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Development of Pico-Hydro Electric Power Plant on Irrigation Canal - Case Study: Menaming Village, Indonesia

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ABSTRACT

One potential that can be utilized as a source of small-scale electrical energy is irrigation canals. The obstacle experienced to utilize irrigation canals is because irrigation canals have low flow speeds and height differences in irrigation canals. In this study, a power plant was made in an irrigation stream with a flow speed of 0.3 m/s and a height difference of only 0.3 meters. This research began with a survey of the design and manufacture of waterwheels, transmission systems, and generators. After all components are installed, the generator output voltage measurement is carried out using lamp loads of 3,6,9,12,25 and 49 Watts. From the measurements, it can be seen that as the load increases, the rotation of the wheel, voltage, and frequency will also decrease. This is due to the lack of water power so that the water is no longer able to turn the waterwheel.

KEYWORDS: Waterwheel, Transmission system, Generator, Induction Motor, Voltage.

NOMENCLATURE

PLN	State Power Plant
PLTMH	Micro-Hydro power plant
PLTPH	Pico-Hydro Power Plant
W	Watt
Kw	Kilo Watt
V	Voltage
Hz	Hertz
N	Newton
Nm	Newton Meter
Rpm	Rotations Per Minute
m/s	Meters per Second
cm	Centimeter

1.0 INTRODUCTION

Electricity is a very important need for the community, uneven distribution of the population and difficult access is one of the causes so that the location is not supplied with PLN electricity. Based on a report from the Ministry of Energy and Mineral Resources in the first quarter of 2021, there are 542,124 households that have not received electricity. Various efforts have been made to utilize water energy as a power plant by using waterwheels and using turbines [1].

Irrigation canals are spread almost throughout Indonesia, one of which is in Riau Province. There are 8500 km of irrigation canals, although 80% of them are damaged or do not function to irrigate agricultural land. The long irrigation canal has enormous potential if used for small and medium scale power plants (PLTMH and PLTPH) and as water pumps in conjunction with waterwheels [2];[3].

In the irrigation canal of *Menaming* Village, a Hydroelectric Power Plant with a power below 5 KW (Pico-hydro) can be built [4]. Power plants developed by waterwheel manufacturers and produced commercially have an application range of 5-100 KW (Micro-hydro) [5]. In areas close to irrigation canals, the construction of Pico-hydro Power Plant is the right solution to meet the electricity needs of simple homes because the cost of pico-hydro equipment required per unit of energy is lower than diesel generator, wind waterwheels, or photovoltaic systems, especially if the equipment is produced locally [6].

Small-scale power plants usually have a low flow discharge and height so it is very difficult to develop even though the potential of Indonesia is very large [7].The problem faced in utilizing irrigation canals to produce electrical energy is the flow speed and small height difference. In order to produce electrical energy, it is necessary to design a plant that is adjusted to the conditions in which the plant is placed. The design of the generation system includes the design of the

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waterwheel, the design of the transmission system and the design of the generator.

An electric generator requires the number of revolutions and torque that must be met by the waterwheel so that the voltage and frequency produced by the generator are stable using the transmission system from the waterwheel to the generator with the appropriate direction and rotation speed [8]. Therefore the generator made must be adjusted to the torque and rotation produced by the waterwheel. In this research is conducted to develop a pico-hydro power plant on *Menaming* irrigation canal that can be used for the street lighting and residents' homes.

2.0 PLANT DESIGN

2.1 Waterwheel

Waterwheel is a wheel-shaped mechanical device with blades around the edges placed on a horizontal axis. The atmospheric pressure and water pressure flowing on the blades cause the waterwheel to rotate at a certain speed. Water flows from the upper surface to the lower surface through the spoons [9].

2.2 Flow Discharge and Hydraulic Power of Water

To obtain flow discharge, it must first determine the wet cross-sectional area of the irrigation canal. Since irrigation canals are trapezoidal, equations are used [10]:

$$A = (b + mh)h \tag{1}$$

Where:
A : Wet cross-sectional area
b : Channel base width
mh : Difference in top width and bottom width
h : Water depth

After the wet cross-sectional area is obtained, the flow discharge is calculated using the equation [11]:

$$Q = VA \tag{2}$$

Where:
Q : Water discharge (m³/s)
V : Flow velocity (m/s)
A : Cross-sectional area of the channel (m²)

