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THE POSSIBILITIES OF A MULTIFUNCTIONAL CONTROL AND MEASURE-MENT SYSTEM INSTALLED IN A SMALL HYDROPOWER PLANT

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ABSTRACT

In 2020, a fully automated hydropower plant was launched on the Guber River near the town of Kotkowo. The plant is operated by a master control and measurement system, which collects data to evaluate the operation of selected systems of the facility. The number and location of sensors controlling the parameters of hydroelectric systems are selected accordingly, to collect complete information from all sensors and analyze the operation of hydroelectric systems in real time. In addition, storing all the controlled parameters allows analyzing the plant's operation over longer periods. This work presents the possibilities of this measurement system, as well as the measurement results obtained in the tested object. Analyzing the operation of the control and measurement system as well as the collected and archived data will be the foundation for a simulation model of a hydropower plant. The model will be helpful in optimizing the operation of existing hydroelectric plants in terms of energy production per unit volume of water, and in designing new ones on existing barrage.

Introduction

In today's world, the demand for energy is constantly growing, and energy production in conventional power plants is becoming more and more expensive, which affects the national economy. Therefore, searching for new solutions for the production of RES energy becomes necessary. The EU directives significantly emphasize this issue (Pavlova-Marciniak, 2014).

One of the most stable, yet underrated RES in Poland is hydroelectric power, especially from small hydropower plants. Poland has a large, unused hydropower potential of rivers. Currently, 766 hydropower plants operate in our country (Ewa Malicka, 2018), of which 752 are the so-called small hydropower plants (SHP), i.e. facilities with an installed capacity of up to 5 (MW) (ERO, 2017). Considering the hydropower potential of Poland's rivers, hydropower plants use only 19% of it. In this respect, Poland holds one of the lowest rankings in Europe. The conditions for the development of hydropower generation, especially the low-scale, are confirmed by the RESTOR Hydro database published in June 2015, containing data on the potential locations of SHP in Europe. In the case of Poland, it is over 6,000 locations.

Hydropower plants use the potential and kinetic energy of the river to generate electric power (Rok, 2008). The water propels a turbine connected to a generator, which generates the power (Hoffmann et al., 1992). The main problems limiting the development of the energy use of low headlands in our rivers include: a negative impact on the water ecosystem and the high unit cost of the investment compared to a conventional power plant. By using special structures to ensure the migration of aquatic organisms, e.g. fish ladders or barriers (Wierzbicki, 2013), hydropower plants generate non-emission power at a high efficiency factor. These systems are still under development as the balance between economic and ecological factors is currently difficult to achieve (Bednarska, 2010).

Due to the constant technological progress and changing hydrological conditions in Poland, hydropower plants have a great potential for the development and optimization of energy production per unit volume of water. The optimization of an already existing small hydropower plant requires a range of critical information related to the watercourse leveraged by the plant, as well as to the operation of individual components (hydraulic systems, hydro unit, power installation). A universal research system should enable the collection, preliminary analysis and storage of the critical operational information over many years (Sołowiej, Neugebauer, 2008).

This type of measurement system is the first step towards improving the existing design and control methods for individual small hydropower plant systems. In order to properly design a hydropower plant and its accompanying elements, such as a weir or a fish ladder, the designer must have access to long-term measurement data of the river's characteristic parameters. However, in many cases, hydropower plants are designed based on inaccurate or approximated estimates, and the selection of equipment itself is performed without a prepared work plan for such a plant. The effects of the operation of the hydropower plant, the shape of the waterway, etc. on the water levels upstream and downstream of the plant are often not taken into account. These levels affect the river's effective slope, which proportionally affects the amount of power generated per unit volume of flowing water. This is closely related to the efficiency of the hydropower plant operation.

This article describes the measurement system installed in a small hydropower plant in the town of Kotkowo in the Warińsko-Mazurskie Province and the results of sample measurements made between June and August 2020. This system is the first step towards identifying all parameters necessary to optimize the operation of a small hydropower plant.

