EVALUATION OF AUTOMATIC SPEED REGULATION PERFORMANCE OF MICRO-HYDRO UNITS BY MONITORING VIBRATIONS IN BEARINGS AND TURBINE HOUSING

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The main challenge for micro-hydropower plants with Banki, Kaplan, Francis, or Pelton turbines and synchronous or asynchronous generators is the automatic regulation of speed and voltage at the generator terminals. This paper presents a method for evaluating the automatic speed regulation performances for a micro-hydro unit, by analyzing absolute vibrations measured in the housing and bearings of the turbine. We excluded the possibility that the turbine is not properly designed for hydropower development, and it is not properly installed within the hydropower plant. Proper speed regulation involves maintaining absolute vibrations within acceptable limits in all operating regimes. Tests were conducted on micro-hydro units with Banki turbine, found in different locations in Romania. The results highlighted improper functioning of the automatic speed regulation system during transient load rejection regimes.

Keywords: micro-hydropower, vibrations, automatic, turbines, evaluation.

1. Introduction

The hydroelectric potential, or the energy potential of water falls, is among the first forms of energy to be exploited. Hydraulic energy is the primary renewable resource that can be most easily utilized with maximum efficiency on an industrial scale.

In recent years, Romania has seen an "explosive" increase in the number of micro-hydropower plants utilizing the energy potential of various watercourses in the Carpathian Mountains [1]. These micro-hydropower plants are often the sole sources of electricity for isolated locations without access to the electrical

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grid. Such micro-hydropower plants are also installed in large hydropower stations, where they operate continuously using the residual flow from secondary intakes [1, 2]. The installed power of these micro-hydropower plants ranges from 10 kW to 1000 kW, and they are equipped with various types of hydraulic turbines: Banki, Kaplan, Francis, or Pelton, and synchronous or asynchronous generators [3, 4].

In most cases in discussion, speed regulation is achieved by adjusting the opening of the guide vanes, effectively regulating the flow rate of the turbinated water. Theory states that controlling the flow through the turbine, especially if done improperly or too frequently, can create unsteady hydraulic forces. These forces can lead to vibrations or resonance in the turbine rotor, which might cause cracking, deformation, or other forms of mechanical damage [5].

As part of a research study, we conducted technical assessments of several hydro units to determine the causes of failures that led to significant economic losses due to the unavailability of the equipment. In most cases, damages were found in the micro-turbine rotor, with the appearance of cracks or breaks in the turbine rotor blades, indicating deficiencies in the speed regulation system that led to high-vibration operation [6, 7].

For this reason, after completing the repairs, the equipment's performance was evaluated during commissioning by measuring the speed and vibrations in the turbine's housing and bearings, as well as the generator's bearings. Experimental tests revealed that these systems maintain the speed at the specified value by adjusting the flow rate of the water passing through the turbine.

By appropriately adjusting the opening of the guide vanes, flow regulation during load rejection is slow, with very large time constants, ranging from tens to even hundreds of seconds, during which dangerous over speed of the turbine rotor occurs [1, 4]. Industry standards do not allow hydro units to operate at such runaway speeds, as these conditions lead to very high vibrations that cause significant damage to the micro-hydro unit.

In the small power plants existing in Romania, various types of turbines are installed, depending on the flow rate and net head of the respective facility. The most common types are:

- ✓ *Type 1* - Small power axial turbines with an S-shaped flow path, designed for net heads within 2 - 25 m and water flow rates within 2 - 45 m^3/s. Ten size types have been developed with capacities up to 5000 kW.
- ✓ *Type 2* - Small power axial turbines with a horizontal shaft and S-shaped flow path, ranging from 15 - 1200 kW, with five size types in this model, characterized by head range H = 2.5 - 20 meters, flow rate range Q = 0.2 - 9 m^3/s, power range P = 15 - 1200 kW, turbine rotor with four fixed blades made of stainless steel, axial guide vane with 12 blades.

- ✓ *Type 3* - Small power axial turbines with the following characteristics: head range H = 1 - 30 m, flow rate range Q = 1 - 50 m³/s, power range P = 100 - 1500 kW, vertical, horizontal, or inclined shaft, rotor with 3 to 6 metal blades, with single adjustment.
- ✓ *Type 4* - Small power turbines designed for heads between 2 and 25 m, with flow rates in the range of 0.5 - 35 m³/s and power between 125 kW and 1500 kW. In Romania, many hydraulic facilities use this model, of the Banki type, coupled with asynchronous or synchronous generators [1].

