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Development of a Pico-Hydro Generating System with SES-BMS for Domestic Use

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Abstract: Non-renewable resources decreased significantly over the past decade, whereas the current renewable energy system is expensive and more focused on large-scale use. The goal of this project is to design a user-friendly pico-hydro system with a Smart Energy Storage Battery Management System (SES-BMS) to utilize the potential of domestic water flow while saving energy consumption and daily costs. The overall system is a combination between the standard pipeline, a pico-turbine, the SES-BMS, and a simple light source. The flow of water is utilized by converting kinetic energy into electrical energy. The design was performed by using the Engineering Design Process (EDP) and coding via Arduino microcontroller. The main outcome of this project is a proof of concept that shows the potential for domestic use of the pico-hydro system combined with the SES-BMS system. Compared to the previous mini-hydro design, the new system shows an increase in performance during the average flow rate in the domestic pipeline, generating an improved value of 68 mW of power during the flow rate of 0.075 x 10^{-3} m^3/s. An optimal charging time of 10 hours is recommended to accommodate the 3.5-hour use of a 12W LED lamp, to maintain the stability and reliability of the system, especially the battery pack.

Keywords: Renewable energy, pico-hydro, BMS (battery management system), Arduino microcontroller, flow rate

1. Introduction

Nowadays, green energy has been the main priority of major businesses as well as researchers. Increased demand for electricity has led these companies to sign contracts for the procurement of renewable energy sources such as wind, solar, hydropower, and others. For example, the study by the Wind Energy Foundation (WEF) in 2018 shows that more than 100 companies in the United States are planning to purchase 60 GW (gigawatts) of renewable energy by 2025 [1]. This is equal to the energy generated by 110 traditional power plants, enough to generate nearly 50 million homes.

In Malaysia, energy consumption also increases. The industrial sectors are the main consumers, followed by transportation, residential and commercial sectors. The Economic Intelligence Unit (EIU) reported that coal-fired power plants accounted for 42.5% of electricity production in Malaysia in 2018 [2]. The new Tuanku Mukhriz power station in Port Dickson, for example, is capable of generating 2,000 MW (megawatts) during peak output. With a 40% efficiency compared to the traditional power plant, Tenaga Nasional Berhad's (TNB) power generation capacity in Peninsular Malaysia was increased to 25,981 MW, as stated by the Malaysian Energy Commission in 2020. Malaysia also sourced 15% of the total electricity generation from renewable sources in 2018 and aims to raise it to 20% by 2025. Malaysia needs to achieve Asean's renewable energy goal by 2025, accounting for 23% of the region's energy mix [3].

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On average, the Malaysian household consumes 251 kWh (kilowatt-hour) of electricity per month, which translates into 171.68 kg of carbon emissions per month [4]. In 2018, TNB stated that the electricity tariff in Malaysia is about 57.10 cents/kWh (for 901 kWh onwards) which is 20% higher than in 2011 (about 45.40 cents/kWh) [5]. In terms of daily water consumption, the average household uses around 1,360 liters per day [6]. From this data, we can see that electricity usage will only increase unless more action is taken. Extracting the energy from the domestic pipeline could be one of the keys.

Hydropower is one of the most established and widely used methods for producing green energy. The benefits include a long life cycle; from 50 to 100 years of potential use (with proper maintenance), low operating and maintenance costs (up to 90% of efficiency) plus other benefits [7]. However, most of them are limited to commercial hydroelectric turbines, from small to large-scale hydropower projects. This is due to the high initial cost that can only be invested by a well-established business. In general, the majority of the hydroelectric plant can be categorized as large, with more than 10 MW of monthly production. In 2019, The World Bank's ESMAP (Energy Sector Management Assistance Program) [8] identified the need to catalyze a new market for batteries and other energy storage technologies that are appropriate for a wide range of grid and off-grid applications and can be implemented on a large scale. Small-scale renewable energy is seen as one of the best solutions to meet the need of small and remote areas.