Description of the test object

The measurement system was designed for the needs of a fully automated small hydropower plant located in the town of Kotkowo in the Warińsko-Mazurskie Province. It is a low-slope hydropower plant on the Guber River, the right tributary of the Łyna River. The plant is equipped with an Archimedean turbine, planetary gearbox, generator with a rated power of 90 (kW), two side discharge sliders, a fish ladder, an inlet gate valve, engine room and control room. The engine room houses the hydraulic system, planetary gearbox, top turbine bearing, belt drive and generator. In the control room there is an inverter, a measurement system, an alarm system and a control system.

The generator with a rated power of 90 (kW) allows the use of over 3 ($m^3 \cdot s^{-1}$) water for power generation. An atypical and innovative solution is the use of two possible modes of operation of the generation system. The generator can be connected to the grid directly, or via an inverter located in the control room. The inverter connection allows adjusting the rotational speed of the generator, and thus to regulate the amount of water used for power generation. This solution enables controlling the upper water level and rationalize power production.

The Guber River, where the plant is located, has a maximum upper water level of 54 m, and the lower water level of 50.4 m, which gives the maximum difference in levels of 3.6 m. During the operation of the plant, this difference decreases effectively to 3 m with the use of the inverter, and during a direct start-up, using the power grid, it can decrease even to 2.3 m, which adversely affects power generation. According to perennial river measurements, the flow at this point is 0.8-4.5 $m^3 \cdot s^{-1}$. The average annual flow is approx. 3 $m^3 \cdot s^{-1}$.

An Archimedean turbine was used for the generation system due to the low effective drop (2.3-3 m). The turbine is mounted on a single frame, together with the engine room, which includes a clutch, bearing, as well as planetary and belt gearboxes. These gears made it possible to transmit the rotational speed of the turbine, from 25 rpm to 1500 rpm of the generator.

The Archimedean turbine is one of the latest innovations in hydropower generation. Particular attention is paid to the greater ecological potential of the turbine since fish can safely migrate downstream due to its low rotational speed (Renewables First). It also has a high operating range. The Archimedean turbine can work at low water levels as well as low-percentage flows (Lashofer et al., 2012). It has a relatively high efficiency, at 74-92%, depending on the information provided by the manufacturer.

The measurement system includes sensors that control the position of the brake, the inlet slide, side discharge sliders, the turbine, water levels, rotational speed, nominal and electric power, as well as temperature. The sensors provide complete information on the condition of the hydropower plant and are necessary for monitoring its operation.

The executor also includes a hydraulic system with actuators that open the inlet slide and the closing flap of the engine room, as well as regulate the turbine's working angle and control the brake. The loss of voltage in the hydraulic system control causes the inlet flap to immediately close and the hydropower plant to shut down.

The measurement system

The measurement system consists of the hydropower plant's measurement unit, a communication system with a SCADA server and a remote access system using VPN technology.

The measurement unit

The measuring unit (Figure 1) is equipped with a Virtual Private Network (VPN) modem Ursalink UR55, a FX5U Mitsubishi controller, two DIx8 digital input modules, two analog input modules, for power and temperature, two T3000-5-A4-0.25-T-10 hydrostatic probes, nine E2B-M12KS04-M1-B1 inductive sensors, a PAC3200 network parameters analyzer, three PT100 temperature sensors, a Linux OS computer with Supervisory Control And Data Acquisition (SCADA) software, three 200/5 (A/A) current transformers, a 24 (VDC) power supply and B6 overcurrent protection.

