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Design of Cross-flow Turbine for Picohydro Power Plant in Singosari Malang

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Abstract

In the area around PPYD Al Ikhlas Singosari, Malang, the river's flow is swift enough to potentially serve as a source for a hydroelectric power station, according to estimates. After investigation, it was found that the potential electrical power that could be generated was 1,118.56 Watts so it was classified as a pico hydro power plant. Therefore, in this research, one of the main parts of the pico hydro power plant, namely the turbine, was designed. The type of turbine designed is a crossflow turbine with an outer diameter of 75 cm and an inner diameter of 3 cm, the width of the runner blades is 40 cm, the distance between the blades is 36 cm, the radius of curvature of the blades 33 cm, the number of 10 blades can produce 843.74 watts of power with a turbine efficiency of 75.43%. So, it can be concluded that the crossflow turbine has good efficiency.

Keywords : Crossflow turbine, hydroelectric power plant, pico hydro power plant, PPYD Al Ikhlas Singosari

1 Introduction

The existence of electricity is extremely beneficial to human life, causing the demand for power to rise from time to time [1, 2, 3]. Small hydro-power has recently gained popularity due to its clean, sustainable, and abundant energy resources for development [4, 5]. Water energy has a high potential for use as a source of electrical energy, which is one of the most important factors in promoting economic development. There are still many individuals living in distant places who do not have access to energy from the power company, but there are several undeveloped micro-scale water resources nearby [6]. Near PPYD Al-Ikhlas, Singosari, Malang Regency, there is a spot that can be utilized as a mini-hydro power plant in the shape of a small river channel. The river's location gives the possibility for a big and generally consistent water flow. Based on our initial hypothesis, the electrical power that can be generated from the river flow is about 1000 W. Based on that initial power output calculation, it was decided to build picohydro power plant. Picohydro is a type of power plant that generate electrical energy with a capacity up to 5 kW from a water flow with a low head (1-3 meters) and a high discharge [7]. Simply said, pico hydro consists of three basic parts: a generator, a turbine, and a source of energy called water flow [8]. A picohydro power plant's major component includes penstock pipe that serve as water channels, water turbine and generator, panels, and power transmission networks [9]. In this study, the turbine was planned first, followed by the planning of the remaining components. The undershoot type Cross-flow turbine was selected due to the Cross-flow turbine's advantages over other types of turbines, specifically that it is more suitable for areas with large discharges and relatively low water fall heights and that the production process is simple and affordable [10]. And also, since the cross-flow turbine is the most affordable and simple hydro turbine to produce, it is frequently utilized in remote power systems for developing nations [11]. Some researchers have designed a cross-flow turbine for the Pico Hydro power plant. In a cross-flow turbine, the flow is accelerated and directed at an appropriate angle toward the runner, that is tangential to the flow. The runner takes the flow's angular momentum. The efficiency of the turbine depends greatly on the runner entering flow. In order to achieve high efficiency cross-flow turbines, Adhikari and Wood presented a new nozzle design technique [12]. Kaunda et al. evaluated the performance of a simplified Cross-flow turbine in order to build a Cross-flow turbine that was deemed suitable for small-scale power production. He discovered that the design must also take into account how to manage the flow inside the runner's internal space so that the jet enters the second stage with the best flow angle [13]. Wiranata et al designed a cross-flow turbine with an effective head of 6 meters. The outer diameter of the runner is 0.15 meters, the inner diameter of the runner is 0.10 meters, and the number of blades is 18. Based on the test results, it was found that the turbine could work well so that the pico hydro power plant could produce electrical energy [14]. In this research, a cross-flow turbine will be designed that works in parallel with the vortex turbine Based on the problem description above, a cross-flow turbine was designed for a pico hydro generator with an effective head of 2.61 meters. So, the objectives of this research include determining the dimensions of the cross-flow turbine for the PPYD Al Ikhlas pico hydro power plant, analyzing the effect of the rotational speed of the cross-flow turbine on the variation of the intake opening in the pico hydro power plant system, and analyzing the efficiency of the pico hydro that has been built

2 Method

2.1 The System Block Diagram

The System block diagram can be seen in Figure 1 below.

