

# Prediction of Francis Turbine Prototype Part Load Pressure and Output Power Fluctuations with Hydroelectric Model

S Alligné<sup>1</sup>, C Nicolet<sup>1</sup>, A Béguin<sup>1</sup>, C Landry<sup>1</sup>, J Gomes<sup>2</sup>, F Avellan<sup>2</sup>

<sup>1</sup> Power Vision Engineering Sàrl, Ch. Des champs courbes 1, CH 1024 Ecublens, Switzerland

<sup>2</sup> Ecole Polytechnique Fédérale de Lausanne, Laboratory for Hydraulic Machines, CH 1007 Lausanne, Switzerland

**Abstract.** The prediction of pressure and output power fluctuations amplitudes on Francis turbine prototype is a challenge for hydro-equipment industry since it is subjected to guarantees to ensure smooth and reliable operation of the hydro units. The European FP7 research project Hyperbole aims to setup a methodology to transpose the pressure fluctuations induced by the cavitation vortex rope from the reduced scale model to the prototype generating units. A Francis turbine unit of 444MW with a specific speed value of  $v = 0.29$ , is considered as case study. A SIMSEN model of the power station including electrical system, controllers, rotating train and hydraulic system with transposed draft tube excitation sources is setup. Based on this model, a frequency analysis of the hydroelectric system is performed for all technologies to analyse potential interactions between hydraulic excitation sources and electrical components. Three technologies have been compared: the classical fixed speed configuration with Synchronous Machine (SM) and the two variable speed technologies which are Doubly Fed Induction Machine (DFIM) and Full Size Frequency Converter (FSFC).

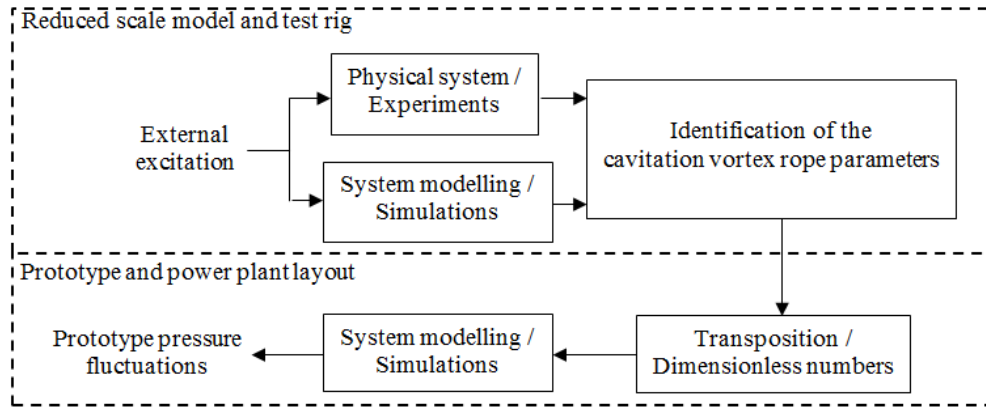
## 1. Introduction

In the framework of the European FP7 research project Hyperbole, a methodology is setup to predict pressure and output power fluctuations on prototype induced by the cavitation vortex rope based on experimental measurements on the reduced scale model. The developed methodology relies on an advanced modelling of the draft tube cavitation flow which main parameters are the cavitation compliance, the dissipation and the excitation source [1]. Specific measurements on reduced scale model to quantify model parameters including dissipation are required [2]. First, this paper presents the methodology and focuses on the transposition to the prototype of the draft tube model parameters identified on the reduced scale model. Then, a numerical model of the power station including electrical system, controllers, rotating train and hydraulic system with transposed draft tube excitation sources is setup. Based on this model, frequency response of the electro-mechanical, the hydro-mechanical and the hydroelectric systems are compared to analyse the influence of the different modelling approaches to predict both pressure and output power fluctuations induced by the cavitation vortex. Three technologies for electrical part have been compared: the classical fixed speed configuration with Synchronous Machine (SM) and the two variable speed technologies which are Doubly Fed Induction Machine (DFIM) and Full Size Frequency Converter (FSFC).

