Machine condition assessment of a 415 MW unit based on off-line and on-line measurements

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Abstract

The paper describes different diagnostics methods, both off- and on-line, that were applied during and after the overhaul on 415 MW vertical Francis hydro-unit, in order to obtain insight into its mechanical state condition for safe operation and future refurbishment.
These included, but were not limited to: visual inspection of different mechanical components, NDT tests, slow-roll rotor and stator geometry , stator frame expansion, vibration, air-gap and magnetic flux on-line measurements.
From the slow-roll rotor and stator measurements it was concluded that the rotor geometry was out of tolerance, with some of the poles protruding by ~2 mm for the 22.6 mm air-gap design value. This had a notable influence on the vibration response, especially when comparing the difference between mechanical rotation vs. that of the excited unit. The on-line analysis and cross-correlation of vibration signals with the air-gap and stator frame expansions showed the influence of rotor geometry on the stator core and frame vibrations, by introducing the 2x component.
The machine also experienced uneven stator frame (and core) radial expansions during load and temperature increase, later confirmed to be due to blocked soleplates, resulting with stator shape and concentricity deviations, that also had an influence on the unbalanced magnetic pull in, both, top and bottom generator planes.
The campaign resulted in recommendations on improvement of both rotor and stator geometry, to reduce the effect on machine reliability.
The paper clearly shows how the combined approach, using different measurement techniques, is highly encouraged in reliability and operability improvements on hydrogenerators.

Intro

After the overhaul, rotor and stator shape(s) were measured in unit off-line mode followed by vibrations, air-gap, magnetic flux and thermal displacement measurements during on-line operation. Main components were tested using visual inspection and NDT methods. The (vertical) unit is powered by Francis turbine (415 MW) coupled to the 480 MVA generator, at 107.1 rpm, nominal voltage 16 kV (50 Hz). It's a large unit with 15.8 m stator and 13 m rotor diameters. The rotor weight is 920 tons.

During the overhaul, four (4) air gap and one (1) magnetic flux probes were installed on the stator core. Both monitoring technologies (and especially air gap) can provide additional useful information on unit's condition, if analysed properly.

Slow roll (off-line) measurements were performed with the use of magnetically attached air gap probes. With the help of diagnostic trigger (typically used for appropriate order analysis during on-line measurements) and proximity probes (to measure any excessive shaft movement within the bearings) – appropriate rotor and stator shapes were obtained for a cold unit.

Additionally, in order to assess unit's vibrodynamical behaviour, proximity probes and accelerometers were temporarily installed (magnetically attached). The main goal was to cover different operating regimes (run-up, run-down, mechanical rotation on nominal speed, excited unit, overspeed and different loads at different temperatures) to obtain insight into the unit's condition.

Measurements on this unit were a part of a more general campaign whose goal was to help create a list of units in order of refurbishment priority. There is a total of five (5) units in the power plant and the measurements are planned on each unit.

Measurement layout

There were two main measurement layouts – one for the slow roll (off-line) rotor and stator shape measurements and the other for the unit in operation (on-line). Some probes used were the same for both measurement with a slightly different purpose. For example, diagnostic trigger probe was used to properly detect position of each pole and one rotation during the slow roll (off-line) measurements while it was additionally used for order analysis during the on-line measurements. Also, the proximity probes during off-line measurements were mainly used to measure the shaft displacements within the bearings during slow roll rotation. This data (if excessive displacements are present) can be used for compensation in order to obtain true rotor shape since the rotor can move within the bearings.

The general layout (top view) is shown in Fig. 1. Not shown are the stator frame vibration probes (accelerometers) at three (3) locations measured at 120° apart and positioned radially.

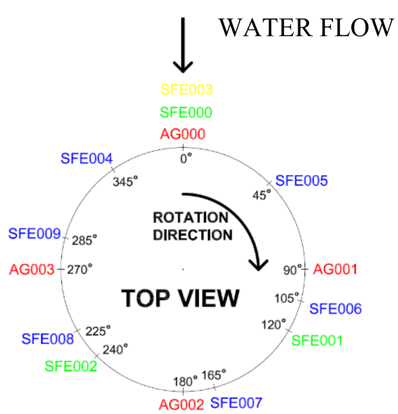


Fig 1. Measurement probes radial layout. Rotation direction indicated (CW). Water flow is direction Y, 270° is direction X. Relative vibration probes and accelerometers measure in X and Y directions. AG = Air Gap, SFE = Stator Frame Expansion.

Beside vibrodynamical behavior monitored by the relative displacement (proximity) probes and accelerometers, air-gap and magnetic flux probes were used to further quantify unit behaviour within the generator air gap. Since the unit is large in diameter – by design there exist the possibility for the stator to expand radially on soleplates. Sometimes this radial expansion isn't symmetrical and the unit's stator core and frame do not expand uniformly, causing additional issues such as rotor to stator eccentricity. In order to measure a relative stator frame to concrete expansion, six (6) proximity probes were placed at equidistant angles radially, following the locations of the soleplates.

The abbreviations used in Fig. 1. are: AG = Air Gap probes, SFE = Stator Frame Expansion

These analog inputs were connected to appropriate monitoring hardware and software used for data collection and interpretation. Portable instrument with connected signals and some probe photos are given in Fig. 2. and Fig. 3.

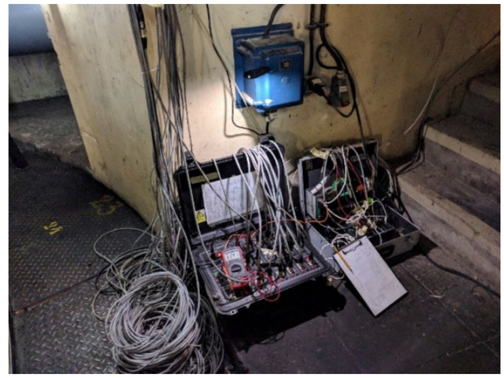


Fig 2. LEFT: Portable Measurement Unit (PMU) – an 18 channel signal conditioning and acquisition device.
RIGHT: Two PMU's running synchrronously with all signals connected. Photo from the power plant.

