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Design of a Data Logging System for a Small Scale Hydrokinetic Turbine

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A suitable data logger is needed for data collection to demonstrate the practicality of Hydrokinetic Turbine (HKT) in a rural application. Currently, commercial data loggers are expensive and consume extensive amounts of energy. The high cost is due to the sophisticated applications or features embedded together with the loggers. However, some of these features are not necessarily needed in Borneo's rural area due to limited power supply and an absence of internet access. Therefore, in this study, a data logger was designed according to Quality Function Deployment (QFD) to feed the specific or critical parameters and applications that suit HKT's data collection. The logger was calibrated and tested in a laboratory. The practicality of the data logger was also verified in a field test. An automatic data-file creation capability was developed, and a Secure Digital High Capacity (SDHC) memory card was chosen to provide high storage capacity. Besides that, the logger was designed with low energy consumption and lightweight. The results showed that the error of voltage divider, propeller type current meter and rotational speed meter were within 1%, whereas, 5% of error was observed at the current transducer. Therefore, the data logger demonstrated an acceptable behaviour of the logging performance test.

Keywords: Hydrokinetic Turbine Energy; Quality Function Deployment; data collection; data logger; output power

I. INTRODUCTION

Hydrokinetic turbine (HKT) is a technology that can be used to extract kinetic energy from river currents of almost zero elevation. The technology is suitable for rural applications because many villages are widely spread throughout the region, far from the power grid system. The people live in a small number of households. A small scale HKT can produce electricity ranging from 15W to 1,000W of power, and the operation can practically be fabricated according to the number of homes. It can also be maintained and repaired by the rural community (Riglin, 2016). Besides, most of the villages in rural areas are situated near the fast-flowing rivers, which flow at speeds between 0.05m/s – 1.35m/s and are 0.2m – 1.3m in-depth and found in regions of Borneo (Ling *et al.*, 2017). f). Thus, technology is considered as a potential solution for off-grid rural communities (Anyi & Kirke, 2010).

Proper data collection of the system's electricity energy production is needed to analyse the potential of HKT for rural applications. Besides that, this data could justify the reliability of this technology for rural electrification in Borneo. Thus, it is essential to measure and record an extensive input of data. The data can be manipulated to determine the efficiency of the system. Therefore, a suitable data logging system is necessary to provide complete documentation required to demonstrate the practicality of HKT. In Malaysia, studies have focused on the potential sites (Aling *et. al.*, 2018; Azrulhisham *et al.*, 2018) and on collecting resource data for a selected rural area in Sarawak (Saupi *et al.*, 2018). However, the appropriate data collection method to demonstrate the practicality of HKT in rural applications in Sarawak has not been found yet.

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Most of the data has been collected to develop the Horizontal Axis Hydrokinetic Turbine (HAHT) blades (Chica, Torres and Arbeláez, 2018). A data logger of good quality is needed for the evaluation of experimental results. A few researchers performed field tests of HAHT prototypes which contained the rotor, gears and the generator. Commercial data logger industries are generally used in the data collection for such tests. Several standard data loggers have been developed and produced by electronic companies or researchers to cater to systems' demands. However, most standard data logger only talks to products from the same manufacturer, covering general parameters and features. (*HOBO U12 4-Channel External Data Logger - U12-006*, 2015). There are unnecessary applications embedded together with standard data loggers, (Siew *et al.*, 2012) such as temperature sensor for a monitoring system or Wi-Fi for a wireless communication unit. Such applications are not necessary for HKT systems in Borneo's rural area due to the limited power supply and absence of internet access. Consequently, these commercial data loggers may not be entirely usable for specific needs or applications, would be unnecessarily expensive and hence increase the cost of research (Fuentes *et al.*, 2014). This research focused on developing a data logger system that exhibits low energy consumption, is not dependent on power grids, and internet access has high storage capacity and comes with a data-file creation capability.

