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DATA ACQUISITION SYSTEM FOR A HYDROELECTRIC TURBINE LOCATED LINEARLY ON THE COURSE OF FLOWING WATER

The present paper presents a system for remote monitoring of the hydrodynamic and electrical parameters of the water course of a hydroelectric generator operating in a linear and floating mode. Research involving many components requires remote transfer and analysis, as it is carried out in conditions that are difficult for humans to access. Remote data transmission was selected as the preferred method due to the inability to directly measure the turbine elements as a complete unit. The data is obtained from the hydroelectric turbine's generator using transducer elements, which convert it into digital signals. These signals are then encoded and transmitted wirelessly to a receiver on the shore. The receiver decodes the signals and processes them in real time. The resulting information is displayed on a computer monitor, allowing for timely decision-making when necessary. Efficient bidirectional data transmission is facilitated by a request/response communication protocol operating in half duplex mode. The authors provide a comprehensive account of the research methodology, research findings, and final conclusions derived from the experimental data, along with the unique contributions produced through this applied research.

Keywords: Embedded systems; telemetry; communication protocol; hydroelectric turbine; hardware

1. Introduction

The shift towards a low-carbon civilization hinges on the augmentation of the capacity for renewable energy. Nevertheless, energy plans have resulted in increased social polarization in certain countries. Hydrokinetic energy, a readily accessible and highly promising energy source, has the ability to address the challenges of escalating costs and the contemporary energy crisis. It can efficiently provide the basic electrical requirements of both rural and urban areas, while remaining cost-effective [1].

Hydroelectric systems use the kinetic energy of flowing water to generate electricity or mechanical power. The most frequently utilized method of harnessing the energy of moving water is through micro hydropower plants, which are systems located alongside rivers which don't require the use of massive storage tanks.

There are various types of turbines, including Pelton, Cross-flow, Kaplan, Vortex, Francis, Very Low Head (VLH), Bulb, and others. For these turbines to operate at their best, they require high velocity and a substantial volume of water, along with water storage.

Hydroelectric turbines pose a significant threat to fish, potentially causing catastrophic harm throughout their passage. Hence, it is crucial to conduct thorough and dependable assessments of fish mortality caused by turbines in order to facilitate an informed discussion on the long-term viability of hydropower [2].

The authors from [2] reaffirm that fish mortality is significantly greater in hydroelectric turbines utilizing the Kaplan, Francis, and Cross-flow designs, in comparison to VLH turbines, water wheels, and Archimedes' screws. The researchers discovered that lesser rotations of the turbines, such as water wheels and Archimedes' screws, do not do any harm to the fish.

In their paper [1], the authors illustrate an intriguing method in Fig. 1 that utilizes water wheels to harness the energy of water in low-flow water courses, namely those with a minimum flow rate of 10 liters per second. This approach offers the advantage of not requiring a dam. This facility has the capacity to generate electricity for a residence of medium size.

An inherent disadvantage of this installation is the necessity for an artificially created disparity in elevation of multiple meters in order to guarantee the focused flow of water.

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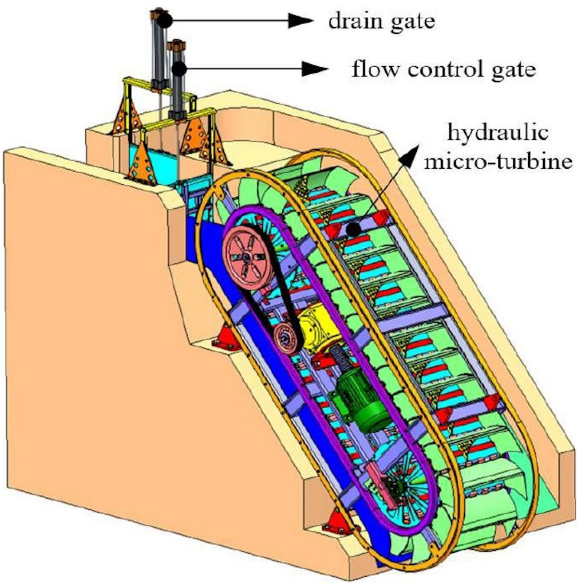

Fig. 1. Hydraulic micro-turbine design [1]

2. Hydroelectric turbine located linearly on the course

A straightforward and streamlined approach for setting up the installation and managing the water flow is provided by the patented “Hydroelectric turbine linearly developed along the river streamline” [3], as depicted in Fig. 2.

This is an application of a hydroelectric turbine that is designed for rivers with low flow. It is based on the principle of “water wheels” and shares similarities with the installation shown in Fig. 1. However, it does not require a difference in water levels and can operate in rivers with a relatively low flow speed of 1-2 m/s. The minimum requirements for the river are a width of 1 meter, a depth of 0.5 meters, and a minimum flow speed of one meter per second. The adjustment to the rise in water level is achieved automatically by its own buoyancy devices located on the side, as shown in Fig. 2b. The minimum operational temperature is the point at which an ice bridge forms, which is below 0°C, considering that the water is flowing. A three-phase electric generator had been used, operating at a nominal speed of 450 RPM, to provide a three-phase alternating voltage of 24 V RMS with a frequency of 50 Hz. The multiplication factor of the turbine in two steps is 8 times, as seen in Fig. 2a, 6, and 7. The diameter of the driving wheels (Fig. 2a, 4) was selected as 314 mm in order to achieve a frequency of 50 Hz at a water speed of approximately 1 m/s, which is a rounded value in the metric system.

