Synchronous condenser operation in Francis turbines: Effects in the runner stress and machine vibration

David Valentín[a, *]

david.valentin@upc.edu

Alexandre Presas[a]

Carme Valero[a]

Mònica Egusquiza[a]

Eduard Egusquiza[a]

[a]Center for Industrial Diagnostics and Fluid Dynamics (CDIF), Universitat Politècnica de Catalunya (UPC), Av. Diagonal, 647, ETSEIB, 08028, Barcelona, Spain

*Corresponding author.

Abstract

Reactive power shortage is one of the current issues that endanger the stability of the power grid systems. Some massive blackouts have been experienced in the past years due to the unbalance of reactive power. One of the solutions to provide the necessary reactive power to the grid is to operate generators as motors and supply or absorb reactive power when needed. Hydraulic turbines are the most suitable machines to perform this task since they can be easily and quickly dewatered to work as motors (Synchronous Condenser (SC) operation).

Nowadays, hydraulic turbines are operating as SC for several hours per day, especially in grids like in US or Canada. The change from generating mode to SC and vice versa can be very fast, depending on the grid requirements. However, these fast changes may affect the mechanical behavior of the machine, reducing its useful life-time or increasing vibrations. In this paper, the effect in the mechanical system of SC operation in a Francis turbine prototype is evaluated. Strains in the runner and vibrations in the stationary parts are analyzed in detail in the fast changes between generating to SC and vice versa.

Keywords: Hydropower; Synchronous condenser; Francis turbine; Reactive power; Grid stability

1 Introduction

Reactive power shortage has been demonstrated to be one of the main reasons of the blackouts occurred in US, Canada and Europe in the last years [1,2]. The lack or surplus of reactive power may unbalance the electrical grid endangering its stability, reliability and efficiency [3,4]. One of the solutions used nowadays to provide to the grid the necessary reactive power is to operate power generators as motors, which is known as Synchronous Condenser (SC) operation [5,6]. Thermal power plants and especially hydraulic power plants are used for this purpose [5]. Thus, generating turbines are operated in air conditions rotating at the synchronous speed driven by the generator acting as a motor. Depending on the grid characteristics and country demand, these turbines need to work at this condition several hours per day. In addition, they need to provide a fast response into the electrical system so they are also subjected to fast transients to go from generating to SC mode or vice versa.

Hydraulic turbines, and specifically Francis turbines, operate as SC dewatering its runner and therefore spinning in air in order to minimize the friction losses [7]. This process is normally done without stopping the machine, which means that the unit is going from generating mode to SC mode in a short period of time. To do that, the guide vanes are closed and compressed air is injected through the draft tube, creating a water free surface in the last (see Fig. 1). Water is at the same time injected in the labyrinth seals for cooling and balancing purposes. A draining system pumps the water injected in the labyrinth seals to the spiral casing in order to maintain constant the height of the free surface. Therefore, the runner in this situation is rotating in air and consuming active power from the electrical grid.

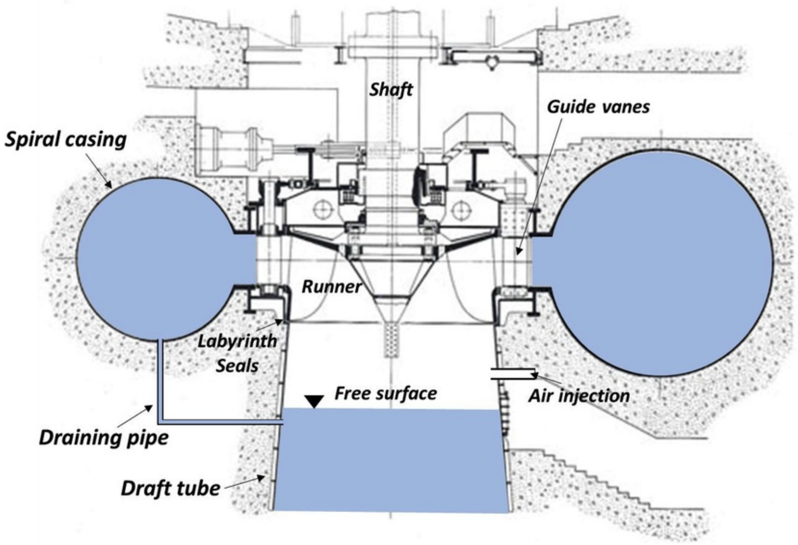

Fig. 1 Francis turbine dewatered for SC operation.

alt-text: Fig. 1

During SC operation, toque and power swings are experienced sometimes which an unclear origin [7,8]. Difficult flow conditions are occurring during this operation since the runner rotating in air induces a motion of the free surface, sometimes exciting sloshing modes of this [9,10]. Furthermore, the sloshing motion of this free surface induces also a mixture of air and water that can enter into the rotating runner, creating a difficult to predict two-phase flow behavior. Another problem that can happen during SC operation is that the water used for the labyrinth seals cooling goes into the vaneless gap between the closed guide vanes and the runner, causing an effect similar to the well-known Rotor Stator Interaction (RSI). All these phenomena related with the flow behavior at this condition have been addressed in different studies based on reduced scale models [7,9–13]. However, the effect of the SC operation into the runner stress or machine vibrations of Francis turbine prototypes has not been studied in the past. The results in reduced scale models may not be transposable at all to prototypes, since normally bearings, seals and supporting structures are not strictly scaled and they are totally different between model and prototype. This means that the dynamic behavior of the structure in a situation like SC operation, where the runner is rotating in air, is not completely transposable, hence analyzing the dynamic behavior in the prototype is essential.

In terms of mechanical stress of the runner and machine vibration, SC operation is expected to not be as critical as generating mode operation [14–17] because the runner is rotating in the air. The main acting forces at this situation are the centrifugal forces due to the rotation and the friction forces due to the water in the labyrinth seals. However, during the transient between generating mode to SC and vice versa high forces can be induced in the runner due to the fast opening or closing of the guide vanes and the sudden air injection. These fast changes can affect the runner integrity as well as other components of the machine if the stress and vibrations induced by this condition are high enough. In addition, if SC operation is increasingly required, fatigue problems can appear in the turbine components.

