Dynamic behavior of hydro units in the rough load zone, with case studies

Ozren Husnjak
Veski d.o.o.
Oreskoviceva 8j, Zagreb, Cro
ozren.husnjak@veski.hr

Ozren Orešković
Veski d.o.o.
Oreskoviceva 8j, Zagreb, Cro
ozren.oreskovic@veski.hr

Franjo Tonković
4-cube d.o.o.
Nova Cesta 121, Zagreb, Cro
franjo.tonkovic@4-cube.hr

ABSTRACT

Francis turbine hydro units often experience issues while operating in Rough Load Zone (RLZ). The RLZ manifests itself on lower loads with the vortex present under the turbine rotor. Additionally, the radial and axial vibrations are present and can be excessive. Sometimes, the vibrations are so large that the unit's operation must be restricted on all loads at which the RLZ is present.

So far, the causes for the excessive vibration response in RLZ has not been clearly determined. The main question is whether or not it's due to the vortex presence which causes the vibrations and, consequently, pressure pulsations in the turbine rotor zone or that the vibrations and vortex presence are caused by some kind of common cause which has not yet been precisely identified.

In order to successfully identify the root-cause it is essential to enable simultaneous measurements of different dynamical signals (pressure pulsations), vibrations, acoustic emissions at the turbine cover and draft tube, axial rotor displacements (at, at least, two positions), flow, active power). The identification of machine behavior in RLZ is conducted using analysis methods for all signals simultaneously acquired and their interdependence analysis.

Such measurements have been performed on several hydro-units with different maximum loads and rotating speeds for which strong RLZ were identified, due to which the load restriction was introduced. It was shown that the hydrodynamic pressure pulsations were often the consequence of vibrations instead of their cause.

Special care was devoted to the rotor axial dynamics in the RLZ since the large axial vibrations are often more dangerous than the radial vibrations (which are present simultaneously with the axial vibrations).

The rotor vibrations in the RLZ are present at low frequencies and for different hydro-unit constructions have well-defined vibrational forms. The identification of these forms is important in order to determine the vibration characteristics in the RLZ. If the rotor vibrations in the RLZ are present at the natural frequency – this is a certain sign that the vibrations are self-exciting in nature. The procedures to rectify this state should then be based on the elimination of the conditions for which the self-excited vibrations appear.

All of the above is presented at the basis of measurements on a couple of hydro-units powered by Francis turbines on which there are significant instabilities present while operating in the RLZ.

Key words: Rough Load Zone (RLZ), vortex, draft tube, pressure pulsation, dynamic loads, axial vibrations, radial vibrations, self-exciting vibrations

1. Introduction

On Francis turbine hydro unit dynamical instabilities sometimes occur during the partial load operation.

Typically, the instability occurs at 30-50% loads, but under certain conditions it can also be present up to 70% of nominal load. The results of these instabilities are increased radial and axial rotor vibrations, especially on turbine and lower generator bearing. These vibrations have often very high levels, sometimes leading to limited machine operation.

Dynamical instability is manifested on subharmonic (low) frequencies, below the nominal rotational speed, typically, in a frequency span from 0.5 to 1 Hz. Additionally, hydraulic pressure pulsations in turbine draft tube are present, accompanied by a vortex occurring below turbine runner. All phenomena listed above occur in very short time period (practically simultaneously), and it is very hard to recognize the sequence of occurrence, which is fundamental for understanding the behavior in RLZ.

Measurements and thorough data analysis of relevant quantities, such as vibration, process and hydraulic, were performed on three hydro-units with strong RLZ effect. The goal was to establish cause-consequential relations between all measured values, and determine the start of RLZ behavior.

2. Measurement description

2.1 Monitored hydrogenator design

Measurement results presented in the paper are obtained from three hydro units in three different power plants.

Basic specifications of mentioned units are the following:

Table 1 – Machine data

Unit #	Design type	Rated Power (MW)	Speed (RPM)
1	Umbrella type design with two guide and one thrust (axial) bearing. Combined bearing is supported directly on concrete foundation.	130	180
2	Umbrella type design with two guide and one thrust (axial) bearing. Combined bearing is supported directly on concrete foundation.	108	125
3	Design with three guide bearings where upper generator guide bearing and thrust bearing are combined, being supported on stator frame. Lower generator and turbine bearings are guide bearings.	114	250

Unit 1 and 2 are equipped with permanent condition monitoring system, used to measure and analyze the data presented in the paper. Unit 3 is analyzed using the portable instrument.

2.2 Measurement layout

It was determined to use the similar sensor layout on all three unit in order to compare and correlate similar values on various machines. Therefor following sensors were installed:

- Relative shaft vibrations on all guide bearings, 2 sensors mounted to measure vibrations in perpendicular directions (provided on all three analyzed units)
- Absolute axial vibrations of axial bearing bracket and turbine cover (provided on all three analyzed units)
- Axial rotor displacement on three positions as follows
    - Above the axial (thrust) bearing referring to stator frame or foundation (provided on Unit 1 and Unit 3)
    - On the axial bearing referring to axial (thrust) bearing bracket (provided on Unit 1 and Unit 2)
    - On the turbine cover referring to concrete foundations (provided on Unit 1)
- Static and dynamic pressure in draft tube and spiral case (provided on Unit 1 and Unit 3)
- Process values – active and imaginary power (provided on all three units)

The schematic diagram of all three (two, since Unit 1 and Unit 2 are practically identical) analyzed units is shown on figure 1, with basic bearing disposition and measurement sensor layout:

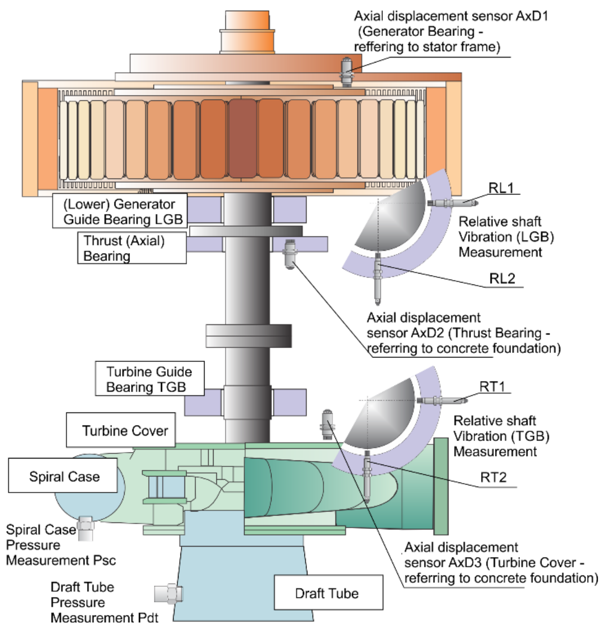

Figure 1 – Basic design, bearing disposition and measurement sensors layout for analyzed units, left side refers to Unit 1 and Unit 2, right side refers to Unit 3

3. Analysis results

3.1 Results for Unit 1

There are six trend values shown on figure 2, describing the Unit 1 vibrodynamic behavior. All the trends are recorded during load reduction operation in range from 120 to 10 MW.

Top diagram on figure 2 refers to rotor axial displacements. Static component of the displacement measured on top of generator, referring to stator frame is drawn with red line. Static component of the displacement measured on turbine cover, referring to foundation is drawn with blue line.

Middle diagram shows active power (red color) and pressure in draft tube (blue color). The bottom diagram shows relative shaft vibrations REST[1] value. Changes of REST value, recorded on lower generator bearing, are shown in blue and on turbine guide bearing in red color.

Vibration component which is dominant in RLZ occurrence is generated on subharmonic frequencies, having no relations with rotational speed frequency. Therefore, REST value is one of very reliable indicators for RLZ-induced vibrodynamic changes.

The RLZ manifestation occurs suddenly with the active power lowered below 85 MW, with maximum at 45MW.

[1] REST is the amplitude of shaft displacement calculated from overall amplitude of vibration signal with first three harmonics (first, second and third rotational speed frequency harmonic) subtracted. This value is used as a fast indicator that vibrations are occurring on frequencies that are not related to machine rotation, usually sub harmonics when analysis used on shaft displacement probes

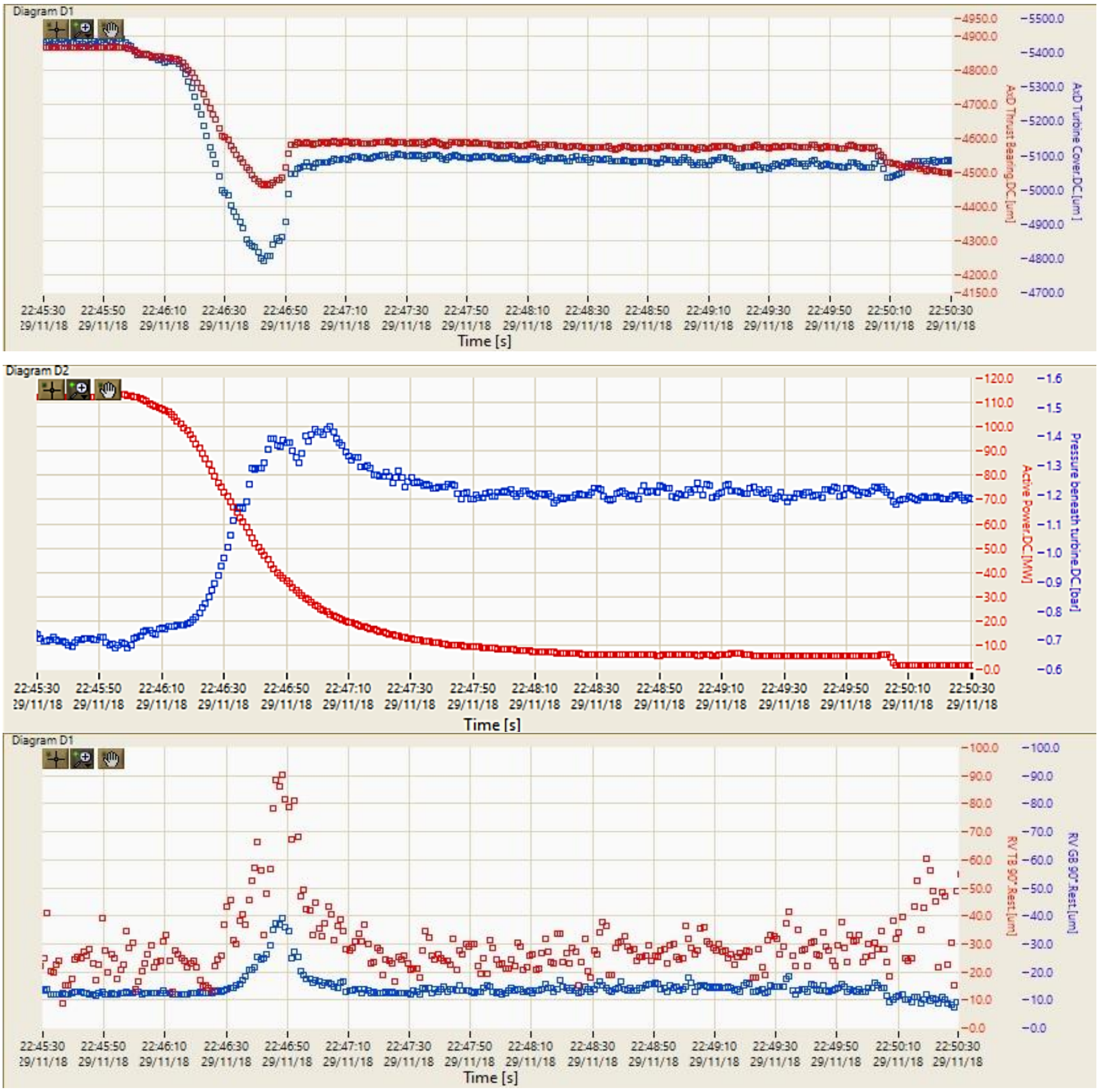

Figure 2 -Static axial displacements on top of the generator (top diagram, red color), on turbine over (top diagram, blue color), active power reduction 120 to 10 MW (middle, red color), static pressure in draft tube (middle, blue color), relative shaft vibration REST value (turbine guide bearing - red color, lower generator bearing – blue color)