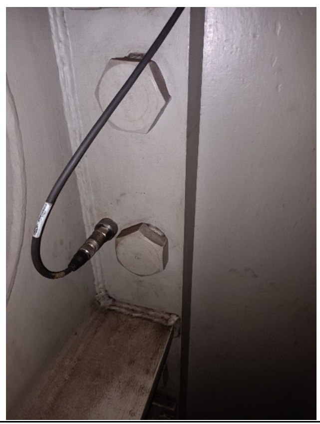
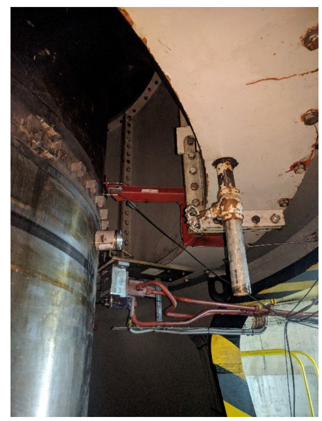
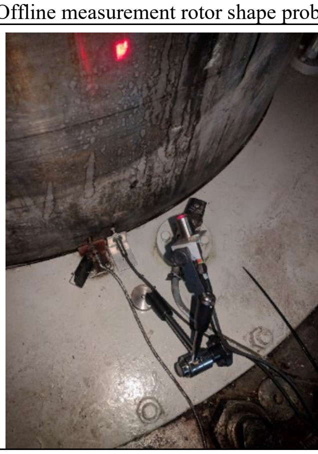
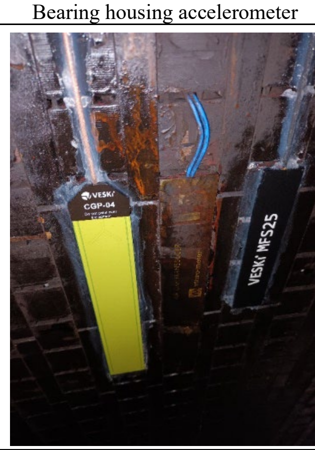
		
Offline measurement rotor shape probe	Bearing housing accelerometer	Proximity probes near thrust bearing
		
Diagnostic trigger and proximity probe in turbine area	Air gap and magnetic flux probes glued to the stator core, top plane	Stator frame expansion probe

Fig 3. Some probes used during the measurements.

Measurement results

Measurement results are presented in two parts –

1. For off-line data analysis
2. For on-line data analysis

Off-line measurement results

As previously mentioned, these measurements were performed with magnetically attached air-gap probes mounted on the rotor and stator in three (3) measurement planes. Since the rotor poles were ~3.30 m in length, three planes were necessary in order to detect any variations in the verticality.

The unit was manually rotated on lift oil and the rotor was rotated for two (2) revolutions for one measurement plane. Two revolutions were chosen to confirm measurement consistency and redundancy.

An example of the waveforms recorded for the measurements in bottom plane are shown in Fig. 4. Additional signal filtering was performed to reduce white noise as indicated in the figure.

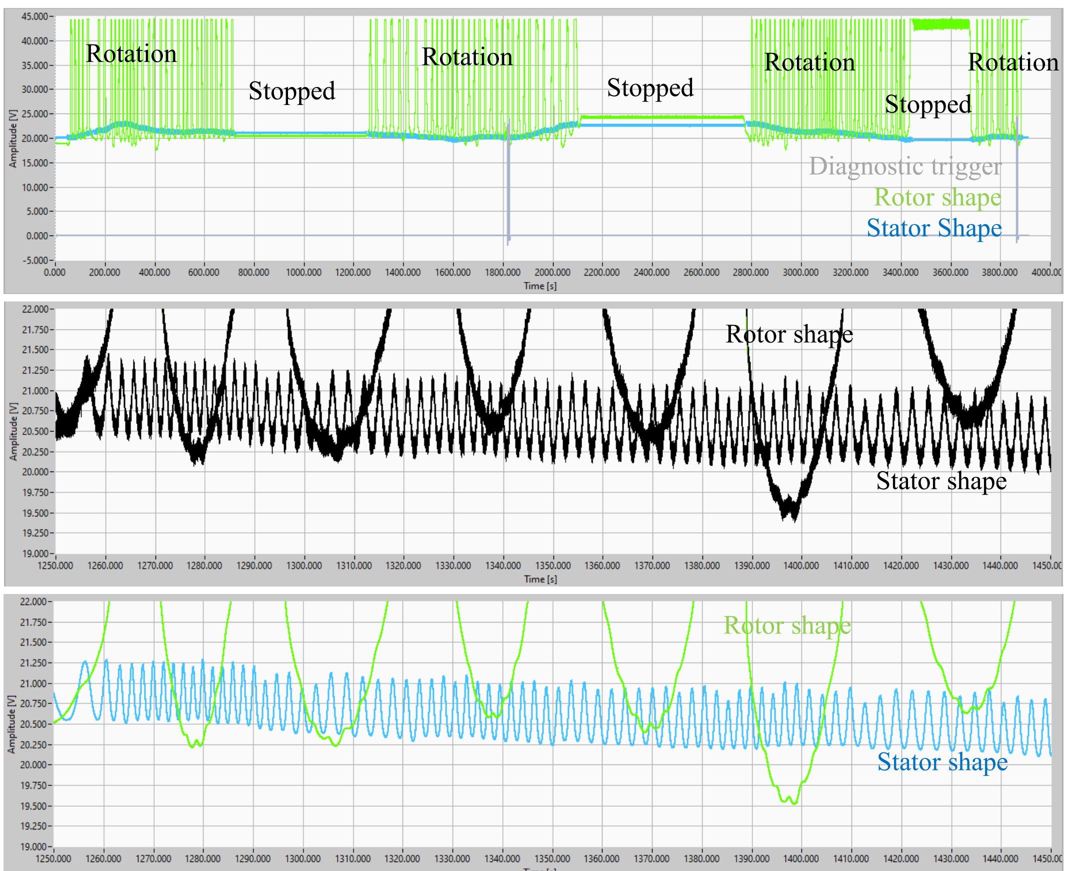
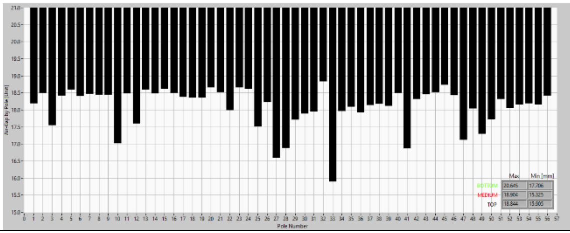
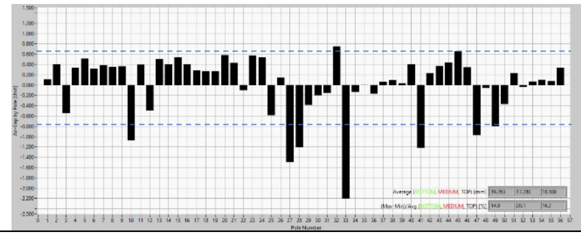
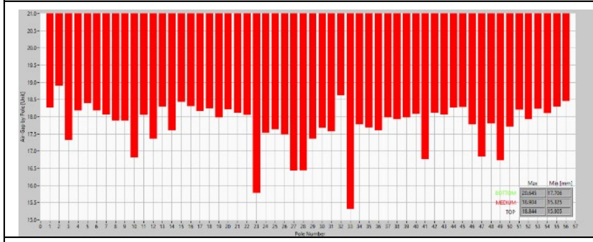
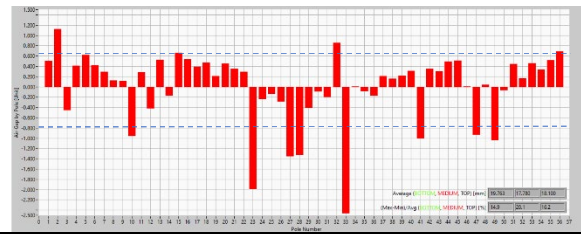


