Root cause analysis on a 110 MW hydro unit based on vibration and air gap monitoring data

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Abstract

The paper describes the root cause analysis of increased turbine shaft displacements on a 110 MW hydro-unit. A monitoring system, which collects vibration, flux and air gap data continuously, detected an unstable machine vibro-dynamic behaviour, manifested through the abrupt (and excessive) shaft displacement and vibration increase on turbine guide bearing (TGB) as well as on generator guide bearings. TGB displacements reached 500-900 µm peak-to-peak and machine was put out of operation. Even though everything pointed to turbine related problem the analysis showed that, alongside vibration increase, the unusual continuous increase in air gap values was present as well, followed by rotor concentricity offset. All resulted in disrupted unit shaft line and consequently with increased shaft displacement on TGB. The paper clearly shows how analysis and cross-correlation of vibration and air-gap signals is crucial in successful diagnostics and localization of the root cause on hydro generators.

Intro

The vibration amplitudes on a 110 MW hydro-unit, during the first days of operation following commissioning, were stable. The relative shaft vibration amplitudes were only slightly above those recommended by ISO 20816-5 standard, for long-term operation.

Destabilization of the unit's vibro-dynamical behaviour began with a slow, continuous and almost linear increase in vibration amplitudes. During the ten (10) days period the vibrations on turbine guide bearing (TGB) increased to extremely high levels, while the vibration increase on the upper guide (UGB) and lower guide (LGB) bearings was significantly lower. The abrupt (and excessive) vibration increase appeared after a period of linear vibration increase and manifested through vibration variation from 500-900 µm peak-to-peak of shaft displacements in turbine guide bearing region. Following the vibration increase, there were changes in the unit's air gap signals as well.

After the abrupt vibration increase, the vibrations were stabilized at extreme values of ~600 µm peak-to-peak. This condition was present for approximately one month after which the vibrations started decreasing. They were reduced to half of the values and after 10 days were, again, at levels similar to those before the destabilization began.

During the entire time, the unit was operating on high loads (above 90 MW) without stopping.

By comparing vibration and air-gap signals the authors tried to diagnose and localize the destabilization root cause.

Long-term (6 months) trends of vibration data are given on Fig 1.

Generator data:

Nominal speed: 300RPM Francis turbine

Suspended type

Nominal Operating Power: 110MW

Nominal design air gap: 32 mm

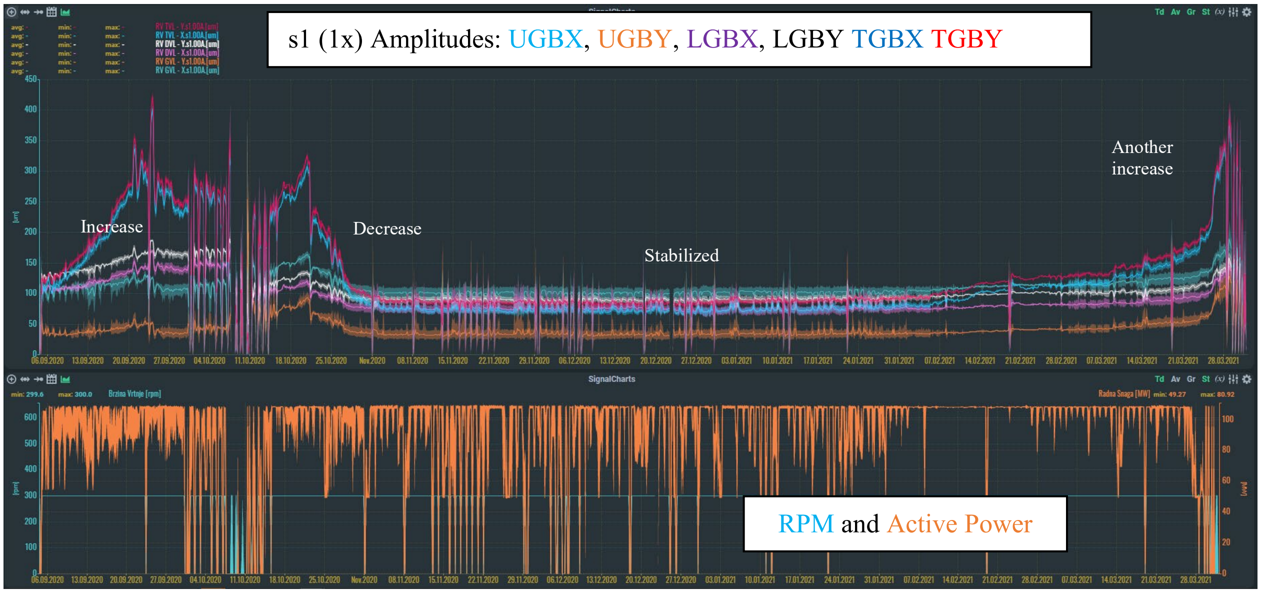

Fig 1 Long-term trends. TOP DIAGRAM: 1x harmonic (relative vibrations peak) for all bearings; BOTTOM DIAGRAM: Rotational speed and active power during the 6-month period.

1. Measurement system, measurements and analysis procedures

The unit is equipped with monitoring system which consists of vibration monitor and, additionally, air gap and magnetic flux monitor. The monitoring system is capable of accepting different type(s) of signal(s), analyse them simultaneously and add them to a common database. Four (4) air gap sensors are installed on the top of the stator core, at equidistant angles (90°). Also, one (1) magnetic flux sensor is installed at position of 0°, next to the air gap sensors.

The monitoring system is connected to the SCADA system from which process parameters are obtained. These, among other, include bearing, core, clamping finger and winding temperatures, unit's electrical and hydraulic parameters etc. All of these are very important for the dynamical state diagnostics as the vibrations can vary significantly with regime change. All processing parameters are being written into the system's diagnostic common database along with the data from the measurement system sensors.

Fig 2. shows the layout of the monitoring system installed and the sensor layout. The unit is of suspended type where the thrust bearing is above the generator and, in this case, thrust + guide bearing is of combined type and supported by the generator stator frame.

It is necessary to properly understand the most important calculated sensor signal values (descriptors) for the vibrations and air gap sensors. These are continuously being written to the monitoring system historical database and enable the continuous historical analysis of recorded data and therefor the root cause analysis.

For the relative vibration sensors (and similarly for the absolute vibration sensors) from each data block (raw signals from the sensors), the following descriptors are continuously being calculated:

- Smax – this is the maximum vibrational shaft displacement in a measurement plane obtained from two, mutually perpendicular, sensors; this parameter was defined in ISO 7919-5 standard and was relevant until 2018 when the new ISO 20816-5 standard replaced the old ones; it's being written to the database even when the unit is stopped
- Sp-p – this is the peak-to-peak vibrational shaft displacement which are relevant according to the new ISO 20816-5 standard from 2018.; it's being written to the database even when the unit is stopped
- Amplitude (peak) of vibrational shaft displacement and the appropriate phases (relative to once-per-revolution signal) of the first (s1n), second (s2n) and third (s3n) harmonic of the rotational frequency
- Rest value of the vibrational shaft displacement – this is the overall vibrational shaft displacement from which the first three harmonics have been subtracted thus indicating vibrations on other frequencies

- statical (DC) vibrational shaft displacement; it's being written to the database even when the unit is stopped