Axial displacement static component show interesting results. At rated power the load axial force acting on the turbine rotor (weight and water) is at the maximal level, acting in direction from generator toward the turbine. During load reduction, this force is decreasing, causing the rotor to move "upward", meaning that the distance between sensor and measurement surface decreases. That is the case during first part of load reduction process. During RLZ operation the changes of axial displacement measured on turbine cover are significantly faster than the changes of axial displacement measured on top of the generator. The explanation of these results is that the part of the rotor in turbine cover area is moving upward much more than the part of the rotor at top of the generator.

The maximal deflection of the rotor is achieved at 40 MW, after which, the rotor is moving in the opposite direction ("downward"), achieving stationary value at 10 MW.

Generator rotor lift, during load reduction from 120 to 40 MW, is approx. 400 μm, and turbine runner lift is approx. 650 μm. During load reduction from 40 to 10 MW, the rotor is moving in opposite direction for about 130 μm, and turbine runner for about 300 μm. The conclusion is that operating in RLZ causes significant axial shaft deformations, approx. 200 μm, between the turbine runner and axial bearing.

Changes in draft tube static pressure are noticed (middle diagram on figure 2.). Static pressure increased 0.7 bar at 120 MW load to 1.4 bar on 40 MW load, and then decreased to 1.2 bar during load reduction to 10 MW.

Based on these results it was concluded that the RLZ occurrence causes significant redistribution of rotor axial forces. Axial force acting on turbine runner is minimizing the impact of the axial force in thrust bearing. Described redistribution of forces is measurable in the rotor part between axial bearing and turbine runner. In the rotor part above the axial bearing there are no axial forces, causing axial displacement measured on top of the generator to be smaller than axial displacement measured on the turbine cover. This indicates that RLZ occurrence causes static instability of the rotor, due to a significant axial force generated below the turbine runner.

Figure 3 shows 130 sec of waveform raw data for:

- relative shaft radial vibrations measured on turbine and generator bearings (top diagram),

- active power and draft tube pressure (middle diagram)

- rotor axial displacement measured on top of the generator and turbine cover (bottom diagram).

All the waveforms are processed through the low pass filter, with cut off frequency at 1 Hz, to show only the subharmonic frequency components.

Besides the static signal components (vectors and scalars), already shown on figure 2, this waveform diagram contains the dynamic signal component as well.

It is visible that the low frequency variations are present on all signals shown on Figure 3, with the frequency of 0.8 Hz.

During this event (load reduction), dynamic component of vibration and pressure pulsations start nearly simultaneously, and from the data it is not possible to determine the sequence of dynamic instabilities.

However, during load increase operation (diagrams on figure 4) it is clearly visible low frequency vibrations at 0.8 Hz, starts almost 10 seconds before dynamic pressure pulsations. This is very significant result, indicating that vibrations on 0.8 Hz frequency are not caused by hydraulic pressure pulsations below the turbine runner.

