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Estimation of energy recovery through the implementation of electric generators in residential hydraulic networks.

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Abstract– The generation of electrical energy from renewable sources is one of the most needed topics of study today, the growing demand for energy and the environmental impact of traditional non-renewable sources, make the scientific community pay attention to the energy potential available in everyday activities. This paper presents the implementation of an energy microgeneration system in residential hydraulic networks, in order to determine the energy potential available in the networks, depending on their volumetric flow and the diameter of the pipe. The work includes the construction of the test module, commissioning, data collection and subsequent analysis. Flows through 0.5-, 0.75- and 1-inch pipes were analyzed. One diameter was found to offer the best performance in the tests, with an 18 V generation.

Keywords-- Hydraulic turbine, microgenerator, pipe system, residential-scale, electric energy.

I. INTRODUCTION

Today, one of the greatest global concerns revolves around the issue of energy supply. This matter encompasses the utilization of non-renewable energy resources, dependence on major oil, gas, and coal producers, and the generation of adverse impacts on the planet. Consequently, in recent years, there has been a quest for renewable energy alternatives to meet the global energy demand while contributing to environmental care and preservation.

Despite advancements in renewable energy usage, they currently constitute only 4% of the world's primary energy, while oil comprises 33.6%, coal 27.2%, and gas 23.9%, maintaining their status as the primary sources of human energy consumption. Other environmentally friendly or low-impact energy sources, such as nuclear energy at 4.4%, and hydroelectricity at 6.8%, are used to a significantly lesser extent [1].

In Colombia, most electricity is produced through hydroelectric and thermal energy sources. In 2022, approximately 76,905 GWh were generated, with hydroelectric power accounting for 83.66% and thermal energy for 14.60% respectively [1].

However, renewable energy's share in Colombia remains notably low. On average, in 2022, solar energy contributed merely 0.6% and wind energy 0.1% [1], with no nuclear energy production sources established in the country yet.

To harness energy from water sources, large-scale projects like hydroelectric power plants are used, relying on substantial amounts of dammed water for operation. Moreover, there exists potential energy in smaller water sources such as undisturbed rivers, small water springs, or domestic water networks. To capture this potential for electricity generation, hydraulic micro-generators are employed, operating as functional small-scale hydraulic power plants without the need for water impoundment [2].

The study of the operation of these small-scale systems is of great importance as it allows for determining characteristics to evaluate the feasibility of implementing these systems [3]. Thus, this work aims to introduce the construction of a prototype capable of studying the operational variables of a micro-generation system in an automated manner. The prototype utilizes Arduino, LabVIEW, Python, and Excel to collect and visually represent data, generating a real-time data table from the sensors used for parameter measurement.

At the heart of the proposed prototype construction is the central question: How does the variation of input parameters in a micro-generation system impact the system's generation capacity. To address this question, the overall objective is projected, seeking to analyze micro-generation variation through the implementation of an automated prototype that controls input variables to determine the electrical generation of micro-turbines and collect system data by varying input values to determine their influence on the system's generation [4].

The specific objectives facilitating the construction of the prototype and addressing the central question alongside the overall objective are as follows:

- Construct a hydraulic micro-generation prototype through a pumping system to measure system variables.
- Develop an automated analysis system for the micro-generation system using electronic components and controlled by an intelligent programming board.
- Gather data from the micro-generation system by varying input values to determine their influence on the system's generation.

II. FRAME OF REFERENCE

A. State of the art

Regarding the research, prototypes for the study of micro-generation applied to other hydraulic processes have been proposed by other research centers. An example from Latin

America is the work of Castro and Guerrero [4], who presented a design and implementation of a hydraulic micro-generation test bench. Their aim was to achieve a real-scale approach, under controlled conditions, to the various circumstances present when operating the proposed prototype [5].

Similarly, Mendoza and Calderón from Chile proposed the assembly and characterization of a power generation installation for educational purposes using a hydraulic micro-turbine (see figure 1). Their objective was to analyze the operation of a micro-hydroelectric power plant using a Pelton turbine [5]. This project provided a more realistic understanding of large-scale generation using industrial-type turbines such as Francis, Pelton, and Kaplan, commonly employed in hydroelectric plants [6].

The work proposed by González and Delgado in Colombia, involves an analysis of a micro-turbine within a water supply network for electricity generation in the Timiza park sector in Bogotá. The project aimed to analyze the operation and optimization of generation through a turbine fed by a 16" diameter pipe supplied by the main aqueduct to maintain a constant flow of this water product, generating a voltage between 500 and 600 Watts as a contribution to the community where the study was conducted [7].