Fig. 4 TOP: Waveforms in duration ~3 h and 5 minutes (two revolutions). MIDDLE: Original waveforms (white noise present). BOTTOM: Waveforms with white noise reduced. Y scale in [mm].

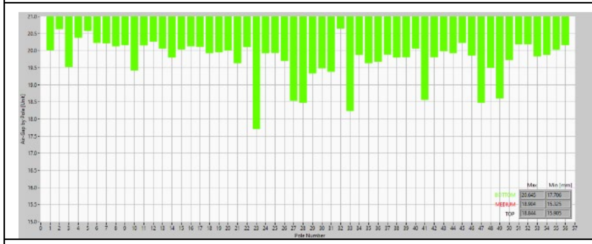
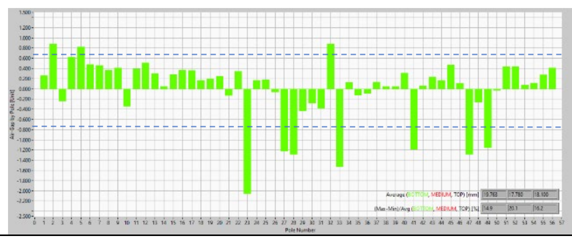
Knowing the position of the poles relative to diagnostic trigger mark on shaft in combination with shaft displacement within the bearing tracking / compensation – rotor bar graph plots can be obtained for different planes. This is shown in Fig. 5.

TOP plane

MEDIUM plane

BOTTOM plane

NOTE: Y scale 15-21 mm (6 mm difference).			NOTE: Y scale from -2.5 mm to 1.5 mm (4 mm difference).		
	Max [mm]	Min [mm]		Average (DC) [mm]	(Max-Min)/Avg [%]
TOP	18.844	15.905	TOP	18.100	16.2
MEDIUM	18.904	15.325	MEDIUM	17.780	20.1
BOTTOM	20.645	17.706	BOTTOM	19.763	14.9

Fig. 5 LEFT side: Bar-graph view of the rotor shape by pole number in all three (3) measurement planes (top, medium, bottom). Numbers at the bottom indicate maximum and minimum air-gaps found. RIGHT side: Bar-graph view of the deviation of the air-gap from average (DC) value by pole number in all three (3) measurement planes (top, medium, bottom). Numbers at the bottom indicate average (DC) and percentage of deviation of the air-gap by measurement planes (top, medium, bottom). ± 3 % (~± 0.7 mm) lines drawn on the graph.

This figure shows that the average air gap is largest at the bottom plane and decreases when reaching top plane (where it's at 18.1 mm). All measured air-gaps are smaller than the design value of 22.6 mm. Additionally, it can be seen from figure that the poles 23 and 33 deviate from average value the most, though there are other poles which deviate as well (poles 2, 10, 27, 28, 32, 41, 47 and 49). The circularity is above recommendations (CEATI).

Rotor shape has a direct influence on the unit's vibrodynamical behavior when excitation is turned on. The easiest way to compare how much an out-of-round rotor influences vibrations is to compare 1x vibration vectors (amplitudes and phases) in mechanical rotation at nominal speed and that of an excited unit. The difference is the influence of the excitation due to rotor out-of-round. If there are significant deviations from circular shape (more so, if there is a rotor "zone" whose shape deviates from circular) and if the design air-gap is smaller – influence on vibrations is larger. This is also the reason why it's important to measure vibrations in different operating modes – which is shown in the next chapter.

Additionally, accelerometers were also mounted on the stator frame to measure the frame and core vibrations. Beside typical responses at 100 Hz (and harmonics) – which correspond to the 56x harmonic (112x etc) of the rotational speed, additionally stator frame was found to vibrate at 2x harmonic. This is directly related to the excitation forces due to an oval (non-circular) rotor which acts magnetically on the frame and core to excite 2x harmonic vibrations.