In all these micro-hydro units, speed regulation occurs through appropriate adjustment of the guide vane opening, thus adjusting the water flow. Industry standards impose certain performance requirements for the automatic speed regulation system of generators, limiting the maximum speed to 1.5 times the nominal speed, i.e., a maximum increase of 50% over the nominal speed in the event of rapid discharges or load rejection. Proper speed regulation performance implies a stable dynamic of the rotor assembly with reduced vibrations in the bearings and housing of the micro-hydro unit [2-5].

In this paper, we present the results obtained through a method used to evaluate the performance of automatic speed regulation. This method involves monitoring the absolute vibrations in the housing and bearings of a micro-hydro unit equipped with a Banki-type turbine, under various operating conditions. Measured values were recorded and analyzed in order to establish the performance of the automatic speed controller.

2. Case study – method of evaluation

The following presents the results obtained for a Banki turbine micro-hydro unit (of Type 4) with a nominal power of 700 kW, for which the speed and vibration levels were recorded in various operating regimes using the proposed method.

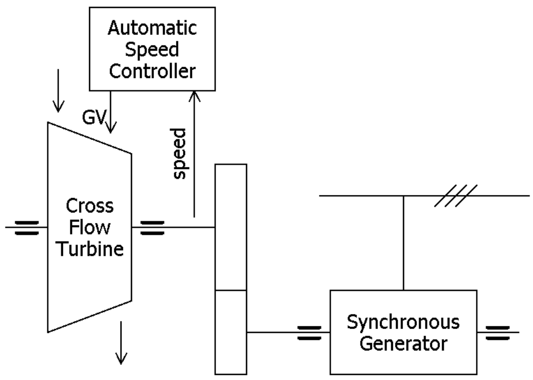


Fig. 1. The schematic diagram of the speed control system of a micro-hydro unit

The hydraulic turbine with a nominal rotor speed of n = 250 rpm drives a synchronous generator with a nominal speed of n = 1000 rpm through a speed multiplier (gearbox) with a ratio of 1 to 4. The automatic speed controller uses the speed feedback and controls the opening of the turbine guide vane, GV, to achieve a constant speed in all operating regimes of the micro-hydro unit, as shown in figure 1 [6, 7].

For all below considered case studies the rotor speed and vibrations were measured and recorded in the following horizontal directions, at the mentioned input pins:

- V1 input pin - vibrations in the turbine bearing opposite the coupling,
- V2 input pin - vibrations in the middle part of the turbine housing,
- V3 input pin - vibrations in the generator bearing towards the coupling.

2.1. Transient start-up regime with load up to 250 kW

The turbine rotor speed and vibrations, acquired at input pins V1, V2, and V3, in the turbine housing and bearings were recorded.

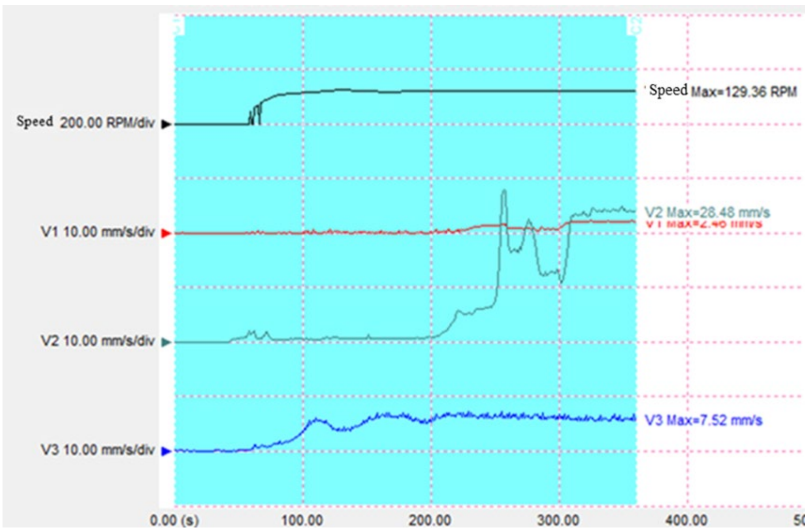


Fig. 2. The rotor speed and vibrations for transient start-up regime with load up to 250 kW

As shown in figure 2, from the recorded variation in speed, it results that the automatic speed regulation system operates properly during the start-up process with load up to 250 kW. However, it is observed that the load application process to the generator is accompanied by very large oscillations in the vibration levels in the turbine housing.