II. DATA LOGGER REQUIREMENT IN HYDROKINETIC TURBINE

Quality Function Deployment (QFD) is used to determine the requirements or find the priority features in designing and fabricating a data logger. The information was also in compliance with researchers' priority features which they felt a data logger should have to monitor the production of electric power aptly. There are nine (9) product objectives that score more than 5.0 in QFD (Mac Donald, 2017). These product objectives are made to help the designer of a data logger focus on characteristics of a new or existing logger from the market needs, manufacturer needs, and technology development needs.

A. The Concept of a Small Scale HKT System

The main concept of the HKT system is shown in Figure 1, where the horizontal axis turbine converts the kinetic energy from the river into mechanical power. Notably, a 90-degree gearbox, a straight shaft enclosed in an aluminium tube, two sprockets and a chain used to transmit such energy and feed the generator. The DC output of the generator is regulated by an Electronic Load Controller (ELC), which is used to maintain the generator terminal voltage. The ELC is driven within 12V D, C and it enables the generator to produce a more stable voltage and frequency by maintaining a near-constant load on the turbine (Melo, Rosa and Ribeiro, 2013). The implementation of the turbine, generator and ELC will not be covered in this paper. Still, this information is necessary to understand the influencing factors that contributed to implementing the data logger. This paper was based solely on the data logging system indicated by the orange colour shown in Figure 1. The data logger is integrated with voltage transducer, current sensor, water current meter, rotational speed meter, processors, programming, data stamping, data storage and communication method.

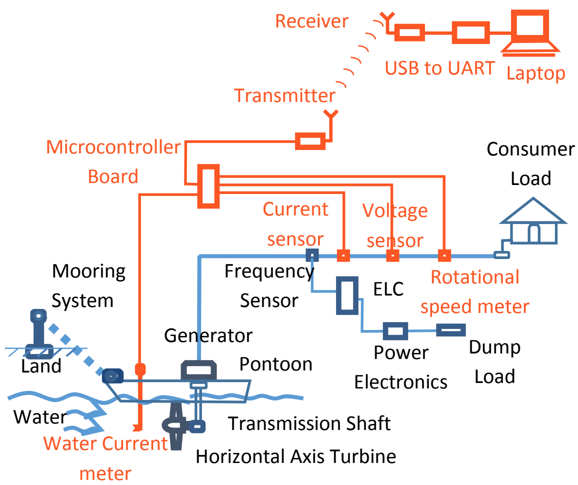


Figure 1. The main concept of a small scale HKT system logger for the system

B. Critical Parameters in the HKT System

Voltage and current are the primary parameters used to determine the power produced by a system. These are the primary parameters used in most wind turbines, micro-hydro, and photovoltaic (PV) systems to measure their electrical outputs. DC voltage was measured by voltage divider because of its acceptable accuracy and competitiveness in price. In other renewable energy systems such as wind and PV systems, meteorological data is used in monitoring the systems' performance, by identifying the capacity of energy provided by the natural resources (Ciobotaru, 2010). In Borneo's rural area, finding reliable meteorological data has been challenging and has its limitations. Moreover, this information can only be used as a reference, and it cannot replace the specific data taken on-site (Pattanaik *et al.*, 2017). Thus, a propeller-type water current meter is needed to measure the flowing river's velocity driven by the kinetic energy.

The HKT system utilises Permanent Magnet (PMDC) generators to generate power from a moving shaft. As such, the revolving shaft's rotation speed is needed to ensure the generators' functionality (Thomas *et al.*, 2012). This information is vital for driving a better decision to choose a suitable generator for the designed turbine and selecting a transmission gear that could generate maximum output power.

III. FABRICATION OF A DATA LOGGER

There are many voltage divider modules available in the market. A voltage divider chosen for our work's purpose should mainly be compatible with the nominal voltage of the HKT turbine, which is approximately 16.95V. However, during an open-circuit test or no-load condition test, the voltage can reach a maximum value of 42.7V at the generator's top rotational speed. But the generator practically never spins in a no-load state to get full speed. 0 to 25V was chosen as the range for the voltage divider module because its typical and nominal values were within that range.