From the flow discharge can be calculated hydraulic power in irrigation canals using the equation [12]:

$$Ph = Q.\rho.g.h \tag{3}$$

Theoretically, without taking into account the losses, the output power of the waterwheel can be determined by the equation:

$$\mathrm{P} = \mathrm{Q}.\rho.\mathrm{g}.\mathrm{h}//\eta \tag{4}$$

Where:
P : Waterwheel power (Watt)
ρ : Water type period (kg/m3)
Q : Water discharge (m3/s)
h : Head (m).
η : Efficiency

2.3 Waterwheel Force and Torque

The moment of force (torque) is a quantity that expresses the amount of force acting on an object that causes the object to rotate. To calculate torque can use the following equation [13]:

$$T = \frac{P}{2\pi\frac{N}{60}} \tag{5}$$

Where:
T : Torque (Nm)
P : Power (kW)
N : Rotation speed (rpm)

2.4 Transmission System

Transmission in mechanical engineering is a system used to change rotational speed and torque. The rotation of the input shaft will change the output rotation lower or higher. If the rotational speed is higher, the torque to be produced will decrease, on the other hand, if the rotational speed is lower, the torque to be produced will increase [14]. In the design of the rotation system in the transmission system, equations are used [9]:

$$\frac{n_1}{n_2} = \frac{d_2}{d_1} \tag{6}$$

Where:
n_1 : Drive rotation speed (rpm)
n_2 : Driven rotation speed (rpm)
d_1 : Drive diameter (m)
d_2 : Driven diameter (m)

2.5 Induction Motor as Generator

Induction motors can be used as generators by providing reactive power supply to the induction motor and by adding permanent magnets so that they do not require excitation from outside to create a magnetic field [15]. The design of the permanent magnet generator is simple enough to make it easy to determine the number of poles and is an alternative to a small-scale power plant where the number of poles that can be made is ideal for application at low speeds, such as lifting equipment, micro-hydro, and wind turbines. Advantages of permanent magnet generators [16]:

1. Able to work at low revs
2. Does not require excitation voltage from outside
3. Relatively low maintenance costs

The stator coil is designed in such a way that it forms poles due to changes in the wave of the voltage source. So that the greater the number of poles will result in the smaller the rotational speed of the stator field and vice versa. The rotational field velocity of the induction motor is expressed by the equation [17].

$$\mathrm{n_s} = \frac{120\,\mathrm{f}}{\mathrm{p}} \tag{7}$$

Where:
$\mathrm{n_s}$: Rotational field speed, rpm
f : Resource frequency, Hz
p : Number of poles

The generator has a coil type that is tailored to the needs. The coil type is the meshes coil type and the centralized coil type[18]. The type of coil will greatly affect the number of windings to be made [19]. Because the kern dimensions are

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limited, the diameter of the wire used is also very influential on the number of windings [20]. So, the specifications of the generator made must match the dimensions of the kern. The number of poles designed must match the type of coil and the number of holes in the kern. The number of windings and the diameter of the wire must match the size of the kern hole.

3.0 METHODS

The qualitative approach was used in this study experimentally. Setting the lamp load (independent variable) is done to find out the change in yield (dependent variable). The construction of waterwheels and electric generators made from induction motors will be carried out. Next, several parameters related to the generator output will be measured.

The location of the study is a *Menaming* dam irrigation canal in *Menaming* Village, Rambah District, Rokan Hulu Regency, Riau Province, which is located at 0°51′54.38"N and 100°02′40.33"E. The research location is depicted in Figure 1. The selection of the location for the construction of the plant considers the hydraulic potential of water in the irrigation canal and the distance between the irrigation canal and the residents' homes.

The first step in this research is to conduct a site survey. The site survey aims to obtain preliminary data consisting of differences in height (head), flow speed, water height and cross-sectional size in irrigation canals. The data from this survey is then analyzed for waterwheel design. In order for the maximum power generated by the waterwheel, the design of the waterwheel is adjusted to the dimensions of the irrigation canal.

Furthermore, a waterwheel was made according to the plan. After the waterwheel is made, then a transmission system is made according to the rotation of the waterwheel. Then a generator is made from the induction motor of the waterjet water pump by changing the stator winding and adding a permanent magnet to the rotor. Because the generator output voltage is AC (Alternating Current) then a rectifier circuit is used, hence the generator output voltage becomes DC (Direct Current). After all components are installed, the generator output voltage is measured with a variation in the 12 Volt DC lamp load. The research scheme can be seen in Figure 2.

