Application of the cascade system to increase the capacity of a pico-hydro power generation

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Abstract. The Pico-hydro power generation is a power plant with a scale below 5 kW. This type of power generation is suitable for areas with streams or rivers with low water levels. One area that has natural conditions like this is the Javan Langur Centre (JLC), a rehabilitation facility for one of the endangered primate species, the langur. To support the operation of JLC, a pico-hydro power plant has been built, which has a capacity of 300 watts. However, due to the water discharge is quite low, the efficiency of the generator is less than 10%, of which, the total output power from the pico-hydro generator is about 27.3 watts. While the electrical energy requirements in JLC is around 50 watts for lighting. To meet the shortage of electricity supply, it is necessary to increase the power generated by the existing pico-hydro power plant, i.e. by applying a cascade system. This system utilizes water from the existing pico-hydro power plant drainage channel as the intake flow for the new pico-hydro power plant. This system also utilizes differences in elevation or water level to make the terraces. With the application of the cascade pico-hydro system, the electrical power requirements at JLC can be met.

1. Introduction
This research was conducted in the central Javan langur, which is approximately 10 km from the centre of Batu City, East Jaw, Indonesia. Javan Langur Centre is a rehabilitation centre for Javan Lutung, one of the primate species that is protected because it is almost extinct.

Until now, there is no electricity network included in this area. Apart from the fact that the area around this area is uninhabited, the management also keeps the environment natural so that the langur rehabilitation process is not disturbed. Because, the Javan Langur Centre management chose Genset as a source of meeting electricity needs.
Figure 1. Javan Langur centre area.

Around the Javan Langur Centre there are tributaries that have the potential to be a source of environmentally friendly electricity generation. The existence of this river flow can be used as a source for the Pico-hydro power plant, which is a type of power plant with a scale of under 5 kW [1][2].

In 2018, a Pico-hydro power plant was built with an electric power of 300 watts. However, this river flow rate is too low and results in a generator efficiency of less than 10%, where the output power that can be utilized is 27.3 watts.

Due to the need for electric power in the Javan Langur Centre area of around 50 watts for lighting, the fulfilment of electric power cannot be fully supplied from the Pico-Hydro Power Plant (PHPP) that has been built. To solve this problem, a pico-hydro power plant design with a staircase system was made. This system utilizes water in the existing PHPP outlet channel, which is at the top position, as an intake flow for the PHPP system which is placed in a lower position. This system makes use of differences in elevation or ground level to create terraced systems. Because the PHPP technology used in the two generation positions is identical, the output power of the PHPP terraced system is double the output power of the previous PHPP system, which is around 55 watts. With 55 watts of electric power generated by the PHPP Cascade system, the electrical energy needs at the JLC, for lighting, can be met.

2. Pico-hydro power plant

In principle, the Pico-hydro Hydroelectric Power Plant utilizes different heights and the amount of water discharge in irrigation canals, rivers or waterfalls [1]. This water flow is used to produce electrical energy using water turbines and generators.

Based on the output produced, Hydroelectric Power (PLTA) can be divided into [3]:

- Large-hydro: more than 100 MW
- Medium-hydro: between 15 - 100 MW
- Small-hydro: between 1 - 15 MW
- Mini-hydro: more than 100 kW, but less than 1 MW
- Micro-hydro: between 5kW - 100 kW
- Pico-hydro: less than 5kW

This Pico-Hydro Power Plant has several advantages, such as [4]:

- The manufacturing cost is relatively cheap
- The materials are relatively cheap because they are easy to find on the market.
- Environmentally friendly because it does not use fossil fuels so that the maintenance is not too complicated.
- Its construction can be integrated with the construction of an irrigation network.
- Small in size, suitable for rural areas that have not been reached by the PLN electricity network.
2.1. Pico-hydro power plant working principle

The Pico-Hydro Hydro Power Plant is a hydroelectric power plant that uses an intake upstream of the river and flows water downstream through a water channel with a rather small gradient. Electric power is generated by using the height of the waterfall and the slope of the river. This power plant also uses the river flow directly by using a reservoir pool where river water is flowed into the pond through an open or closed channel by being filtered first and stored in a pond that functions to settle sand and mud as well as a reservoir. The water from the pond is flowed through a rapid pipe driving a turbine to generate electricity. The reservoir pool is equipped with several floodgates for filling or emptying when maintenance is being carried out on the reservoir pool.

