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Integrated Micro Hydro System for Sustainable Rural Energy

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Abstract

Reliable electricity remains limited in rural areas due to the high cost of grid extension. This study presents the design and experimental evaluation of an integrated micro hydro system with real-time IoT monitoring for sustainable rural energy. The prototype consists of a 3D-printed overshot waterwheel, a DC generator, an ESP32 microcontroller, and the Blynk platform. Performance was evaluated using single-pulley and two-pulley drive configurations under a 60 cm water head. The single-pulley system achieved a maximum output of 3.50 V with less than 10% deviation from simulation, whereas the two-pulley system reached 3.20 V with 93.75% error. The proposed system demonstrates a practical, low-cost solution for off-grid rural electrification.

1. Introduction

Access to reliable electricity remains a major challenge for rural and remote communities due to the high cost and technical difficulties of extending the utility grid [1]. Micro hydro systems have emerged as a promising renewable energy solution for off-grid electrification because they provide stable power generation, low environmental impact, and relatively low operating costs [2],[3]. For low-head applications, overshot waterwheels offer a simple and cost-effective design capable of converting hydraulic energy into electrical energy [4], [5].

Recent studies have integrated Internet of Things (IoT) technologies into micro hydro systems to enable real-time monitoring of electrical parameters and improve operational reliability [6],[7],[8]. However, most existing studies focus primarily on turbine performance or monitoring independently, with limited investigation of how different mechanical transmission configurations influence electrical output under low-head conditions [9],[10]. Mechanical transmission losses can significantly reduce the efficiency of small-scale micro hydro systems, highlighting the need for an integrated design that combines efficient energy conversion with continuous monitoring [11],[12],[13].

Therefore, this study presents the design and experimental evaluation of an integrated micro hydro system incorporating a 3D-printed overshot waterwheel, a DC generator, and an ESP32-based IoT monitoring system using the Blynk platform. The performance of single-pulley and two-pulley drive configurations was experimentally compared to identify the most effective transmission mechanism for low-head applications and providing a practical, low-cost solution for sustainable rural electrification.

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2. Methodology

2.1 System Overview

The proposed integrated micro hydro system was developed by combining a low-head waterwheel, a DC generator, and an Internet of Things (IoT)-based monitoring platform. The system consists of three major subsystems: the mechanical subsystem, the electrical subsystem, and the monitoring subsystem. Water flowing through the pipeline rotates a 3D-printed overshot waterwheel, which drives the DC generator through a belt-pulley transmission. The generated voltage is measured by the ESP32 microcontroller and transmitted to the Blynk cloud platform for real-time monitoring.

2.2 Material and System Components

The prototype was fabricated using a custom-designed overshot waterwheel with a diameter of 180 mm manufactured from Polyethylene Terephthalate Glycol (PETG) filament through fused deposition modelling (FDM) 3D printing. PETG was selected because of its high mechanical strength, water resistance, and suitability for continuous operation in wet environments.

The electrical subsystem consisted of a permanent magnet DC generator, an ESP32 microcontroller, voltage sensing circuit, water flow sensor, and the Blynk cloud platform for remote monitoring. A closed-loop water circulation system equipped with a centrifugal water pump supplied a constant water flow throughout the experiments.

2.3 Prototype Development

The prototype was built in stages. The generator used was a DC 310V, 1050 rpm. The waterwheel was designed in AutoCAD and fabricated with a Creality Ender-3 V2 Neo 3D printer. The other mechanical parts were prepared separately and assembled with the generator and frame. The setup included 20T and 60T pulleys.
Two transmission mechanisms were investigated:

- **Single-pulley direct drive:** Generator was directly coupled to the waterwheel using one pulley system.
- **Two-pulley step-up drive:** Additional pulley was introduced to increase generator rotational speed.

An ESP32-based monitoring circuit was then integrated into the prototype to acquire voltage and water flow data continuously and upload the measurements to the Blynk cloud platform through Wi-Fi communication.

2.4 Experimental Setup

Experimental testing was conducted under laboratory conditions using a closed-loop recirculating water system with a constant water head of 60 cm. Water was pumped continuously through PVC piping to the overshot waterwheel while maintaining a stable flow condition.

The experiments were performed for flow rates ranging from 1.0 L/min to 5.0 L/min. For each operating condition, the generated voltage was measured and recorded through the ESP32 monitoring system. The same experimental procedure was repeated for both the single-pulley and two-pulley transmission systems to ensure a fair performance comparison.

