

Effects of extended operating conditions in pump-turbines

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I. INTRODUCTION

During the last years, new renewable energies (NRE) like wind and solar have experienced a strong entrance in power generation. Because the energy generated is of random nature NRE produce instabilities in the electrical grid. Hydropower plants are the only ones able to generate different levels of power according to the demand of electricity (generation has to match demand for the stability of the electrical grid). Because of that they are becoming key components in the grid.

To regulate power turbines have to work at off-design conditions what can lead to severe pressure pulsations, cavitation, and unsteady loads on structural members [1]. In order to avoid potential damage, limits for maximum and minimum power (load) are given by the manufacturers, who limit the operating range of the machines. All hydropower operators are interested in increasing the regulation capacity, because this is translated into a large increase in revenues [2], even if the life-time of the machine is reduced.

When machines operate at extreme off-design conditions many problems may appear. Strong pressure pulsations, instabilities in the draft tube and excessive turbulence can generate excessive vibration levels that can damage the machine. The only way to determine the effects on the machine of extreme off-design operation is measuring vibrations on-site in existing machines.

In this paper, some results obtained in a hydropower plant where the operating range was increased are shown. Changes in vibration and oscillatory behavior observed after one year of on-line monitoring are described.

II. MACHINES AND MONITORING SYSTEM

The power plant under study has four reversible pump-turbine units with a maximum power of 85MW each, rotating at 500rpm. They are vertical shaft machines (generator at the top and turbine at the bottom) with three radial bearings and one axial bearing (Figure 1). The runner has 7 blades and the distributor 16 vanes.

Vibration sensors, pressure transducers and monitoring systems (MVX from OneProd with XPR software) were installed in all units. For vibration monitoring two accelerometers located at 90° were installed in each

bearing. Pressure transducers were also installed in the draft tube for the surveillance of the pressure fluctuations. The monitoring system is continually acquiring signals calculating overall levels, spectral bands and spectral signatures. The evolution is controlled from a remote diagnostic center [3].

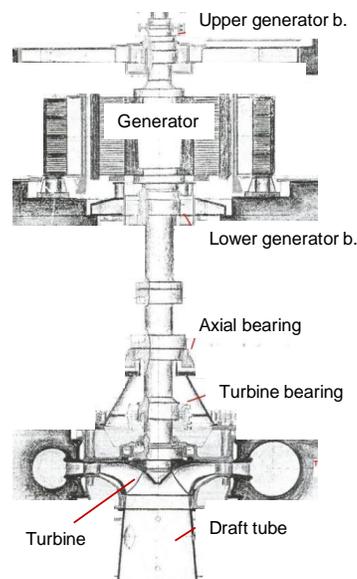


Fig. 1. Sketch of the machine

III. OPERATING CONDITIONS

Pump-turbines are used for pumping storage. The surplus of electricity generated (by wind mills) in hours with low demand is used to pump water from the lower reservoir to the higher reservoir of a hydro power plant for energy storage. In hours of high demand the water is turbinated generating electricity again. The power generated during turbine operation could be regulated between 45MW and 85MW. The head (difference of levels between higher and lower reservoir) changes continually between 300 and 330m. Because vibrations

generated depend on the operating conditions the monitoring is complex.

The operating range was increased by changing the lower load from 45MW to 20MW. Regular inspections of the unit were carried out to detect possible damage produced by this increase.

To determine how vibration levels and signatures change with operating conditions, especially at deep part load, the data acquired during one year were analyzed. First the turbine mode and second the pumping mode are analyzed.

IV. TURBINE OPERATION

To adapt to the electrical grid demand, machines are changing their load continually. At the same time the head is also changing (increasing when pumping and decreasing in turbine operation). Therefore, the influence of both parameters on the vibration levels has to be analyzed.