The electric power generated can be calculated based on the following formula [5]:

\[ P = \rho \cdot Q \cdot h \cdot g \]

- \( P \) is theoretical output power (watts)
- \( \rho \) = density of fluid (kg / m\(^3\))
- \( Q \) = discharge of water (m\(^3\) / s)
- \( h \) = effective height (m)
- \( g \) = gravity (m/s\(^2\))

The electric power generated is the product of the height of the fall and the discharge of water, therefore the success of hydropower generation depends on the effort to get the water drop height and the large discharge effectively and economically.

![Pyco-hydro power plant diagram](image)

**Figure 2.** Pyco-hydro power plant [6].

2.2. Components of a Pico-hydro power plant

Some parts of a Pico-hydro Power Plant can be seen in the following explanation [6]:

2.2.1. Dam. A dam or dam is a construction built to withstand the rate of water so that water will be accommodated in a certain area.
2.2.2. **Headrace.** Headraces are water-carrying channels that follow the contour of the land to maintain the elevation of the channeled water so that water does not spread everywhere.

2.2.3. **Garbage filter.** Garbage filters are very useful for keeping fast pipes from becoming clogged with garbage and sand material that is carried away by the water flow.

2.2.4. **Head tank or forebay.** The function of the soaking tub is to regulate the difference in water output between the headrace and penstock, as well as to separate impurities in the water such as sand, wood.

2.2.5. **Penstock.** The penstock is connected at a lower elevation to the soaking tub to accommodate the water used to turn the water turbine.

2.2.6. **Generator house.** In the generator house there is a sink, turbine, generator and other equipment. To maintain the safety of the equipment, the generator house is equipped with a fence and roof.

2.2.7. **Hydro turbine.** The choice of turbine type can be determined based on the advantages and disadvantages of the types of turbines, especially for a very specific design. At the initial stage, the selection of the turbine type can be taken into account by considering the special parameters that affect the turbine operating system, namely:

- The factor of the effective water drops height and the discharge that will be utilized for turbine operation is the main factor affecting the choice of turbine type, for example: Pelton turbines are effective for operating at high heads, while propeller turbines are very effective at operating at low heads.
- The power factor (power) desired is related to the available head and discharge.
- The speed (rotation) of the turbine will be transmitted to the generator. For example, for a direct couple transmission system between the generator and the turbine at low head, a reaction turbine (propeller) can achieve the desired rotation, while the Pelton and crossflow turbines rotate very slowly (low speed) which will cause the system to not operate.

2.2.8. **Pulley system.** The torque and power from the main shaft are being transmitted to the shaft of the alternator through belt pulley system. Figure 4 shows the pulley system [6].

![Figure 3. Belt-pulley system.](image)

2.2.9. **Generator.** A generator is an electric machine that converts mechanical power into electrical power. Electric machines can be in the form of generators and motors and based on the direction of the current, electric machines are divided into direct current electric machines and alternating current electric machines.

2.2.10. **Charge controller.** Charger Controller is an electronic device used to regulate direct current which is charged to the battery and taken from the battery to the load. Or it can also be said that an electronic circuit regulates the process of charging the battery (Battery Bank) and the current loading from the battery to the load.
2.2.11. **Battery.** The battery is an electric cell in which a reversible electrochemical process takes place, where the discharging process can take place in the battery, namely converting chemical energy into electric power, and the recharging process by regenerating the electrodes used, namely by passing an electric current in the opposite direction / polarity inside the cell.