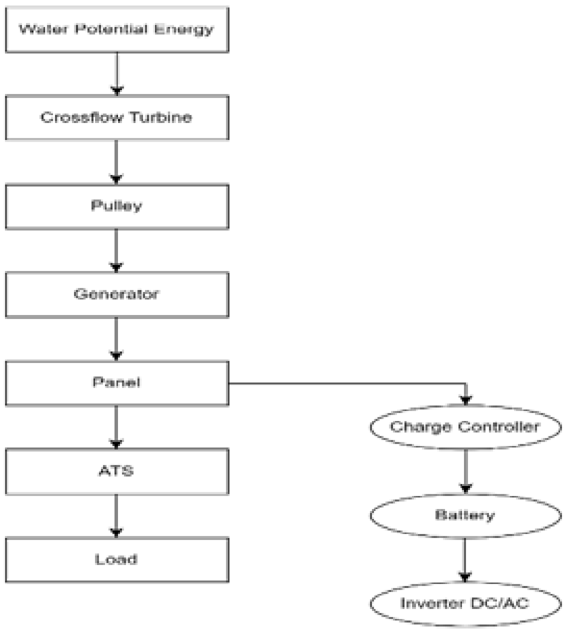


Figure 1: Pico Hydro Power Plant System Block Diagram

The work system of this pycohydro power plant makes use of the energy of water currents to propel the turbine area to rotate, as can be seen from the block diagram above. Since the generator's job is to transform motion energy into electrical energy, the turbine and generator, which share a single shaft, rotate in order to produce electricity. The generator produces DC and AC current as its output.

2.2 Turbine Initial Design

This small hydroelectric power plant uses the cascade method, which uses the cross-flow and vortex turbines as its two turbines [15]. The cascade design of turbines can be seen in Figure 2.

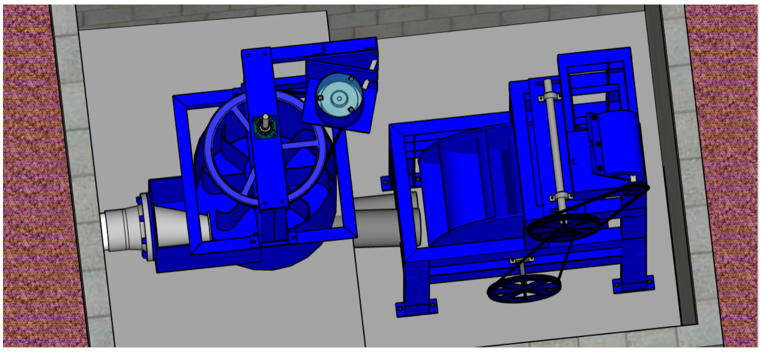


Figure 2: Cascade Turbines Method

A maximum of 1000 watts can be converted by each of those turbines. This paper discusses the cross-flow turbine (within a red circle on Figure 2), which pulls water from both the calming tank and the output of the vortex turbine. The cross-flow turbine was equipped with the pulley that connected the generator and the turbine. The DC generator of the Cross-flow Type Pico-Hydro Power Plant will produce a voltage that is sent to the control panel box, which contains the ATS, inverter, and DC-DC converter before loading. For the battery itself, it has a distinctive battery rack. The DC voltage generated by the DC generator being sent to the DC-DC converter, which lowers, raises, and stabilizes the generator's output voltage. The battery will thereafter be the target of it. Electrical energy from the generator is first stored in the battery before being sent to the load. The DC voltage, in addition to going to the battery, will also go to the inverter, which aims to convert DC voltage to AC voltage in order to feed outside loads.

2.3 Availaible Hydro Power (Pa)

It is the amount of potential energy available from a water source that depends on the size of the falling point (head) and the discharge of water flowing every second. It can be calculated by:

$$Pa = 997.13kg/m^3 \times 0.04381285m^3/s \times 9.81m/s^2 \times 2.61m = 1.118.56Watts.$$

