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Behavior of Francis turbines at part load. Field assessment in prototype: Effects on power swing.

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Abstract. Francis turbines are increasingly demanded to work at part load in order to satisfy the electricity generation demand and to compensate the non-constant generation of other renewable sources such as wind or solar. At part load, Francis turbines present complex flow patterns dominated by cavitation and especially by the draft tube vortex rope. The vortex rope phenomenon affects the structural behavior of the machine as well as the hydraulic circuit response and, for certain conditions, it could become unstable. At this situation, the output power can significantly swing endangering the electrical grid stability. This condition has to be well-known and avoided as far as possible. In this paper, the phenomenon of the power swing at part load in prototypes is studied. For this purpose, different Francis turbine prototypes have been selected. The units have different specific speeds and therefore different power, head and geometry. All of them present the power swing phenomenon at part load. Different sensors, such as accelerometers, proximity probes, pressure sensors or strain gauges, have been placed in different positions of all the machines in order to detect and quantify the phenomenon. The relationship between the hydraulic phenomenon and the output power swing is presented for all the turbines studied. Results obtained permit to asses on the on-site detection of power swing as well as the possibility to avoid it in real-time.

1. Introduction

In order to compensate the non-constant electricity generation of new renewable sources, such as wind or solar power, hydropower units are required to extend their operating range [1]. Pelton and Kaplan turbines present rather good efficiency at their whole operation range, hence they can adapt better to this new scenario in the energy market. However, Francis turbines are optimized to work at their Best Efficiency Point (BEP), therefore they suffer from different dynamic problems when they work at off-design conditions. One of the most studied dynamic problems in Francis turbines is the part load vortex rope [2-4]. This vortex rope is formed by a spiral cavitating core in the draft tube with a precession frequency of about 0.25-0.35 times the rotating speed of the runner. The pressure pattern induced by this cavitating vortex rope can be decomposed in two different components: the asynchronous and the synchronous [3, 5]. The first one corresponds to a rotating pressure pattern in the draft tube and the second to an axial pressure pattern.

The synchronous component of the vortex rope is propagated to the entire hydraulic circuit. When its frequency coincides with a natural frequency of the hydraulic circuit (draft tube, runner or guide vanes passages, or penstock) a hydraulic resonance occurs, amplifying the amplitude of the pressure pulsation. This fact is dangerous for the system stability as well as to the mechanical parts in contact with the hydraulic circuits, such as pipes or the runner. It is also seen that during these hydraulic resonances, the electrical power generated by the turbine fluctuates considerably [6, 7]. Therefore, this phenomenon has to be avoided during the operation of Francis turbines at part load.

The effects of this phenomenon on the hydraulic circuit has been studied theoretically, numerically and experimentally in laboratory for many years. However, the effects on the runner and the power swing generated by hydraulic resonances at part load in prototypes have not been presented in those studies. This has been investigated recently by the authors of the present paper in reference [8]. In this study, the effects on the runner, shaft torque and power swing were analyzed for a large Francis turbine instrumented with several sensors. It was demonstrated with experimental results and numerical simulation that a planar pressure wave propagated through the entire hydraulic circuit is able to deform the runner axially and torsionally. This fact produces a high axial vibration in the machine as well as a torque and power fluctuation.

In this paper, the experimental results that demonstrates the relationship between a planar wave propagated in the entire hydraulic circuit with the torque and power fluctuation are presented. Moreover, a numerical simulation which confirms this relationship is also shown. This study has been carried out for a large medium-head Francis turbine (444 MW of rated power). Results obtained in this prototype permitted selecting the best sensor and position to detect part load resonances in Francis turbines. With this information, two other Francis turbine prototypes with different specific speed have been studied for their whole range of operation. These other prototypes also present power swing at certain load below their BEP. In this paper it is demonstrated that the power swing of those prototypes is also related with hydraulic resonances at part load. Therefore, a procedure to detect this problem experimentally and try to avoid it is explained for different specific speed Francis turbines.

