Monitoring magnetic poles of hydro-generator using vibration data: Case Study and Results

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Introduction

This case study shows how a predictive maintenance program was installed, used. On one of the hydropower unit: Cerrón Grande unit 1, there was high vibrations on the generator bearing. A vibration analysis report gave conclusion whereas generating poles were incriminated. The recommendations were followed up by the maintenance team at site and OEM teams, who could first confirm the fault, and then replaced or repaired 7 poles over the 48 of this generator. After the maintenance works, the poles are back in good conditions, and the vibration levels back to normal.

1. The installation on the rio Lempa

1.1 Overview

The Executive Hydroelectric Commission of the Lempa River (Comisión Ejecutiva Hidroeléctrica del Río Lempa), CEL, is a government company, founded in 1945 in the Republic of El Salvador. It owns 5 hydroelectric power plants located on the Lempa River, with a total installed capacity of (467.80 MW):

- **Guajoyo** (1x 20 MW), (1963) located West, close to the border to Guatemala, (Metapán Jurisdiction)
- **Cerrón Grande** (2x 86.4 MW), (1976-77) Francis units, located North of San Salvador, capital city.
- "**5 de Noviembre**" with 5 horizontal Francis units (3 x 20 MW +1 x 18 MW + 1x 21.4 MW), (1953~66) located in Cantón Nombre de Jesús, and an expansion with vertical Francis units: 2x 40 MW.
- "**15 de Septiembre**" (2x90 MW), (1983-4) vertical Kaplan units, East, downstream, in jurisdiction of San Idelfonso.
- The Central "**3 de Febrero**" (2 X 30 MW) is under construction, in Municipality of San Luis de la Reina.

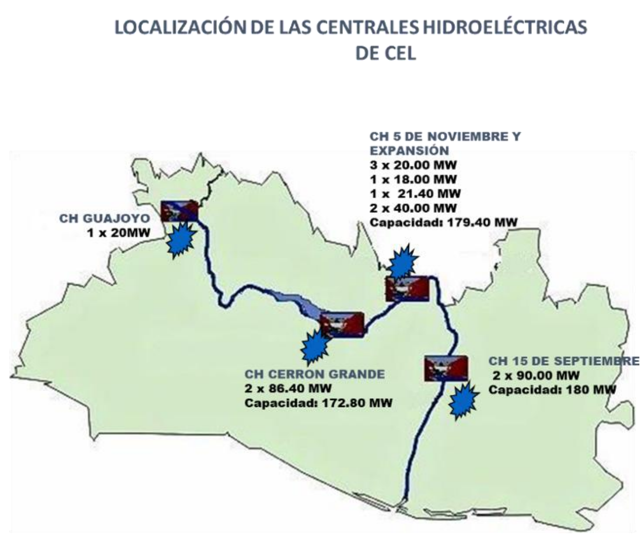

Fig. 1: *Power Plants along the Lempa River, El Salvador*

CEL is the government company that distributes electrical energy from this renewable hydraulic energy, with a contribution of 50% of energy demanded, and therefore it has been interested in updating new predictive maintenance technologies applied to main and auxiliary equipment, such as: Partial Discharges, Vibrations, Non-destructive testing, ultrasound, dissolved gas analysis, Hydraulic oil analysis, thermographic tests, among others; in order to ensure the availability and reliability of the electric power generation process in the country.

1.2 Cerrón Grande Power Plant

CH. Cerrón Grande PP is located 78 km north of the capital San Salvador, on the Lempa River, between the municipalities of Potonico (Chalatenango) and Jutiapa (Cabañas), it is formed by a dam 90 meters high, with a length of 800 meters, a reservoir with a storage capacity (2,180 Mm^3) and an area of 135 km^2, a concrete spillway with 4 gates with a total discharge capacity of 7,900 m^3/s, with a hydraulic head of 57 meters, 2 turbines vertical axis Francis type (2 x 86.4 MW) and ELIN brand repowered generators with a nominal power of 96MW. The repowered was done in 2003 and involved poles windings, magnetic core and stator windings.

The generator has a class F insulation and a nominal voltage of 13.8 kV.

During winter (dry season), the installation has another important role: the reservoir fills and serves as a regulating plant for the rest of the downstream plants ("5 de Noviembre" & "15 de Septiembre").

Fig. 2: *Panoramic View - Cerrón Grande HPP and dam*

2. Predictive maintenance using vibration measurements

When CEL started the Predictive Maintenance program, it was decided not to equip the units with exhaustive instrumentation, but to concentrate on technologies with high-quality instruments, that had also good reliability. Cost was optimized. The locations were remote and not easy to access with wideband Ethernet networks all the time.

Therefore the instrumentation focus on the essentials for vibrations of the hydropower units:

- Relative vibration of the shaft in each bearing, in X and Y direction with proximity probes
- Axial position and vibration in Z direction with proximity probe(s)
- Tacho probe for speed and phase reference, with a proximity probe also
- Later on, the systems are extended with absolute vibration measurements: low-frequency accelerometers on the bearings. This was performed in 2019 in Cerrón Grande. They could confirm the identified signatures, but also uncovered other vibration signatures on the units.

Other measurements like generator airgap and magnetic flux, cavitation measurements, draft tube and turbine cover vibrations, etc. would be added to the system in future as need be.
Presently the system encompasses a Condition Monitoring System (CMS) and a Machine Protection System (MPS). The MPS is not presently automatically acting on the control system, but can, at any moment, be in service, as needed also.

