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Internet of Things-Based Micro Hydro Power Generation Technology for 3T Regions in Realizing Sustainable Renewable Energy

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ABSTRACT : This research developed an Internet of Things-based Micro-Hydro Power Plant (PLTMH) system to address the need for electricity access in 3T areas that still face energy infrastructure limitations. This system utilizes irrigation water flow to drive a turbine connected to a dynamo, thereby generating electricity at a low operational cost. In addition to designing the generator, this research also developed a web-based monitoring system and application that displays real-time data on water discharge, head, and power output. Trials were conducted on irrigation flows in Surakarta to assess turbine performance, sensor reading stability, and data transmission capabilities. The test results showed that the system was able to work stably and the monitoring process could still be carried out even though the device was placed at a location far from the observation point. This approach shows that the integration of micro-hydro power plants with IoT technology can be a practical and sustainable solution in supporting community energy independence, especially in areas that are not yet reached by conventional electricity networks. The designed system is also modular so that it has the potential to be replicated in other areas with similar conditions.

Keywords - 3T regions, renewable energy, Internet of Things, micro-hydro, system monitoring

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1. INTRODUCTIONS

Electricity is a fundamental necessity that plays a crucial role in supporting the social and economic activities of communities. However, the distribution of electricity access in Indonesia still faces significant challenges, particularly in the frontier, remote, and underdeveloped regions known as 3T areas. Limited infrastructure, difficult geographic conditions, and reliance on fossil energy sources such as coal, oil, and natural gas remain the primary obstacles to energy supply in these regions [4]. As a result, many communities in 3T areas still lack adequate electricity access to support daily activities and local economic development.

On the other hand, Indonesia possesses a vast hydropower potential, with surface water availability reaching approximately 2.78 trillion m^3 per year. Nevertheless, only a small portion of this potential has been utilized optimally [1]. This presents an opportunity for the development of renewable energy, particularly through Micro Hydropower Plants (MHP). MHP systems are small-scale power generation technologies that harness the potential energy of flowing water from rivers, irrigation channels, or waterfalls, offering several advantages such as simple construction, low investment cost, environmental friendliness, and suitability for rural conditions [3].

Alongside advancements in digital technology during the Industrial Revolution 4.0 era, the use of the Internet of Things (IoT) has increasingly enabled real-time monitoring and control of MHP systems. Through this technology, parameters such as water discharge, head height, and electrical power output can be monitored via the internet, thereby improving operational efficiency and facilitating evaluation and maintenance efforts, especially in inaccessible areas [2].

Based on these conditions, the development of IoT-based MHP systems becomes an innovative step to meet sustainable energy needs in 3T regions. This innovation not only aligns with the government's target of achieving a 23% renewable energy mix by 2025 but also promotes community-level energy independence. The integration of digital technology with the utilization of local natural resources is expected to provide an efficient, environmentally friendly, and sustainable energy solution for communities living in remote areas.

2. RESEARCH METHOD

This research was conducted through several main stages, including literature study, PLTMH system design, integration of Internet of Things (IoT) technology, and field testing at irrigation flow locations in Surakarta.

2.1 Literature Review

The initial stage was conducted by reviewing references on micro-hydro power plant technology, water resource characteristics, and the application of IoT in energy monitoring systems. Literature was used to determine important parameters such as water discharge, head, and the need for appropriate sensors. Previous studies have shown that micro-hydro power plants are effective in areas with small to medium water potential [3].

2.2 System Design

The system was designed by developing turbines and dynamos as the main components of the generator. The turbines were made from PVC sheets, which were chosen for their strength, light weight, and malleability. The monitoring system was designed using an ESP32 microcontroller, which transmits data on water discharge, drop height, and power output via the internet.

2.3 IoT Integration

The IoT system was developed to enable real-time monitoring via a website and mobile application. Sensors are placed near the generator units to read hydraulic conditions, while the data received is sent to a visual dashboard that displays graphs and data logs. The system is designed to remain functional even if the devices are installed in locations far from the monitoring point.

2.4 Installation and Field Testing

Testing was conducted on irrigation flows in Surakarta to determine turbine performance, sensor measurement stability, and data transmission reliability. Testing included measurements of water discharge, turbine rotation speed, and electrical power generated. An evaluation was also conducted on the stability of IoT communication in limited network conditions.

2.5 Data Analysis

The measurement and monitoring data were analyzed to assess the relationship between water discharge, head, and power output. The analysis was conducted to determine the efficiency of the power plant and the consistency of IoT performance in displaying data in real time. These results form the basis for assessing the feasibility of implementing the system in 3T areas.

3. RESULTS AND DISCUSSION

This chapter presents the results of the developed system, including the design and implementation of equipment placement at the study site, an explanation of the PLTMH system's energy flow scheme, and details of the design and components used in the system's construction.

