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Advanced condition monitoring of Pelton turbines

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***Abstract* – The ability of hydropower to adapt the electricity generation to the demand is necessary to integrate wind and solar energy to the grid. Nowadays hydropower turbines are required to work under harsher operating conditions and an advanced condition monitoring to detect damage is crucial.**

In this paper an improved method for condition monitoring procedure of Pelton turbines is introduced.

A numerical model for the dynamic behavior of the machine has been built-up so that vibrations, deformations and stresses can be calculated for every operating condition.

To improve the model, the data obtained during several years of monitoring was used. The analysis of the machines before and after overhauls was studied to determine the symptoms of damage and to up-grade the model.

The operating conditions can be applied to the digital turbine model to calculate vibrations, deformations and stresses. Eventually, the remaining useful life of the turbine can be estimated.

I. INTRODUCTION

Hydropower is the largest and most efficient renewable energy source. Its flexibility also provides a key technology for the integration of intermittent renewable sources of energy like wind and solar into the grid. Nowadays, hydro utility companies are changing the way they operate their plants, switching from baseload to more flexible power production [1].

One of the most important types of turbines used in power generation is the Pelton wheel, which was patented in 1880 by the American inventor Lester Allan Pelton. It is widely used for high head power plants (the head is the difference in elevation between the upper reservoir level and the turbine level) and represents around 20% of total installed hydroturbines. The most powerful Pelton turbines are installed in BIEUDRON hydropower plant, Switzerland. BIEUDRON features 3 Pelton turbine units, D = 3.993 m, n = 7.143 Hz runner frequency, P = 423 MW unit rated power, 1'883 m rated head, 25 m3/s rated discharge, 5 injectors [2].

Pelton turbines have good efficiency and a large regulation capacity. They can change its power from 5 to 100% of total capacity with an efficiency that can be larger than 92%. In terms of maintenance, the disassembling and the inspection of the machine are carried out easily.

The basics of operation of a Pelton turbine are as follows: the high pressure of the water at the end of the penstock is converted almost completely into kinetic energy by means of a nozzle. The high speed jet coming out of the nozzle impacts on the wheel, thus converting the kinetic energy of the water into a tangential force that produces the rotation of the machine.

A Pelton wheel consists of a disk to which a series of buckets are forged along its edge. During operation the buckets receive the impact of the water jets, thus being subjected to strong pulsating forces that lead to large structural deformations. These deformations give rise to stresses that, after a long time of operation, may break the wheel because of fatigue. In order to prevent the wheel from breakage, a periodic surveillance of the machine is mandatory. In Figure 1 a picture of a horizontal shaft Pelton turbine open for inspection is shown.

Fig. 1. Pelton turbine open for inspection

II. STRATEGY

Carrying out the monitoring of a machine requires a deep knowledge of the dynamic behavior of the whole structure. This analysis enables determining how all the components of the machine are deforming when the turbine is in operation, and, at the end, allows seeing which locations of the wheel are more prone to suffer fatigue problems. In the real machine, the vibrations are detected by the monitoring system, and with an accurate signal analysis the condition of the machine can be estimated if the dynamic behavior is known.

A good and validated numerical model of the machine, as well as an accurate experimental investigation, is mandatory to analyze the dynamic behavior the machine. The strategy used to improve the existing monitoring procedure is indicated in Figure 2. This process consists of two different parts: one regarding the theoretical model and the other related to the field tests.

First the prototype Pelton turbines available, which belonged to the hydropower company, were analyzed and classified. The classification was done depending on the turbine and structure characteristics: head, power, the number of jets, the number of buckets; horizontal and vertical shaft machines, and number and location of the bearings.

A numerical model based on Finite Element Method (FEM) was built-up for the most common types of turbines. The accuracy of the model was done with detailed on-site tests.

Afterwards, the data base available was analyzed by checking the vibration signatures of all existing machines and looking for the history cases of failure. For the most severe failure cases a detailed analysis was carried out in order to identify the symptoms of damage in the vibration signatures, and the best location to detect them.

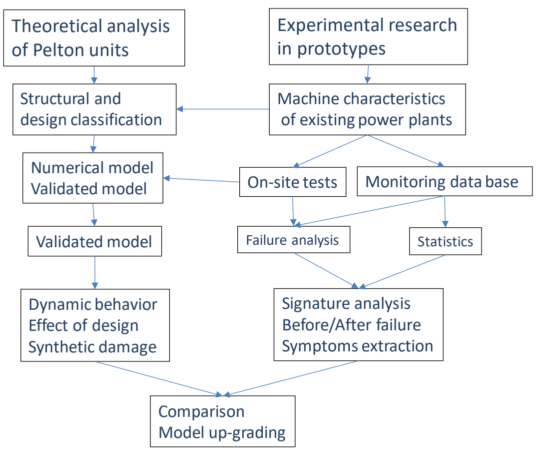

Fig. 2. Procedure

III. NUMERICAL MODEL

The first step consisted in obtaining a numerical model that resembled the existing machine and could be able to simulate its dynamic behavior. For this purpose, a model was created by means of FEM and was later compared to the real machine. In Figure 3 the numerical model of a Pelton wheel and the real wheel during experimental tests are shown.