In 2013, TERMOGRAM (from Costa Rica) did finish the installation of the vibration monitoring system VM600 (vibro-meter ®) from MEGGITT on all units on the rio Lempa, including in C.H. Cerrón Grande. The system installed had all sensors and cards necessary for reliable protection and condition monitoring, including local panel-PCs with colour display in real-time, and a Desktop PC for extensive library of vibration-specific plots.

The scope of installation included a final check with calibration, sensors bracket verification, configuration check and improvements with real data, and, importantly, training courses given to operators and users of the system. From this point and on, the system is accepted to be integral part of all the HPP of the system on the rio Lempe. Vibration data can be accessed, on demand, from the CEL central office. There are continuous recordings since 2014 up until today.

Fig. 3: *Training attendance on local monitor and display of vibro-meter_VM600 Protection and Monitoring System*

As part of the project a vibration analysis report was submitted. According to this analysis from the authors of this paper, there was a magnetic unbalance in the rotor due to poles anomalies (probably short circuits in one or more windings turns), recommending to carry out further electrical measurements of the poles; when machine be stopped at least.

3. Vibration Analysis

3.1 Comparison between Units

The relative and absolute vibration levels on Unit 1 raised the attention, in comparison with unit 2 levels, as shown in the mimics, under *approx.* the same operating condition.

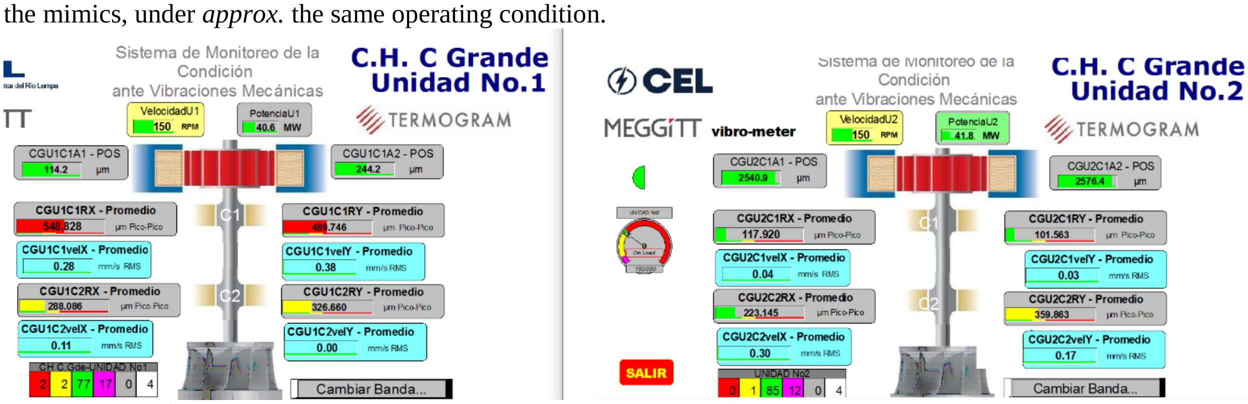

Fig. 4. *Mimics of Unit1 and Unit 2, as shown on the local display in control room. The relative vibrations at generator bearing are concerning on unit 1 while reasonable on unit 2. Alerts on the turbine bearing are a consequence, or related to hydraulic phenomena. Light blue value-boxes represent vibration velocity, measured by low-frequency accelerometers.*

The levels are in alarm (red colour) and well beyond the limits defined in the standard ISO 7919-5 [2] for relative vibrations:
Limits are, for 150 RPM: A/B: 155 ; B/C: 250 ; and C/D: 510 µm_Pk-Pk.
The unit should be stopped, according to this standard, if not according to ISO 10816-5 [1] for the absolute vibrations.
The check against the new ISO 20816-5 [3] (encompassing both standards) gives the same conclusion.

The spectral content showed that the (1X) synchronous vibration at 150 RPM is clearly the dominant signature. Let us examine how this (1X) component changes with machine stop sequences.

3.2 (1X) analysis

In the sequence, first the load is brought quickly to 0 MW, avoiding the vortex rough zone at mid load, then the machine is de-synchronised. We asked to remain 3~4 minutes in this un-synchronised condition to examine vibrations, before the unit runs down.

The radial (1X) components are known to reflect the unbalance condition of the rotor. The polar plot of X and Y proximity probes, across the synchronisation event, allow to segregate between a mechanic and a magnetic participation.
The sequence is shown below for Unit 2, which is affected also, to a smaller extent, recently.