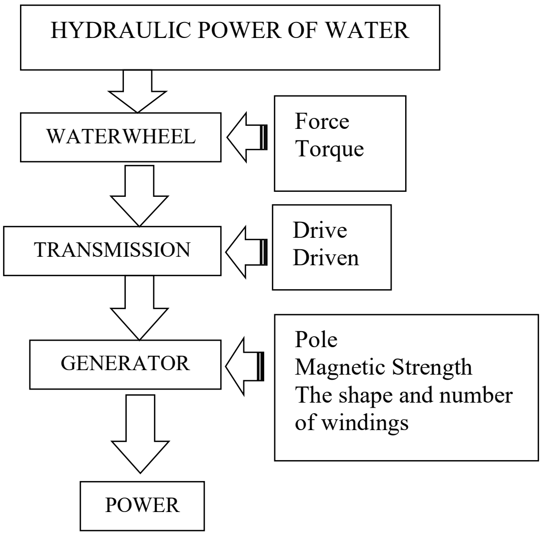

Figure 2: Research Scheme

Figure 1: Research location

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4.0 RESULTS AND DISCUSSION

4.1 Survey Results

Preliminary data was obtained from a survey as a basis for designing a waterwheel in *Menaming* Village. Data obtained from the measurement results are depicted in Table 1.

Table 1: Survey results

No	Description	Size	Unit
1.	Water level	0.70	m
2.	Irrigations base width	1.20	m
3.	Irrigations top width	2.50	m
4.	Flow velocity	0.3	m/s
5.	Difference in top width and bottom width	1.30	m
6.	Head	0.3	m

To obtain flow discharge, it must first determine the wet cross-sectional area of the irrigation canal. Since irrigation canals are trapezoidal, equations are used (1):

$$A = (b + mh)h$$
$$mh = 2.5 - 1.2 /2$$
$$mh = 0.65$$
$$A = (b + mh)h$$
$$A = (1.2 + 0.65)0.7$$
$$A = 1.3\, m^2$$

After the wet cross-sectional area is obtained, the flow discharge is calculated using the equation (2):

$$Q = VA$$
$$Q = 0.3\ x\ 1.3$$
$$Q = 0.38\ m/s$$

The hydraulic power in the irrigation canal according to the survey data is calculated using the equation (3):

$$Ph = Q.\rho.g.h$$

Hence:

$$Ph = 0.38\ x 1000\ x\ 9.81\ x\ 0.3$$
$$Ph = 0.38\ x 1000\ x\ 9.81\ x\ 0.3$$
$$Ph = 1118\ Watt\ atau\ 1.118\ kW$$

The power of the waterwheel is calculated using the equation (4):

$$P_k = n_k . p_h$$
p_k= 0.6 x 1.118 kW
With 60% undershot waterwheel efficiency
p_k= 0.67 kW

4.2 Waterwheel

Waterwheel design must pay attention to the dimensions of irrigation canals, flow discharge, head so that the type and dimensions of the waterwheel to be designed and made can be determined. From the design of the waterwheel is obtained the number of revolutions and torque produced by the waterwheel.

Figure 3: Waterwheel

Waterwheel manufacture requires several work processes, including cutting, turning, milling, welding, and painting. Cutting work was carried out to create the main frame, transmission mounts, blades, frame and walls of the waterwheel. Turning work was carried out to create the waterwheel and transmission shaft. Milling work is carried out to create grooves on the shaft. After all the components are made, welding is carried out to connect the waterwheel parts. Then painting is done so that the waterwheel is rustproof. The manufacturing result of waterwheel is depicted in Figure 3. From the results of the survey conducted, a waterwheel was made with specifications that is depicted in Table 2.