To check the validity of the numerical model, the natural frequencies and mode-shapes were calculated and then compared to those of the real runner. The modal behavior of the real runner was obtained by doing impacts on the wheel and carrying out an Experimental Modal Analysis (EMA). In Figure 4, the comparison between simulation results and experimental results can be observed.

Once the model was checked, deformations and stresses in the wheel for different operating conditions could be computed and the life-time of the machine estimated. The value and distribution of the jet force on the buckets were simulated by means of Computational Fluid Dynamics (CFD). The resulting force was then applied to the FEM model and the response of the structure simulated. The effect of load and head differences can be calculated by changing the velocities and discharge of the jet.

Nevertheless, the dynamic behavior of a real machine cannot be completely simulated due to its complexity. For that reason, field data is necessary in order to upgrade the models. On-site tests were used for that purpose.

Fig. 3.Wheel model and experimental validation

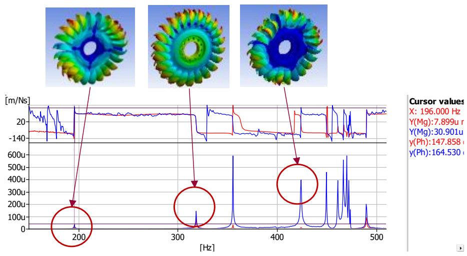

Fig. 4.Comparison between theoretical resulta and experiment

In Figure 5 a sketch of the model of a horizontal shaft machine with two radial bearings and a single jet is shown. The model incorporates the wheel, the rotor and the electrical generator. The forces resembling the jet excitation were applied to the model and the response of the structure was calculated, thus obtaining the corresponding deformations and stresses.

Finally, the model was checked with experimental tests by measuring the vibration during operation in several positions.

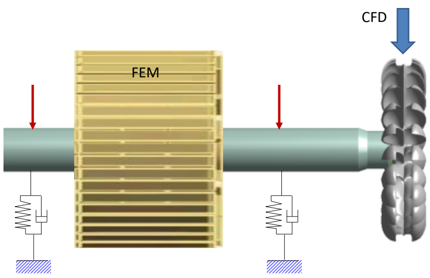

Fig. 5.Digital model

IV. DATA BASE

As indicated before, real machines are quite complex and the dynamic behavior not only depends on the design of the wheel but also on the installation type, mounting conditions, etc.

To tackle the real problem, the experimental data obtained from the monitoring of 28 different Pelton turbines over 25 years has been studied. By carrying out an accurate analysis of the corresponding vibration signatures, the influence of the design parameters has been determined. In addition to that, the effect of the - different types of damage on the vibration signatures has been detected. All damage suffered by the machines throughout the years has been analyzed and the symptoms for each case have been determined.

Pelton turbines can suffer from different types of damage. Most of the cases are due to sand erosion, fatigue or cavitation. Erosion problems are very common in areas like the Alps and the Andes, where the water carries a large amount of sand particles. In these cases, the most affected locations will be the surfaces where the water velocity and/or the acceleration are high, for example in nozzles, needles and runner buckets.

However, the most dangerous damage is caused by fatigue [3,4]. The cyclic appliance of the jet forces leads to a large concentration of stresses at the root of the buckets. After long operation times, these stresses may end up cracking the material. In Figure 6 a crack developed in the cut-out of a bucket can be seen. Cracks like that can develop quickly and, if unnoticed, can result in a bucket rupture with potentially disastrous results [5]. To avoid major damage, the design and manufacture of the turbine has to be of excellent condition and refine monitoring and periodic inspections are necessary.

Fatigue problems have been largely studied and treated throughout the years. At present, reliable runners are constructed using forged blocks of stainless steel because of its improved mechanical properties (such as fatigue strength and fracture toughness) with respect to cast steel.

Fig. 6. Example of fatigue crack

For the main types of damage found during monitoring the evolution of vibration signatures before and after repair were analyzed and the main symptoms of damage extracted.

V. ADVANCED MONITORING

The wheel is the most critical component of a Pelton turbine. Advanced condition monitoring and diagnostics are necessary to detect wheel damage.

The online monitoring system collects real-time data in the power plant. This information is sent to the center of diagnostic for accurate analysis and prognostic of the condition of the machine. In the central server, unlimited capacity for calculations is available. Advanced software can be used for fluid dynamics and structural dynamics simulation and signal analysis to refine the diagnostic and estimate the remaining useful life of the machine.

To follow up the condition of a Pelton turbine, data is acquired from different locations on the bearings. The determination of the normal vibration signature is supported by a large database available after years of acquisition and by the numerical models. Changes in the vibration signature are detected and analyzed, as they give information about the faulty condition of the machine.