Pico-hydro is capable of generating a small amount of electricity compared to large-scale hydropower, with high significance and a contribution to rural and off-grid regions. Pico-hydropower also offers a better option for areas with limited space. However, due to the size and unavailability of a natural and continuously flowing water supply, such as small rivers and streams, it may not be ideal for urban households. But with proper planning; for example, through the utilization of domestic pipelines, small-scale hydropower may be more cost-effective and more efficient to provide renewable electricity. The flow of water in the domestic pipeline has a promising potential to produce electricity from it as the potential flow is usually left to waste. With a minimum efficiency of 50% [7], it is one of the best options for cost-effective renewable energy, especially for local use.

In terms of product, there are a few potential ones on the market that aims to produce electricity from the flow of water. Unfortunately, the choice is still limited compared to other renewable sources, such as the solar PV panel system. In terms of research, Zainuddin et al. showed that the pico-hydro system can be operated by utilizing distributed water to several households with a maximum output power of 1.2W [9]. However, the performance is lower compared to the specification of the generator (around 13.8V), with an efficiency of less than 5%. The previous conceptual research on the mini-hydro design by Jusoh et al. [10~11] also indicates the ability to produce energy from the water flow of the pipeline, generating a small amount of 10 mW of power at a minimum flow rate of 0.254×10^{-3} m^3/s. However, more research needs to be conducted to further explore the efficiency of the base design.

Despite this, a fully-featured system for producing energy in the domestic pipeline is still unavailable. For the device to be workable, it is best to include an independent charging unit such as a battery pack with a complete monitoring system. The lithium-ion battery is most suitable to be used as a storage solution due to the low cost [12]. However, it is also sensitive and easy to overcharge and discharge, which could damage and degrade the battery and reduce its lifespan. Even the battery can be seriously damaged if the voltage level is extremely low. The implementation of the battery monitoring system (BMS) on the battery pack is capable to prevent such problems. It also ensures the safety of users from potential harms resulting in high voltage. For example, the 2016 Fujitsu Technical Report [13], highlights the importance of using BMS to ensure the safety of lithium-ion battery users from failures such as smoke, fire risks, electrical shocks, and other problems.

Considering all the highlights and results of the previous studies, the importance of building a complete pico-hydro energy generation system that includes a charging system and a storage system for the energy produced is stated. At the same time, the majority of consumers can obtain a completely workable system that can minimize monthly costs, at the same time supports conservation energy and the environment.

2. Methodology

Hydroelectric energy is generated through the potential of water flow. The force of falling water strikes the rotary blades of the turbine. The energy generated depends on the flow rate and also on the falling height (also known as the head) [14]. The rotation of the turbine induces electricity, where the electromagnet in the motor plays a major role in the conversion of the energy. For a conventional plant, the transformer is used to increase the voltage so that there is less failure during the transmission in the power lines. This project is focused on designing a system to power up an outdoor light source. This system includes a pico-hydro turbine, the SES-BMS, and the battery pack. In the design stage, we need to estimate how much power can be extracted during the average flow rate of 0.3×10^{-3} m^3/s, as stated in the previous research.

The average pressure from the communication pipeline to a household pipeline is between 124.1 to 172.4 kPa [15]. By choosing the minimum value, it can be converted to the head value of approximately 12.7m [16]. Using the simplified equation from the USBR guidelines [17], where the theoretical horsepower is equal to the flowrate times head, and divided by 8.8, resulting in the theoretical horsepower of approximately 35.2W of power. However, more detailed experimentation is required to validate this value. The layout and schematic of the overall system shall be generated during the preliminary design, starting from the input (pico-hydro generator) to the output (light source).

2.1 The Engineering Design Process (EDP)

Based on Shigley's EDP [18], the project shall be focusing on two major phases, which are the conceptual design and preliminary design stage, as shown in Fig.1 flow chart. The conceptual design stage involves gathering data from other resources such as journals, books, and others. During the preliminary design stage, the conceptual design of the system shall be studied in detail to produce a workable product. As for this project, the emphasis is more on validating the overall design of the system. Basic parts and components such as the pico-hydro turbine (as shown in Fig.2(a)) and other electronic components shall be procured to maintain the stability of the result. Before the prototype is assembled, a schematic diagram of the system is created using CAD software. The Fritzing software was used to construct the schematic diagram. The schematic diagram must include all basic components such as the turbine, the BMS, the battery pack, and the light source as output.

