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Development of Small-Scale Hydro Energy Harvester using Piezoelectric Sensor

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Abstract

This study explores the development and performance of a small-scale hydro energy harvester using piezoelectric sensors. It addresses the growing need for clean, renewable energy sources suitable for powering low-energy devices, particularly in remote areas. The harvester was designed to utilize the kinetic energy from artificial waves, flowing water, and falling water to generate electricity. Using PVDF-based piezoelectric materials and aluminum-stainless steel construction, the prototype was tested under multiple water conditions. Results showed measurable energy generation, with the highest output recorded under falling water scenarios. This project demonstrates the feasibility and scalability of piezoelectric-based hydro energy harvesting systems for decentralized power generation.

1. Introduction

The increasing demand for renewable energy has stimulated global research into sustainable alternatives to fossil fuels, which are finite and environmentally harmful [1]. Among these, hydropower has long been recognized as a reliable source of clean energy. However, conventional large-scale hydropower systems require substantial infrastructure, incur high costs, and often have significant ecological impacts [2]. As a result, recent studies have shifted focus toward small-scale hydro energy harvesters, particularly for localized or off-grid applications where centralized power supply is unavailable [3].

Piezoelectric materials present a promising solution for micro-energy harvesting, as they are capable of converting mechanical stress from water flow, vibration, or impact into electrical energy [4]. Their adaptability, compact size, and ability to operate in diverse environments make them suitable for powering low-energy devices such as sensors, Internet of Things (IoT) modules, and environmental monitoring systems [5]. Recent research demonstrates that piezoelectric elements, such as PVDF and PZT, can generate sufficient power under flowing water, rainfall, or wave conditions to sustain small-scale electronics [6,7].

In Malaysia, the abundance of water resources due to its tropical climate and geography provides untapped potential for micro-hydro energy harvesting. Developing efficient and cost-effective harvesters could support rural electrification and reduce dependency on fossil fuels, aligning with the nation's renewable energy goals [8]. This study therefore investigates the development of a small-scale hydro energy harvester using piezoelectric sensors. The harvester is designed to harness energy from artificial waves, flowing water, and falling water to evaluate performance under different dynamic conditions.

By integrating piezoelectric technology with hydro-based energy harvesting, this research aims to provide a practical and sustainable approach to powering low-energy devices in remote or off-grid settings. The findings are expected to contribute to the advancement of green energy technologies by demonstrating the feasibility of piezoelectric-based hydro harvesters for small-scale renewable energy applications.

2. Research Methodology

The research methodology for this project was structured into four main phases: design, fabrication, testing, and analysis. During the design phase, the conceptual framework of the small-scale hydro energy harvester was developed, focusing on capturing energy from water movement using piezoelectric sensors. PVDF and PZT sensors were selected based on their suitability for different water conditions, with PVDF being flexible and ideal for low-frequency movements, and PZT offering higher sensitivity for stronger flows. The mechanical structure, including the watermill and tank, was designed using stainless steel and aluminum due to their durability and resistance to corrosion. In the fabrication phase, components were assembled, and sensors were mounted on strategic parts such as the watermill blades and rigid frames to ensure optimal mechanical stress transfer. A power management circuit was constructed to rectify, regulate, and store the electrical output from the sensors, incorporating protection mechanisms and voltage regulation. For the testing phase, the prototype was evaluated under three water conditions—artificial waves, flowing water, and falling water. Each scenario was tested repeatedly to measure voltage, current, and power output using a multimeter and Arduino. This structured approach allowed for systematic evaluation of the device's performance, ensuring that the energy harvesting capability could be accurately assessed under different environmental conditions.

This study adopted an experimental approach to design, fabricate, and test a small-scale hydro energy harvester using piezoelectric sensors. The research process was divided into four phases: design, fabrication, testing, and analysis [9].

In the design stage, a conceptual framework of the energy harvester was developed, focusing on mechanisms for capturing energy from water waves, flowing water, and falling water. Suitable piezoelectric materials were selected, specifically PVDF (polyvinylidene fluoride) and PZT (lead zirconate titanate), due to their proven efficiency in low-frequency and high-frequency water flows, respectively [10,11]. The structural framework was fabricated using stainless steel for durability and aluminium for the water tank and watermill, ensuring lightweight yet corrosion-resistant construction [12].