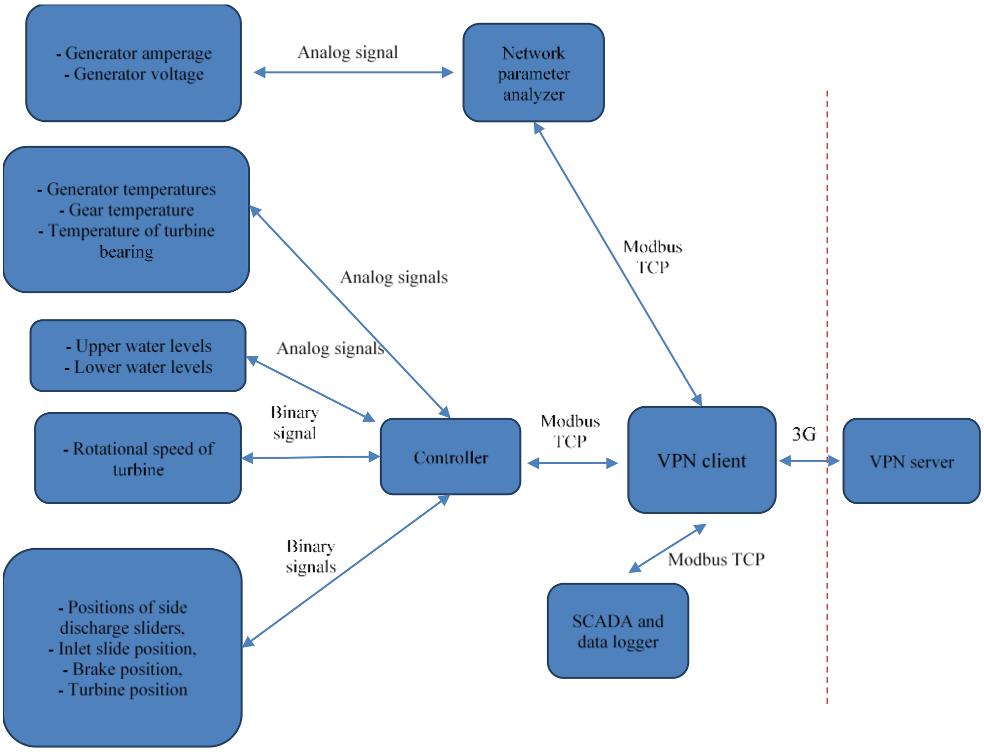

Figure 1. Block diagram of the measurement unit in the hydropower plant in Kotkowo

Hydrostatic probes T3000-5-A4-0.25-T-10 provide measurements of the upper water levels in front of the plant, and the lower water level behind the plant. Due to their structure, the probes are characterized by high measurement accuracy (class 0.35 is standard), low interference impact, easy scalability and a broad measurement range.

The E2B-M12KS04-M1-B1 inductive sensor was used to measure the turbine rotational speed. These sensors are usually mounted on a structure near the turbine shaft, so that the turbine revolutions can be counted based on a control indicator. Moreover, inductive sensors used in the discussed system provide information about the position of the side discharge sliders, the inlet slide, the turbine and the turbine shaft brake.

The network parameter analyzer is designed to measure and record changes in the plant's power and the amount of electric power it generates. In addition, the analyzer determines and records parameters such as: Total Harmonic Distortion (THD, as well as indexes related to power generation, currents and voltages.

Communication systems

The test system is equipped with two communication systems: master and slave. External communication is designed to allow remote access to measurement data, while internal communication is used to collect data on a computer with a SCADA system. Internal communication uses a communication protocol based on the master-slave Modbus TCP transmission. Data is collected in the controller and then sent to a SCADA system for storage and analysis. The structure of the master communication system is shown in Figure 2.

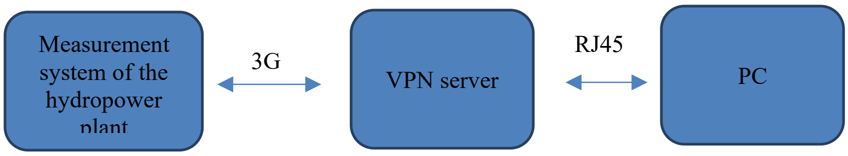

Figure 2. The structure of the master communication system

The system consists of a measurement unit that connects to the internet via wireless technology (GSM, LTE, 3G, 4G, etc.) and a VPN server with a static IP. Each of the measurement systems connects to the server by opening the encrypted VPN subnetwork tunnel, which allows secure transmission of encrypted data. The server allows connecting a significant number of individual measurement systems via VPN.

SCADA and remote access

The SCADA system is used to supervise the process of power generation in the tested hydropower plant. Its main functions are:
- collecting data,
- visualizing the course of the power production process and basic operating parameters,
- controlling the production process,
- alerting,
- storing the historical data.

With a computer connected to the VPN server, the operator can log into a computer with a SCADA system, which visualizes operating data and production parameters and stores them (Figure 3). In addition, this system allows controlling selected functions of the plant.