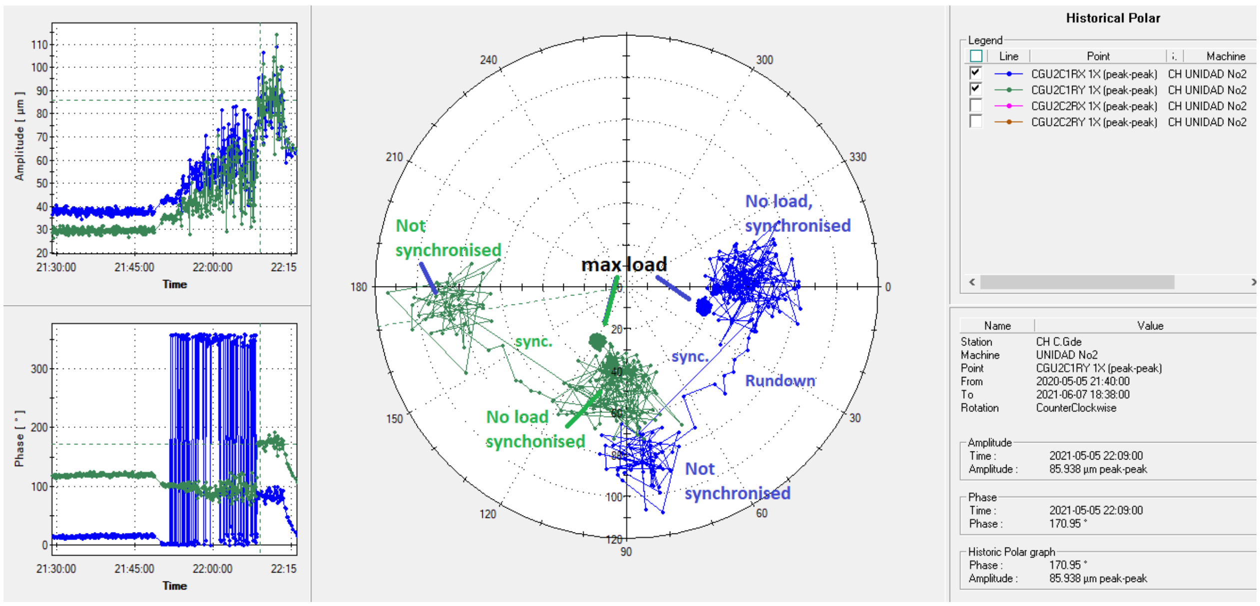

Fig. 5. Polar plot of X and Y probes in unit 2_generator bearing, showing successively: max load, unloaded, unsynchronised and the rundown. As the X and Y probes are 90° apart, the vectors also show the same 90° offset in phase between X and Y in the diagram.

For Unit 2 in *Fig. 5*, at full load, the vectors are represented by small and compact bowls. Then the vectors go apart in more unstable zones (larger bowls), nearby, due to more stochastic instabilities. Then the unsynchronisation causes the vector to shift rapidly to another zone on the polar plot. Eventually the vectors go back gradually to their synchronisation zones. For Unit 2 the synchronisation shift represents approximately 120 microns_pk-pk in length. But this shift consists more in a phase shift, so that vibration amplitudes remain below 100 microns_pk-pk on average in all cases. Note that the vector changes with synchronisation and with rundown are in the same direction. This summary on unit 2 shows that the same phenomenon may build up also, like in unit 1. The amplitude of this vector change is acceptable according to the standard ISO20816-5 [3].

On Unit 1, before the refurbishment in April 2021, the same happened with the synchronisation event, but the amplitudes were much larger.

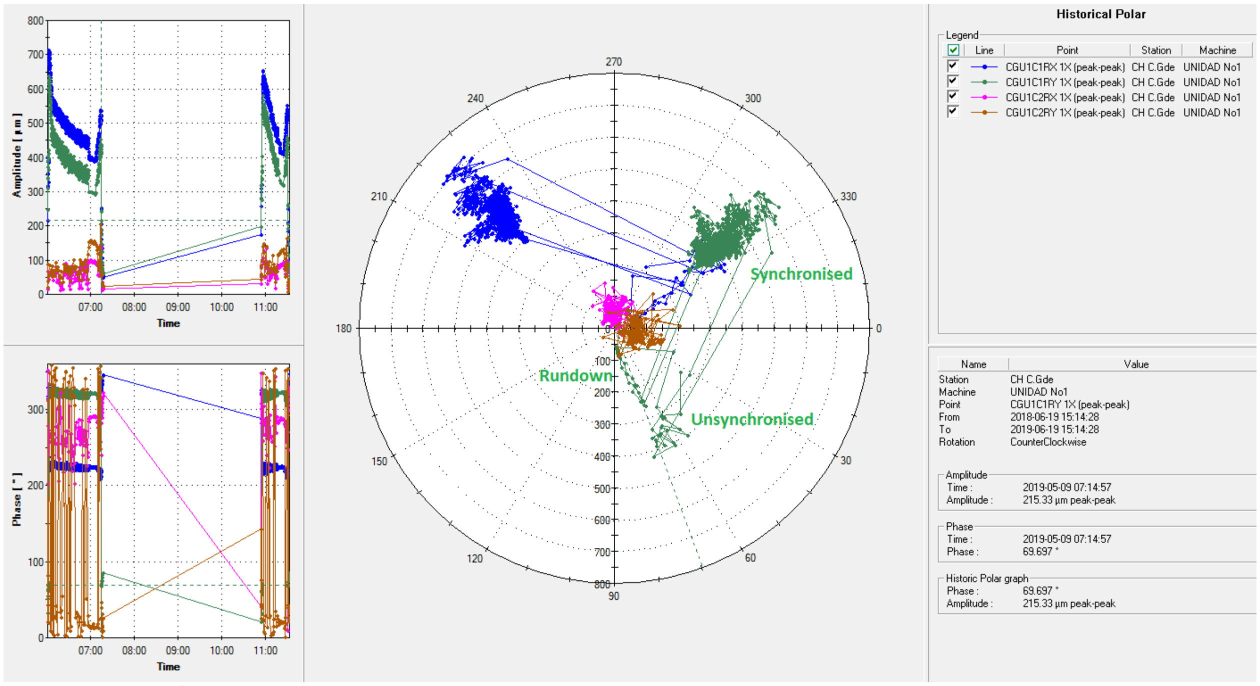

***Fig. 6**. Polar plot of X and Y probes in unit 1_generator bearing, showing successively: max load, unloaded, unsynchronised and the rundown. The vibration at the turbine bearing is represented also on this plot.*

For Unit 1, the change in the vectors is also 90° apart between X and Y at the synchronisation event, and also mostly consists of a phase shift for each direction. However, the amplitude of the vectors changes is 800 microns_pk-pk before the refurbishment.