In this paper, the SC operation of a large Francis turbine prototype is experimentally analyzed in detail. The transient operation between generating mode to SC and vice versa is studied from the point of view of runner mechanical stresses and machine vibrations. For that, the Francis turbine prototype was instrumented with several sensors all along the machine, including strain gauges in the runner and vibration sensors in the stationary parts of the turbine. Results obtained permit to compare stress and vibrations generated by the SC operation and the transients when changing from generating mode to SC and vice versa. In that way, the useful life-time of the turbine components can be compared and evaluated.

2 Experimental investigation

2.1 Prototype characteristics

The prototype used in this paper is a large medium-head Francis turbine located in British Columbia, Canada. This Francis Turbine has a rated power of 444 MW in generating mode with a rated head of 170 m. The rated power in SC mode of this machine is of 12 MW. The study of this turbine is part of European Project Hyperbole (FP7-ENERGY-2013-1) [18]. The runner has 16 blades and the distributor 20 guide vanes. The rotating speed of the machine is

128.6 rpm (2.14 Hz) and its specific speed is 46. During an overhaul in the power plant, the machine was accessible to install several sensors in the rotating parts and in the stationary parts. The machine was operated at all its operating range, including SC operation, in order to determine its dynamic behavior.

2.2 Instrumentation

Several sensors were installed in the mechanical, hydraulic and electrical systems. In the mechanical system, the runner was instrumented with strain gauges (Gauge factor 2, Sensitivity 3.266 mV/(µm/m)) and pressure sensors located in two different blades. The mechanical torque was also measured with strain gauges in the shaft. Additionally, several accelerometers were placed in the bearings, head cover and guide vanes as well as displacement probes to measure the shaft vibration. In the hydraulic system, different pressure sensors were located in penstock, spiral case and draft tube. Electrical parameters such as current, voltage and active power were also measured simultaneously. The operating conditions signals of guide vane opening and rotating speed were also measured.

The nomenclature and location of the sensors used for analysis in this paper are shown in Fig. 2. AGR12 and AGA12 (Kistler 8752A, 100 mV/g) are accelerometers located in the generator bearing, AT12 (Kistler 8752A, 100 mV/g) is a radial accelerometer in the turbine bearing, DT12 (3300 XL 8 mm, Bently Nevada) is a displacement probe in the shaft and PSC10 and PDT10 (Kistler K-line 0–20 bar) are pressure sensors located in the spiral casing and draft tube respectively. The strain gauges in the runner are called according their position in the blade, where PS means pressure side, CR near the crown and BD near the band. Further information about the sensors characteristics is found in Refs. [14–16,19–21].

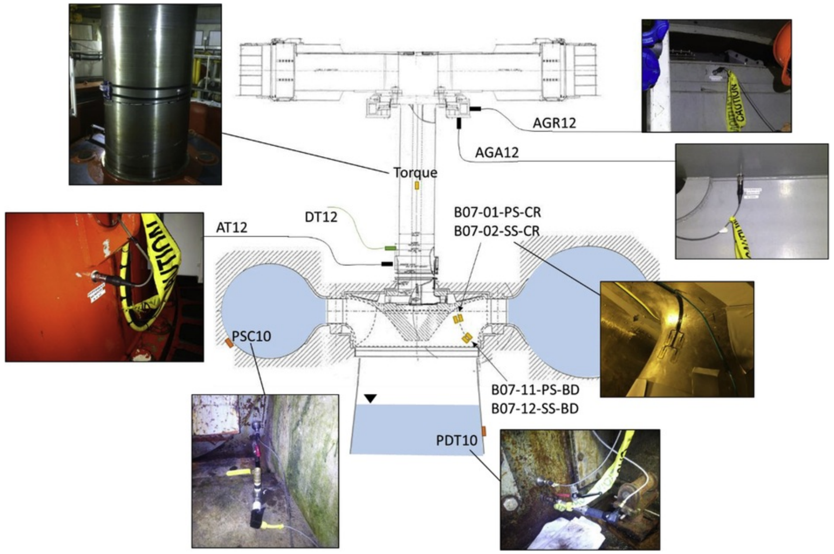

Fig. 2 Position and picture of the sensors used for the analysis.

alt-text: Fig. 2

2.3 Acquisition

All the signals coming from all the sensors installed were acquired simultaneously using a distributed Bruel&Kjaer LAN XI 3053 acquisition system. The acquisition frequency was set to 4096 Hz without any hardware or software filtering.

2.4 Testing procedure

The machine was operated in SC mode for several minutes. In addition, different transient sequences going from generating mode to SC and vice versa were performed. These sequences followed the current protocol used in the power plant to enter and to exit from SC. The time of these sequences was always the same. Fig. 3 shows the absolute value of active power, reactive power and apparent power of the machine during the transients between the two modes. It is observed than in generating mode only active power is delivered by the generator to the grid, whereas in SC mode, the reactive power is increasing until reaching a maximum of about 22 MVAR. The process to inject reactive power to the grid is slow, as it takes approximately 3 min to deliver constant reactive power. The opposite process, from SC to generating mode, needs again almost 3 min to stop providing reactive power to the grid.

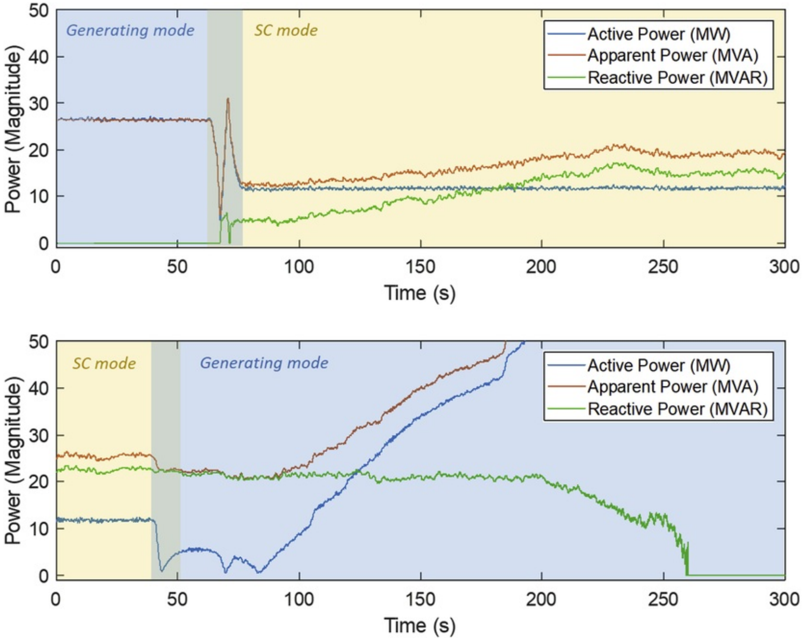

Fig. 3 Absolute values of Active Power, Reactive Power and Apparent Power during the transitions from generating mode to SC (up) and vice versa (down).