3.1 Design and Implementation

The design of the Agnivolt micro-hydro power plant system began with the development of mechanical and electrical designs tailored to the characteristics of the irrigation flow at the test site. The turbine was designed using PVC material because it is lightweight, strong, and easy to shape according to the blade profile requirements in order to capture the energy of the water flow optimally. The turbine was then directly connected to a dynamo so that the rotation of the turbine from the water flow could be converted into electrical energy.

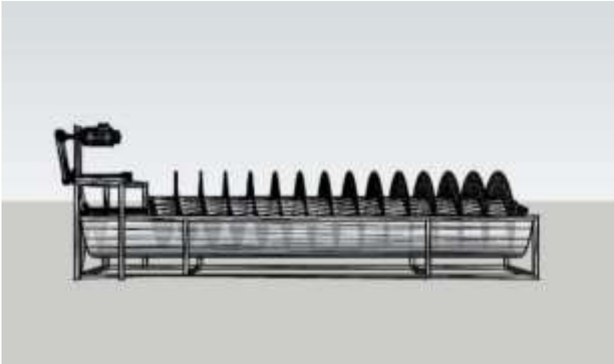


Fig. 3.1 PLTMH Circuit Design

The overall design of the micro-hydro power plant is shown in Figure 3.1, which illustrates the relationship between the turbine, generator, and main support frame. The mechanical structure is reinforced with a stainless steel frame to withstand exposure to water and aquatic environmental conditions.

After the design phase was completed, the prototype was realized and tested directly on the Surakarta River irrigation flow. The turbine and dynamo were installed in a section of the flow that had sufficient discharge to produce optimal rotation. A special mount was made to keep the device stable and prevent it from being easily carried away by the current. On the edge of the channel, an IoT-based monitoring system was installed, consisting of a microcontroller, water flow sensor, head sensor, internet communication module, and GPS. This unit was placed on a support pole to protect the electronic components from direct contact with water while ensuring that the internet signal could still be received properly. The placement of the device in the field can be seen in Figure 3.2.

Fig. 3.2 Product Placement Location

After all components were installed, integration and initial testing were carried out to ensure that the entire system was functioning properly. Testing included checking turbine rotation, generator output voltage stability, accuracy of flow rate and water drop height sensor readings, and real-time data transmission to the Agnivolt dashboard. Testing conducted in the Surakarta irrigation waters showed that the system was able to operate as designed, and that the hydraulic data was successfully recorded and displayed through the monitoring platform without any significant obstacles.

3.2 Energy Conversion Mechanism

The energy conversion mechanism in the micro-hydro power plant system is explained through the flowchart shown in Figure 3.5.

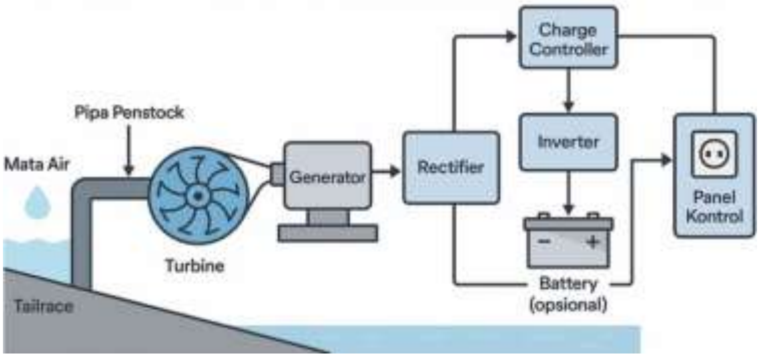


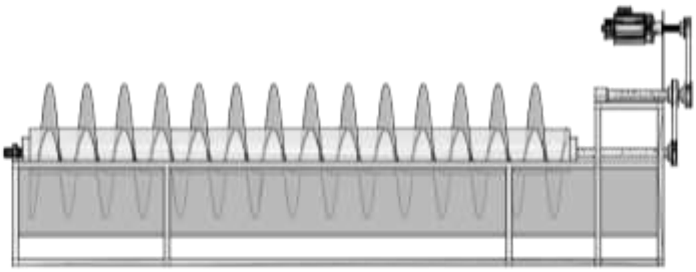
Fig. 3.5 Energy Conversion Mechanism

Based on the design scheme shown in Figure 3.5, the PLTMH operational system begins with the conversion of potential energy from water flowing through the penstock pipe to rotate the turbine, where the wastewater is then returned to the irrigation channel through the tailrace. The mechanical energy generated from the rotation of the turbine shaft triggers the generator to produce electrical energy. As shown in the electrical component diagram, the electrical output from the generator is processed through a rectifier and charge controller that functions to rectify the current while regulating the charging of the storage battery. The stored energy is then converted back into alternating current (AC) using an inverter to make it compatible with standard electrical loads before entering the control panel. This entire circuit is monitored through a microcontroller-based monitoring system on the control panel, which is capable of recording voltage and current fluctuations in real time, allowing for accurate monitoring of the device's performance stability during field testing.