2.2. Transient loading regime from P = 250 kW to P = 500 kW

The turbine rotor speed and vibrations, acquired at input pins V1, V2, and V3, in the turbine housing and bearings were recorded. It is observed in figure 3 that the partial load operating regime is characterized by proper speed regulation but also by pronounced oscillations in the vibration levels within the turbine housing. The maximum level of these vibrations reaches dangerous values. In the stabilized operating regime at 500 kW, a decreasing trend in the vibration levels within the turbine housing is noted.

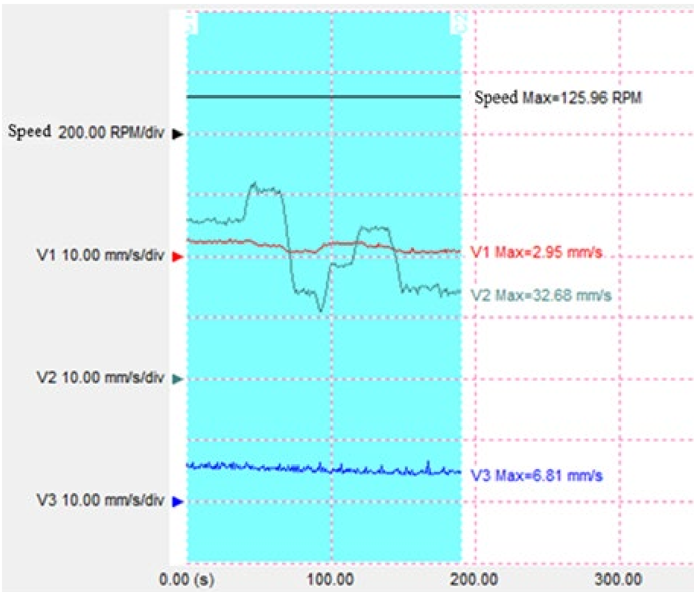


Fig. 3. The rotor speed and vibrations for transient loading regime from P=250 kW to P=500 kW

2.3. Transient start-up regime with load up to P = 700 kW

The micro-hydro unit, being in a stopped state, was started and connected to the grid with automatic loading until reaching the nominal load P = 700 kW. The turbine rotor speed and vibrations acquired at input pins V1, V2, and V3, in the turbine housing and bearings were recorded.

During the start-up process and loading to the nominal load of 700 kW, appropriate performance of the speed control system is observed, as it can be noticed in figure 4. The loading process up to the nominal value is characterized by a pronounced increase of the absolute vibration level in the turbine chamber, reaching maximum value of 32 mm/s, which is unacceptably high.

In the stabilized operating regime under load, the vibration level in the turbine housing settles at 22 mm/s, exceeding the maximum allowable limits defined by standards. Pronounced oscillations of the absolute vibration level also occur in the generator bearing, which are determined by turbine vibration oscillations.

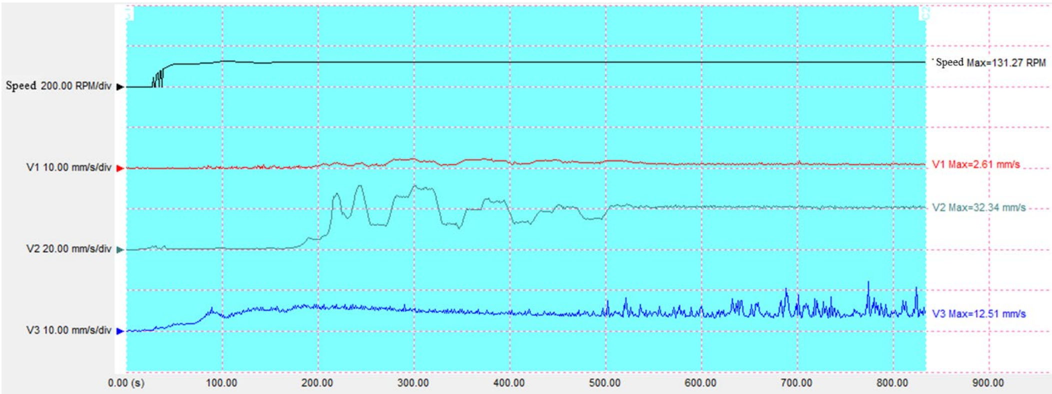


Fig. 4. The rotor speed and vibrations for transient start-up regime with load up to P = 700 kW

2.4. The normal shutdown regime from the load P = 700 kW

With the generator connected to the grid and loaded at the nominal load of P = 700 kW, the normal shutdown command was issued, with automatic discharge from the load.

