Predictive Maintenance in hydrogenerators

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Introduction

Hydroelectric generators plant maintenance is becoming everyday most relevant:

- Most of the older machines are arriving or surpassed their design life limit established around 30 years. Machines with this age won't necessary break down at the end of their life, but will precise a bigger control due to the insulation aging.
- Most of the new machines are the same size than older units but rated with more power and higher voltage so they will afford bigger stress.
- Nowadays, our societies impose a better reliability in power generation and distribution. It is necessary to know the punctual generator condition using predictive maintenance techniques, as well as test trending to be confident for the future.

These factors command utilities to improve their predictive maintenance policies by adapting their protocols to include field testing. This is an efficient practice to identify problems in hydrogenerators that will:

- Increase reliability.
- Decrease maintenance costs.
- Limit service failures.
- Increase the life of the machines.

For a long time, a lot of electronic engineers have been developing instrumentation that is intended for field testing of rotating machines. We will introduce several techniques and instruments that must:

- Be portable enough to allow testing in the field.
- Meet the applicable safety and EMC standards.
- Perform test accepted by international standards and proved empirically

1. Field Testing on Hydrogenerators

Every hydrogenerator, depending on its criticism, should have a customised predictive maintenance protocol. Reliable literature exists for complete maintenance on hydro units; this paper focuses in electrical tests that can be applied to check both stator and rotor, mainly concerning the insulation elements.

Tests are grouped and organized based in both international regulations and our experience and work with several Spanish power generation utilities, workshops and maintenance companies. We will introduce these best practices, indicating for every test the corresponding theory, the obtained parameters with their justification and their utility. This means which problems could be shown by those parameters. For every test, frequency (DC, AC, VLF) is indicated, together with the usual dimensions and units expected in the results [mΩ for resistance, No for adimensional]. The tests are roughly defined so extra information of each test can be found in references.

1.1 OFF-Line Testing

In this kind of tests, the machine is taken out of service. For the main part of the related tests (unless PD location) it is not necessary to have the rotor disassembled.

- **Winding Resistance (DC) [mΩ].** The test injects a current and measures the terminal voltage in each phase. The result is the pure resistance of each phase and must be temperature corrected. The resistance per phase should be very similar between them. It gives an indication of the integrity of the windings and the connections, indicating shorted turns, loose connections, wrong connections and open circuits. [Ref:1,2,3,4]

- **Insulation Resistance [GΩ] and Polarization Index (DC) [No].** This test is performed injecting a stabilized high DC voltage and measuring the current after 1 minute to calculate Insulation Resistance (IR). We can perform this test between phases or between the 3 phases and the ground. IR highly depends on temperature and must be corrected. It also depends on the winding class and on the curing state of the machine. IR should be above a minimum value related with the rated voltage of the generator. The Polarization Index (PI) is the ratio between IR after 10' and after 1'. As a ratio, it is almost no temperature dependant. The results indicate insulation contamination, moisture, cracks or fissures in the insulation. Standards indicate that this test should be carried out before more aggressive tests like Hipot or Surge tests. [Ref: 1,5]

- **EDA test (DC) [GΩ, NO, seg, nF, nA].** This is a test based in several standards and its main characteristic is that the charge period is enlarged up to 30' while the discharge takes 2'. During the test, IR, PI, time constant and charge and discharge currents are evaluated to analyse the dielectric absorption in the tested insulation. The test is performed at two different level of voltage to appreciate linearity behaviour of the insulation. Low voltage DC & AC capacitances are also measured to increase diagnose capabilities around contamination. The system using the parameters indicated, and also Absorption index, capacitance ratios, leakage currents and reabsorption currents is able to evaluate if the insulation has contamination (dust, oil, moisture) and discerns if it is external or internal. The system also reports if the insulation is very degraded, etc. [Ref: 5…12]

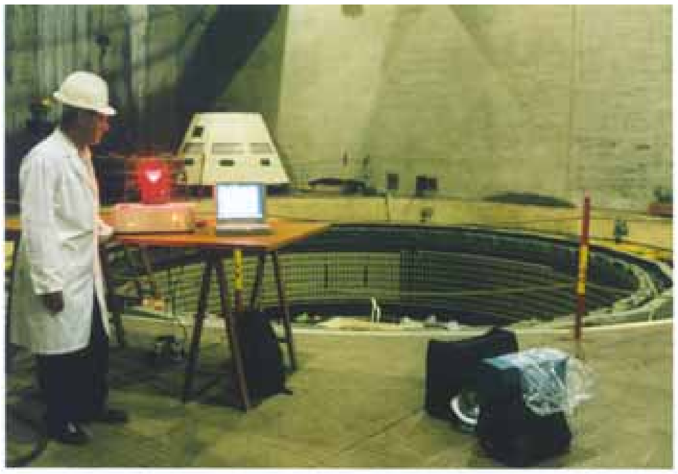

Fig. 1. EDA test in Iberdrola's hydro power plant.

