Efficiency improvement and economic analysis of micro hydro power plant by using twin vertical hydro turbine

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Abstract. This research aimed at improving the efficiency of and comparing the production costs of micro hydropower plants by using twin vertical hydro turbines as low headwater sources. This micro hydropower plant was designed with the highest capacity of 3 kW and utilized a directly connected transmission system and induction generator by modifying two 3 HP induction motors. At the inlet area of the turbines, guide vanes were installed on the 25 turbines at 24°. The ratio of turbine diameter was equal to 0.68. After the experiment was completed, it was found that the highest electrical power generated from the plant had been 1.38 kW with an efficiency of 49% at head 0.7 m. When compared to the plant without any installed guide vanes, the increase was 26.94%. Regarding the electrical production cost, the total cost was 5,844 USD or 1,948 USD/kW.

1. Introduction
Micro hydropower plants, which are used for low headwater sources, are lower-cost operating systems at less than 2,500 USD/kW [1]. These are suitable for residential areas that are far away from the transmission system, but which have a water source nearby. European countries, currently, have been widely showing interest in and developing micro hydropower plant technology. Micro hydropower plants have power generation capacities that do not exceed 100 kW with water heads less than 10 m [2]. Therefore, the selected turbines, which are appropriate for the head level and water flow rate, play an important role in highly efficient power generation and can consequently lower the production costs. A suitable type of turbine and proper installation are essential factors that can yield a highly efficient power plant. A micro hydropower plant is a system that operates with headwaters lower than 10 m, where such a head is found to work appropriately with a cross flow turbine. Cross flow turbines are lower in cost due to their simple designs and compared to the ones by Kaplan and Francis, they neither require the latest production technology nor are modern machines needed [3]. The results showed that cross flow turbines have an average efficiency of 78% between 3-20 m at the head. However, the design of the cross flow turbines is an impulse type, which results in poorer efficiency when utilizing a head lower than 3 m. Hence, in order to study the factors; which influence cross flow turbine efficiency, such as the numbers of blades, the inlet angle of attack, and the proper water turbine size, etc.; a water turbine, which is more appropriate for the water source, needs to be created in order to achieve a greater degree of efficiency from the power plant. Mockmore and Merryfield studied cross flow turbines with 20 blades, a 16° inlet angle of attack, and a diameter ratio of 0.66. Their findings suggested that an efficiency of 68% was the highest, which could be achieved from a water turbine. In contrast, V. R. Desai and Nadim M. Aziz conducted experiments to determine the influences of significant variables, which had been made to the cross flow turbines.
Their study revealed that water turbines with a 24° inlet angle of attack, with 25 blades, and with a diameter ratio of 0.68 had given the highest efficiency of 88%. At present, there are hydropower plants, which are being created with twin vertical hydro turbines. Such types of plants are designed to be located near low headwater sources like irrigation canals, floodgates, and waste water treatment facilities in factories where the water head ranges from 0.7 - 2 m in order to generate 1.5 kW of power and to achieve a water turbine efficiency of 54.26% [4]. Obviously, from the present research, the results indicate a greatly lower degree of efficiency. Therefore, studying the variables that can influence the efficiency of water turbines, as well as examining the weaknesses of the cross flow turbine power plants, can assist in establishing some guidelines to better develop the plants’ efficiency. In addition, they can lower the costs of power generation. Furthermore, these efforts can stimulate interest, increase motivation, and promote the future employment of micro hydropower plants in low headwater sources.

2. The Design of the Cross Flow Turbine

2.1. The design of the cross flow turbine

Mockmore and Merryfield suggested their cross flow turbine design with the inlet blade angle ($\beta_i$) as calculated below:

$$\beta_i = \tan^{-1}(2 \tan \alpha_i)$$  \hspace{1cm} (1)

The curvature of the blades was determined by:

$$\rho = \frac{([r_i^2] - [r_2^2])}{2r_i \cos \beta_i}$$  \hspace{1cm} (2)

In which $r_i$ and $r_2$ are the radiuses of the inside and outside edges of the water turbine (m) and its central angle was derived from the following:

$$\delta = 2 \left( \tan^{-1} \left( \frac{\cos \beta_i}{\sin \beta_i + \left( r_2/r_1 \right)} \right) \right)$$  \hspace{1cm} (3)

The diameter of the blades’ outside edges was calculated using the following equation:

$$D_i = \left( \frac{30V_i \cos \alpha_i}{\pi N} \right)$$  \hspace{1cm} (4)