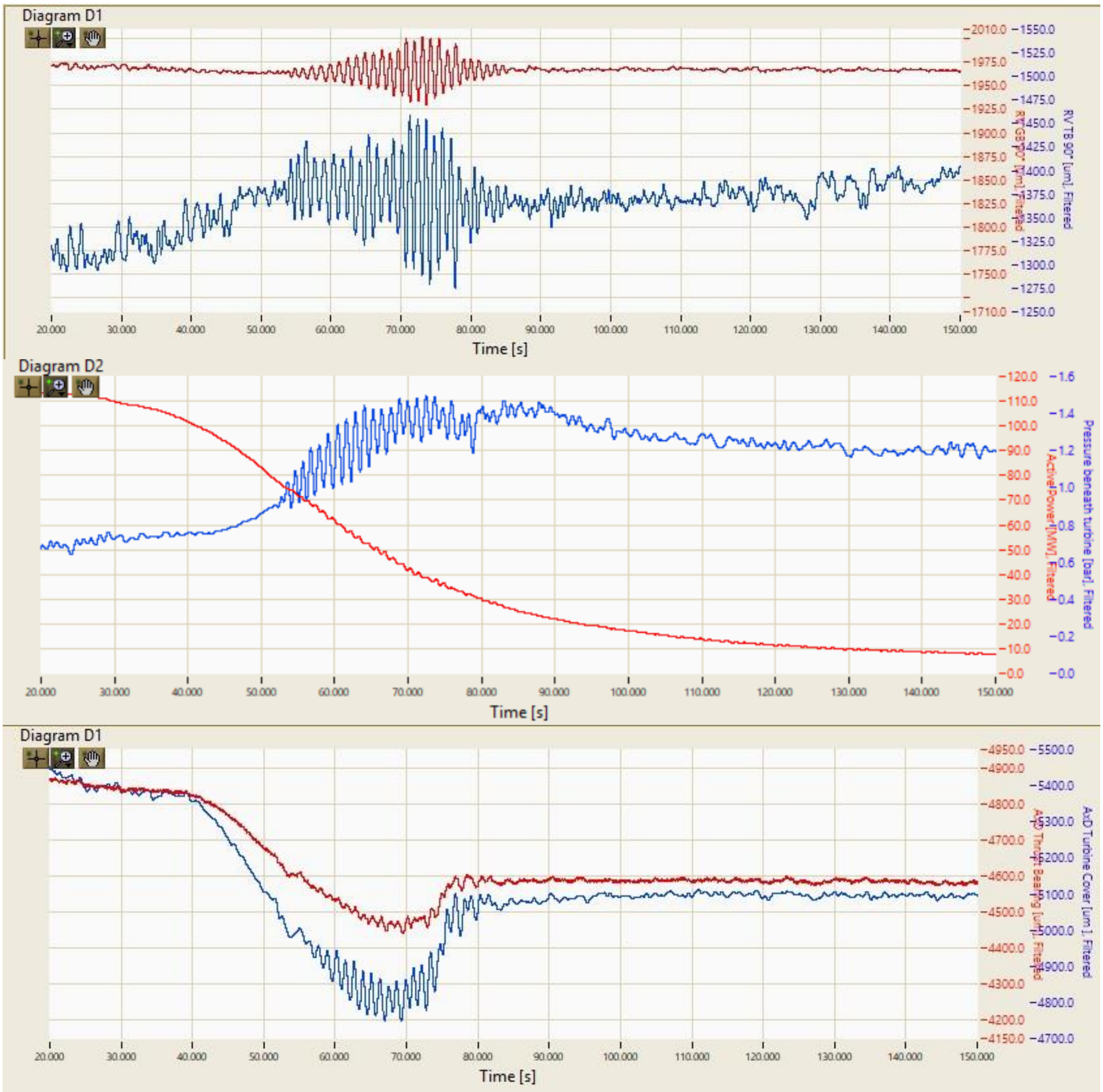

Fig. 3 - Dynamic signal components during RLZ occurrence, load reduction operation – Radial relative shaft vibrations on generator (blue) and turbine (red) bearing on top diagram, active power (red) and static draft tube pressure (blue) on middle diagram, axial displacements on top of generator (red) and turbine cover (blue) on bottom diagram

During RLZ operation the appearance of vortex below turbine runner is a common phenomenon. In this paper there are no direct indications of vortex appearance, except draft tube pressure pulsations (below the turbine runner), which are obviously related. Due to a fact that data presented in the paper are insufficient for detailed vortex appearance diagnostics, this part of analysis is omitted.

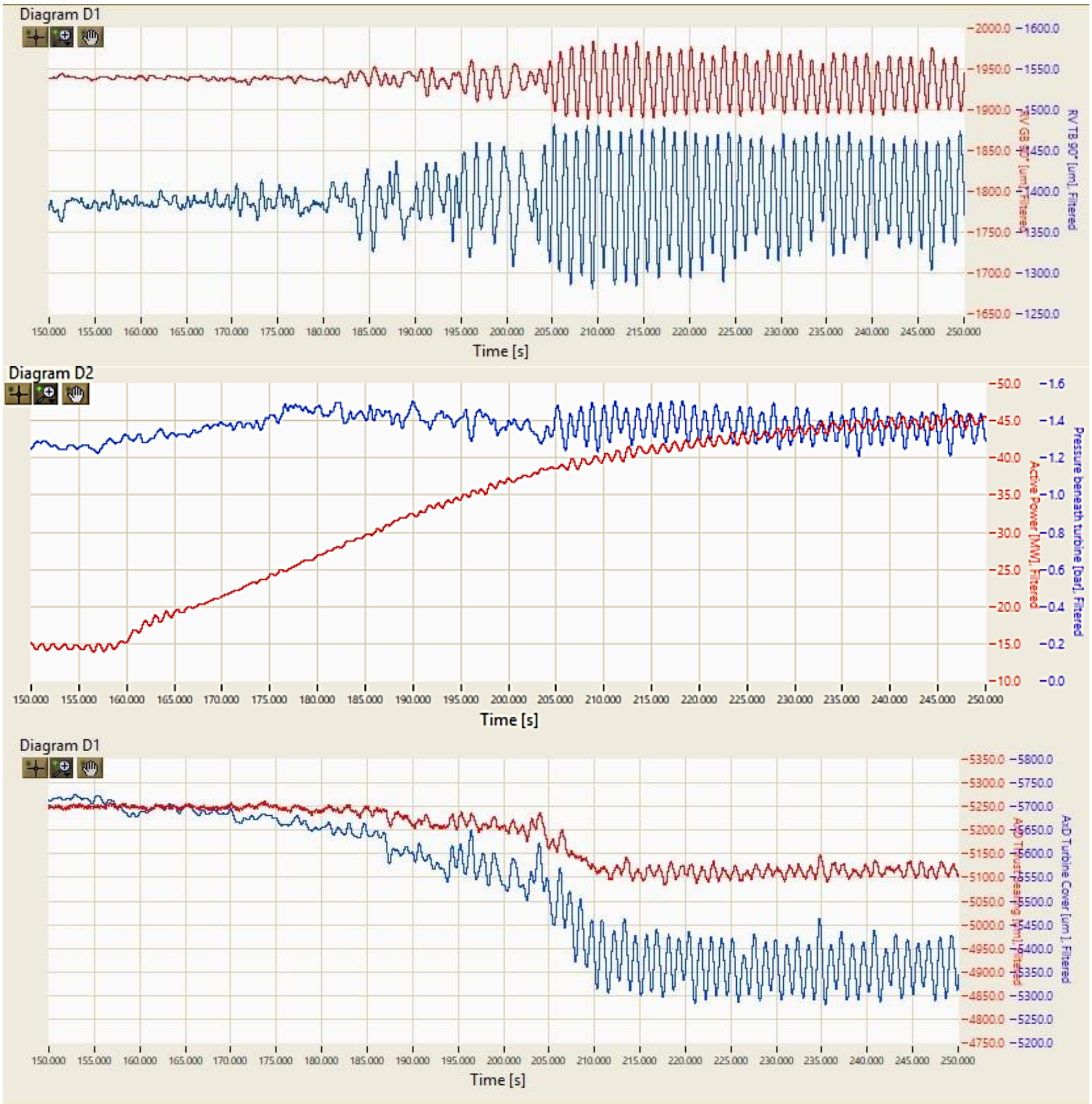

Fig. 4 - Dynamic signal Waveforms during RLZ occurrence, load increase operation – Radial relative shaft vibrations on generator (blue) and turbine (red) bearing on top diagram, active power (red) and static draft tube pressure (blue) on middle diagram, axial displacements on top of generator (red) and turbine cover (blue) on bottom diagram