This amplitude change is fast and clearly due to the synchronisation alone, so is related to the rotating magnetic field in the generator and not related to the mechanical unbalance, which has another phase evolution on the polar plot. We notice that on unit 2, the vector changes with synchronisation and with rundown are no more in phase, but more than 60° apart.

On Unit 2, the amplitudes of the vectors changes (=800 microns) are not acceptable according to the standard ISO20816-5 [3].

3.3 Other possible causes

This shall not be mixed with other phenomena, commonly found on relative vibrations on this type of hydro-units, such as:

- Runout
- Mechanical unbalance
- hydraulic phenomena at the turbine (vortex)
- Magnetic eccentricity
    - of the rotor
    - or of the stator

The runout is read when the machine speed approaches the stop condition. In *Fig. 5* as well as in *Fig. 6*, the rundown curves end at about 60 microns, keeping the 90° phase relationship. This is clear in the plots of the following rundown.

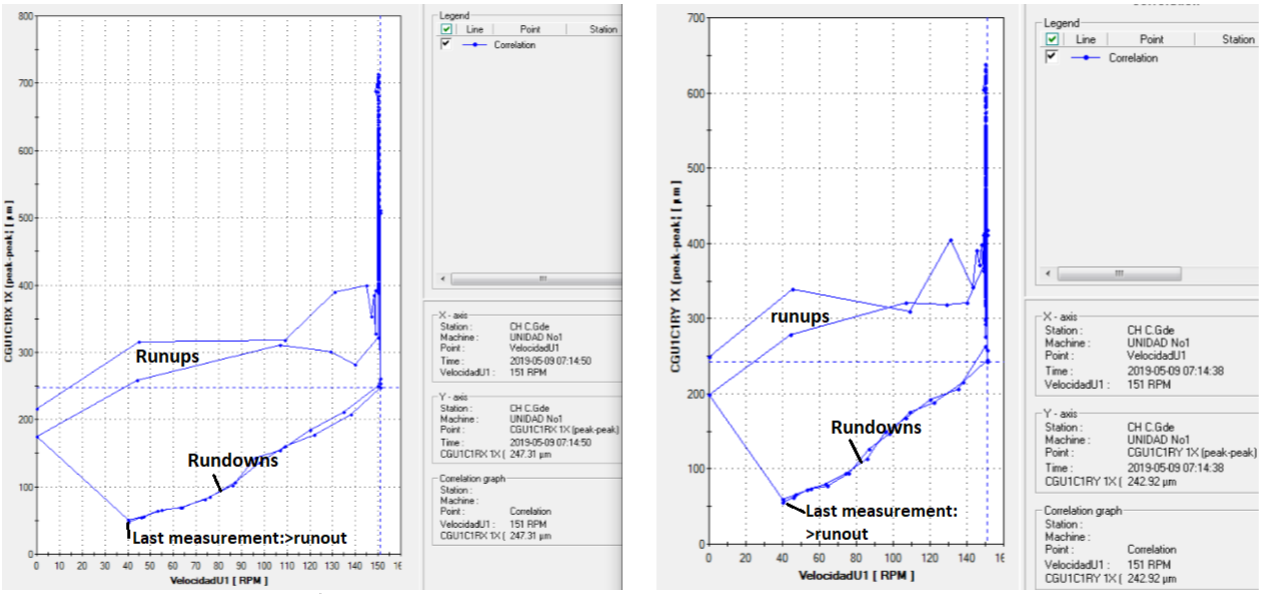

Fig. 7: on unit 1, rundown, the Bodé plot (amplitude), shows that the runout on the X and Y pickups, should be lower than 80 microns.

At low speeds, the measurements (“slowroll”) are not more than 60 microns, so the runout shall not be a concern for the interpretation of amplitudes as high as 800 microns.

The mechanical unbalance is identified without synchronisation, so it is read (***Fig. 6***, “unsynchronised”) at 350 microns on both directions X and Y. This is high enough, but is not the main signature. The mechanical unbalance has quite a different phase direction on the plot, than the phase direction of the synchronisation event.

