular to the axis, oriented into the direction of the flow or tidal current. These turbines are capable of high efficiency, self-starting, lack of torque fluctuation and high speed operation [3], [5], [6].

2.1. Hydrokinetic turbine modeling

2.1.1. Hydrodynamic model. The maximum output power of a hydrokinetic conversion device P_{max}, taking into account losses due to Betz law, is [7]:

$$P_{max} = \frac{1}{2}\eta_t \rho Q v^2 \quad (1)$$

where ρ is the specific density of water [kg/m^3], v is the flow rate of water [m/s], η is the total hydraulic efficiency of the turbine and Q is the volume of water flowing through the turbine [m^3/s]. Q is given by:

$$Q = A * v \quad (2)$$

where A is the cross sectional area of the turbine [m2]. Thus:

$$P_{max} = \frac{1}{2}\eta_t \rho A v^3 \quad (3)$$

If we consider η_t as being composed of the turbine efficiency $C_P(\lambda)$ and other losses η, (3) would become [7]:

$$P_{max} = \frac{1}{2}\eta C_P(\lambda_i, \theta) \rho A v^3 \quad (4)$$

The $C_P(\lambda)$ factor represents the turbine power coefficient, giving the real amount of power that the hydrokinetic turbine can be extracted from the water. This factor takes into account the efficiency of the turbine itself while other losses, such as those dissipated by the internal mechanisms of the drive train are represented through the drive train efficiency which is typically around 0.7 [8], [9].

Using (4), the output power of the hydrokinetic turbine (P_{wt}) can be calculated as:

$$P_{wt} = \frac{1}{2} C_P(\lambda_i, \theta) \rho A v^3 \quad (5)$$

This equation constitutes the aerodynamic model of the hydrokinetic turbine. It can be seen that the output power of a hydrokinetic turbine is proportional to the speed of the current cubed. Thus the available power depends primarily on the speed of the current. Hydrokinetic devices work best in locations with relatively steady flow throughout the year and without extended periods of low water level. The energy conversion factor C_p is a function of the λ_i factor and the pitch angle θ, being able to render the behavior of the modeled turbine. C_p has the following equation [6], [8], [9]:

$$C_p(\lambda_i, \theta) = 0.22\left(\frac{116}{\lambda_i} - 0.4\theta - 5\right)e^{\frac{-12.5}{\lambda_i}} \quad (6)$$

where:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\theta} - \frac{0.035}{\theta^3+1} \quad (7)$$

The λ_i factor is a function of the tip-speed ratio λ, which is defined as:

$$\lambda = \omega_r R/v \quad (8)$$

where R is the turbine blade radius [m] and ωr is the rotation speed [rad/s];

With the power coefficient equation, it is possible to obtain the power coefficient curves for the turbine, which can be compared with the information provided by the turbine manufacturer. This makes it possible to reproduce the real behavior of the axial rotor, ensuring the accuracy of the turbine model [9].

2.1.2. The mechanical model. The chosen turbine is connected to a synchronous generator with permanent magnets. The mechanical part is considered to be a two-mass model. The motion equation is [8], [9]:

$$T_{ht} - T_g = J * \frac{d\omega_r}{dt} \quad (9)$$

where T_{ht} is the turbine torque [Nm], T_g is the generator torque [Nm] and J is the inertia of the hydro system [$kg\cdot m^2$]. J is composed of:

$$J = J_{ht} + J_g \quad (10)$$

where J_{ht} is the inertia of the turbine [$kg\cdot m^2$]and J_g is the generator inertia [$kg\cdot m^2$]. The power of the system can be expressed by the following relationship:

$$P_{ht} = T_{ht} * \omega_r \quad (11)$$

2.2. HKECS Hardware-in-the-Loop System

The hydrokinetic Hardware-in-the-Loop emulator consists of a rotational motor-generator system: a 7.5 kW/720 rpm three phase squirrel cage induction motor (IM) connected to a 5kW/120rpm permanent-magnet synchronous generator (PMSG) [10]. A 1/6 gearbox is needed in order to adjust the speed of the IM to the necessary value for the generator. The IM is controlled by a ABB ACS800 motor drive system through an National Instrument embedded controller (NI cRIO 9068). The controller simulates the hydrokinetic turbine using mathematical modeling. The mathematical model of the hydrokinetic turbine is based on the mathematical equations presented in the preceding chapter: the aerodynamic model and the mechanical model, both translated into LabVIEW, as can be seen in Figures 1 and 2.

