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Increasing hydro-equipment value with field measurements

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INTRODUCTION

The operating regime of hydraulic machines has considerably changed in the past years. The global electric market asks for more dynamic operation, with numerous start stops and part load operation for example. These modes are very demanding on the mechanical equipment.

In parallel, there is a trend in increasing the inspection intervals and minimizing the maintenance costs. To maintain a safe and reliable operation, it is time to time required, if not necessary, to establish an assessment of the machine for which measurement engineers are recommended.

For the continuous assistance of the client during assessment, commissioning, trouble shooting or upgrade studies of a machine, there are different fields of measurement techniques and competences needed. It ranges from efficiency, vibration, strain gauge to geometry measurements. Even more beneficial for the client is when these measurement engineers are not only skilled in theoretical and applied measurement technologies, but also have strong expertise in hydro-turbines.

The combination of know-how in measurement techniques and the analytical background allows caring for a sustainable and complete customer support, to minimize involved interfaces, to reduce the effort and therefore ensure a high level of reliability and safety regarding the result evaluation.

The paper presents project examples of different fields of measurement, with selected technologies, and gives an overview how these joint competences created added value to the client.

CROSS COMPETENT MEASUREMENT ENGINEERS

The Hydro market is asking more and more for an assessment of a hydraulic machine in general. Site tests are used to properly assess the hydraulic machines and are followed with derivation of maintenance recommendations and possibly improvement potential. Site tests are therefore today often used not only for guarantee measurement. The main reasons of today’s site test are the following:

- Assessment of machine
    - Improve machine safety,
    - Increase of machine availability,
    - Reduction of maintenance cost,
    - Define residual life time,
- Contractual measurements
    - Comparison of machine behaviour before and after rehabilitation,
    - Proof of guarantees,
- Root cause analysis

In the past site tests were extremely time consuming for which also a lot of heavy weight material was needed. The drawback of this equipment was the necessity of a specialist to operate it. Special knowledge about electronics, measurement techniques… was needed.

Modern equipment is reduced in size and weight and today's software allows measuring correct data without having deep knowledge of electronics and measurement techniques. More and more important gets the interpretation of the results, ideally live time at site.

Therefore a well skilled engineer at site is still necessary but ideally this is the same person who analyses the measurement results and derives out of it improvement potential or gives recommendations for rehabilitation or changing of the operating regime with the support, if needed, of back office experts. Several combinations were derived as ideally in the past such as:

- Laboratory test engineer ←→ Site test engineer
- Efficiency test engineer ←→ Hydraulic layout engineer
- Vibration test engineer ←→ Dynamic calculation engineer (rotor dynamic, FE)
- Strain gauge test engineer ←→ FE calculation engineer
- Generator test engineer ←→ CFD and analytical engineer

Beside technical advantages of the above discussed concept also commercial advantages are visible since the numbers of interfaces are reduced. This reduces not only the risk of interface information loss but also cost and timeline.

In several projects the benefit of these joint competences of measurement engineers could be demonstrated. For this also constant investment in state of the art equipment and training is necessary.

This not only helps to minimize the installation time for sensors and therefore the shutdown of the machine and increases the productivity of the power plant. It also secures the up to date analysis of the results and feeds directly life assessments of hydro-turbine components.

BUTTERFLY VALVE VIBRATION REDUCTION USING EXPERIMENTAL AND NUMERICAL MODAL ANALYSIS

Introduction and measurement setup

During commissioning of a new unit which was connected to an existing pipe system high vibrations were detected in the area of the butterfly valve which is close to the upper reservoir and about 1000m upstream of the installed hydro units.

Due to the arrangement of the older power plant which was taken out of operation (two separate penstocks fed several ternary pump turbines) two parallel penstocks were connected using a bifurcation to feed the new unit.