The nominal current of the HKT system is around 13A and can reach a maximum value of 18.10A at the maximum rotation speed of the generator. 0 to 20A was chosen as the range for the current transducer module. A resistive divider circuit is used to convert the Hall Effect ACS712 sensor output signal level at the ADC input. The resistive divider and the ADC are components that affect measurement system accuracy. According to the manufacturer specification sheet, the offset value of ACS712 is 2.5 V. Still, after the sensor was tested inside the lab, the actual offset was found to be 2.23 V. The error of the offset voltage is rejected later in the programming stage.

Companies have produced several standard propeller-type current meters to cater to their respective demands, but these products are too costly. In our study, a meter was designed and fabricated using copper mounted on the top of its propeller shaft, while a proximity switch was used to produce pulses. In a typical operational scenario, the copper rotates with the propeller. It induces pulses using electromagnetic energy in the waterproof coil inside the proximity switch on every full rotation. These rotations are proportional to the water-current speed. The conditional circuits use 1kΩ and 510Ω resistors that are placed as voltage dividers. The output pulse produces a low signal at 0.1V and 4.98V for a typically high signal. The microcontroller counted these pulses for every 1 second passed, proportional to the water velocity in m/s. The impeller's circumference is 0.06317 m, these pulses are recorded in m/s by the embedded timer in the microcontroller. At a velocity of 0.5 m/s, the sensor produces about 7.9 revolutions per second (rps). In dry seasons, the river flows with speeds of around 0.8 m/s to 1 m/s and hence produces 12.7 to 15.8 rps. In wet seasons the river flows from 1 m/s to 1.2 m/s, and the sensors produce up to 19.0 rps. The maximum value of rotational speed can only be reached if the river velocity is around 2 m/s or 31.7 rps, which lies within the sensor switching frequency. The meter is placed at the same altitude at a distance of 1 meter in front of the hydrokinetic turbine. It uses a stainless-steel rod as its wading rod. This arrangement provides a good estimation of the river velocity conditions experienced by the turbine.

A rotational speed meter is used to measure the rotational speed of the generator shaft. Operating speed range and accuracy are two of the most critical parameters to consider when specifying a rotational speed meter. Operating speed range is the range of rotary speed measurements that the meter can monitor. In contrast, the accuracy is the closeness of agreement between a measured value and a true value in ± revolutions per minute (rpm). The generator's rotational speed's minimum value is 74.8 rpm, and the maximum is 523.4 rpm. The typical values are between 173.7 rpm and 260.7 rpm. These speed ranges are based on the velocity of the river at the field site. The meter was fabricated by utilising a magnetic pickup. It consisted of a pole-piece, a permanent magnet and a sensing coil, all encapsulated in a cylindrical case. A target object near the pole-piece cause a distortion of the magnetic flux field, which induces an AC signal voltage in the coil. The objects are evenly spaced on the gear, and one complete cycle of voltage is generated for each object passed. The total number of cycles measured indicates one full rotation of the gear. Thus, the AC voltage frequency was directly proportional to the rotational speed of the generator's shaft. The frequency can be measured by determining the period of the AC voltage signal. In Zero Cross Algorithm, sinusoidal waves in the AC signal are transformed into pulses. A counter unit in an integrated circuit LM2917 counts these pulses in unit time (Sondkar, Dudhane and Abhyankar, 2012). LM2917 also converted these frequencies into voltages that suit the microcontroller board's analogue input.

A. Selection of Components

An Atmel ATmega2560 microcontroller board was used because it is easy to adapt to any design and is low in cost. Signals from transducers are converted into a digital electrical form for the microcontroller to understand the data and process. The 0 - 5V signal conditioning circuit's output is converted to a digital signal from 0 – 1024, built in a 10-bit ADC embedded in the microcontroller board. The board also support different bus protocols such as I^2C, SPI and TTL. This support makes the microcontroller board capable of managing the RTC, SD module, and sensors using these bus protocols.