The floating turbine on the water consists of several components:
– Mechanical paddles (Fig. 2a – 8) – Chain track (Fig. 2a – 4) – Speed multiplier (Fig. 2a – 6) – Floating body (Fig. 2b)

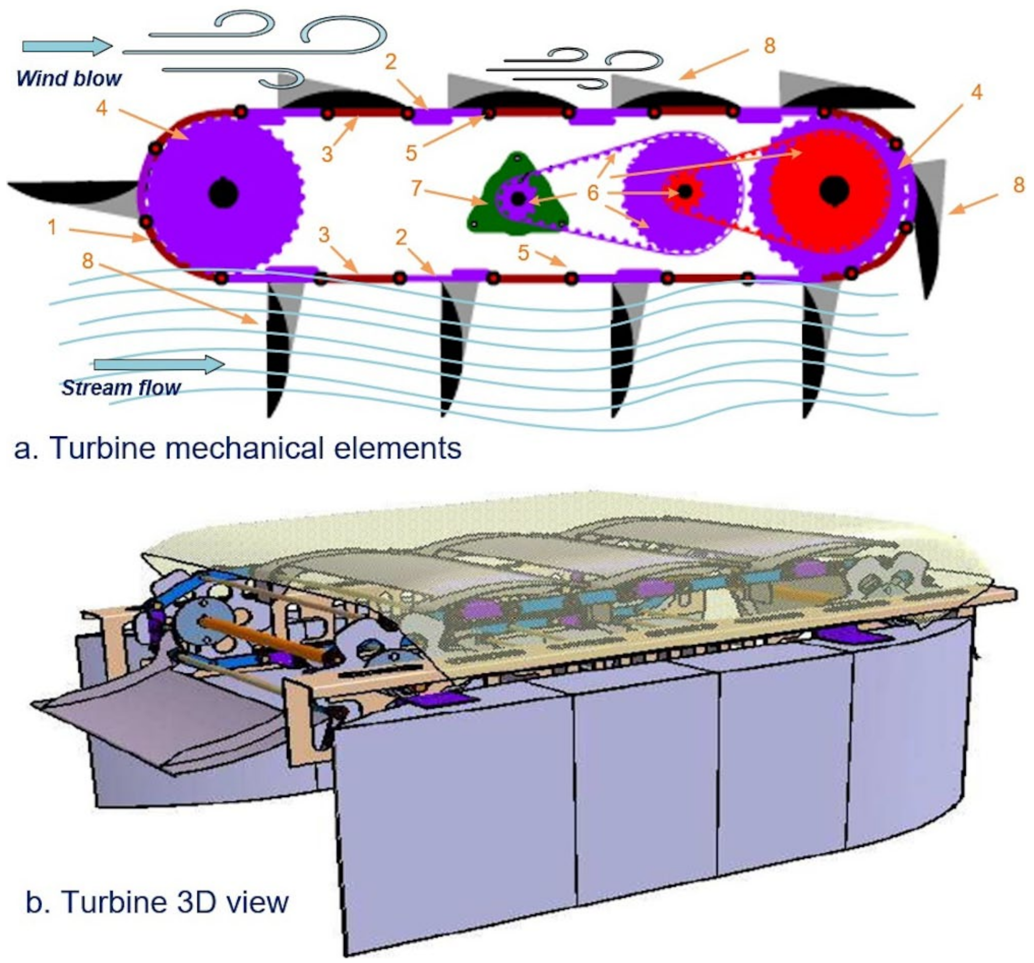

Fig. 2. Hydroelectric turbine linearly developed along the river streamline

– Three-phase electric generator with permanent magnets (Fig. 2a – 7 and Fig. 3b)

When the paddles arrive on the upper section of the installation, they horizontally fold to prevent air currents, which flow in the same direction as the river, from creating resistance. Therefore, the mechanical work is significantly optimized.

Furthermore, the electronic part is situated within the electronic turbine, which incorporates the subsequent component blocks:

– The rectifier block, as shown in Fig. 3c, comprises: A three-phase bridge rectifier, filter, and converter that transforms a sinusoidal signal into a rectangular signal.
– The data acquisition system for generator voltage and frequency, called Embedded System 1 (ES1), is depicted in Fig. 3d. It comprises Microcontroller 1 (MCU1), a UART radio transceiver operating at a frequency of 433 MHz, and a NiMH 3.6 V battery. The electrical consumers depicted in Fig. 3e establish a connection between the power generated by the turbine and the shore.

The objective of Embedded System 1 is to locally measure the electrical parameters generated by the turbine.

ES1 transmits these electrical characteristics to the shore through ES2 in Fig. 3f. ES2 then transfers them to a computer via the USB connector in Fig. 3g.

An embedded system utilizes a fusion of electronic components, computer hardware, and software. The electronic system serves as an intermediary between computer software and its hardware components. The computer program is integrated into computer hardware, serving as a controller that facilitates communication between them [4].

