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# HYDRAULIC PRESSURE MEASUREMENT IN SPIRAL CASING OF A FRANCIS TURBINE

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**Abstract:** An experimental analysis of water pressure in the spiral casing of a Francis turbine is presented. Measurements are conducted to analyze the pressure variation in a radial section of the spiral casing in correlation wtih changes in electric generator output power. The equipment and the software used for signal acquisition and analysis are described. Pressure transducer selection and preparation are carried out to ensure acceptable accuracy for this specific experiment. Existing connectors for turbine monitoring devices are utilized as pressure measurement points in this experiment. Output power is monitored indirectly through the electric signal of the guide vanes opening, with power values used in post-processing from SCADA logs. Hydraulic pressure and pressure differences across different output power levels and operating conditions are discussed.

**Keywords:** hydropower, hydraulics, Francis turbine, spiral casing, pressure measurement, output power

## INTRODUCTION

Hydraulic pressure and flow rate are key quantities for evaluating the efficiency of hydraulic turbines. Hydraulic pressure, along with vibration and noise, can indicate instability in hydraulic processes, cavitation, losses, and issues related to the manipulation speed of vanes and valves Pressure measurements in penstocks and spiral casing are commonly used for monitoring and maintaining hydraulic turbines [1]. These measurements may also serve to validate numerical analysis of hydraulic processes in turbines [2]. The main reason for it is simple pressure transducers installation and their high accuracy and durability. Measurement of flow rate through turbines is more challenging to implement. One of most accurate and easy-to-implement methods is ultrasonic method which measures the time difference between the outgoing and reflected ultrasonic waves, with an accuracy of up to 0.5% [3]. Main problem to implement this method is requirement for a straight part of penstock, which is inaccessible in many cases. In most cases flow rate control is achieved using the Winter-Kennedy method based on pressure difference measurement along spiral casing radial section produced by centrifugal force [3],[4]. Disadvantages of this flow rate measurement method is necessity for its calibration to fit pressure difference-flow rate curve by another method or by model measurements. Winter-Kennedy method has also lower accuracy than other flow rate measurements methods.

This paper presents and discusses measurements of hydraulic pressure in the spiral casing of Francis turbine in normal operating conditions. Transducers sensors are mounted on connectors of existing Winter-Kennedy equipment. Additionally, one control pressure transducer is mounted on the beginning of spiral casing to measure hydraulic pressure without effects of centrifugal force.

The pressure in the spiral casing is measured at two different points belonging to the same radial section. To ensure high accuracy measurement, pressure transducers with strain gauges in full bridge connection, of a high accuracy class and nominal sensitivity are used. Full-bridge connection of strain gauges produces automatic elimination of transducer temperature change during long time measurements. Transducer measuring range is selected according to estimated maximum expected pressure. One transducer is calibrated using a hydraulic scale of higher accuracy then transducer. To avoid increasing measuring uncertainty in determination of pressure difference, the sensitivity of the second sensor is adjusted to match the readings of the first one. The measurement signal is acquired and amplified by an amplifier and recorded to PC using measuring software. The pressure is measured during stationary turbine operation at seven different power levels, ranging from technical minimum to maximum. Pressure change in transition processes (generator start, free running and synchronization) are also measured continuously but not separately analysed in the paper. Because of output power variations during measurement, short periods of stable operations are used for nominal pressure value at given power level. Power stabilization and achievement of conditions for pressure measurement is monitored by measuring an electrical signal indicating opening grade of the turbines' guide vanes. Nominal pressure value for given output power is than determined as average

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value of recorded values within the short stable period of measurement.

In addition to the Introduction and Conclusion, the paper is organized into four main sections. The first section presents the sensor selection and preparation for pressure measurements under specific operating conditions. The second section presents selection of sensor locations and their installation using existing equipment. The third section describes the experimental setup, including turbine operating conditions and an overview of the measurement results. The fourth section discusses the results of the pressure measurements in detail.