Surprisingly the vibration occurs only on one pipe (highlighted in the figure below) and the other remains of the vibration level before the connection of the both pipes. The only difference in this area is the about 1m different position of the butterfly valve

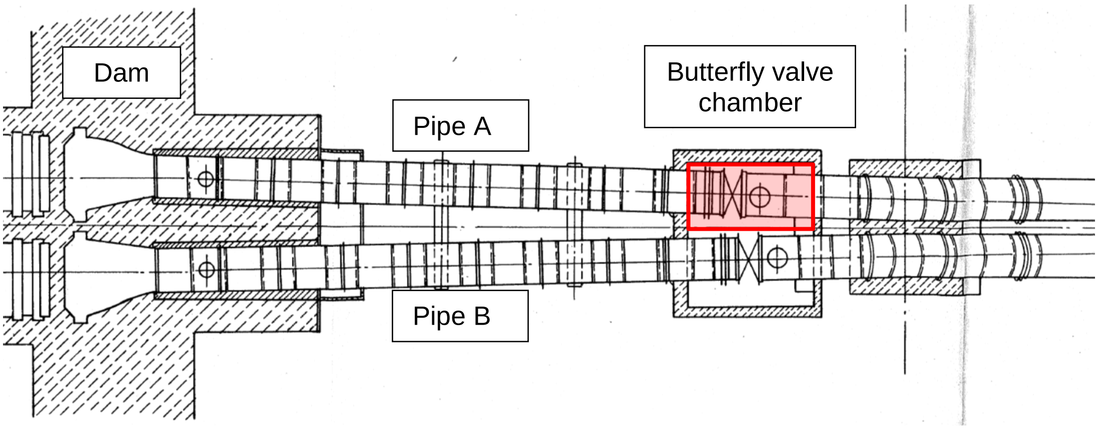


Figure 1: Penstock arrangement around the butterfly valve

Vibration measurement

To identify the present frequencies and the mode shapes a vibration measurement at site was performed. The measurement setup exist of three measurement sections with four acceleration sensors respectively (0°, 90°, 180°, 270°) on the vibrating pipe and one measurement section at the non-vibrating pipe. Additional dynamic pressure was measured at both pipes upstream of the butterfly valves.

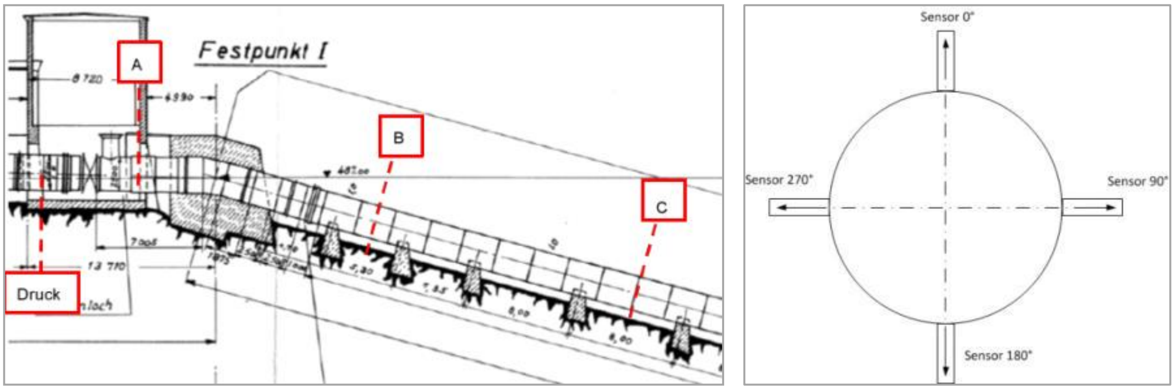


Figure 2: Measurement sections (left) and sensor location per section (right)

Figure 3 shows the comparison of the vibration values depending on the turbine power on both pipes. Highest vibrations were measured at part load while pipe A shows remarkable higher vibration than pipe B.