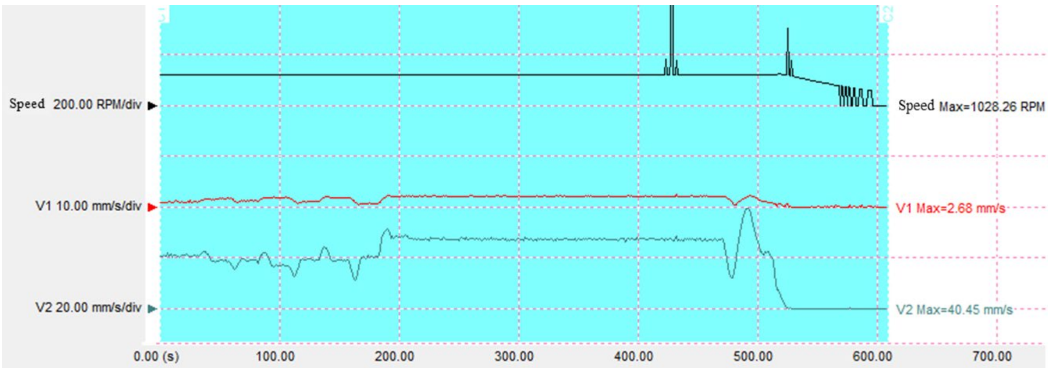


Fig. 5. The rotor speed and vibrations for normal shutdown regime from the load P = 700 kW

In figure 5, the time variation of the turbine speed and vibrations, acquired at input pins V1 and V2, in the turbine housing and bearing are presented. It is noteworthy that during a normal shutdown with gradual discharge from the load, the speed regulation process proceeds normally, with the observation that pronounced vibrations occur in the turbine housing and bearing during the transient load discharge regime and speed reduction, which can have a destructive effect over time.

2.5. Transient load rejection regime at the nominal load of P = 700 kW

With the generator connected to the grid and loaded at the nominal load of P = 700 kW, the command to disconnect the breaker through a protection was issued, and the following were recorded: the turbine rotor speed and vibrations, acquired at input pins V1, V2 and V3, in the turbine housing and bearings. The time variation of these quantities during the transient load rejection regime is shown in figure 6.

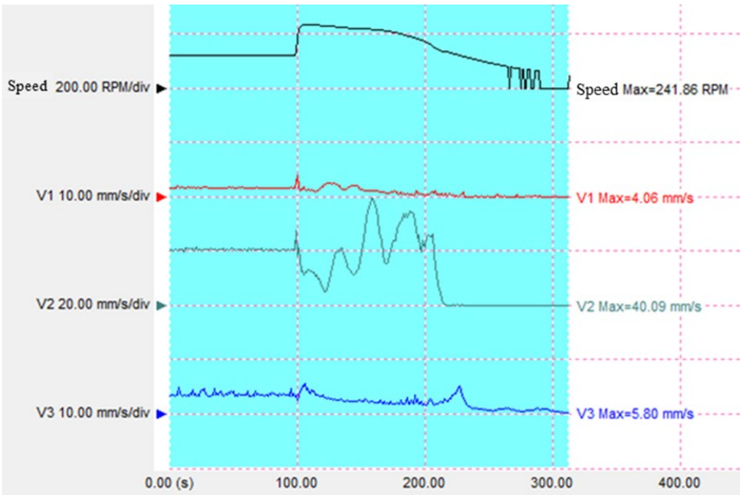


Fig. 6. The rotor speed and vibrations for transient load rejection regime at the nominal load of P=700 kW

Based on the recordings, it is found that the transient load rejection process from the nominal 700 kW load is accompanied by pronounced oscillations in the turbine housing vibrations, with a maximum value of 40.09 mm/s. The maximum speed reached the over-speed value of 241.86 rpm, maintained for a period of 80 seconds.