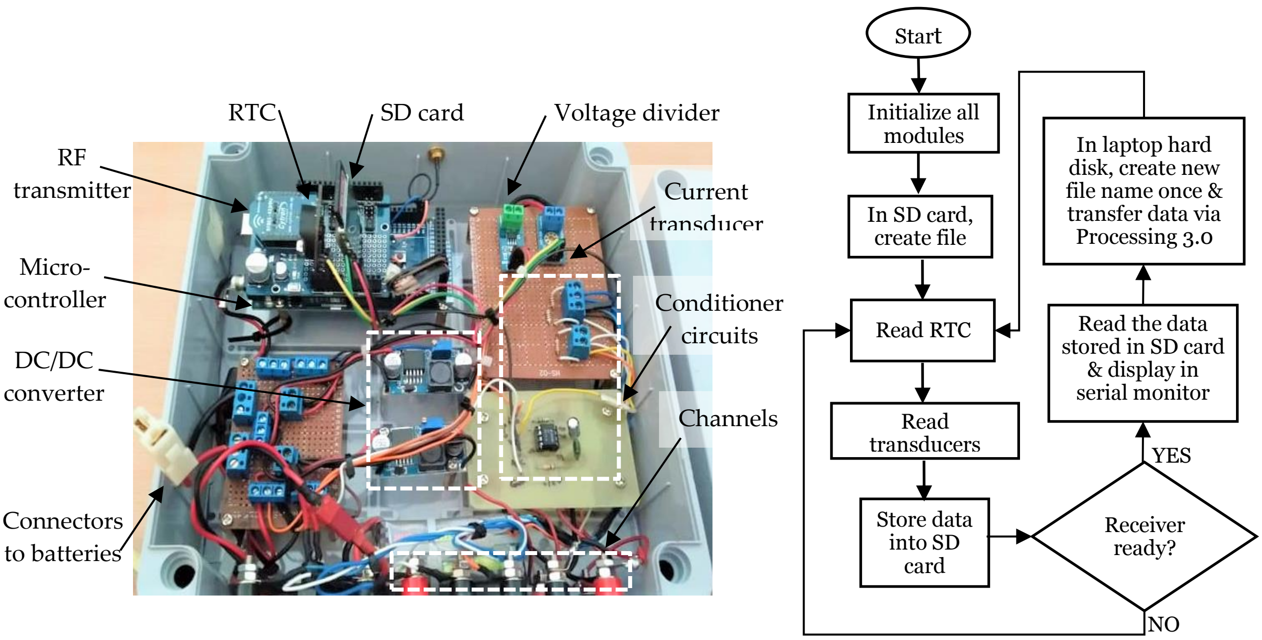
Selecting suitable data storage and estimating the data volume to be collected are essential parts of data acquisition. An SDHC/microSDHC card uses FAT32 as its file format, which is compatible with personal computer (PC) operating systems such as Windows ME, XP and 8.1. The file format is saved and read as comma-separated values (.csv) that use the extension .csv, which can be opened by Microsoft Excel or a relational database application. The file contains the values in a table as a series of ASCII text lines organised so that a comma separates each column value from the next column's value and each row starts a new line. This organisation is very convenient for the data logger's data storage. The SDHC/microSDHC card used in this project is 2GB in capacity and can store a large volume of data for an extensive range of the HKT operation timescales. One test was conducted to examine each cell's size during the logging period (Mahzan *et al.*, 2013). The purpose was to estimate the data logger operational days. For one cell of 'date', the size was 15 bytes; for one cell of 'time' it was 11 bytes; for other cells, it was 6 bytes. Hence, the formula is as follows:

$$Estimation\ (days) = \frac{Total\ capacity\ size\ of\ SDHC}{(l \times m \times (6n + 11 + 15) \times 24)} \quad (1)$$

l is the expected number of reading per day, m is the number of samples per reading, and n is the number of channels. In this case, the designed data logger has four channels, and the sampling rate is 1 S/s. Since the high data rate of transfer is not compulsory, each day, the logger is expected to execute 48 times of data reading and recording. The logger will read and save the data for 30 samples per reading with 30 minutes interval within 24 hours. Hence, the data will consume 1.5K bytes of SDHC card capacity for every cycle, equivalent to 72K bytes per day. Therefore, the storage can save data for 1157.4 days or more than three years if a higher number of readings per day is needed (for example, 15 minutes interval within 24 hours or 96 reading per day). Then, the capacity of the SDHC card will last for 578.7 days. The DS3232 is used for a Real-Time Clock (RTC) to maintain an accurate time and date for the main controller board. It is selected to avoid losing the time base if a system power supply failure's measurement is needed (Alegria and Travassos, 2008).