2.2.12. **Inverter.** An inverter is a device used to convert the DC (Direct Current) input voltage into an AC (Alternating Current) output voltage. The inverter input voltage source can use batteries, fuel cells, solar power, or another DC voltage source.

2.2.13. **Cable.** Cable is a medium for conducting electric current. The material of this cable is various, especially as a conductor of electric current, generally made of copper and generally coated with a protector. the maximum ability of the cable to pass current continuously without causing damage to the cable is known as KHA (Current Conductivity).

2.2.14. **MCB (Miniature Circuit Breaker).** MCB is a component in an electrical installation that functions as a switch or a device that functions as a protector of electrical installation circuits from overcurrent. The MCB has the same function as a fuse, which will cut off the current flow of the circuit when there is an overcurrent disturbance.

3. **Workflow and system design**

3.1. **Problem solving workflow**

The method used in this study follows the order of work as mentioned below:

- Analysis of the electricity requirements required for the operational activities of the Javan Langur Centre.
- Estimation of the potential power that can be generated from the water flow around the Javan Langur Centre location to calculate the estimated capacity of turbines and generators.
- Construct civilian constructions required for turbine construction.
- If you get a generator power potential that is smaller than the load requirement, a priority scale of the load that must be supplied is arranged.
- In addition, if the potential power output of the generator is less than the load requirement, the battery requirements needed to support the energy supply during peak load are analyzed.
- The next step is to design a turbine that is suitable for the existing conditions in the Javan Langur Centre river basin. Turbine materials must be made of materials that are corrosion resistant.
- Determine the generator that matches the power and speed of the turbine designed. The generator that is planned must have high flexibility, efficiency and can rotate at low speed according to the turbine.
- Testing of generators in the lab. Electric machines Malang State Polytechnic. The test includes testing the characteristics of open circuit, short circuit generator and load characteristics.
- Turbine testing was carried out at the Javan Langur Centre.
- The design of electrical installations for the energy supply needs of the Javan Langur Centre including the protection system including the needs of batteries, charger controllers and inverters.
- Combined turbine and generator testing including zero load and full load loading. In this step, testing of the charger controller and inverter is also carried out.
- Implementation of comprehensive works including: turbine-generator installation in the constructed construction, installation of LDP panels in suitable locations, carrying out electrical installation work.
3.2. Block diagram of the pico-hydro power plant cascade system
The block diagram of the cascade Pico-hydro power plant system can be seen in Figure 4. From the block diagram, it can be seen that the cascade system applied to the Pico-hydro Power Plant is a combination of two Pico-hydro power generation systems in a larger system.

In the cascade system that is applied, 2 water turbines, 2 generators, and 2 charge controllers are needed, where all similar components are selected which are identical, the same in specifications and dimensions. The output of both charge controllers will be connected to a battery or accumulator. After that, it is connected to an inverter, to convert the DC voltage from the battery into AC voltage, which is then supplied to the AC load.

![Figure 4. Block diagram of the cascade system pico-hydro power plant.](image)

3.3. Reservoir design
The planning of the reservoir for the PHPP terraced system can be seen in the following figure 5.

![Figure 5. Pool Design (a) top view (b) side view.](image)

From the figure 5 above, it can be seen that there are 2 PHPP systems, where 1 PHPP system is placed in the upper reservoir and 1 PHPP system is placed in the lower reservoir. Although the sizes of the two reservoirs are not the same, (1.6m x 1.2m and 1.5m x 1.5m), the types and specifications of the PHPP system used are identical, including the type and size of the turbine, pulley system, and generator specifications.
3.4. Hydro turbine design

The water turbine design used is a portable spiral vortex hydro turbine [8] as shown above. The turbine and turbine housing have a height of 100 cm and a diameter of approximately 60 cm. The turbine intake is equipped with a water steering plate so that water entering the turbine housing will directly hit the circular wall of the turbine house. This process will produce a spiral-shaped whirlpool which has stronger power to rotate the turbine blades.