## 2. Methodology

The methodology to predict the pressure fluctuations on prototype is illustrated in figure 1. The first step is to identify the hydroacoustic characteristics of the draft tube cavitation vortex rope on a Francis turbine reduced scale model installed on a test rig. To achieve this, the test rig hydraulic circuit is excited by an external periodical discharge source and the system response is compared to the

response of a numerical model of the test rig [2]. An identification process comparing experimental and numerical hydraulic responses enables to identify the parameters of an advanced model of the draft tube cavitation flow. Then, these reduced scale model parameters are transposed to the prototype and used in the numerical model of the prototype power plant for the prediction of the resulting pressure and output power fluctuations.



**Figure 1.** Methodology for prediction of pressure fluctuations on prototype.

The modelling of the draft tube cavitation flow is described by continuity and momentum equations including the convective terms and the divergent geometry [1]. For this investigation, two cavitation vortex rope parameters of this model have been identified experimentally at the reduced scale model:

- the local wave speed  $a$  defined implicitly by the cavitation compliance  $C_c$  ;
- the second viscosity  $\mu''$  introducing dissipation induced by the phase change during cavitation volume fluctuations.

The wave speed and the second viscosity identified at the reduced scale model are normalized by the outlet pressure level of the draft tube, leading to two dimensionless numbers respectively  $\Pi$  and  $M''$  [2]. These dimensionless numbers can be approximated by a power function of the void fraction  $\beta$  which are not dependent on the operating point of the hydraulic machine in the range of part load conditions. To use these dimensionless numbers for transposition purpose, the void fraction  $\beta$  must be known and is derived from a cavitation curve  $\beta = f(\sigma)$  depending on the operating point and the Froude number obtained from experiments. By assuming the Froude similitude the prototype void fraction  $\beta^P$  is equal to the reduced scale model void fraction  $\beta^M$  allowing deriving the transposed draft tube flow parameters at the prototype scale.

### 3. Hydraulic layout modelling of the power plant

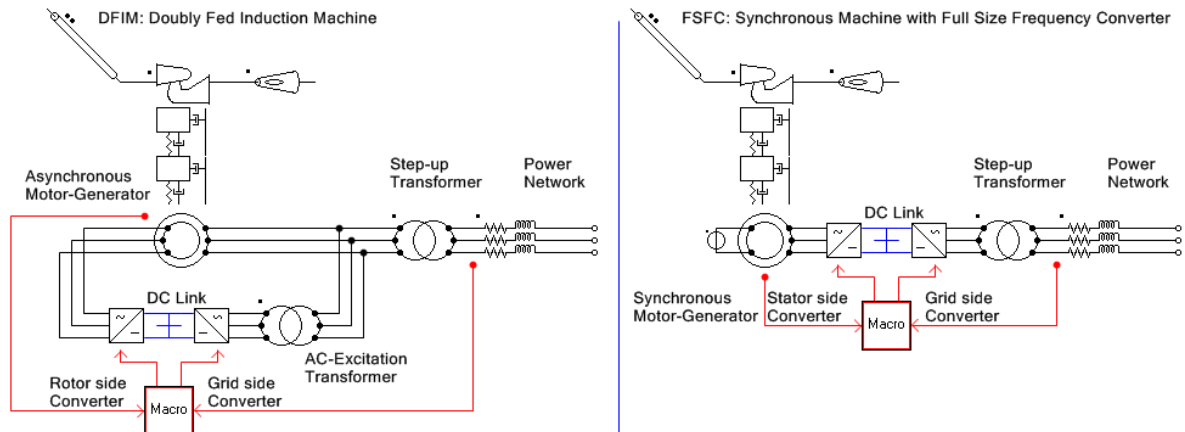
The power plant of interest features four Francis type turbines rated at power output of 444 MW under the 171m rated net head. Each unit is supplied by individual penstock. A numerical model of the power plant is set up with the SIMSEN software including reservoirs, penstock, the two quadrant characteristic of the turbine, the rotating inertia and the advanced cavitation draft tube model [3]. The draft tube model parameters at reduced scale model have been derived for two part load operating points named PL1 and PL2, defined in table 1a). A distributed model of the draft tube is used considering several control volumes along the draft tube length where continuity and momentum equations are applied [3]. Constant wave speed and second viscosity parameters are considered along the draft tube length. The table 1b) shows the influence of the operating point on the transposed prototype draft tube parameters and on the resulting first eigenmodes of the power plant defined by frequency and damping  $s = \alpha + j(2\pi f)$ . By changing the operating point from PL1 to PL2, the void fraction is increased. Hence, the first eigenfrequency value  $f_1$  is decreased from 0.30 to 0.18 times the runner frequency  $n$  and the eigendamping value  $\alpha_1$  is increased towards positive values.