An RF transceiver module is a single device that can transmit and receive RF signals. The RF transceiver requires two modules to communicate at the frequency band (Bong-Hyuk Park, Jong-Won Kim, 2013) of 433MHz. The baud rate was set as 9600 with the UART pins connected in cross arrangement to the microcontroller. The data was transmitted through a wireless transmission which was about 1.0 km away from its transmitter. The signals transferred to a USB-UART converter for decoding before it is fed into the laptop computer for data display. A multi-channel power supply with a DC/DC converter is used to power up all the transducers, RTC, SDHC modules and transceivers using 7000 mAh Li-Po batteries connected in a parallel arrangement. Besides this, there is another 2100 mAh of battery for emergency.

B. Hardware Improvement



(a) (b)

Figure 2. (a) Main board of the data logger and (b) Flow chart of the control algorithm

Electronic noise sensitivity can be reduced by separating high noise functions such as voltage and current transducers from conditioner circuits, as shown in Figure 2(a). Moreover, for safety reasons, each module was electrically isolated. Five manual actions per measurement were needed to make the logger operate, including pushing the ON/OFF button. The logger was light in weight without a battery compartment, weighing around 0.9 kg with a volume of 0.005m^3, making it easier for transportation.

C. Software Programming

The control algorithms were coded using the Arduino IDE. In the programming stage shown in Figure 2(b), the initialisation was to check on transducers' status, SD card, and RTC. Then, the datalog1.csv is created by utilising the SD.open() function whereas the myFile.read() function will read from the file and display data on the serial monitor. Once a file is created, the microcontroller will process the signals from transducers. The combination with Processing 3.0 makes the Arduino IDE handier by converting the file format data into .csv format. The variable port index and baud rate were set to match the port and the baud rate used by the microcontroller board and the RF transceiver. Once, the RF receiver was detected, Arduino IDE was programmed to read recorded data inside the SD card and print it on a serial monitor. The serial handshake between Arduino and Processing 3.0 controls data flow where both sides have to agree when to send and receive data. All the information that was received on the serial monitor was recorded by the Processing 3.0 tool. The file was automatically created and saved into the laptop's hard disk with a variable filename as the title. The combination of Arduino IDE and Processing 3.0 makes data retrieval from the SD card of the data logger plausible in a hard to reach location.

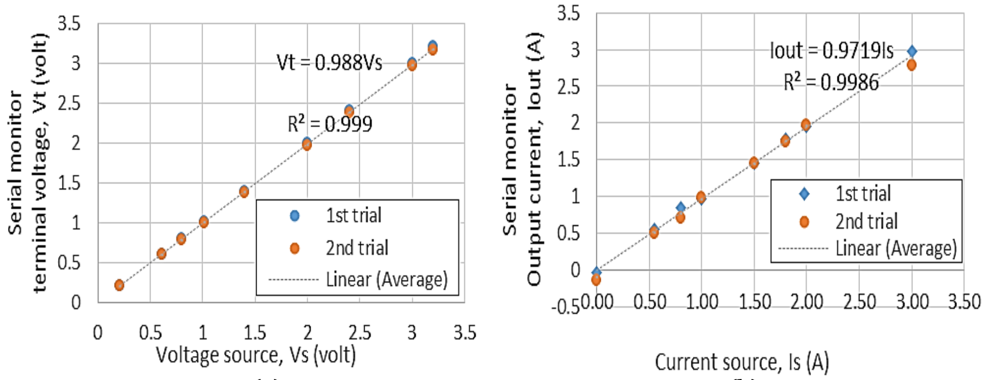
IV. RESULT AND DISCUSSION

A. Laboratory Test

The voltage divider module's calibration curve demonstrated a 1% error. Figure 4(a) shows that the correction factor was 0.988. After the correction factor was applied in the programming stage, the test result's systematic errors expressed less than 0.7% of error.