- **HiPot Test (DC, ramped DC, AC or VLF) [µA, µA/V, mA, No].** As the previous ones, this test applies to the insulation a voltage for 1 minute, but in this case it's above nominal values. Maintenance test voltage is less than the factory test voltage. The result is generally pass or fail. This test will insure that the machine will support extraordinary service conditions but because of its aggressiveness, it's usually not carried out as a predictive maintenance tool. There are three options of test voltage application: AC (50Hz), DC, ramped DC or AC VLF (0.1Hz). These last two options allow the test instrument to be smaller and in most of the hydrogenerators, they are the only possible option for field testing. Ramped DC and VLF bring more information to predictive maintenance because currents evolution can be monitored and registered for future references The shape of leakage DC current ramp [µA to kV] can also give some indications of moisture, cracks, contamination, uncuring… [Ref: 1, 4,13,14]

- **Tan Delta testing, capacitance & tip-up (AC) [No, %, pF, graph % to %Un].** Tan delta is obtained from the angle between the AC capacitive to total currents applied to the insulation. The usual method of testing uses a balanced bridge. The result of the measurement are 1) Dissipation factor or Tan Delta to the test voltage and 2) Equivalent insulation capacitance to the test voltage. Tan Delta should be very small and will increase proportionally with dielectric losses. The value should be temperature corrected. Tan delta is also dependent on the test voltage. Because losses are monitored, when the voltage goes up, internal voids begin to activate and change test results. This way appears the concept of Tip-up test that is performed at different AC voltage values up to Un. Using this graph as an indirect partial discharge measurement, different insulation problems can be detected, as: humidity, contamination or delamination. [Ref: 14,15]

- **Off-line partial discharge (AC) [plots mv/counts, Qm, NQN].** Partial discharge (PD) corresponds to ionization of gas around or within solid insulation. Reactive species degrade the adjacent solid insulation because of the cumulative effect. Phase to ground insulation is energized up to normal operating voltages. Separated phases or individual windings can be tested this way. Capacitive couplers are the most popular and effective means to sense the level of partial discharges in the insulation. This coupler separates AC from PD's and the system counts the PD's correlated with their level, phase position and number. The differences from on-line testing are: 1) Slot discharges due to loose winding do not manifest so high, 2) winding temperature is lower and 3) neutral area is subject to high voltage as a difference from normal operation and this may increase the Partial Discharge (PD) level. This kind of testing helps confirming problems detected from on-line PD, EDA or tan delta. As the standards say, more important that punctual values are trending values obtained with this measurement. [Ref: 1, 2, 17, 18]

Fig. 2. Usual connection of hydro capacitive couplers.

- **Partial discharge probes (AC) [mA, No].** Once partial discharge activity is detected, it is important to locate the exact position. From the test set-up in the previous test, portable detectors give two approaches to implement this test: 1)Radio Frequency (RF) detectors that detect the radiated component around 5MHz from PD, and 2) Ultrasonic detectors that detect the ultrasonic (40KHz) component from PD. The result is a maximum numeric indication that allows knowing if the discharge is in the coil surface or in the slot and also in which of the inspected slots. [Ref: 1, 2, 17, 18]

- **Surge testing (AC pulsed) [plot µs/kV].** Previous related tests only check the main or groundwall stator insulation. Most ground faults begin with previous inter-turn discharges or faults. In order to use a portable system for this test, the instrument applies to both ends of the winding to inject a very fast pulse. This way, using less energy, each turn of the winding is exposed to values above rated voltage and the turn to turn insulation is so stressed. The result is a waveform that represents a personal "signature" for each winding. Every change in the different signatures both between the phases and in the same phase but in different dates will indicate problems. This test can indicate degraded insulation before a fault happens. The test is standard regulated for coils, but most recent studies suggest it is fully applicable to complete windings [1, 19, 20, 21].

1.2 On-Line Monitoring

The machine is tested while in operation for signs of premature degradation.

- **Thermal monitoring [ΔºC].** Monitoring of hydro units is usually implemented from internal punctual sensors installed in strategic locations to check for overheating. Another approach is through thermography, but the problem is that in operation, only external accessible places can be monitored.

