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Hydroelectric power generator using vertical axis turbine with adaptive blades

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ABSTRACT

The implementation of micro-hydro power plants (MHPPs) offers a strategic solution for achieving energy independence, particularly within remote communities. This study proposes the development of a hydroelectric power generator with a vertical axis turbine, designed not only as a source of clean energy but also to minimize visual pollution. The system maximizes submerged components, thereby reducing its visual impact. Although MHPPs technology is widely applied to address electrification challenges in remote areas, the system proposed in this study, with its components predominantly submerged below the water surface, offers a visually unobtrusive solution that is also well-suited for urban environments. However, conventional locked-blade turbines often experience significant efficiency losses due to counter-flow pressure acting on blades moving against the water stream, highlighting the need for an adaptive mechanism to minimize drag and optimize energy capture. The hydroelectric power generator using vertical axis turbine with adaptive blades consistently demonstrated better performance than a system using locked blades. The adaptive-blade configuration outperformed the locked-blade system, exhibiting a 5.1% increase in average turbine efficiency and a 3.5% improvement in overall system efficiency.

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1. INTRODUCTION

Global reliance on fossil fuels highlights the urgent need to transition to more sustainable and environmentally friendly renewable energy sources. Indonesia possesses abundant hydropower potential, but its utilization remains suboptimal. With strong commitment and appropriate policies, a transition to a clean and sustainable energy system is highly achievable [1], [2]. According to [3], Indonesian Government plans to add 11.7 GW of hydropower capacity, including 6.0 GW of pumped-storage systems, to meet growing electricity demand and support renewable energy integration. Hydropower is projected to be the second-largest contributor to new renewable capacity after solar, reflecting its strategic role in balancing supply and ensuring grid reliability. This hydropower potential can be harnessed through the development of micro-hydro power plants (MHPPs). MHPPs, with capacities ranging from 10 kW to 1 MW, or even pico-hydro (<10 kW), offer a promising alternative for meeting electricity demands, especially in remote areas not yet reached by the national electricity grid [4], [5]. The advantages of MHPPs include relatively low cost, ease of operation, and minimal environmental impact [6]. The implementation of MHPPs technology can be a strategic solution for achieving energy independence in communities [7], [8]. Furthermore, active community involvement in MHPPs management can foster a collective spirit to independently meet the energy needs of the community

[9]. MHPPs operate by converting the kinetic energy of water into mechanical energy via a turbine, which is then converted into electrical energy by a generator. The main components of an MHPPs consist of a generator, a turbine, and a water source [10]. The turbine is one part that has the potential to be engineered; even a difference in the number of blades on a certain type of turbine can significantly affect its performance [11]. Depending on the specific needs and location of MHPPs, a monitoring system may be necessary to easily track its performance [12]. Hydrokinetic turbines, in particular, are suitable for a relatively low waterfall such as in irrigation channels, canals, or rivers because they do not require a significant head, but rather rely on the waterflow velocity to drive their shaft [13], [14]. Vertical axis hydrokinetic turbines are not only utilized in open-channel MHPPs, such as in rivers or canals, but also show great potential for converting the kinetic energy of in-pipe water flow [15], [16].

This research focuses on evaluating the performance of a vertical-axis turbine with adaptive blades for a MHPP application in open-channel. A vertical-axis turbine was chosen due to its ease of installation. The adaptive blades concept proposed in this research involves a free-swing blades turbine, meaning the addition of hinges on the turbine blades. The expectation is that this design can allow the turbine to adapt better to various waterflow conditions. On-site testing in an irrigation canal conducted to investigate the electrical characteristics of a MHPP utilizing vertical-axis turbine configuration with adaptive blades.

2. ADAPTIVE BLADES IN VERTICAL AXIS TURBINE

As a preliminary note, the adaptive lamella mechanism in the Oryon Turbine allows the blades to open and close passively under hydrodynamic load, enabling the blades or the lamellas connected to the three turbine arms to adapt depending on the flow. This capability is achieved without active control systems, as the lamellas respond naturally to water pressure and flow direction. The design minimizes drag during the recovery phase of the rotor arms, enhancing overall efficiency [17]. In contrast, the adaptive blades turbine in this research uses hinged blades connected surround a vertical water-wheel turbine that passively respond to flow direction by opening to capture energy and closing to reduce resistance when facing against the flow. While both systems aim to optimize energy extraction through adaptive blade behavior, the Oryon Turbine passively mitigates counter-flow pressure by opening its lamellas, whereas my design focuses on similar function by retracting the blades.