## 1. SENSOR SELECTION AND PREPARATION

Pressure transducers for electrical pressure measurement could be based on different principles of converting pressure to electrical signal. All of them are based on deformation of membrane under pressure action. Strain gauges, piezoceramics or capacity plates could be used to produce electric signal proportional to pressure on the transducer membrane [5]. To ensure high accuracy measurement, pressure transducers with strain gauges, accuracy class 0.3, are used. Full-bridge connection of strain gauges inside a transducer produces automatic elimination of transducer temperature change during long time measurements. Because of estimated maximum pressure in spiral of 12 bar, pressure transducers P8AP of a measuring range of 0–20 bar is selected [6]. Nominal sensitivity of transducers with strain gauges is 2 mV/V for measuring range, but for achieving declared accuracy class, calibration may be required. Because of that, one transducer is calibrated using a hydraulic scale with declared weights, with an accuracy class of 0.1.

To avoid increasing measuring uncertainty in determination of pressure difference, the sensitivity of the second sensor is adjusted to match the readings of the first one.

The signal measured from the transducer was amplified using a SPIDER8 device, which was controlled by a PC running Catman 5 software. The equipment used for signal acquisition and recording is shown in Figure 1.

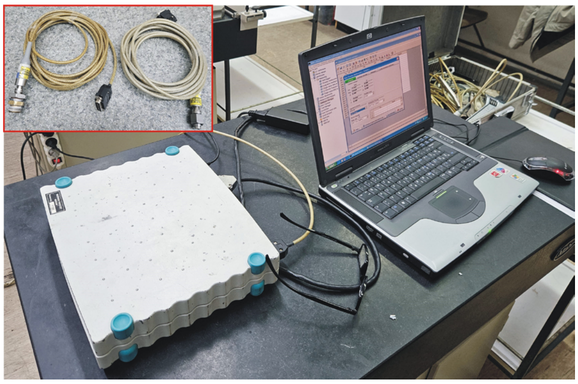

Figure 1: Transducers, signal amplifier SPIDER8 and PC with CATMAN software for measurement acquisition.

## 2. TRANSDUCERS INSTALLATION

The pressure in the spiral casing is measured at two points along the same radial section (pressure $p_1$ and $p_2$). One transducer is connected at measuring place closed to horizontal midplane of the spiral casing (transducer for $p_1$ measurement). Because of guide vanes, transducer closer to spiral centre is attached at height 0.49 m above the spiral casing midplane (transducer for $p_2$ measurement). The transducers are connected to existing connectors of equipment for flow rate measurement by Winter-Kennedy method. Locations of transducer installation are shown in Figure 2.

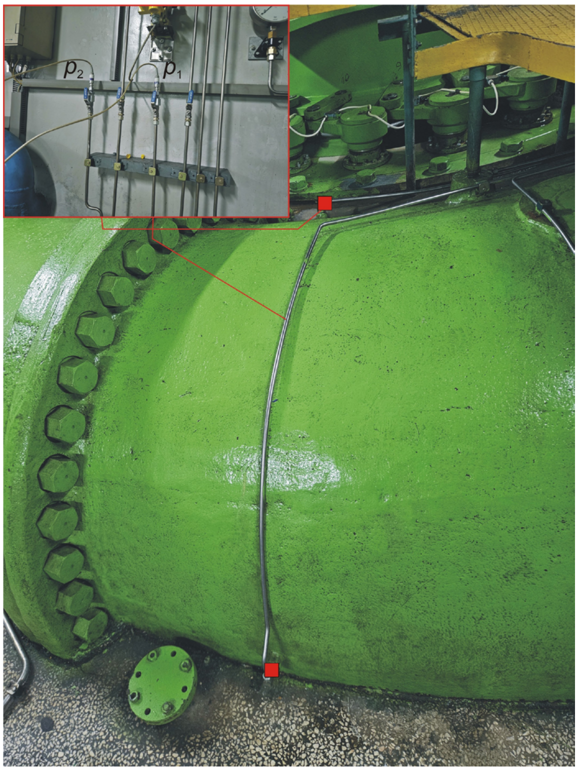


Figure 2: Locations of transducer installation on spiral casing.