alt-text: Fig. 3

Nevertheless, from the hydraulic point of view, the transients from SC to generating mode and vice versa are rather fast. Fig. 4 shows the active power and Guide Vane Opening (GVO) in % for these transient sequences. It is seen that the machine goes from generating 26 MW to consume 12 MW in 20 s (in the plot, negative power means power absorbed by the motor, and positive power means generated power). During this time, the GVO goes from 14% to 0% (0% means guide vanes completely closed and 100% completely open). The air is injected once the guide vanes are completely closed, this is why the power consumption suddenly decreases. However, the change from SC to generating mode is smother since the GVO for the generating mode is only 7%. In this case, the power goes from 12 MW in SC mode to 6 MW in generating mode in 10 s. The rotating speed of the machine is maintained constant during the transient sequences.

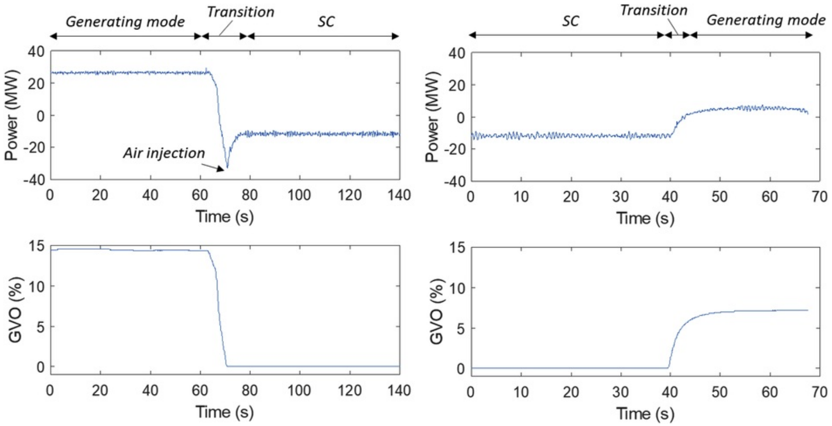

Fig. 4 Power and Guide Vane Opening (GVO) for the transition from generating mode to SC (left) and vice versa (right).

alt-text: Fig. 4

2.5 Signal analysis

To analyze the data measured with the different sensors, four different signal analysis methods are used in this paper: (1) time-signal, (2) peak-to-peak values versus time, (3) time-frequency analysis and (4) relative damage estimation due to fatigue.

The time-signals shown in the paper are directly the signals measured by the acquisition system. It is helpful to see the time-signals during transients to see how the global levels change. The peak-to-peak values have been computed using the difference of the maximum and the minimum value at uniform widows of 1 s of duration without overlap. In that way, the change of those values during the transient events is clearly appreciated. Additionally, time-frequency analyses have been performed during the transient sequences. This time-frequency analysis is based on SFFT (Short Fast Fourier Transform) performed using Hanning windows of 8 s of duration (frequency resolution of 0.25 Hz) with an overlap of 95% between them.

Finally, with the strain results obtained with the strain gauges in the runner, a fatigue analysis is carried out to estimate the number of cycles to fatigue of the structure in the different operating conditions of the machine (generating mode, SC mode and transient events). To do so, a rainflow counting algorithm [22] is used with the time-signal of one strain gauge. This algorithm is based on the idea of the cumulative damage. This means that the damage caused by the different excitations due to different frequencies and amplitudes can be summed to obtain the total damage.

3 Results and discussion

3.1 Time-signals

The time-signals obtained with the different sensors during the operation in generating mode, SC mode and transient between them are shown in Figs. 5–7. Fig. 5 shows the time-signals of four different strain gauges located in one blade of runner, two near the crown in the pressure and suction side and two near the band in the pressure and suction side. It is seen that the transient event from generating mode to SC present a higher strain level than the transient event from SC to generating mode. In fact, this last seems to not be very important in terms of runner strain. Furthermore, the strain increase during the transient event from generating mode to SC is especially detected in the strain gauge located in the pressure side of the blade and near the crown, whereas the other strain gauges present smother changes. Therefore, the strain gauge position is important to detect this phenomenon. The shaft torque is also seen in Fig. 5. In this case, the torque behavior is the same than the electrical power presented in Fig. 4.

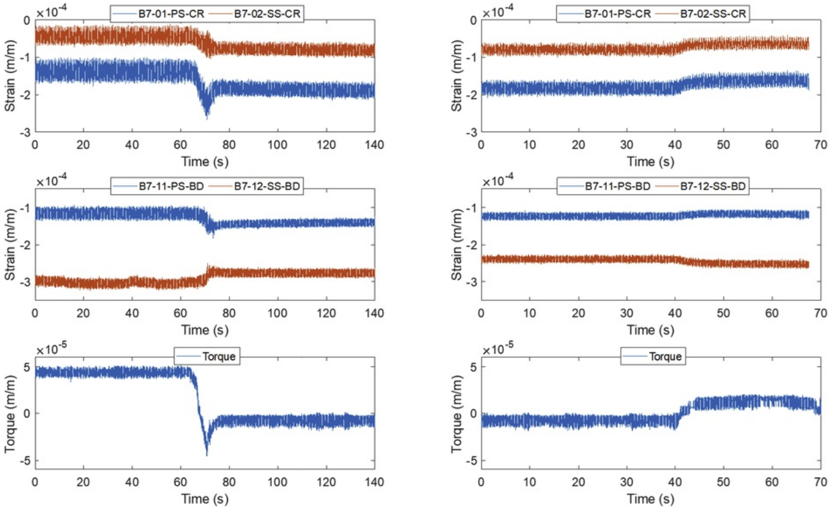

Fig. 5 Time-signals of the runner strain gauges and torque shaft during the transient sequences. From generating mode to SC (left) and vice versa (right).