The turbine parameters are presented in the following table:

Table 1. Parameters of the hydrokinetic turbine [10]

Parameter	Value
Rated power	$P_n = 2.5$ [kW]
Nominal water speed	$v_0 = 1.5$ [m/s]
Nominal speed	$n = 130$ [rpm]
Inertia of the turbine	$J_{wt} = 0.0018$ [kg m^2]
Inertia of the generator	$J_g = 1.05$ [kg m^2]
Surface covered by turbine blades	$A = 3.14$ [m^2]
Turbine blade radius	$R = 1$ [m]
Maximal power factor	$C_{p_{max}} = 0.4382$
Nominal speed ratio	$\lambda_0 = 6.325$
Specific water density	$\rho = 1027$ [kg/m^3]

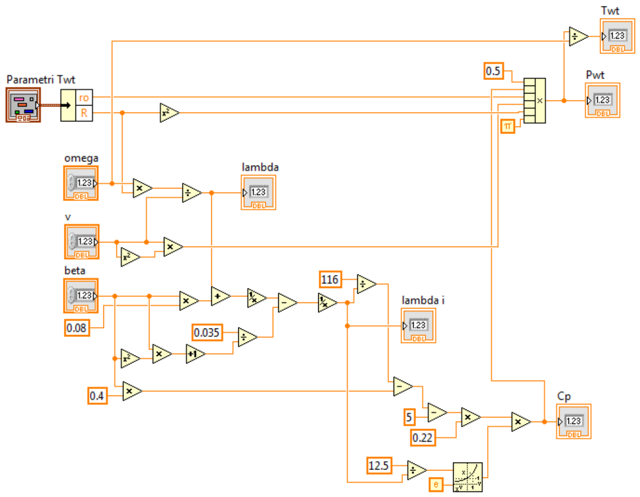

Figure 1. The hydrodynamic model implemented in LabVIEW

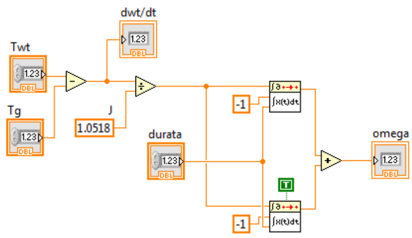

Figure 2. The mechanical model implemented in LabVIEW

The HIL emulator developed in this paper is designed to simulate the behavior of the hydrokinetic turbine in different situations. Usage of HIL enhances the quality of the testing by increasing the scope of the testing. Specifically, the NI cRIO 9068 runs a real-time mathematical model of the hydro turbine implemented in LabVIEW. These mathematical representations are referred to as the "plant simulation". The embedded system to be tested interacts with this plant simulation; the program reads the torque estimated by ACS800 and calculates the new rotating speed (ω_r) which is prescribed to the ACS800 [11-14].

The emulator hardware is depicted in Figure 3.

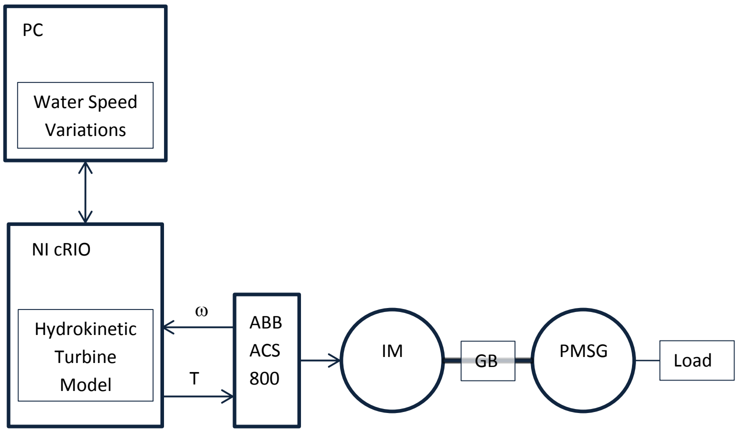

Figure 3. HIL emulator

The turbine characteristics were obtained through LabVIEW simulation varying the flow speed between 0.1 and 1.5 m/s. The performance of the turbine has been verified using these graphics. The power characteristic of the turbine can be seen in Figure 4.