Matajira and Páez's research focused on analyzing the energy potential in a half-inch (½") pipe at the Santander Technological Units (UTS), using a micro-turbine in the water service of the city of Bucaramanga. Their project aimed to emulate the hydraulic system of Building B at the Santander Technological Units through a prototype design and assembly. The goal was to obtain a realistic estimate of the generation potential from the water flow in the bathrooms' cisterns for each discharge over a half-inch pipe [8].

Analyses have even been carried out using conventional pumps working as turbines in urban drinking water distribution networks [9] this analysis showed that it could generate an approximate annual energy of 17.52 MWh/year.

A review of the technologies used in microgeneration is presented, where the PAT's (Pump as Turbine) and the Vortex microturbines, which reach an efficiency of 85%, stand out [10].

Choi et al [11] shows in his study the use of a superhydrophobic nanostructured aluminum tube to estimate the electrical performance of solid-water contact electrification in a tubular system.

The formulation and development of these works enable this research to demonstrate the feasibility of the study while providing theoretical, methodological, and technical tools for the analysis of input and output variables in an automated hydraulic micro-generation system, as proposed herein.

B. *Theoretical and conceptual framework*

To structure this proposal theoretically, it is necessary to understand that the micro-generation system performs the conversion of mechanical energy into electrical energy. Its operation is explained when the turbine rotates upon water coming into contact with its blades. The mechanical energy obtained in this manner is utilized to power an electrical generator and is referred to as hydroelectric energy [12].

Figure 1. Microgenerator

Regarding the measurement of energy obtained through mechanical processes, the appropriate use of flow meters is essential. These meters conduct measurements of two types of flow: volumetric and mass. Volumetric meters determine the volume of fluid per unit of time, whereas mass meters quantify the mass flow rate within a specific time frame.

With respect to the proposed prototype, numerous elements are required to support its construction. However, the consistent theoretical application of mathematical principles is essential, particularly for measuring Ohm's Law and the Bernoulli's Theorem. Ohm's Law relates voltage, current, and resistance within a circuit and asserts that the voltage V across a resistor is directly proportional to the current I flowing through the resistor [13].

Concerning Bernoulli's theorem, it represents an equation and an approximate relationship between pressure, velocity, and elevation. It holds validity in regions of steady and incompressible flow where net friction forces are negligible, as is the case in the application of our prototype.

III. Research design

The methodology employed for this project is of a quantitative nature. This research is divided into five main phases:

Phase 1 involves constructing a hydraulic micro-generation prototype using a pumping system to measure system variables. Within this phase, three significant activities will be undertaken: gathering technical information and operation manuals for the project's execution; 3D modeling of the micro-hydrogeneration system; and constructing the micro-generation prototype.

Phase 2 aims to develop an automated control system for analyzing the micro-generation system. Two activities are proposed for this phase: first, the automation of the micro-generation system, and second, performance tests to comprehend the prototype's viability.

In Phase 3, the objective is to calibrate all necessary functional systems, programming, and variables used by this prototype to facilitate the data collection process.

Phase 4 involves collecting data from the micro-generation system by varying input values to determine their influence on the system's generation. The sole activity allocated to this phase, but of vital importance for understanding the operation, is data collection.

Finally, Phase 5, the last phase, aims to present the data analysis. Utilizing the data acquired during the monitoring period, different control parameters for flow rates and generated voltage will be compared, enabling us to demonstrate the study results from this prototype.

IV. PROTOTYPE DEVELOPMENT AND TESTS.

A. Prototype construction (Phase 1)

During this initial phase, a preliminary system design was created using SolidWorks software (see figure 2). This tool facilitated the development of a preliminary design for the automated hydraulic micro-generation system, involving the identification of key system components like hydraulic turbines, centrifugal pumps, generators, solenoid valves, pipelines, among others. Pipe sizes primarily used in domestic settings—½", ¾", and 1"—were also selected. The final construction of the prototype is similar to the preliminary one, with a minor difference in the flow recirculation section, which is no longer in the middle section but in the lower part of the circuit. (See figure 3).

Compatibility with selected pipe diameters was considered during the micro-generation prototype assembly. For components incompatible with the pipe diameters, accessories were used for installation. The Evans 3HME100 pump, capable of delivering a flow rate of 165 L/min, was utilized for the project. It can operate at 110/220v; in this project, a voltage of 220v was utilized.