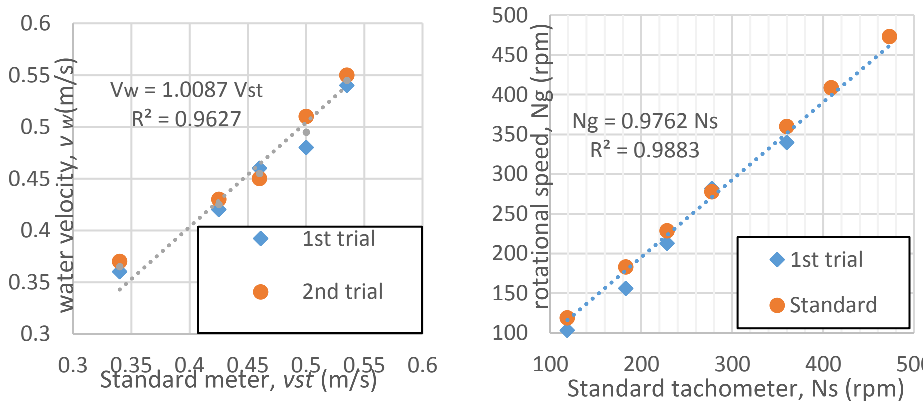
The current transducer is calibrated by using a current source and a current clamper as a standard instrument. The current transducer calibration curve demonstrated 5% of errors. Figure 3(b) shows that the correction factor was

0.9719. However, when the correction factor was applied at the programming stage, it couldn't minimise the transducer's uncertainty. Thus, we assumed the transducer had suffered from random errors and could not be corrected by any calibration method. However, the readings were within the accepted value claimed by the component's manufacturer.



(a) (b)

Figure 3. (a) The output of the voltage divider module was proportional to its source and (b) Current transducer values displayed by serial monitor were proportional to its source



(a) (b)

Figure 4. (a) Propeller type current meter values were proportional to its standard instrument and (b) Test meter values were proportional to standard digital tachometer

The propeller-type current meter prototype testing was performed in a straight open channel with flowing water. It was tested in an 8-meter-long Flow Channel, where the flowing speed varied from 0.3 m/s to 0.6 m/s. The experimental uncertainty of the standard flow velocity measurements was around ± 0.1 m/s from Nixon Flowmeter. The accuracy was determined by comparing the standard meter to the velocity measured by the prototype meter. Figure 4(a) shows that the correction factor was 1.0087. After the correction factor was applied at the programming stage, the tests' systematic errors demonstrated less than 7% of error.

Rotation speed meter is monitored using a calibrated digital tachometer. The experimental uncertainty of standard rotation speed measurements is ± 10 rpm. The same amount of input is applied to the prototype and the standard instrument. During the process, the magnitude of input is not essential. However, the information supplied by the source to both meters must be reasonably stable. The values displayed in the test meter are compared with the standard meter. The test meter calibration curve demonstrates 10% of error. Figure 4(b) shows that the correction factor was 0.9762. After the correction factor was applied in the programming stage, its calibration curve drastically dropped to ±1% of error.

B. In-situ Testing

Under laboratory test condition, the data logger was demonstrated by the acceptable behaviour and accuracy of transducers reading. The next aim is to monitor the complete HKT system under harsh rainforest conditions. An experimental campaign that spanned for two days was performed at Sungai Sarawak Kiri, located at Puncak Borneo in Sarawak. Figure 5 shows the terminal voltage and output current as a function of time. Based on the graph's readings, the average terminal voltage was 14.77 V, and the output current was 4.02 A.