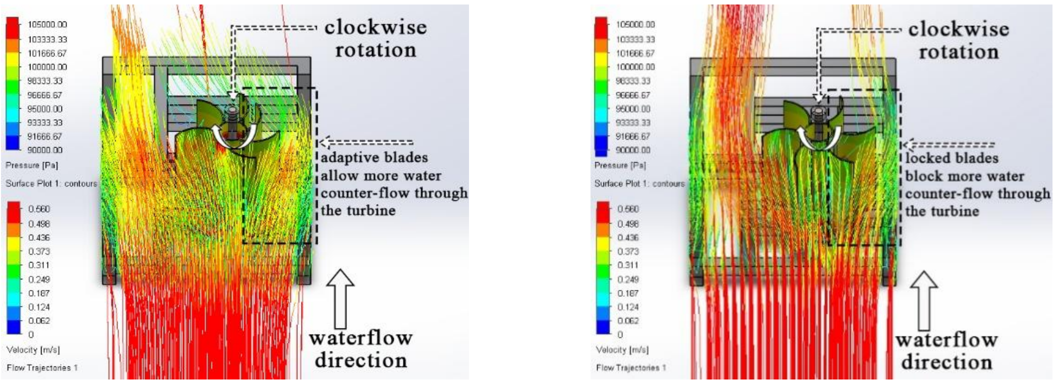
The selection of a vertical axis water turbine aims to minimize the parts of the system visible above the water surface. This approach is implemented to reduce potential visual pollution and maintain the environmental aesthetics around the installation site [18], [19], also the sustainability of the river [20]. A vertical axis water turbine harnesses the hydrokinetic power of a water flow using a run-of-river (ROR) principle, which does not require a difference in water surface elevation (no-head) [21], [22]. The potential hydrokinetic power can be calculated using the following formula [23], shown in (1).

$$P_{hk} = \frac{1}{2}\rho A v^3 = \frac{1}{2}\rho Q v^2 \tag{1}$$

Where P_{hk} is hydrokinetic power in watts; ρ is density of water in kg/m^3 (where ρ of water = 1000 kg/m^3); A is area of water intake in m$^{2;}$ v is water velocity in m/s; Q is water flow rate in m^3/s (where Q = Av).

Prior researchs was conducted on hydroelectric power generators using vertical axis turbines. A few of them are as follows. Chaulagain *et al.* [24] investigated the performance of a turbine they named the new vertical ultra-low-head hydro turbine. Their findings indicated that this turbine, consistent with its name, still requires a minimal head and can achieve an efficiency of over 50% in their experimental setup. Reddy and Bhosale [25] conducted a study on the performance of a vertical axis helical hydrokinetic turbine. They found that this type of turbine can cause turbulence as the water inflow velocity increases. From their tests, the turbine with four blades was able to produce a power coefficient of up to 0.24. Mereke *et al.* [26] investigated a diffuser augmented dual vertical axis hydrokinetic Banki-Michell turbine. They reported that using a diffuser could increase energy recovery by up to 33.7% and boost efficiency by up to 16%. Kong *et al.* [27] conducted research to improve the performance of a straight-bladed H-type Darrieus turbine. Their results showed that a turbine with a deflectable leading-edge can enhance its self-starting capability and improve the stability of the torque.

The turbine used in this study is inspired by the basic design of a waterwheel. The turbine's blades are designed to be adaptive, able to open and close depending on the direction of water pressure relative to the turbine's axis of rotation. When the water flow is in the same direction as the turbine's rotation, the blades will open to capture the maximum amount of hydrokinetic power. Conversely, when the flow direction is opposite, the blades will close to reduce drag resulted by the opposing forces. This mechanism aims to maximize the resulting tangential or rotational power in the desired direction. Overall, the system analysis focuses on the performance of the power generation system as a single unit. An initial fluid flow simulation of the turbine design conducted using SOLIDWORKS software is presented in Figure 1. Figure 1(a) shows the vertical axis turbine with adaptive blades, while Figure 1(b) shows the turbine with locked blades.