2. Experimental investigation

2.1. Description of the selected turbine

A detailed experimental investigation in a medium-head Francis turbine were carried out in order to study its dynamic behavior for its whole range of operation. This Francis turbine has a specific speed (n_{sq}) of 46 and a rated power of 444 MW. This study is part of the collaborative European Project Hyperbole (FP7-ENERGY-2013-1) [9]. The runner has 16 blades, whereas the distributor has 20 guide vanes. The rotating speed of the machine is 128.6 rpm (2.14 Hz).

2.2. Instrumentation

Several sensors were installed in the different parts of the machine and their signals were acquired simultaneously using a distributed acquisition system Brüel&Kjaer LAN XI Type 3053. Sensors were placed in the hydraulic, mechanical and electrical systems of the machine.

For the hydraulic system, a total of 18 pressure sensors were installed in the draft tube (4), runner (8), spiral casing (4) and penstock (2). In that way, the pressure pattern for the different operating conditions could be identified. In the mechanical parts, a total of 9 accelerometers were located in the stationary parts of the machine (bearings, head cover and spiral casing and draft tube walls), as well as 24 strain gauges in the runner, 2 strain gauges in the shaft to measure the torque and 4 displacement probes (2 in the generator bearing and 2 in the turbine bearing). Aside from these sensors, the active power generated by the turbine, the intensity and the voltage of one phase were also acquired simultaneously. Further information and pictures of the location and characteristics of these sensors are found in [8, 10, 11].

2.3. Testing procedure

The machine was operated at its whole range of operation during about 10 hours. Different slow ramp-up and ramp-down (from minimum to maximum power and vice versa) were done, as well as different steps at constant power during 10 minutes in order to have steady conditions of the machine.

2.4. Results obtained

The relationship between the pressure in the draft tube and in the spiral casing with the torque in the shaft for the whole range of operation of the machine is seen in **Figure 1**. In this picture, only low frequency phenomena (0.4-4 Hz) is shown, in order to separate the vortex rope from other hydraulic pressure fluctuations such as the Rotor Stator Interaction (RSI). It is clearly seen that there is a direct relationship between the pressure and the torque fluctuation. Three different resonances can be identified in the range of operation: the part load resonance, the high load resonance and the overload instability. All of them have a common characteristic: a planar wave propagating from the draft tube to the penstock and vice versa [8]. This paper is focused only in the part load resonance.

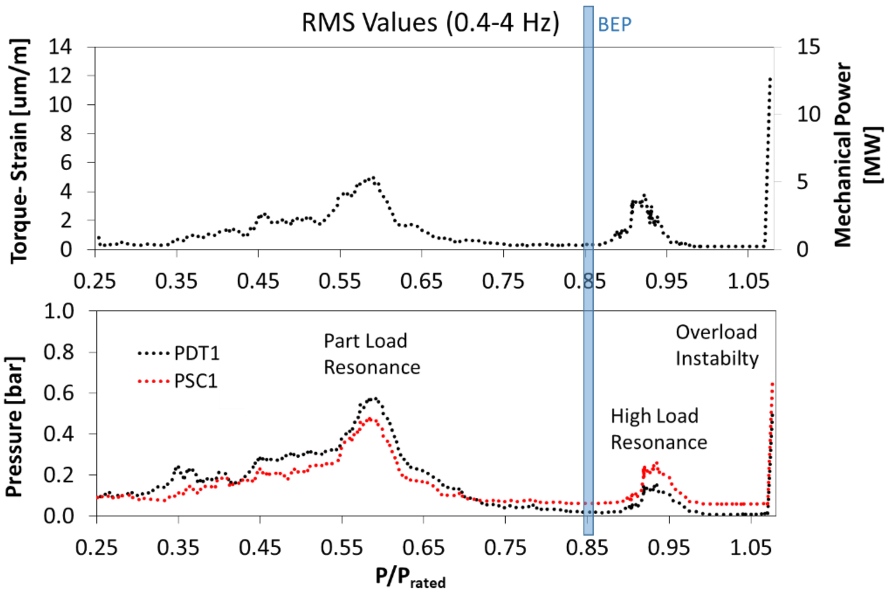

Figure 1. Root Mean Square (RMS) values of the pressure in the draft tube (PDT1), spiral casing (PSC1) and mechanical torque and power for the whole range of operation of the machine. Picture published in [8].