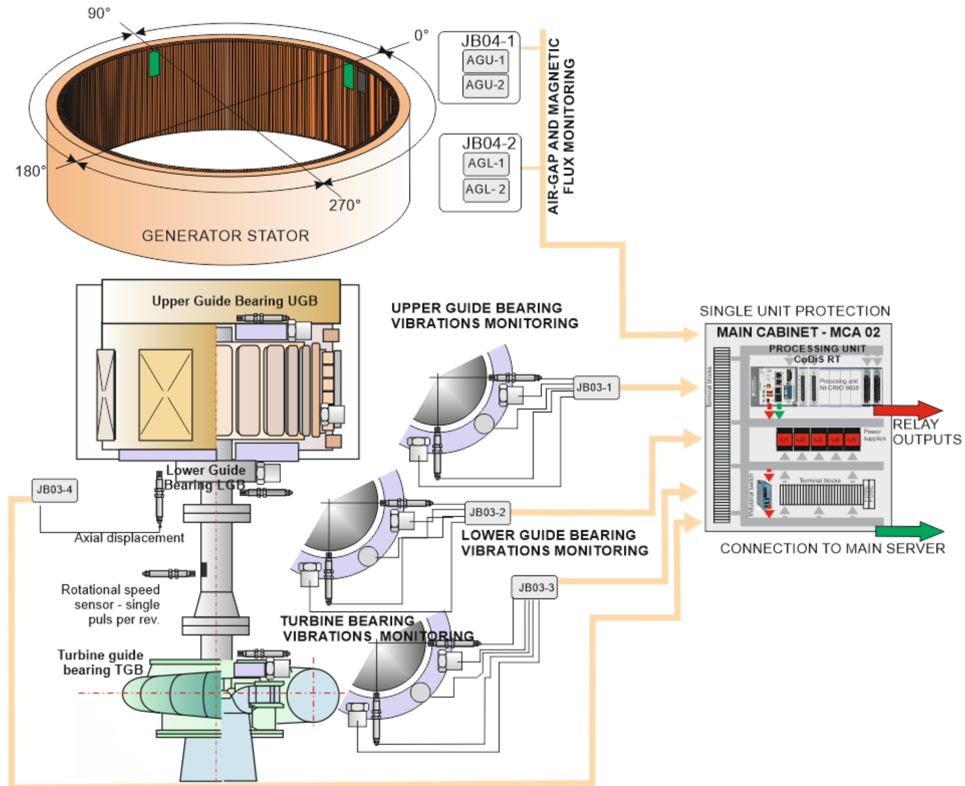

Fig 2. Sensor layout of installed online monitoring system

For the air gap (and magnetic flux) sensors from the same data blocks [1] the following descriptors are continuously being calculated:

- Air gap value of each pole passing the sensor
- Maximum air gap value and position (pole number)
- Minimum air gap value and position (pole number
- Average (DC) value of all air gap values by pole
- First (1x) and second (2x) harmonic (amplitude and phase, relative to once-per-revolution signal) of
- rotational frequency for rotor within the air gap
- Average (DC) value of the air gap sensor signal; it's being written to the database even when the unit is stopped

2. The first vibration destabilization

The vibration increase began after five (5) days of continuous unit operation on loads above 90% full load. The unit's temperatures were stabilized (unit reached steady-state operating temperatures).

Fig. 3 shows trends of 1x harmonic of relative shaft vibration for each bearing plane (X and Y directions, mutually perpendicular), DC value at each proximity probe for each bearing plane (X and Y directions, mutually

[1] Data block is a signal sample for analysis in duration of 4s

perpendicular), DC values of the air gap (average of all poles), process parameters (stator core temperature, active power, rotational speed).