(a) (b)

Figure 1. CFD pre-simulation for designed turbine with (a) adaptive blades and (b) locked blades

3. METHOD

This research is conducted through four main stages: i) system design, ii) turbine fabrication and testing, iii) power generation system fabrication and testing with the turbine integrated into the system, and iv) data acquisition and analysis. The whole system testing conducted directly at the testing site, which is a water canal in Dusun II, Wadung Getas, Wonosari District, Klaten Regency, Central Java Province, Indonesia. Each stage is designed to evaluate the performance of the developed turbine and power generation system. Before commencing each main stage, monitoring and coordination activities with the team carried out to ensure readiness and data suitability. All testing equipment and its resolution are shown in Table 1.

3.1. System design

The system design stage encompasses general component design, mechanical design, and electrical design. General design, as seen in Figure 2, is illustrated through a system block diagram. Mechanical design, as seen in Figure 3(a), is performed using SOLIDWORKS software to visualize and optimize the physical structure. Mechanical parts of the system consists of: 1) frame (length 75 cm; width 55 cm; height 60 cm), 2) inner cylinder (Ø 10 cm; height 45 cm), 3) turbine shaft, 4) torque meter mounting, 5) belt, 6) pulley Ø 40 cm, 7) pulley Ø 10 cm, 8) generator mounting, 9) pulley Ø 30 cm, 10) pillow block bearing, 11) side cover, 12) blade (6 blades, chord length 15 cm; camber 3 cm; height 45 cm), 13) shaft reinforcement. Meanwhile, electrical design, as seen in Figure 3(b), is depicted in the form of a system wiring diagram. Some sensors used in the system, a dynamic torque meter, and some INA219 sensors, to help measuring process. The battery is used primarily to supply the charge controller.

Table 1. Resolution of testing equipments

No.	Name	Type	Resolution
1	Dynamic torque meter	DYN-200	0.01 Nm
2	Tachometer	DT-6236B	0.1 rpm
3	Clamp meter (for calibration)	HABOTEST HT207D	0.1 mV / 0.001 A
4	Voltage/current sensor	INA 219	4 mV / 0.8 mA

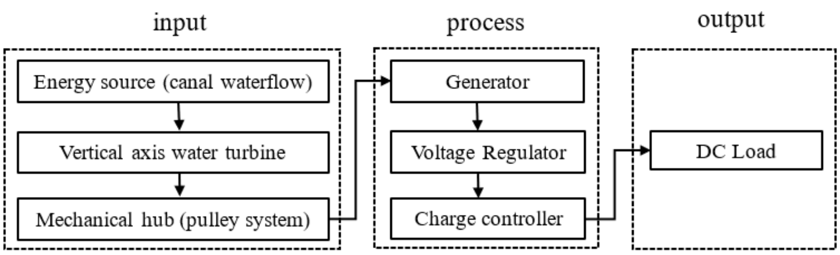


Figure 2. Experimental-system block diagram

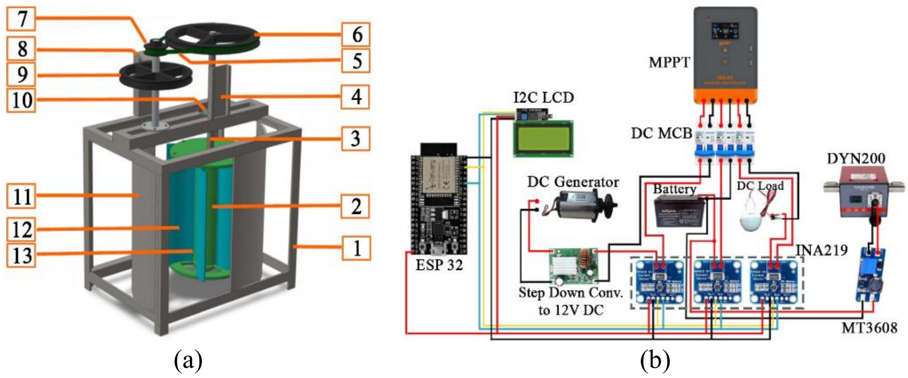


Figure 3. Technical design of (a) 3D mechanical design and (b) experimental-system wiring diagram

