Renewable Energy 83 (2015) 828–836

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Experimental investigations of a model Francis turbine during shutdown at synchronous speed

Chirag Trivedi [a, b], Bhupendra K. Gandhi [a, *], Michel J. Cervantes [b, c], Ole Gunnar Dahlhaug [c]

[a] Indian Institute of Technology Roorkee, India
[b] Luleå University of Technology, Sweden
[c] Norwegian University of Science and Technology, Norway

ARTICLE INFO

Article history:
Received 31 July 2014
Accepted 14 May 2015
Available online 29 May 2015

Keywords:
Francis turbine
Hydropower
Pressure
Runner
Shutdown
Transient

ABSTRACT

Hydraulic turbines are widely used to meet the real-time electricity demand at moderate to low cost. Intermittency in the power grid due to high penetration of wind and solar power has raised significant concerns for grid stability and reliability. The intermittency results in an increase of the start–stop cycles of hydraulic turbines. Each cycle induces fatigue to the turbine runner because it experiences unsteady pressure loading of high amplitude. The turbine runner accelerates freely due to an instantaneous transition into no load during shutdown. The amplitude of the unsteady pressure pulsation increases as the runner accelerates. To investigate the unsteady pressure pulsation, a shutdown slightly different from the normal shutdown was performed. Guide vanes were closed completely before the generator was disconnected from the load. The runner was spinning at constant angular speed through the generator. Amplitudes of the pressure pulsations were 20% and 35% lower in the vaneless space and the runner, respectively, compared to the normal shutdown of the turbine.

1. Introduction

Hydropower is one of the most reliable sources of renewable energy and is extensively used to meet real-time electricity demand. The global hydropower capacity reached more than 1135 GW by the end of 2013, and it increases by 4% every year [1]. The imbalance between electricity demand and generation often disrupts the power grid. Governmental incitation for alternative renewable and sustainable energies, such as wind and solar energy, has also increased grid disruption because they do not produce electricity according to demand [2,3]. Thus, variable power generation from wind/solar energies and variable electricity demand have affected hydraulic turbine operation. The turbines are forced to pass through transient conditions, such as load variation, start-stop, and total load rejection. A load peaking hydraulic turbine experiences 3–5 transient cycles per day [4].

Startup and shutdown follow complex operating sequences of hydraulic turbines [5,6]. For a normal shutdown of a Francis turbine, power output from the generator is brought down to the minimum by closing the guide vanes. Then, the generator is disconnected from the grid/load by opening the circuit breakers. The guide vanes are closed further, and the transition into no-load occurs. The angular speed of the runner decreases slowly as the discharge to the runner decreases. However, during the transition into no-load, an overshoot of the runner angular speed takes place, accelerating the runner [7,8]. The speed overshoot depends on the inertia of the rotating components, including the runner and instantaneous discharge to the runner. During the speed overshoot, the amplitudes of the instantaneous pressure pulsations in the runner increase rapidly [9].

Unsteady pressure measurements on a model Francis turbine have shown that turbine shutdown is more damaging than startup [9]. During the shutdown cycle, the turbine passes through critical conditions and experiences significant vibrations as well as unsteady pressure loading [4,10]. Each cycle induces fatigue to the turbine runner equivalent to 15–20 operating hours [11–13]. Furthermore, the guide vane closing law and rate largely affect the instantaneous pressure loading on the blade surfaces. However, the closing law is generally defined at the time of turbine

* Corresponding author. Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, Uttarakhand 247 667, India. Tel.: +91 1332 285544; fax: +91 1332 285665.

E-mail addresses: chirag.trivedi@ntnu.no (C. Trivedi), bkgmefme@iitr.ac.in (B.K. Gandhi), Michel.Cervantes@ltu.se (M.J. Cervantes), ole.g.dahlhaug@ntnu.no (O.G. Dahlhaug).

http://dx.doi.org/10.1016/j.renene.2015.05.026
0960-1481/© 2015 Published by Elsevier Ltd.

commissioning, and it is followed during subsequent start-stops of the turbine [5,6,14–16]. The closing law is defined by considering the water hammer and surging effects in the water conduits and not the unsteady pressure loading and rate of runner acceleration [17,18].

The main objective of the present measurement is to investigate the unsteady pressure amplitude in the turbine by limiting the runner acceleration during shutdown. During the shutdown, the generator was connected to the load until the complete closing of the guide vanes and was then decoupled from the load. Unsteady pressure measurements in the vaneless space, runner, and draft tube were performed during the shutdown and are presented. The experimental results are compared to the results obtained with a traditional (normal) shutdown.

2. Materials and methods

Experimental investigations were conducted on a model Francis turbine. The test rig of the Francis turbine is shown in Fig. 1. The turbine is a scaled-down (1:5.1) model of the prototype operating at the Tokke Power Plant, Norway. The turbine includes 14 stay vanes integrated inside the spiral casing, 28 guide vanes equally arranged before the runner inlet, 15 splitters and 15 blades inside the runner, and an elbow type draft tube. The reference diameter at the runner outlet for the model is 0.349 m. During the measurements, water was pumped to the overhead tank where a constant level was maintained. Water flowed down to the turbine through the connected pipelines. Discharge to the turbine was controlled by the guide vanes only. The outlet of the draft tube was connected to a downstream tank where a constant water level was maintained at the atmospheric pressure. The net head across the turbine was 12 m at the best efficiency operating point (BEP).