Table 2: Waterwheel specification

No	Description	Size	Unit
1.	Outer diameter of waterwheel	2.44	m
2.	The inner diameter of waterwheel	1.3	m
3.	Waterwheel width	1.20	m
4.	Waterwheel volume	0.467	m^3
5.	The circumference speed of the waterwheel	0.106	m/s
6.	Waterwheel rotation	0.833	rpm
7.	The rotational speed of the waterwheel	0.106	rpm
8.	Number of waterwheel blades	12	
9.	Distance between outer blades	0.631	m
10.	Cross-sectional area of the blade	0.684	m^2
11.	Blade length	0.57	m
12.	Blade width	1.20	m
13.	The volume of water received by each waterwheel blade	0.197	m^3
14.	Force for turning the waterwheel	116.55	N
15.	Waterwheel Torque	138.86	Nm
16.	Water hydraulic power enters the waterwheel	1.156	kW
17.	Output power	884.83	W

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4.3 Transmission System

The transmission system must be adjusted to the needs of the generator. The greater the transmission ratio used will make the torque produced by the waterwheel smaller. When the channeled torque is small, the waterwheel will not be able to rotate the generator. While the greater the load given to the generator, the torque needed to rotate the generator will also be greater. This needs to be considered because the generator needs rotation and torque values to produce electrical energy.

In this study, the power transmission system chosen was to use a chain formed into gears with sprockets as a pair and using pully and V belts. This option was chosen because the torque and water velocity are very low.

The use of a chain formed into gears aims to get a larger ratio reduce the number of transmission shafts, so that the torque to rotate the generator is greater when compared to only using pully and V belts in the transmission system. The research transmission system is shown in Table 3.

Table 3: Research transmission systems

No	Description	Size	Unit
1.	Chain As Drive Gear (Waterwheel)	314	Tooth
2.	Sprocket 428 Driven (Shaft 1)	50	Tooth
3.	Pully Drive (Shaft 1)	36	cm
4.	Pully Driven (Shaft 2)	7.5	cm
5.	Pully Drive (Shaft 2)	40	cm
6.	Pully Driven (Generator)	10	cm

4.4 Generator

The design and manufacture of the generator must also be adjusted to the discharge of water flow, torque and rotation produced by the wheel. Adjustments to the generator part are made by increasing the number of poles, the design of the winding shape and adjusting the number of windings. This is very important because the number of poles will affect the number of rotations the generator, the shape and number of windings will greatly affect the voltage and current released by the generator. The generator manufacturing scheme can be seen in Figure 4.

The design of the generator in this design is made based on the condition of the induction motor that will be used as a generator. In the stator section, the determination of the number of poles, the number of windings and the diameter of the wire used is taken based on the dimensions of the induction motor kern used. Since the rotation of the waterwheel is very low, the number of poles must be made according to the working rotation produced by the waterwheel. The number of stator poles is made into 12 poles with a centralized coil type. The number of poles is limited by the number of holes in the induction motor used (24 holes).

Figure 5: Stator and rotor

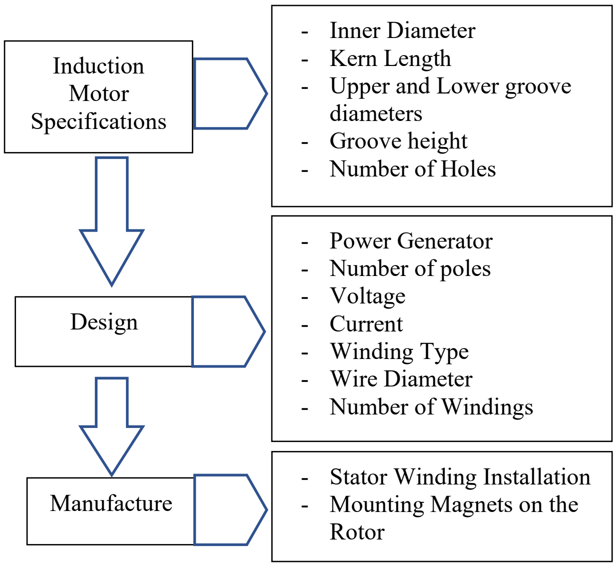

Figure 4: Generator manufacturing scheme

The installation of the winding on the stator is carried out in several steps, including: Installation of prespan paper as an insulator with wire, Installation of windings must pay attention to the direction of the winding according to the design poles, and tie the winding so that the winding is neater and does not touch the stator. The installation of permanent magnets on the rotor the number of poles is made equal to the stator. The installation of magnets is made opposite so that it forms the north and south poles. The size of the magnet used is adjusted to the dimensions of the induction motor. The rotor is installed with 12 neodymium grade 52 magnets with a size of 40x10x5 mm and 12 pieces of 35 x 10 x 5 mm.

From the specifications of the induction motor used as a generator, a generator is made with specifications in accordance with Table 4. Finally, the waterwheel installation scheme of the power plant components is depicted in Figure 6.