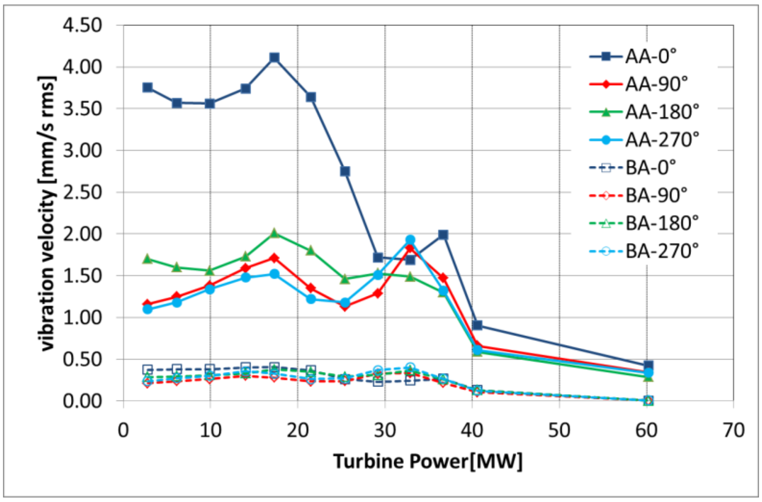


Figure 3: Pipe vibration velocity depending on turbine power.

The frequencies and phasing of the four sensors located at the different measurement sections indicates a wide band of existing frequencies and mode shapes (mainly bending and ovalization of the pipe). Reducing the vibration by adding of additional support was the first idea. However, the measurement results show the highest vibration at the top of the pipe and additional investigations were necessary. This leads to the conclusion that numerical modal analysis, calibrated with measurement results, would be beneficial to analyse the root cause of this vibration difference of the two pipes.

Numerical simulation

Numerical FE simulations were used to identify the difference between the two pipes and to reduce the vibration amplitudes on pipe A. This was done by means of numerical modal analysis and harmonic response analysis.

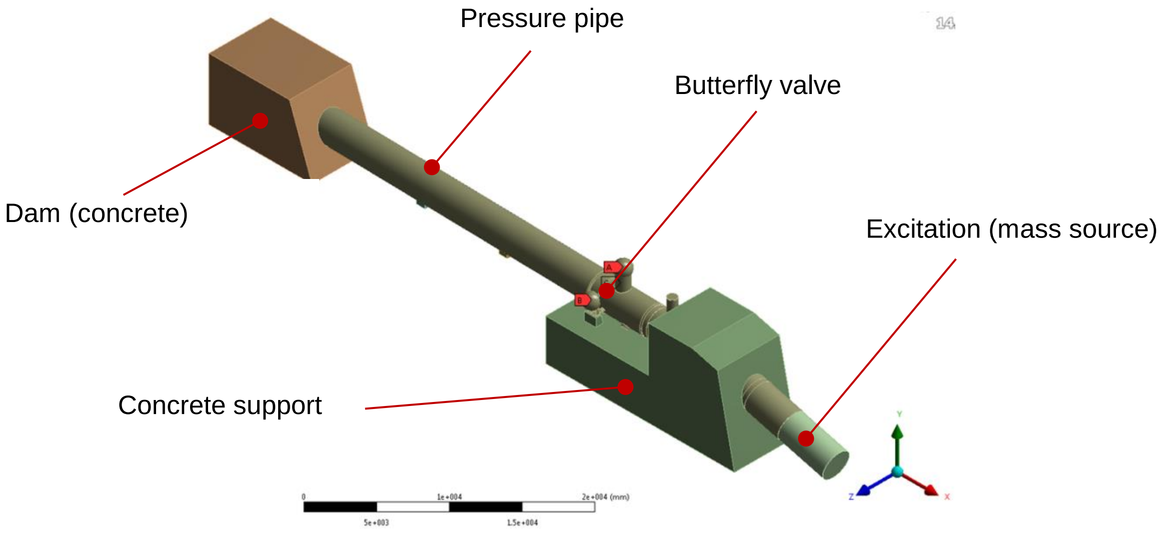
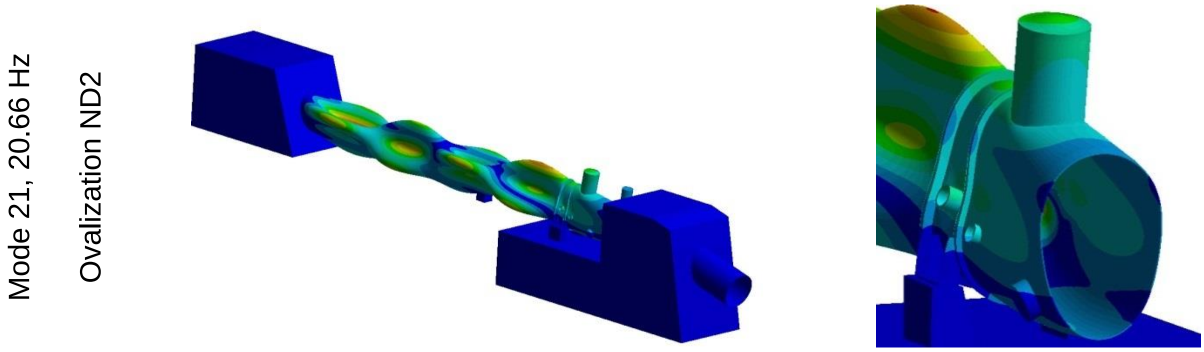