3.3 Design and Components

The design of this micro-hydro power plant system was developed taking into account the geographical conditions of the 3T region, which has limited access to energy, so the design must be modular, efficient, easy to install, and durable in an outdoor environment. Each component was selected to ensure that the process of converting water energy into electricity can run optimally and still support the Internet of Things (IoT)-based monitoring process to improve the operational reliability of the system.

The micro-hydro power plant (PLTMH) system design in this study is modular, so that each major component can function in an integrated manner while remaining easy to assemble, maintain, and replicate. The main structure consists of a micro-hydro turbine that converts the potential and kinetic energy of water flow into mechanical energy. The turbine material uses PVC sheets because they are strong, moisture-resistant, and easy to shape according to the required blade contours. The mechanical energy from the turbine rotation is then transmitted through the shaft, gears, and pulley and belt system to adjust the rotation ratio for optimal power supply to the generator.



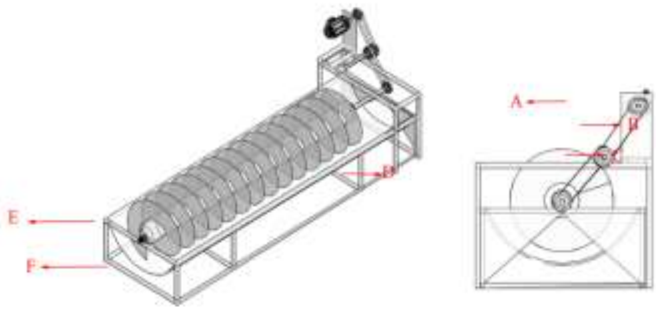


Fig. 3.6 Schematic of the micro-hydro power plant

Figure 3.6 shows the layout of the main components in the micro-hydro power plant design. Part A is the generator, which converts mechanical energy into electrical energy. Part B is the pulley and belt that transmits rotation from the turbine shaft to the generator. Part C shows the gear wheel, which adjusts the rotation ratio to optimize power output. Part D is the micro-hydro power plant frame, which supports the entire system. Meanwhile, part E is the turbine shaft that receives rotation from the water flow, and part F is the bucket blade that captures the water flow to generate rotational force on the turbine.

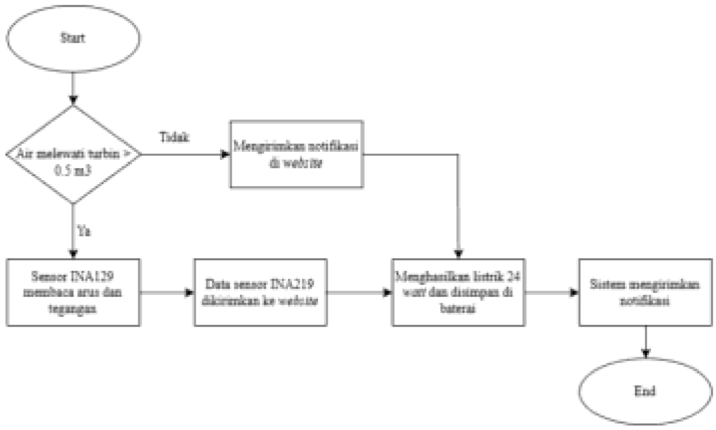


Fig. 3.7 Flowchart of the working principle of the tool

The working mechanism of the Agnivolt system is comprehensively mapped through a flow chart in Figure 5, which illustrates the logical sequence of the system from the initiation of water flow to energy storage. The operational process begins with the hydraulic parameter validation stage, where the system automatically detects whether the volume of water passing through the turbine has met the minimum threshold of 0.5 cubic meters. This decision logic is crucial: if the water discharge is insufficient, the system will take an alternative route by sending a warning notification to the website, but if the discharge requirements are met, the INA129 sensor will be immediately activated to acquire vital data in the form of electrical current and voltage. The data read by the sensor is then processed and transmitted by the INA219 module to the website database, enabling digital monitoring of parameters. Along with the telemetry process, the conversion of mechanical energy to electrical energy continues until it reaches the target power output of 24 watts, which is then channeled to the battery for charging and storage. This work cycle ends with the sending of an operational status notification to the user as confirmation that the system is running properly. From a broader perspective, the Agnivolt design prioritizes a modular architecture that utilizes the potential of water flow as the main source of renewable energy. This design approach was chosen not only to facilitate the installation and maintenance of components in various terrains, but also to provide an adaptive and sustainable electrification solution for isolated areas that are not yet connected to conventional electricity infrastructure networks.