alt-text: Fig. 5

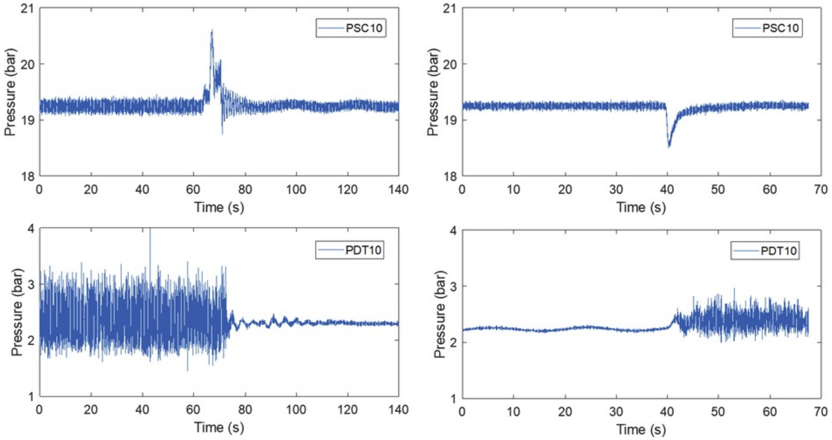

Fig. 6 Time-signals of the pressure sensors in the spiral casing (PSC10) and in the draft tube (PDT10) during the transient sequences. From generating mode to SC (left) and vice versa (right).

alt-text: Fig. 6

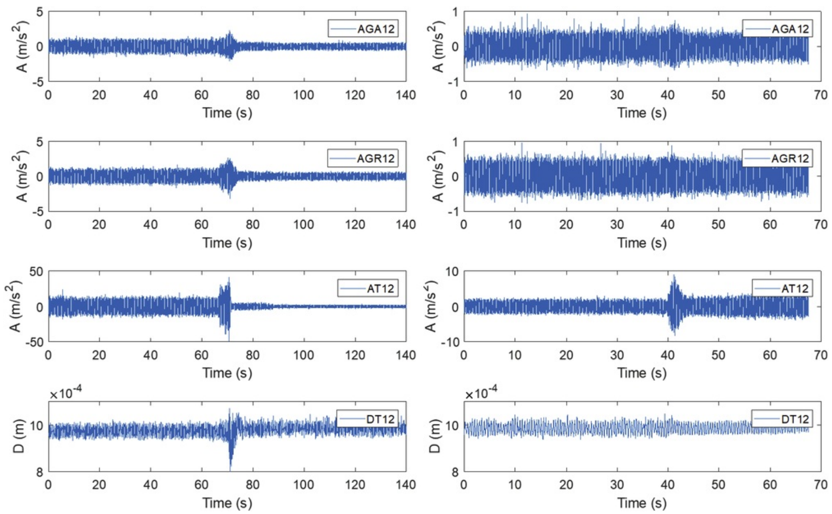

Fig. 7 Time-signals of the accelerometers in the bearings and the displacement probe in the turbine bearing during the transient sequences. From generating mode to SC (left) and vice versa (right).

alt-text: Fig. 7

Fig. 6 shows the results for the pressure sensors in the spiral casing (PSC10) and in the draft tube (PDT10). It is observed that during the generating mode the pressure fluctuation is very high because it is working at a very low load (6% of the rated power) and, when the guide vanes close and the air is injected, the pressure fluctuation disappear, measuring only the static component due to the tail water level. In the spiral casing, the closing of the guide vanes produces an instantaneous overpressure that reaches about 2 bar amplitude.

The vibration of the machine for the transient sequences is summarized in Fig. 7. It is observed than the machine receives a high impact during the change from generating to SC mode, which is detected in the whole structure and with higher amplitude in the turbine bearing. This impact is received at the moment of the air injection (see Fig. 4), just when the guide vanes close completely. This impact is also detected in the shaft displacement. This situation is able to excite natural frequencies of the mechanical system, hence it is always undesirable. Once the guide vanes are closed and the machine is in SC operation the vibration levels decrease considerably. For the other transient event, from SC to generating mode, the vibration levels are not that high, being only detectable an impact with less energy than before in the turbine bearing.

3.2 Peak-to-peak values

In order to compare the fluctuation of the signals obtained in the different sensors, the peak-to-peak values versus time have been computed. In comparison with the time-signals, with the peak-to-peak values only the dynamic component of the signal is shown, which is normally the responsible of fatigue problems in mechanical systems. Fig. 8 shows the peak-to-peak values versus time for the strain gauges in the runner and the shaft torque. It is seen that they are lower in the SC operation than in generating mode, something which is expected because the runner is rotating in air in SC mode. However, during the change from generating to SC mode those values increase considerably, something that is not happening in the reversed transient event from SC to generating mode. As commented before, the impact received due to the fast guide vane closing and the air injection in the runner is able to excite natural frequencies of the whole system, increasing therefore the dynamic component of the signals.

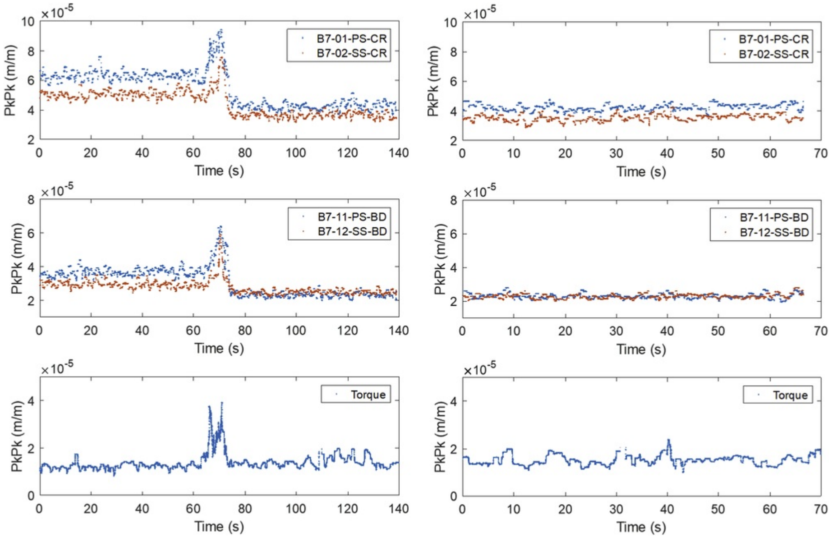

Fig. 8 Peak-to-peak values of the runner strains and torque shaft during the transient sequences. From generating mode to SC (left) and vice versa (right).