- **Smoke and ozone detectors [ppm].** Some hydros can have systems to detect overheating areas with the analysis of the different gases emitted by special paintings. Generator Condition Monitors (GCM) detect particles in parts per million in air (ppm) coming from pyrolysis (overheating) from this paintings and can give an early detection of problems in different areas. This detection should be faster than punctual temperature sensors because that ones can only detect problems in the next area. Ozone (O_3), is a gas derived from the presence of high partial discharge activity, so high ozone indications give a faster clue of high levels of PD that might anticipate surface insulation degradation. [Ref: 2, 17]

- **ON-Line Partial Discharge (AC) [plots: mv/counts, Qm, NQN].** The theory is the same than for off-line measurement but now not all the windings are excited with the same voltage. In hydrogenerators, the most extended technique over the last 50 years is to use 2 capacitive couplers per phase as high-pass frequency filters and rejecting the noise using flight time noise rejection techniques. This way, external noise is rejected and only PD coming from machine are measured. PD data directly let know about the degradation evolution of the machine insulation. The interpretation of levels correlated to phase, stator temperature, moisture, active and reactive load will guide the expert to know about the possible defect in stator insulation (voids, delamination, thermal aging or cycling and loose windings) and its geometric location (voids or delamination next to cooper, in the groundwall, out in the semiconductive layer or in the endwindings). [Ref: 1, 2, 17, 18]

Fig. 3. Dust associated to partial discharge in endwindings.

- **Vibrations [mm/s, plots with Hz].** Mechanical vibration of the machine is recorded from transducers that convert vibration [mm/s or mm/s^2] into an electrical signal [mV]. A simple approach is to extract the general vibration that gives a number in mm/s and a more complex approach is to decode the signal into the frequency spectrum. Each one of the elements that compose the moving structure presents a peak in the frequency spectrum. With an initial baseline and the study of each frequency and changes, both punctual diagnosis and trending are useful to detect problems. The system can detect most mechanical problems: imbalance, misalignment, clearances, failures in gears, bearings…

1.2 Magnetic Core Testing

The core is functionally a medium that must provide:

- The mechanical support for stator / rotor windings. We should check the correct pressure between laminations and perform a visual inspection looking for faults.
- An element that should provide a path for thermal flow to remove heat from internal losses.
- Also a conductive path for the operating magnetic flux. The laminations should be correctly isolated from each other to minimize losses; the building bars should also be properly isolated.

Therefore, the core should be tested to avoid problems that could lead to core and adjacent insulation faults. For most of the tests indicated it is necessary to have the rotor disassembled.

- **Visual inspection (manual or camera).** The inspection consists in checking a complete list of points in the machine. Some places can be inspected directly or with the aid of a boroscope. Today, robotic vehicles can mount a camera to check inaccessible locations both in stator and rotor while moving through the air gap or between pole spaces. This can save a lot of time avoiding extracting the rotor. Results of previous tests can guide the inspector about what evidences of problems he should look for. The expert can find changes of color denoting overheated areas, pieces of laminations denoting loose core, dust coming from partial discharges or semiconductive coating, signs of deterioration,… [Ref: 1, 2, 24]

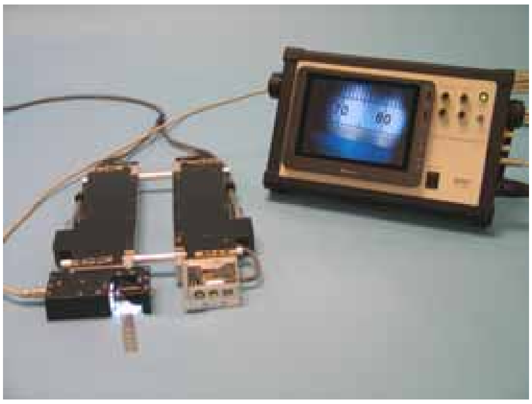

Fig. 4. Robotic inspection vehicle with a camera to perform visual inspection.
Applicable to systems Digital EL-CID and Wedge Tightness Detection (Iris Power).

- **Lamination looseness test [mm, MΩ].** The laminations in the core should be tight enough to avoid any movement between them. A knife is sometimes used to check that the blade is not allowed to enter into adjacent laminations. Compression Bolts should be checked both to comply with their function and to be properly insulated from laminations. [Ref: 1]

- **Wedge tightness survey detector (manual or automatic) [Tight, loose, jammed, broken, No].** Stator wedges retain coils into their slots with the proper tightness. This prevents movements of the bars into the slots degrading semiconductive coating and wall insulation. Manual test consist in an operator tapping with a hammer the wedge and detecting the vibrations with the other hand. As it was a very subjective test, an automatic electronic version have been developed to detect looseness degree. This version uses a probe including a small electronic hammer to hit the wedge and an accelerometer to check the returning vibration. In some situations (wide airgap or a pole extracted) a robot could perform the test with the rotor in place. If a big number of wedges is detected to be loose or hollow it is going to be necessary some partial or complete rewedge of the stator. This test could be performed on a routine basis or guided from another test as on-line partial discharge. [Ref: 1]