The SCADA system allows recording both analog and digital data. The recorded analog values include:
- generator temperature,
- gear temperature,
- bearing temperature,
- rotational speed of turbine,
- power generated,
- electric power produced,
- upper water levels,
- lower water levels,
- grid voltage.

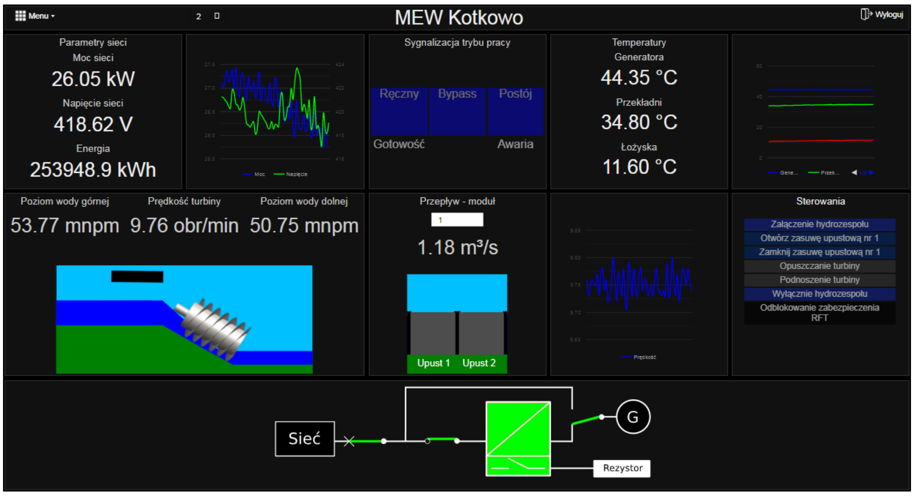

Figure 3. Screenshot of SCADA

All digital parameters (e.g. the positions of the side discharge slider, the intake slide and the brake) are recorded along with the time of their occurrence. This allows analyzing potential errors and failures.

Results for the Kotkowo hydropower plant

The implemented measurement system allows registering and extensively analyze all measured parameters in the selected periods. Selected results per daily work are presented below.

Figure 4. Examples of changes in the turbine rotational speed on July 17, 2020. presents changes in the rotational speed of the turbine on July 17, 2020. Chart analysis shows that the hydropower plant was started with the controller five times that day, with one attempt ending with an immediate shutdown of the plant.

The shutdown could be caused by vibrations affecting the inductive sensors responsible for identifying e.g. the position of the turbine brake. During each start-up, the plant was running at the minimum speed set on the inverter, i.e. 9.8 (rpm). This was caused by the river's low flow. The inverter controller automatically brought the speed to a minimum to keep the top water level as high as possible. After reaching the minimum water level, the plant was stopped, and water was collected during the standstill to raise the upper water level.

Figure 5 presents the readings from the lower water level sensor on July 17, 2020. As observed in the graph, the water level increased five times. This means one of two possibilities: either the plant was started, or that the water was discharged through the side slider at the time.

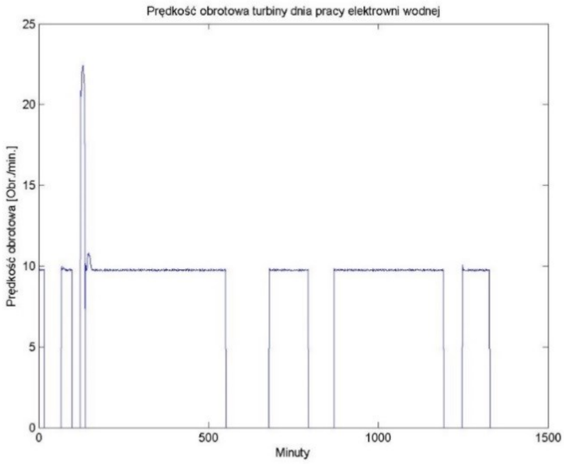

Figure 4. Examples of changes in the turbine rotational speed on July 17, 2020.