The smart monitoring device consists of a relay module, which serves as a switch to control the charging and discharge status of the battery. It also includes a current sensor for measuring the current value of the battery, a series of resistors serving as a voltage divider, an LCD to display battery information, and also a potentiometer to control the brightness of the LCD. The boost converter (step-up converter) is a DC-to-DC power converter to step up voltage (while stepping down current) from its input (supply) to its output (load). The booster converter helps to raise the output voltage to reach the required voltage to charge the battery pack. The DC power supply represents the hydro turbine (refer to Fig.2(a)) while the Li-ion batteries represent the four-series and three-parallel Li-ion battery as shown in Fig.2(b). The coding shall be performed using Arduino software. After finalizing the preliminary design with a working prototype of the device, an experiment shall be carried out to monitor the overall performance of the product. The main objective is to track the induced voltage of the pico-hydro turbine while at the same time evaluating the charging and discharging rate of the battery pack. All findings shall be summarized for improvement during the detail design stage.

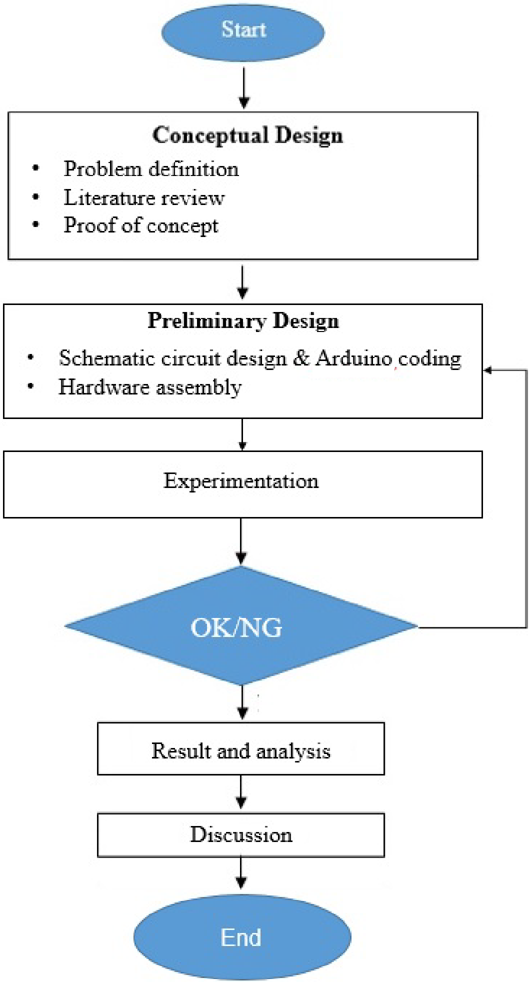
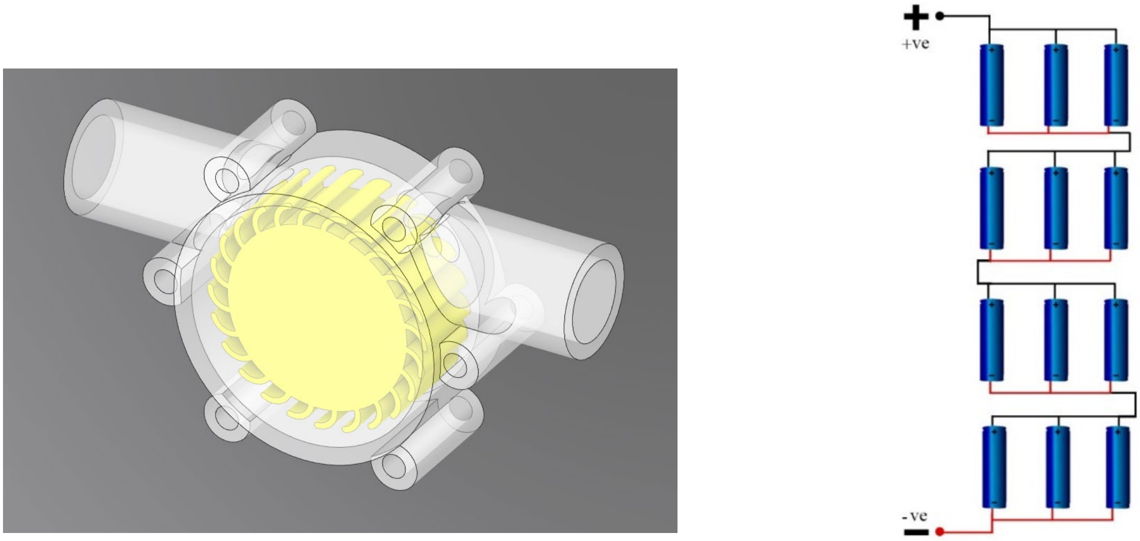