The asynchronous and synchronous components of the vortex rope can be clearly detected with the displacement probe at the turbine bearing and the axial accelerometer in the thrust bearing respectively. **Figure 2** shows a time-frequency plot of different sensors during a slow ramp-up, focusing on the part load operation. It is observed in the draft tube pressure sensor that the frequency of the vortex rope is decreasing when increasing the power and, for a certain power, the amplitude of the pressure is amplified. This point is the part load resonance, where the frequency of the vortex rope coincides with a natural frequency of the hydraulic circuit. At this point, the pressure pattern has basically synchronous component, therefore a planar wave is travelling from the draft tube to the penstock and vice versa. This axial motion is clearly detected with the axial accelerometer located in the thrust bearing (see **Figure 2**, AGA1). However, before this point, the asynchronous component of the vortex rope is more important than the synchronous component and this is why it can be detected better in the shaft displacement in the radial direction (see **Figure 2**, DT1).

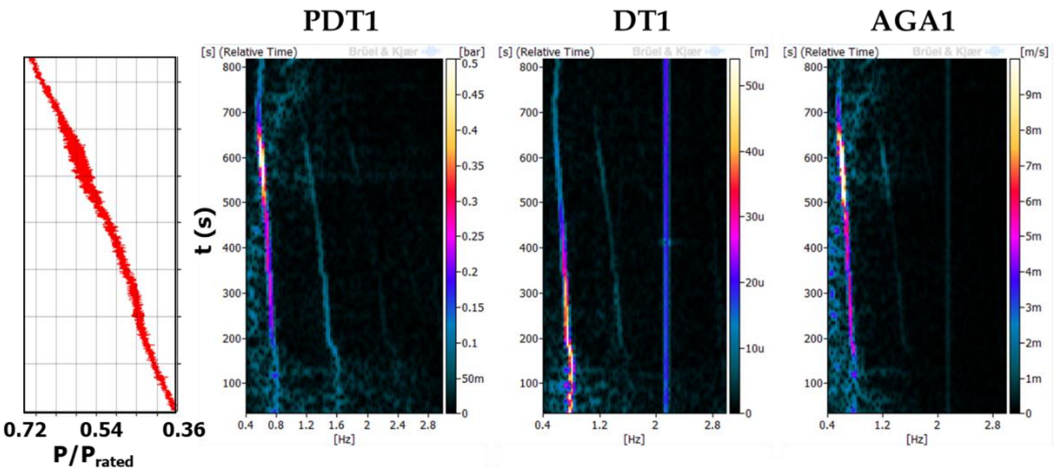

Figure 2. Time-frequency plot of the pressure in the draft tube (PDT1) and the displacement probe in the turbine bearing (DT1) and the accelerometer in the thrust bearing (AGA1) for the part load operation.

3. Numerical validation

3.1. Numerical model

An acoustical-structural FSI numerical simulation [12] of the whole machine was performed in order to correlate the hydraulic phenomenon with the torque and power swing. The simulation model considered the runner, the shaft, the generator and the water including the spiral case and part of the draft tube (see **Figure 3**). The fluid domain is modeled using acoustic formulation [12]. Mesh information and sensitivity analysis can be found in [8].