3.5. Pulley system design

The circumference of the large pulley used in this research is five times that of the small pulley; the small pulley will rotate five times for every 1-time rotation of the large pulley.

3.6. Generator specification

The generator used in the PHPP system is a 3-phase AC generator which has a nominal output power of 300 watts, a nominal voltage of 48 Vac, and a nominal rotation of 750 rpm. The generator weight is about 3.4 kg. This generator is rust resistant because the shaft is made of stainless steel and the cover is made of aluminium alloy. The dimensions of the generator can be seen in the following figure.

3.7. Charge controller and battery specification

The charge controller specifications used in this research are MPPT type charger controller with a maximum current of 20A, maximum input voltage of 48VDC, float charge 13.8V, nominal voltage 12V, charge disconnect 10.6V, charge reconnect 12.6V. While the battery used in this study has a capacity of 40 Ah and a nominal voltage of 12 V.

3.8. Inverter specification

The inverter used in this research is pure sine wave type 500 W, with a power inverter of 500 W, input: 12V (10 - 15V) DC, output: 220 - 240V AC, output frequency: 50 Hz +/- 2 Hz, output wave: pure sine wave, peak efficiency: 60 - 95%, low battery shutdown: 10.0V +/- 0.5V DC, low battery alarm: 10.5V +/- 0.5V DC, and high voltage shutdown: 15.0V +/- 0.5V DC.

4. Testing and analysis data

4.1. Water discharge measurement

The measurement of water discharge is carried out using a simple method, namely placing a 1.5 liter bottle in the water channel. Then note the time it took to fill the bottle to the brim. Measurements were made in 2 places, namely the river flow and the channel leading to the water turbine intake. The results of water discharge measurements can be seen in the following table, namely for river water discharge around 0.00035 m³ / s. Meanwhile, the turbine intake water discharge is around 0.00023 m³ / s.
Table 1. Water discharge measurement results.

| Volume (liter) | Time (second) | Water Discharge (liter/second) | Volume (liter) | Time (second) | Water Discharge (liter/second) |
|---------------|--------------|-------------------------------|---------------|--------------|-------------------------------|
| 1.5           | 3.67         | 1.5                           | 1.5           | 7.19         |                               |
| 1.5           | 4.03         | 1.5                           | 1.5           | 6.27         |                               |
| 1.5           | 5.09         | 1.5                           | 1.5           | 5.84         |                               |
| 1.5           | 4.10         | 1.5                           | 1.5           | 6.29         |                               |
|               | Average      |                               |               | 4.23         | 0.00035                      |
|               | Average      |                               |               | 6.40         | 0.00023                      |

4.2. Generator output voltage measurement

From the measurement results, it can be seen that the turbine rotation and the generator output voltage for the two PHPP systems installed have values that are not much different. When the turbine rotation is in the range of 78 rpm, the generator rotation is around 390 rpm with a generator output voltage of about 21 volts.

Table 2. Measurement results of generator output voltage.

| No | Turbine 1 Rotation (rpm) | Generator Rotation (rpm) | Generator Output (Vac) | No | Turbine 2 Rotation (rpm) | Generator Rotation (rpm) | Generator Output (Vac) |
|----|--------------------------|--------------------------|------------------------|----|--------------------------|--------------------------|------------------------|
| 1  | 78.3                     | 391.5                    | 21.6                   | 1  | 77.9                     | 389.5                    | 22.8                   |
| 2  | 76.1                     | 380.5                    | 20.4                   | 2  | 76.1                     | 380.5                    | 20.4                   |
| 3  | 76.7                     | 383.5                    | 20.4                   | 3  | 77.6                     | 388.0                    | 21.6                   |
| 4  | 78.3                     | 391.5                    | 21.6                   | 4  | 75.3                     | 376.5                    | 21.6                   |
| 5  | 78.2                     | 391.0                    | 21.6                   | 5  | 79                       | 395.0                    | 20.4                   |
|    | Average                  | 77.52                    | 187.6                  |    | Average                  | 385.8                    | 21.36                  |