The conclusion that pressure pulsations are not causing the vibrations to increase leads to a question of the cause and and nature of vibrations. Vibrations can either be forced or self-excited, as a consequence of instability conditions. Results presented in figure 4 diagrams are indicating the conclusion that rotor vibrations in radial and axial directions are self-excited.

It is common knowledge that self-excited vibrations appear only on lowest resonant frequency and rarely on higher resonant frequencies. If 0.8 Hz frequency is really the lowest resonant frequency of Unit 1, why is it excited only during RLZ occurrence and not in other load ranges as well?

The explanation can be found on diagrams shown on figures 3 and 4. During RLZ occurrence (same for load increase and reduction), the whole rotor is lifting. With the maximal intensity of RLZ the highest rotor position is achieved. This is a result of axial force appearance in draft tube, reducing the load on the axial bearing. Due to this axial bearing load reduction the axial bearing oil film thickness increases, causing significant reduction in axial bearing stiffness. Bearing stiffness reduction causes self-excited vibrations at resonant frequency of 0.8 Hz.

3.2 Results for Unit 2

Analysis results for Unit 2 are based on a slightly different measurement layout compared to Unit 1, with axial displacements on Unit 2 measured only on axial bearing, tracking the axial bearing oil film and axial bearing segment support springs. Axial displacement sensors on top of generator and on turbine cover, as well as draft tube pressure sensors, were not installed on Unit 2.

Figure 5 shows the scalar and vector values of:

- radial relative shaft vibrations on the generator and turbine bearing - on top diagram

- rotational speed, active power and axial displacement - on bottom diagram.

All values were recorded during load increase operation.

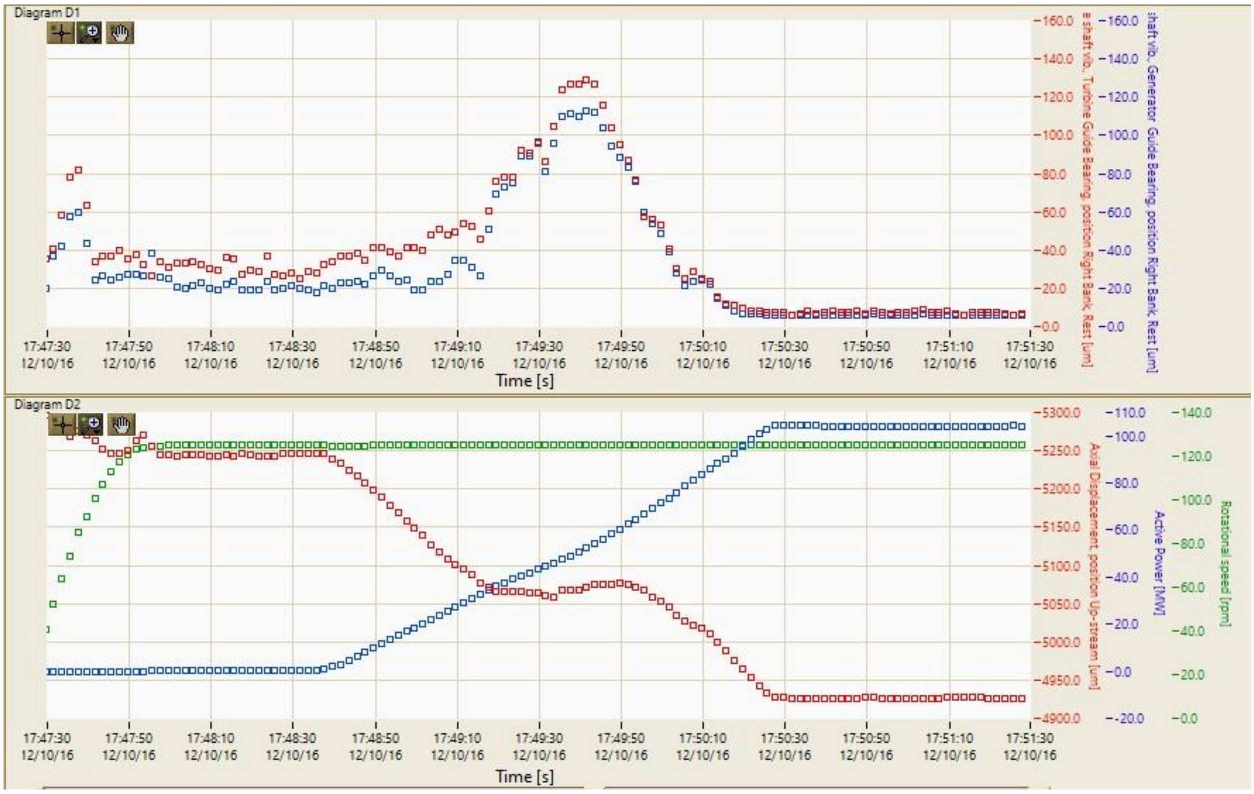

Fig. 5 – Radial relative shaft vibrations REST value on generator (blue) and turbine (red) bearing on top diagram, active power ascending from 0 to 108 MW (blue), axial displacement of rotor referred to axial bearing bracket (red) and rotational speed (green) on bottom diagram

Similar axial displacement response described on Unit 1 is also present on Unit 2. The measurement direction of axial displacement sensor on Unit 2 is opposite from direction of sensors on Unit 1. Thus, the axial displacement signal increases when rotor lifts and vice versa.