For flow measurement, the YF-S201 flowmeter device was employed. This digital measuring device receives voltage from the Arduino board and returns a signal used by Arduino to display the real-time flow value passing through the pipeline.

Data collection required the independent use of each of the previously selected pipelines. The ZE-4F180 12V solenoid valve was chosen as a water flow blockage device. This low-consumption device operates through solenoid action, using two valves per line in this project to prevent water backflow into the system.

Figure 2. Preliminary system design.

B. Development of the parameter measurement system (Phase 2)

The initial step in developing parameter measurement system involved the electrical and control design. This electrical circuit design comprised two stages: the first stage being the power circuit design, and the second stage, the control circuit design. The power circuit involved the use of the motor pump and solenoid valves. For the motor pump, a 12 AWG conductor with a 15 A protection was selected, while 12-gauge cable was used for the solenoid valves to power the 12 V source.

The control system incorporated the following components: Arduino, the integrated circuit, flow meters, generators, and resistors. As these elements function at 5V, a 22 AWG bridge-type male and female connection cable were chosen.

Upon designing the electrical system, the automation system assembly commenced. A model was developed using SolidWorks, which contained the prototype's dimensions. These dimensions guided the PVC pipe cutting, considering the accessory dimensions used to avoid sections of the pipe being longer than others.

The assembly included PVC pipes, solenoid valves, generators, and flow meters for the preliminary system assembly. Following this, electrical connections were made from the prototype to the Arduino circuit. A multiple cable connector was used for these connections. Finally, the prototype's mounting location was determined, integrating the pumping system, water reserve tank, and interconnecting all cables.

Figure 3. Assembly of the functional prototype with its automated electrical network

Once the functional prototype was assembled, it was simulated using the Arduino Mega2560 programmed with the necessary code to control the sensors installed in the module. The Datasheet for each sensor was considered, and the appropriate library in Arduino (Arduino_FreeRTOS.h) was determined. This library utilizes the Arduino Watchdog to execute the Scheduler (responsible for allocating CPU time to execution tasks and can utilize various scheduling algorithms such as priority) at configurable intervals, enabling the execution of non-blocking tasks.

C. Calibration of functional systems and variables for data collection (Phase 3)

The third phase is the lengthiest process in this prototype. To discuss data collection in the microgeneration process, it's essential to clarify certain parameters and working variables within this process. Firstly, it's important to identify that in this prototype, specific variables were defined for monitoring: the flow rate and the voltage produced by the generators. These real-time data were monitored and stored in an Excel file for subsequent analysis.

It's essential to understand that this data collection exercise considered a regression system planned in four processes: simple linear regression between the two variables, water flow, and generated power; multiple linear regression, if more than one input variable affected the output—for instance, considering variables like water flow, fall height, and flow rate in the analysis as inputs; nonlinear regression, when the relationship between the variables wasn't linear—for instance, if the relationship between the fall height and system efficiency followed a nonlinear function; finally, power and exponential models, where, in some situations, relationships between variables may follow power or exponential patterns.

During the process of collecting data from the automated hydraulic microgeneration prototype, Arduino played an essential role in capturing and processing the voltages generated by the system. Programmed to function as a data acquisition device, Arduino monitored the voltages generated by the hydraulic generators during operation. Using its analog-to-digital conversion function (ADC), Arduino collected the voltages generated by the hydraulic generators. To adapt these voltages to the ADC's operating range, voltage divider resistors were employed. These resistors allowed adjusting the voltages to levels compatible with Arduino's reading capacity, ensuring precise and reliable measurements of the voltage generated by the system.

Once the generated voltages were captured and adjusted using resistors, Arduino proceeded to parameterize this data, which could be used to evaluate the system's performance. Through programming, the data was sent to the LabVIEW interface for real-time visualization. The generated graphics and visual representations provided an immediate view of the relationship between flow rate and voltage.

The integration of the LabVIEW programming language in conjunction with the Arduino board was used as a solution to achieve interactive control and real-time data visualization. This approach allowed for an interactive and enriching experience in monitoring and controlling the automated hydraulic microgeneration system. The integration enabled direct interaction with the system and an instant representation of key variables, significantly enriching the data acquisition process.