4.3. Battery charging current measurement

Table 3. Battery charging current measurement results.

| Charging Current (A) | Charging Time for a 40 Ah Battery |
|----------------------|----------------------------------|
| Generator 1          | 0.75                             | 53.3333                        |
| Generator 2          | 0.75                             | 53.3333                        |
| Total                | 1.50                             | 26.6667                        |

From the table 3 above it can be seen that the charging currents for generator 1 and generator 2 are relatively the same, which is around 0.75 A. If you only use 1 generator (1 PHPP system), then charging the 40 Ah battery to full will take approximately 53 hours. Meanwhile, if using 2 generators (2 PHPP systems) with the cascade method, with a total charging current of 1.5 A, charging a 40 Ah battery to full will take approximately 26 hours.

4.4. Generator efficiency calculations

The calculation of generator efficiency can be seen in the following description:

Generator specifications = 3 phase, 48 volts, 300 watts. Then the nominal current value can be calculated as below:

\[
I_{\text{nominal}} = 300 \times (1.732 \times 48) = 3.6 \, \text{A}
\]

To find out the value of the generator output current, it can be seen in the charging current value, which is 0.75 A. While the generator output voltage is 21 volts. Then the output power value can be calculated as below:

\[
P_{\text{output}} = 1.732 \times 21 \times 0.75 = 27.3 \, \text{watts}
\]
Then the generator efficiency value can be calculated as below:

\[
\text{Generator efficiency} = \frac{\text{Actual Power}}{\text{Rated Power}} \times 100\%
\]

\[
= \left(\frac{27300}{300}\right) \times 100\% = 91\%
\]

### 4.5. Battery loading capacity calculation

**Table 4. Load variations.**

| Number of Lamps | Power (W) | Voltage (V) | Current (A) |
|-----------------|-----------|-------------|-------------|
| 1               | 10        | 214         | 0.05        |
| 2               | 20        | 214         | 0.09        |
| 3               | 30        | 214         | 0.14        |
| 4               | 40        | 214         | 0.19        |
| 5               | 50        | 214         | 0.23        |
| 1 incubator     | 60        | 214         | 0.28        |
| 6 lamps         | 110       | 214         | 0.51        |

**Table 5. Battery loading capacity.**

| Battery Capacity in 1 day (Ah) | Full Load in 1 day (A) | Loading Time in 1 day (hours) | Loading Capacity in 1 day (Ah) | Battery/Loading Ratio |
|-------------------------------|------------------------|-------------------------------|--------------------------------|-----------------------|
| 40                            | 0.51                   | 12                            | 6.17                           | 6.48                  |

Based on the load variation table and the calculation of loading capacity in 1 day, it can be seen that the battery is fully charged after 18 hours and can meet the needs of electrical energy (lighting & incubator) in one day, with a ratio of battery capacity: loading capacity = 6.48.

### 5. Conclusion

- Measurement of water discharge in the Javan Langur Centre area shows that the water discharge in the river flow is very small, around 0.00035 m$^3$/s. Meanwhile, the water discharge that can be used for pico-hydro power plants is 0.00023 m$^3$/s. Low water discharge causes low generator efficiency. From the measurement results, it is found that the efficiency of the generator is less than 10% with the power generated around 27.3 watts.
- The 2-stage cascade system applied to the Pico-hydro power plant in the Javan Langur Centre area is able to double the power generation capacity, around 55 watts.

### 6. Future work

The water discharge must be enlarged to increase the rotation and torque of the water turbine. If the rotation and torque of the water turbine increases, the generator rotation will also be faster and will produce a higher output voltage. One possible option to increase the flow of water entering the turbine house is to increase the height of the existing dam, so that the volume of water collected in the dam becomes larger.

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