Stator circularity was also measured in three planes and it was found to be at 4.05 mm (17.9 %) in the top plane, 3.28 mm (14.5 %) in the middle and 3.33 mm (14.7 %) at the bottom plane. Polar plots of the rotor and stator in the top plane are shown in Fig. 6.

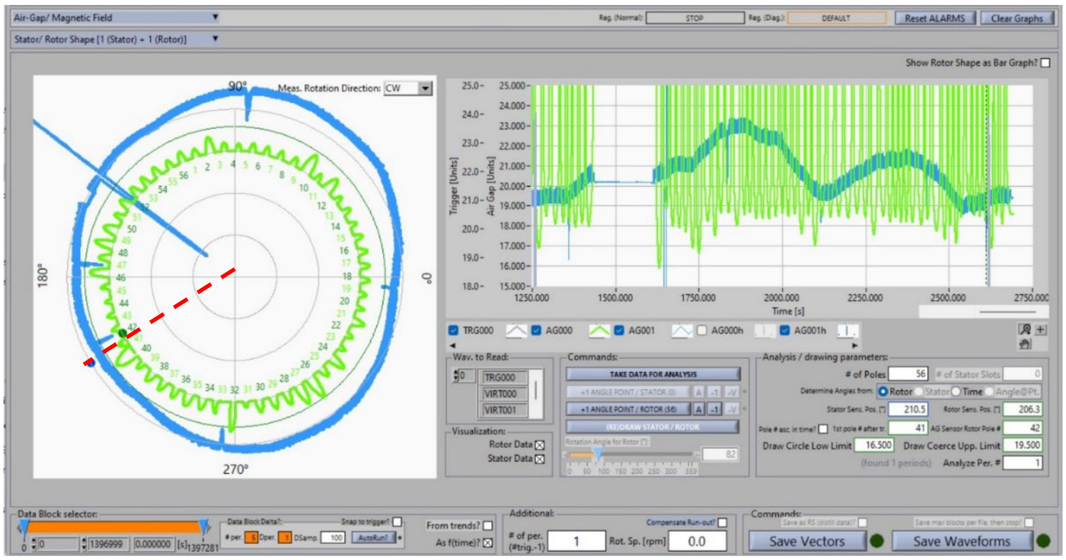


Fig. 6 Rotor (green) and stator (blue) polar plots measured in the top plane. Gray color shows the signal from the diagnostic trigger. Values of air-gap are given in [mm]. Red line indicates the direction of the smallest air-gap in which it's expected for the rotor to move with excitation.

From the shapes, it is clearly visible that the rotor and stator are eccentric due to the stator shape. This is the reason why it's expected that there will be unbalanced magnetic pull of the rotor present (UMP) with excitation as one side of the stator is always closer to the rotor. Furthermore, from these (slow roll) measurements alone it cannot be predicted how the rotor and stator shapes will change with additional forces and temperatures. This is why there were 4 air-gap probes mounted on the core permanently – to track both the rotor and stator shapes.. The advantages of this method are that it's possible to obtain true rotor shape (it's given by each probe) if the software used for analysis has the possibility to compensate for vibrations within the air-gap, should they be present. As for the stator shape, it is possible to obtain it in an interpolated form and the number of points for interpolation depends on the number of air-gap probes glued to the stator core in one measurement plane. In this case, on customer demand, four probes were installed though for larger stators (rotor diameter is 13 m) more probes (at least 8 from author's experience) would have given a more precise stator shape information.

Online measurement results

Measurements have been performed in different regimes: mechanical rotation, rotation on nominal speed with excitation on, changes (within allowed limits) of rotational speed of the excited unit, operation on 50, 300 and 390 MW loads including short-term operation on 140 MW (within the rough load zone, typical for Francis turbines) until unit thermal stabilization. During the entire measurements, vibrations and air-gap signals were analysed and calculated values (descriptors) trended into the files. Additionally, in all interesting regimes, raw waveforms were stored for further post process analyses.

Fig. 7 shows the signals of rotational speed and magnetic field (RMS value). For analysis purposes, magnetic field can be used to track magnetization of the rotor. Additionally, this signal can be used to track any possible rotor pole shorted turns by comparing adjacent poles. On this unit, none were found so the results are not presented in this paper.

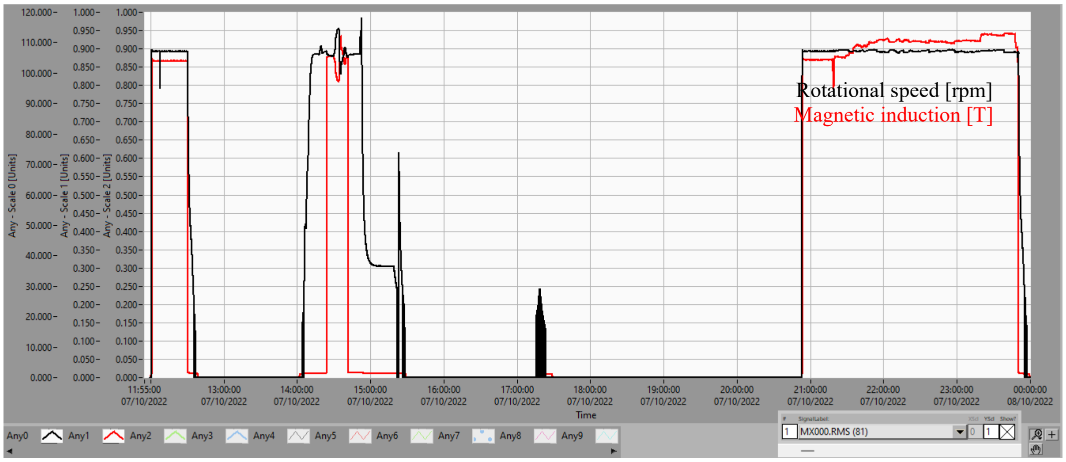


Fig. 7 Rotational speed (rpm, black, Y scale 0) and magnetic induction RMS value (T, red, Y scale 1).