In which $V_i$ is the inlet velocity (m/s), and $N$ is the turbine’s speed (rpm), then water turbine’s height was derived from:

$$L = \frac{2Q_i}{D_i V_i (\theta \pi / 180)}$$  \hspace{1cm} (5)

$Q_i$ indicated the inlet water flow rate (m³/s) and $\theta$ represented the inlet angle to the runner (degrees). Then the water turbine was designed to generate 3 kW of power as illustrated in Table 1.

| Design Parameters | Values | Descriptions of the Design Parameters |
|-------------------|--------|--------------------------------------|
| $\alpha_i$        | 24     | Inlet angle of attack (degrees) [5]  |
| $N_b$             | 25     | Number of blades [5]                 |
| $D_2/D_1$         | 0.68   | Diameter ratio [5]                   |
| $\beta_i$         | 41.68  | Inlet Blade angle (degrees)          |
| $\delta$          | 58.08  | Central Angle (degrees)              |
| $\rho$            | 0.0899 | Curvature of the blade (m)           |
The results, obtained from the cross flow turbine design, indicated that the blade inlet angle was 41.68°, the center of the angle was 58.08°, the curvature of the blades was 0.0899 m, and that water turbine’s diameter and height were 0.5 m as illustrated in Fig. 1.

![Diagram of water turbine profile design](image)

**Figure 1.** The typical water turbine profile design from the given parameters.

### 2.2 Guide vane design

The purpose of the guide vane is to assist in more appropriately controlling the inlet angle of attack. Vincenzo Sammartano, et al. [5] suggested their equations and design for guide vanes. They found that the radius of the guide vanes would change by degrees (BC), as shown in Fig. 2 (a), and that it could be calculated using the correlated equations (6)-(9):

\[
r(\theta) = K\theta + \frac{D}{2}
\]

(6)

When K is a constant, the following could be determined from equation (7):

\[
K = \frac{1}{\lambda - \gamma} \left[ \frac{S_0 \cos \alpha_1 + r_i}{\cos \gamma} - r_i \right]
\]

(7)

In which \( \lambda \) is the inlet angle of turbine, when considering Fig. 2 is (a) and (b), they referred to rectangular AOD and \( \gamma \) was determined using equation (8):

\[
\gamma = \tan^{-1} \left( \frac{S_0 \sin \alpha_1}{S_0 \cos \alpha_1 + r_i} \right)
\]

(8)

The nozzle’s height (\( S_0 \)) was derived from equation (9):

\[
S_0 = \lambda (r_i \sin \alpha_1)
\]

(9)

Fig. 2 (a) and (b) represent the elements and installation positions of the guide vanes from equations (6) – (9). These guide vanes more appropriately offer the inlet angle of the turbine and offer it equally to all vanes.
Figure 2. (a) shows the turbine’s curvature to obtain hydropower and (b) shows the inlet profile into blades after the nozzle curvature installation.

2.3 The construction of the hydro power plant with twin vertical turbines

Then, the hydro power plant was constructed with twin vertical turbines (see Fig. 3). The major portions of the configured hydro power plant consisted of the following: the runner, chambers (No. 1-3), and the guide vanes, made from 304 stainless steel and 1.5 mm thick. The transmission system was supplied with power from turbine’s shaft axis to the direct-drive electric generator, which was generated by the direct injection system from the 2 induction motors 3HP (3 phase).

![Diagram of a hydro power plant](image)

Figure 3. An illustration of the hydro power plant at low head level built with twin vertical turbines.

2.4 Electrical efficiency calculation

After the hydro power plant had been installed and the irrigation canal blocked, there was headwater found in system \( H \) and a flow rate \( Q_1 \) flowing through turbine. The power produced from the generator demonstrated the results of an electric current \( V \) and a voltage \( I \), which were displayed on the digital screen. Hence, the electrical efficiency, generated from this hydropower plant, could be calculated as follows:

\[
\eta_{\text{system}} = \frac{VI}{\rho g Q_1 H}
\]
2.5 The installation of and experiments on the micro hydropower plant