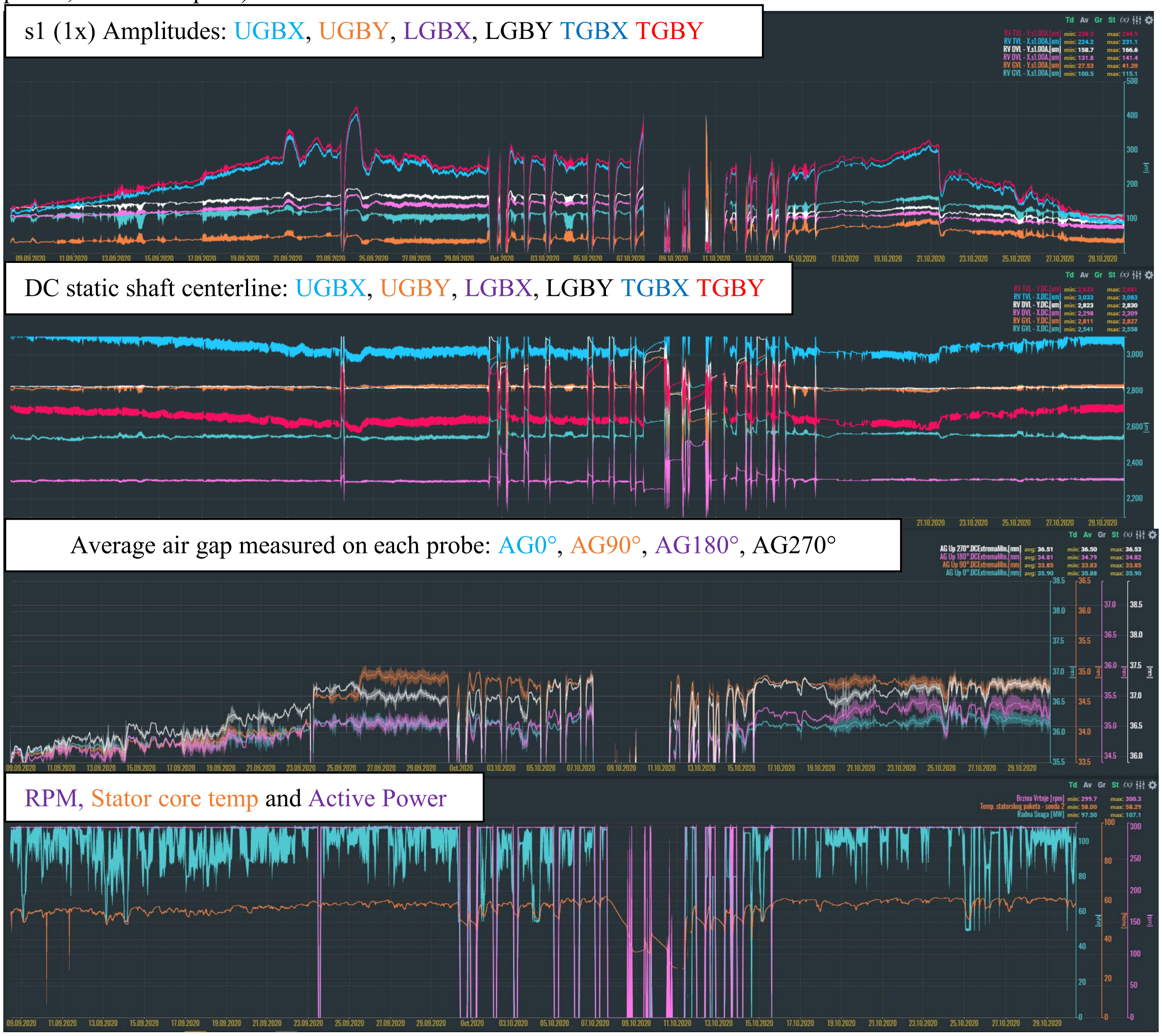

Fig. 3 DIAGRAM 1 (TOP): 1x harmonic (relative vibrations peak); DIAGRAM 2: Statical shaft position on UGB, LGB and TGB; DIAGRAM 3: Average (DC) value of all air gap values by pole; DIAGRAM 4 (BOTTOM): Stator core temperature, active power, rotational speed.

The diagrams show trends of the mentioned descriptors during the one-month period where the unit almost continuously operates at loads close to full load. Also, from the trend beginning the unit is already thermally stabilized. This is best seen by the stator core temperatures which are, practically, unchanged during the entire analysis period.