Similarly, the LabVIEW interface provided an interactive platform for dynamically controlling the system. This interface was very useful for adjusting parameters such as water flow, speed, and other essential factors for the system's operation. It allowed for active and real-time control, providing operators with a higher level of flexibility and customization in prototype operation. The standout feature of this integration was the real-time visualization of the data generated by the system. As adjustments were made through LabVIEW, the results were immediately reflected in the form of graphs and numerical data on the screen. This ability to observe the influence of changes in input and output variables allowed for a better understanding of what was happening in the system.

The detailed analysis of the relationship between input and output variables was conducted using Arduino in combination with the Python development platform. This method allowed real-time data export to Excel for further analysis. The programming role in Arduino facilitated the implementation of regression techniques to analyze the relationships between variables. This involved the continuous collection of input data, such as water flow, along with output measurements, such as generated voltage.

For the final analysis phase of the project, the obtained data was needed to generate the graphs for analysis. Arduino provided the data, LabVIEW allowed visualization on an interactive real-time screen, and Python generated a code aimed at permanently exporting the data to Excel in real-time for analysis purposes.

D. Microgeneration system data collection (Phase 4).

To commence the data collection process, the selected components in the prototype were assembled to create a functional circuit simulating a typical hydraulic microgeneration setup. Two analog measurement components were installed in the system: a YF-S201 flow meter, an F-50 Microgenerator, and two ZE-4F180 solenoid valves. Before data acquisition, prototype functionality tests were conducted. Initially, proper maintenance was performed on the water pump, including impeller replacement and rectifying electrical connections. The solenoid valves' functionality in performing open and close functions was verified. Generator checks were carried out using a multimeter to verify output voltage. Finally, input and output signals of the flow meter were confirmed.

To enhance the system's performance, a check valve was installed in the suction section to prevent the water pump from operating in a vacuum, potentially affecting its performance and long-term operation negatively. This device is crucial to ensuring the pump's stability and durability. Additionally, a manometer was installed in the system. This manometer plays an important role, allowing real-time visualization of the pressure within the system. While its primary use is informative, it provides a valuable tool for monitoring the pump's operation. Pressure visualization is crucial for verifying the water pump's performance.

To ensure the accuracy of the obtained data, calibration of the flow meters was conducted using software. A LZT G25 rotameter was utilized for analog observation of the discharge flow and digital flow meter calibration. Voltage values were measured using a multimeter and compared with the values displayed in LabVIEW. Following optimization adjustments, data collection was initiated. Seeking test diversity, a data acquisition process for the microgenerators was carried out under various operational flow conditions. A communication program with the Arduino Mega programmable board was developed. This programming enabled capturing and logging flow
and voltage values as the Dimmer positions changed during tests, facilitating the analysis of the sensor-generated signals and providing a detailed insight into their response to different flow rates.

The combination of measurement devices such as the YF-S201 flow meter, rotameter, F-50 Microgenerator, and commercial voltmeter, along with customized programming on the Arduino Mega board, ensured the collection of precise and reliable data. Additionally, the code enabled control of the opening and closing of the installed solenoid valves in each line. Data collection occurred at sixty-second intervals, providing a stable measurement for each pipe diameter in each of the 6 Dimmer positions, totaling 18 measurements. This provided a comprehensive set of information. These planned intervals were selected to ensure the acquisition of data in sufficient quantities for analyzing system behavior. Each data collection session produced a series of measurements detailing the behavior of the data in each system line.

IV. RESULTS.

To carry out real-time data acquisition and subsequent logging, a Python program was implemented that interacted with the Arduino Mega board. This program allowed continuous real-time data capture, stored in an Excel file. The amount of data collected during these sessions was used to develop system graphs. These visual representations played a fundamental role in understanding the system's dynamics under diverse operating conditions. Each graph was designed to visualize how flow varied concerning generated voltage, identifying operational change patterns crucial for achieving the set objectives. In the automated hydraulic microgeneration project, tests were conducted by varying the pump voltage using the Dimmer, enabling variation in the water flow delivered by the water pump. These parameters are critical in the analysis since they are directly related to the quantity of electrical energy generated by the system. Voltage variations ranged from 158.8 volts to 220 volts, while flow rates were tested using pipes of different diameters: ½", ¾", and 1".

From the measurements taken using a Dimmer in intervals starting at position 6.5 and increasing by 0.5 in each test, approximately 400 records per test were obtained, resulting in a considerable amount of information. To effectively visualize and analyze this data, a series of graphs were created that related flow on the vertical axis and voltage on the horizontal axis, as explained in phase 5.