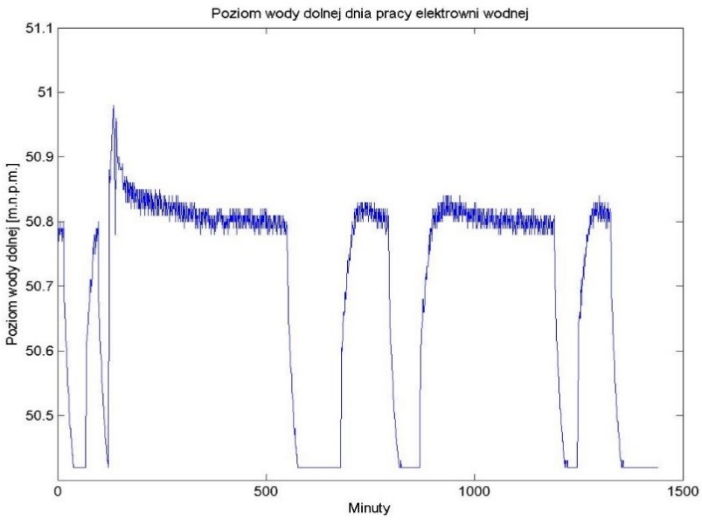

Figure 5. Changes in the lower water level on July 17, 2020.

The degree of the bottom water level build-up is directly dependent on the water flow, which is clearly visible in Figures 4 and 5. At high turbine speed, even short-term, a corresponding increase in the lower water level can be observed. At constant speed input, the graph seems to stabilize at 50.8 m above sea level, after which the plant is shut down.

The graph below presents the readings from the upper water level sensor on July 17, 2020. The stream flowing through the plant consists of water passing through weirs, the fish ladder and the turbine.

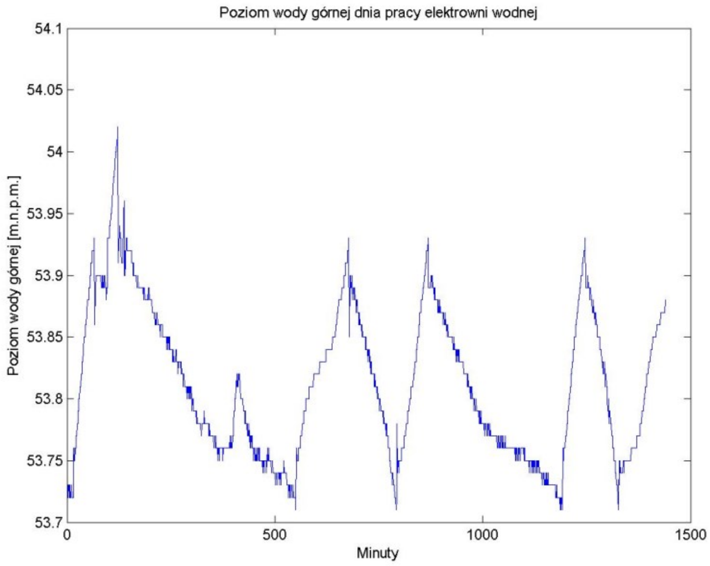

Figure 6. Examples of changes in the upper water level for July 17, 2020.

When the flowing water is higher than the incoming one, the drops can be clearly observed, and the build-up is observed when the plant is stopped. Variations in the graph can be the result of the set control parameters (e.g. turbine speed) or weather conditions (e.g. rain increasing the inflow stream).

The last chart (Figure 7) of July 17, 2020 demonstrates the changes in power generated on the output. The above diagram shows that this power correlates with the rotational speed of the turbine (Fig. 4) and, as in the case of the rotational speed of the turbine, the value of generated power grows progressively.

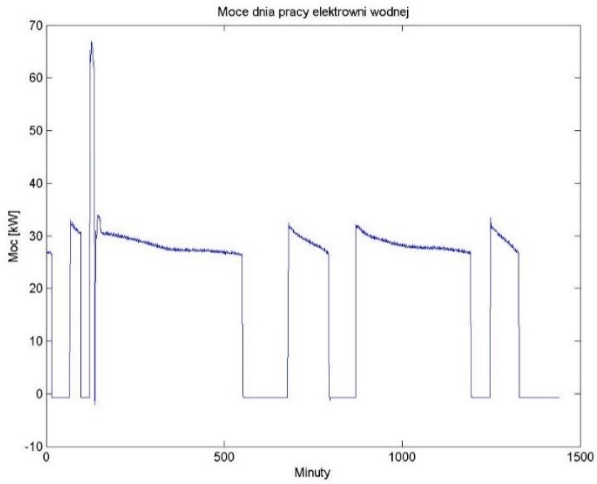

Figure 7. Examples of generated power value changes on July 17, 2020.