alt-text: Fig. 8

Fig. 9 shows the dynamic components of the pressure in the spiral casing and draft tube. As seen in the time-signals (Fig. 6), as soon as the runner is rotating in air, the dynamic pressure is attenuated, having only the static pressure of the upper and lower reservoir in the spiral casing and draft tube respectively.

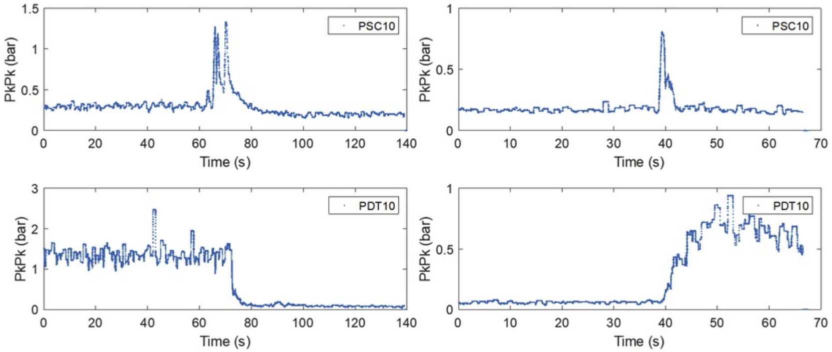

Fig. 9 Peak-to-peak values of the pressure sensors in the spiral casing (PSC10) and in the draft tube (PDT10) during the transient sequences. From generating mode to SC (left) and vice versa (right).

alt-text: Fig. 9

The vibration peak-to-peak values are presented in Fig. 10. The vibration levels in SC operation are lower than in generating mode as it is the case of the runner strain. Again, the maximums are found in the transient event from generating mode to SC, as it was also observed in the time-signals (Fig. 7). To understand what is exciting the strong impact detected in all the accelerometers duting this transient event, a time-frequency analysis is necessary.

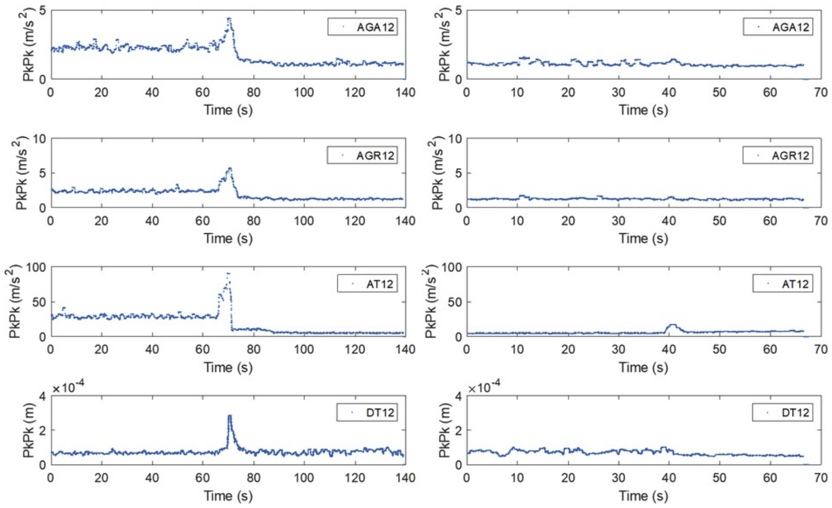

Fig. 10 Peak-to-peak values of the accelerometers in the bearings and the displacement probe in the turbine bearing during the transient sequences. From generating mode to SC (left) and vice versa (right).

alt-text: Fig. 10

3.3 Time-frequency

The time-frequency plots of the different sensors are shown in Figs. 11–14. The maximum frequency has been selected as 50 Hz because the main hydraulic phenomena happening in generating mode or the rest of the phenomena taking place in SC mode are below this value. In generating mode, the most important hydraulic excitation comes from the RSI [23], which is defined by the number of guide vanes multiplied by the rotating frequency viewed from the rotating point of view $(f_{RSI_{rot}} = 20 \cdot 2.14 = 42.80\ Hz)$, or the number of runner blades multiplied by the rotating frequency viewed from the stationary side $(f_{RSI_{stat}} = 16 \cdot 2.14 = 34.24\ Hz)$. Fig. 11 shows the time-frequency plots for two different strain gauges, one in the pressure and crown side, and another in the pressure and band side. It is observed that the excitation from the RSI $(f_{RSI_{rot}} = 42.80\ Hz)$ decreases a lot when entering to the SC mode but it is still existing, which means that there is still some interaction with the two-phase flow inside the runner and the guide vanes, as seen in Refs. [7,9–13]. In these plots, the rotating speed of the runner (f_f) is also clearly seen at 2.14 Hz as well as its second harmonic ($2f_f$). The amplitude of the rotating frequency decreases considerably when the runner enters to SC mode. At the moment of the air injection in the transition from generating to SC mode, a wide range of frequencies is excited in the runner. However, in the transition event from SC to generating mode, these frequencies are not excited since the transition is smother.

