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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 into the electrical 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 the methodology to improve the condition monitoring of Pelton turbines is presented. First, the field data obtained from the vibration monitoring of 28 different Pelton turbines over 25 years has been studied. The main types of damage found were due to fatigue, cavitation and silt erosion. By analyzing the vibration signatures before and after maintenance tasks, the symptoms of damage detected from the measuring locations were determined for each case.

Second, a theoretical model using numerical methods (FEM) was created in order to simulate the dynamic behavior of the turbine. The model was validated with the results obtained from on-site tests that were carried out in an existing turbine. The deformations and the stresses of the runner under different operating conditions could then be computed.

The calibrated model was used to analyze in detail the effect of misalignment between nozzle and runner. In historic cases, this abnormal operating condition lead to severe damage in the turbine, due to the effect of fatigue in some locations of the buckets. The model reproduced well the symptoms detected in the field measurements. The stresses could be calculated, which eventually can be used to estimate the remaining useful life of the turbine.

1. Introduction

Hydropower is regarded as one of the most important sources of energy in sustainable power generation. The biggest share of worldwide electricity production from renewable energies comes from hydroelectricity [1], which also retains one of the highest efficiencies. Hydro utilities are also known for their regulation capacity: power plant operators are capable of adjusting the power outcome depending on the electricity demand. With the implementation of new renewable energies, such as wind and solar, there is an increasing percentage of power that is tied to the variability of its sources, and thus cannot be adjusted to the demand. As electricity production has to match demand at any time, hydropower has become a key player to keep the grid stability [2]. In order to adapt to this new scenario, hydro utility companies have been progressively switching from baseload to a more flexible power production.

The Pelton turbine stands as one of the main types of turbines used in hydropower. This was patented in 1880 by the American inventor Lester Allan Pelton and it is the only impulse turbine used for high power generation. Pelton turbines are generally used in locations where head is higher than 500 m (the head is the difference in elevation between the upper reservoir level and the turbine level) and represent around 20% of total installed hydropower turbines. The most powerful Pelton turbines in the world are located in Bieudron, Switzerland. The Bieudron Power Station features three Pelton turbine units with a diameter of 3.993 m, rated power per unit of 423 MW and a rated head of 1.883 m [3]. While low/middle head turbines (Francis and Kaplan) have been extensively exploited, high head hydropower still waits for its full development, especially in some countries like China. At present, the research on dynamic problems and silt erosion is of great interest to increase the design head and to reduce maintenance.

A Pelton turbine is an action-type turbine. This means that the mechanical power is only obtained from a change in the kinetic energy of the water. In the power plant, one or more nozzles (called injectors) expel a high-speed water jet that impulses the runner. Pelton turbine plants offer some advantages over those of reaction-type turbines. On the one hand, they have a large regulation capacity: power can be regulated from 10% to 100% of total capacity with a maximum

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Fig. 1. Pelton turbine open for inspection. The turbine runner and the electrical generator can be seen.

efficiency of 92%. This is adjusted by means of a sharp-pointed piece (needle) placed inside the injector that can be easily controlled by a servomotor to regulate discharge. In terms of maintenance, the disassembling and inspection of a Pelton turbine is carried out with relative ease compared with a Francis or a Kaplan turbine, due to its simpler installation [4]. In Fig. 1 a horizontal shaft Pelton turbine ready for inspection is shown.

The runner of a Pelton turbine basically consists of a disk whose rim is surrounded by several buckets. These buckets are designed to receive the impact of the high-speed water jet coming out of the injectors. The inner surface of the buckets is molded as to split the jet into two and divert it almost 180°, thus taking advantage of all the water's kinetic energy. As a result, a strong force is applied to the bucket (and in the tangential direction of the runner), and maximum torque is transmitted to the shaft. Fig. 2 shows a picture and a sketch of the buckets of a Pelton runner with the injector and the needle. The attachment of the bucket to the disk is, due to its cantilever structure, the area that bears the highest stress values in a Pelton runner. In addition, each bucket receives the impact of the water jet several times during operation, which depending on the number of nozzles can range from one to six times per revolution. In the long term, the periodic stresses at the base of the bucket (and other locations of the bucket) end up damaging the structure due to the fatigue of the material. After some time of operation, the material may present some cracks. If these are untreated, the turbine is prone to suffer serious damage in the future. In order to avoid expensive disassembling and reparation costs, a periodic monitoring of the machine is mandatory.