Figure 4: Simulation model

The excitation of the system was reached by adding an excitation source downstream of the butterfly valve which excites the simulated water in the pipe and causing a standing wave in the system. This water again excites the pipe structure in the defined frequency range by fluid-structure coupling.

The simulation confirms the measurement and shows many possible mode shapes in the problem causing frequency range. Dominant mode shapes of either ovalization ND2 and ND3 were found on both pipes. However the pipe B shows the similar mode shapes but at an about 3Hz higher frequency than the problem causing pipe A.



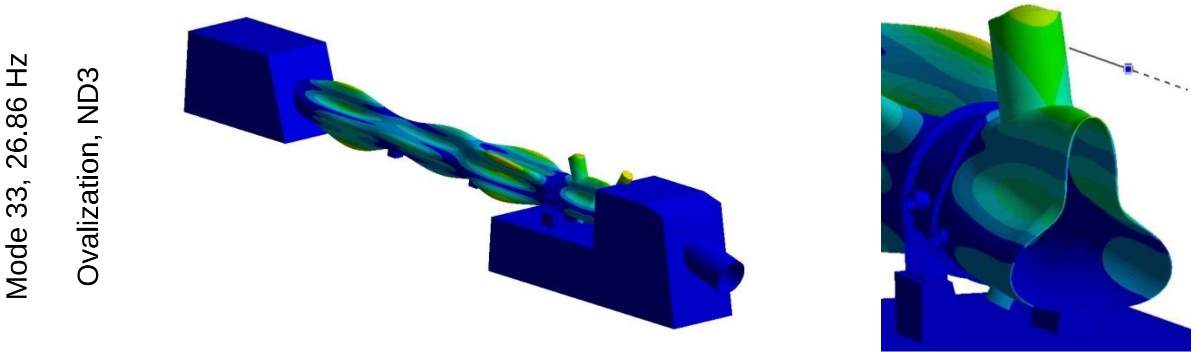


Figure 5: Exemplary mode shape of pipe A

By using harmonic response analysis the response of a defined excitation force was analysed at the measurement location and correlation between the measured and the simulated mode shapes was done. Since the measurement was performed by using 4 sensors at one measurement section, only mode shapes up to nodal diameter 1 can be analysed explicitly out of the measurement data. However, if the ovalization ND3 is reduced to the four sensor locations (0°, 90°, 180°, 270°) the phasing of these sensors are the same as a bending of the pipe, which was firstly mentioned as dominated mode shape only with the analysis of the measurement results.

As main analysing parameter a factor called D_{radial} was defined. This factor is summarizing the radial vibration amplitudes at the four measurement locations (indicated with red flags in Figure 6).

$$D_{radial}[mm] = \sqrt{\sum_{y=1}^{4} d_y^2 + \sum_{z=1}^{4} d_z^2}$$

Vibration amplitude reduction – pipe detuning

Two shamrock rings were added to the pipe in order to reduce the vibration amplitudes by means of detuning of the dominant mode shapes. One shamrock with four “leaves” to detune ovalization with ND2 and a second six-leaf shamrock in order to reduce the ovalization with ND3.