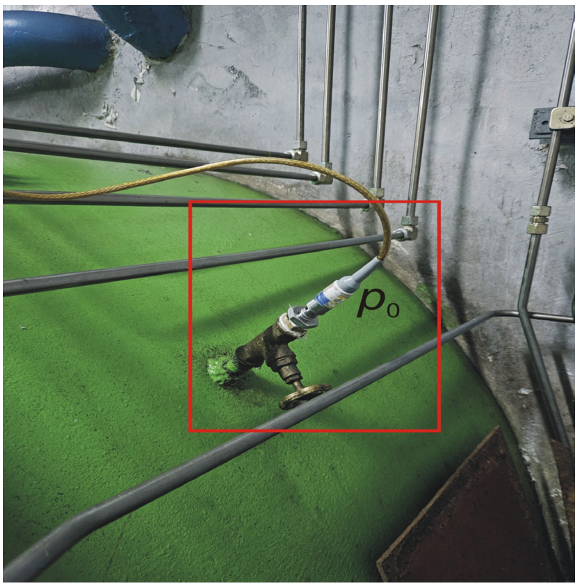


Figure 3: Locations of installation of the control transducer at the beginning of spiral casing.

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Additionally, one control pressure transducer is mounted on the beginning of spiral casing to measure hydraulic pressure in the pipeline without effects of centrifugal force (pressure $p_0$). This transducer is used as control of pressure level and transducer P8AP of range 0-100 bar is selected. Location of transducer installation is shown in Figure 3. Power stabilization and achievement of conditions for pressure measurement is monitored by measuring the 4-20 mA electrical signal from SCADA indicating the opening grade of the turbines' guide vanes. It is assumed that stable value of guide vanes opening indicates stable output power level.

## 3. SETUP OF THE EXPERIMENT

Measurements are provided in real operating conditions, where generator worked on grid and final power level stabilization was influenced by it. Measurements are provided for all phases of starting and synchronisation of aggregate to work on grid with different load levels. Levels of generator output power for pressure measurement are chosen to start on 12 MW (technical minimum) and increases to 30 MW (technical maximum) by 3 MW power increments. Output powers 12 MW and 21 MW are not achieved, and measurements are conducted at 12.5 MW and 22 MW. Realized output power and working conditions are given in Table I.

Table I: Hydraulic aggregate working regimes

| No. | Power (MW) | Headrace (m) | Tailrace (m) |
|---|---|---|---|
| 1 | 12.5 | 265.39 | 158.37 |
| 2 | 15 | 265.39 | 158.23 |
| 3 | 18 | 265.39 | 158.26 |
| 4 | 22 | 265.39 | 158.24 |
| 5 | 24 | 265.39 | 158.24 |
| 6 | 27 | 265.39 | 158.11 |
| 7 | 30 | 265.39 | 158.15 |

An overview of conducted measurements is shown in Figure 4.

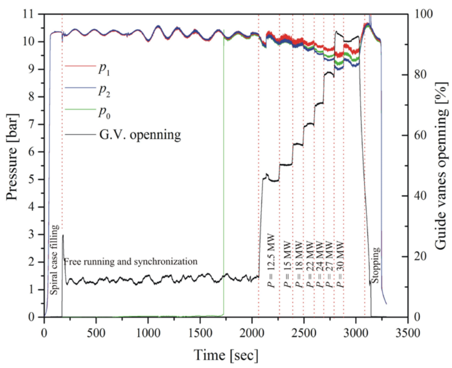


Figure 4: An overview of pressure variations for different guide vanes openings during measurement.

The first phase of measurements corresponds to the filling of the spiral casing, where all transducers indicate pressure raising from zero to the static pressure for given head while guide vanes were closed. Second phase corresponds to the turbine running from zero to nominal speed and aggregate synchronisation. Fast changes of guide vanes opening during this phase cause significant pressure oscillation equally indicated at all measuring points. The lowest output power was 12.5 MW characterised by unstable work and the biggest pressure oscillation. Pressure oscillation was caused by big changes of guide vanes opening to obtain stable power output. The most stable value of guide vanes opening was at powers 15 MW and 18 MW Pressure values change at given values of output power even if guide vanes opening is quite stable.

## 4. RESULTS ANALYSIS

Each operating period at a given power is recorded, and the pressure data from the spiral casing are analyzed using 10 s long intervals in measurement where guide vanes opening exhibits minimal variations. The results are calculated as the mean pressure value over these intervals of stable work.

