Enhancing Renewable Energy Generation in Off-Grid Rural Areas: An IoT-Based Controller for Solar-Powered Pico-Hydro Systems

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Abstract – The access to reliable electricity in off-grid rural areas remains a serious problem in the Philippines up to this date. This study proposes a method to enhance renewable energy production in off-grid rural areas by combining solar-powered pico-hydro systems with an Internet of Things (IoT)-based controller. These systems enable remote communities to receive sustainable energy by combining hydroelectric power generation with solar energy. Moreover, improving their reliability and performance is crucial for efficient energy provision. The implementation of an IoT-based controller enables real-time monitoring and control of system parameters, which permits the effective use of accessible resources and adaptive environmental conditions. By this method, the quality of life for the locals will be enhanced in off-grid communities through advances in the accessibility and availability of electricity.

Keywords – Renewable energy sources, Pico-hydro power, IoT-based, Solar power, Valves, Automatic generation controller

I. INTRODUCTION

Studies about pico-hydro systems are continuously expanding as researchers seek more renewable energy, which is great because it originates from natural sources of energy. This alternate option for making this project more economical and environmentally friendly is beneficial, particularly to individuals who live near natural sources such as waterfalls. The Pico-Hydro system will operate by generating power from running water going to the turbine and improving the Pico-hydro's operation by including a flow meter that measures water flow as it enters the tubes at a given time. The solar panel will provide enough power for AGC to monitor the frequency and voltage while serving as an electrical source and minimizing environmental impact. Moreover, the integration of the Internet of Things (IoT) into this renewable energy has relevance due to its potential to improve efficiency and enable remote monitoring. One of the project's goals is to generate the standard voltage and frequency values of 220 V and 60 Hz, respectively.

Incorporating the IoT-based controllers into the project solar-powered pico-hydro enhances the system's overall performance and the reliability of off-grid renewable energy in rural areas. The IoT-based controller will enable the real-time monitoring of key parameters such as the frequency, voltage, and water flow rate, allowing the user to monitor and do proactive maintenance and troubleshooting. Assessing the system will be conducted in multiple tests as it has the ideal design and the gate valve connected to a chain mechanism is highly dependable for regulating the system's water flow. The Pico-hydro system needs a sturdy foundation to ensure its resilience against potential damage and mitigate adverse effects on the natural resources of our environment. This project's combined approach between the solar-powered pico-hydro systems and IoT-based controller enhances energy accessibility for off-grid rural communities and promotes sustainable development and independence in tackling climate change challenges.

II. BACKGROUND OF THE STUDY

According to Silverio (2023), the recent data gathered showed that the Philippines' electrification level of 94 percent lagged other Southeast Asian countries. Despite the continuous advancement of electrification efforts, 2.4 million families, or more than 11 million Filipinos, still lack electricity. These families usually live in areas far from the main grid infrastructures, which makes it laborious and expensive for the power distributors to extend their electricity distribution networks. Consequently, their isolated positions make it more difficult for them to obtain dependable electricity, which increases the demand for creative off-grid alternatives. Additionally, the country is surrounded by sea and endowed with sunshine, which has substantial potential for using renewable energy sources to help with these concerns. The Philippines has several renewable energy sources, including solar, wind, hydro, and geothermal. According to the DOE Energy Statistics 2020, the most used renewable energy sources in the Philippines are hydro and geothermal. Although solar and wind are more familiar, it is relatively new in the Philippines and has been growing rapidly in recent years.

Off-grid rural areas can be supplied with sustainable and ecological electricity with the help of solar-powered pico-hydro systems. By this, communities that can't be reached by traditional electricity can gain a more dependable and continuous power supply, even during low sunlight, by integrating solar energy with pico-hydro systems. Along with the advancement of electricity in the Philippines, internet connectivity is also rapidly developing. By this, rural communities can benefit from a better and more efficient Internet of Things (IoT) technology in monitoring and surveillance of their renewable energy sources. Real-time monitoring and surveillance of energy production, storage, and distribution can be achieved by IoT-based devices, which detect early errors and reduce time waste. In this study, the researchers aim to merge IoT technology with solar-powered pico-hydro systems to develop, execute, and assess an Internet of Things controller that is tailored for these kinds of systems. Successful deployment of an Internet of Things-based controller for solar-powered pico-hydro systems in off-grid rural communities can increase electricity access and reliability. The study could help these communities' socioeconomic advancement and ecological environment. Despite the advantages of IoT technology with renewable energy sources, this is still crucial since engineers, environmentalists, social scientists, and local governments must work together. By interacting with communities early on, it is ensured that the suggested solution will satisfy end users' unique demands and preferences while also being socially and culturally acceptable.