From the vibro-dynamical perspective – the peak-to-peak vibrations for relative shaft displacements and RMS values for the vibration velocity (obtained by integrating signal from the accelerometers) are recommended by the ISO 20816-5:2018 standard.

Howeer, during the measurements, it was established that, due to the shaft damage (scratches) in some measurement planes – for example Upper Guide Bearing (UGB) plane the peak-to-peak value is unrealistically large and is not representative of the vibrations. Detailed overview of the spectra showed that the most important contribution to vibrations originates from the 1x so, these values were tracked and later compared to the ISO 20816-5:2018 standard.

The unit belongs to group 3 in this standard, which are vertical units whose upper guide bearing is braced against the station foundation and the vertical load is supported by head cover. The standard is based on statistical correlation of vibrations and increased frequency of malfunctions of 7000+ analyzed units which gave recommended limits between vibrational zones (A-B/C and C/D, where A-B zone is allowed for unrestricted operation, C is allowed for short-term operation and D is forbidden, since it represents a large risk of potential damage to the unit).

Fig. 8 shows an aerial view of the plant with top covers removed showing upper guide bearing bracings against station foundations.

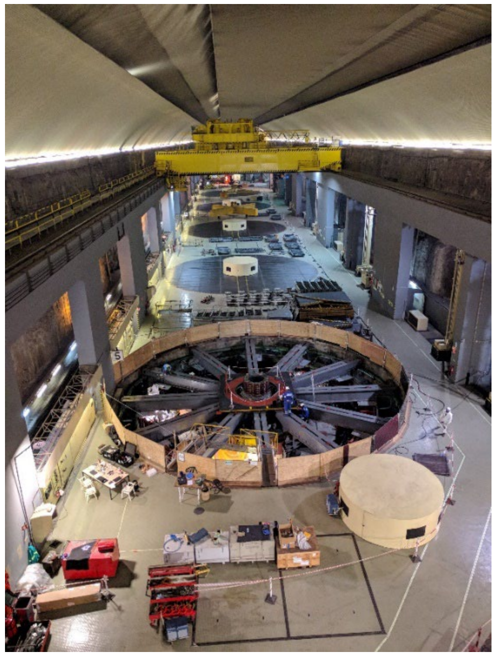
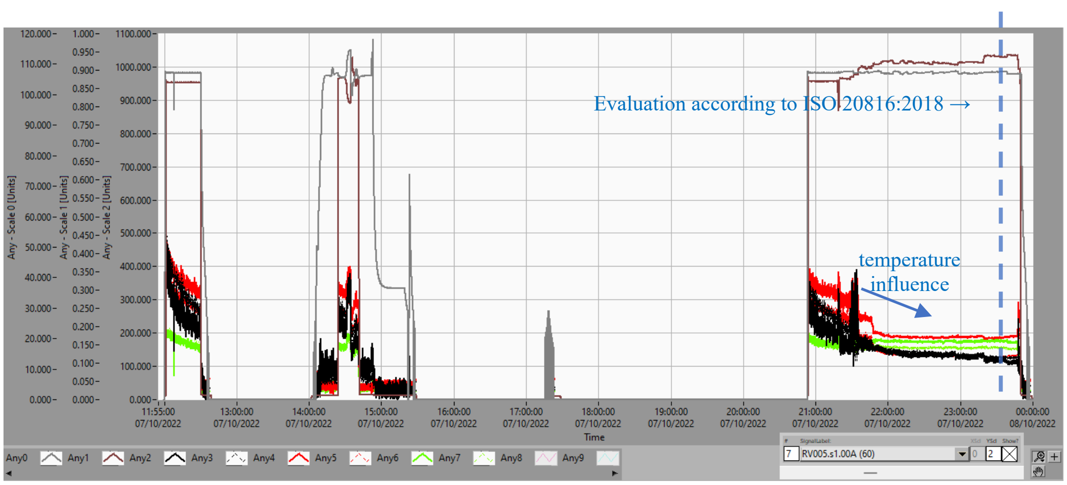


Fig. 8 Aerial view of the analyzed units that belong to group 3 according to the ISO 20816-5:2018 standard.

Typical recommended numbers for action limits between zones A-B/C are 160-180 μm peak-to-peak and between zones C/D 250-280 μm peak-to-peak for relative shaft vibrations. For the bearing housing vibrations – zone limits for the generator bearings are A-B/C at 0.5 mm/s and C/D at 0.8 mm/s while the allowed numbers are larger for turbine bearing. These are all to be measured at 70-100 % rated load of thermally stabilized unit.

Fig. 9 shows the most important vibrodynamical descriptors for the relative and absolute vibrations.



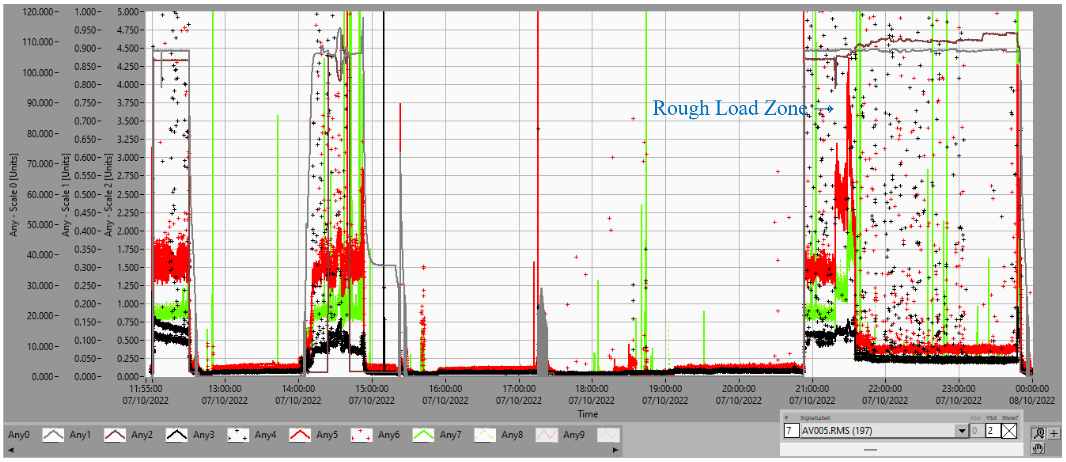


Fig. 9 TOP: Rotational speed [rpm] – Y scale 0, magnetic field RMS value [T] – Y scale 1, relative vibrations 1x peak-to-peak values [µm]. UGB – black, THRB – red, TGB – green. Direction X – thick line, direction Y – dashed line. BOTTOM: Rotational speed [rpm] – Y scale 0, magnetic field RMS value [T] – Y scale 1, absolute vibrations RMS values [mm/s]. UGB – black, THRB – red, TGB – green. Direction X – thick line, direction Y – dashed line. Rotational speed – gray, Magnetic field – brown.