Figure 5 shows pressures and guide vane opening for $P$ = 12.5 MW. Pressure values are determined for the last 10 s of measurement where pressure also becomes stable. Guide vanes opening changes for 3.9% while pressure $p_1$ changes between 10.399 bar to 9.918 bar and $p_2$ between 10.276 bar and 9.894 bar.

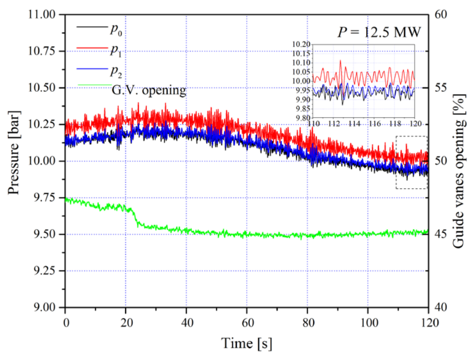


Figure 5: Extraction of measurements for $P$ = 12.5 MW.

In Figure 6 pressures and guide vane opening for $P$ = 15 MW are shown. Guide vanes opening is more stable than in previous measurement and changes only for 0.76%. Pressure $p_1$ changes between 10.281 to 9.952 bar and $p_2$ between 10.116 and 9.915 bar.

In Figure 7 pressures and guide vane opening for $P$ = 18 MW are shown. Guide vanes opening changes for 1.08%. Pressure $p_1$ changes between 10.155 to 9.89 bar and $p_2$ between 9.981 and 9.783 bar.

Figure 8 shows pressures and guide vane opening for $P$ = 22 MW. Guide vanes opening is very stable in this measurement and changes for 0.79 %. Pressure $p_1$ changes between 10.029 to 9.838 bar and $p_2$ between 9.799 and 9.649 bar.

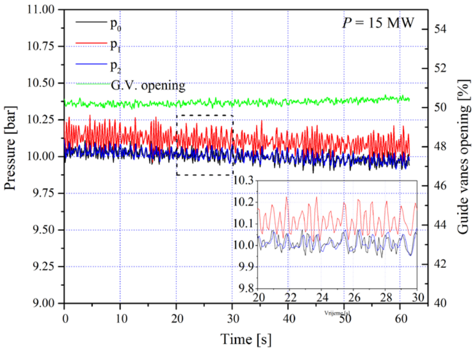


Figure 6: Extraction of measurements for $P$ = 15 MW.

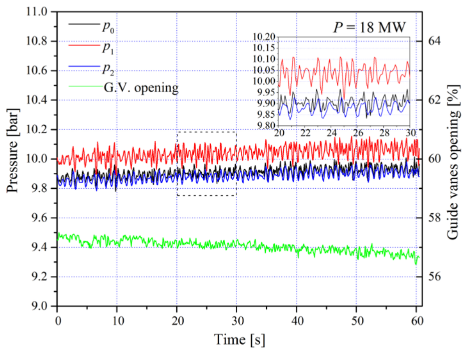


Figure 7: Extraction of measurements for $P$ = 18 MW.

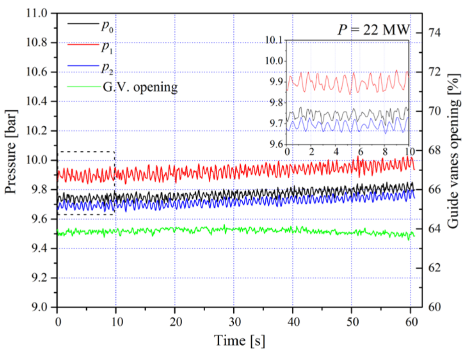


Figure 8: Extraction of measurements for $P$ = 22 MW.

In Figure 9 pressures and guide vane opening for $P$ = 24 MW are shown. Guide vanes opening changes for 1.00 %. Pressure $p_1$ changes between 9.908 to 9.768 [bar] and $p_2$ between 9.600 and 9.520 [bar].

In Figure 10 pressures and guide vane opening for $P$ = 27 MW are shown. Guide vanes opening changes for 1.07 %. Pressure $p_1$ changes between 9.798 to 9.631 bar and $p_2$ between 9.398 to 9.225 bar.

Figure 11 shows pressures and guide vane opening for maximum output power $P$ = 30 MW. Guide vanes opening changes for 1.55 % and represents the second biggest variation in all measurements. Pressure $p_1$ changes between 9.649 to 9.410 bar and $p_2$ between 9.124 and 8.965 bar.