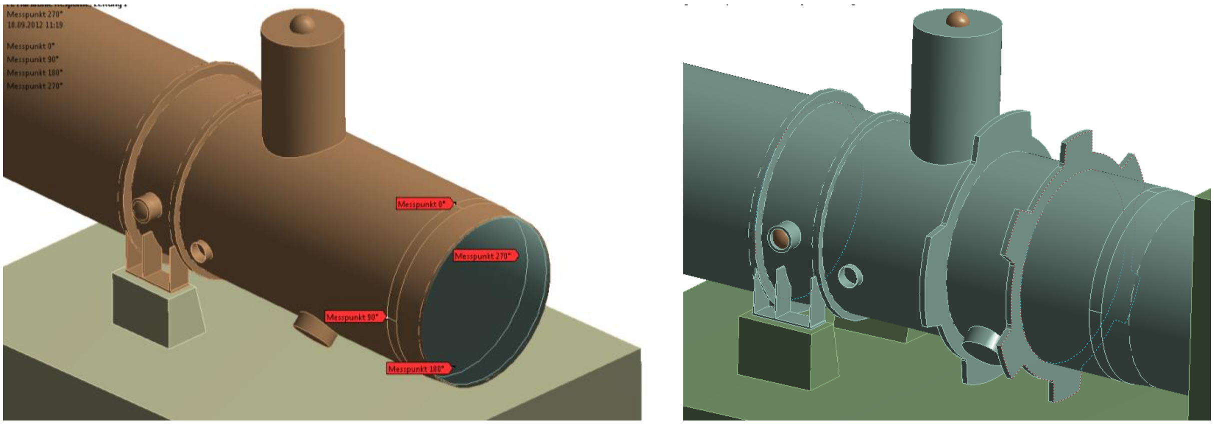


Figure 6: Existing geometry (left) and final solution “shamrock” (right)

The following image shows the relative D_{radial} of the two existing pipe and the final solution. The vibration amplitudes could be reduced significantly by adding the two shamrock rings on the pipe. Even more obvious is the vibration amplitude reduction visible in Figure 8 where the same scale is used.