III. STATEMENT OF THE PROBLEM

Pico-hydro generates a small amount of energy using hydroelectric system. Pico-hydro can be used by utilizing the force of flowing water. This project aims to control the output of voltage and frequency of water turbine using the automatic generation controller. By controlling the energy output of using a pico-hydro, it eases users' concerns about potential appliance damage due to overpowering. The study will answer the following questions:

1. Is the gate valve and chain mechanism reliable in controlling the water flow?
2. Is the designed system will maximize the performance of the pico-hydro?
3. How long will the voltage and frequency stabilize at 220v and 60hz?

IV. RELATED LITERATURE

A. Pico-Hydro Systems

A pico-hydro system is a renewable energy source that produces electricity without the need for non-renewable energy sources by connecting a small generator or motor to turbines. The pico-hydro system produces less than 5kW of power. (Awang, et al., 2021) Among the most plentiful and effective renewable energy sources is hydroelectric electricity. Because it produces enough electricity at a cost that is environmentally benign, the use of these resources for power generation is prevalent around the world. Parameter controls are necessary for off-grid hydropower generation to guarantee electricity output standards and safety. (Madrigal et al., 2020) Tolentino (2018) discusses a substitute electrical energy source. In remote locations where power transmission seems unattainable, the developed pico-hydro power generation technology is perfectly suited. The Pelton turbine is used in order to optimize the intended concept since it is particularly well-suited for high and low water flow rates in the Philippines.

B. Solar Power

One of the most important renewable and green energy sources, solar energy is also a cost-effective technology. Reaching sustainable development energy solutions is significantly aided by it. Solar energy is therefore a very appealing resource for producing power due to the enormous amount of energy that can be obtained every day. (Maka & Alabid, 2022) The solar energy that is generated by sunlight is a renewable energy source that never runs out and is a renewable energy source that never runs out and is not environmentally harmful. Enough solar energy falls on Earth each hour to cover a year's worth of global energy needs. In the modern period, it requires electricity constantly. This solar energy is produced for use in commercial, residential, and industrial settings. It can readily absorb radiation as energy. (Shaikh et al., 2017)

C. Internet of Things (IoT)

A new paradigm known as the Internet of Things (IoT) has transformed traditional living into a high-tech manner of living. Such changes brought about by IoT include smart cities, smart homes, pollution reduction, energy conservation, smart transportation, and smart industries. To improve technology through IoT, numerous important research studies and investigations have been carried out. To fully realize the potential of IoT, many obstacles and problems still must be resolved. (Kumar et al., 2019) IoT security is important for a few reasons. Because there are so many devices and because people and organizations have insecure habits, legacy threats are magnified. These dangers include information theft, malware attacks that can turn devices into bots for cyberattacks, and weaknesses in software and gadgets. IoT ecosystem security is further complicated by new problems like the proliferation of connected devices in homes and offices; the increase in remote work, and the impending rollout of 5G technology. Because these attacks can affect both virtual and physical systems, the repercussions can be significantly more severe than with typical cyberattacks. (TrendMicro, 2021)

V. METHODOLOGY

The nation is heavily dependent on natural gas for the continuous generation of electrical energy. As these source causes enormous risk environmentally and to physical health of people's lives, addressing this by implementation of renewable energies is the utmost priorities specifically on rural areas that are being trailed compared to cities in Metro Manila. To address these challenges, the methodology for Pico-Hydro system begins with a comprehensive approach to assess the potential locations for the source and evaluate the feasibility of the hybrid renewable sources. Engaging this with site analysis to the local community to ensure that the proposed solutions are being aligned with the energy deficiency and scarcity in the localities. Adheres with the initial phase of methodology, the focus is the system design and selection of hardware components. At the hardware section, it contains a Pico-hydro, AGC, Solar power and a flowmeter. In acquiring the 220V and 60 Hz for the operation of electricity in the Philippines, necessitating careful considerations for the overall efficiency of the system were being performed to significantly contribute to the enhancement of renewable energies.