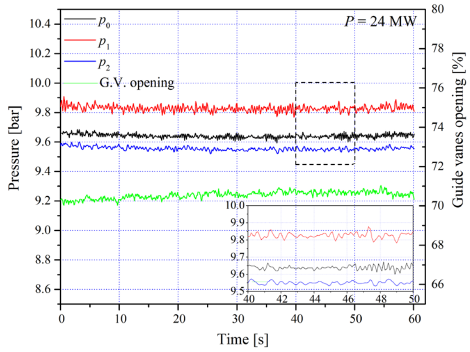


Figure 9: Extraction of measurements for $P$ = 24 MW.

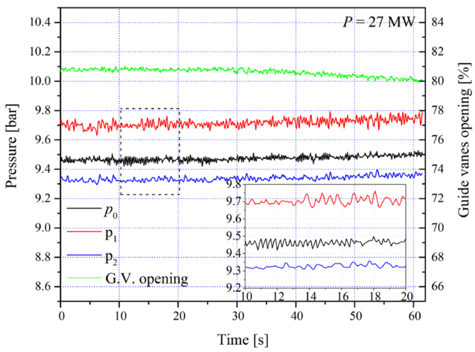


Figure 10: Extraction of measurements for $P$ = 27 MW.

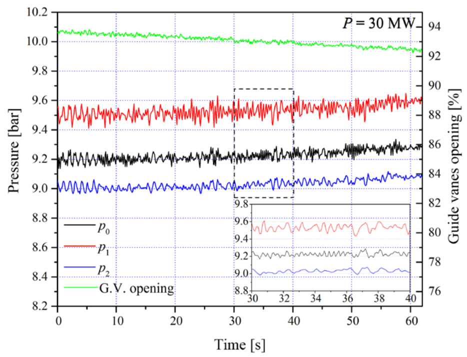


Figure 11: Extraction of measurements for $P$ = 30 MW.

According to presented measurement, maximum and minimum value of pressure $p_1$ changes from 10.399 bar to 9.410 bar, while maximum and minimum value of pressure $p_2$ changes from 10.276 bar to 8.965 bar. Guide vanes opening changes about 0.76% - 1.08% except for minimum and maximum output power. For maximum power it changes for 1.55 % while for minimum power it changes even 3.9 %. Unstable work at this power and flow stabilization after fast increasing guide vane opening to set power to 12 MW could be reason for registered less pressure than at next bigger power level of 15 MW.

Figure 12 shows values of measured mean pressure and their difference for corresponding output power. While pressures $p_1$ and $p_2$ increase between first and second power level, and decrease monotonically for others, pressure difference increases continuously from minimum to maximum power level. Increasing of pressure difference shows square parabolic dependency on generator output power with correlation factor R = 0.99.

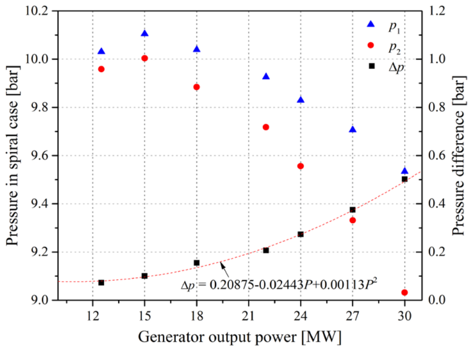


Figure 12: Results of pressure measurements.

## 5. CONCLUSIONS

Pressure measurements in the spiral casing of a Francis turbine at various generator output power levels are presented and analyzed. Pressure is measured at a single radial section, and the results are suitable for calculating pressure differences and estimating flow rates. Pressure fluctuations in the spiral casing, caused by changes in the guide vane openings, impact the accuracy of pressure readings for specific generator output power levels. The results indicate an increase in pressure when operating near the technical minimum, while for the other generator output power levels, pressure decreases due to the rise in flow rate and output power. For more accurate results, simultaneous power measurements are recommended, instead of relying on post-measurement SCADA log data. Pressure measurement is straightforward to implement and analyze, and it may be recommended for validating numerical analyses of hydraulic processes in the penstock and spiral casing, as an alternative to flow measurement.

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## BIOGRAPHY

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