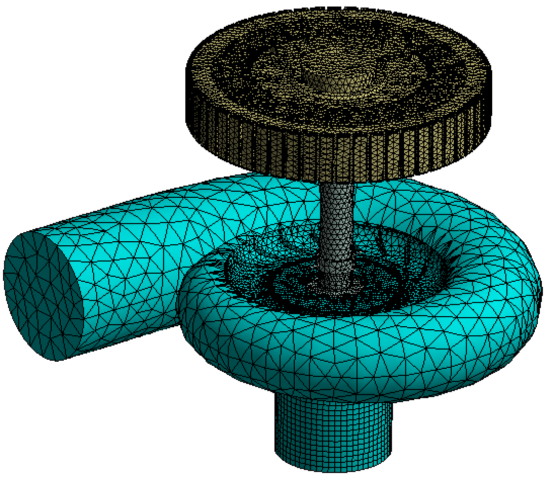

Figure 3. Finite Element Method model of the Francis turbine.

The experimental value of the pressure obtained with the pressure sensor located in the draft tube was introduced as input in the numerical model. In that way, a planar wave is modelled in the simulation and its effects over the structure can be studied. The boundary condition at the inlet of the spiral casing was defined as radiation boundary condition, so the pressure waves con go across it. The nodes of the water in contact with the runner were defined as FSI interface and the ones in contact with walls are fixed without any displacement in all directions.

3.2. Results and comparison

After applying a planar wave in the numerical model, the displacement of the runner due to this planar wave can be obtained (**Figure 4**). In this figure, it is seen that the runner has an axial displacement due to the planar wave passing through it, but it has also a torsional displacement (see the points marked in red in **Figure 4**). The planar wave is producing the same pressure amplitude in the pressure and suction side of the blades, and as both blade sides have different surface, a resulting tangential force appear in every blade. This fact is producing the torsion fluctuation in the runner and therefore in the shaft.

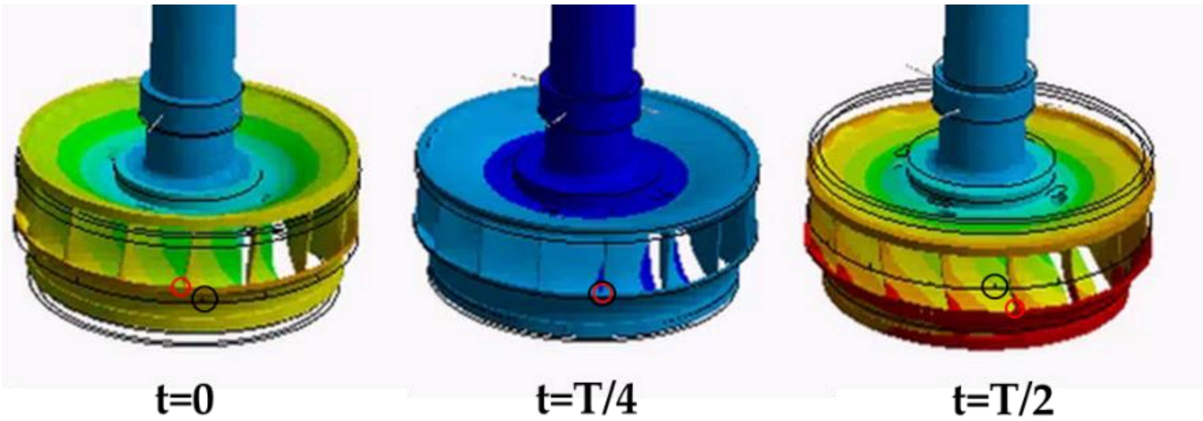

Figure 4. Total displacement of the runner during one cycle. Black line represents the non-deformed runner and the black and red circles the relative displacement between two points. Published in [8].

To check the accuracy of the simulation, the pressure in the spiral casing inlet obtained by simulation was compared with the one measured on-site. Moreover, the torque fluctuation produced by the planar wave in the simulation was also compared with the measured one. Both parameters accurately agree with less than 5% of error.

4. Application to other prototypes

In the previous sections, the power swing phenomenon has been explained in detailed with experimental measurements compared with numerical simulations. It has been demonstrated that the asynchronous component of the vortex rope can be detected using proximity probes in the turbine bearing and the synchronous components can be detected using accelerometers in the thrust bearing. Two more Francis turbines prototypes (FT2 and FT3) have been studied in order to detect in them the power swing phenomenon due to hydraulic resonances. The prototypes are located in Spain and they have different specific speeds (see **Figure 5**) than the one studied in the previous sections (FT1): FT2 has a specific speed of 54 and FT3 of 80 (see **Figure 5**).