One of the common problems in Pelton turbines is the misalignment between the wheel and the water jet. When this happens the flow on both sides of the bucket is unbalanced and gives rise to a resulting axial force that excites the wheel structure. This produces an increase of the stress levels in the bucket area and can lead to cracks and bucket failures. An example will be used to show how these cases can be detected and diagnosed.

In Figure 7 the change in the vibration signatures of a Pelton turbine can be observed before and after an incipient damage. The vibrations were measured in the axial bearing. The effect of the jet deviation is recognized mainly by an increase of the vibration levels at the blade passing frequency (band around 220 Hz). The evolution of these levels is shown at the bottom of the figure.

In Figure 8, the change in the same spectra but at higher frequency can be seen. In this case the excitation of the axial natural frequencies of the wheel is detected indicating an axial vibration of the wheel that in normal conditions did not appear (500-600 Hz frequency band).

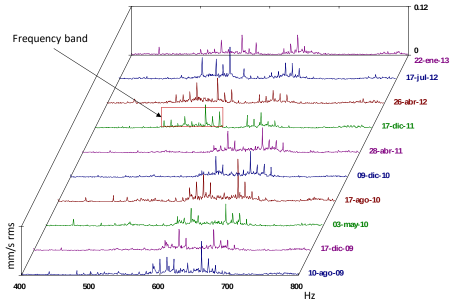

Fig. 8. Damage detection, evolution and stress computation with damage

Another case of incipient damage generated by jet misalignment detected during monitoring is shown in Figure 9. In this case with the computation of the model the stress distribution in the wheel could be determined. Comparing the stress distribution when the wheel is in good condition with that of the misaligned wheel some changes can be seen. The misalignment increases the load in one part of the bucket, generates an axial force and changes the distribution of stresses. The possibility to have fatigue damage can be estimated. With this information the owner of the machine can optimize the profit of the machine by adjusting its operating conditions. This can be done by either reducing the load in order to reduce stresses and increase the useful life, or by operating with maximum power in case the price of the energy is high.

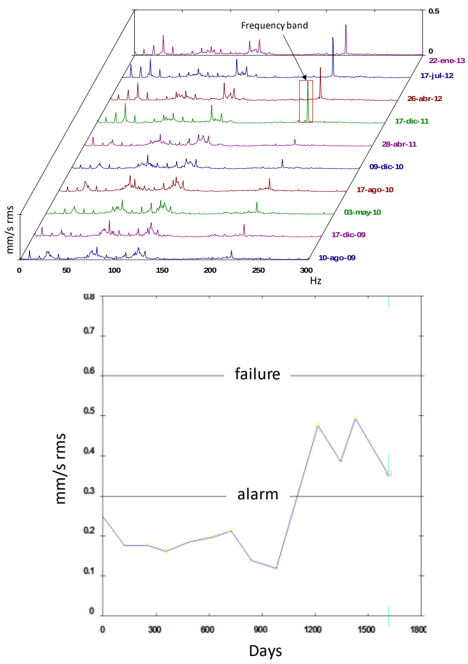

Fig. 7. Waterfall plot and evolution of the bucket passing frequency band

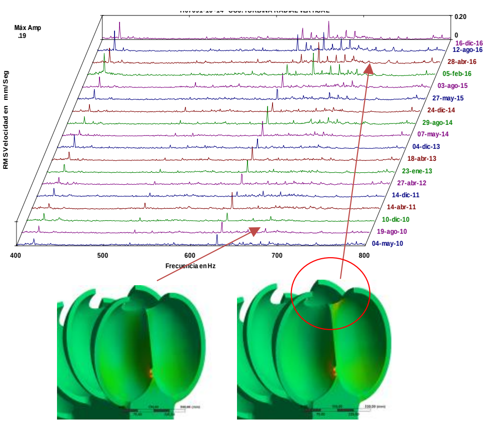

Fig. 9. Damage detection, evolution and stress computation with damage

VI. CONCLUSIONS

In this paper a procedure to improve the diagnostic of Pelton wheel problems has been introduced.

The most dangerous type of damage (breakage of the wheel buckets) due to fatigue has been studied. The study consisted in analyzing the dynamic behavior of the turbine in operation. A numerical model was built-up including a FEM model of the turbine and the results of a CFD model of the jet. The deformations and stresses generated on the wheel depending on the number of jets and power can be calculated.

The model was checked with experimental data measured in real turbines. The transfer function between the turbine and the monitoring points was also studied to see the feasibility to detect the wheel vibrations generated during operation.

Field data obtained during 25 years of monitoring was used to calibrate the model. History cases of damage that have occurred during this time were carefully studied and the symptoms extracted.

When a symptom is detected the model can calculate the change in stress distributions so that a fatigue calculation can estimate the reduction in the useful life.

VII. ACKNOWLEDMENTS

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