From the beginning of trends on Fig. 3, till September 21st the vibration amplitudes on turbine bearing (TGB) increase, practically, linear to values of ~250-300 µm. On UGB and LGB this increase exists too, but is much slower. On LGB the values reached are ~140-180 µm and on UGB in direction X up to ~120 µm and in direction Y ~50 µm.

From September 21st begins the uncontrolled vibration increase in which the vibration amplitudes on TGB exceed 400 µm peak values.

The statical (DC) shaft positions on UGB and LGB are, practically, unchanged during the entire analysis period, and the same statical shaft positions on TGB are continuously changing up to the moment the vibrations increased abruptly and excessively. After the vibration have stabilized at very large values (250-300 µm on TGB, 160 µm on

LGB and 100 μm on UGB) the statical shaft position stops changing on TGB (red and blue lines on diagram 2, Fig 3.).

Very unusual properties are visible on trends of average (DC) values of the air gap[2].
It is important to note that in the DC value of the air gap all of the rotor vibration influences are eliminated, so this descriptor only contains information about the rotor statical position and stator core thermal expansion. Of course, rotor thermal expansions are also influencing the air gap but this influence is smaller by an order of magnitude from the stator core thermal expansion in operation.
The bottom two diagrams (diagrams 3 and 4) on Fig. 3 show process quantities (stator core temperature, active power, rotational speed) and average (DC) value of all air gap values by pole for all four (4) air gap sensors. The vertical scale range for air gap is 3 mm and the way the starting point is selected is that at the diagram beginning all of the air gaps start from the same point. In this way, changes in air gap on all measurement positions can be tracked visually. For example, the scale of sensor at 0° is from 35.5 mm to 38.5 mm and the sensor at 270° from 36.0 mm to 39.0 mm.

It is noticeable from Fig. 3 that the air gap continuously increases even though machine operates at the same load and in the same thermal conditions. The air gap increase is smaller in the 0°-180° direction (this is direction X) than in the 90°-270° direction (this is direction Y).
It should also be noted that the trends of changes in the air gap data and TGB statical shaft positions correlate. There is a simultaneous increase in the air gaps and changes in the statical shaft positions on TGB, after which the vibrations on TGB stabilize along with the shaft statical position. At the same time, the increase in the air gap stops.
So, it can be clearly seen that there is a correlation between the increase in the shaft vibrations, shaft statical position in TGB and the average air gap value.
The continuous increase in the air gap, in steady-state thermal and operating conditions indicates there is a stress induced on the generator parts such as, for example, the stator frame to core interface or upper guide bearing bracket arm beams (which is braced against generator stator). This kind of increase is hardly possible without the irreversible deformation of some construction part(s).
The authors think that it is possible that the asymmetry of radial deformations on the upper bracket connection to stator frame, caused a shift of the upper guide radial bearing centre and its bracket on which the upper guide bearing is founded. These displacements can result in the entire rotor line displacement, due to which shaft's run-out in the turbine region is increased and, consequently, vibrations are increased.
In the conditions which were permanently present after September 30th the unit was continuously operating with very large vibrations for the next twenty (20) days, followed by sudden decrease in the vibrational amplitudes. As shown on Fig. 3 at the end of the process it seems that the vibration-wise the unit state has stabilized (if only shaft displacements were observed).
In the same time period, the statical shaft position at TGB returned to it's original position before the vibrations started increasing.
It is also visible that change in shaft statical position was followed by decrease in shaft displacement (relative vibrations) on TGB.

3. The second vibration destabilization

The second vibration destabilization manifested as a slow and continuous vibration amplitude increase. As in a previous destabilization, the fastest increase was on a turbine bearing. An abrupt vibration increase occurred after six (6) months when the vibrations on TGB increased for 100 μm (from 220 to 320 μm) in one day. Fig 4. shows changes for the same vibrational descriptors (calculations) as those on Fig. 3 when new changes (vibration increase) were present.