2.1. Offshore Unit – Rectifier Block

In Fig. 4, the three-phase generator is directly connected to the input of the rectifier block. The rectifier block consists of a three-phase rectifier bridge made by D1, D2, D3, D4, D5, and D6, which are connected to the connectors R, S, T. The rectifier

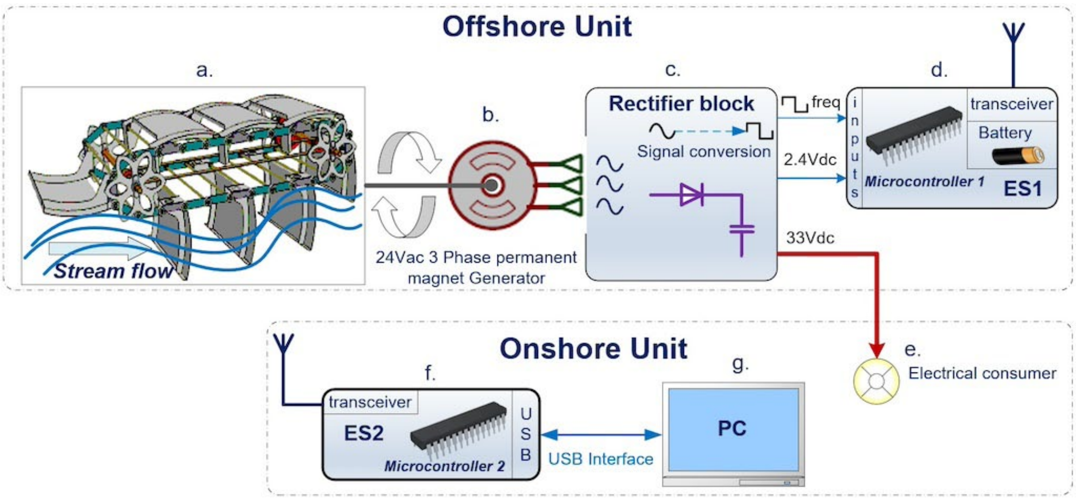

Fig. 3. Acquisition data system for a hydro-electrical turbine

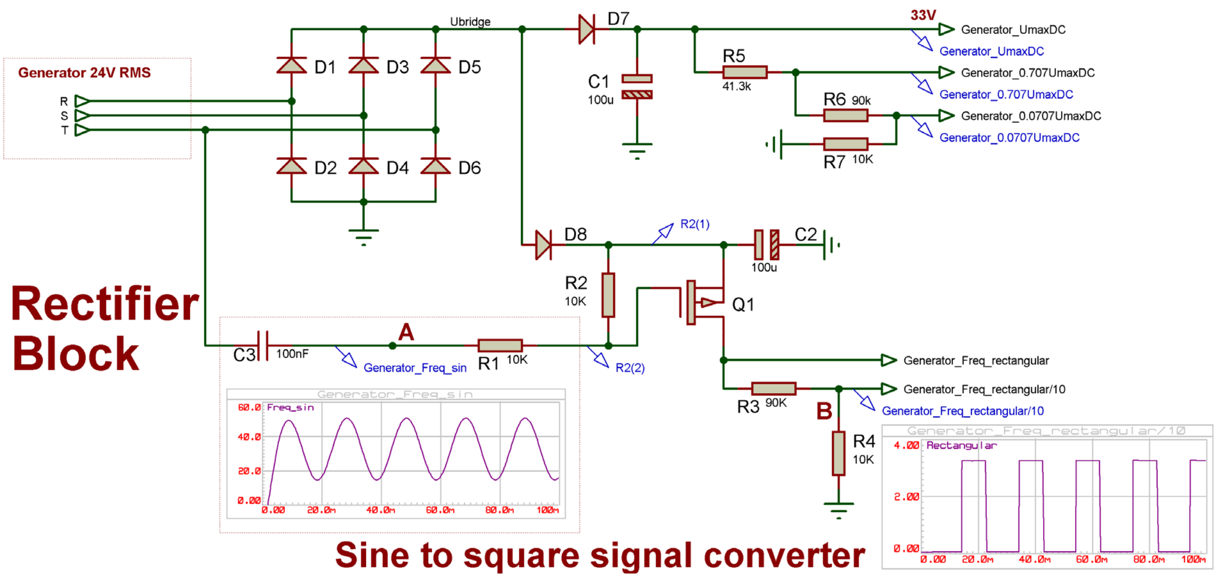

Fig. 4. Rectifier Block

block comprises a filter (C1), a continuous signal attenuator (R5, R6, R7), and a sinusoidal signal to rectangular signal converter (C3, R1, R2, Q1, C2, R3, R4).

After passing through filter C1, the voltage "*Generator_UmaxDC*" can be determined using Eq. (1) at the nominal voltage of 24V RMS of the three-phase generator.

$$Generator\_UmaxDC = \sqrt{2} \cdot 24V - V_{fD7} \quad (1)$$

$$V_{fD7} = Forward\ Voltage\ of\ D7 \approx 0.9\ \text{V} \quad (2)$$

The nominal value of "*Generator_UmaxDC*" obtained by substituting the value from Eq. (2) into Eq. (1) is approximately 33 V.

The resistors R5, R6, and R7 function to decrease the voltage of the "*Generator_UmaxDC*" by 0.0707 in order to make it suitable for use with the embedded ES1 data acquisition device. The point "*Generator_0.707UmaxDC*" has a continuous voltage comparable to 24 V RMS. In order to be eligible for acquisition, it had to be reduced by a factor of 10. At the point in the diagram "*Generator_0.0707UmaxDC*", there is a constant voltage of 2.4 V. The voltage will then be utilized in the acquisition mechanism of ES1, as shown in Fig. 5.