Table 4: Specifications of the generator made

	Description		Volume	Unit
1.	Generator Specifications			
	a.	Output Power	200	Watt
	b.	Number of Poles	12	Poles
	c.	Voltage	162	Volt
	d.	Frequency	50	Hz
	e.	Efficiency	90	%
	f.	Power Factor	0.8	
	g.	Current	2	Ampere
	h.	Rotation	500	Rpm
	i.	Wire Diameter	0.66	m^2
	j.	Number of Windings of one groove	50	Windings
2.	Data of Kern			
	a.	Inner Diameter	55	mm
	b.	Kern Length (L)	750	mm
	c.	Groove Diameter (B1)	4.5	mm
	d.	Groove Diameter (B2)	4	mm
	e.	Groove Height (H)	8	mm
	f.	Number of Groove	24	groove

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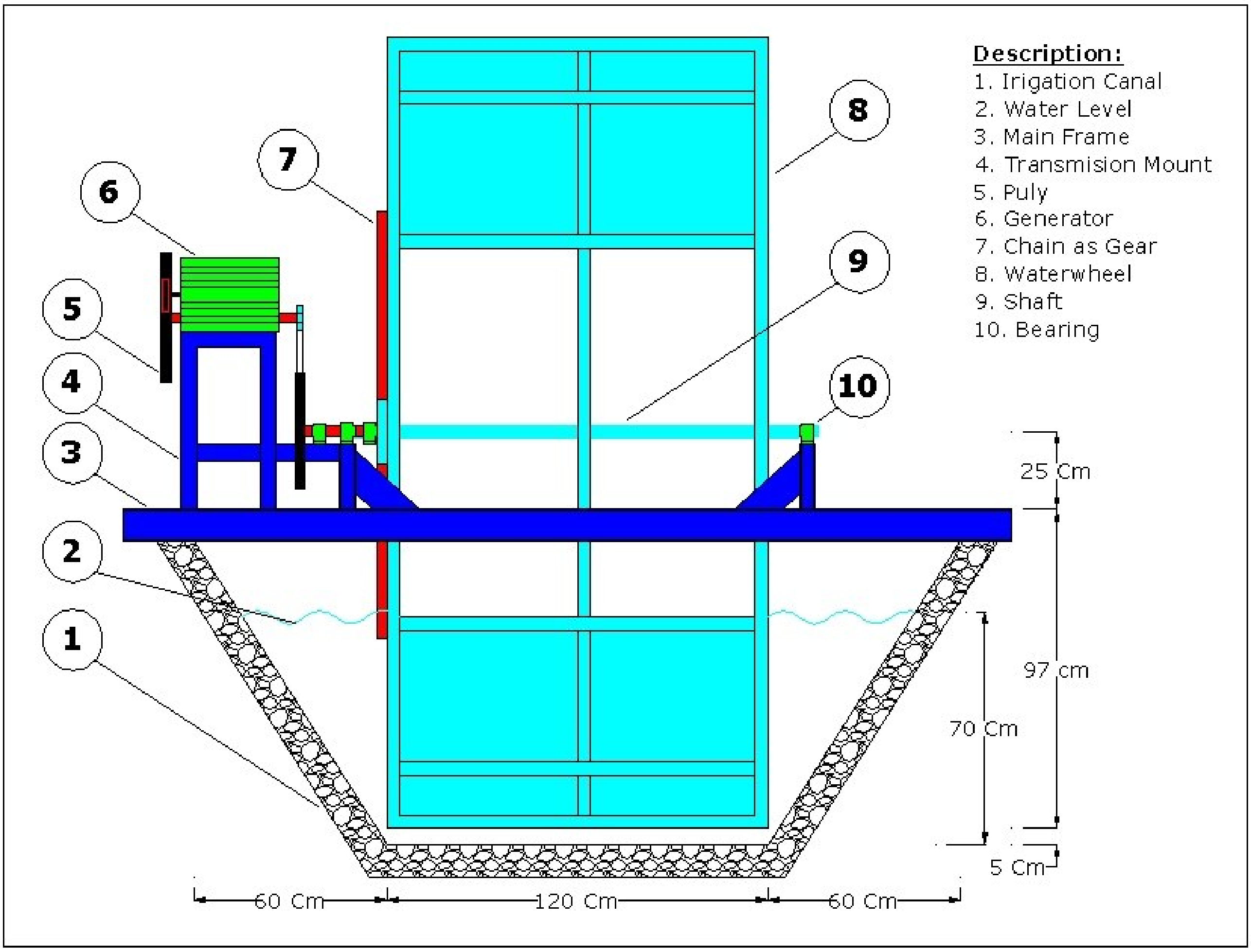

Figure 6: Waterwheel installation scheme

4.5 Test Results

The test is carried out by installing the generator on the transmission system, then measuring the rotation on the waterwheel shaft and the rotation on the generator shaft. This measurement is carried out by setting several load conditions.