3.2. Turbine fabrication and testing

The developed turbine is a vertical-axis turbine with six adaptive blades, constructed from thin plate material. The turbine has a height of 50 cm. Detailed turbine design was created using 3D design software before the fabrication process. The main body of the turbine is made from 8-inch rounded thin plate. The turbine was connected to a hollow steel shaft via bearings to ensure smooth rotation. The adaptive blades extend from the bottom to the top edge on the outer perimeter of the turbine body. The adaptive blades are arranged to have a maximum opening angle of approximately 80° and a maximum closing angle of approximately 5°. This design aims to maximize the capture of propulsive energy from the waterflow when the blades move in the direction of the flow and to minimize back resistance when the blades move against the flow. During the turbine pre-testing stage, the parameters to be measured include rotational speed for two blades conditions, adaptive and locked, in no-load condition, at a specific water flow rate. Datas from this stage used to determine pulley ratio when compared with generator specification. Turbine rotational speed was measured using a tachometer. Data of turbine pre-testing results show adaptive blades produce higher turbine rotational speed, as seen in Table 2.

3.3. Power generation system fabrication and testing

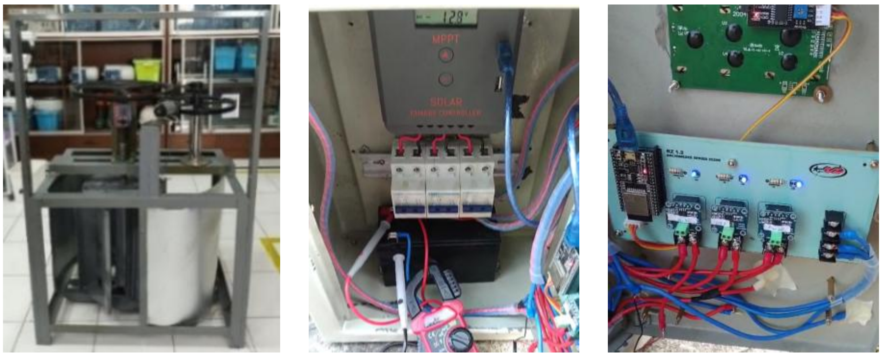
The generator shaft was connected to turbine by pulley system. The entire power generation system, consisting of the generator and turbine, was mounted on a frame for stability, portability, and ease of installation in the desired irrigation canal area. Generator, pulley system, and torque meter mounted on top of the frame, to keep them away from submergence in water. Other electrical components built separately inside panel box. Whole fabricated system can be seen in Figure 4. Generator used in this research has written specification as 12V 30W DC generator, though the generator was tested using DC lamp as the load and the results can be seen in Table 3.

Table 2. Turbine pre-testing results

Attempt	Turbine (adaptive blades) rotational speed (rpm)	Turbine (locked blades) rotational speed (rpm)
1	53.4	50.3
2	82.6	82.4
3	66.2	62.4
4	91.4	83.5
5	88.6	84.3
Average	76.44	72.58

Table 3. Generator pre-testing results

Attempt	Shaft rotational speed (rpm)	Measured voltage (V)	Measured current (A)	Calculated power (W)
1	151.1	5.108	0.1056	0.54
2	306.0	5.300	0.1144	0.61
3	507.4	5.900	0.1408	0.83
4	731.2	6.872	0.1760	1.21
5	1037.0	6.888	0.2640	1.82
6	1512.0	7.704	0.3960	3.05
7	1819.0	7.928	0.4848	3.84
8	2117.0	8.916	0.5728	5.11
9	2446.0	12.412	0.7312	9.08
10	2748.5	13.020	0.7696	10.02
11	3058.5	13.632	0.8224	11.21



(a) (b) (c)

Figure 4. Fabricated system: (a) mechanical, (b) electrical, and (c) microcontroller-based sensor

3.4. Data acquisition and analysis

Data acquisition and analysis were performed at each testing stage (turbine testing and generator testing). This approach aims to identify potential issues in completed sections early on. If the results of the data analysis are deemed satisfactory, the research can proceed to the next stage. During the power generation system testing stage, the parameters to be measured include turbine torque, rotational speed, and generated electrical power at a specific water flow rate. Measurements were taken using a torquemeter, tachometer, and calibrated sensors, respectively. Figure 5(a) shows on-site testing process for no-load turbine, and Figure 5(b) shows on-site testing process for the whole system. Testing process was conducted on-site in the irrigation canal to obtain realistic data under field conditions.