2.5 Simulation Method

The system was first simulated in MATLAB/Simulink using the generator specifications and pulley configurations. The model predicted the expected rotational speed and voltage output for both the single-pulley and two-pulley setups under different flow rates. These simulated values acted as a baseline reference, making it easier to compare and validate the performance of the prototype during testing.

2.6 Data Collection and Performance Evaluation

The experimental data collected from the ESP32 monitoring system. Fig. 2 shows the displayed monitoring in real time using the Blynk cloud dashboard. Fig. 3 is the control circuit where measured voltages obtained from laboratory experiments were compared with simulation results to evaluate system performance.

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Fig. 2 *Blynk web dashboard interface for monitoring and control*

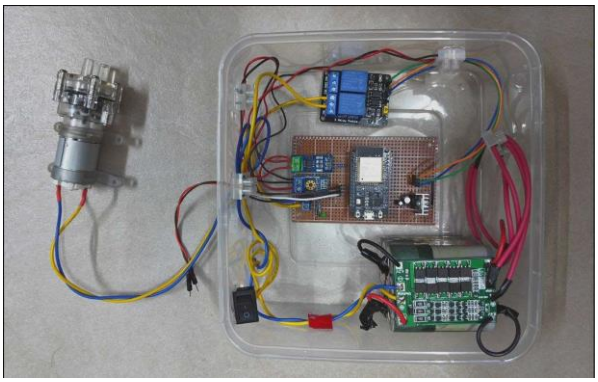


Fig. 3 *Control circuit of the micro hydro prototype*

Performance evaluation focused on:

- Maximum output voltage.
- Mechanical transmission efficiency.
- Experimental deviation from simulation results.
- Operational stability of each transmission configuration.
- Overall suitability of the proposed system for low-head rural electrification.

The comparative analysis was used to identify the most efficient mechanical transmission configuration and assess the effectiveness of integrating IoT technology into the proposed micro hydro system.

3. Results and Discussion

3.1 Prototype Development

The integrated micro hydro prototype was successfully developed by combining a 3D-printed overshot waterwheel, a DC generator, an ESP32 microcontroller, and an IoT-based monitoring platform. Fig 3, the completed system employed a closed-loop water recirculation mechanism to simulate low-head operating conditions under laboratory testing. Two mechanical transmission configurations, namely the single-pulley direct drive and the two-pulley step-up drive, were constructed to investigate their influence on electrical power generation. The ESP32 continuously collected voltage and water flow data and transmitted the measurements to the Blynk cloud platform for real-time monitoring, enabling users to observe system performance remotely.



(a) **(b)**

Fig. 3 *Prototype configuration of the micro hydro system: (a) one pulley (single-pulley drive) (b) two pulley (two-pulley drive)*

3.2 Performance of the Single Pulley Drive System

The single-pulley drive system demonstrated stable and consistent performance throughout the experimental evaluation. As the water flow rate increased, the generated voltage also increased proportionally, indicating effective conversion of hydraulic energy into electrical energy. As presented in Table 1, the maximum flow rate of 5.0 L/min produced a peak output voltage of 3.50 V. The experimental measurements closely agreed with the simulation results, with an overall deviation of less than 10%, demonstrating that the proposed design performed as expected under low-head operating conditions. The reduced number of mechanical transmission components minimized frictional losses, allowing more rotational energy to be transferred directly to the generator.

Table 1 *Single Pulley System experimental and simulation measurements*

Time Interval (s)	Flow Rate (L/min)	Total Water Used (L)	Simulation	Actual	Error (%)
			V(V)	V(V)	
0 - 30	4.2	2.10	0.50	0.52	3.85
30 - 60	4.8	4.50	1.25	1.21	3.31
60 - 90	5.0	7.00	2.40	2.35	2.13
90 - 120	5.0	9.50	3.42	3.50	2.29

3.3 Performance of the Two Pulley Drive System

The two-pulley transmission system was developed to increase generator rotational speed through a step-up mechanism. However, the experimental results showed that this configuration produced lower performance than anticipated. As presented in Table 2, the highest recorded output voltage was 3.20 V, which was lower than that of the single-pulley configuration despite the increased transmission ratio. Furthermore, the experimental results differed significantly from the theoretical prediction. On average the deviation was above 100%. This performance reduction was primarily attributed to additional belt friction, mechanical losses, and insufficient torque transfer under low-head conditions. These losses reduced the effective rotational speed delivered to the generator and limited the electrical output.