The generator's frequency was determined by transforming it into a rectangular signal. The sinusoidal signal is converted into a rectangular signal by the components C3, R1, R2, Q1, and C2. This conversion occurs specifically on phase T of the generator. The rectangular pulses encountered a ten-time decrease in amplitude due to the resistive divider R3 R4, in preparation for their subsequent acquisition by ES1. The amplitude at the position "*Generator_Freq_rectangular/10*" in Fig. 4 is 2.4 V. The signal is passed to the ES1 system's input stage in Fig. 5 for processing.

2.2. Offshore Unit – Embedded systems 1

Both Embedded System 1 (ES1) and Embedded System 2 (ES2 shown in Fig. 6) utilize a MICROCHIP microcontroller, specifically the PIC18F2550 [5], as their fundamental component. The operational frequency of the microcontroller MCU1 seen in Fig. 5 is 20 MHz.

The hardware resources utilized by MCU1 include an ADC converter, timers 0 and 3, and a UART asynchronous serial interface.

The ADC converter is set to its highest resolution of 10 bits, and only 2 out of the 10 available acquisition channels are utilized. Specifically, AN1 is used to measure the voltage of the electric generator, while AN0 is used to measure the voltage level of the supply battery for MC1.

Out of the four timers in MCU1, Timer 0 is set up as a counter, whereas Timer 3 is utilized as a 1-second time base for measuring frequency. The UART asynchronous serial interface is set to a baud rate of 19200 for communication with the radio transceiver.

The transceiver involved is the HM-TRS433 model manufactured by HOPERF [6].

2.3. Onshore Unit – Embedded systems 2

The ES2 serves as a communication interface connecting the PC computer with the ES1 embedded devices, as seen in Fig. 6.

The microcontroller adopted is the PIC18F2550. The hardware resources utilized by ES2 include the USB interface and the UART asynchronous serial interface.

The ES2 device establishes a connection with the PC using the USB port, and communication between both devices is facilitated through 8-byte data packets. The ES1 is connected to the transceiver using the UART interface, and communication is established using 5-byte data packets.

Benefit from the USB interface of MCU1 establish the CPU's operating frequency at 48 MHz. Despite the usage of a 20 MHz quartz crystal, the oscillator with the engaged PLL function increases the operational frequency of MCU2 to 48 MHz. Fig. 7 displays the circuit diagram for ES2.