At the end of the diagram, the amplitudes of the first harmonic of relative vibrations on TGB reached 300 μm peak in X and 320 μm in Y directions.

Average air gap values on four (4) sensors (second diagram on Fig. 4) have increased when compared to the beginning of the process (Fig. 4) and during the entire period from the first destabilization. It is noted that the stator core (and most probably the frame) thermal deformations are present manifested through continuous air gap increase.

The air gap values in the same operating regime are, on average, 2 mm larger when compared to the period before the first destabilization as shown on Fig. 5.

[2] Average air gap on a sensor calculated from all pole minimums

Fig. 4 DIAGRAM 1 (TOP): 1x harmonic (relative vibrations peak); DIAGRAM 2: Statical shaft position on UGB, LGB and TGB; DIAGRAM 3: Average (DC) value of all air gap values by pole; DIAGRAM 4 (BOTTOM): Stator core temperature, active power, rotational speed.

The diagrams on Fig. 5 show the filtered plot of the daily air gap average value (DC) only on 90-100 % full load. Regression curve is also shown.

This kind of continuous air gap increase, obviously influences the rotor concentricity (change in rotor centreline position from ideal centre). Fig. 6 shows an air gap polar plot of the rotor and stator geometry in different time periods; Sep. 10th 2020., Sep. 24th 2020., Nov. 23rd 2020. and Mar. 22nd 2021.

It is visible that the rotor shape did not change, and continuous increase in stator core diameter is present, which manifests as through the air gap increase (shown on Fig 5). A gradual change in rotor concentricity[3] moving from its ideal centre is also present.

The figure 6 shows a change in rotor concentricity for 1.2% of nominal air gap, or ~0.5 mm in 6-month period.

The conclusion following from the graphs is that the entire upper guide bearing bracket, including the Upper guide bearing, which is founded on the bracket, has shifted along with the rotor (clearly visible from Fig 6), disrupting the shaft centreline of the unit, from the upper guide bearing to turbine bearing. This also explains the fact that statical shaft displacements relative to the bearings are not changing on upper generator bearing but are changing on turbine guide bearing. This way the shaft centreline is out of tolerance, which explains the low-speed run-out measured on turbine guide bearing.

[3] Rotor current centre position compared to ideal rotor centre

Minimum air gap value (which is automatically calculated in the polar plot on Fig 6) has increased during the first destabilization for 1.05 mm (from 33.08 mm to 34.12 mm) and, after the second destabilization increased additionally to 35.03 mm.