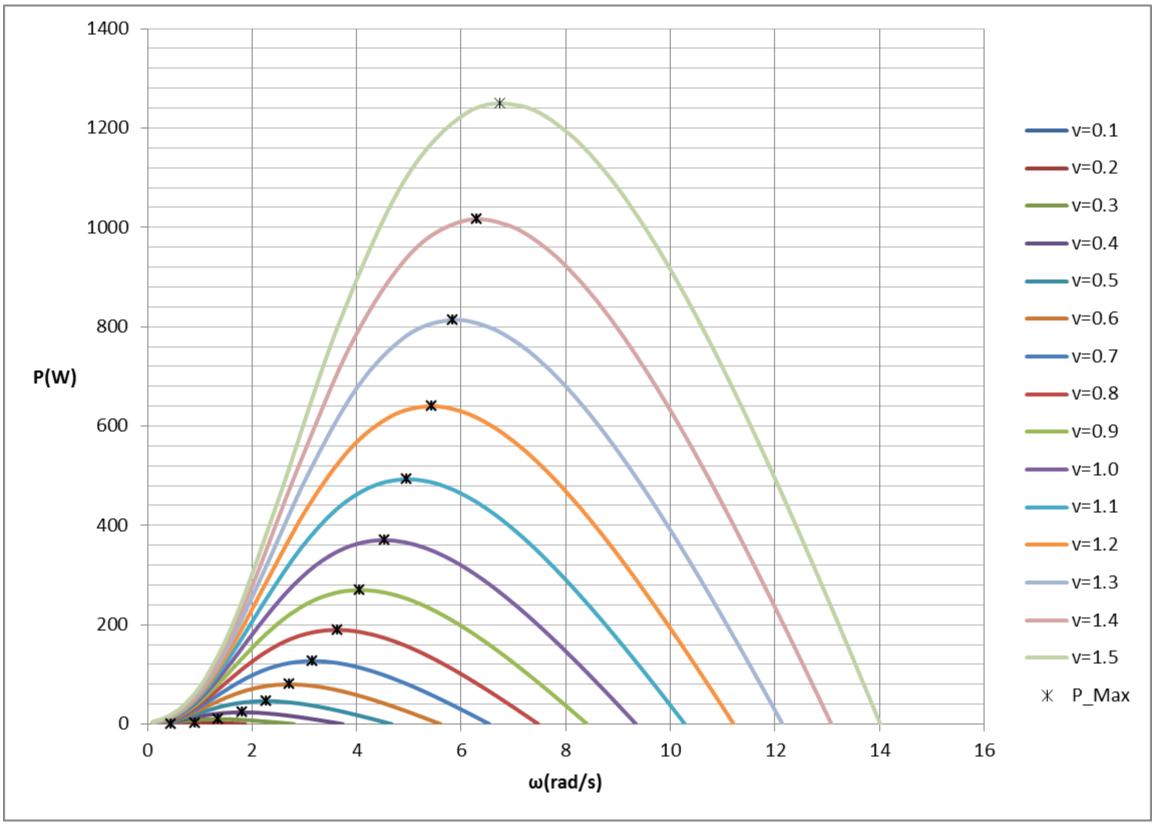

Figure 4. Power versus angular speed

Using the turbine power equation from (5), we obtain:

$$P_{ht} = 0.5A\rho C_P(\lambda) * v^3 = 0.5A\rho C_P(\lambda) * \frac{v^3}{\omega^3 R^3} * \omega^3 R^3 = 0.5\pi R^5 \rho C_P(\lambda) * \frac{1}{\lambda^3} * \omega^3$$

The maximum power for a certain θ is obtained at the optimum value of λ:

$$\lambda = \lambda_{\text{opt}} = constant \text{ and } C_P(\lambda_{opt}) = C_{P_{opt}} = constant \tag{12}$$

So the optimum hydrokinetic turbine power is given by:

$$P_{ht_{opt}} = 0.5\pi R^5 \rho C_{P_{opt}} * \frac{1}{\lambda_{opt}{}^3} * \omega^3 = k\omega^3 \tag{13}$$

As can be seen, the optimum power is proportional to the cube of the angular velocity (Figure 5). Hence, by measuring the hydrokinetic turbine rotor speed, it is possible to determine the optimum power. But this requires knowing the optimal power points for cross correlation [15].