When load starts to increase, the rotor is moving down, due to ascending axial force caused by the water. With RLZ occurrence, axial displacement signal stabilizes and even lifts (same behavior is already noticed at Unit 1).

Outside the RLZ the rotor is moving down again with the load. During RLZ vibrations increase on 0.5 Hz frequency, as shown on figure 5. Additionally, Unit's 2 accelerometer on axial bearing bracket measured excessive absolute axial vibrations on 0.5Hz.

Figure 6 shows the waveforms data recorded on 45MW:

- rotor relative axial displacement to axial bearing bracket on two measurement positions – upper diagram

- axial bearing bracket vertical displacements (green) – upper diagram.

- radial shaft vibrations on generator and turbine bearing - lower diagram

- diagnostic trigger signal (single pulse per revolution) - lower diagram

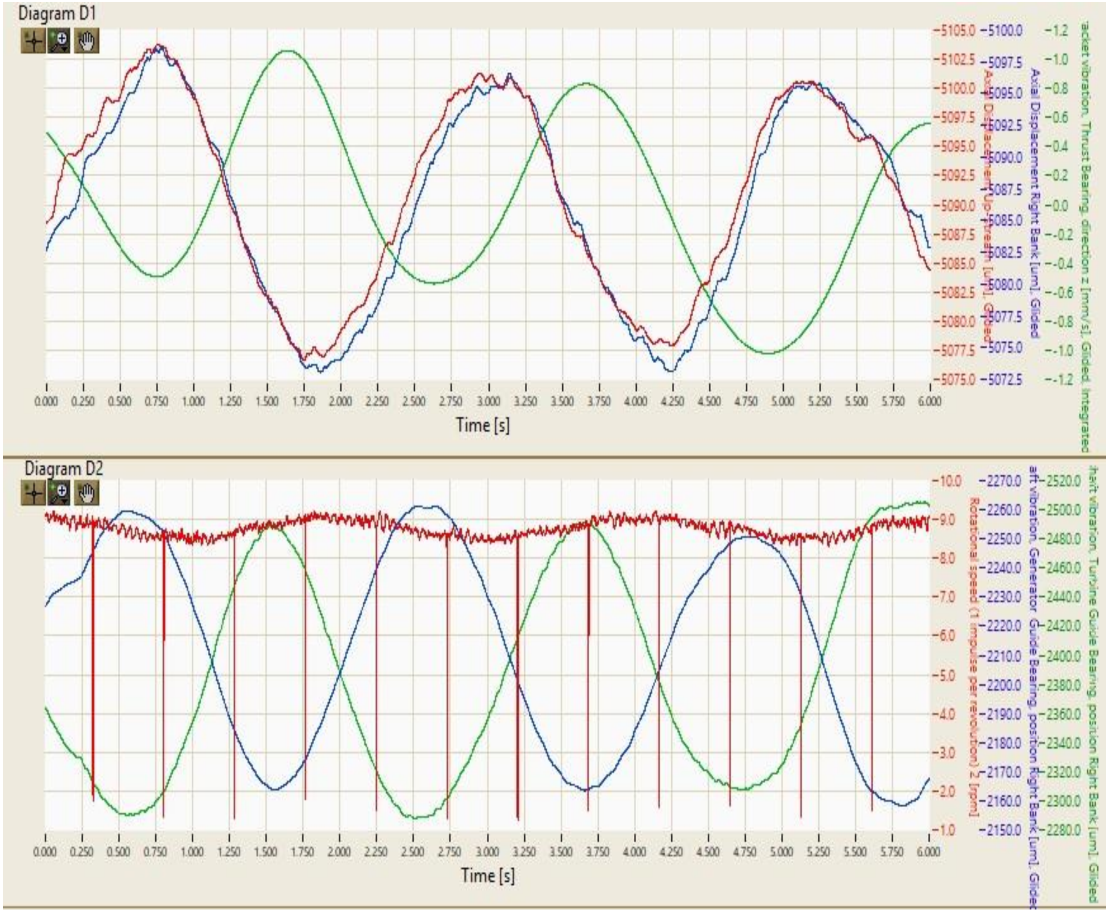

Fig. 6 – Rotor axial displacement (red and blue), axial bearing bracket displacement (green) on top diagram, relative radial shaft vibrations on generator (blue) and turbine (green) bearing and diagnostic trigger signal (red) on bottom diagram. Data recorded on 45 MW (RLZ)

During RLZ the dynamic component of rotor relative axial displacements to axial bearing is about 40 µm p-p[2] value.

However axial bearing bracket displacements, calculated from accelerometer mounted on the bracket, reaches up to 1.5 mm p-p.

Radial relative shaft displacements on generator and turbine bearing are opposite in phase, same as measured at Unit 1. This indicates the “tilt” of the whole unit around the point between the generator and turbine.

It is important to mention that outside the RLZ power span, there are no vibrations on 0.5 Hz frequency and shaft displacements are in phase.

Such extremely high displacement levels, measured on axial bearing, indicates that the whole generator is moving with 0.5Hz for 1.5mm p-p.

These excessive vibrations eventually cause cracks in bearing to foundation supports and limit the machine operation to power span only outside the RLZ.

3.2 Results for Unit 3

Relative shaft vibrations were measured on all three guide bearings and rotor axial displacement was measured on top of generator similar to measurements on Unit 1. Draft tube and spiral case pressures were measured as well.