Measurements are carried out with no-load conditions, 3 watts lamp loads, 6 watts lamp, 9 watts lamp, 12 watts lamp, 25 watts lamp and 49 watts lamp. As the load increases, the voltage generated by the generator and the rotation of the waterwheel will change.

In addition to measuring rotation on the waterwheel shaft and generator shaft using a tachometer, measurements of the voltage produced by the generator are also carried out using a digital multimeter. This measurement is made by setting the multimeter probe at the Vdc position and affixed to the generator output cable.

The rotation of the waterwheel will affect the rotation of the generator. From the rotation of the generator calculated voltage frequency in theory. The data from shaft rotation measurement, frequency calculation, and generator voltage measurement will be analyzed.

The test design scheme of the research to be carried out is shown in the Figure 7. The test results are shown in Table 5.

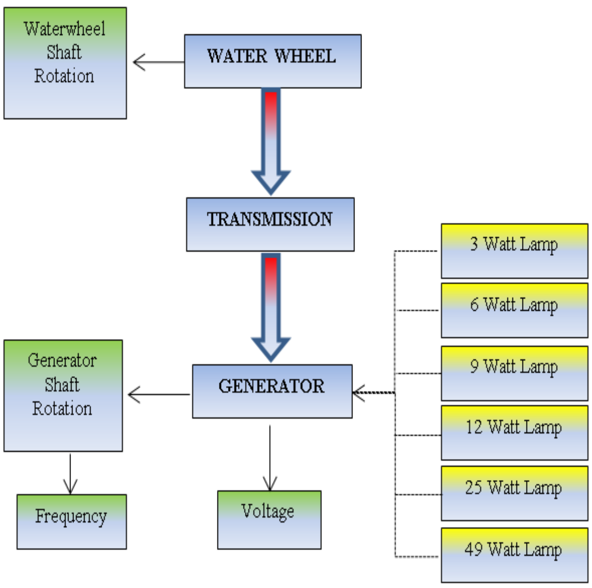

Figure 7: Test Scheme

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Table 5: Test results

No	Lamp Load (Watt)	Water wheel Rotation (Rpm)	Genera-tor Rotation (Rpm)	Voltag e (Volt)	Frequenc y (Hz)
1	3	1.41	170	10	17
2	6	1.4	169	9.8	16.9
3	9	1.39	168	9.6	16.8
4	12	1.28	167	9.2	16.7
5	25	1.35	163	8.6	16.3
6	49	1.32	160	8.2	16

The result of graph comparison between the rotation of the waterwheel and the load of the lamp is shown in Figure 8.

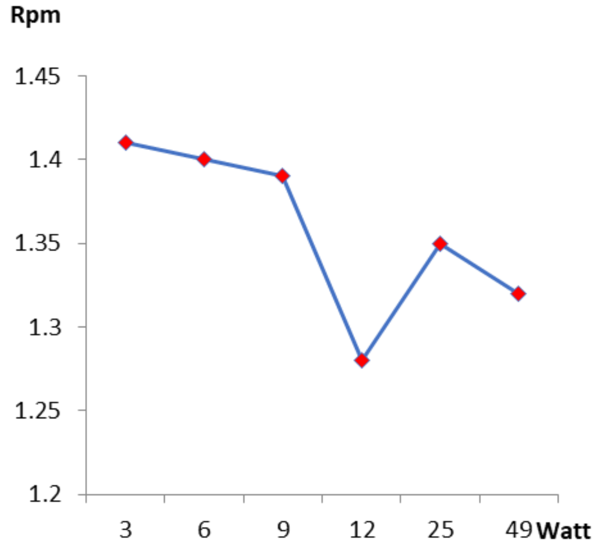

Figure 8: The Relationship of waterwheel rotation to lamp load

The relationship of the generator rotation to the lamp load is shown in Figure 9.