The hydraulic phenomena would rather show on the turbine bearing vibration and elsewhere at the turbine surroundings. In ***Fig. 6*** , the vibrations at turbine bearing are small. A vortex phenomenon exists on this Francis unit, and has been identified at (0.3X), but the (1X) component does not change, or even decrease slightly, when the vortex appears, as shown in next figure:

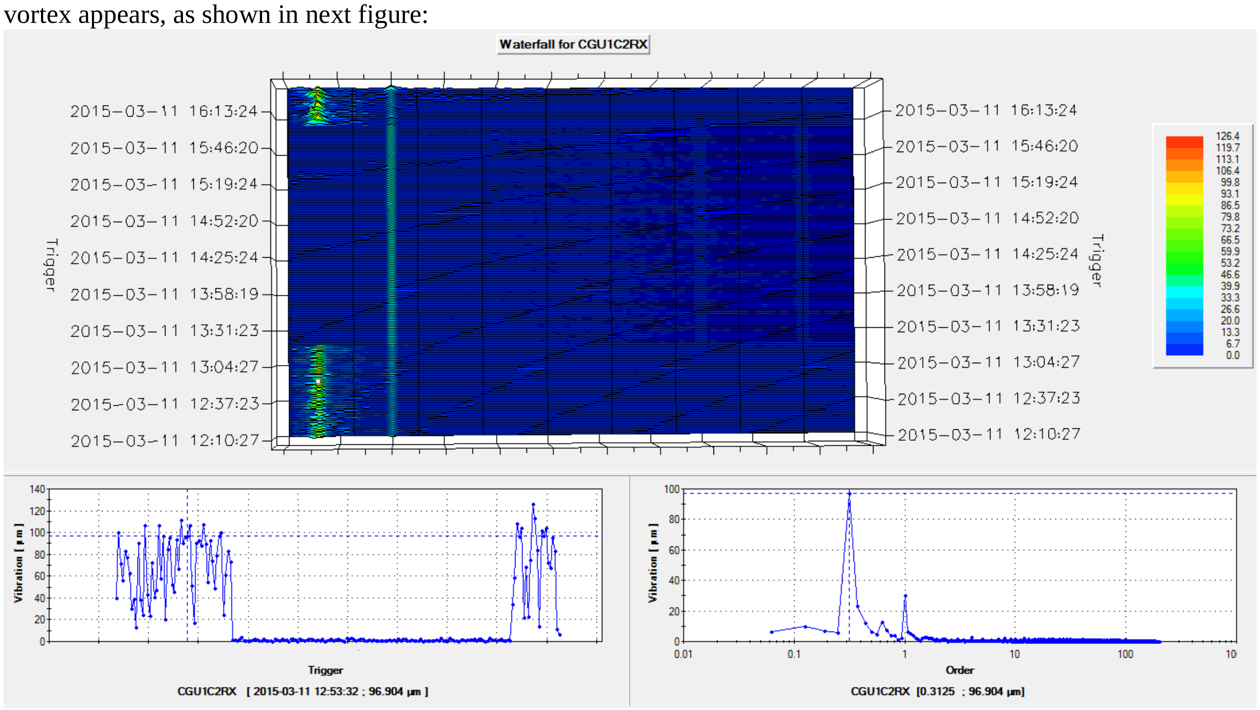

Fig. 8: Spectrogram showing the vortex signature at 0.3X, when load is decreased below60% of max load: before 19h20 and after 22h10 approx.. The (1X) decreases slightly when this happens.

The hydraulic vortex amplitude reaches 100 microns in this example. It concerns 0.3X, and cannot be responsible for the huge increase on the (1X).

The eccentricity between rotor and stator is indeed an interesting parameter for characterisation of generator wear. A lack of concentricity can be caused by the rotor or by a stator displacement relative to its original and centered position. If it is a rotating eccentricity then it would appear on the vibrations as an unbalance, and if it is a static eccentricity, it then appears on the DC of the proximity probes measuring the radial relative vibrations. In this unit, as well as in unit 2, no sign of eccentricity exists:

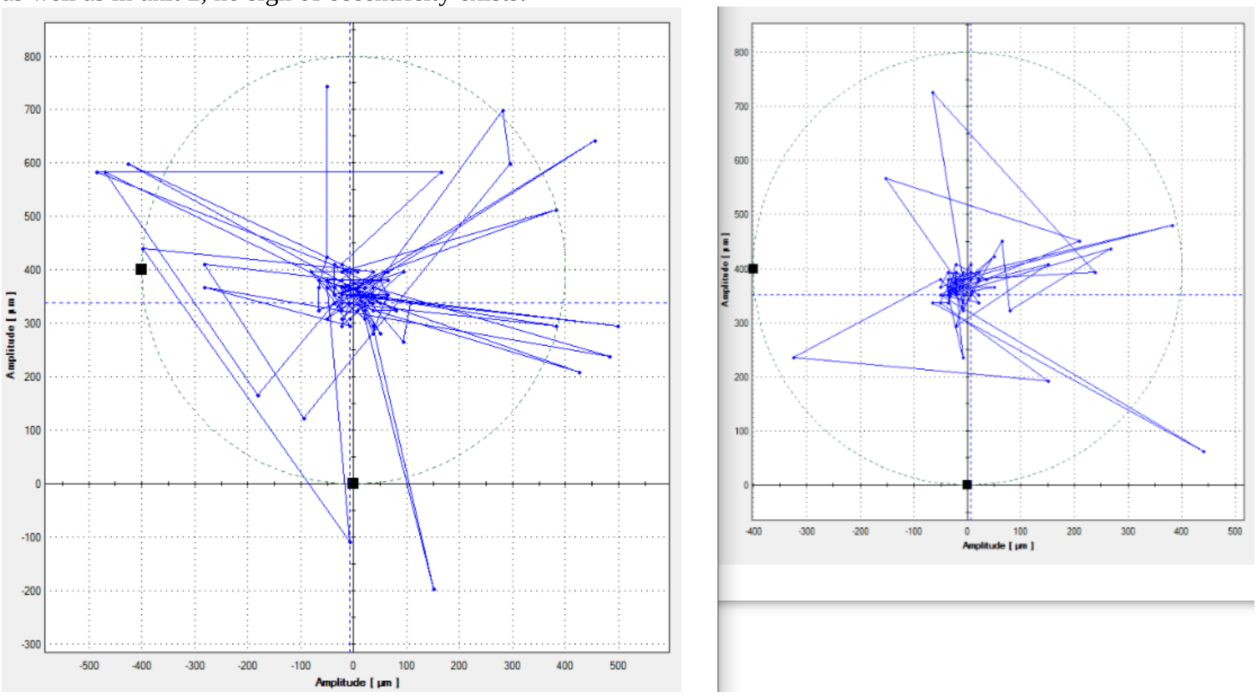

Fig. 9 *: Shaft Centerlines of unit 1 (left) and unit 2 (right) across the synchronisation event in the upper generator bearing. The circles diameters would represent the clearance in the bearings, Spikes can be explained by other events. There is no dispersion of points in 2 groups like in next figure.*

Although spikes are present due to other events (starts, stops, braking steps, load increases and drops), no shift can be clearly seen, related to the synchronisation.

As an example, when such a stator eccentricity exists, a similar Shaft Centerline plot can be observed.

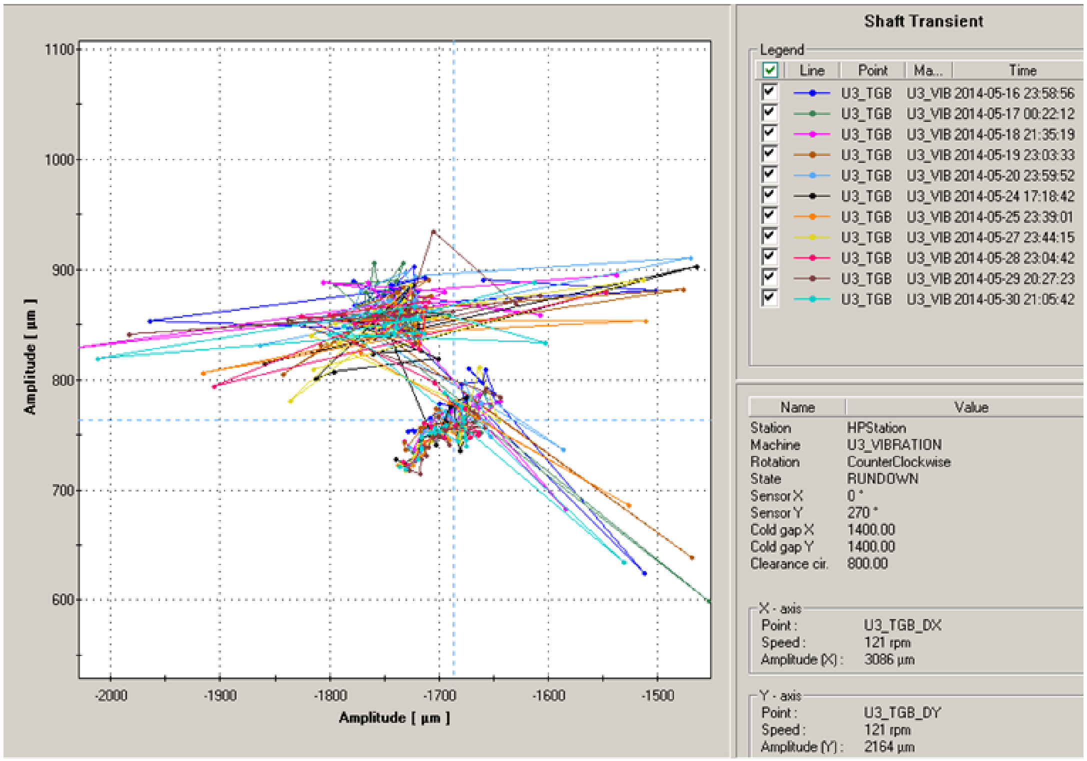

Fig. 10*: Shaft Centerline plot on another similar hydropower unit where eccentricity is strong, Across several synchronisation&de-synchronisation events, the location of the shaft center shifts quickly resulting in 2 groups of points. This is a sign of a stator wear.*

As a consequence, an eccentricity can result in magnetic unbalance. This would mean a discrepancy between the magnetic center of the stator and the rotating center of the rotor.
This is not the case in the units at Cerrón Grande.
An eccentricity of the stator is not obviously the cause: it would not generate (1X) vibrations, only DC.

A magnetic eccentricity of the rotor frame (cause by rotor shape deformation, rotor rim movements, cannot be the cause of the issue either. In this case, a similar increase of the (1X) vector could also be observed, but it would be in phase with the mechanical unbalance. In this scenario; the vectors of the mechanical unbalance and of the magnetic unbalance would be aligned on the polar plot (same phase), and together with the runup signature because mechanic and magnetic unbalances would be in the same direction. The magnetic unbalance would worsen the mechanical unbalance and *vice-versa*.
Here in unit 1, the mechanic vector and the magnetic vector are clearly out-of-phase, almost in quadrature.
Note that on unit 2, these vectors are opposed, so that a cancellation of effects occur.

3.4 Diagnostic conclusion and references

Therefore, only remain the possibility of magnetic unbalance due to the rotor poles; the rotor frame and rim being out of concern. The stator magnetic participation is also out of concern.