- **Full flux test & infrared inspection (AC) [Δ°C].** This test uses a powerful AC source transformer that energizes a toroidal winding around the core. This induces a flux close to the nominal operation of the generator. This excitation should be maintained around 1 hour, depending on the machine. The stator core should show a uniform temperature. The inspector uses then an infrared camera to detect any kind of hot spot. If an area of higher temperature than the average is detected, it should be investigated. When interlamination insulation is damaged, losses increase and then the temperature as well. Usually this way allows detecting loose laminations, interlaminar insulation degradation, hits or damages in the core and other defects that can lead to a fault without previous indication. [Ref: 4, 22, 23]

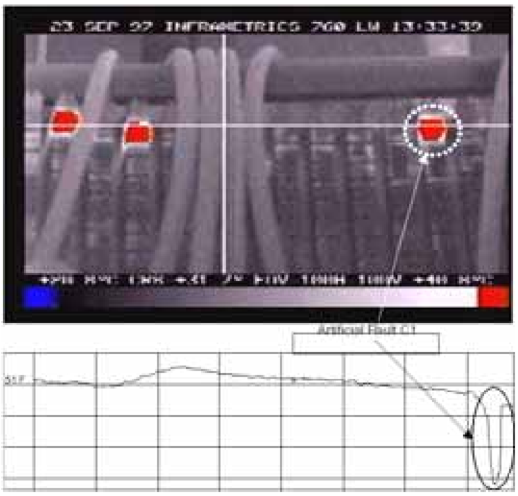

Fig. 5. Correlation of a Full flux test to reduced flux test (EL-CID). The plot below is the indication of the upper fault.

- **ELCID test (AC) [mA].** This test shares the same concept than the full flux test, but the flux is only 4% of the nominal value. This way, energy requirements and machine degradation chances are significatively reduced. This test is actually a field test version easier to perform than the full flux. With the power extracted from a normal wall plug, the core is energized up to 4% with the aid of a small toroidal winding. A manual exploration coil called chattock discerns with the aid of some electronics the magnetic currents coming from faults for each slot. In some circumstances, it is possible to perform the test with a robot making unnecessary to have the rotor disassembled. The result is a graph per slot where magnetic currents indicate fault magnetic irregularities. [Ref: 1, 22, 23]

2. Diagnosis and Trending

An expert diagnosis criterion depends on normalized values and tolerances, manufacturer's data and other empiric data to detect faults. The maintenance expert with all the information in his hands will give final diagnosis.
It is obvious that the machine history plays a very important role, so another approach comes from historical data / trending, where the parameters evolution may help detecting degradation speed and change maintenance periods / strategy.

When problems are detected, another confirming test can usually be used to corroborate the problem. The last steps should be a visual inspection, problem solution and another test to confirm the reparation. You can deduce from this the importance of an initial or zero test with baseline values.

Technical Site: Taller
Machine Type: Motor de media tensión
Function: Cogeneración
Instrument: EDA3

Reversible Problems
Insulation State: Clean and Dry
Insulation Resistance: Normal
Surface Currents: No Trace
Surface Moisture: No Trace
Surface Contamination: No Trace
Internal Moisture: No Trace
Internal Contamination: No Trace

No Reversible Problems
Transverse Current: Traces of Cracked Insulation
Abnormal Aging: Trace
Agglomerant State: Normal
Dielectric Structure: Weak Degradation Trace, but it's normal due to the " Total Running Hours"

Fig. 6. Stator Insulation diagnostic tool help from EDA system.

2. Conclusions

As we mentioned, every hydrogenerator depending on its criticity should have a personalized predictive maintenance protocol.

In each hydro unit and around field maintenance there are different papers:

- The **Owner**: He is the final responsible of the hydro machine; he can perform these tests by himself or subcontract them.
- The **Manufacturer** who should perform an adjusted test program to insure warranty periods or execute the maintenance contract.
- **Subcontracted** maintenance companies, similar to manufacturers but usually guided by the owner.
- **Workshops**. They try to know if it's necessary to rewind the machine or perform some special treatment on it.

Anyway, the mission of the owner is to supervise the work of the others, prepare or supervise the procedure, plans and protocols used (which of the test choose and periodicity) and the most important: validate, interpretate and diagnose test results.

The owner should only allow test inspectors for the hydro unit duly qualified or certified. These personnel must be skilled working around high-voltage testing and have a deep knowledge of field testing in order that they can offer:

- Congruent results: The test must be properly performed without errors, inconsistencies, fault data and no controlled extra influence around (temperature, moisture, rain, wind, connections,…).
- Safe personal and machine testing: The tests are performed with proper knowledge of personal safety rules and also for the machine.

Maintenance personal works are every day more relevant for hydrogenerators. In them rely the proper installation operation and the increase in reliability and economy of the installation. With the use of an adapted predictive maintenance program with adapted tests intervals it is possible to detect with anticipation deep faults that could lead to stop in production or great damage in hydrogenerators.

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