A. Parameter comparison, data analysis (Phase 5).

To carry out the parameter comparison exercise and data analysis process, three graphs were devised: Figure 4. which allows the analysis of flow rate vs. time and voltage vs. time in the ½" pipes; Figure 5. enables the analysis of flow rate vs. time and voltage vs. time in the ¾" pipe; finally, the Figure 6. facilitates the analysis of flow rate vs. time and voltage vs. time in the 1" pipe.

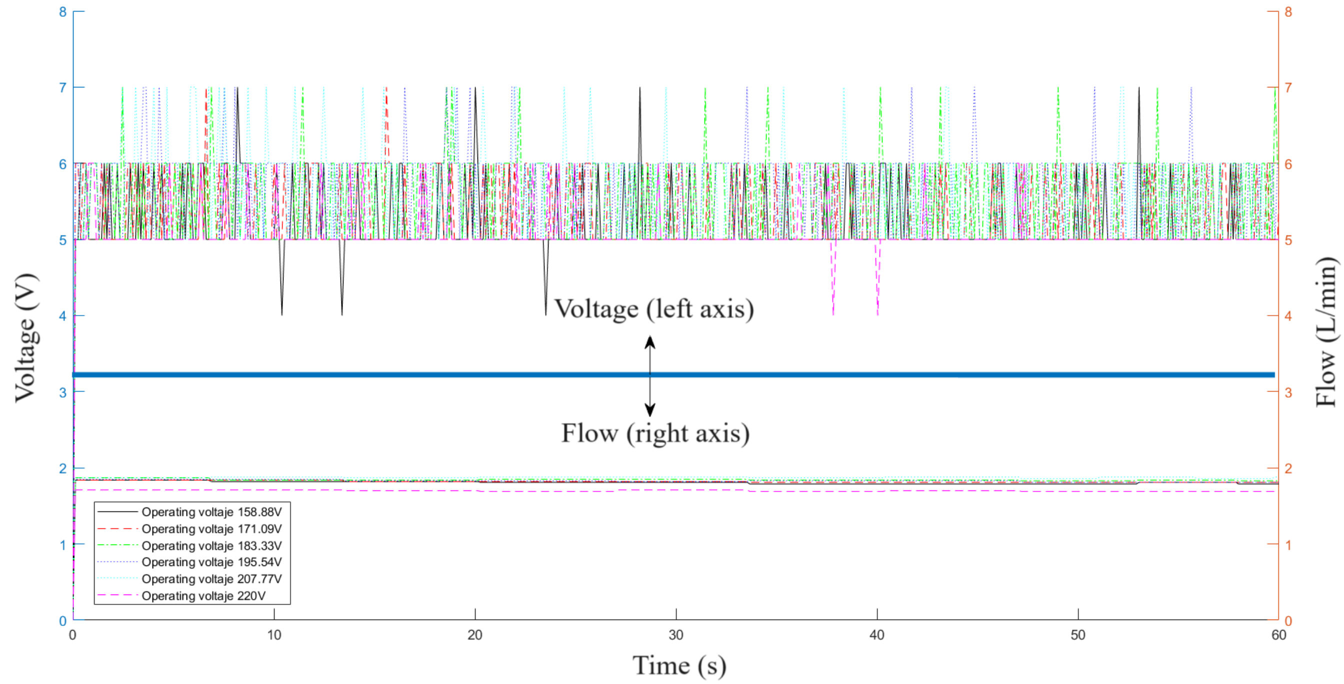

Figure 4. Flow vs. time and voltage vs. time graph for 1/2" pipeline.