The power plant was designed to be located in the actual setting of an irrigation canal, which was blocked so that headwater could accumulate in the plant (see Fig. 4). The irrigation canal was 2.7 m in width, 1.8 m in depth, and the depth of water before the plant was installed was 1 m. Moreover, the flow rate within the canal was equal to 2.1 m$^3$/sec. The power plant consisted of a set of turbines, a generator, and an electricity meter, which displayed the amount of power and the electrical load by using two 1,500 W fluorescent bulbs. For the convenience of the experiment, the power plant was designed so that it could be moved in and out of irrigation canal. Once installation was completed, the water head would continue to rise. Water velocity ($V_1$) would be due to head accumulation and inletting with the angle of the blade ($\beta$). Inlet angle of attack was equal to $\alpha$, and hydropower, which was transmitted to blade, resulted in turbine rotation with the speed of $N$. Then further forward power was generated by the direct connection transmission system via a gearbox with a gear ratio 1:15, which led to higher speeds at the shaft axis. This caused the generator axis to rotate with speed, making it able to generate power. The generated power was represented as voltage and electric current on the digital screen (Fig. 4). The process of data collection was divided into 7 trials, which were distinguished by the head levels of 0.25, 0.3, 0.4, 0.5, 0.55, 0.6, and eventually 0.7 m. The highest head that the irrigation canal was able to support was 0.7 m. From each trial, the inlet flow rate was recorded by employing a digital water velocity meter, Model BA1100, which displayed the flow rate in a digital format. The water velocity was measured at between 0.1-6.1 m/sec and afterwards, water head was brought to be calculated as the energy input into the plant. The power, obtained from the power plant, was recorded as the electric current and voltage. Then, this data was used to calculate the power efficiency.

3. Results

Fig. 5 (a) indicates the correlation between the generated power and water head level within power plant. After the plant was installed by blocking the irrigation canal, the initial head in plant was equal to 0.25 m, which indicated that this head level was not sufficient to generate any power. Consequently, when the water head level was increased to 0.3, 0.4, 0.5, 0.55, 0.6, and 0.7 m, the power plant was considerably able to utilize the increase in order to generate 36.40, 129.30, 457.80, 950.60, 1135.20, and 1379.90 W, respectively.
Figure 5. The correlation between the power generated and the water head level within the power plant.

After that, data obtained from these experiments was calculated as the efficiency of the power plant. The curve of the electric efficiency from the hydro power plant looked similar to a parabola from head between 0.25-0.55 m. Furthermore, its efficiency signified the constants at the head level of 0.55 onwards and the highest efficiency indicates was 49% as Fig. 5 (b).

The useful data, received from our experiment, allowed for the power curve of 1,500 W to be plotted, so that the power consumption to generate could be compared. Fig. 6 shows the flow rates with guide vane installation (solid line) and without guide vane installation (broken line).

The results indicated the following: with the guide vane installation, the efficiency was equal to 49.6% from a hydropower consumption of 2.952 kW (A), and without the guide vane installation, the efficiency was equal to 38.6% from a hydropower consumption of 3.796 kW (B). The increased efficiency was determined to be approximately 26.94%.

Table 2 represents the costs of building and installing the power plant, which was divided into four parts: (1) the cost of the turbine generator was at 41%, (2) the cost of electrical control system was at 45%, (3) the cost of the civil work and the installation as 6%, and (4) the cost for management was 5%. When these ratios were considered, it was decided that the cost of civil labor for installing the plant in the irrigation canal had been relatively low due to its convenience and the fact that this type of system is less time consuming than installing a water-diversion system. Moreover, the costs for the turbine generator and the electrical control equipment were close (only a 4% difference). The reason
for the similar costs might stem from the fact that they are the essential parts of a micro hydro power plant. After analysing these four costs, the total expenditures had been 5,844 USD or 1,948 USD/kW. These figures suggest that the cost from the present study was lower than the cost estimated by A.H. Elbatran, et al., [1] who determined the cost of building a micro hydro power plant to be 2,500 USD/kW.

| Types of Cost                  | A.H. Elbatran [1] | This study |
|-------------------------------|-------------------|------------|
| Civil labor (%)               | 40                | 6          |
| Turbine Generator set (%)     | 30                | 41         |
| Control Equipment (%)         | 22                | 45         |
| Management (%)                | 8                 | 5          |
| Total budget (USD/kW)         | 2,500             | 1,951      |

4. Conclusion
The power plant design for low water head utilizes twin vertical turbines with a maximum power generation 3 kW. After that, the plant was actually installed by blocking a concrete wall irrigation canal with a size of 2.7 m and a water depth of 1.8 m. The flow rate in the canal before installation was 2.1 m³/sec measured at 1 m of water depth. The experiments were carried out at separate head water levels of 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7, respectively. This power plant was designed with and inlet angle at guide vanes of 24° and with 25 blades. The height and the outside diameter of water turbine was 0.5 m, and the ratio of turbine diameter was 0.68. The results found that with the guide vane installation, the efficiency had increased and constants were found at the water head level of 0.55 onwards. The plant system indicated that the highest efficiency was 49% at a water head level of 0.7 m. Finally, the cost for building and for installation was 1,948 USD/kW.

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