[2] P-P = Peak to Peak

Figure 7 shows the waveforms recorded during load increase from 15- 50 MW:

- active power dynamic component
- axial displacement dynamic component
- draft tube pressure
- spiral case pressure.

All the signals are band-pass filtered in frequency range 0.1 to 2 Hz.

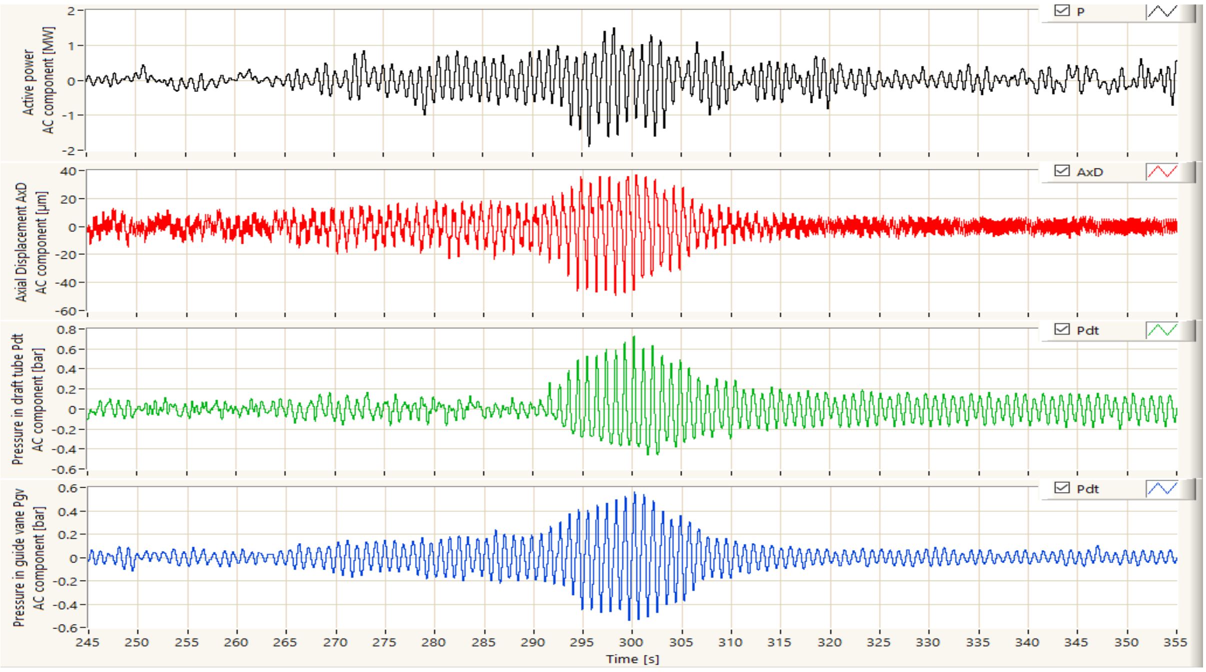

Fig. 7 – Bandpass (0.1 to 1 Hz) filtered waveforms of active power (black) on top diagram, axial displacement on top of generator (red), draft tube pressure (green), spiral case pressure (blue), recorded during load increase at 45 MW load

Figure 8 shows the trend values such as scalars and vectors:

- active power
- axial displacement
- draft tube static pressure
- spiral case static pressure
- radial relative shaft vibration p-p values

RLZ occurs after about 300 seconds of load increase at about 40 MW.

Sudden significant increase of turbine guide bearing relative shaft vibrations occurs in this moment. Significantly smaller increase of vibrations is also recorded at lower generator bearing, while vibrations increase on upper generator bearing are almost negligible. The characteristic low frequency for this unit is 1 Hz. Additional to radial relative shaft vibrations there is also an appearance of axial rotor vibrations, draft tube and spiral case pulsations, and little but noticeable active power oscillation, all appearing on 1 Hz.

As already measured on Unit 1, axial rotor vibrations (dynamic component of axial displacement) precede the draft tube pressure pulsations, confirming the self-exciting nature of response to operating in RLZ.

Most significant results are presented on top diagram on figure 8. With RLZ occurring at about 40 MW, draft tube static pressure (below turbine runner) increases rapidly and simultaneously with rotor axial displacement (measured referred to upper support bracket). As measured at Unit 1 and Unit 2, during RLZ occurrence rotor is moving upward, reducing load at axial bearing.

That is the moment when radial and axial vibrations start to appear on 1 Hz frequency. Static pressure in spiral case is decreasing continuously from 16.7 bar at 0 MW load to 15.8 bar at 105 MW load with no visible changes induced by RLZ.