In Figure 2 the change in the overall vibration levels in unit 1 with load for a constant head of 320m has been represented. Vibration levels in the turbine bearing are higher than in the generator bearing. Both change with the operating load. When the machine passes from the maximum load (position C1) to the minimum load (position C3) vibration levels suffer a dramatic change. First the levels decrease and later increase.

The minimum levels are produced when the machine operates around the nominal load (position C2 in Figure 2). Vibration levels are higher at maximum load (C1) and especially at part load (C3). The maximum levels are reached when machine operates at deep part load (C4).

The other machines of the power plant have a similar behavior. In Figure 3 the change in load and the change in vibration levels in unit 2 during regulation can be observed. Although vibration levels are different the change in levels with load is similar to unit 1. The machine passes from the maximum load (position C1) to the minimum load (position C3) in a few minutes; the levels change from 1.1mm/s to 0.5 and to 1.8mm/s.

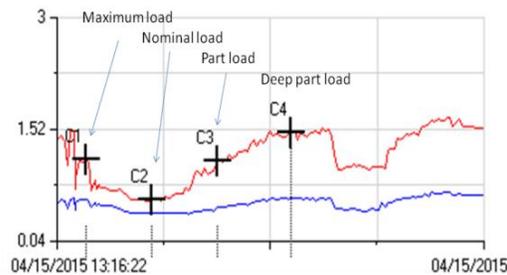


Fig. 2. Change in overall levels (mm/s rms) with load for nominal head (320m)

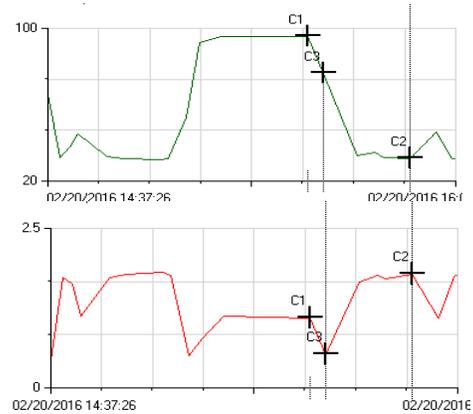


Fig. 3. Unit in operation regulating power. Top) load in %; Bottom) overall vibration levels (mm/s rms)

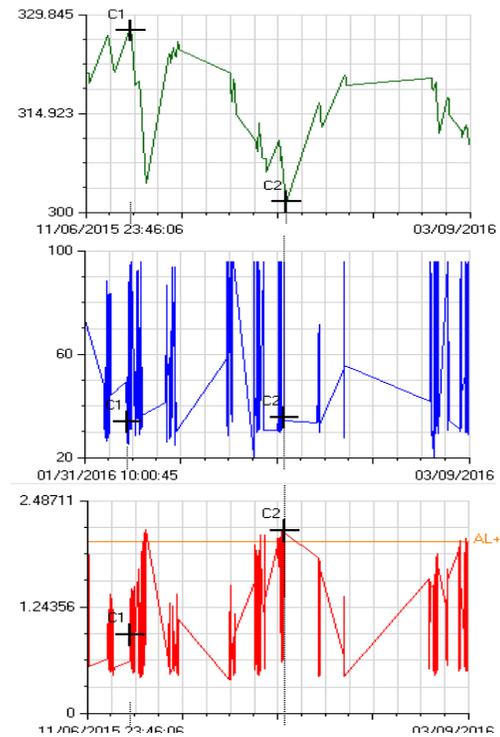


Fig. 4. Change in vibration levels with the head: Top) Head (m); Middle) Load (%); Bottom) Vibration level (mm/s rms)

Another significant parameter affecting the vibration levels is the head. In Figure 4 the change in vibration levels with head can be seen. In this Figure the changes in vibration level with head for different loads can be observed. The decrease in head from C1 to C2 produces a significant increase in the vibration levels; in both cases

the machine is operating at minimum load. Vibration levels for the same load are at maximum when head is the lowest.