The piezoelectric sensors were strategically mounted on surfaces experiencing maximum stress from water flow. PVDF sensors were placed on curved or flexible surfaces to capture irregular water movements, while PZT sensors were embedded on rigid structures exposed to high-energy water impact [13]. To enhance energy conversion efficiency, a power management circuit consisting of a full-wave rectifier, voltage regulator, and storage system (capacitors/batteries) was integrated [14].

Testing was conducted under three simulated water conditions—artificial waves, flowing water, and falling water—to evaluate energy generation performance. Voltage and power outputs were measured using digital meters and data acquisition systems, while efficiency was compared across conditions to identify the most effective energy harvesting scenario [15]. The experimental data were analysed to determine the feasibility of deploying piezoelectric-based hydro harvesters in real-world small-scale applications.

3. Results and Discussion

The performance of the small-scale hydro energy harvester using piezoelectric sensors was evaluated under three different water motion conditions: artificial wave, flowing water, and falling water. The findings revealed that falling water generated the highest power output, averaging 1.528 mW at 1.07 V, due to its high mechanical impact on the sensors. This shows that vertical impact forces, such as from rain or tank discharge, are highly effective in inducing strong piezoelectric responses. In contrast, flowing water produced moderate output with 0.820 mW at 0.72 V, benefitting from consistent rotational movement of the watermill that induced cyclic deformation on the sensors—indicating its potential for stable energy generation in streams or canals. The artificial wave condition had the lowest output, averaging only 0.379 mW at 0.42 V, due to its weak and irregular force, highlighting its limitation in generating usable energy without highly sensitive sensors. The results demonstrate that the efficiency of piezoelectric energy harvesting is strongly influenced by the intensity and consistency of the mechanical input. Falling water proves to be the most efficient, followed by flowing water, while artificial wave motion is the least suitable unless improved with resonance-based sensor designs.

Table 1 Output Under Artificial Wave Condition

Trial	Time (s)	Voltage (V)	Current (mA)	Power (Pw)
1	0-30	0.41	0.88	0.361
2	30-60	0.40	0.91	0.364
3	60-90	0.42	0.90	0.378
4	90-120	0.43	0.93	0.400
5	120-150	0.41	0.89	0.365
6	150-180	0.44	0.94	0.414
7	180-210	0.42	0.90	0.378
8	210-240	0.43	0.92	0.396
9	240-270	0.40	0.89	0.356
10	270-300	0.41	0.91	0.373
Average	-	0.42	0.91	0.385

Table 2 Output Under Flowing Water Condition

Trial	Time (s)	Voltage (V)	Current (mA)	Power (Pw)
1	0-30	0.72	1.12	0.806
2	30-60	0.70	1.14	0.798
3	60-90	0.71	1.13	0.802
4	90-120	0.74	1.16	0.858
5	120-150	0.73	1.12	0.18
6	150-180	0.75	1.17	0.878
7	180-210	0.72	1.15	0.878
8	210-240	0.73	1.13	0.825
9	240-270	0.70	1.11	0.777
10	270-300	0.71	1.14	0.809
Average		0.72	1.14	0.820

Table 3 Output Under Falling Water Condition

Trial	Time (s)	Voltage (V)	Current (mA)	Power (Pw)
1	0-30	1.05	1.40	1.470
2	30-60	1.10	1.45	1.595
3	60-90	1.07	1.42	1.519
4	90-120	1.10	1.45	1.595
5	120-150	1.09	1.44	1.570
6	150-180	1.07	1.41	1.509
7	180-210	1.08	1.42	1.534
8	210-240	1.06	1.40	1.484
9	240-270	1.09	1.45	1.580
10	270-300	1.07	1.43	1.530
Average	**-**	**1.07**	**1.42**	**1.528**

Conclusion

In conclusion, this project successfully developed and evaluated a small-scale hydro energy harvester utilizing piezoelectric sensors to convert water movement into electrical energy. The prototype demonstrated that the falling water condition was the most effective, producing the highest voltage and power due to strong impact forces on the sensors. Flowing water showed moderate but stable output, making it suitable for continuous low-power applications, while artificial waves generated the lowest energy, limited by their weak and inconsistent force. Despite the modest power output, the system proved feasible for powering ultra-low-power devices such as LEDs or sensors in off-grid or rural areas. The study confirms the potential of piezoelectric materials for renewable energy harvesting in small-scale hydro applications and provides a foundation for further improvement through better sensor placement, energy storage systems, and real-environment testing.

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