**Table 1.** a) Investigated operating points b) Influence of the operating point on the draft tube parameters and on the resulting two first eigenfrequencies.

a)	PL1	PL2	b)	PL1	PL2
GVO	15.2	12	$\sigma$ (-)	0.11	0.11
nED / nED BEP	1	1	$\beta$ (-)	0.0124	0.0421
QED / QED BEP	0.8	0.64	a (m/s)	76.9	45.3
Fr	5.6	5.6	$\mu''$ (Pa.s)	3.06E+05	6.14E+04
$\sigma$	0.11	0.11	$\alpha 1$ (s <sup>-1</sup> )	-0.40	-0.10
			f1/n (-)	0.30	0.18
			$\alpha 2$ (s <sup>-1</sup> )	-0.86	-1.02
			f2/n (-)	0.78	0.69

#### 4. Electrical layout modelling of the power plant

For the electrical layout modelling, the current three motor-generator technologies are considered: the classical fixed speed configuration (SM) with PSS2B and the two variable speed technologies which are Doubly Fed Induction Machine (DFIM) and Full Size Frequency Converter (FSFC). To have detailed information about the different components models and control strategies, the reader can refer to [4]. The connection to the grid is modelled with an infinite power three phase voltage bus behind a short-circuit impedance, to represent the short-circuit power limitation of the connection point. The hydroelectric models are shown in figure 2.



**Figure 2.** Hydroelectric SIMSEN models of DFIM (Left) and FSFC technologies.

#### 5. Frequency analysis of the hydroelectric powerplant

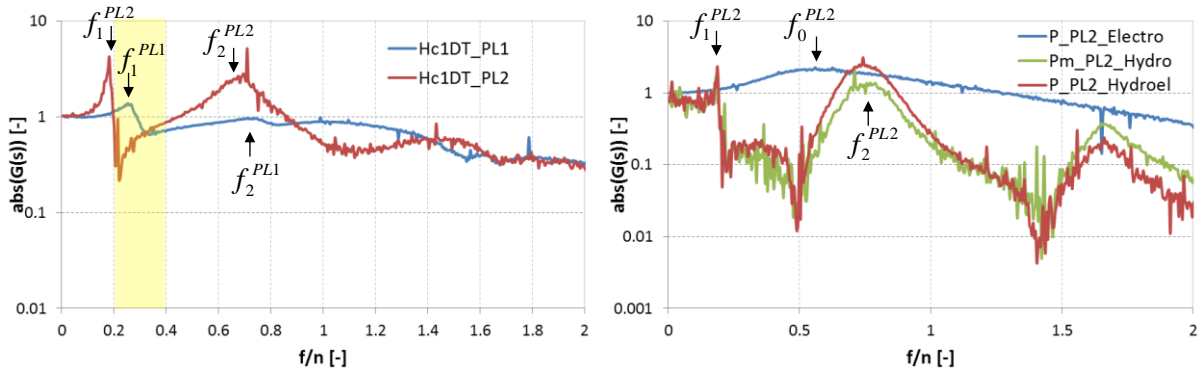
To characterize the dynamic system response in the frequency domain, transfer functions are computed by performing a time domain simulation with a white noise excitation modelled by a Pseudo Random Binary Sequence (PRBS) considering two different types of excitations:

- a momentum excitation source in the draft tube for the hydro-mechanical and the hydroelectric systems located at one pressure node in the draft tube;
- an external torque on the rotating masses for the electro-mechanical system.