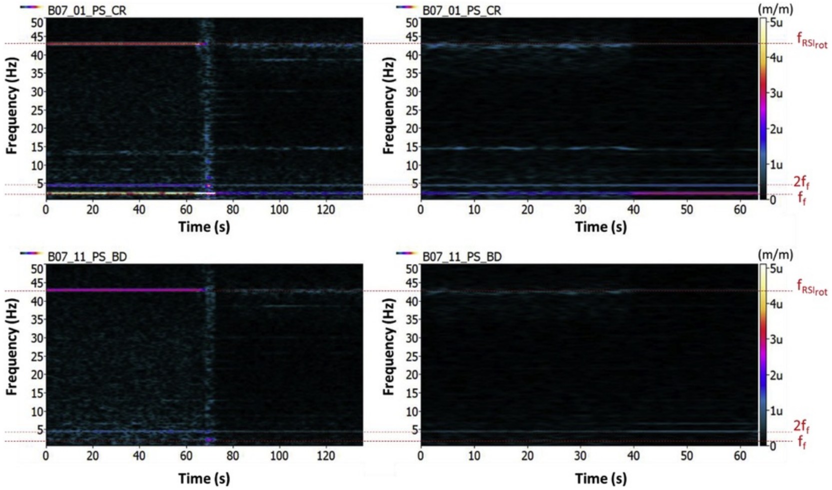

Fig. 11 Time-frequency plot of the runner strains and torque shaft during the transient sequences. From generating mode to SC (left) and vice versa (right).

alt-text: Fig. 11

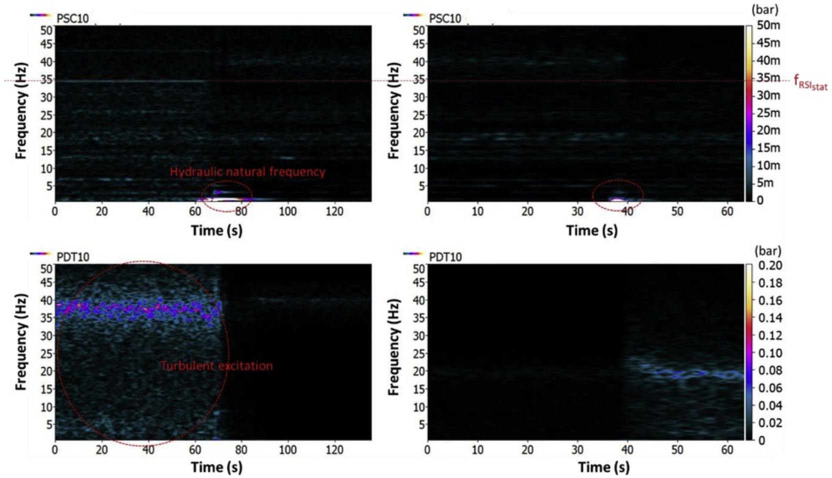

Fig. 12 Time-frequency plot of the pressure sensors in the spiral casing (PSC10) and in the draft tube (PDT10) during the transient sequences. From generating mode to SC (left) and vice versa (right).

alt-text: Fig. 12

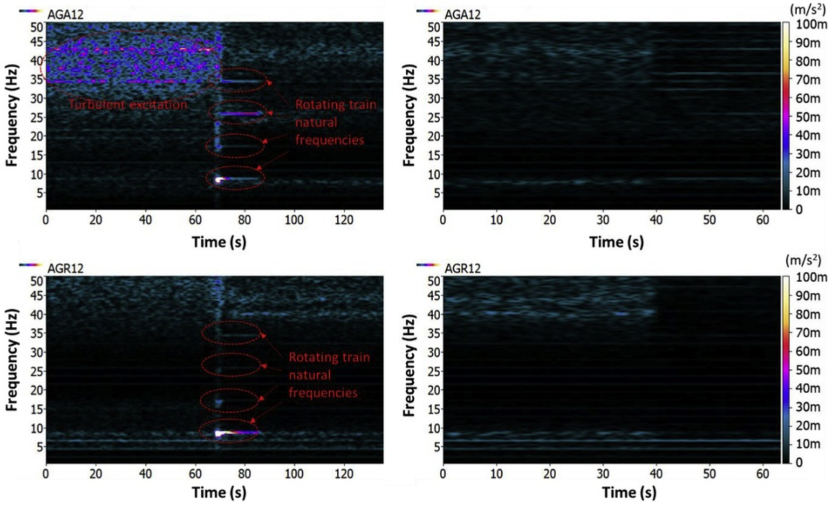

Fig. 13 Time-frequency plot of the accelerometers in the generator bearing during the transient sequences. From generating mode to SC (left) and vice versa (right).

alt-text: Fig. 13

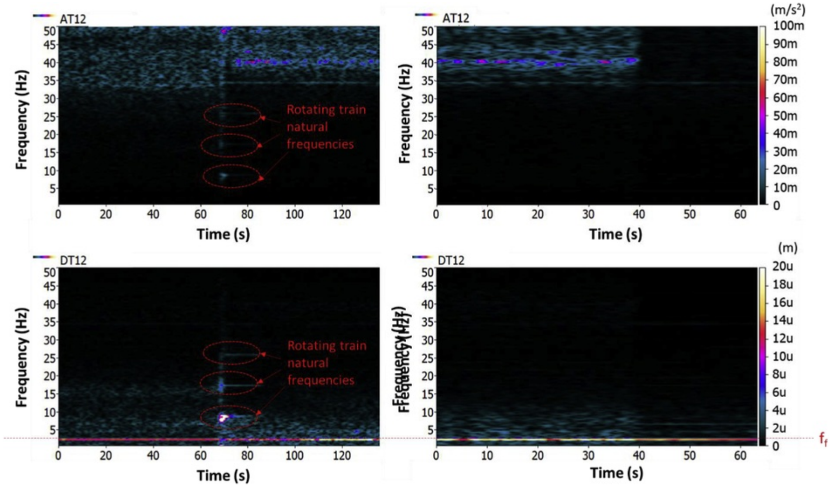

Fig. 14 Time-frequency plot of the accelerometer (AT12) and the displacement probe (DT12) in the turbine bearing during the transient sequences. From generating mode to SC (left) and vice versa (right).

alt-text: Fig. 14

The time-frequency plots for the pressure sensors are shown in Fig. 12. In the spiral casing, the excitation coming from the RSI $\left(f_{RSI_{stat}} = 34.24\ Hz\right)$ is observed during generating mode and it disappears during SC because the water is not flowing at this moment in the spiral casing. The sudden change of the guide vanes excites one hydraulic natural frequency at low frequency (about 2 Hz) [24] which is clearly seen in both transient events from generating mode to SC and vice versa. In the draft tube, during generating mode a wide range of frequencies are excited due to the very turbulent flow at this condition (very low load, only 6% of the rated power). This excitation disappears completely once in SC mode.