Fig. 1 - Overall flow chart of the project



(a) (b)

Fig. 2 - (a) 3D model of the F50-12V pico-hydro turbine; and (b) configuration of the battery pack

2.2 Evaluating The Performance of The BMS

The Battery Monitoring System (BMS) is an electronic device that measures and analyzes the parameters of the battery using a code and transmits the output to the end-user through an LCD screen. The selection of battery type is important in this stage. There are various types of batteries available on the market. The NCR18650 lithium-ion (Li-ion) battery was chosen as the main candidate because it is easy to obtain, rechargeable, widely used in electronics, and also value for money. Li-ion dominated the mobile power source due to fewer competing alternatives. APP Corp. [12] highlighted the importance of monitoring Li-ion battery output to avoid any serious battery failure, as it is susceptible to fire hazards and electrical shock potential. If the item is handled incorrectly, the risk is higher. The charging and discharge characteristics of the battery are available in the Panasonic NCR18650 datasheets [19].

Therefore, the BMS is required when a battery pack is used in any application, as suggested by Fujita et al. [13] and also by Lelie et al. [21]. This includes other components inside the BMS, such as the power supply unit, the voltage sensing module, the microcontroller, the temperature sensing module, the current sensing module, and the LCD. The voltage divider theorem was used to measure the voltage while the current sensor was used to measure the magnetic flux produced by the current conductor. The digital thermal probe DS18B20 is used to determine the temperature. For this BMS, the Arduino microcontroller was used as a stackable data logger with a secure data card slot. This component is essential for the storage of all the data collected. The board shall be programmed using Arduino programming language combined with C and C++ programming languages. The experimental performance is divided into two categories:

2.2.1 To Investigate the Output Voltage Produced by The Pico-Hydro Turbine

The objective of this experiment is to investigate the output voltage produced by the pico-hydro turbine. The data obtained should be in sync as stated in the datasheet of the turbine. In this experiment, a 12V pico-hydro turbine was used. Detail specification of this product is accessible in Shenzen Global Tech datasheets [20]. Other apparatus includes the stopwatch, the multimeter, the hydraulic bench, and the turbine. The first procedure is to prepare specific apparatus, such as coupling and others. Then, the pico-hydro turbine is mounted and connected to the coupling and the hose. The hydraulic bench shall be tested and set up to ensure that there is no leakage. The flow rate is gradually increased to find the optimal flow rate for the turbine to spin. Finally, the time and multimeter readings shall be recorded with a minimum of three readings.

2.2.2 To Investigate the Charge and Discharge Rate of The Battery Pack

The next goal is to investigate the charging and discharge rate of the battery pack. The data obtained from the experiment should be similar to the theoretical value. The apparatus used in this experiment is the stopwatch, the multimeter, the hydraulic table, the turbine, and the battery management system. The arrangement of the apparatus is shown in Fig.3. To define the charging rate of the battery pack, first, attach the battery pack to the pico-hydro turbine. The time of charging shall then be recorded. At the same time, the voltage of the battery must be tracked from time to time using a voltmeter. The process ends once the voltage reaches the maximum theoretical value of 16.8V. Finally, all results shall be recorded.