With a period of  $dT = 0.1$  s, the energy spectrum of the PRBS signal is distributed uniformly in the range 0 to 5Hz, covering the excitation range of the helical vortex rope being between 0.2 and 0.4 times the runner frequency  $n$  corresponding respectively to 0.43 Hz and 0.86 Hz. The normalized transfer functions are defined as the ratio between the output of interest  $Y$  and the excitation source.

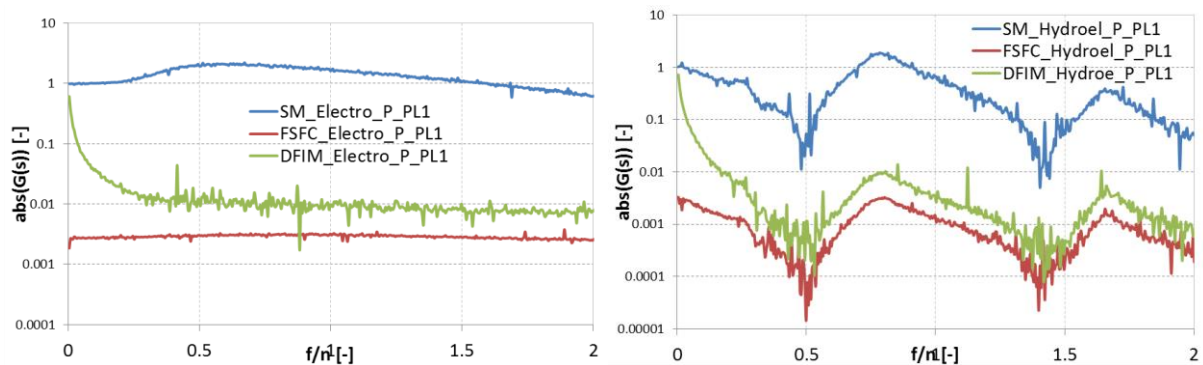
$$G(s)_{hydro/hydroel} = \frac{Y(s)/Y_n}{S_h(s)/H_n} ; G(s)_{electro} = \frac{Y(s)/Y_n}{T_{ext}(s)/T_n} \quad (1)$$

The amplitude of the normalized transfer function of the hydro-mechanical system, defined as the ratio between the draft tube pressure cone and the momentum excitation source in the draft tube, is represented in figure 3 for the two investigated operating points. Due to the higher void fraction for PL2, the second viscosity is lower and therefore, damping values of the eigenmodes and system response amplitude are higher. The vortex rope frequency being between 0.2 and 0.4 times the runner frequency  $n$  (yellow area in figure 3), a match with the first eigenfrequency is only possible for PL1 where amplitudes are rather small for resonance conditions. For PL2, the amplitude response obtained for the second eigenmode at this location is higher than the one obtained for PL1 despite a higher damping value  $\alpha$  for PL2. This effect is due to the difference of cavitation parameters between PL1 and PL2 that affects the spatial distribution of pressure amplitudes along the piping system and also to the difference of relative position of the excitation source in the eigenmode. These transfer functions, for both operating points, are unchanged using hydroelectric models whatever the electrical system technology considered. However, for the prediction of the output power fluctuations, it depends on the level of modelling approach. In figure 3, the amplitude of the normalized transfer functions defined as the ratio between the output power and the external excitation source are plotted for the fixed speed technology and comparison is performed between electro-mechanical, hydro-mechanical and hydroelectric models considering synchronous machine with PSS2B and without turbine governor.



**Figure 3.** (Left) Hydro-mechanical transfer function of draft tube pressure cone – (Right) Comparison of active power transfer functions between electro-mechanical system and hydroelectric system.