To identify the causes of the change in the overall levels and the effects of operating the machine at deep part load, the vibration signatures for different loads and heads were analyzed. In Figure 5 the spectral signatures of the vibration for high load and low load are shown. A predominant peak at 116.56 Hz can be identified in both spectra. This peak is generated by the interaction between the rotating blades of the runner and the stationary guide vanes called rotor stator interaction (RSI) [4]:

$$f_b = n \cdot Z_b \cdot f_f$$

Where f_f is the rotating frequency of the runner, Z_b the number of rotating blades and n the order of harmonic. As a result, pressure pulsations at the blade passing frequency ($f_b=58.3\text{Hz}$) and harmonics are produced. For a combination of 7/16 blades the predominant frequency is twice the blade passing frequency (116.6Hz). The amplitude is lower at minimum load. This is normal because, when load is reduced, the distance between the impeller and the distributor increases. In this case lower pressure pulsations appear.

At low load the RSI excitation is reduced but there is an increase in the random vibrations because when the machine operates off-design the flow is more turbulent [5]. Operation at very low load (Figure 6) results in an important increase in the random vibrations [6]. The effect of operation at deep part load can also be observed in Figure 7, where the change in high frequency vibration is shown.

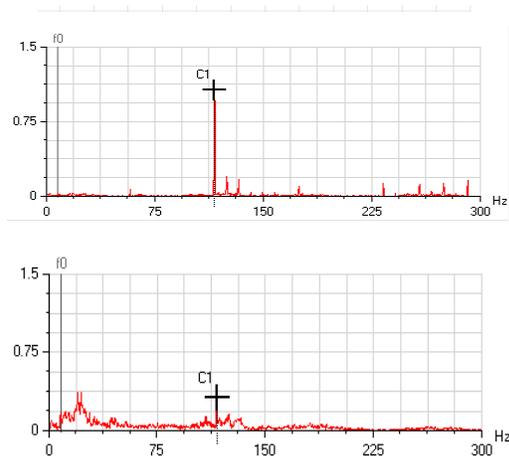


Fig. 5. Variation of vibration signatures with load at constant head: Top) High load; Bottom) Low load

Other typical hydraulic excitations that could impair the operation of the turbine at part and full load are the cavitation vortex ropes generated in the draft tube.

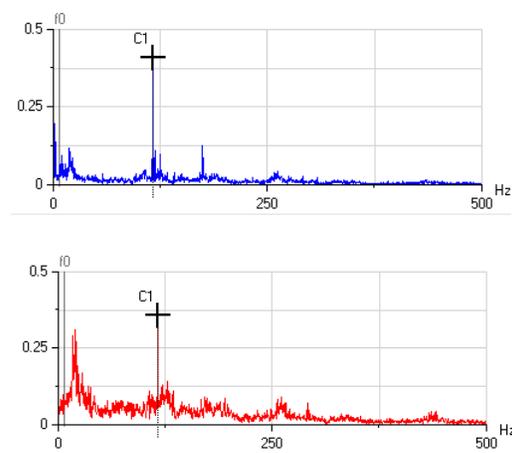


Fig. 6. Change in spectral signatures with load (mm/s rms). Top) Low load; Bottom) Very low load