3.4 Prototype Test Results

The prototype performance evaluation was conducted directly on irrigation channels in Surakarta to validate the system's ability to convert water discharge into electrical energy. Based on feasibility analysis calculations, river hydraulic conditions with a discharge ranging from 0.02 to 0.025 m^3/s and a head of approximately 3 meters proved capable of generating a power potential of 20 to 30 watts. This figure has met the prototype's design output target of 24 watts, while also confirming that the application of the run-of-river concept with effective head specifications of 2–5 meters and a minimum flow of 15 L/second is sufficient to support a DC 12V/2A voltage output and conversion to 220V AC through an inverter. Along with mechanical testing, the focus of observation was also directed at the reliability of the ESP32 microcontroller-based data transmission system. Despite the limitations of cellular network quality in the irrigation area, the IoT module used managed to maintain the stability of real-time data transmission without significant interference. The reliability of this system is evident from the optimal data accessibility despite the monitoring point being more than 10 km away from the device location. All performance monitoring results are visualized in an integrated manner through the Agnivolt website interface, as illustrated in Figure 3.8.

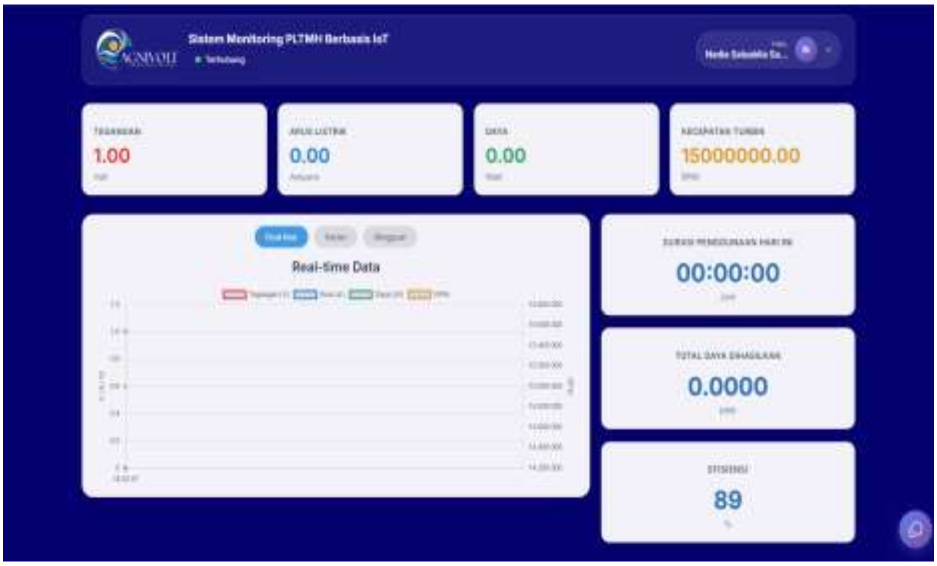


Fig. 3.8 Website Display

The image above shows the Agnivolt platform interface, developed as an Internet of Things-based system monitoring center. Through this dashboard, operators can access real-time system performance data without space and time limitations, providing high flexibility in operational monitoring. The platform structure is designed with a dedicated domain scheme for each micro-hydro power plant unit to ensure more precise monitoring focus, where operational parameter information is presented in both numerical and automatically updated trend graph formats. To support technical analysis and reporting needs, Agnivolt is equipped with comprehensive data management features, allowing users to download hydraulic and electrical data history in Excel format and set up automatic recording synchronization to Google Sheets. The system's functionality is further enhanced by the integration of GPS-based geolocation features, which visualize the physical location of all power generation units on a digital map to facilitate accurate inventory and monitoring of assets in the field.

4. CONCLUSION

The development of an Internet of Things (IoT)-based micro-hydro power plant system in this study has shown that this technology can improve the effectiveness and reliability of energy generation in areas that are difficult to reach by the electricity grid. The prototype was successfully tested on an irrigation channel in Surakarta with stable power output ranging from 20 to 30 watts, and system performance monitoring can be carried out in real-time through an online platform even though the monitoring point is more than 10 km away. The modular design and use of economical materials such as PVC make the system easier to install, maintain, and replicate in areas with similar characteristics, thereby potentially supporting accelerated electrification in 3T regions.

However, this system still has limitations in terms of its dependence on internet network quality and its household-scale power capacity. Therefore, further development is needed in both turbine design and data transmission modules to enable the system to operate more optimally in areas without network coverage. Overall, the integration of PLTMH with IoT has provided a practical, adaptive, and sustainable renewable energy solution for remote communities, while contributing to the fulfillment of national energy mix targets based on new and renewable energy.

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