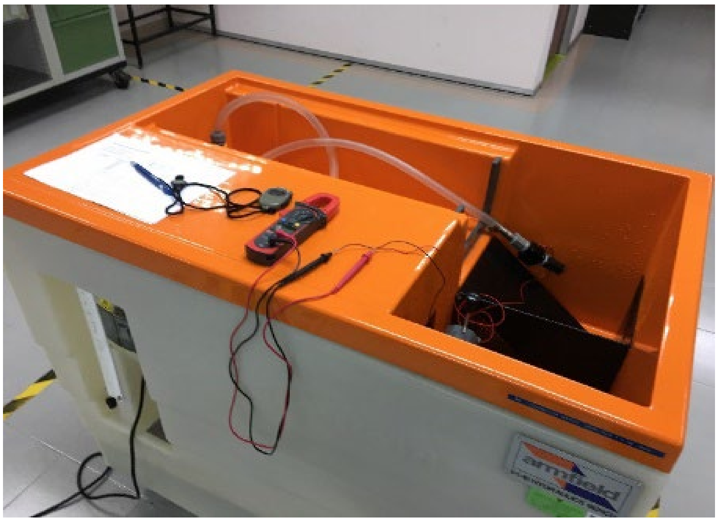


Fig. 3 - The hydraulic bench

3. Result and Discussion

3.1 Review on The Preliminary Result

As the initial result, the amount of power produced by the system based on the average flow rate has been estimated. To calculate power, the value of the flow rate inside the pipeline and also the head has been defined. The average water pressure in the Malaysian pipeline (from the contact pipeline to the household pipeline) was estimated between 124 and 173 kPa. From the methodology section, the potential electrical power was estimated to be approximately 35.2W. This is only an initial estimation and needs to be validated with the experimental outcome.

From the manufacturer's datasheet, the output current (from the pico-hydro turbine) is estimated at around 0.22A with a voltage output of 12V. The experimental result shows a similar value to the datasheet. To measure the power generated by the turbine, the basic electrical power formula P=VI is used, where P represents the power, I is the current output and V is the voltage. From this equation, the power output (by the turbine) is estimated at around 17.6W, which is sufficient to power the 12W LED light. Next, the system's charging and discharge rate was measured. Li-ion (cylindrical) batteries were selected as the power storage unit, with a battery capacity of 2500 mAh. The voltage produced is 3.7V. The battery configuration is of four-series and three-parallel battery connections; with a total of twelve Li-ion batteries as shown in Fig.2(b).

Fig.4 shows the full-assembly sketch, while Fig.5 shows the schematic diagram of the device consisting of the turbine, the SES-BMS, the battery pack, and the LED light. The smart monitoring device consists of a relay module acting as a switch to regulate the charge and discharge of the battery, a current sensor to monitor the current value of the battery, a resistor set acting as a voltage divider, an LCD to display the battery information and also a potentiometer to control the brightness of the LCD. The final assembly is shown in Fig.6.

As a result, the system integration was successful where the 12V pico-hydro turbine, the SES-BMS, and the battery pack worked as expected. The battery monitoring system works where the charging system is capable of disconnecting the circuit when the voltage reading exceeds 16V and manages to reconnect when the voltage value is below the limit. The LED light also works after it is attached to the fully charged battery pack.

3.2 Comparing between The Previous M/Hydro and The New Pico Hydro Design

An investigation has been carried out to monitor the output voltage produced by the pico-hydro turbine. This is to identify the optimal flow rate inside the pipeline to produce electricity. It is important for the system to charge the battery pack and to be able to light the 12W LED light. Based on the procedure, the measurement of the water level needs to be taken every 60 seconds to determine the water flow rate. Next, the voltage and current values are measured and plotted. The result was obtained by using a 30-mm diametrical household pipeline and concentrating on the range of the water flow rate between 0.25×10^{-3} to 0.73×10^{-3} m^3/s as the base. The 12V pico-hydro turbine will produce approximately 12.02V electricity at a minimum flow rate of 0.075×10^{-3} m^3/s. Experimentally, the maximum flow rate depends on the limit of the hydraulic bench.

As a result, the 12V pico-hydro turbine is capable of generating a small voltage output. To solve this problem, a buck booster converter is required to step up the supply of 12V pico-turbine voltage. Based on the result in Fig.7, it is shown that the 12V pico-hydro turbine is ideal for use as a power generator for the device since it needs a small voltage (before stepping up) to charge the battery and requires a minimum flow rate to start generating the electricity.

Comparing this to the previous mini-hydro design, we can see that the new design can achieve better performance without overstressing it, generating at least 68 mW of power with a lower flow rate of 0.075×10^{-3} m^3/s.