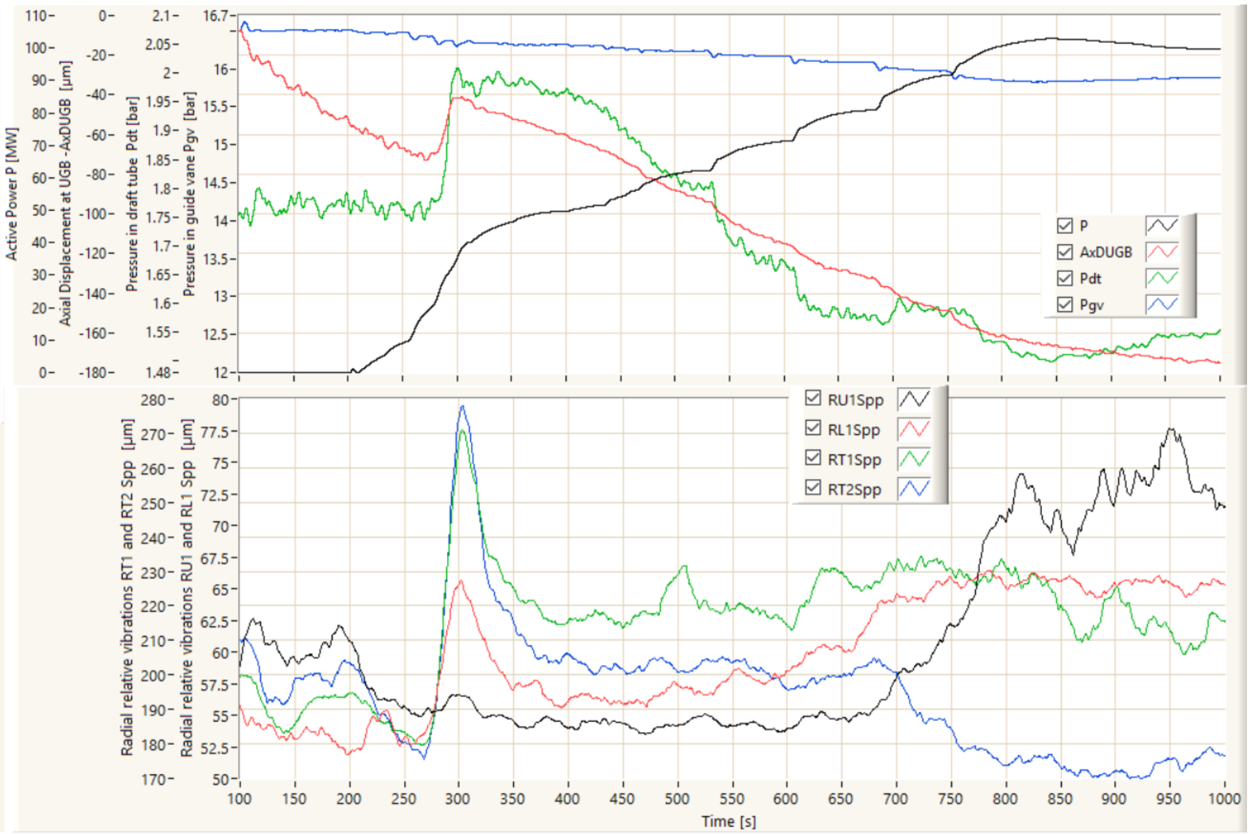

Fig. 8 – Static axial displacement (red), draft tube pressure (green), spiral case pressure (blue), active power (black) on top diagram. Radial relative shaft vibration p-p values at upper generator bearing (black), lower generator bearing (red), turbine bearing both directions (green and blue).

4. Conclusion

Rough load zone (RLZ) often occurs at most hydro units with Francis turbines in load range of typically 30%-50% (sometimes event to 70%) of rated power. With RLZ the significant radial and axial rotor vibrations appear on subharmonic frequencies (typically 0.5-1 Hz). Simultaneously with vibrations, draft tube pressure pulsations occur on the same frequencies. The paper presents two cases where vibration appearance precedes draft tube pulsations (or appear simultaneously). Draft tube pulsations preceding vibration occurrence is not recorded in any of three cases.

This is an indicator that pressure pulsations are not cause of vibrations but vice versa. Concerning that during RLZ operation there is no external dynamic force on such a low frequency a conclusion is imposed that vibrations generated during unit operation under RLZ conditions are self-excited. On all three analyzed units the rotor lift (upward movement) is recognized, together with reduced axial bearing load. The most probable cause of this rotor lift is the increase of static pressure during RLZ (maximal pressure is measured in the middle of RLZ), resulting in static axial force with direction opposite to rotor's weight.

Load reduction on axial bearing causes decrease of bearing stiffness and resonant effect appearance at low frequencies at which the self-excited vibrations are generated.

High axial vibrations measured on thrust bracket appear on low frequencies, below 1 Hz, which results with large axial displacement of rotor and bracket and consequently with cracks in bracket to foundation supports. Same frequencies are measured on radial vibrations as well, pointing to machine low frequency resonance appearing as result of self-excited vibrations.

Possible procedure to lower the level of vibrations generated during RLZ is lowering the static pressure in draft tube at the moment when RLZ starts, under condition that such procedure is possible.

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The Authors

Ozren Husnjak

Education: Master of Science at Department of Physics, Faculty of Science in Zagreb

Working experience: Four years (2002.- 2006.) employed as an assistant at Department of Physics

involved in experimental laboratory research on superconductivity.

Since 2006. employed at VESKi on software development, vibration troubleshooting and problem solving.

Ozren worked on numerous Machine Condition Monitoring projects as system commissioning engineer and as a technical expert for machine condition evaluation. Ozren has written and contributed to more than 20 papers published on international conferences.

Ozren Orešković

Education: Master degree at Faculty of Mechanical Engineering and Naval Architecture in Zagreb

Working experience: over 15 years of experience, employed at VESKi.

From 2004-2009 Worked as Field Service Engineer commissioning Machine Condition Monitoring systems and troubleshooting vibration problems on rotating machines.

From 2009-2012– Working as Sales and Marketing manager at VESKi

From 2012 – Works as CEO at VESKi

Ozren has written and contributed to more than 15 papers published on international conferences.

Franjo Tonković

Education:

- Master degree at Faculty of Electrical Engineering in Zagreb
- National Instruments (NI) Certified LabVIEW Architect (CLA)

Working experience:

- 2018 – Current 4-cube –CEO and Lead SW Developer
- 2010 – 2018 VESKi Ltd – Lead Research and Development Engineer and SW Developer
- 2008 – 2010 National Instruments – Measurement and Automatization Expert

Franjo is an expert in planning and implementing development projects, particularly new software and hardware modules for CoDiS, keeping them on schedule from start to completion date. This includes assessing technical feasibility of concepts and confirming operational compatibility, managing activities listed in project timelines and monitoring output of all project participants, including co-workers, contract manufactures and consultants.