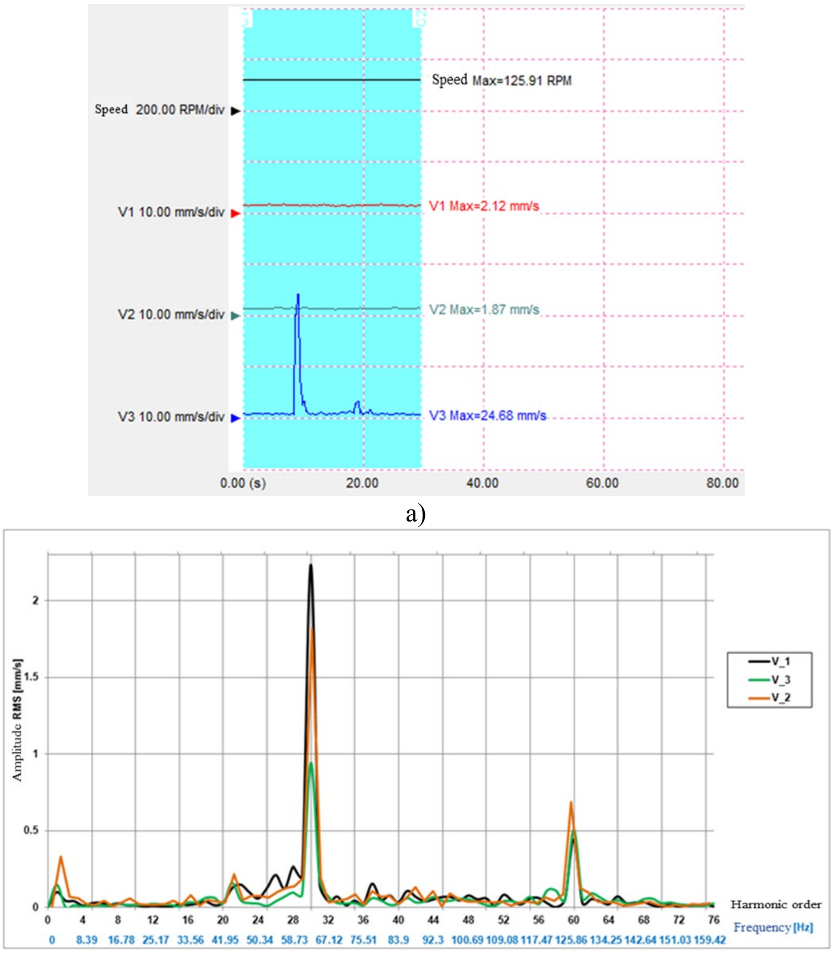
Standard IEC 60545 [8] and industry practice restrict over-speed tests during commissioning, especially during operation. From this perspective, the automatic speed regulation system is deficient, allowing the micro-hydro unit to operate in an unacceptable vibration regime, with a destructive effect upon the turbine rotor assembly and housing.

The control system performs adequately in stationary regimes across the entire range of power delivered to the grid, but it shows reduced performance during transient loading and unloading conditions, especially during load shedding.

3. Spectral analysis of vibration signals at nominal load operation

Under the conditions where the generator operates connected to the grid at the nominal load of P = 700 kW, vibrations were measured in three directions: horizontal - acquired at input pin V1, vertical - acquired at input pin V2, and axial - acquired at input pin V3, in the turbine bearing opposite the coupling, the turbine housing (middle part), and the generator bearing towards the coupling.

In the following, we analyze the time variation of the absolute vibrations measured in velocity, as well as the frequency spectrum of the respective vibration signals in the three directions. We consider the subsequent three case studies shown in figures 7.a, 7.b, 8.a, 8.b, 9.a, and 9.b.