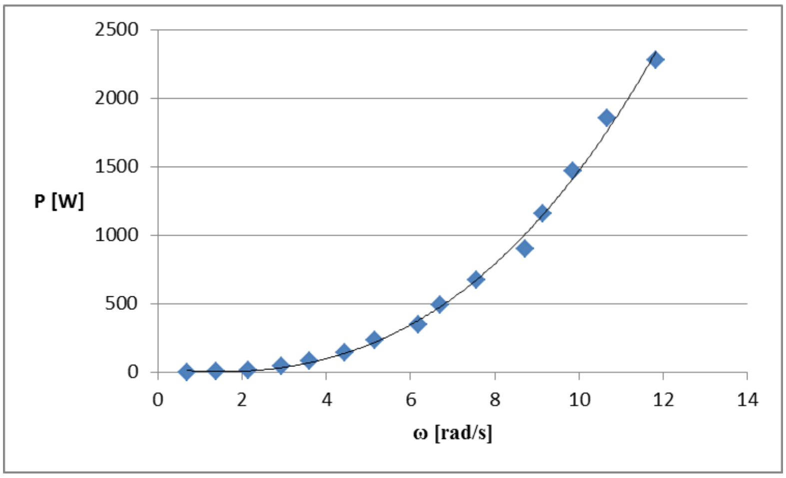

Figure 5. Optimal power versus angular speed

In (12) we have deduced that for the maximum power point to exist, there has to be a $\lambda = \lambda_{opt}$ and a $C_P(\lambda_{opt}) = C_{P_{opt}}$ corresponding to this point. Using the hydrodynamic equation of the turbine (5), the following relationship is obtained:

$$P_{wt_{opt}} = 0.5A\rho C_{P_{opt}} * v^3 = kv^3 \tag{14}$$

Therefore, the optimal power is directly proportional to the cube of the water speed (Figure 6). So, by measuring the flow speed, it is possible to determine the optimum power. This result is also visible in the following Figure.

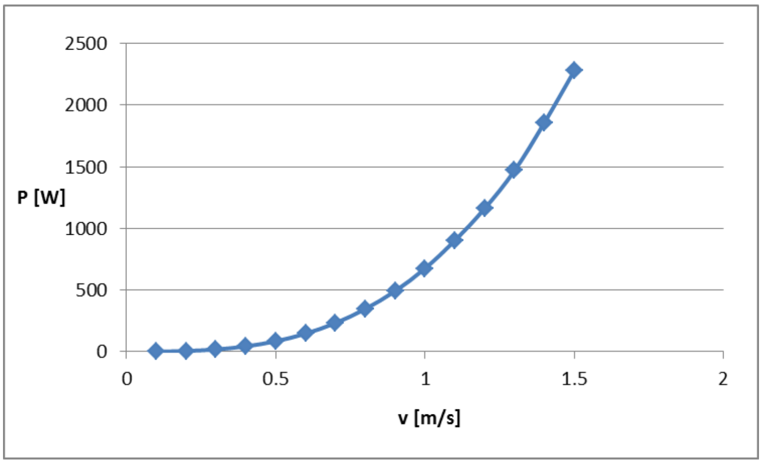

Figure 6. Optimal power versus water speed

The turbine torque relation is obtained from (11) and (5):

$$T_{wt} = 0.5A\rho C_T(\lambda) * v^2 \quad (15)$$

where C_T is the torque coefficient ($C_p = \lambda C_T$). The turbine torque characteristics obtained through varying the flow speed between 0.1 and 1.5 m/s can be seen in Figure 7.