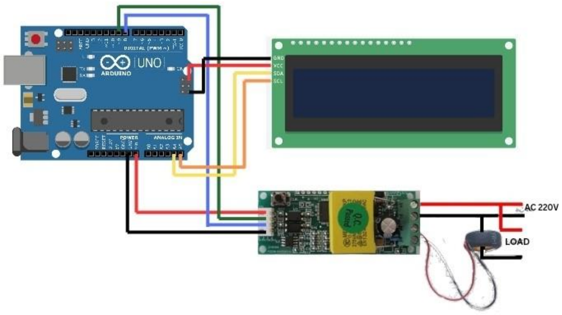

Figure No. 1 *LCD Display, Arduino UNO and PZEM-004T*

Figure 1 illustrates the schematic diagram of AGC or Automatic Generation Controller. It was composed of PZEM-004T, Arduino UNO, ESP-32, LCD I2C 1602, and Stepper motor driver. The PZEM-004T sensor is programmed by the Arduino UNO to be responsible for acquiring and measuring parameters of voltage, frequency and water flow displayed on the LCD I2C 1602.

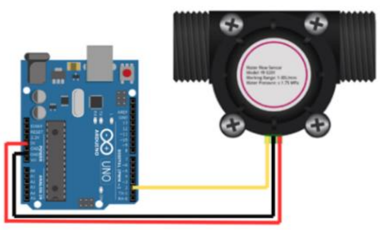

Figure No. 2 *Arduino Uno and Flowmeter Sensor*

As shown in figure 2, it illustrates the interconnection between Arduino UNO and Flowmeter sensor. The main function of the flowmeter sensor was to gauge the volumetric rate of water passing through it to determine the water intake of the Pico-Hydro system to meet 220V and 60 Hz.

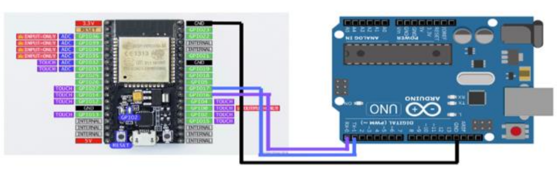

Figure 3. *Arduino UNO and ESP-32*

Figure 3 shows the schematic diagram involving Arduino UNO and ESP-32 wherein each microcontroller is capable of deriving power from its own USB port.

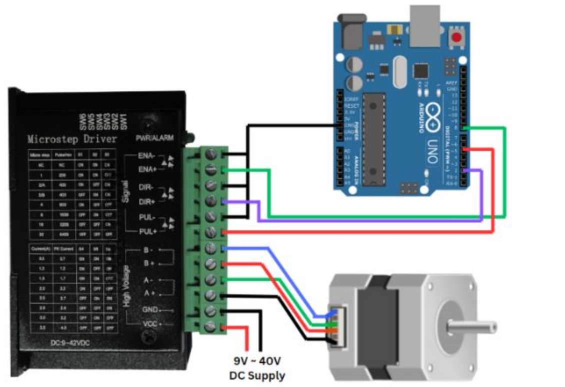

Figure 4. *Arduino UNO and Stepper Motor Driver*

As shown in figure 4, it illustrates the interconnection between the Arduino UNO and the TB6600 stepper motor driver, which governs the chain sprocket connected to the Gate valve. In this configuration, the Arduino UNO and TB6600 stepper motor driver collaboratively manage to exchange and transmit data. It involves monitoring the voltage and frequency generated by the pico-hydro.

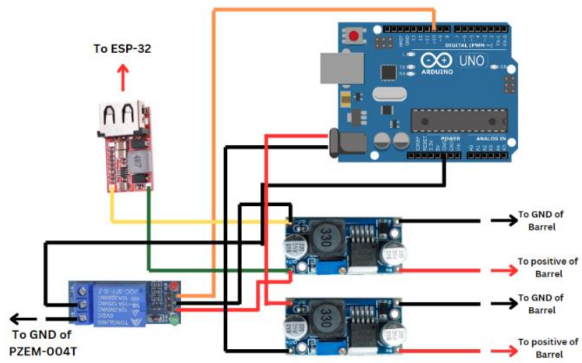

Figure 5. *Connection of the Arduino UNO, Buck Converter, and Relay Module.*

Figure 5 illustrates the connection between the Arduino UNO and the relay module. This connection provides power to the relay module and minimizes the use of the barrel jack for the power supply. The DC-DC Buck Converter LM2596S was connected to a DC power port and powered the Arduino UNO. The power supply was plugged into the barrel port, which connected to the buck converter's input positive and negative terminals. The other buck converter was connected to a USB DC-DC Buck Step-Down Converter, which powers the ESP-32 through a micro-USB cable.