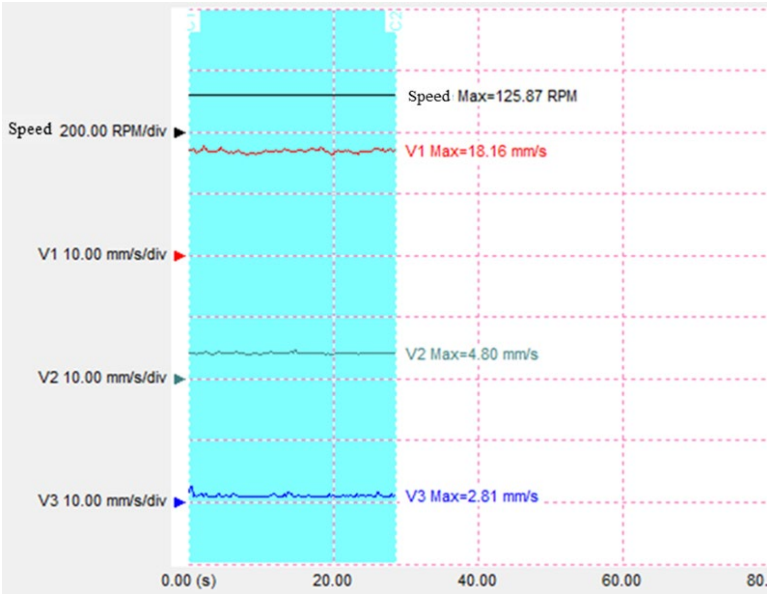


a)

b)

Fig. 7. Vibrations in the turbine bearing opposite the coupling: a) Time variation of vibrations; b) Frequency spectrum of vibration signals

Analyzing figure 7.b and figure 8.b, one may observe that in the frequency spectrum of vibrations at the level of the turbine housing and in the turbine bearing opposite the coupling, the dominant component is the 30th harmonic, whose amplitude is very high compared to the fundamental. This indicates that the vibrations of the housing are determined solely by the turbulent water flow through the turbine.



a)

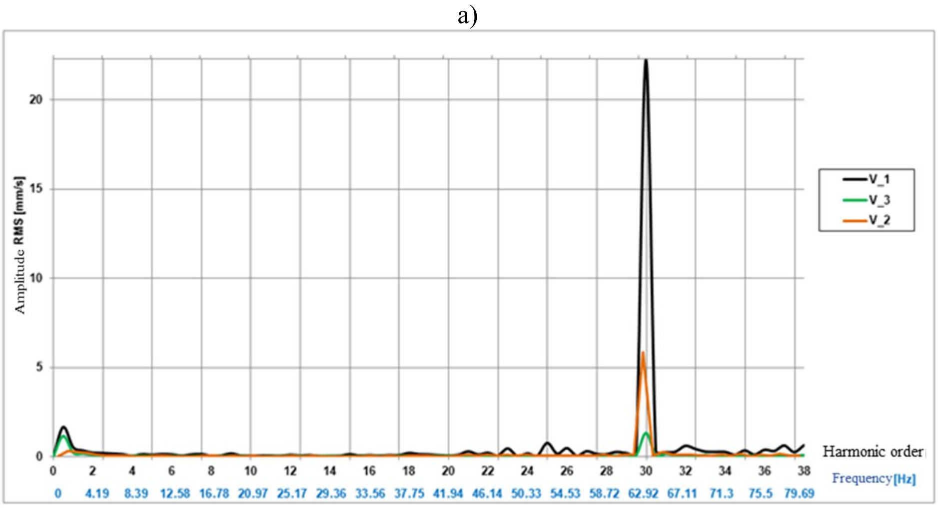


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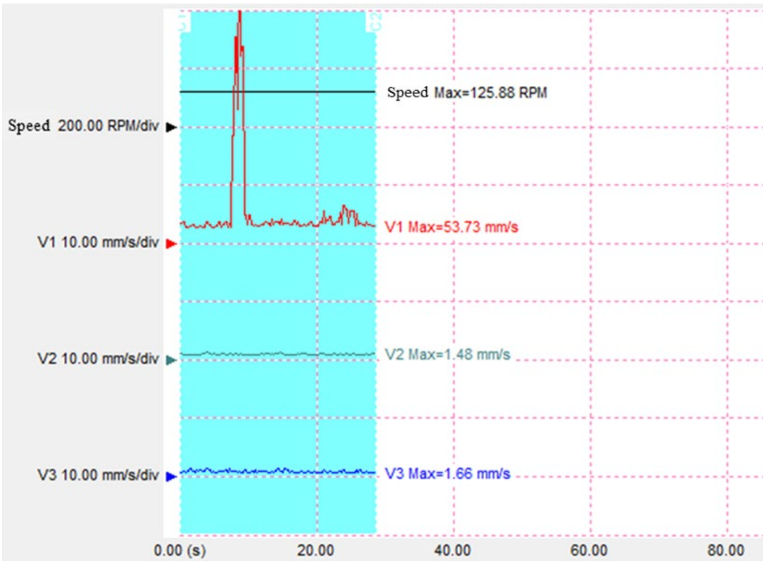
Fig. 8. Vibrations in the turbine housing (central part): a) Time variation of vibrations; b) Frequency spectrum of vibration signals