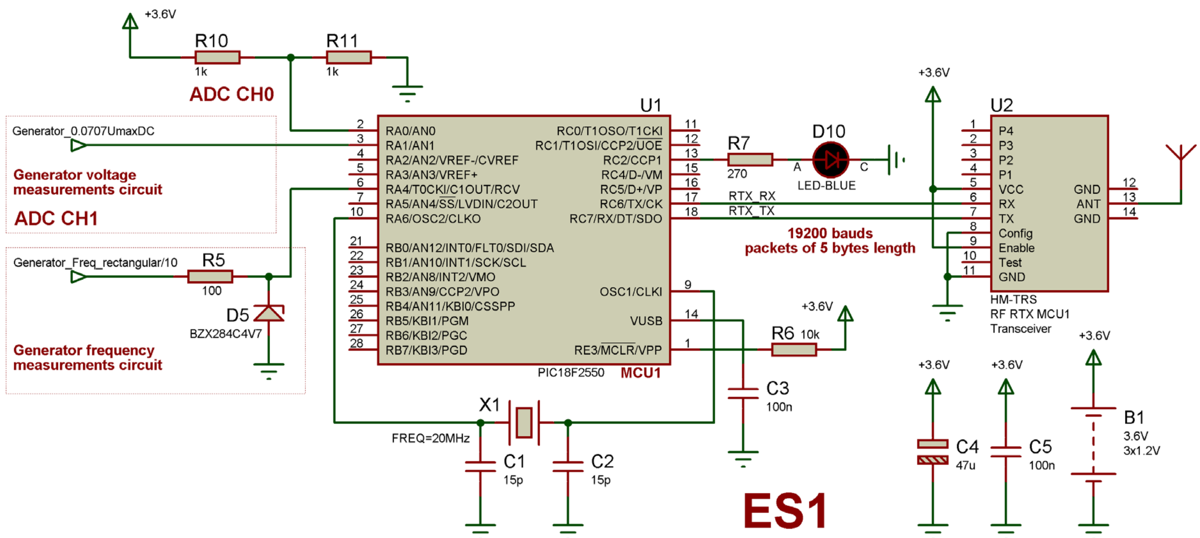

Fig. 5. Embedded System 1

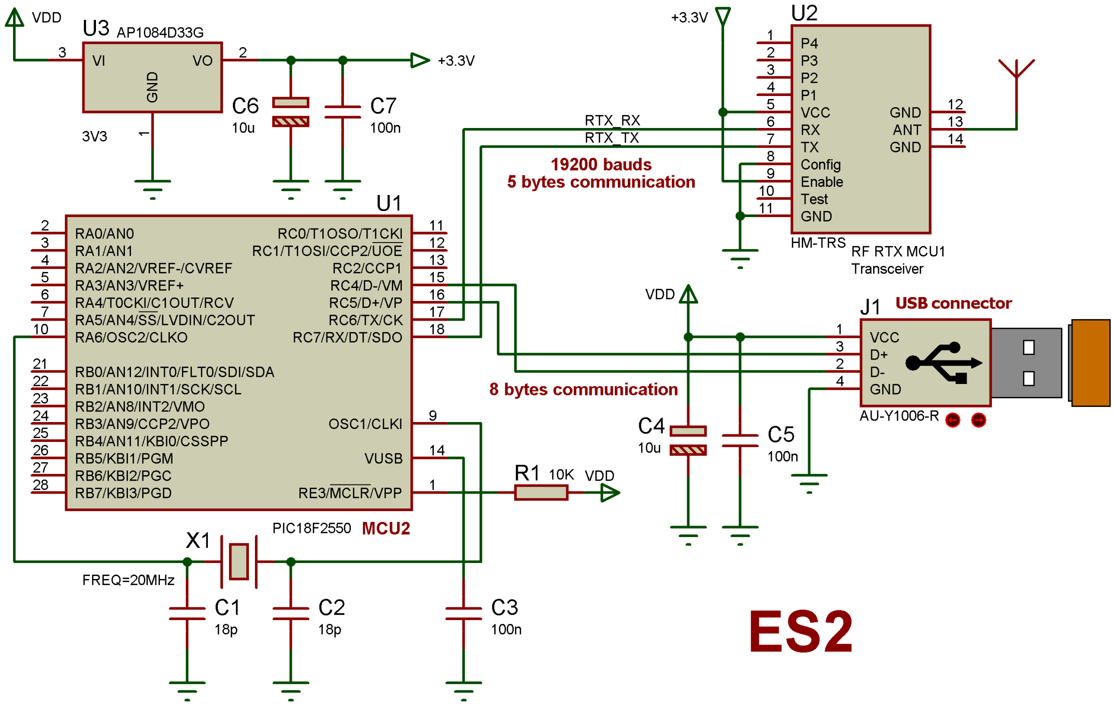

Fig. 7. Embedded System 2

The communication speed between MCU2 and Transceiver U2 is set at a rate of 19200 baud. The PC, equipped with the Windows operating system (Windows 7, 10, 11), is using the associated software to oversee and regulate the electrical measurements conducted by ES1. This is achieved by utilizing the ES2 system as a wireless transmission relay.

3. Communication protocol

The communication between the two embedded systems, ES1 and ES2, is conducted wirelessly using FSK technology at a frequency of 433 MHz. The transmission is half duplex and employs UART at a baud rate of 19200. The maximum distance across which the communication can take place is 200 meters in an open space environment. The computer and ES2 communicate using 8-byte data packets through the USB interface, while ES2 and ES1 communicate using 5-byte data packets wirelessly, as shown in Fig. 6.

The "*WinUSB*" driver developed by Microsoft was installed to establish the connection between the computer monitoring application and the USB port [7].

According to the information provided in Fig. 8, the initial two bytes (#0, #1) in the communication between the computer and ES2 are specifically allocated for USB commands (referred to as control bytes). The subsequent five bytes (#2…#6) are used to transmit commands to ES1. The final byte (#7) is not utilized and is reserved for future usage.

More details regarding the communication processes can be found in the authors' study in [8] for the same patent "Hydroelectric turbine linearly developed along the river streamline".

Message requested from PC	Communication direction	PC -> USB -> ES2 (8 bytes)							
		Message 1							
	Byte nr.	#0	#1	#2	#3	#4	#5	#6	#7
	Byte value	0x11	0x0B	0x11	0x05	CH	0x00	0x00	0x00
		USB cmd		Commands for ES1					
Response message to PC	Communication direction	PC <- USB <- ES2 (8 bytes)							
		Message 4							
	Byte value	0x51	0x0B	0x51	0x05	CH	MSB	LSB	0x00

Communication direction	ES2 -> wireless -> ES1 (5 bytes)				
	Message 2				
Byte nr.	#0	#1	#2	#3	#4
Byte value	0x11	0x05	CH	0x00	0x00
	The voltage is being measured on ES1				
Communication direction	ES2 <- wireless <- ES1 (5 bytes)				
	Message 3				
Byte value	0x51	0x05	CH	MSB	LSB

Fig. 8. Communication protocol

3.1. Voltage and frequency measurement from turbine

In order to determine the voltage on the CH channel (input AN1 in MCU1 as shown in Fig. 5), the PC computer transmits the command "0×11 0×0B 0×11 0×05 0×01 0×00 0×00 0×00" (Message No. 1.1 from TABLE 1) to ES2 via USB. ES2 wirelessly transmits the command "0×11 0×05 0×01 0×00 0×00" which corresponds to Message No. 1.2 from TABLE 1.

ES1 gets the request and carries out the voltage measurement on pin 3 "AN1" of U1 (MCU1), which is acquisition channel 1, as depicted in Fig. 5. The voltage on AN1 is "*Generator_0.0707UmaxDC*" originating from the rectifier block shown in figure 4. The value of "*Generator_0.707UmaxDC*" is decreased by a factor of k = 10 in order to safeguard the input to ES1 from excessive voltage. When the generator is operating at its standard alternating voltage of 24 Vac RMS, the voltage at the "*Generator_0.0707UmaxDC*" point is 2.4 Vdc. The voltage fluctuates over time due to the varying water flow in the river. At a specific instance, a voltage of 1.898 V (18.98 V from the generator) is supplied to input 1 (CH = 1) of the ADC converter (Analog to Digital Converter) in the microcontroller MCU1. The ADC conversion has a resolution of 10 bits, meaning that each bit represents a voltage value of 0.0037 V (Q = 0.0037 V).