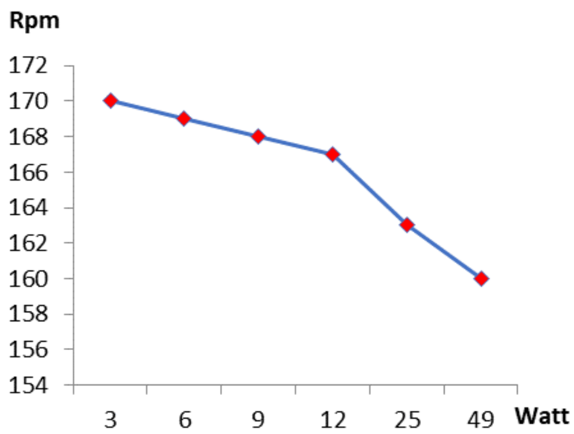

Figure 9: The relationship of generator rotation tolamp load

Based on Figure 9, it can be seen that the rotation of the generator will decrease as the lamp load increases. This rotation is reduced because hydropower is unable to maintain the rotation of the generator. The decrease in generator rotation is directly proportional to the load of the lamp given. The relationship of the rotation of the generator with the voltage is shown in Figure 10.

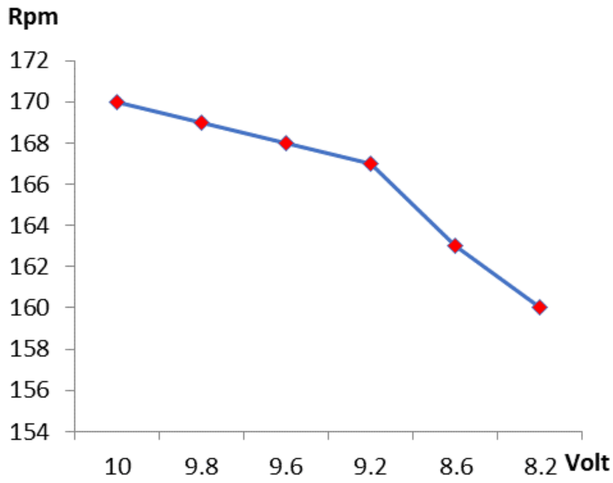

Figure 10: The relationship of generator rotation to voltage

The voltage generated by the generator is greatly influenced by the rotation of the generator. The higher the rotation of the generator, the higher the voltage produced by the generator. With the increase in load, the voltage will decrease according to the decrease in rotation of the waterwheel.

The relationship of generator rotation with frequency is shown in the Figure 11. The voltage frequency is affected by the rotational speed of the generator. With the increase in load, the frequency will decrease because the generator speed also decreases. With a decrease in voltage frequency, it causes the lamp to flicker even though the voltage source is DC voltage.

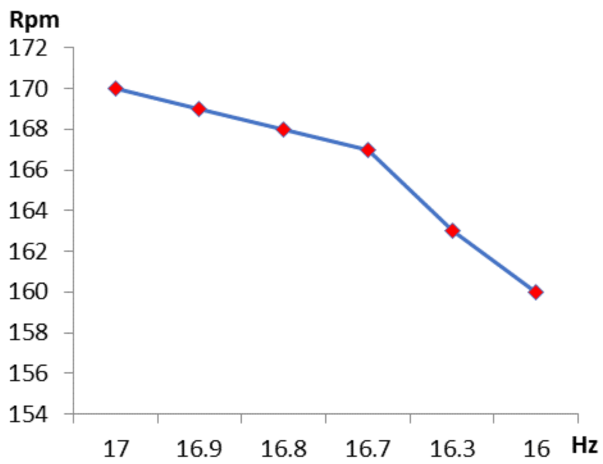

Figure 11: The relationship of generator rotation to frequency

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5.0 CONCLUSION

Based on the measurement results obtained, it is known that in this study the output of the generator is still very far from what was expected. Water hydraulic power from the survey results obtained 1.18 kW. The power of the waterwheel made has an output power of 0.67 kW and the power released by the generator is only 0.049 kW.

One of the causes of differences in measurement results is due to the working rotation, frequency and voltage of the generator that is made different from the conditions when measuring.

From the measurements, it can be seen that as the load increases, the rotation of the wheel, voltage, and frequency will also decrease. This is due to the lack of water power so that the water is no longer able to turn the waterwheel.

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