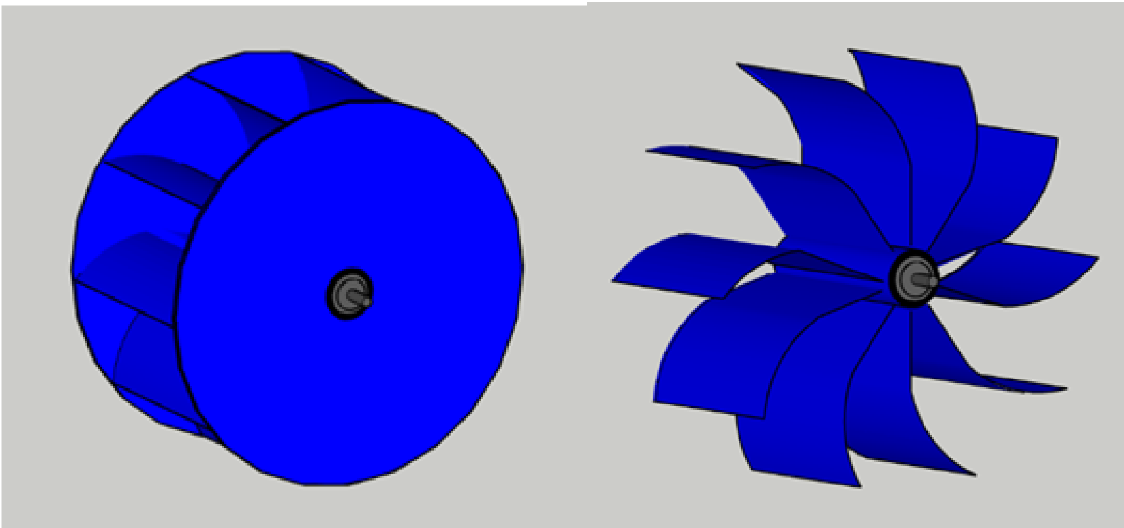
From the calculation above, it is known that the potential power can be generated in PPYD Al-Ikhlas is 1.118.56 Watts so, it can be classified as pico hydro power plant.

3 Results and Discussion

3.1 Dimension of Turbine

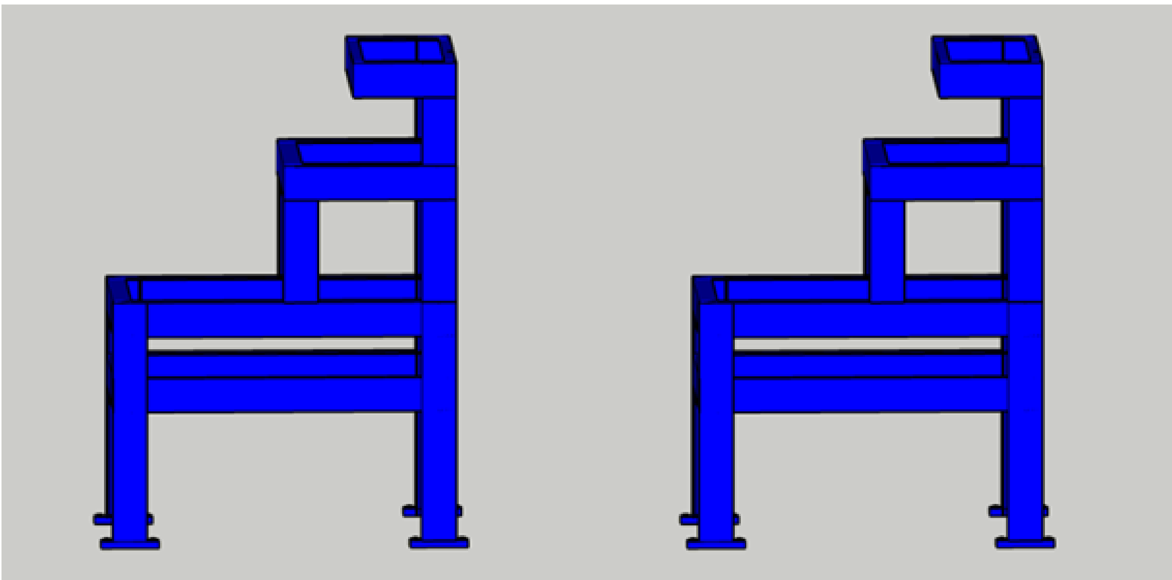
Diameter of turbine is 75 cm with 40 cm wide and the sides of turbine is covered by iron plate in 5 mm thick. There are 10 blades with the thickness is 3 mm for single blade. The turbine design can be seen in Figure 3 below.