All collected data and their analysis results formed the basis for evaluation and identification of future development notes for the power generation system. These results also served as the foundation for preparing the research outputs, including the research report and publication article. Regular team monitoring and coordination before each main research stage ensured that preparations and collected data are suitable and ready to proceed to the next stage.

(a) (b)

Figure 5. On-site testing process of (a) no-load turbine and (b) whole system

4. RESULTS AND DISCUSSION

Fabricated system then tested directly at the testing site, which is a water canal in Dusun II, Wadung Getas, Wonosari District, Klaten Regency, Central Java Province, Indonesia. Before on-site testing on the canal was conducted, sensor calibration was performed to ensure the accuracy and validity of the measurement data. This calibration procedure is essential to minimize potential systematic errors and maintain the reliability of the research findings.

4.1. Sensor calibration

Voltage and current measurements were carried out using three INA219 sensors installed at crucial points: the generator output, battery, and load. The data obtained from these sensors were then used to calculate power. Before testing, each sensor was calibrated by comparing its readings against a standard measuring instrument, specifically an AC/DC clamp meter HABOTEST HT207D. Error percentage calculated using (2). The calibration results showed high measurement accuracy, with the maximum error for voltage measurement being less than 1% and the current measurement error being less than 5%, as presented in Table 4.

$$error\ percentage = \frac{|\ meter\ readings - sensor\ reading\ |}{meter\ reading} \times 100\% \quad (2)$$

Table 4. Voltage and current sensors calibration results

Attempt	Generator Meter readings V (V)	Generator Meter readings I (A)	Generator Sensor readings V (V)	Generator Sensor readings I (A)	Generator Error percentage %V	Generator Error percentage %I	Battery Meter readings V (V)	Battery Meter readings I (A)	Battery Sensor readings V (V)	Battery Sensor readings I (A)	Battery Error percentage %V	Battery Error percentage %I	Load Meter readings V (V)	Load Meter readings I (A)	Load Sensor readings V (V)	Load Sensor readings I (A)	Load Error percentage %V	Load Error percentage %I
1	12.18	0.71	12.15	0.72	0.25	1.41	12.42	0.55	0.43	2.27	0.00	1.82	11.75	0.44	11.80	0.45	0.43	2.05
2	12.01	0.7	12.12	0.73	0.92	4.29	12.42	0.55	0.43	0.00	0.00	3.64	11.75	0.45	11.80	0.45	0.43	0.00
3	12.09	0.72	12.09	0.73	0.00	1.39	12.41	0.56	0.34	0.00	0.08	1.79	11.75	0.46	11.79	0.46	0.34	0.87
4	12.05	0.69	12.08	0.72	0.25	4.35	12.41	0.55	0.34	2.22	0.00	3.64	11.75	0.45	11.79	0.46	0.34	2.89
5	12.10	0.72	12.07	0.73	0.25	1.39	12.41	0.56	0.34	0.00	0.08	1.79	11.75	0.46	11.79	0.46	0.34	0.87
	Average				0.33	2.56	Average				0.03	2.53	Average				0.37	0.90

4.2. Performance testing with adaptive blades

The testing of the hydroelectric power generator using vertical axis turbine with adaptive blades yielded two main data sets, which are presented separately. The mechanical performance test data, covering components from the turbine to the rotor shaft of the generator, are summarized in Table 5. Meanwhile, the results of the electrical performance test on the generator output are presented in Table 6. Water flow rate and hydrokinetic power are calculated using (1). Turbine and rotor shaft of the generator are connected using 1:60 pulley ratio, so mechanical slip can be calculated using (3).

$$\%slip = \frac{|\ n_0 - n_t\ |}{n_0} \times 100\% \quad (3)$$

Where n_0 is expected rotational speed of rotor shaft in rpm (n_0 = turbine rpm × 60); n_t is measured rotational speed of rotor shaft in rpm.

