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Investigation of the unsteady pressure pulsations in the prototype Francis turbines – Part 1: Steady state operating conditions

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ABSTRACT

Hydropower is one of the most reliable renewable sources of electricity generation. With high efficiency and good regulating capacity, hydropower has the ability to meet rapid changes in power demand. Large investments in intermittent renewable energy resources have increased the demand for balancing power. This demand has pushed hydraulic turbines to generate electricity over the operating range from part load to full load. High-amplitude pressure pulsations are developed at off-design conditions, which cause moderate damage to the turbine components. The pressure pulsations may be either synchronous- (axial)-type, asynchronous- (rotating)-type or both. In this study, pressure measurements on low specific-speed prototype Francis turbines were performed; one of them was vertical axis and another was horizontal axis type. Four pressure sensors were mounted on the surface of the draft tube cone. Pressure measurements were performed at five operating points. The investigations showed that, in the vertical axis turbine, amplitudes of asynchronous pressure pulsations were 20 times larger than those of the synchronous component; whereas, in the horizontal axis turbine, amplitudes of asynchronous pressure pulsations were two times smaller than those of the synchronous component.

For part 2 of the paper, please read Trivedi, C., Gogstad, P. J., and Dahlhaug, O. G., 2017, “Investigation of Unsteady Pressure Pulsations in the Prototype Francis Turbines during Load Variation and Startup,” Journal of Renewable Sustainable Energy, 9(6), p. 064502. https://doi.org/10.1063/1.4994884.

1. Introduction

Global electricity demand is met by both renewable and non-renewable energy sources. A hydropower source is one of the most stable sources of renewable energy used to generate electricity. Hydropower sources contribute more than 20% of generated energy globally [1]. The hydraulic turbine is an important component in a hydropower plant that converts available waterpower into mechanical power (torque). The mechanical power is used by a coupled generator to produce electricity. Hydraulic turbines are designed for given head and discharge conditions where the maximum efficiency of the turbine is obtained, known as the best efficiency point (BEP). The current trend of flexible electricity market does not allow hydraulic

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Nomenclature

BEP	best efficiency point
D	runner outlet diameter (m)
E	specific hydraulic energy (J kg^{-1})
F_s	data sampling rate (Hz)
f	frequency (Hz)
H	head (m)
IEC	International Electrotechnical Commission
N	number of samples
N_{QE}	specific speed (–)
n	runner angular speed (rps)
n_{ED}	speed factor (–)
P	power (MW), signal power (dB)
p	pressure (kPa)
$\bar{p}$	average pressure (kPa)
$\bar{p}_S$	average pressure (kPa), $\bar{p}_S = (S1 + S2 + S3 + S4)/4$
$\tilde{p}_{eff}$	standard deviation (kPa)
Q	discharge (m^3 s^{-1})
Q_{ED}	discharge factor (–)
RMS	root-mean-square
rps	revolutions per second
SINAD	signal-to-noise and distortion ratio
SNR	signal-to-noise-ratio
S1, S2, S3 and S4	locations of the pressure sensors mounted in a draft tube cone
THD	total harmonic distortion

Greek letters

σ	standard deviation (kPa)
ρ	water density (kg m^{-3})

Subscripts

asyn	asynchronous component (rotating) of the pressure pulsation
i	integer, where i 1, 2, 3 and 4
syn	synchronous component (axial) of the pressure pulsation

turbines to operate at the BEP constantly. The turbines are operated over the complete range of power generation, starting from part load to the full load [2,3].

Power generation at off-design conditions affect the dynamic stability of hydraulic turbines [4,5]. High-amplitude pressure pulsations developed in a draft tube cause fatigue damage to the turbine [6,7]. The pressure pulsations developed in a draft tube are related to the vortex breakdown. The pressure pulsations are composed of two different phenomena occurring simultaneously at the same frequency [8,9]. These pressure pulsations may be explained reasonably when a clear distinction between synchronous (axial) and asynchronous (radial) type pressure pulsations is made [10–13].

- The synchronous component may have equal phase and amplitude in the runner and the draft tube. The pressure may be considered as a plane wave propagating to hydraulic system through the draft tube.
- The asynchronous component is a pressure pattern developing at the runner downstream and rotating about the circumference of the draft tube. The rotation period is dependent upon the circumference and the runner angular speed.
- The synchronous component may not be present at high load conditions.

Both synchronous and asynchronous types of pressure pulsations cause different impacts on turbine operation. Therefore, it is important to analyze and distinguish the pressure pulsations. The majority of studies have investigated the draft tube flow condition of a model turbine [14–17]; however, few studies has been reported on the investigation of synchronous- and asynchronous-type pressure pulsations in prototypes. Measurements on the model turbines are not completely representative of the prototype and its dynamic behavior [18–21]. An isolated test facility available in the laboratory has different dynamic characteristics [6,22] and has limited scope for scaling the data.

This paper discusses investigations conducted on prototype Francis turbines at five operating points. Four pressure sensors were mounted in the draft tube cone to acquire the unsteady pressure values. Low frequency pressure pulsations and decomposition into the synchronous and asynchronous components are of special interest in this paper. These pressure pulsations typically occur between 0.2 and 0.3 times the runner angular speed [22]. Moreover, repeated measurements