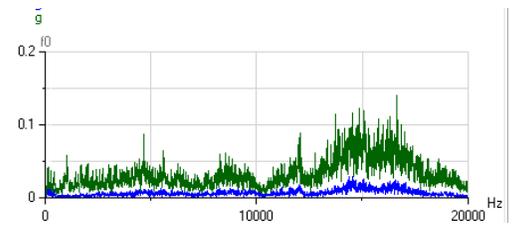


Fig. 7. Change in high frequency acceleration

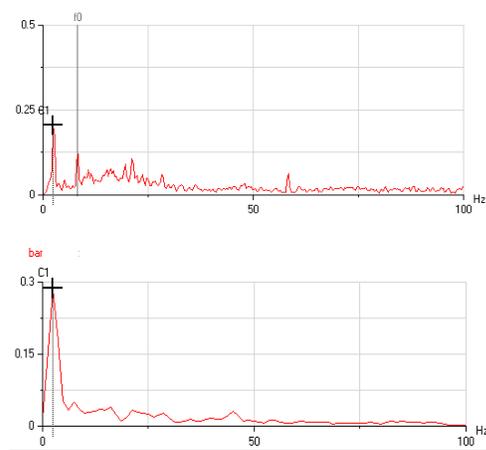


Fig. 8. Detection of cavitation vortex rope at part load. Top) Turbine bearing vibration (mm/s rms) Bottom) Pressure fluctuation (bar)

This phenomenon may appear when turbine is at part load because the flow leaving the runner has a rotational component that generates a strong vortex. The precession of the vortex core can generate low frequency pressure fluctuations in the draft tube.

At about 35% of load a rotating vortex core in the draft tube is identified by the turbine accelerometer and by the pressure transducer located in the draft tube (Figure 8). A pressure fluctuation at 2.5Hz, what is about 30% of the rotating speed of the machine, can be identified [7]. Anyway the pressure fluctuation is not too high and does not increase significantly the vibration levels.

V. PUMP OPERATION

In pump operation the machine operates with a rather constant power (same guide vanes opening). In this case the only parameter affecting the vibration behavior is the head. As it can be observed in Figure 9 the vibration levels are much influenced by the head. When the head decreases the overall vibration levels much increase.

To determine the cause of this change, an analysis of the vibration signal is made (Figure 10). High frequency vibration is generated when pump operates at the lowest head, what is a symptom of cavitation [4].

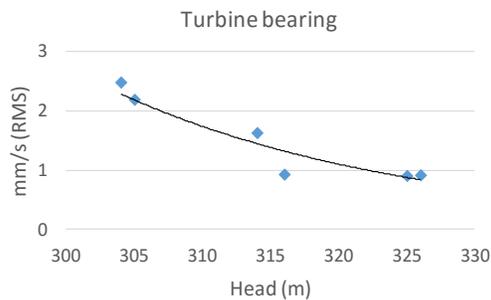


Fig. 9. Changes in vibration levels with head

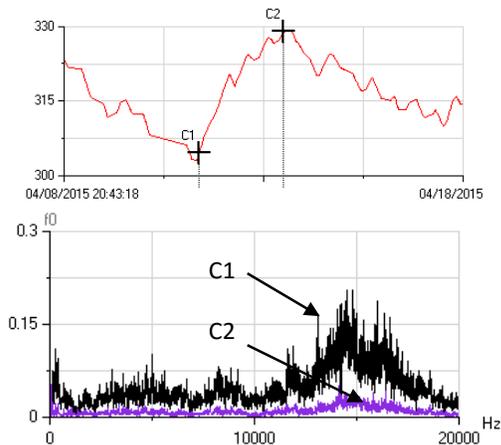


Fig. 10. Change in high frequency vibrations (g) with head. Spectrum with higher levels correspond to low head operation (C1)

VI. CONCLUSIONS

The consequences of extending the operating range have been studied by analyzing the data measured from an existing turbine. Data have been collected continually during one year. It can be observed that vibration levels depend very much on both load and head.

First the influence of operation at deep part load, for the same head, has been studied. Operation at deep part load is accompanied by an increase in the vibration levels caused by an increase in turbulence and cavitation. However, at low loads the pressure pulsation generated by the RSI decreases.

Second the influence of head on the vibration levels has also been studied. This effect is more important than expected. Operation at low heads double the vibration levels with an increase in cavitation.

Flow oscillations are detected at part load, in the extended range, but do not produce instability in the machine operation.

The worse conditions are achieved when machine is operating at deep part load with the minimum head.

Taking into account the effects of the head, the operating range could be extended if operation at minimum heads is avoided. Regular inspections of the machine are mandatory to check the cavitation erosion and the appearance of cracks in the runner.

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