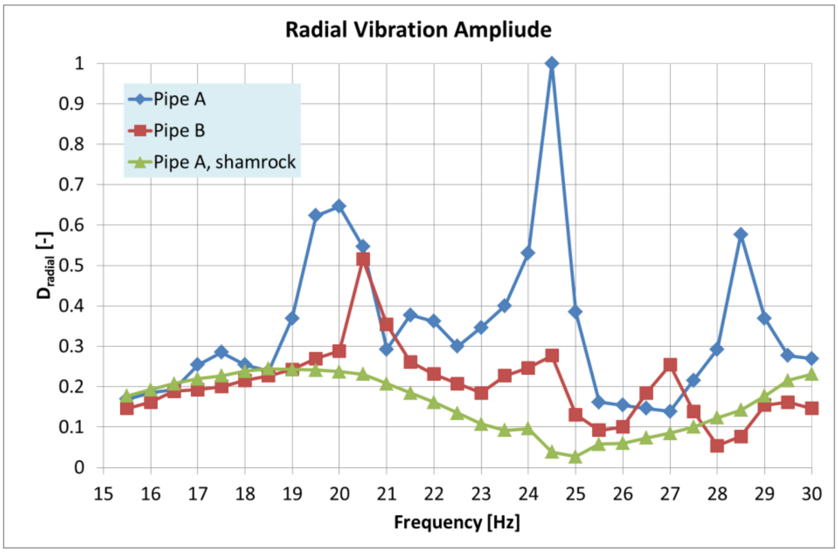


Figure 7: Relative radial amplitude of the different configurations

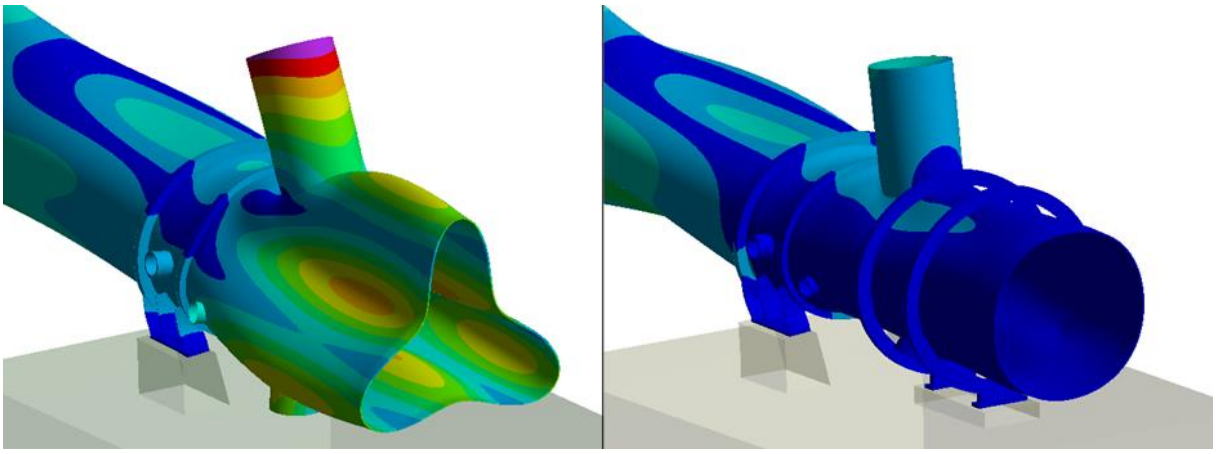


Figure 8: Mode shape comparison of original and modified pipe

The combination of dynamic vibration measurement including experimental modal analysis and numerical investigation by means of numerical modal analysis and harmonic response analysis was the success factor to reduce the vibration amplitudes in this significant way. This example shows the benefit of this combination and leads to an increased life time of existing components.

THERMAL DIAGNOSIS ON HYDRO-GENERATORS

The purpose of this section is to describe the advantages and current trends in the field of thermos-diagnosis on hydro-generators.

It is becoming increasingly considered among power plant operators. This technique provides detailed experimental information about two critical features during operation:

- Air flow distribution within the generator
- Temperatures in all critical static parts of the machine

These features are interconnected and represent a limiting factor for power output and efficiency of the generator.

The evaluation of this measurement data, together with the use of the most advanced calculation tools, which include in-house Generator Flow Resistance Models, in-house 3D finite difference temperature solvers and automated complex 3D computations, allow the identification of common operational problems in hydro-generators like:

- Hotspots,
- Temperature gradients,
- Flow and/or temperature asymmetry,
- Unnecessary ventilation losses.

The measuring equipment consists of:

- Up to 32 pressure transmitters for low pressure range (-10 : +15 mbar),
- Up to 32 resistance thermometers (PT100),
- Differential pressure manometer,
- Vane Anemometer,
- Thermal imaging camera.

A thermo-diagnosis on a hydro generator may include some or all of the activities represented in Figure 8