Table 5. Testing results on mechanical area of hydroelectric power generator using vertical axis turbine with adaptive blades

Attempt	Measured water velocity (m/s)	Calculated flow rate (m^3/s)	Calculated hydrokinetic power (W)	Turbine torque (Nm)	Turbine rotational speed (rpm)	Calculated turbine power (W)	Turbine efficiency (%)	Generator-shaft rotational speed (rpm)	Mechanical slip (%)
1	0.53	0.097	13.5	2.17	46.4	10.6	78.1	2696.0	3.16
2	0.55	0.099	14.9	2.19	48.0	11.0	74.0	2812.3	2.36
3	0.55	0.100	15.3	2.20	48.2	11.1	72.4	2866.2	0.90
4	0.57	0.102	16.3	2.25	50.4	11.9	73.0	2876.2	4.89
5	0.57	0.102	16.3	2.25	50.8	12.0	73.6	2936.4	3.67
6	0.57	0.102	16.4	2.25	51.0	12.0	73.1	2950.4	3.59
7	0.57	0.102	16.4	2.25	51.4	12.1	73.7	2954.0	4.22
8	0.57	0.103	16.8	2.25	52.0	12.3	73.1	3022.3	3.14
9	0.58	0.104	17.3	2.28	52.0	12.4	71.7	3088.2	1.03
10	0.58	0.105	18.0	2.30	52.2	12.6	69.9	3098.1	1.09
Average	0.56	0.102	16.1	2.24	50.2	11.8	73.3	2930.0	2.81

Table 6. Testing results of generator output of hydroelectric power generator using vertical axis turbine with adaptive blades

Attempt	Calculated flow rate (m3/s)	Calculated hydrokinetic power (W)	Generator-shaft rotational speed (rpm)	Generated voltage (V)	Generated current (A)	Calculated power (W)	System efficiency (%)
1	0.097	13.5	2696.0	12.592	0.7536	9.490	70.2
2	0.099	14.9	2812.3	12.944	0.7584	9.820	66.0
3	0.100	15.3	2866.2	12.960	0.7624	9.880	64.4
4	0.102	16.3	2876.2	13.372	0.7664	10.25	63.0
5	0.102	16.3	2936.4	13.488	0.7696	10.38	63.8
6	0.102	16.4	2950.4	13.588	0.7784	10.58	64.3
7	0.102	16.4	2954.0	13.688	0.7784	10.65	64.8
8	0.103	16.8	3022.3	13.888	0.7944	11.03	65.8
9	0.104	17.3	3088.2	13.788	0.8320	11.47	66.1
10	0.105	18.0	3098.1	14.100	0.8536	12.04	67.0
Average	0.102	16.1	2930.0	13.441	0.7847	10.56	65.5

4.3. Performance testing with locked blades

The testing of the hydroelectric power generator using vertical axis turbine with locked blades yielded two main data sets, which are presented separately. The mechanical performance test data, covering components from the turbine to the rotor shaft of the generator, are summarized in Table 7. Meanwhile, the results of the electrical performance test on the generator output are presented in Table 8. Water flow rate and hydrokinetic power are calculated using (1). Turbine and rotor shaft of the generator are connected using 1:60 pulley ratio, so mechanical slip can be calculated using (3).

4.4. Performance comparison

Based on the test results, the mechanical efficiency of the hydroelectric power generator using a vertical axis turbine with adaptive blades is slightly higher than that of the locked blades system. In line with the proposed concept, the system with adaptive blades can minimize the force from water flow that moves against the turbine's rotational direction. A similar trend is observed in the overall system efficiency, where the hydroelectric power generator using a vertical axis turbine with adaptive blades tends to show better performance. A visual comparison of the mechanical and whole system efficiency is presented in Figures 6(a) and 6(b), respectively.

Table 7. Testing results on mechanical area of hydroelectric power generator using vertical axis turbine with locked blades

Attempt	Measured water velocity (m/s)	Calculated flow rate (m3/s)	Calculated hydrokinetic power (W)	Turbine torque (Nm)	Turbine rotational speed (rpm)	Calculated turbine power (W)	Turbine efficiency (%)	Generator-shaft rotational speed (rpm)	Mechanical slip (%)
1	0.53	0.096	13.7	2.15	40.6	9.15	67.0	2416.4	0.80
2	0.54	0.097	14.1	2.16	43.2	9.79	69.5	2444.4	5.69
3	0.54	0.097	14.1	2.17	43.4	9.87	70.1	2500.1	3.99
4	0.54	0.097	14.1	2.17	43.4	9.88	70.1	2578.2	0.99
5	0.54	0.098	14.5	2.18	44.0	10.1	69.2	2614.2	0.98
6	0.54	0.098	14.5	2.18	44.2	10.1	69.6	2628.3	0.89
7	0.54	0.098	14.5	2.18	45.0	10.3	70.9	2646.0	2.00
8	0.55	0.099	15.0	2.19	45.0	10.3	68.9	2648.0	1.93
9	0.57	0.103	16.9	2.25	45.2	10.7	63.2	2652.2	2.21
10	0.58	0.105	17.9	2.29	47.4	11.4	63.7	2682.3	5.69
Average	0.55	0.099	14.9	2.19	44.1	10.2	68.2	2581.0	2.52