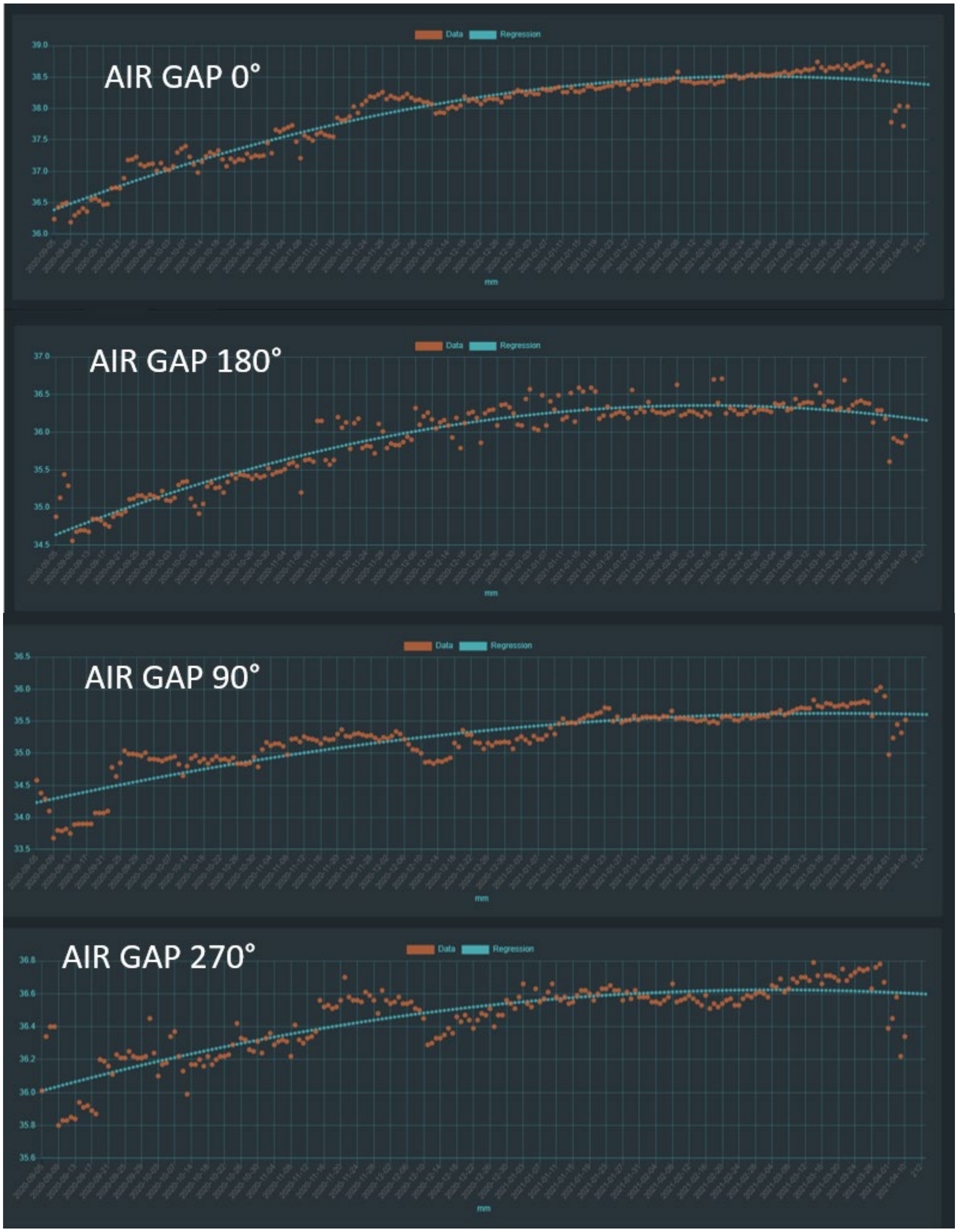

Fig. 5 Average daily (DC) value of an air gap signal, from each sensor, for a 6-month period, filtered to operation at full load.