With dimensions of 100 mm x 50 mm and a 10 mm iron plate thickness, the turbine frame has a maximum height of 150 cm, front length of 80 cm, and side width of 50 cm. The design of turbine frame can be known in Figure 4. In the overall design, the height from the feet under the ground to the top of the generator stand is 150 cm. While the length from front to back side is 100 cm. This design uses a multilevel pulley design where to use a pulley ratio of 1:3 using two pulleys with a diameter of 10 cm and 30 cm. The design of turbin set up on the frame can be seen in Figure 5



(a) with side cover (b) without side cover

Figure 3: The design of turbine



(a) side view (b) rear view

Figure 4: The design of turbine frame

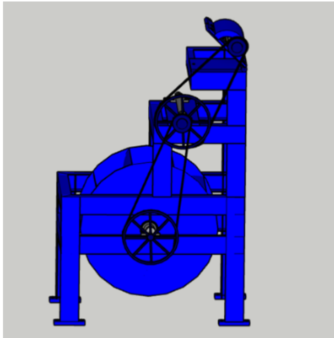


Figure 5: The design of turbine on its frame

3.2 Transmission Design

Multilevel pulleys are used in this crossflow turbine design. The goal is to increase and maximize the speed from the turbine to the generator [16]. The DC generator's pulley size is 10 cm, while the turbine's pulley size is 30 cm. The belt, meanwhile, makes use of sizes A71 and A64. The following figure shows the pulley design in Figure 6.

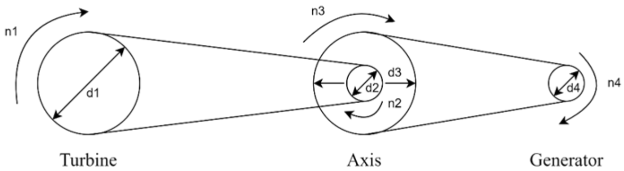


Figure 6: Pulley circuit

The expected generator speed is 1000 rpm, Table 1 shows the results of measuring turbine rotation with various variations of intake openings.

Table 1: Initial Turbine Speed Measurement

No.	Opening of intake channel (%)	Speed (rpm)
1	50	70.71
2	75	100.74
3	100	114.6

In order to determine the pulley diameter, the highest speed, 114.6 rpm, was taken in calculation. Because n_2 and n_3 have one axis, and $n_2 = n_3$, then:

$$n_4 = \frac{n1(d1.d3)}{(d2.d4)} = \frac{114.6(0.3x0.3}{(0.1x0.1)} = 1031.4rpm \quad (1)$$

3.3 Cross-flow Turbine Speed with Impulse Type Blade Form

The duration of the water flow hitting the turbine blades determines the turbine speed. In this experiment, the penstock hole's closing was varied in an effort to achieve the highest turbine power. Penstock openings of 50%, 75%, and 100% with or without pulleys are the available options. The process of gathering data involved gathering information on the generator output in the form of DC voltage, the turbine speed, the generator speed, the turbine mass to calculate torque, and the speed of the water in the penstock to calculate discharge. The crossflow turbine's intake source, the vortex turbine, is used to measure the flow of water discharge by measuring the size of the water channel between its intake and outflow [17]. The water output must be understood in order to compute the water power related to crossflow turbine efficiency [18]. Based on measurement on the field, the data are: P (intake length) : 2.61 m d (pipe diameter) : 6 inch = 0.1524 m The value of water velocity:

$$v = \frac{s}{taverage} = \frac{16.3}{6.78} = 2.4030448m/s \tag{2}$$

Then the value of the discharge of flowing water (Q):

$$Q = A \times v = ((\frac{1}{4} \times \pi \times (d)^2) \times v = (\frac{1}{4} \times 3.14 \times (0.1524)^2) \times 2.4030448 = 43.81l/s \tag{3}$$

Then the value of turbine torque:

$$T = F \times L = (m.g) \times L = (53kg \times 9.81m/s^2) \times 0.15m = 77.98Nm \tag{4}$$

The relationship between turbine speed without connected to pulley and torque can be seen in Figure 7.

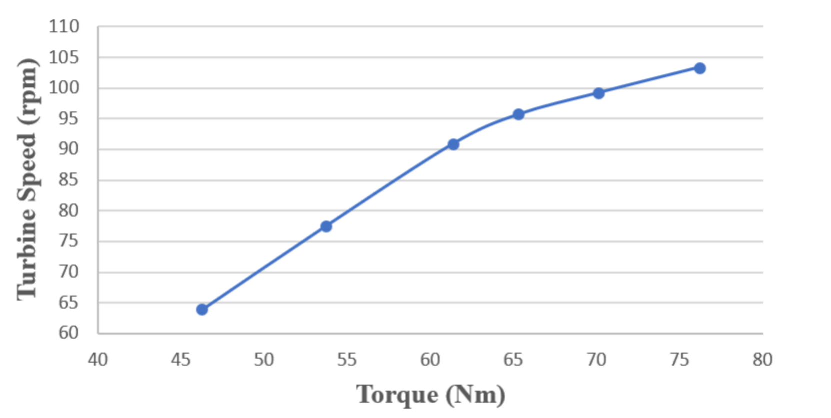


Figure 7: Turbine speed and torque, without pulley

The relationship between turbine speed connected to generator and torque can be seen in Figure 8