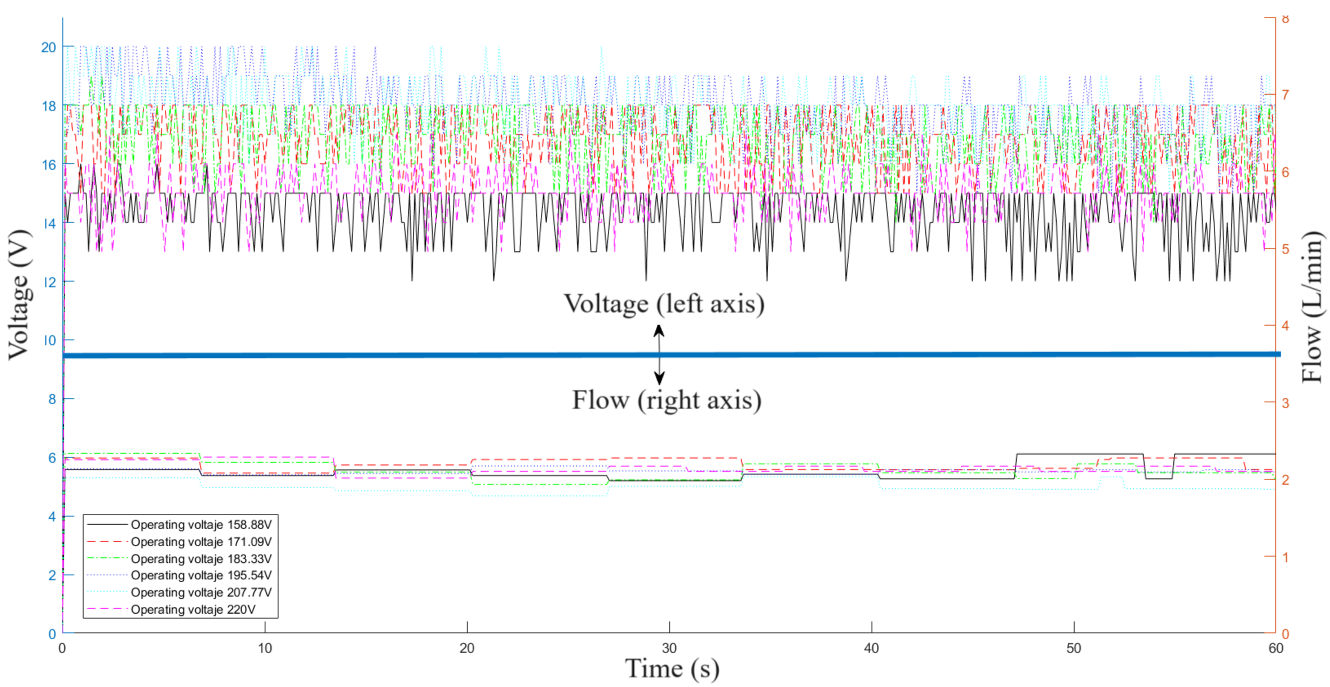

Figure 5. Flow vs. time and voltage vs. time graph for 3/4" pipeline.

In Figure 4, it can be observed that the voltage generation maintains a constant trend of 6 volts, regardless of the variation in the controlled flow rate at different Dimmer positions. There is a correlation between an increase in the flow rate through the ½" pipe, but the stable trend of 6 volts persists. Peaks of voltage increase can be noticed due to inherent system vibrations. In summary, this graph illustrates how the voltage generation remains steady at 6 volts, even amid fluctuations in flow rate and system vibrations.

In the figure 5, it can be observed that the voltage generation maintains a constant trend of 18 volts, irrespective of the controlled flow rate variation at different Dimmer positions, resulting in a substantial increase in voltage generation. An increase in the flow rate through the ¾" pipe is apparent, yet the stable trend of 18 volts persists, although at one of the position 6 of the Dimmer, the voltage increases to a maximum of 20 volts. In summary, this graph demonstrates how the voltage generation remains steady at 18 volts, even amidst fluctuations in flow rate and system vibrations.