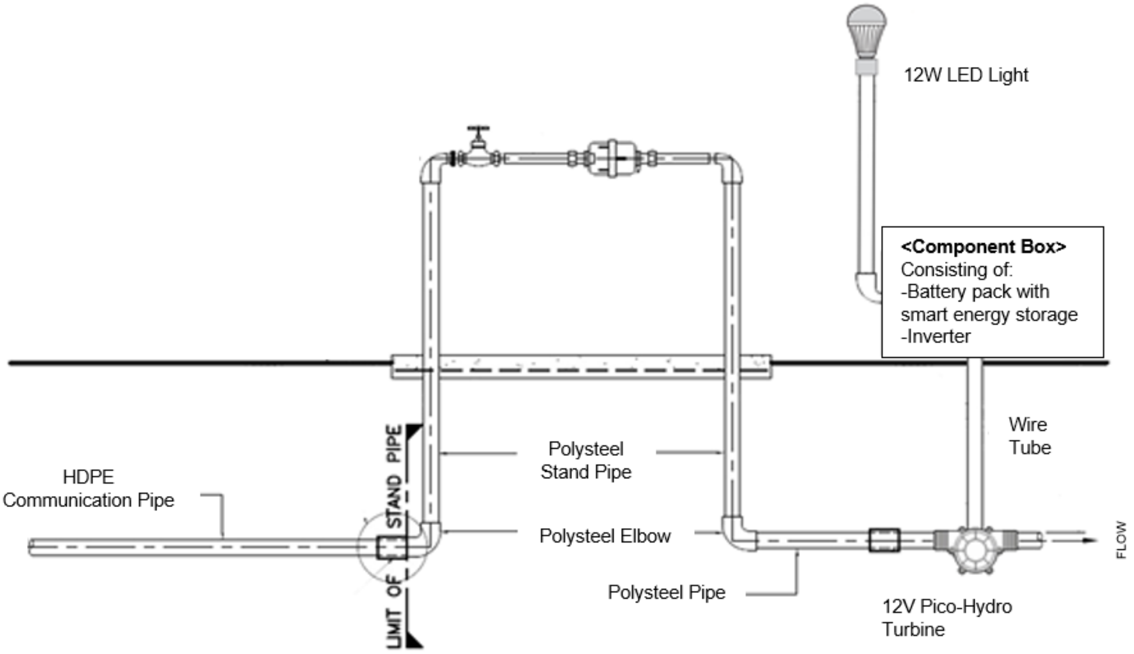


Fig. 4 - Full assembly sketches

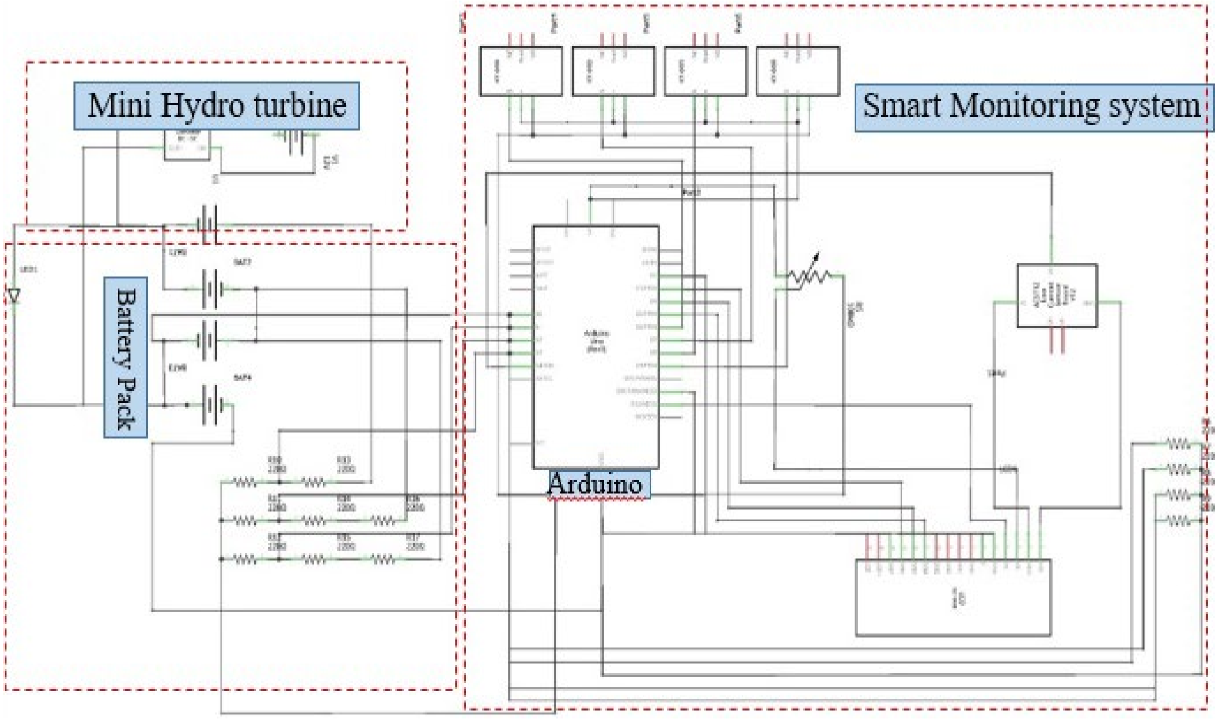


Fig. 5 - Schematic diagram of the system

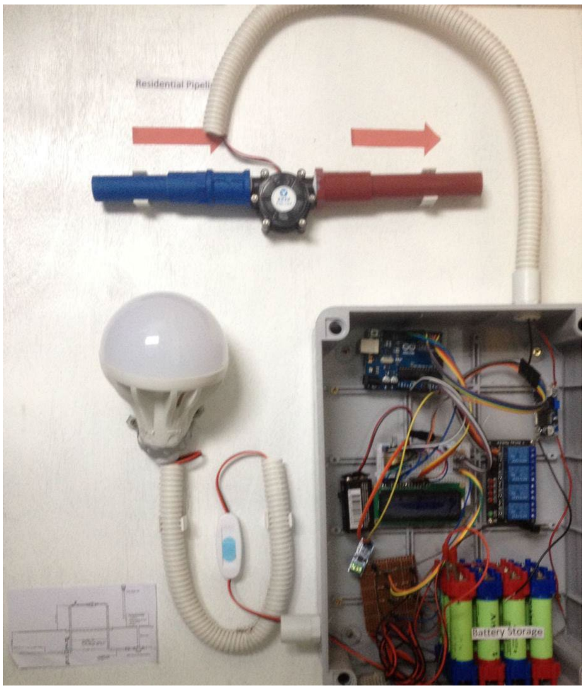


Fig. 6 - Overall assembly of the system.

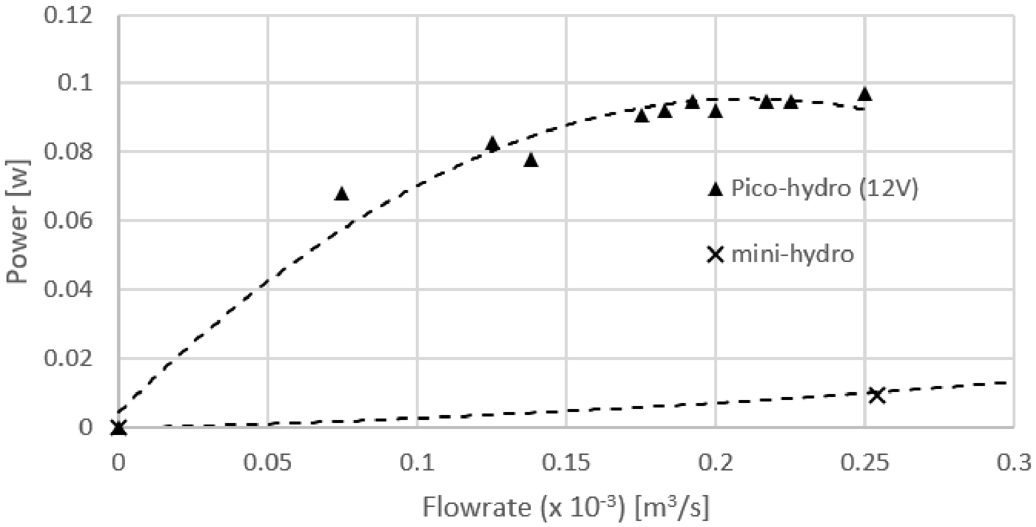


Fig. 7 - Graph of power vs flowrate

3.3 Charging and Discharge Rate of Battery Pack

From the experiment carried out, it is shown that a completely drained battery pack requires a maximum charge of about 23 hours. However, if the battery pack is held at a minimum voltage (12V), it will take just around six to seven hours to completely charge it to 16V, as shown in Fig.8. To ensure that the battery is not deeply undercharged, the coding must be correctly constructed, where the minimum and maximum voltage limits of the battery pack must be set. The minimum voltage is approximately 12V. Therefore, if the light bulb needs more power, the device will automatically connect to the relay and the charging mode will be switched on.