$$V_{ADC} = \frac{V_{IN}}{Q} = \frac{1.898}{0.0037} = 512.972 = 0 \times 201 \quad (3)$$

Using Eq. (3), the input voltage of 1.898 V corresponds to a numerical value of 0×201. Due to the communication protocol's requirement of 5 packets, each consisting of 8 bits, the result of the analog-to-digital conversion in equation (Eq. (3)) was divided into 2 packets of 8 bits (2 bytes) in equation (Eq. (4)) to facilitate transmission.

$$0 \times 201 = (0 \times 02 \cdot 0 \times 100) + 0 \times 01 \quad (4)$$

$$0 \times 02 = MB,\ 0 \times 01 = LB \quad (5)$$

The formula (Eq. (5)) yields two values: the Most Significant Byte (MB) and the Last Significant Byte (LB). ES1's reply to ES2's request "0×11 0×05 0×01 0×00 0×00" in Message No. 1.2 from TABLE 1 is "0×51 0×05 0×01 0×02 0×01" as seen in Message No. 1.3 from TABLE 1. The ES2 device receives this data packet consisting of 5 bytes. It changes this packet into a new packet with 8 bytes, specifically Message No. 1.4 from TABLE 1. The ES2 device communicates this new packet to the PC using the USB interface. The purpose of this transfer serves to allow the data to be evaluated by the monitoring software installed on the PC.

In order to determine the frequency, Timer 0 and Timer 3 are utilized among the four timers of MCU1 as shown in Fig. 5. Timer 0 is set up in counter mode. The content of Timer 0 grows with each pulse received from the sinusoidal signal to rectangle signal converter shown in Fig. 4, which is then inputted to the T0CKI input (pin 6 of MCU1). Timer 3 serves as the time base for one-second intervals. Timer 3 generates an event every second. During this event, the value of Timer 0, which is set up as a counter, is read. After reading the value, Timer 0 is reset to 0. The outcome is subsequently retained in memory until the following second. The acquired value corresponds to the frequency of the signal that is applied to the input of Timer 0 counter. The method for reading the frequency is indicated in Message Nr. 2.1, 2.2, 2.3, 2.4 from TABLE 1, and the voltage measurements are obtained in a similar manner.

4. Data obtained using the graphical user interface and discussion

The monitoring software comprises two functional blocks: the data acquisition request block and the data receipt and analysis block. Fig. 9 depicts the graphical user interface.

The data acquisition request is initiated within a loop, occurring at regular intervals of 500 milliseconds, to capture the voltage and frequency measurements of the generator. TABLE 2 (line numbers 1.1, 2.1, 3.1 and 4.1) provide an illustration of the initial four requests in the data collecting process.

The data reception and analysis module receive messages from the USB, performs processing on them, and subsequently presents them on the graphical user interface. The responses obtained from the turbine are provided in TABLE 2, specifically in rows 1.2, 2.2, 3.2 and 4.2. The software employed a graphical interface to facilitate the transfer of data obtained from the turbine to the personal computer. The data is presented on the graphical interface in both numerical and graphical formats, and subsequently exported to Excel files for additional analysis. Fig. 10a

TABLE 1

Commands used for communication between PC and ES1

Message Nr	Message description	Message name	Direction	Command frame							
				#0	#1	#2	#3	#4	#5	#6	#7
1.1	Read analog value from turbine (ES1)	MCU1 RD Analog	PC –> ES2	11	0B	11	**05**	CH	00	00	00
1.2			ES2 –> ES1	11	05	**CH**	00	00			
1.3			ES2 <– ES1	51	05	**CH**	**MB**	**LB**			
1.4			PC <– ES2	51	0B	51	**05**	**CH**	**MB**	**LB**	00
2.1	Read frequency from the turbine (ES1)	MCU1 RD Timer	PC –> ES2	31	0B	31	**13**	00	00	00	00
2.2			ES2 –> ES1	31	**13**	00	00	00			
2.3			ES2 <– ES1	71	**13**	00	**MB**	**LB**			
2.4			PC <– ES2	71	0B	71	**13**	00	**MB**	**LB**	00