It is reported in literature, that poles defects such as shorts between turns cannot be detected with only vibrations [4]. It might be because not enough turns are shorted to generate the magnetic unbalance. But the vibration analysis of those cases do not show the (1X) participation to the overall level, and importantly nor their (1X) phase relationship. Also there are more conditions to the repartition of failed poles in the rotor circumference in order to show an overall vibration signature (§4). In our case (Cerrón Grande Unit 1, the distribution of failed poles is within a limited angular sector.
Of course in [5] and other publications, studies show that the poles defects are surely shown on the magnetic flux on-line measurements, with a dedicated magnetic flux sensor glued on the stator wall. But the units at Cerrón Grande are not equipped with such type of measurement, neither with airgap sensors and monitoring or protection systems. So the poles defects could not be checked with magnetic measurements.

4. Electrical Testing

4.1 Preamble

In October 2019, the alarm “64F” was activated at the protection relays (Stator ground fault), in Unit No.1, for which maintenance personnel carried out a review, in which it was verified that the poles had accumulated dirt by oil and carbon dust from the collector rings; Therefore, an unavailability of the unit was programmed, in which an exhaustive cleaning of the poles was carried out, in addition to applying paint in some parts due to degradation of the varnish layer, the problem was solved at the time, but sporadically the aforementioned alarm was triggered.

During the months of June to August a mayor maintenance was carried out, which included the revision of the generator (rotor and stator), as well as auxiliary equipment for generation. Therefore, corresponding electrical tests were carried out.

4.2 Tests performed

Following the recommendations from the vibration analysis, on August 2021, the poles were dismantled, and these tests were carried out:

- Insulation resistance (to earth),
- Ohmic resistance,
- Impedance,
- Voltage drop per pole to the rotor,
- El Cid tests, and
- Tangent delta to the stator.

4.3 Results

The most significant measurements was the insulation resistance test. It showed poles n°: 10, 18, 21, 23, 28, 34 and 46 were low and out of the standard.

Magnetic Pole No.	Insulation Resistance (Ω) Before	Insulation Resistance (Ω) After repair
10	40.10 M	7.3 G
18	9.85 M	19.75 G
21	16.91 M	21.2 G
23	116.70 M	34.5 G
28	14.02 M	25.8 G
34	57.3 M	12.47 G
46*	67.3 M	7.25 G

Table 1: *Insulation Resistance Measurements - Rotor Unit 1*

According to IEEE 43 Std Recommended Practice for Testing Insulation Resistance of Electric Machinery, this generator must fulfil the minimum required for “Most of the windings manufactured after 1970 (form wound)” equals to R = 100 MΩ (1 minute testing).

The distribution on the poles that show low resistance to ground, is not even around the circumference of the rotor, as shown in the following polar diagram representing, in a log scale, the conductance of all poles, before (in April) and after the refurbishment (in July).