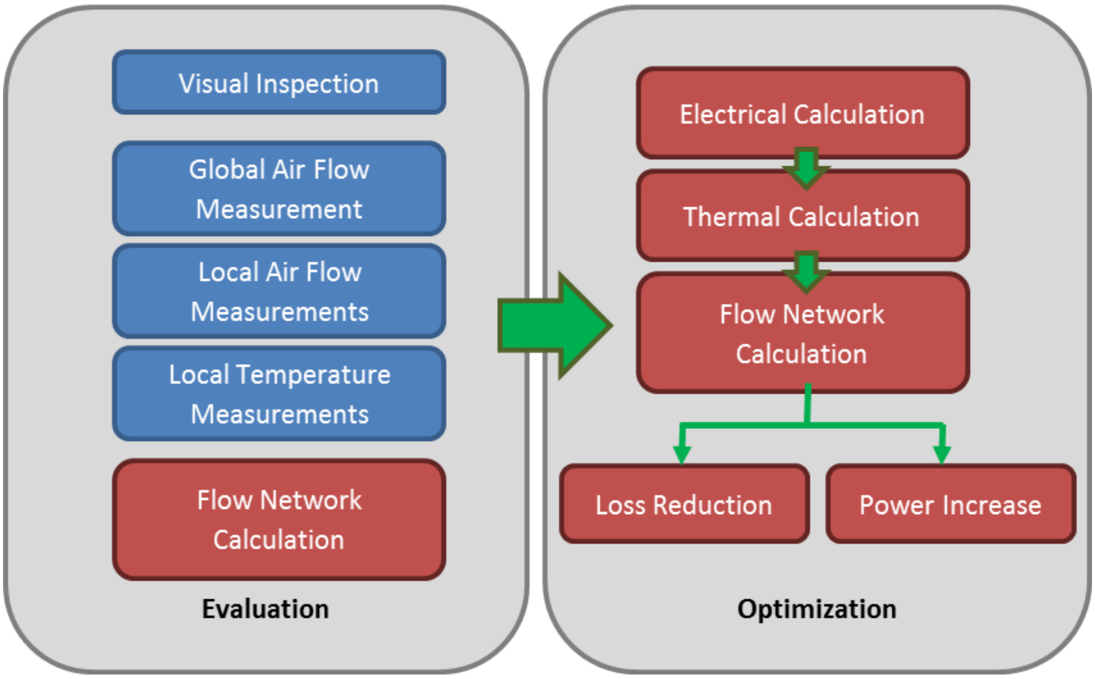


Figure 9: Steps of a thermos-diagnosis on a hydro generator.

The generator under study can be seen in Figure 10.

Figure 10: Image of the Generator under investigation

The visual inspection has shown an issue regarding the end-winding diaphragm. Its performance has been reduced drastically after an exchange of the stator winding and should be replaced.

The global air flow measurements have shown a much higher air flow rate than necessary.

The temperature sensors provide the time evolution given in Figure 11 (end-winding) and Figure 12 (stator core) for the air temperature inside the generator.

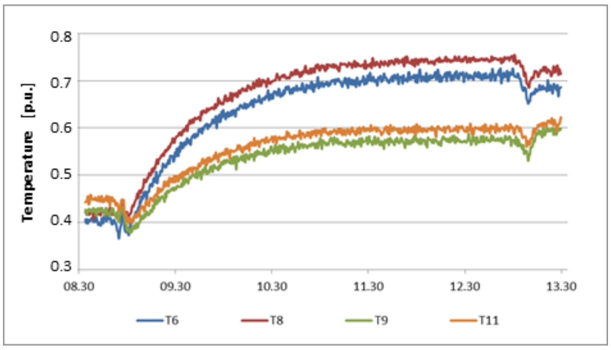


Figure 11: Time evolution of air temperatures in the end-winding

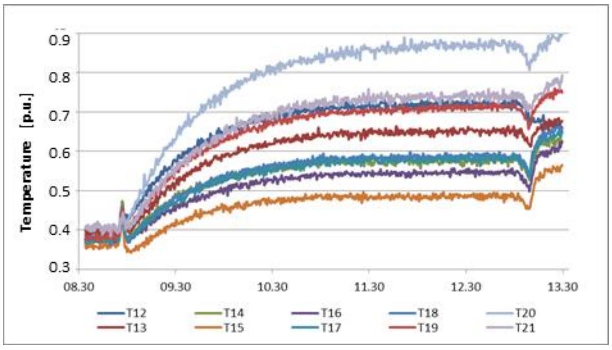
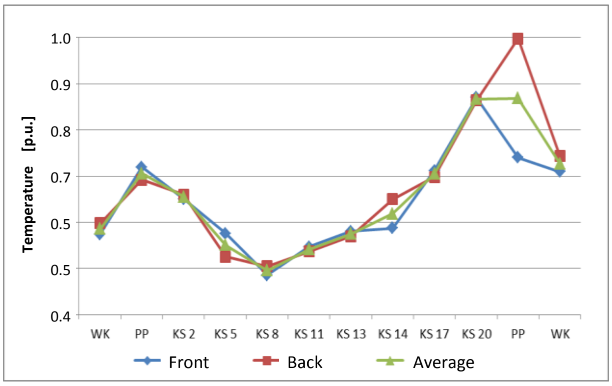