Table 8. Testing results of generator output of hydroelectric power generator using vertical axis turbine with locked blades

Attempt	Calculated flow rate (m3/s)	Calculated hydrokinetic power (W)	Generator-shaft rotational speed (rpm)	Generated voltage (V)	Generated current (A)	Calculated power (W)	System efficiency (%)
1	0.096	13.7	2416.4	12.360	0.7136	8.820	64.6
2	0.097	14.1	2444.4	12.392	0.7256	8.992	63.8
3	0.097	14.1	2500.1	12.408	0.7296	9.053	64.3
4	0.097	14.1	2578.2	12.420	0.7296	9.062	64.3
5	0.098	14.5	2614.2	12.432	0.7424	9.230	63.5
6	0.098	14.5	2628.3	12.448	0.7456	9.281	63.9
7	0.098	14.5	2646.0	12.460	0.7488	9.330	64.2
8	0.099	15.0	2648.0	12.472	0.7520	9.379	62.6
9	0.103	16.9	2652.2	12.488	0.7536	9.411	55.8
10	0.105	17.9	2682.3	12.500	0.7568	9.460	53.0
Average	0.099	14.9	2581.0	12.438	0.7398	9.202	62.0

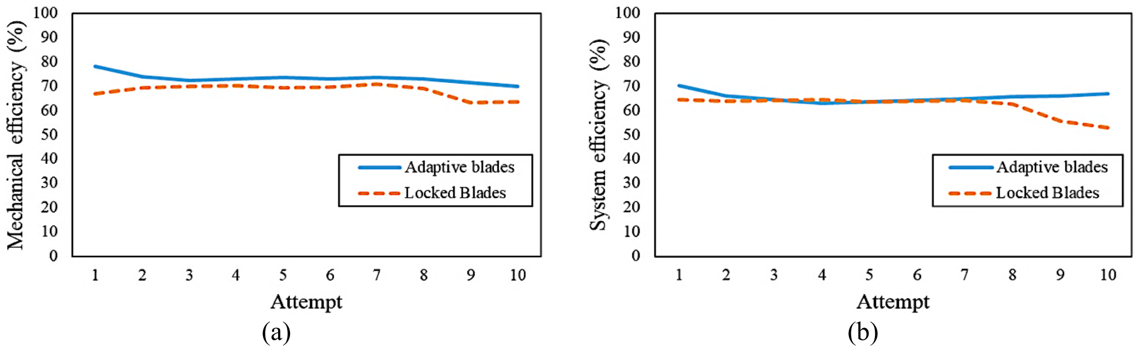


Figure 6. Graph comparison of both systems for (a) mechanical efficiency and (b) whole system efficiency

5. CONCLUSION

The results of this study show that the hydroelectric power generator with vertical axis turbine and adaptive blades exhibits superior performance compared to a system using locked blades. The adaptive-blade configuration outperformed the locked-blade system, exhibiting a 5.1% increase in average turbine efficiency and a 3.5% improvement in overall system efficiency. However, the efficiency pattern still lacks stability, indicating the need for further optimization. This study has several limitations that should be acknowledged. First, the system testing was conducted at a single irrigation canal location, which may not fully represent the variability of river or canal characteristics in other environments. Second, the CFD simulation performed was preliminary and has not been extensively validated under diverse field conditions, limiting the accuracy of performance predictions. Third, economic aspects and long-term system reliability were not the focus of this research. For future work, it is recommended to conduct testing at multiple sites with different flow characteristics, perform comprehensive validation of CFD simulations, and include economic and reliability analyses to ensure feasibility for large-scale implementation.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors declare that there is no conflict of interest in this research.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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