Different loads were analyzed for every prototype in order to define their whole range of operation and to identify the loads where the power swing phenomenon appears. **Figure 6** shows the RMS values for the displacement in the turbine bearing and acceleration in the thrust bearing in the frequency range of 0.1-0.4 times the rotating speed. The amplitude has been normalized against the maximum amplitude in the graph (A/A_{max}). This is a similar range than it was used for the first Francis turbine prototype (Section 2 and 3). It can be observed that a vortex rope appears in the part load operation with high asynchronous component at P/P_{rated}≈0.4 approximately for both prototypes studied. The synchronous component is maximum at P/P_{rated}≈0.6, which is the same point where the power output fluctuates with 10% the rated power for FT2 and 6% for FT3. Therefore, the behavior observed for the first prototype discussed in the paper is again seen for the other two prototypes with different specific speed and at about the same P/P_{rated} ranges.

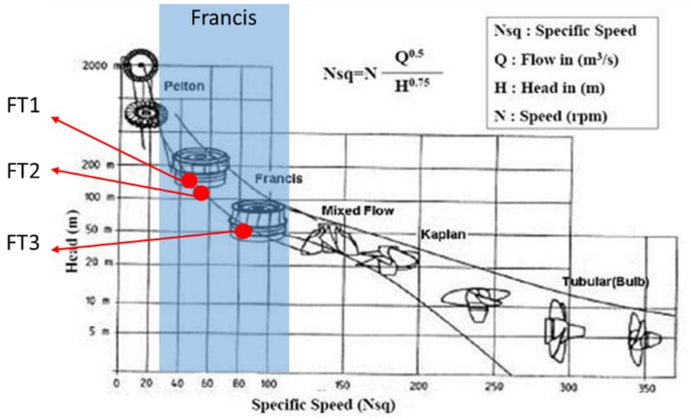

Figure 5. Francis turbines selected according to specific speed n_{sq}.

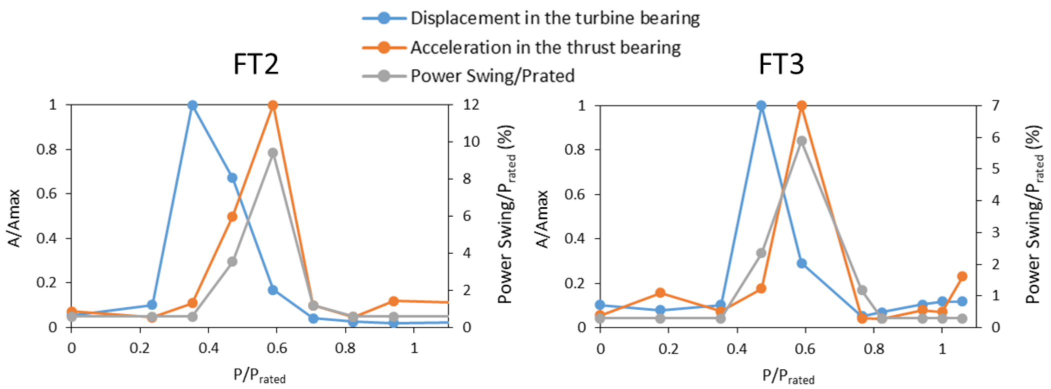

Figure 6. Displacement in the turbine bearing, acceleration in the thrust bearing and power swing in two different prototypes.

This fact demonstrates that if a hydraulic resonance occurs during the operation of the turbine producing the propagation of a planar wave from the draft tube to the penstock, the runner is deformed axially and torsionally, which makes the torque and the power fluctuate as well as produces an axial motion of the whole rotating train.