As already mentioned, the main reason of using 1x peak-to-peak value instead of the peak-to-peak value lied in the fact that scratches were present on the shaft in measurement plane which is why the 1x peak-to-peak was a better representative of the vibrations. Vibrations were also measured radially in the thrust bearing plane. Though, they are not compared to the standards, this data is, still, informative.

Fig. 9 shows that the vibrations have stabilized at the top of the zone A-B after the unit reached steady state temperatures. Also, from the bottom diagram on Fig. 9 it can be seen that some points 'jump' to high values and returns to previous values. The trend is clearly visible, though, and the reason for this sensor behavior is related to the saturation of the piezo-electric crystal with high frequency acceleration and not the machine vibrations. Mechanical filters can be used to attenuate this but were not available in the power plant during the measurements.

One diagram which is interesting to see is the difference in behavior of vibrations (AC part of the signal) and statical shaft position (DC part of the signal) during excitation vs. mechanical rotation. This is given in Fig. 10. These plots were obtained by filtering 1x harmonic (representing AC part) with DC shaft position.

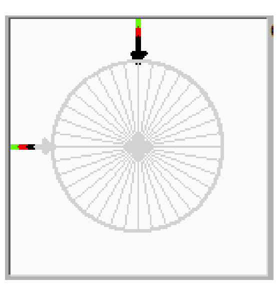
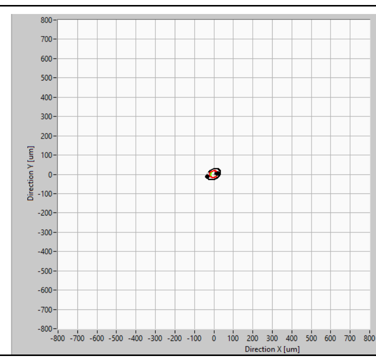
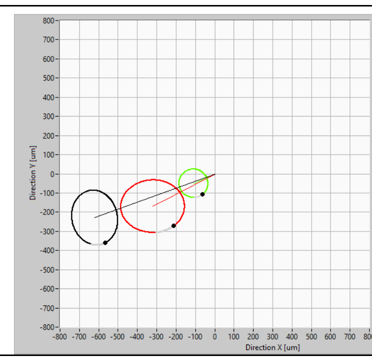
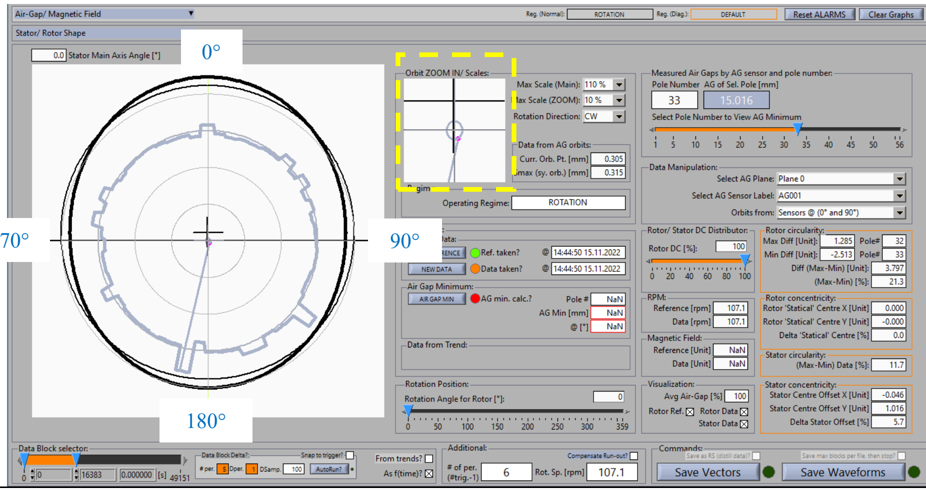
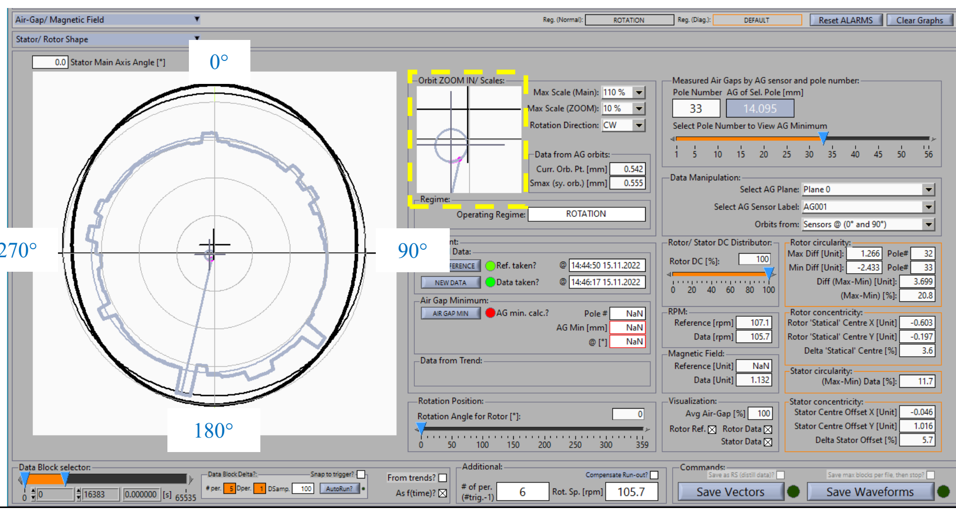
		
Probe layout	At 14:23:34 h (Mech. Rot.)	At 14:26:36 h (Exc. ON)

Fig. 10 LEFT Probe layout, top view. MIDDLE: 1x filtered orbits in mechanical rotation. BOTTOM: 1x synthesized orbits of the excited unit.