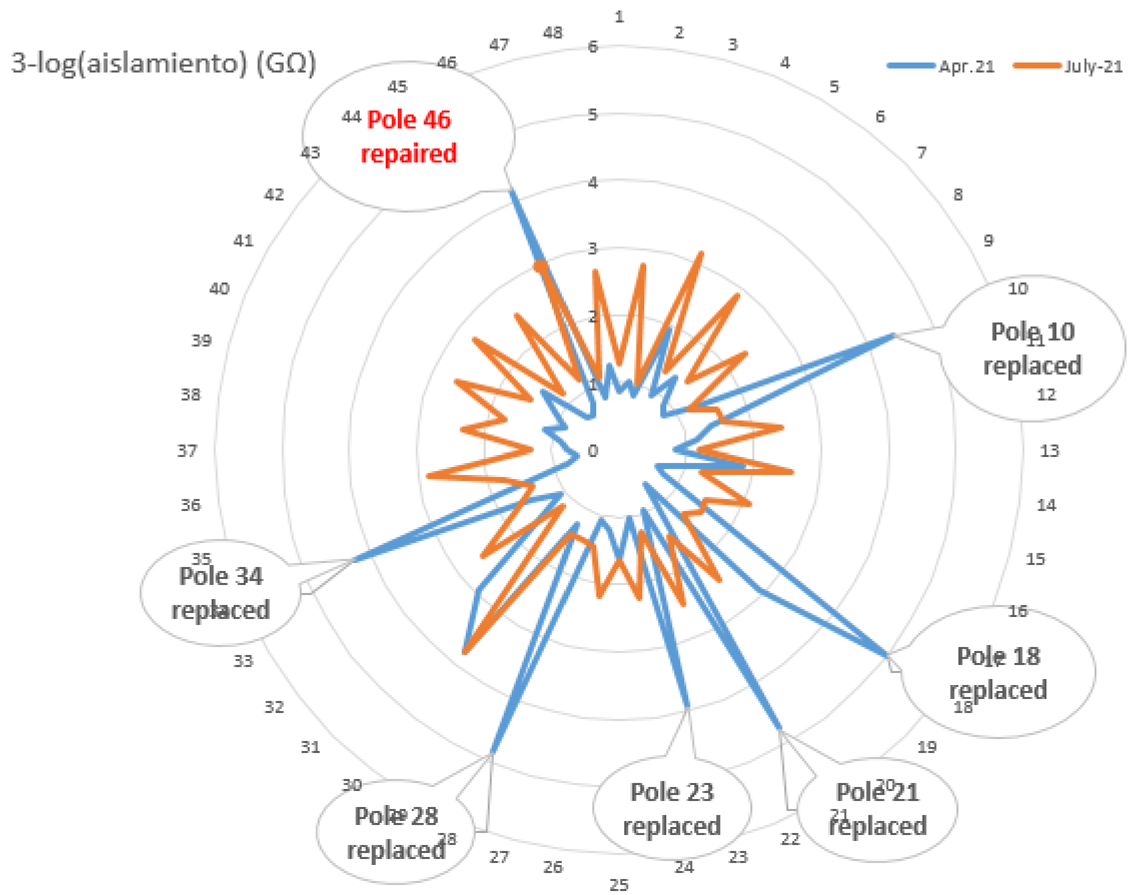

Fig. 11 : *Diagram of poles conductance to ground (inverse of the pole insulation) in log scale. The faulty poles (according to the standard) are spikes in the diagram, before the refurbishment (April, in blue). After refurbishment (July, in orange), the values are all within normative values (> 100 MΩ). Environment variables, in particular humidity, may explain lower values for the good poles, after the change.*

In the polar representation, we notice that all failing poles: from 10 to 34, are on one half side of the rotor: amongst 24 poles over the 48 totally. Only one pole was in the other side, out of this angular sector, and it was only repaired, for having a higher value of resistance than other 6.

5. Repair works

After cleaning, all the failing poles were found burnt in their middle part (around the mid-height of each pole concerned). It is supposed that dust and carbon powder degraded the insulation varnish and eventually short some of insulation plates, as shown on *Fig. 12* . Once the insulation becomes low, spreading currents would cause overheating, thus this aspect of burnt windings.

Although the magnetic field has not been measured, it is verified that the poles failing to pass the insulation test (R> 100 MΩ) also appear to be "burnt", then may have shorted turn(s). The poles have each 14 turns, and then each shorted turn would then reduce the magnetic force by ~7% (provided that the magnetic field does not saturate the stator bars as mentioned in [3]). While this occurs on 6 poles on one side of the rotor, we can understand that the resulting magnetic force is uneven, and strong enough to generate a measurable unbalance.
According to the values recorded in the insulation resistance measurements of the poles, 6 poles were replaced and N°.46 was repaired. After this was done, they were mounted on the rotor and a new measurement of insulation resistance and voltage drop in the poles were carried out, achieving the nominal resistance values presented in Table 1.

Although we are not sure whether turns are shorted nor how many had been, the resulting vector of all insulation resistance, as if the measured insulation were representing the defect, is interesting:

Before the maintenance action, resulting vector was: 11.5 at -3°, and after it becomes 0.3 at +132°, (in log(S)), representing a big improvement. The unit of this resulting vector is in Siemens, analogue to a conductance (inverse of a resistance), in log scale.

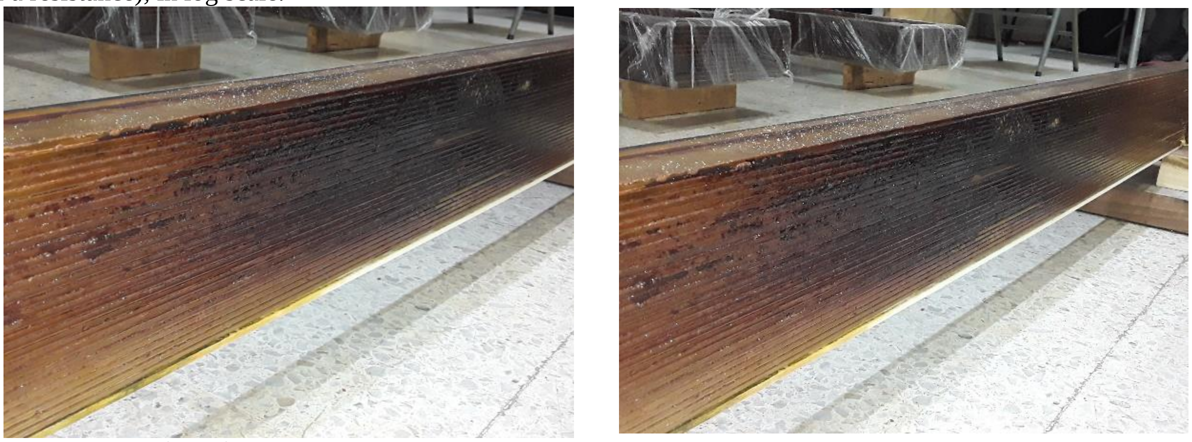

Fig. 12: *Field coil of one of the poles to be rehabilitated, the damage due to overheating is observed, which causes a short circuit in the coils and the subsequent low resistance in the pole.*

Extensive works have been performed to replace the poles, then install in their slot with insulating and anti-fire materials, then painted with special varnish and paint.

Fig. 13 : *Insertion of poles of Unit No.1 in Cerrón Grande HPP, post maintenance and electrical tests performed on the repaired poles.*

6. Conclusion

The Predictive maintenance strategy of CEL resulted is a wise and productive action. By analysing the vibration data, the decision to inspect the poles led to dismantle them and replace abnormal ones with shorted turns. After the maintenance action, and verification of new insulation values, the vibration data returned to normal. It is quite probable that this action alone paid off the complete monitoring system, by putting the unit in production with optimal performance, and probably avoiding further damage to the generator.

Acknowledgment

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