5. Conclusions

The relationship between power swing and pressure fluctuations due to hydraulic resonances have been studied in the present paper. To do so, experimental measurements taken from a large medium-head Francis turbine have been analyzed in detail. Several sensors were located in the machine in order to study its dynamic behavior. Results obtained show that hydraulic resonances provoked by the coincidence of the part load vortex rope with a natural frequency of the hydraulic circuit cause a propagation of a planar wave from the draft tube to the penstock and vice versa. This planar wave is able to deform the runner torsionally and axially when it passes through it.

A structural-acoustical FSI simulation has been also performed to validate the experimental hypothesis. The numerical model considers the runner, shaft and the generator, as well as all the surrounding water, from the draft tube to the spiral casing. A planar wave was imposed in the draft tube and the displacement of the runner was obtained. Results show that this planar wave deform the runner torsionally and axially as it was seen experimentally. Moreover, values of pressure and torque fluctuation match with experimental results confirming the accuracy of the numerical simulation.

Two other Francis turbine prototypes with different specific speed and experiencing the power swing problem have been also analyzed. The power swing in both prototypes is related also with hydraulic resonances due to part load vortex rope. Same kind of results are found for both prototypes, showing a clear relationship with axial motion of the machine and power fluctuation. This study permits improving the actual techniques of detection of power swing with different sensors and therefore the possibility to avoid it during operation.

Acknowledgments

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References

[1] Gaudard L and Romerio F 2014 The future of hydropower in Europe: Interconnecting climate, markets and policies *Environmental Science & Policy* **37** 172-81

[2] Dörfler P 1982 System oscillations excited by the Francis turbine's part load vortex core: mathematical modeling and experimental verification *Dissertation Techn. University Vienna*

[3] Favrel A, Müller A, Landry C, Gomes J, Yamamoto K and Avellan F 2017 Dynamics of the precessing vortex rope and its interaction with the system at Francis turbines part load operating conditions. In: *Journal of Physics: Conference Series*: IOP Publishing) p 012023

[4] Nicolet C, Arpe J and Avellan F 2004 Identification and modeling of pressure fluctuations of a Francis turbine scale model at part load operation. In: *Proceedings of the 22nd IAHR Symposium on Hydraulic Machinery and Systems*: Stockholm, Sweden)

[5] Duparchy F, Favrel A, Lowys P, Landry C, Müller A, Yamamoto K and Avellan F 2015 Analysis of the part load helical vortex rope of a Francis turbine using on-board sensors. In: *Journal of Physics: Conference Series*: IOP Publishing) p 012061

[6] Rheingans W 1940 Power swings in hydroelectric power plants *Trans. ASME* **62** 171-84

[7] Müller A, Favrel A, Landry C and Avellan F 2017 Fluid–structure interaction mechanisms leading to dangerous power swings in Francis turbines at full load *Journal of Fluids and Structures* **69** 56-71

[8] Valentín D, Presas A, Egusquiza E, Valero C, Egusquiza M and Bossio M 2017 Power Swing Generated in Francis Turbines by Part Load and Overload Instabilities *Energies* **10** 2124

[9] https://hyperbole.epfl.ch 2013 HYdropower plants PERformance and flexiBle Operation towards Lean integration of new renewable Energies.

[10] Valentín D, Presas A, Bossio M, Egusquiza M, Egusquiza E and Valero C 2018 Feasibility of Detecting Natural Frequencies of Hydraulic Turbines While in Operation, Using Strain Gauges *Sensors* **18** 174

[11] Presas A, Valentin D, Egusquiza E and Valero C 2017 Detection and analysis of part load and full load instabilities in a real Francis turbine prototype. In: *Journal of Physics: Conference Series*: IOP Publishing) p 012038

[12] Valentín D, Presas A, Egusquiza E and Valero C 2016 On the Capability of Structural–Acoustical Fluid–Structure Interaction Simulations to Predict Natural Frequencies of Rotating Disklike Structures Submerged in a Heavy Fluid *Journal of Vibration and Acoustics* **138** 034502-