Table 2 *Two Pulley System experimental and simulation measurements*

Time Interval (s)	Flow Rate (L/min)	Total Water Used (L)	Simulation	Actual	Error (%)
			V(V)	V(V)	
0 - 30	4.2	2.10	1.00	0.45	122.22
30 - 60	4.8	4.50	2.30	1.10	109.09
60 - 90	5.0	7.00	4.40	2.15	104.65

90 - 120	5.0	9.50	6.20	3.20	93.75

3.4 Comparison Between Simulation and Experimental Results

A comparison between the simulation and experimental results indicates that the single-pulley drive system achieved considerably better agreement with theoretical predictions than the two-pulley configuration. The direct-drive mechanism provided a more efficient transmission path by reducing mechanical interfaces that contribute to energy loss. In contrast, the additional pulley introduced frictional resistance and belt slip, resulting in significant discrepancies between simulated and measured outputs.

The findings demonstrate that theoretical increases in rotational speed do not necessarily translate into improved electrical performance when mechanical losses become dominant. Therefore, minimizing transmission complexity is more beneficial than increasing gear ratio for ultra-low-head micro hydro applications.

3.5 Discussion

The experimental results confirm that mechanical transmission plays a critical role in determining the overall efficiency of small-scale micro hydro systems. Although the compound pulley system was designed to increase generator speed, the increased mechanical resistance outweighed its theoretical advantages. Conversely, the single-pulley configuration maintained stable operation with lower transmission losses and produced superior electrical performance.

The integration of the ESP32 microcontroller with the Blynk cloud platform also proved effective for real-time monitoring. The monitoring system continuously displayed voltage and water flow information, enabling users to observe operating conditions remotely without interrupting system operation. Such monitoring capability can facilitate preventive maintenance, rapid fault identification, and improved operational management, making the proposed system more suitable for rural electrification applications.

Overall, the developed prototype demonstrates that combining a simplified mechanical transmission with IoT-based monitoring provides a practical and cost-effective solution for sustainable energy generation in remote communities. The study also highlights that reducing mechanical complexity is more effective than increasing transmission ratios when operating under low-head conditions.

4. Conclusion

This study presented the design, development, and experimental evaluation of an integrated micro hydro system for sustainable rural energy applications. The proposed prototype successfully combined a 3D-printed overshot waterwheel, a DC generator, and an ESP32-based Internet of Things (IoT) monitoring platform to generate and monitor electrical energy under low-head conditions. Experimental evaluation demonstrated that the single-pulley transmission system achieved superior performance compared with the two-pulley configuration by producing a maximum output voltage of 3.50 V while maintaining less than 10% deviation from simulation results. In contrast, the two-pulley system generated a maximum output voltage of 3.20 V and exhibited approximately 93.75% deviation due to increased friction and transmission losses. These findings indicate that minimizing mechanical transmission components significantly improves energy conversion efficiency in low-head micro hydro systems. Furthermore, the ESP32 and Blynk monitoring platform successfully enabled real-time visualization of voltage and water flow, demonstrating the practicality of IoT integration for remote monitoring and maintenance. Overall, the developed prototype provides a simple, economical, and reliable solution that can support sustainable rural electrification using locally available water resources.

5. Recommendations

Several improvements are recommended to enhance the performance and practicality of the proposed integrated micro hydro system. Future studies should consider replacing the timing belt transmission with lightweight polyurethane belts or a direct-drive coupling to reduce mechanical losses and improve power transfer efficiency. The waterwheel blade geometry may also be optimized by adopting Pelton cup or hybrid blade designs to increase hydraulic energy capture under low-head conditions. In addition, the use of high-efficiency permanent magnet generators specifically designed for ultra-low rotational speeds could further improve electrical output. The IoT monitoring system may be expanded to include additional electrical parameters such as current, power, battery charging status, and energy consumption, thereby providing more comprehensive system performance monitoring. Furthermore, long-term field testing under actual river conditions is recommended to evaluate the durability, environmental performance, and operational reliability of the proposed system. Finally, future work may investigate the integration of maximum power point tracking

(MPPT) techniques and intelligent energy management algorithms to maximize power generation efficiency and enhance the overall performance of the micro hydro system.

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