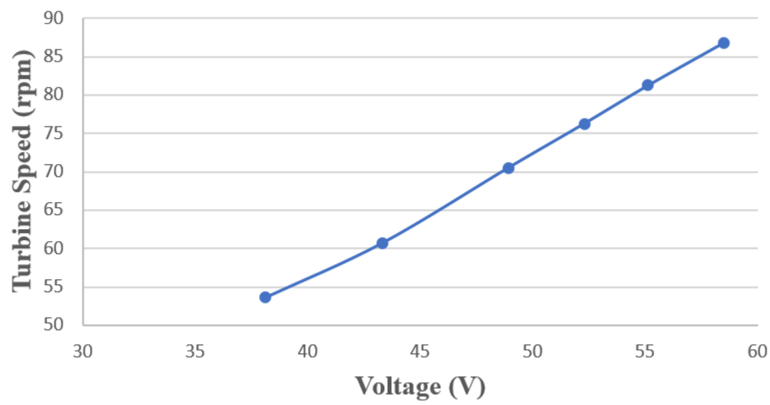


Figure 8: Turbine speed and torque, connected to generator only

The relationship between turbine speed, connected to generator then load, and torque can be seen in Figure 8.

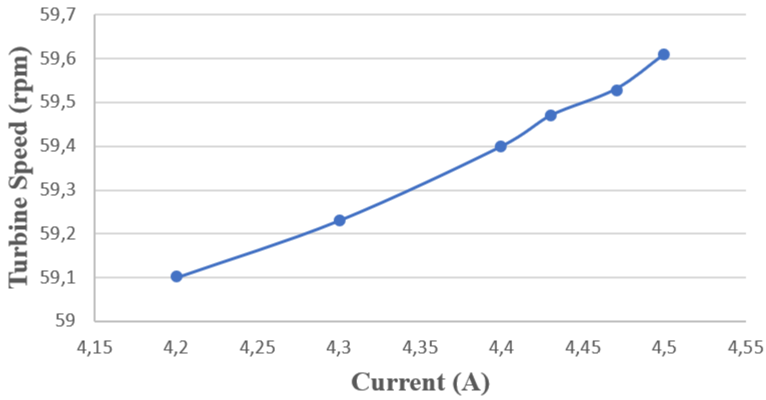


Figure 9: Turbine speed and torque, connected to the system

3.4 Losses in Cross-flow Turbine Speed

After being analyzed, there was difference between the turbine speed and the generator speed. These were caused by several factors, one of these is the frictional force between the pulleys and the belt [19]. The efficiency can be calculated as follow:

$$Efficiency(\%) = \frac{RPMturbine}{RPMgenerator} \times 100\% = \frac{89.6}{771.9} \times 100\% = 11.6\% \tag{5}$$

After calculating the efficiency, the percentage of losses is:

$$speedlosses(\%) = 100\% - \%efficiency = 100\% - 11.6\% = 88.4\% \tag{6}$$

Value of speed losses in percentage can be converted into units of speed by:

$$speedlosses(rpm) = \%efficiency \times \frac{RPMturbine}{RPMgenerator} = 88.4\% \times \frac{89.6}{771.9} = 10.25rpm \tag{7}$$

So, it can be seen that the speed losses are 10.25 rpm.

3.5 Performance Testing and Efficiency of Cross-flow Turbine

It can be seen in Table 2 data of turbine performance in three conditions that are: the turbine without pulleys, the turbine is connected to the generator, and the turbine is connected to the system.

Table 2: Table of output data of crossflow turbine

No.	Speed (rpm) Turbine	Speed (rpm) Generator	Voltage (DC)	Current (A)	Torque (Nm)	Water Speed (m/s)	Water Discharge (m^3/s)	Note
1	101,1	-	-	-	74,31	2,298	0,04189	Without
2	102	-	-	-	76,51	2,350	0,04284	pulley
3	103,4	-	-	-	77,98	2,403	0,04381	
1	84	757,8	57,9	-	-	1,909	0,03480	Connected
2	86,9	762,1	58,2	-	-	1,975	0,03600	to
3	89,6	771,9	59,4	-	-	2,036	0,03711	Generator
1	59,1	531,9	30	4,2	-	1,343	0,02448	Connected
2	59,4	534,7	30,2	4,4	-	1,350	0,02461	to
3	59,61	536,5	30,4	4,5	-	1,355	0,02470	system

The performance of the Crossflow turbine is the mechanical power generated from the turbine. To get these data, it is done by performing the following calculations.