Figure 6 shows the output power, generator rotational speed and river velocity as a function of time. The graph shows that the average output power was 60.89 W, the rotational speed of the generator was 256.6 rpm, and the river

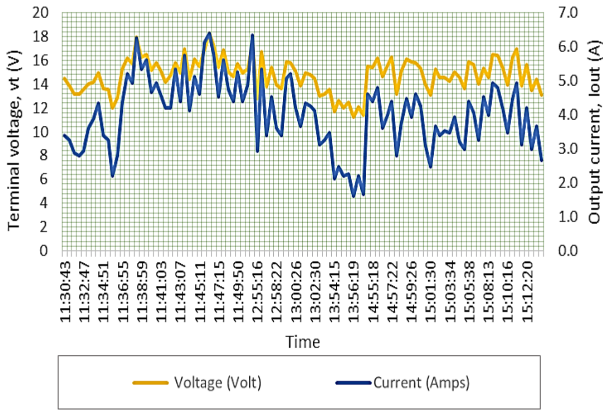


Figure 5. The graph of terminal voltage and output current produced by the generator

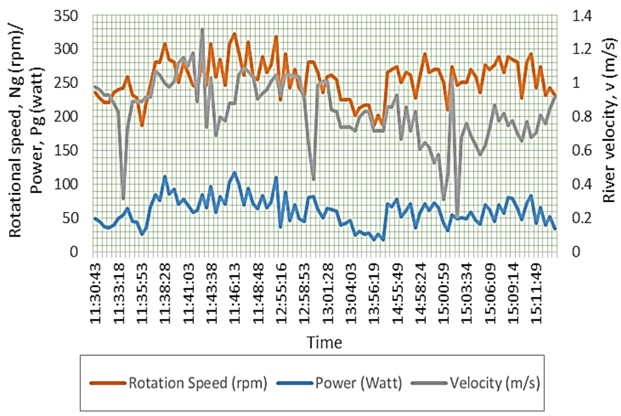


Figure 6. The graph of output power, rotational speed of generator and river velocity

velocity was 0.84 m/s. Regarding the propeller type current sensor, a flaw was identified in the sensor's interfacing, as the sensor is not suitable nor calibrated for values larger than 1m/s. The in-situ test run revealed that the data presentation was missing a filter, as the values of the river velocity fluctuated heavily. The water-current meter was assumed to have skipped some raw input values and only registered treated data. The problem can be overcome by using a different counter separate from the microcontroller's embedded timer. Positive results were obtained from other channels such as voltage, current and rotational speed, without any faults or interference from the electrical noise. The data transfer operated usually, and the collected data was successfully saved to the SDHC card with the date and time data. The test data was collected in two days, with a total period of about 10 hours. During the test, LED bulbs were used as a consumer load that allowed the electrical resistance to be changed manually. The data logger consumed approximately 9% of the total battery capacity. Thus, if the logger were to run without stopping, the batteries would be expected to operate it for four days and 16 hours before recharging. However, there was also an emergency battery that had a capacity of 2100mAh. Thus, the data logger could extend its operational time to 6 days and 1 hour.

V. CONCLUSION

A data logger along with four sensors was designed, implemented and experimentally tested. The data logger was built with used components and sensors available in the market, such as a 25V voltage module, ACS712 current module, M8 proximity sensor from Icon (Taiwan) and MP-62TA magnetic pick up from Red Lion Controls. The logger was also adapted to open source and free software such as Arduino IDE and Processing 3.0. The data logger consumed low energy, around 64mAh, thereby making it almost independent from power grids. RF transmission was used for effective data transfer without depending on internet access. The storage could save data for more than three years. The data-file was automatically created at two locations. The proposed data logger has achieved seven (7) high priority product objectives based on the QFD requirement. Thus, the data logger was considered to cover the necessary features for a suitable HKT's data logger. A suggested future improvement is that the data logger should be operated for a longer time to detect system failure occurrences. The data logger should also be tested for durability in body material where it can receive a 20 Mpa minimum of tensile strength. It is necessary to identify the logger's robustness when operating for an extended period and in a harsh rainforest environment.

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