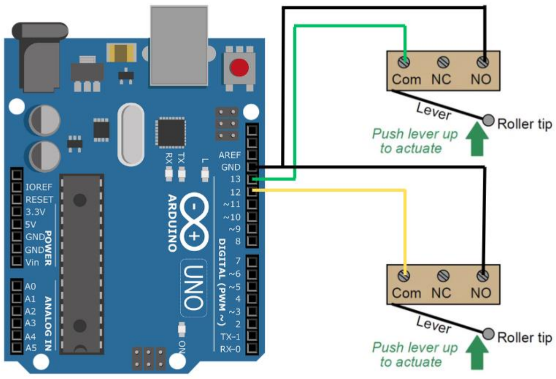

Figure 6. *Connection of the Arduino UNO and Limit Switch.*

The figure above shows the connection of an Arduino UNO and two limit switches, which were installed for the gate valve. The first limit switch was connected to digital pin 12 on the Arduino UNO, while the other limit switch is connected to pin 13. The C pin on both limit switches is connected to the GND of the Arduino UNO. The purpose of installing them was to prevent the gate valve from being damaged. When the gate valve reached its maximum open or closed position, the stepper motor's direction was reversed for a 400-step revolution. This precautionary measure was implemented to prevent potential damage to the stepper motor and gate valve. Without this feature, if the gate valve had already reached its fully open or fully closed position but the pico-hydro's voltage and frequency had not yet stabilized, the stepper motor would continue rotating unnecessarily. Such continued rotation, despite the gate valve being already at its maximum position, could potentially cause harm to the stepper motor and the gate valve.

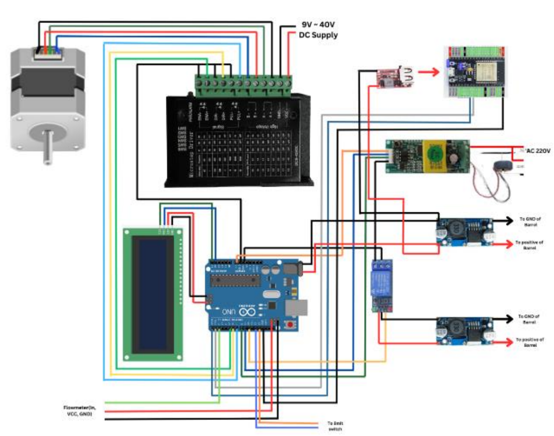

Figure 7. *Overall connection of the components in AGC.*

As shown in figure 7, it illustrates the overall connection of the components of the AGC. Includes various components, consist of stepper motor driver, LCD I2C 1602, PZEM-004T, water flow sensor and Arduino uno. The water flow sensor, Pzem-004T is connected to Arduino Uno to measure parameters such as water flow, voltage and frequency and display it to the LCD as well as send the data to the esp32 for monitoring of such parameters. The measured voltage and frequency dictate the direction of the stepper motor to open and close the gate valve to control the electrical output of the system. Lastly, DC-DC Buck Converter LM2596S supply the power to Arduino Uno and a USB DC-DC Buck Step-Down Converter to power the esp-32, researchers also installed two limit switches to prevent damage to the gate valve and stepper motor.

5.1 Research Locale

The deployment of this study will be conducted in Atimonan, Quezon which is situated in one of its Barangays, specificized as Barangay Magsaysay for testing and evaluation process. This location is known as one of the underserved communities in the Philippines. By incorporating this system into Barangay Magsaysay, researchers are anticipating the potential modernization of this community by providing a continuous generation of energy.

5.2 Computational Analysis

The researchers used a mixed-method study that combined qualitative and quantitative research to determine the prototype's effectiveness for the user. The study employed an exploratory sequential design, which involved collecting and analyzing qualitative data to gain insights, develop a hypothesis, and then apply it to a larger scale of respondents using a survey questionnaire. The researchers integrated the two data sets to comprehensively understand the conflicts. The researchers initially analyzed the collected data from the professionals about the prototype and transcribed it to find patterns on how the system would be effective (Alele & Malau-Aduli, 2023).

In this study, researchers utilized a mixed-method research approach to gather data. Initially, qualitative data was collected from one individual to formulate a preliminary hypothesis. Following this, a survey was conducted with a larger sample to validate and expand upon the initial findings. This design was used because it allowed for the development of an in-depth understanding of the subject matter through qualitative insights, which could then be tested and quantified with a broader sample, ensuring comprehensive and robust conclusions.