As for the discharge rate, the energy capacity of the battery pack decreases with respect to time. It takes about 11 hours to completely discharge the battery pack. This means that 12W LED lights can be used over a particular time frame, e.g., from 10 p.m. to 6 a.m. without any complications, including 5 additional hours for backup purposes. For optimal use, it is recommended that the device is charged for approximately 10 hours (beginning from minimum voltage condition), resulting in a 3.5-hour lighting cycle of 12W LEDs. This is to maintain the stability and reliability of the system, especially the battery pack.

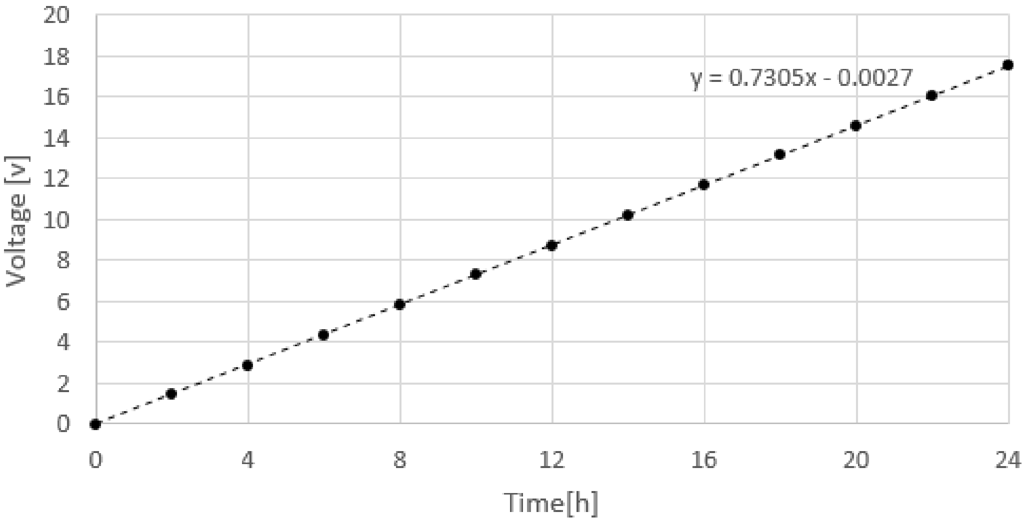


Fig. 8 - Charging rate using 12V hydro-turbine (Voltage vs time)

4. Conclusion

Based on the design and experimentation carried out, the pico-hydro system with the SES-BMS can generate electricity as proposed. The charging system is also working as expected. By combining the pico-hydro turbine and the battery management system, we can use the kinetic energy from the flow of water within the domestic pipeline to produce free electricity.

From the experiment, the use of a 16V battery pack is necessary to illuminate a single 12W LED. The battery pack can also be upgraded to light up multiple LED lights if needed, but with a longer charging time. The SES-BMS supports energy storage for potential applications and helps to protect the device from damage. The buck-boost converter provides an increase in voltage and the Arduino medium enables the coding process to become more convenient. A 12V pico-turbine was chosen due to the system requirement. 23 hours of charging time should not be a concern, as the main pipeline in most residential areas is always running 24 hours. During the nighttime, the energy stored can be used to provide light for at least 10 hours. The 10-hour charging period with a 3.5-hour lighting alternative is recommended for optimal use. Finally, the new pico-hydro system shows a more marketable potential due to the small size and low-cost factor. For future research, this idea could be expanded for application in the industrial sector, where the water flow is always present with a higher flow rate compared to the domestic pipeline. It is a good opportunity to produce free energy from the flow of water, thus reducing overhead costs.

In conclusion, the goal of the project has been accomplished. The contribution of this product in supporting green technology is positively viewed especially towards improving the local economic sector [22], considering the future reduction of resources such as the natural gas reserve and other natural resources. Further work shall be carried out to refine the design and performances, at the same time to eliminate possible problems.

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