After a power jump, the generated power values slowly decrease under normal operating conditions. If the inverter is left energized after closing the water supply to the turbine, it will cause losses, as presented in the diagram: during standstill, generated power values were negative.

The system is designed to collect all necessary parameters within max. 4 months (Figure 8). The measurements are saved every minute. The system's capabilities enable a 24-hour data display.

Figure 8 shows changes in weekly generated power, starting from July 17, 2020. The plant started up thirty-two times during that week.

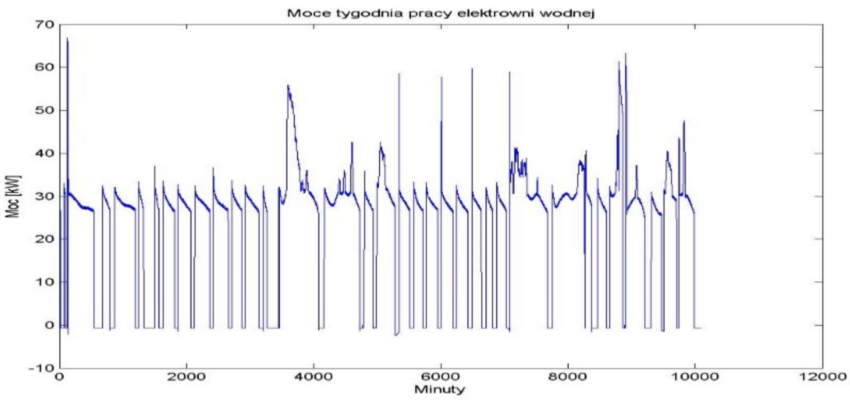

Figure 8. Exemplary weekly generated power changes from July 17, 2020.

There are visible generated power fluctuations resulting from changes in the amount of water flowing into the plant. Based on the frequency of start-ups and the length of the plant's operation, it is possible to determine the volume of water that flowed down the river on a given day.

The above Figure presents examples of changes in the turbine rotational speed for the working week starting on July 17, 2020. The dependence of the generated power on the rotational speed of the turbine can be observed here.

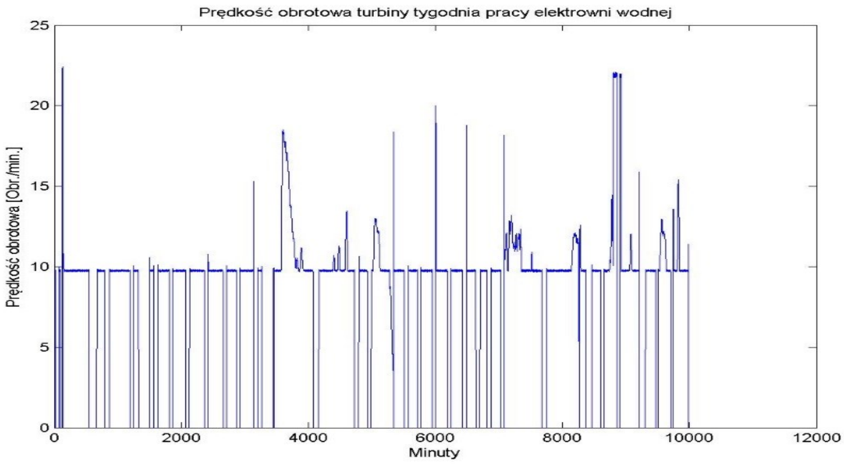

Figure 9. Examples of changes in the turbine rotational speed for a week, starting on July 17, 2020.

The lack of proportionality between power generation and the rotational speed of the turbine can be clearly observed, which means that the generated power is dependent not only on the rotational speed of the turbine.