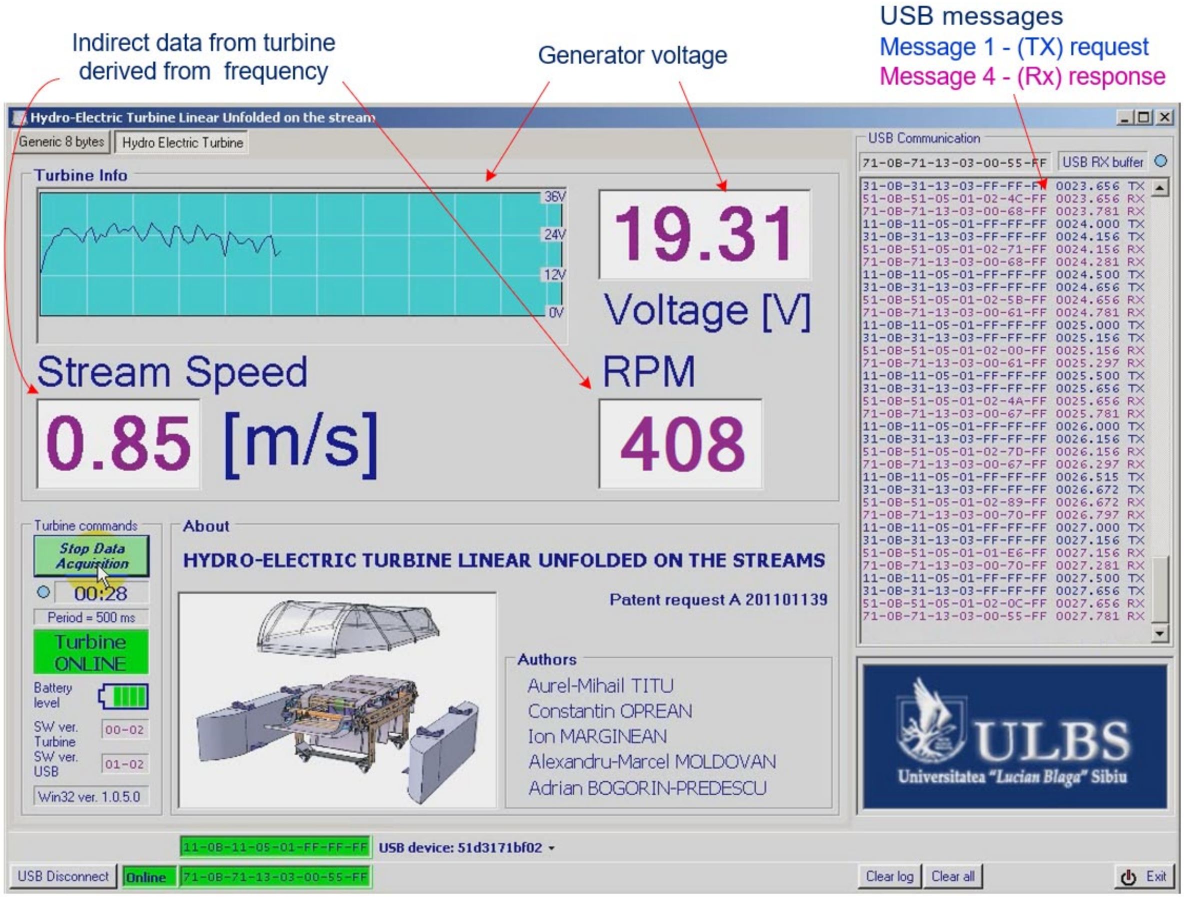

Fig. 9. PC Software monitor [9]

TABLE 2

Acquisition timeline request/response from PC to Turbine

Message Nr	Time Stamp [s]	Message description	Direction	Command frame							
				#0	#1	#2	#3	#4	#5	#6	#7
1.1	0.00	Read analog value from turbine	PC –> ES2	11	0B	11	05	01	00	00	00
1.2	0.05		PC <– ES2	51	0B	51	05	01	02	01	00
2.1	0.10	Read frequency from the turbine	PC –> ES2	31	0B	31	13	00	00	00	00
2.2	0.15		PC <– ES2	71	0B	71	13	00	00	68	00
3.1	0.50	Read analog value from turbine	PC –> ES2	11	0B	11	05	01	00	00	00
3.2	0.55		PC <– ES2	51	0B	51	05	01	02	4C	00
4.3	0.60	Read frequency from the turbine	PC –> ES2	31	0B	31	13	00	00	00	00
4.4	0.65		PC <– ES2	71	0B	71	13	00	00	68	00

depicts the progression of the frequency parameter from the turbine, whereas Fig. 10b illustrates the direct voltage obtained by the conversion of the alternating voltage from the turbine.

The high accuracy of the data capture ensured that the reproduction included the exact fluctuations in speed and voltage as each blade entered the water.

The speed of the flowing water, which moves the turbine blades and generates load, can be indirectly determined based on the collected frequency. This is computed using Eq. (6).

$$v = \frac{n}{k \cdot 60} \tag{6}$$

$$f = \frac{n \cdot p}{60} \tag{7}$$

Where: v – stream speed [m/s]; k – 8× turbine multiplication ratio; n – generator shaft speed; f – generator frequency; p – number of pole pairs of the generator (6 from the manufacturing data).

Applying Eq. (7) in Eq. (6) results Eq. (8):

$$v = \frac{\frac{f \cdot 60}{p}}{k \cdot 60} = \frac{f \cdot 10}{8 \cdot 60} = f \cdot 0.020833 \tag{8}$$

According to Eq. (8), the turbine blades are moved by a water flow speed of 1.04 m/s when the generator operates at its nominal speed, which is equivalent to a frequency of 50 Hz. The speed of the water was determined indirectly based on the frequency of the generator. The significance of long-range wire-