Figs. 13–14 show the time-frequency plots corresponding to the vibration sensors. The accelerometers located in the generator bearing (Fig. 13) detect the turbulence due to the low load operating in generating mode and it is clearly observed that some natural frequencies of the machine are excited in the moment of the air injection [25]. More specifically, natural frequencies at 9 Hz, 16Hz, 26 Hz and 35 Hz are detected in the bearings with accelerometers and in the shaft with the proximity probe at this moment. This means that those natural frequencies are related to mode-shapes with displacement in the whole rotating train. This situation is undesirable for the machine, since vibration increases considerably. In the transient event from SC to generating mode, which is smother, those natural frequencies are not excited.

3.4 Fatigue estimation

With the strain gauges installed in the runner, a fatigue analysis to know the useful life-time of the runner can be performed. In this case, what is interesting to know is the damage caused by the transient events into the runner. To calculate that, a rainflow counting algorithm has been used as explained in section 2.5. Fig. 15 shows the results obtained for the different operation calculated with respect to the SC operation. It is observed than the generating mode at 26 MW is about 10 times worse in terms of damage than the SC operation. The transient from generating mode to SC is the worst situation, being more than 300 times worse than the damage due to the SC operation. However, the other transient event, the change from SC to generating mode produces almost the same damage than the SC operation, since it is a very smooth transient event as it has been demonstrated before.

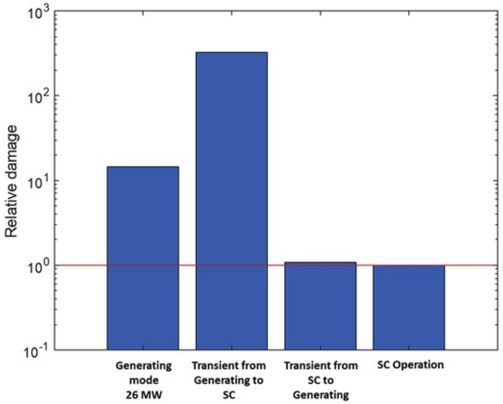

Fig. 15 Relative damage calculated with the strain gauges in the runner for the different operations. Values normalized against the SC operation.

alt-text: Fig. 15

4 Conclusions

The synchronous condenser operation of a Francis turbine prototype has been analyzed experimentally in this paper. More specifically, the effects on the mechanical system, i.e. runner stress, fatigue and machine vibration, have been studied for this operating condition. The Francis turbine prototype was instrumented with several sensors including strain gauges in the runner and vibration sensors in the stationary parts. The machine was operated at synchronous condenser mode for several minutes. Furthermore, the actual sequences used in the power plant to go from generating mode to synchronous condenser and vice versa have been also studied.

To evaluate the influence of synchronous condenser in the mechanical behavior of the machine, different signal analysis methods have been used: time-signal, peak-to-peak values versus time, time-frequency analysis and fatigue life estimation. These methods were applied to the transient events changing from generating mode to synchronous condenser and vice versa. Results show that, in general, the most problematic operation is the transient when changing from generating mode to synchronous condenser.

The strains in the runner as well as the vibrations in the machine suddenly increase in the fast transient from generating mode to synchronous condenser. During this transient, the guide vanes close very fast and compressed air is injected through the draft tube in order to have the runner rotating in the air. In the moment of the air injection the structure receives a strong impact which is able to excite the different natural frequencies of this, as it is demonstrated with the time-frequency plots. The vibration and strain levels increase substantially at this moment, making this transient event a critical situation to take into account.

However, the transient event from synchronous condenser to generating mode is not that harmful for the machine. This transient event consist of opening the guide vanes slowly and stopping the air injection, which makes the process smother than the opposite transient sequence. At this operation, vibration levels and strains in the runner do not increase considerably. In the synchronous condenser operation, the machine does not experience high vibrations or strains in comparison with the generating mode operation. This behavior is expected because the runner is rotating in the air.

A fatigue analysis has been also performed with the strain gauges installed in the runner. Generating mode at low load, synchronous condenser mode and the transients between these both modes have been compared in this analysis. The relative damage has been computed with respect to the synchronous condenser operation. Results show again that the worse scenario is the transient from generating mode to synchronous condenser, followed by the operation as generating mode at low load. Therefore, optimizing the transients speed may help to decrease the runner stress and machine vibration, increasing the life-time of the turbine components.

Acknowledgements

The authors would like to acknowledge HYPERBOLE research project, granted by the European Commission (ERC/FP7-ENERGY-2013-1-Grant 608532).

The authors would also like to thank BC Hydro for making possible the experimental tests in the prototype and Voith and GE teams for the strain gauges and pressure sensors installation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2019.07.041.

References

[1] G. Andersson, P. Donalek, R. Farmer, N. Hatziargyriou, I. Kamwa, P. Kundur, N. Martins, J. Paserba, P. Pourbeik and J. Sanchez-Gasca, others, Causes of the 2003 major grid blackouts in North America and Europe, and recommended means to improve system dynamic performance, *IEEE Trans. Power Syst.* **20**, 2005, 1922–1928.

[2] Y.V. Makarov, V.I. Reshetov, A. Stroev and I. Voropai, Blackout prevention in the United States, Europe, and Russia, *Proc. IEEE* **93**, 2005, 1942–1955.

[3] J. Dixon, L. Moran, J. Rodriguez and R. Domke, Reactive power compensation technologies: state-of-the-art review, *Proc. IEEE* **93**, 2005, 2144–2164.

[4] Y. Han, L. Chen, H. Ma and Z. Wang, Optimization of reactive power compensation for distribution power system with small hydro power, In: *Power Syst. Technol. (POWERCON), 2014 Int. Conf,* 2014, 2915–2920.

[5] M.L. Hendry and J.C. Mcgough, Synchronous condensing using the generator of peak load plant, In: *ASME 1995 Int. Gas Turbine Aeroengine Congr. Expo.,* 1995, V004T11A004--V004T11A004.