Based on the results obtained in longer periods, it is possible to forecast a change in trends in the most important parameters of a hydropower plant's operation. It will be possible to define river flows in selected periods (spring, summer, autumn, winter, month, year). Moreover, the analysis of long-term data will allow to optimize the operation of the hydropower plant in terms of power production per unit volume of water flowing through it. Upon analyzing the changes in the power produced by the plant over a longer period (320 days – Figure 10) trends affecting power production can be observed. By comparing the changes in power generation with the changes in the river flow, the use of the flowing water's energy can be determined.

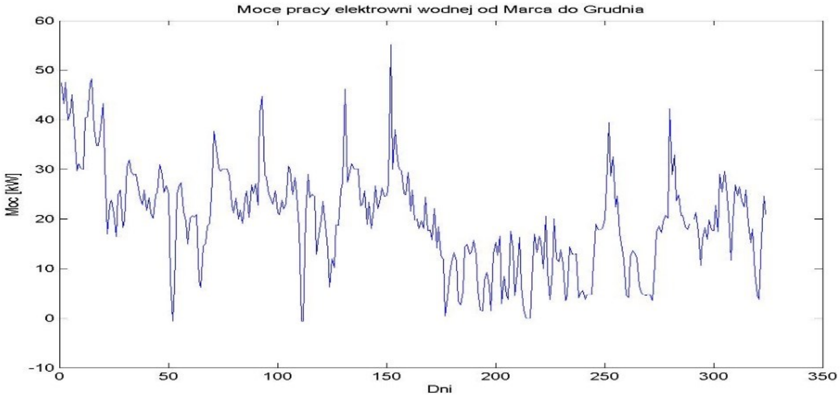

Figure 10. Changes in the average daily generated power from March 1 to December 16, 2020.

Conclusions

The research was conducted from June to August 2020. Even at the present stage of the research, correlation can be observed between such parameters as the rotational speed of the turbine, the generated power, the upper water level, and the lower water level. The dependence of the generated power on the rotational speed of the turbine is obvious (Figure 11). The diagram clearly presents that the change in rotational speed causes a proportional change in the generated power.

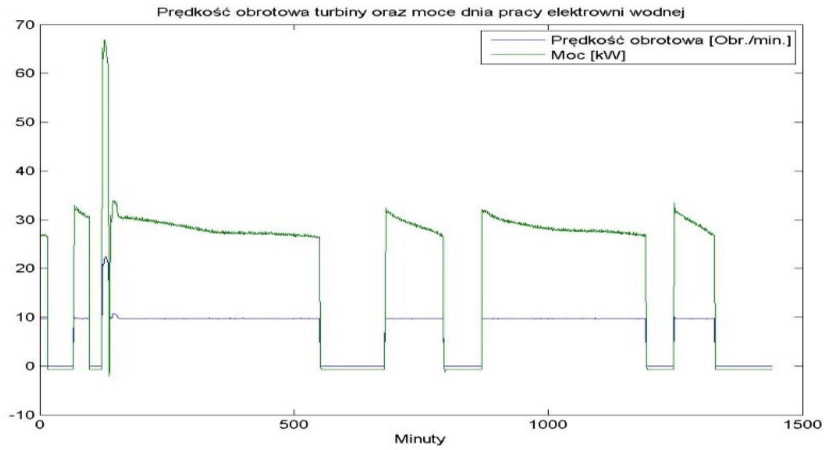

Figure 11. Rotational speed of the turbine and power generated during a hydropower plant's working day

As observed in the graph above, despite the constant rotational speed of the turbine, the generated power is slowly decreasing.

$$P = \gamma \cdot Q \cdot \eta \cdot g \cdot H_u \tag{1}$$

where:

- P – generated active power, (W)
- Q – turbine flow, ($m^3 \cdot s^{-1}$)
- γ – volume mass of water, 1000 $kg \cdot m^{-3}$
- η – unit efficiency coefficient,
- g – gravitational acceleration, 9.81 $m \cdot s^{-2}$
- H_u – effective water drop, (m)

The correlation of the power drop with the decrease in the water level difference can be observed(Figure 12), which is the counterpart to H_u from the formula above (1) (Rudnicki, 2003).