5.3 Hardware Design

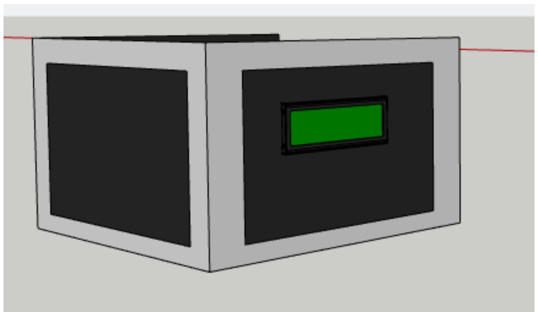

Figure 5. *Side view of AGC*

Figure 5 shows the Automatic Generation Controller. It consists of an exhaust fan for cooling conditions, LCD display, and a weatherproof junction box.

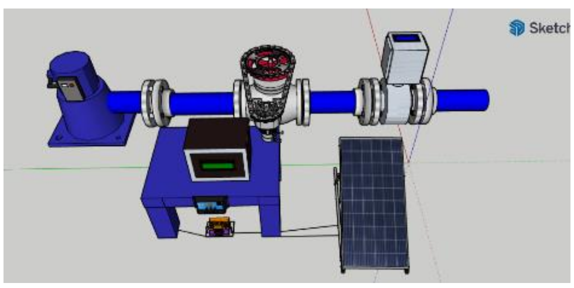

Figure 6. *Overall System flow*

Figure 6 illustrates the overall system flow. It consists of interconnected pico-hydro, gate valve, flowmeter and AGC. Including the Solar Panel for the power source of AGC.

VI. RESULTS AND DISCUSSION

The Automatic Generation Controller demonstrates its capacity and successfully controlled the voltage and frequency output of the system. When the voltage output exceeded 150V, the controller maintained the voltage within the range of 213.4V to 226.6V and the frequency within 59.7Hz to 60.3Hz. Conversely, when the output voltage fell below 150V, the controller adjusted the range to 103.4V to 116.6V for voltage and 29.7Hz to 30.3Hz for frequency, depending on the intensity of the water flow.

The AGC and pico-hydro could reliably produce, maintain stable voltage and frequency outputs to provide electricity, the limited water flow in the Atimonan region posed a challenge, restricting the system's operational duration. However, the Automatic Generation Controller (AGC) demonstrated its effectiveness in regulating the output voltage and frequency, achieving stabilization within an average duration of 40 seconds. This represented a significant improvement compared to the previous study, which had only implemented the ANFIS algorithm and required an average of 48.425 seconds for stabilization.

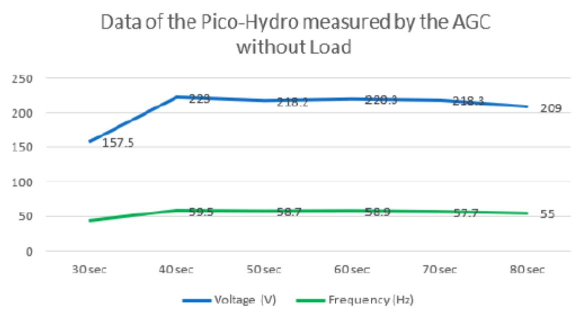

Figure 6. *Data of the Pico-Hydro measured by the AGC without Load*

VII. CONCLUSION

The researcher concluded that the designed Automatic Generation Controller effectively regulated the gate valve to stabilize both voltage and frequency outputs. When the voltage output exceeded 150 V, the controller maintained the voltage within the range of 213.4 V to 226.6 V and the frequency within 59.7 Hz to 60.3 Hz. Conversely, if the output voltage fell below 150 V, the controller adjusted the range to 103.4 V to 116.6 V for voltage and 29.7 Hz to 30.3 Hz for frequency, depending on the water flow intensity. Researchers implemented an enhanced algorithm known as the Adaptive Neuro-Fuzzy Inference System-Particle Swarm Optimization (ANFIS-PSO) algorithm. This enabled to develop precise techniques and rules, which were interpreted by an Arduino microcontroller, to effectively regulate the gate valve’s opening and closing. The control mechanism, motor, and chain system facilitated this regulation. This demonstrated the controller's capability to adaptively manage output parameters based on varying conditions.

VIII. REFERENCES

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