[6] S.S. Kalsi, D. Madura and M. Ingram, Superconductor synchronous condenser for reactive power support in an electric grid, *IEEE Trans. Appl. Supercond.* **15**, 2005, 2146–2149.

[7] E. Vagnoni, Two-phase Flow Phenomena in Hydraulic Turbines and Pump-Turbines Operating in Synchronous Condenser Mode, 2018, EPFL.

[8] T. Tanaka, Sloshing motion of the depressed water in the draft tube in dewatered operation of high head pump-turbines, In: *Proc. 17th IAHR Sympo,* **1**, 1994, 121.

[9] E. Vagnoni, L. Andolfatto and F. Avellan, On the sloshing free surface in the draft tube cone of a Francis turbine operating in synchronous condenser mode, In: *J. Phys. Conf. Ser,* 2017, 12034.

[10] E. Vagnoni, A. Favrel, L. Andolfatto and F. Avellan, Experimental investigation of the sloshing motion of the water free surface in the draft tube of a Francis turbine operating in synchronous condenser mode, *Exp. Fluid* **59**, 2018, 95.

[11] E. Vagnoni, L. Andolfatto, R. Guillaume, P. Leroy and F. Avellan, Interaction of a rotating two-phase flow with the pressure and torque stability of a reversible pump-turbine operating in condenser mode, *Int. J. Multiph. Flow* **111**, 2019, 112–121.

[12] H. Tanaka, Vibration behavior and dynamic stress of runners of very high head reversible pump-turbines, *Int. J. Fluid Mach. Syst.* **4**, 2011, 289–306.

[13] G. Rossi and V. Zanetti, Starting in air and synchronous condenser operation of pump-turbines—model research, In: *9th IAHR-SHMEC Symp,* 1978, 337–352.

[14] D. Valentin, A. Presas, M. Bossio, M. Egusquiza, E. Egusquiza and C. Valero, Feasibility to detect natural frequencies of hydraulic turbines under operation using strain gauges, *Proceedings* 2017, https://doi.org/10.3390/proceedings1080821.

[15] D. Valentín, A. Presas, E. Egusquiza, C. Valero, M. Egusquiza and M. Bossio, Power swing generated in Francis turbines by Part Load and overload instabilities, *Energies* **10**, 2017, 2124.

[16] A. Presas, D. Valentin, M. Egusquiza, C. Valero, E. Egusquiza, A. Presas, D. Valentin, M. Egusquiza, C. Valero and E. Egusquiza, Sensor-based optimized control of the full load instability in large hydraulic turbines, *Sensors* **18**, 2018, 1038, https://doi.org/10.3390/s18041038.

[17] C. Valero, M. Egusquiza, E. Egusquiza, A. Presas, D. Valentin and M. Bossio, Extension of operating range in pump-turbines. Influence of head and load, *Energies* 2017, https://doi.org/10.3390/en10122178.

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

[19] J.G. Pereira, Jr., L. Andolfatto and F. Avellan, Monitoring a Francis turbine operating conditions, *Flow Meas. Instrum.* **63**, 2018, 37–46.

[20] A. Favrel, J.G.P. Junior, C. Landry, S. Alligné, L. Andolfatto, C. Nicolet and F. Avellan, Prediction of hydro-acoustic resonances in hydropower plants by a new approach based on the concept of swirl number, *J. Hydraul. Res.* **0**, 2019, 1–18, https://doi.org/10.1080/00221686.2018.1555556.

[21] A. Presas, D. Valentin, E. Egusquiza and C. Valero, Detection and analysis of part load and full load instabilities in a real Francis turbine prototype, *J. Phys. Conf. Ser.* 2017, https://doi.org/10.1088/1742-6596/813/1/012038.

[22] S.D. Downing and D.F. Socie, Simple rainflow counting algorithms, *Int. J. Fatigue* **4**, 1982, 31–40 https://doi.org/10.1016/0142-1123(82)90018-4.

[23] A. Presas, E. Egusquiza, C. Valero, D. Valentin and U. Seidel, Feasibility of using PZT actuators to study the dynamic behavior of a rotating disk due to rotor-stator interaction, *Sensors* **14**, 2014, 11919–11942, https://doi.org/10.3390/s140711919.

[24] M. Bossio, D. Valentín, A. Presas, D.R. Martin, E. Egusquiza, C. Valero and M. Egusquiza, Numerical study on the influence of acoustic natural frequencies on the dynamic behaviour of submerged and confined disk-like structures, *J. Fluids Struct.* **73**, 2017, 53–69 https://doi.org/10.1016/j.jfluidstructs.2017.05.008.

[25] D. Valentín, D. Ramos, M. Bossio, A. Presas, E. Egusquiza and C. Valero, Influence of the boundary conditions on the natural frequencies of a Francis turbine, In: *IOP Conf. Ser. Earth Environ. Sci,* 2016, IOP Publishing, 72004.

Appendix A. Supplementary data

The following is the Supplementary data to this article:

Multimedia Component 1

Multimedia component 1

alt-text: Multimedia component 1

Highlights

- Synchronous condenser operation in a Francis turbine has been studied.
- Runner stress and fatigue have been evaluated for this operating condition.
- Vibration behavior of the machine is studied during synchronous condenser operation.
- Transient events from generating mode to synchronous condenser and vice versa are investigated.

Queries and Answers

Query: Please confirm that the provided email “david.valentin@upc.edu” is the correct address for official communication, else provide an alternate e-mail address to replace the existing one, because private e-mail addresses should not be used in articles as the address for communication.
Answer: Yes, it is the correct address

Query: Please note that author’s telephone/fax numbers are not published in Journal articles due to the fact that articles are available online and in print for many years, whereas telephone/fax numbers are changeable and therefore not reliable in the long term.

Answer: Ok

Query: Have we correctly interpreted the following funding source(s) and country names you cited in your article: European Commission, European Union?

Answer: Yes

Query: Please confirm that given names and surnames have been identified correctly and are presented in the desired order and please carefully verify the spelling of all authors' names.

Answer: Yes

Query: Your article is registered as a regular item and is being processed for inclusion in a regular issue of the journal. If this is NOT correct and your article belongs to a Special Issue/Collection please contact v.subramanian@elsevier.com immediately prior to returning your corrections.

Answer: Yes