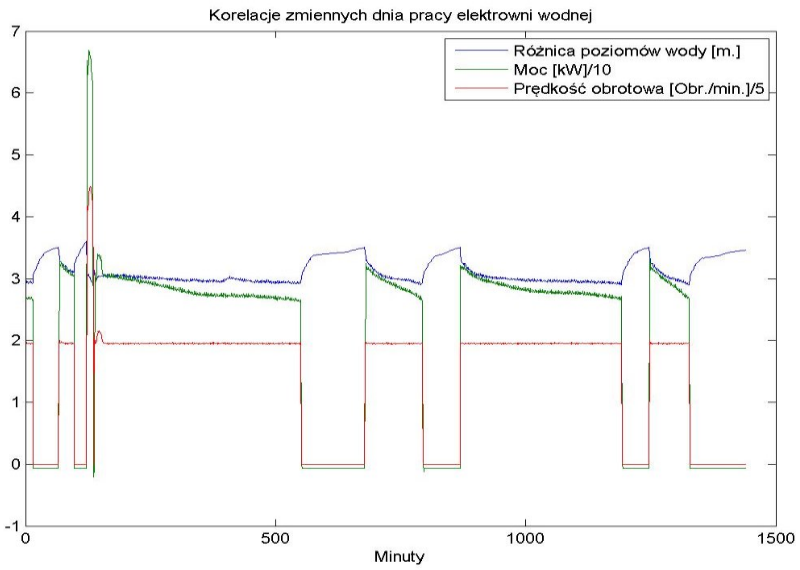

Figure 12. Correlations of variables of the hydropower plant's working day

As observed, long-term observations of operation of a single hydropower plant will allow demonstrating the dependencies between the various variable parameters of the hydroelectric plant. These dependencies will allow creating a simulation model and referring it to the actual hydropower plant system. In a further step, this will enable modeling the flow dynamics of strategic water courses. It will also show the impact of the plant on water level maintenance and retention in the selected area. The obtained models of the river and of the hydropower plant with an Archimedean turbine can be used to optimize power production in similar facilities (Terlikowski, Łuć, 2020) in real time and in planning their annual operation. The obtained results will also allow verifying the model and simulation data (Waters, Aggidis, 2015; Dedić-Jandrek, Nižetić, 2019; Dellinger et al., 2016). Knowing the river dynamics, it is possible to predict its response to the imposed extensions of the river levels and to optimize the production of power. These models can also open up new possibilities for designing hydropower plants, positively impacting the scale of hydropower production in Poland. The next step in the research is to collect data from a number of hydropower plants (Cyr et al., 2011), which will allow to estimate the condition of hydropower plants in the region and then in the country.

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MOŻLIWOŚCI WIELOFUNKCYJNEGO SYSTEMU KONTROLNO--POMIAROWEGO ZASTOSOWANEGO W MAŁEJ ELEKTROWNI WODNEJ

Streszczenie: W roku 2020 uruchomiono w pełni zautomatyzowaną elektrownię wodną na rzece Guber przy miejscowości Kotkowo. Elektrownia ta jest obsługiwana przez układ kontrolno-pomiarowy nadzorujący pracę hydroelektrowni, oraz zbierający dane, które pozwalają ocenić funkcjonowanie wybranych systemów obiektu. Ilość i lokalizacja czujników kontrolujących parametry pracy systemów hydroelektrowni jest tak dobrana, aby komplet informacji zebranych z wszystkich czujników pozwolił na analizę pracy systemów hydroelektrowni w czasie rzeczywistym. Ponadto rejestracja wszystkich kontrolowanych parametrów pozwala na analizę pracy w dłuższych okresach. Praca ta przedstawia możliwości tego układu pomiarowego, jak i wyniki pomiarów uzyskanych w badanym obiekcie. Analiza pracy układu kontrolno-pomiarowego oraz zebranych i zarchiwizowanych danych będą stanowiły podstawę do stworzenia modelu symulacyjnego hydroelektrowni. Model taki będzie pomocny w optymalizacji pracy, pod względem produkcji energii na jednostkę objętości wody, istniejących już hydroelektrowni oraz projektowaniu nowych na istniejących stopniach wodnych.

Słowa kluczowe: elektrownie wodne, OZE, System pomiarowy