In the frequency spectrum of vibrations at the level of the generator bearing towards the coupling, the appearance of the 16th harmonic, as it can be noticed in figure 9.b, indicates a certain misalignment of the shaft line. It was found that the optimal operation in terms of turbine assembly vibrations occurs at 3/4 of the nominal power. In general, the vibration level depends on the net head and the flow rate through the turbine. Furthermore, the results indicate installation deficiencies leading to additional vibrations in the generator bearing towards the turbine.



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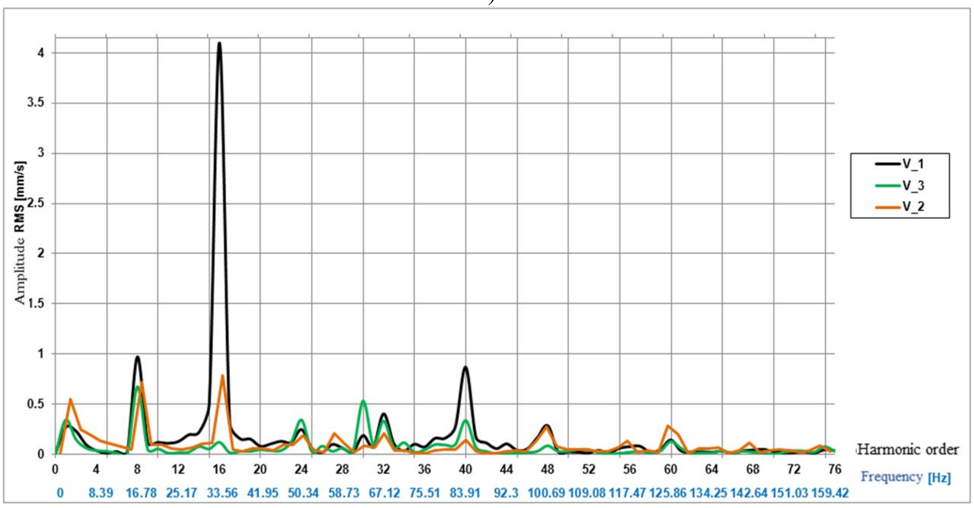

b)

Fig.9. Vibrations in the generator bearing towards the coupling a) Time variation of vibrations b) Frequency spectrum

In all operating regimes considered for the Banki turbine micro-hydro unit, with a nominal power of 700 kW, a very high level of vibrations was observed in the turbine housing, emphasizing a mismatch between the hydraulic parameters of the hydropower development and the hydraulic parameters of the turbine. Thus, the operating point is outside the optimal range of flow and head for the hydro unit, causing additional vibrations in the turbine housing.

4. Conclusions

It is well known that safe operation with maximum efficiency of a micro-hydro unit is conditioned by its operation with a low level of vibrations in all regimes. Regarding bearing vibrations, for units that show operation outside the ADMITTED rating, according to SR6910-2012 [9], it is required to stop and perform technical maintenance on them. Evaluating the performance of the automatic speed regulation of micro-hydro unit by monitoring the absolute vibrations in the bearings and turbine housing for the Banki model, reveals functioning of the system with high levels of vibrations, classifying their operation outside the ADMITTED rating (maximum level of 11 mm/s), which, according to SR6910-2012 [9], requires stopping them for technical maintenance.

The measurement results presented in this paper highlight a main cause leading to additional vibrations: the automatic speed regulation system of the rotor during the transient load rejection process. The automatic speed regulation system shows reduced performance during transient loading and unloading conditions, particularly during sudden load application. The duration of the transient load rejection process is very long, reaching up to 100 seconds, which can have negative consequences for the entire power plant, requiring major interventions to bring the installation back to nominal parameters.

Since all micro-hydropower plants operate without personnel, it is necessary to install advanced vibration monitoring systems to ensure the safe operation of these micro-hydro units. It is very important that these monitoring systems prevent major damage through preventive shutdown of the hydro unit. Considering that safe operation is desirable for each hydro unit, the user of such equipment should take into account the observations and recommendations from this paper.

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