Figure 12: Time evolution of air temperatures in the stator core



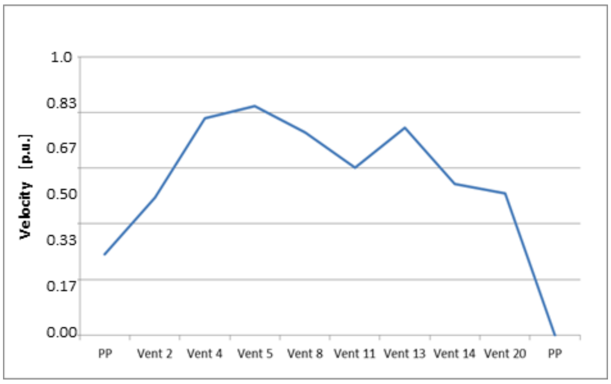


Figure 13: Steady state air temperatures along the axial coordinate of the generator

Figure 14: Steady state air velocity along the axial coordinate of the generator

Figure 13 reveals two negative aspects of the temperature distribution within the hydro generator: axial asymmetry of the temperature and higher temperature at both ends than in the centre of the machine. Both aspects have been confirmed by the axial distribution of air velocity along the ventilation ducts (Figure 14).

These two aspects are in this case not critical and the unit can be further operated without risk.

The thermal imaging camera shows as well low temperatures in end-winding and stator core (see Figure 15 and Figure 16)

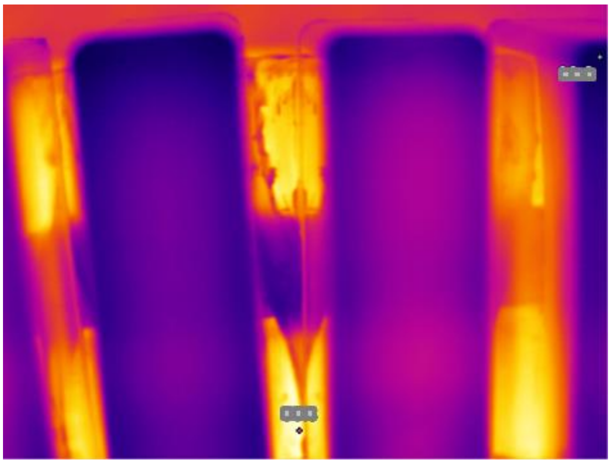


Figure 15. Temperature distribution at stator bars and caps in end-winding region

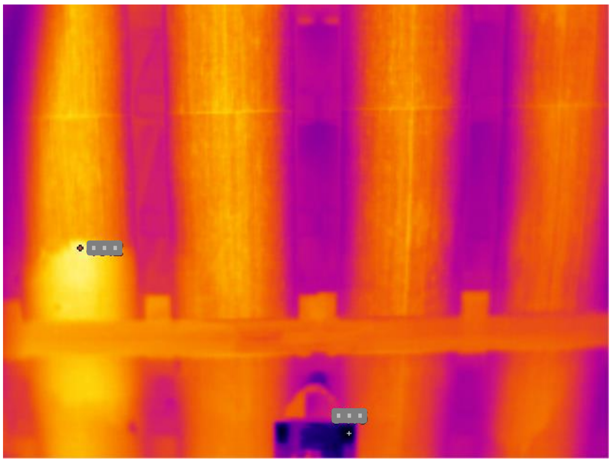


Figure 16. Temperature distribution of stator packages in stator core region

The final optimization study showed that slight changes in the ventilation scheme of the generator could save up to 58% of all ventilation losses while keeping the temperatures at acceptable levels.

The results of the thermo-diagnosis campaign carried out on this hydro-generator unit can be summarized as follows:

- Higher flow rate as necessary,
- Defect operation of the end-winding diaphragms on both sides,
- Acceptable operating temperatures with slight asymmetry,
- Higher flow rates in the middle ventilation ducts,
- Very high reduction potential in ventilation losses.

This information can be used by the operator to better plan future maintenance or refurbishment activities.

PERSPECTIVES

The analytical and simulation developments presented in both above projects took profit of the combination of multi-expertise held by the engineer performing the measurements. Even though the “back-office” hydro-turbine experts gave full support to the analytics, the problem-solving gained a lot (full overview, reduced interfaces, fast-response...) from the direct field experience of the measurement engineer.

These “multi-competences” are established from practicing the wide range of developments involved in designing, engineering, manufacturing and commissioning a hydro-generator unit.