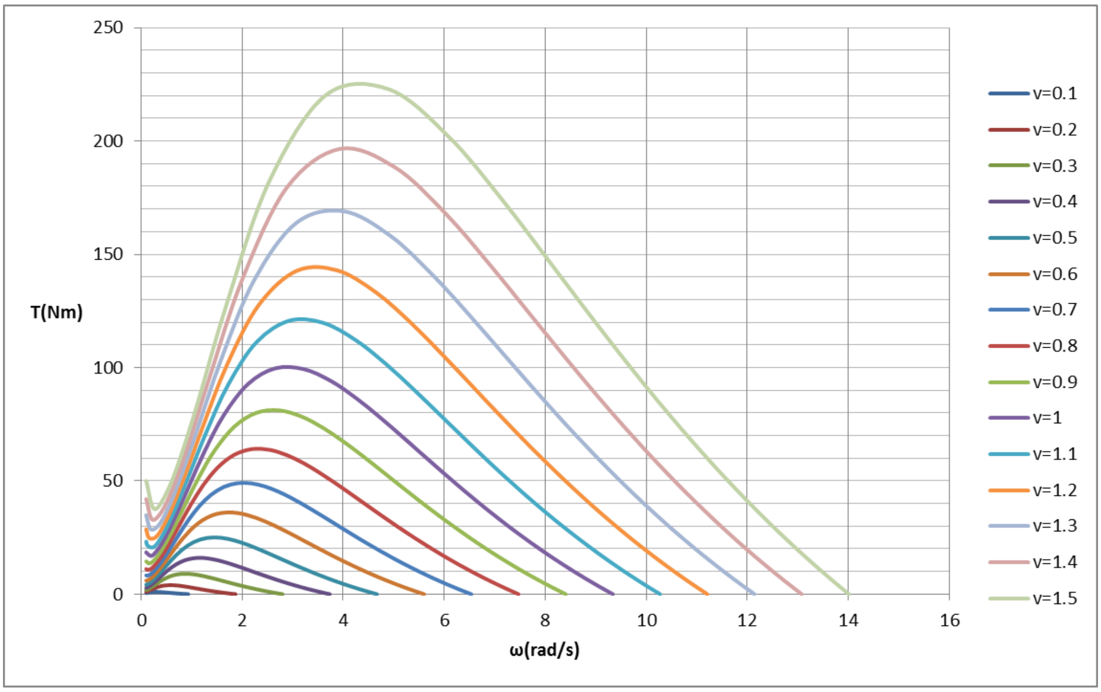

Figure 7. Mechanical torque versus angular speed

The turbine torque equation is obtained using (15):

$$T_{wt} = 0.5A\rho C_T(\lambda) * v^2 = 0.5A\rho C_T(\lambda) * \frac{v^2}{\omega^2 R^2} * \omega^2 R^2 = 0.5\pi R^4 \rho C_T(\lambda) * \frac{1}{\lambda^2} * \omega^2$$

Maximum torque is obtained at the optimal value of λ and C_T:

$$\lambda = \lambda_{opt} = constant \text{ and } C_P(\lambda_{opt}) = C_{P_{opt}} = constant \quad (16)$$

The maximum torque point does not correspond to the maximum power point. So the optimal torque of the hydrokinetic turbine is:

$$T_{wt_{opt}} = 0.5A\rho C_{T_{opt}} * \frac{1}{\lambda_{opt}{}^2} * \omega^2 = k\omega^2 \quad (17)$$

Therefore, the maximum torque is directly proportional to the square of the angular velocity, which is also visible in the following Figure:

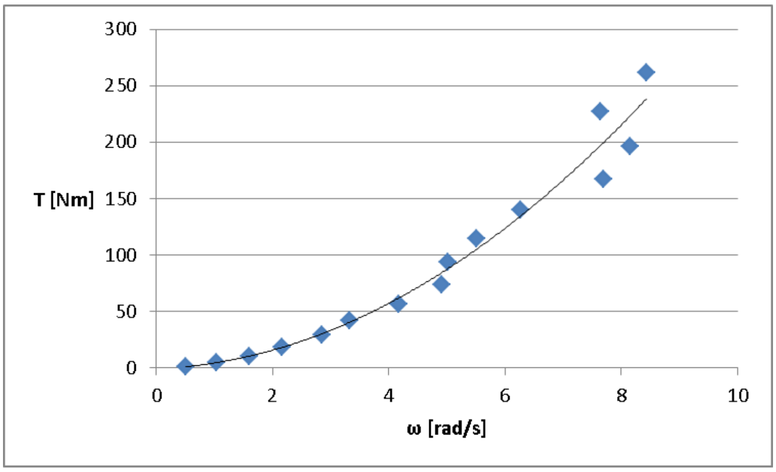

Figure 8. Optimal torque versus angular speed

In (15) we have deduced that for the maximum torque point to exist, there has to be a $\lambda = \lambda_{opt}$ and a $C_T(\lambda_{opt}) = C_{T_{opt}}$ corresponding to this point. Using the hydrodynamic equation of the turbine (5), the following relationship is obtained:

$$T_{wt_{opt}} = 0.5A\rho C_{T_{opt}} * v^2 = kv^2 \tag{18}$$

Therefore, the maximum torque is directly proportional to the square of the flow speed, which is also visible in the following Figure:

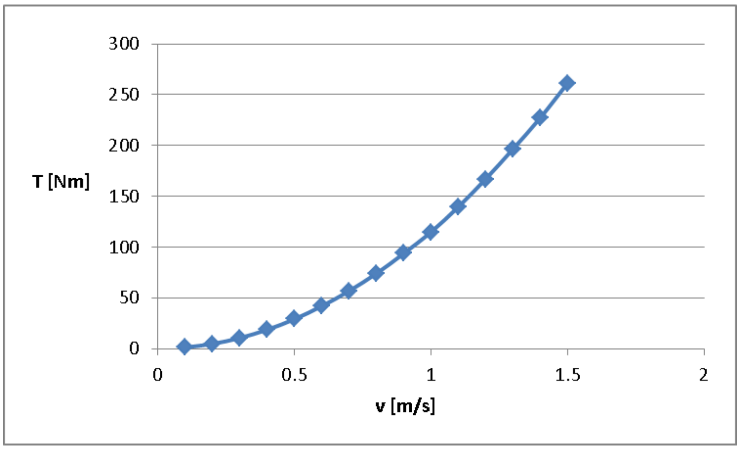

Figure 9. Optimal torque versus flow speed

The optimal power versus pitch angle is shown below. It was obtained based on experimental result and has been found to be a 2nd order polynomial function.

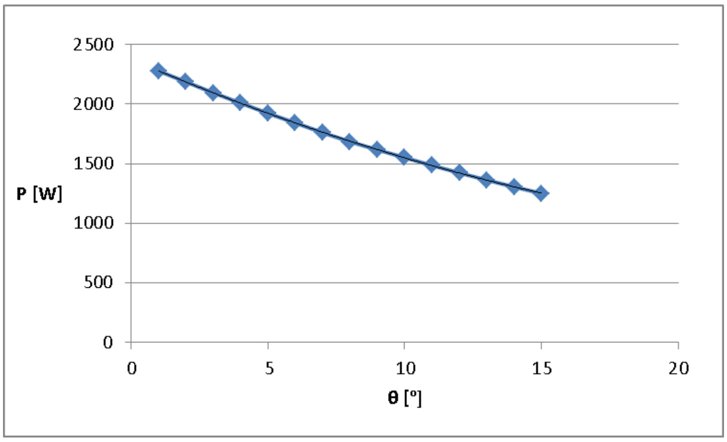

Figure 10. Optimal power versus pitch angle

The voltage versus flow speed is shown below. It was obtained based on experimental result and has been found to be a 2nd order polynomial function.

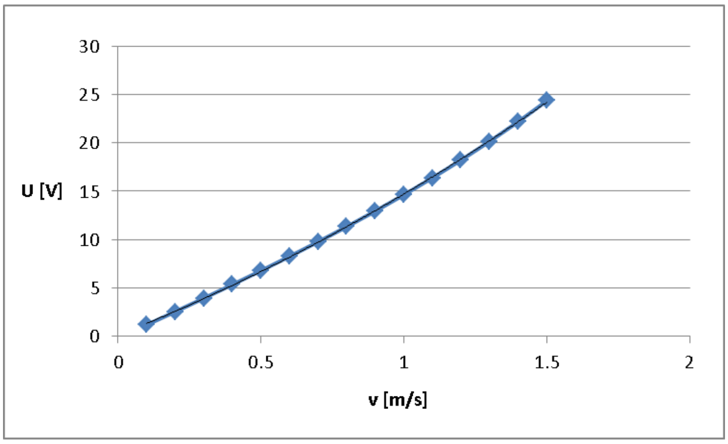

Figure 11. Actual voltage versus flow speed

3. Conclusions

The objectives of this paper were to conduct a study on a small axial river turbine in a hydrokinetic energy conversion system. The hydrokinetic converter is constructed without significantly altering the natural pathway of the water stream, specifically in run-of-the-river configuration. The power is generated by capturing the energy of naturally flowing water – stream flows, tidal flows, or wave motion – without impounding the water. This represents one of the most cost effective and environment friendly technologies. The hydrokinetic energy conversion system presented in this paper demonstrates how much use can be made of small river systems. Micro-hydropower plants are reliable, small sized; they have a low cost and can be installed to power remote areas or stand-alone loads harvesting energy from local rivers or streams [5], [6].

In this paper, the effects of the main parameters of the turbines on their operation were analyzed. There is a polynomial dependence between the angular velocity and the optimal power point, respectively the optimal torque. Dependent is 3rd order for power and 2nd order for the torque. A similar dependence exists between these parameters and water speed. The output voltage from the generator has 2nd order dependency on the variation of the flow speed. The optimal power versus pitch angle has also been found to be a 2nd order polynomial function.

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