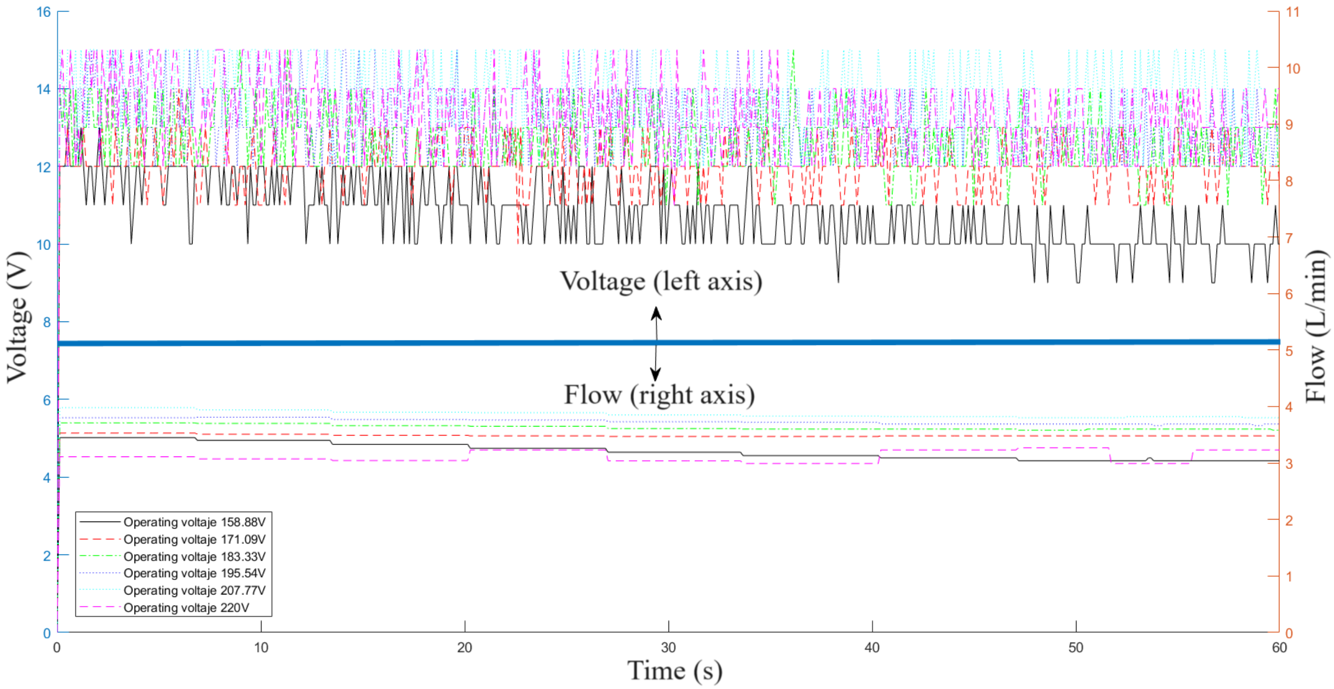

Figure 6. Flow vs. time and voltage vs. time graph for 1" pipeline.

In the Figure 6, it can be observed that the voltage generation remains constant at 14 volts, regardless of the variations in flow rate controlled at different Dimmer positions. There is a substantial increase in voltage generation.

An increase in the flow rate through the 1" pipe is evident, but the stable trend of 18 volts persists, although at position number 6 of the Dimmer, the voltage increases to a maximum of 17 volts. In summary, this graph demonstrates how the voltage generation remains steady at 14 volts despite fluctuations in flow rate and system vibrations.

These graphs allowed the identification of patterns and trends in the relationship between water flow rate and generated voltage. Through visual representation, it was observed how the generated voltage varied based on changes in water flow rate.

These relationships are crucial to understanding how to adjust and optimize the system based on available flow rate values. Furthermore, these graphs helped determine the most effective flow rate ranges for energy generation, which is crucial for maximizing the performance and efficiency of the automated hydraulic microgeneration system.

CONCLUSIONS

The findings underscore the importance of adjusting operational conditions to achieve a balance between generated voltage and system flow rate. This information can serve as a guide for optimizing similar systems and for making informed decisions in planning future hydraulic microgeneration installations.

Through meticulous measurement and enhanced understanding of the performance of the automated hydraulic microgeneration system, a profound insight has been gained into how key variables, such as water flow rate and applied voltage, impact power generation.

Extensive testing and data analysis have revealed complex and dynamic relationships among these variables, enabling the identification of optimal ranges to maximize system efficiency and energy production.

The three graphs synthesizing the system's behavior demonstrate a consistent trend in generation when liquid flows through the ¾" pipe. This pipe exhibited the best behavior during data collection, maintaining the highest and most stable generation (18V). This outcome can also be attributed to the various reductions, expansions, and connections present in the other two pipe diameters.

The ½" diameter displayed the poorest performance, with its maximum stable generated voltage reaching only 7 volts. Despite increasing the flow rate at different Dimmer positions, the increase in generation in this pipe had an insignificant impact compared to the other two control diameters. This might be explained by the prototype design, which was specifically tailored to install the generator in series and accurately assess its behavior through this particular pipe.

This study has laid the groundwork for future improvements and optimizations, offering valuable insights for the design and operation of similar systems. Additionally, it underscores the importance of rigorous research and experimentation in advancing sustainable energy generation technologies, contributing to a cleaner and more efficient future in electricity production from hydraulic resources.

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