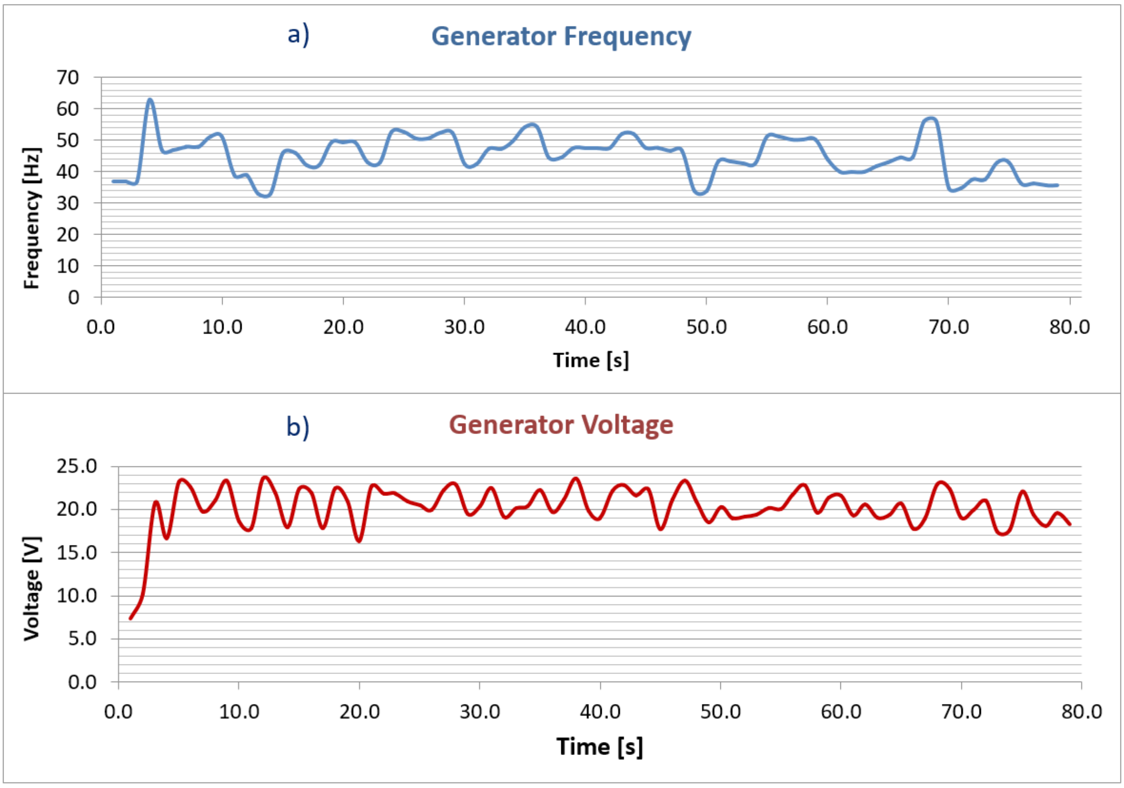

Fig. 10. Experimental data

less data transmission is evident in its ability to precisely show real-time information on a computer, such as the instantaneous velocity of the water that propels turbine blades.

5. Conclusions

The conducted experiments have conclusively shown that by utilizing remote data transmission and computer processing, it is possible to accurately, numerically, and effortlessly determine the optimal location for the hydroelectric generator along the river. This is done in order to achieve the highest possible efficiency in converting the kinetic energy of the water into electrical energy.

During the testing conducted on the Cibin river in Sibiu, Romania, a series grouping of three 1.2 V NiMH accumulators was employed as the power supply source for MC1. The selection of this method was not influenced by the amount of energy provided by the turbine. The purpose was to ensure that ES1 can still respond to commands even if the generator does not produce electricity at particular periods during the water course location tests. Due to the battery's discharge throughout the testing, it is required to recharge it periodically. In order to accomplish this, the ES1 must be outfitted with a battery charging mechanism that is powered by the generator itself.

The system enables remote monitoring of hydrodynamic and electrical parameters, which is crucial for locations that are difficult to access. Data is transmitted wirelessly from the turbine to a receiver on the shore, allowing real-time processing and display on a computer monitor. The system can be used to generate electricity from the kinetic energy of flowing water, providing a renewable energy source for both rural and urban areas and can monitor environmental parameters such as water flow speed and temperature, aiding in ecological studies and conservation efforts. It is ideal for remote and rural areas where traditional power infrastructure is lacking, providing a sustainable and cost-effective energy solution.

In paper [10], the authors describe a gravitational water vortex hydro turbine system, that uses vortex dynamics to generate power, suitable for remote and rural areas due to their small scale and low cost. The advantages of that solution are high efficiency in low-flow conditions, minimal environmental impact, and cost-effective implementation, but the disadvantages are limited power output compared to larger hydroelectric systems.

Another solution is described in [11], which uses the Archimedes screw principle to convert kinetic energy of water into mechanical energy, having the advantages of high efficiency, low maintenance, and minimal harm to aquatic life, but with the disadvantage that it requires specific installation conditions and may not be suitable for all river types.

Compared to the two examples from [10] and [11], the system proposed in this paper operates in rivers with low flow speeds and does not require a difference in water levels, making it suitable for a wide range of environments. The floating design and use of mechanical paddles minimize harm to aquatic life compared to traditional turbines. The system uses cost-effective hardware and robust microcontroller programming, making it accessible for small-scale implementations. The wireless data transmission and real-time processing capabilities allow for timely decision-making and optimization of turbine placement and operation. By comparing the proposed system to other solutions, the authors can highlight its unique advantages and potential applications, emphasizing its contribution to sustainable and efficient hydroelectric power generation.

Despite the cost-effective of the hardware system used for data capture and transmission, the project is intricate. However, it makes up for this complexity with the effective communication protocol and the robust microcontroller programming, which enables it to carry out frequency and voltage measurements. In a time when the market is influenced by the capabilities of processing power and hardware resources, remarkable accomplishments can still be made with older generation embedded systems that rely on obsolete, 8-bit computing architectures.

These principles align with [12], where the authors advocate for the use of microcontrollers that are appropriate for the specific project in terms of hardware processing resources. In other words, don't waste resources!

Standard 8-bit microcontrollers are still capable of performing common tasks.

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