Figure cleary shows that there is a statical shaft displacement (given in µm) with excitation which is most dominant in the upper guide bearing plane and is, around, 700 µm. Comparison with Fig. 6 showhs that for the cold unit at, approximately, 240° (check Fig. 1) – the rotor is closest to the stator and it's also in this direction that the shaft is displaced when the unit is excited, which was expected. The same displacement is visible from the air-gap polar plots shown in Fig. 11, with and without excitation.



Mechanical rotation at, approximately, nominal speed.



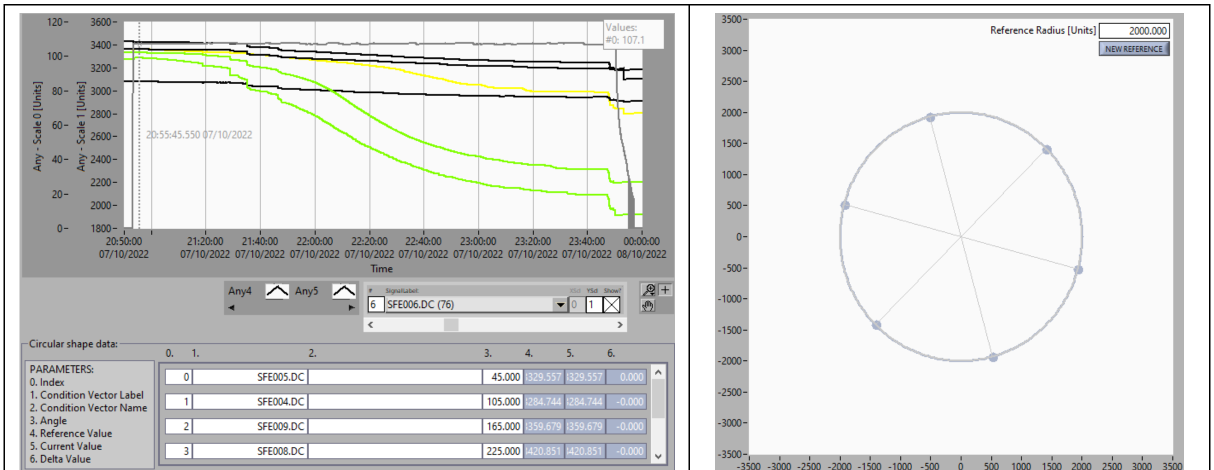
Excited unit at nominal speed.

Fig. 11 Rotor and stator polar plots in mechanical rotation at nominal speed (TOP) and excited unit at nominal speed (BOTTOM). Orbit ZOOM IN shows the direcion of the statical (DC) displacement, which correlates well to Fig. 6 and Fig. 10. The same Orbit ZOOM IN shows increase in orbit size due to vibrations within the air-gap (AC).

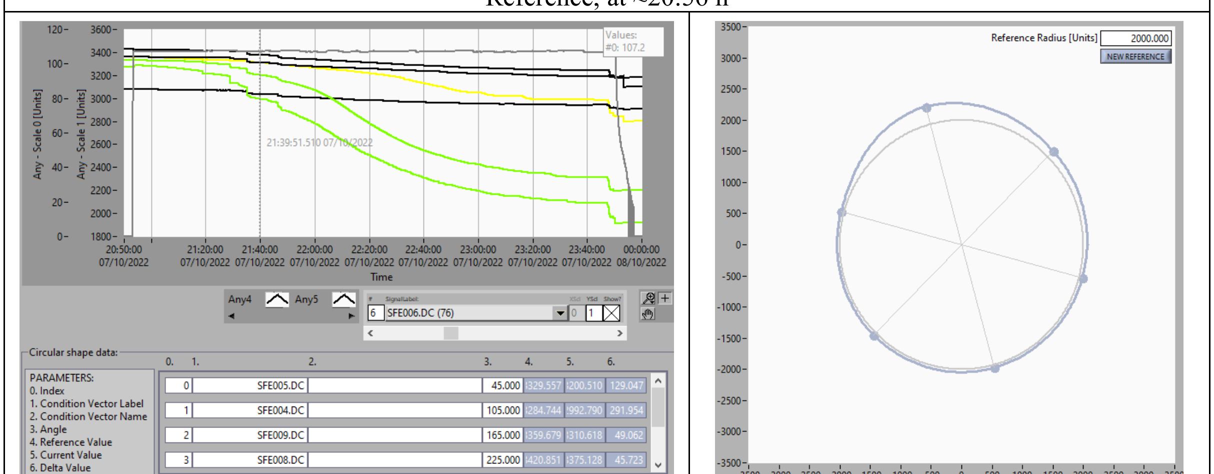
Fig. 10 and Fig. 11 shows displacement as a consequence of the unbalanced magnetic pull due to the asymmetry within the air.gap. Detailed analysis of the influence of magnetic asymmetry around stator and rotor clearly showed that there is a correlation between 1x vibrational vectors within the bearings and the air-gap which, practically, proved that the rotor non-circularity is the main reason for the magnetic unbalance. As such, recommendation was given to the plant to rewedge some poles (related to the offline measurement results) which would improve magnetic unbalance influence and also reduce 2x stator frame vibrations originating from the rotor shape. After that, most likely, balancing would be required.

As the last part, in Fig. 12, results of the stator frame expansion on soleplates in radial direction is given. When the measurements were prepared, on 6/12 positions of the soleplates – proximity probes were placed. These had the purpose of establishing how the stator frame expands on radial pins. The main question was whether or not the stator frame expanded radially equal in all directions.