The “local eigenmode” of the synchronous machine representing the rotor oscillations against the power grid is found at 1.2Hz, i.e.  $f_0/n=0.56$  times the runner frequency  $n$ . This mode is clearly observed with the transfer function of the electro-mechanical system. With the hydroelectric model, the transfer function of the active power is influenced by the hydraulic system, since hydraulic eigenfrequencies can be observed. Hence, with an electro-mechanical model, the modelling of the vortex rope excitation source by just an external source torque is not representative of the hydraulic system dynamics. Indeed, hydraulic eigenfrequencies, which may interact with the vortex rope precession frequency, are not visible in the frequency spectrum. It has been mentioned above that the hydroelectric model predicts the same pressure fluctuations in the hydraulic system as the hydro-mechanical model. However, for prediction of output power fluctuations, the modelling of the electrical part is necessary and the hydro-mechanical model is not sufficient anymore. Indeed, the hydroelectrical transfer function is the result of the multiplication between the hydro-mechanical and the electro-mechanical transfer functions. Hence, the transfer function of the electro-mechanical model, featuring the synchronous machine local eigenmode, amplifies or reduces the prediction of the mechanical power fluctuations of the hydro-mechanical model. For the PL2 operating point, this local eigenmode amplifies the second hydraulic eigenfrequency and results in prediction of higher amplitude than the electro-mechanical model. The active power transfer functions of the electro-mechanical models with variable speed technologies are compared to the fixed speed case for PL1 in figure 4. Since the control strategy of the variable speed technologies imposes a constant active power at the point of connection to the grid, the transfer functions feature low gain compared to the fixed speed technology. Hence, this low gain cancels the mechanical power fluctuations of the hydro-mechanical model as shown in figure 4: amplification of a hydraulic eigenmode is not possible.



**Figure 4.** (Left) Comparison of electro-mechanical (Left) and hydroelectric (Right) transfer functions between technologies.

## 6. Conclusions

Prediction of pressure and output power fluctuations induced by cavitation vortex rope at part load conditions has been compared by means of frequency analysis between the classical fixed speed configuration and the variable speed technology.

For the fixed speed technology, it has been shown that in the low frequency range, hydro-mechanical models are sufficient for prediction of pressure fluctuations in the hydraulic system. This could be different for weaker or isolated power networks. However, for prediction of output power, the hydroelectric model is necessary. Compared to the electro-mechanical model, the detailed hydraulic modelling enables to take into account potential hydraulic resonances and anti-resonances resulting from the interaction of the cavitation vortex rope precession frequency with the hydraulic system that influences potential power fluctuations transmitted to the power network. On the other hand, compared to the hydro-mechanical model, the dynamics of the electrical machine can amplify or reduce the mechanical power fluctuations.

Due to the control of the variable speed technology, rotational speed fluctuations are experienced to ensure constant active power at the grid connecting point which could influence the dynamics behaviour of the cavitation vortex rope. However, the amplitudes of rotational speed fluctuations are very low inducing a weak feedback on the hydraulic response. Hence, the use of a hydroelectric model is not necessary for prediction of pressure fluctuations and they are similar to the hydro-mechanical model with constant speed. This could be different for weaker or isolated power networks. Measurements on prototype are foreseen to validate these results.

## 7. References

- [1] Alligné S., Nicolet C., Tsujimoto Y., Avellan F, Cavitation surge modelling in Francis turbine draft tube *J. of Hydraulic Research*. 2014, **52** (3).
- [2] Landry C., Favrel A., Müller A., Nicolet C., Avellan F., Experimental identification of the local wave speed and the second viscosity in cavitating draft tube flow *J. of Hydraulic Research* 2014.
- [3] Alligné S., Landry C., Favrel A., Nicolet C., Avellan F., Francis turbine draft tube modelling for prediction of pressure fluctuations on prototype. In Proc. of 9<sup>th</sup> International Symposium on Cavitation, 2015.
- [4] Béguin A., Nicolet C., Assessment of power step performances of variable speed pump-turbine unit by means of hydro-electrical system simulation. Hyperbole Conference, Porto, 2017.

## Acknowledgments

The research leading to the results published in this paper is part of the HYPERBOLE research project, granted by the European Commission (ERC/FP7-ENERGY-2013-1-Grant 608532). The authors would like to thank BC Hydro for making available the reduced scale model and the prototype for validation, in particular Dany Burggraeve and Jacob Iosfin. Finally, parameters of the electrical model have been provided by Mr. Johann Hell from ANDRITZ Hydro who authors would like to thank.