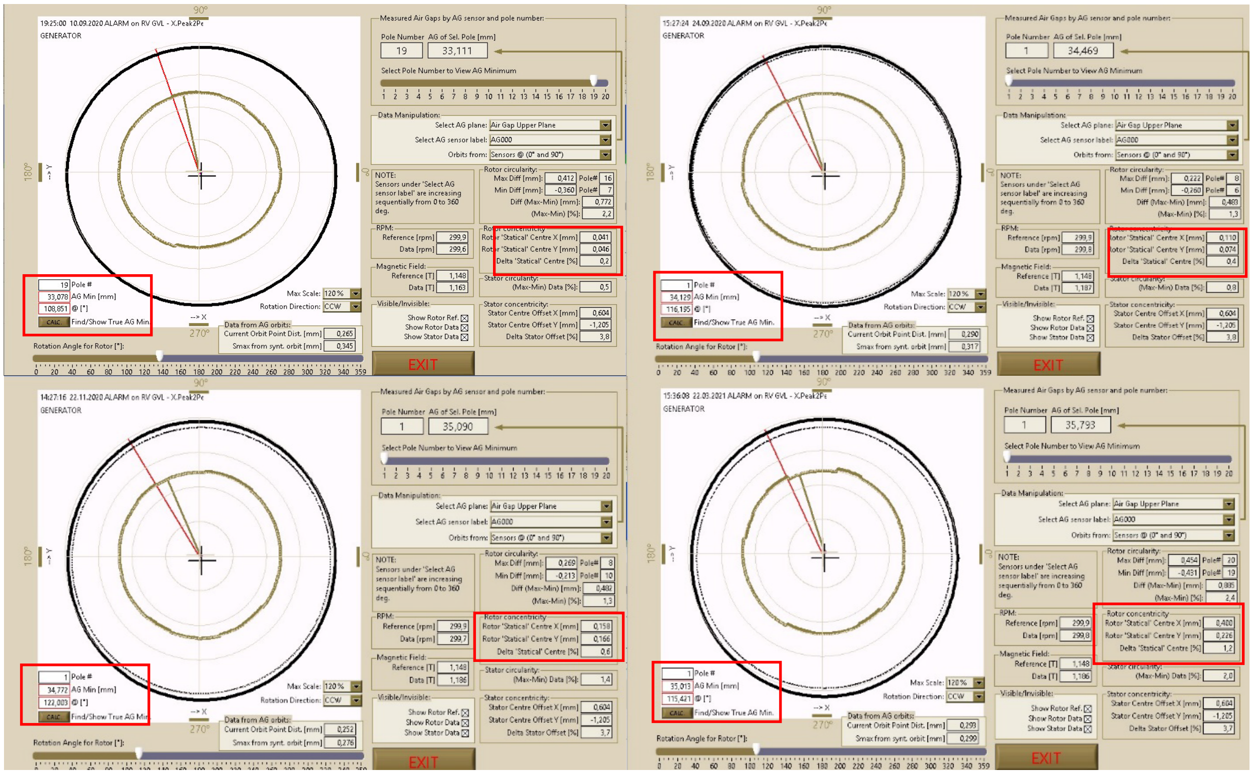

Fig. 6 Air Gap polar plot analysis at the beginning, middle and end of the process. Plots taken for steady-state operation on full load (100-110MW).

Table 1 – value readouts for air gap and rotor concentricity offset

Date	Air Gap minimum (mm)	Rotor concentricity offset (% of nominal gap[4])
10.09.2020	33.08	0.2
24.09.2020	34.12	0.4
22.11.2020	34.77	0.6
22.03.2021	35.03	1.2

As seen from diagrams on Fig 6 as well as the table 1 an average air gap, observed from pole No1, has changed for 2.6 mm and the rotor centre position has shifted (rotor concentricity offset) for additional 1% of nominal air gap.

4. Conclusion

This paper shows the process of vibration and generator air gap signal cross-correlation, with the purpose of determining the root cause of a turbine shaft vibration displacement increase. At first it seemed that the problem is related to the turbine rotor, considering the vibrations were increasing rapidly on turbine guide bearing.

However, an in-depth analysis of historical monitoring system data, and cross corelation of air gap and shaft displacement data resulted with an entirely different root cause, which is a generator bearing concentricity shift.

The actual root-cause, which resulted with a rotor and bearing centre shift is still being evaluated by the owner. Most probably it is related to stator core heating, which is causing the core and frame thermal expansion and consequently a generator bracket deformation leading to rotor and bearing concentricity offset.

[4] The offset is calculated to a rotor ideal position, compared over nominal air gap value

The paper shows how proper correlation of multiple measurement technologies can be utilized in order to perform a more in-depth root cause analysis on hydrogenerators.

Cross correlation of multiple signal indicators (e.g. first harmonic of shaft displacement, static shaft centreline position, average airgap and air gap concentricity) enables to reconstruct a more complex behaviour and failure mechanisms, and conclude about the possible sources.

This clearly indicates the great importance of installing a comprehensive machine condition monitoring on hydro generators as well as the importance of having the right software tools to present the data in a meaningful manner.

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