There are different procedures to evaluate the state of a turbine. Historically, periodic inspections were carried out to check the structural condition of the machine [5]. However, the costs of downtime and disassembling were high, and the possibility of preventing damage was very limited. Some years ago, power plant operators took notice of the importance of measuring vibrations, as they were proved to be closely related to the state and operating conditions of the machine. Nowadays, monitoring systems are widely used to keep track of the condition of the machine in real time. Sensors are placed in different locations, usually on the bearings, and several parameters are measured constantly in the power plant. This data is then sent to a processing center where trending and diagnostics are made.

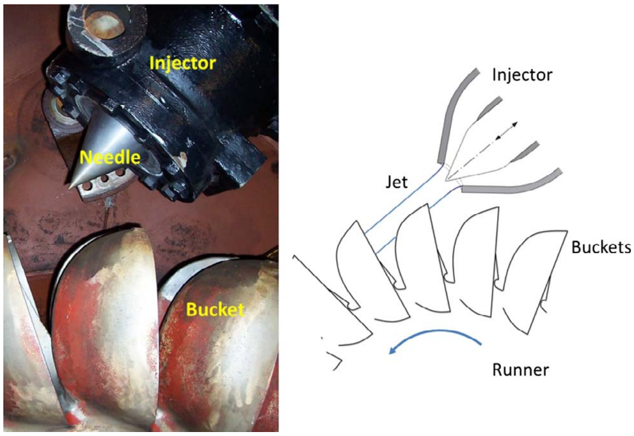

Fig. 2. Pelton turbine showing injector and buckets.

Nowadays, many studies are available on how to monitor and diagnose rotating machinery problems using vibration analysis. Most of them are aimed at common machines like pumps and fans with components such as roller bearings and gearboxes [6]. Usually, these are industrially standardized elements, for which common vibration features can be obtained. However, a hydropower plant is more complex: all the unit (turbine and generator) is a tailor-made piece, the installation includes multiple components, and their distributions differ from one power plant to another. Little information can be found about monitoring and damage detection of hydraulic turbines [7–11], and almost nothing about Pelton turbines [12–15]. The objective of this paper consists in upgrading the current state of condition monitoring of Pelton turbines.

2. Condition monitoring in pelton turbines

In the beginning of the 90s, vibration monitoring started to be implemented in some hydropower plants with the aim of progressively introducing predictive maintenance. At present, the time intervals between overhauls have been extended and the major problems in the machine are detected before damage is too severe. The general procedure used for monitoring is described in the next paragraphs.

2.1. Implementation of the system

The first step for vibration monitoring consists in determining the most suitable measuring locations. In a hydraulic machine, like in other rotating machines, the dynamic forces of the rotating train are transmitted to the bearings and their casing, which are also accessible areas. Hence the location selected to place the sensors (accelerometers) was the rigid part of the housing of the main bearings of the machine. In each bearing two orthogonal radial measurement directions were selected on the cap, pedestal or housing. Care was taken to avoid any vibration amplification by local resonances. For horizontal shaft machines, measurements were taken in the vertical and horizontal directions 90° apart (perpendicular to the shaft axis) and in the axial direction. In the case of vertical machine sets, measurements were also taken in all bearings in both the upstream direction and at 90° to that. In all cases the transducers were aligned in all the bearings. Representative locations are shown in Fig. 3 for a horizontal shaft machine. Once the sensors were installed, the vibrations were measured in all the locations at periodic intervals with portable data collectors.

2.2. Analysis of vibration

The vibration values obtained from the measurements were represented in the frequency domain to characterize the state of the machine. The resulting signal is known as the vibration signature, which depends on the structure and the operating conditions of the turbine (power delivered). Looking at the signature, one can easily detect the frequencies at which the vibration is higher, thus making it easier to identify their causes. In case of wear or damage, other frequencies are excited and the signature varies.

In Fig. 4, a typical spectrum of the vibrations measured in a Pelton turbine bearing is shown. In this vibration signature some periodic