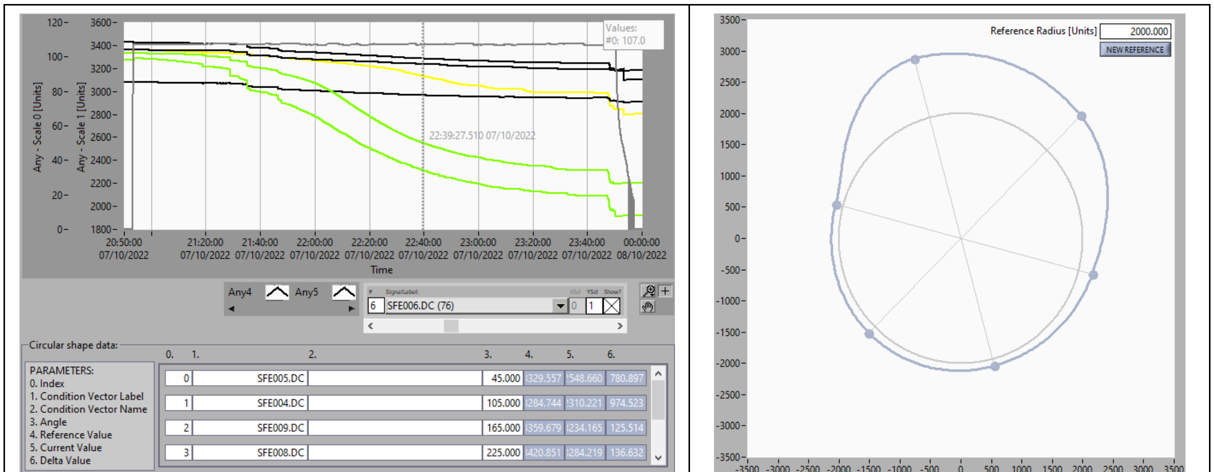
Although the figure is emphasized, it clearly shows that the stator is not expanding uniformly in all radial directions. Recommendation was given to grease certain areas of the pins and soleplates due to large friction in those zones. It can be clearly seen that the 240° zone expands less influencing the rotor and stator eccentricity further. After greasing is done and expansion checked by measurements, stator to rotor eccentricity could also be corrected by stator displacement in the direction of the unbalanced magnetic pulls, if necessary.



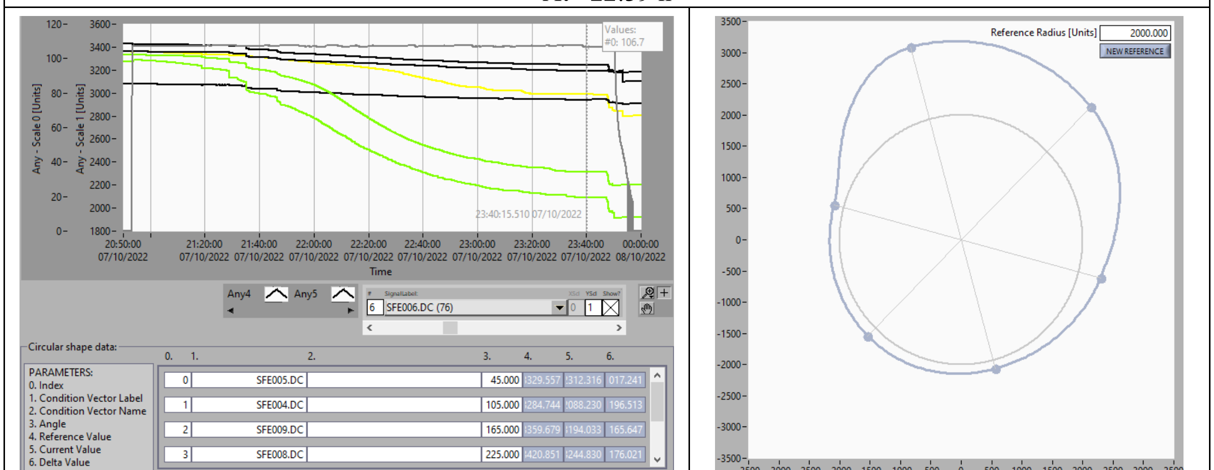
Reference, at ≈20:56 h



At ≈21:40 h



At ≈22:39 h



At ≈23:40 h, near end of thermal stabilization

Fig. 12 Stator frame shape change at different timestamps during the loading and temperature increase.

The NDT and visual inspection of the unit revealed the cracks in the part of the radial pin which was welded to the frame (top part) in order to prevent it's migration during stator expansion. This is shown in Fig. 13.

Fig. 13 Linear indication (crack) on securing weld on stator soleplate radial pins.

Conclusion

This article presents certain useful diagnostic methods related to the hydro-unit during the off-line and on-line phase. Vibrations can be nicely correlated to the air-gap measurements revealing several problmes resulting from inadequate stator and rotor geometry:

- stator core and frame uneven expansion resulting with stator to rotor eccentricity and broken welds on soleplate pins
- unbalanced magneti pull on rotor due to stator to rotor eccentricity
- magnetic unbalance due to rotor circularity deviation
- stator vibration and cycling on seconf harmonic due to rotor circularity deviation

Visual inspection complemented by NDT helps plan monitoring activities and increases unit operation reliability. In this case, recommendation was given to rewedge some poles which would reduce magnetic unbalance and the related stator frame vibrations. Also, recommendation was given to grease certain areas of the soleplates to allow for a more uniform stator frame expansion. After this is done stator to rotor eccentricity could be checked and stator moved, if necessary, to reduce any remaining stator to rotor eccentricity on unbalanced magnetic pull.

References

[1] ISO 20816-5:2018; Mechanical vibration – Measurement and evaluation of machine vibration — Part 5: Machine sets in hydraulic power generating and pump-storage plants; 2018

[2] CEATI Hydroelectric Generator Units-Guide for Erection Tolerances and Shaft System Alignment Part I, II

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