3.5.1 The Turbine Without Pulley

Calculating the angular velocity of the turbine (ω) with the turbine speed used in equation was the highest speed, when the turbine was without pulleys. Calculation as follows:

$$\omega = \frac{2\pi \times n}{60} = \frac{2\pi \times 103.4}{60} = 10.82 rad/s \tag{8}$$

Calculating turbine efficiency (η) by:

$$\eta = \frac{Pt}{Pa} \times 100\% = \frac{843.74}{1118.56} \times 100\% = 75.43\% \tag{9}$$

3.5.2 Turbine Efficiency When Connected to a Generator

Calculating the angular velocity of the turbine (ω) with the turbine speed used in equation was the highest speed, when the turbine was connected to a generator. Calculation as follows:

$$\omega = \frac{2\pi \times n}{60} = \frac{2\pi \times 89.6}{60} = 9.38 rad/s \tag{10}$$

Calculating turbine power (Pt) by:

$$Pt = \omega \times T = 9.38 rad/s \times 77.98 Nm = 731.45 W \tag{11}$$

Calculating turbine efficiency (η) by:

$$\eta = \frac{Pt}{Pa} \times 100\% = \frac{731.45}{1118.56} \times 100\% = 65.39\% \tag{12}$$

3.5.3 Turbine Efficiency When Connected to System

Calculating the angular velocity of the turbine (ω) with the turbine speed used in equation was the highest speed, when the turbine was connected to system. Calculation as follows:

$$\omega = \frac{2\pi \times n}{60} = \frac{2\pi \times 59.61}{60} = 6.24 rad/s \tag{13}$$

Calculating turbine power (Pt) by:

$$Pt = \omega \times T = 6.24 rad/s \times 77.98 Nm = 486.59 W \tag{14}$$

Calculating turbine efficiency (η) by:

$$\eta = \frac{Pt}{Pa} \times 100\% = \frac{486.59}{1118.56} \times 100\% = 43.5\% \tag{15}$$

3.6 Electrical Generator Specification and Testing

The generator used is a Single-Phase DC Permanent Magnet Generator. This generator was used for charging the battery, with an output voltage of 220 V and a speed rating of 2000 rpm capable inproducing a maximum power of 1000 watts. Here is a block diagram in the field: Before being applied to the field, the generator had been be tested at the Power Electronics Laboratory of Politeknik Negeri Malang. To find out the value of the internal resistance and the maximum total power of the generator by testing it connected to a load. It was done by setting the VSD selector to find out the generator RPM rotation strength when it was given up to a huge load. The test results obtained rotation, current, and output voltage that can be generated by the generator under in load conditions. Table 3 shows the results of generator testing at the Power Electronics Laboratory.

Table 3: Data of Generator Testing

No.	Rotation (rpm)	Voltage (V)	Current (A)	Power (W)
1	1932	98.4	1.74	171.216
2	1912	89.3	2.01	179.493
3	1874	73.6	2.5	184
4	1828	55.8	2.98	166.284
5	1761	34.4	3.5	120.4
6	1680	12.5	4.3	53.75

Based on Table 3, for the 1-phase Permanent Magnet DC Generator under loaded condition, the highest power was obtained at 179-Watt with 1912 rpm rotation and a DC voltage of 89.3 Volts. Number of data was taken only 6 times because when the rheostat load was so high and the output voltage from the generator was also high it would cause a spark at the rheostat terminal.

4 Conclusion

Following are a few conclusions from the installation of the cross-flow turbine at PPYD Al-Ikhlas based on the findings of the analysis that was done.

1. The transmission device for this cross-flow turbine design consisted of a multi-layer pulley system with a ratio of 1: 3 and diameters of 10 cm and 30 cm, respectively, and belt sizes A67 and A71.
2. When there were no pulleys present, the cross-flow turbine's maximum speed was at 100% intake opening, which is 103.4 rpm. When the turbine was connected to the generator, its speed dropped to 89.6 rpm, and when it was connected to the system, it fell even further to 59.61 rpm.
3. The efficiency of cross-flow turbine is 75.43% in the condition of Pa = 1118.56-watts and Pt = 834.74-watts.

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