The calibrations, experimental measurements and computations were performed using the procedure and guidelines available in the IEC standards [20]. Data from the instruments/sensors were recorded on a computer through a program developed in LabVIEW. There were two acquisition systems: one to record the data specific to the test rig, sampled at 1.4 Hz, and another to log the pressure-time signals of the installed sensors, sampled at 2083 Hz. Fig. 2 shows the locations of the pressure sensors mounted in the model: on the vaneless space (VL01), the pressure side of the blade (P42 and P71), the suction side of the blade (S51), and on the wall of the draft tube cone (DT11 and DT21).

The Summation Research SRI-500e wireless telemetry system was used to transmit the pressure-time data of sensors P42, P71, and S51 to the stationary receiver located outside the turbine. The accuracy and calibration uncertainty of the sensors are presented in Table 1. A hydraulic dead-weight tester (General Electric Series 3200) was used to calibrate two PTX610 pressure transmitters (PTX1 and PTX2, for location see Fig. 1) and one PTX1400 pressure transmitter. The PTX1400 was used as a primary calibration sensor for the calibration of the Kulite LL080 type strain gauge based miniature pressure sensors P42, P71, and S51. The estimated uncertainties were below 0.62%, 0.45%, and 0.22% for P42, P71, and S51, respectively.

Steady state measurements were performed over the turbine operating range before the present measurements. Fig. 3 shows the constant efficiency hill diagram of the model Francis turbine. A total of 150 operating points were obtained for guide vane angular positions varying from 3.9 to 14°. The maximum hydraulic efficiency of 93.4% was obtained at $n_{ED} = 0.18$, $Q_{ED} = 0.15$, and $\alpha = 9.9°$, the BEP. The observed net head and hydraulic energy (ρE) were 12 m and 116.84 kPa at the BEP, respectively. The total estimated uncertainty was ±0.16% in the hydraulic efficiency under the steady state operating condition at the BEP [19]. The discharge factor (Q_{ED}) and speed factor (n_{ED}) were calculated using equations available in IEC 60193 [20] as follows:

$$Q_{ED} = \frac{Q}{D^2 \cdot \sqrt{E}} \quad (-) \tag{1}$$

$$n_{ED} = \frac{n \cdot D}{\sqrt{E}} \quad (-) \tag{2}$$

where Q is the discharge in $m^3\ s^{-1}$, D is the reference diameter in m, E is the specific hydraulic energy in J kg^{-1}, and n is the runner angular speed in revolutions per second.

Transient pressure measurements were performed during shutdown from the steady state BEP load. The torque output from the runner was reduced by closing the guide vanes from 9.9°. The runner was operating at a synchronous speed of 5.53 Hz until the guide vanes were completely closed. The generator was then disconnected. The runner was spinning at no-load, and the angular speed was decreasing slowly. The runner was not accelerated after disconnecting the generator from the load as observed for the normal shutdown scheme because there was no discharge to the runner.

3. Data reduction

The pressure-time data of all eight sensors were analyzed in the time domain. The pressure values were correlated with the guide vane angular movement and the runner angular speed. Spectral analysis was conducted to investigate the amplitude and corresponding frequency. Apart from the pressure-time data, the discharge, guide vane angular movement, head, shaft torque,

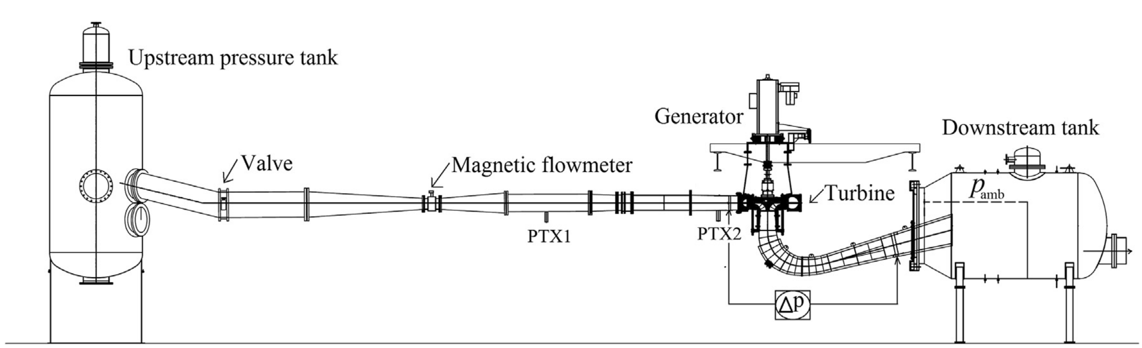

Fig. 1. Experimental setup of the model Francis turbine [19]. PTX1 and PTX2 are the pressure transmitters used to monitor the pressure variation at the inlet pipeline during shutdown. Δp is the differential pressure across the turbine. The dotted line in the downstream tank indicates the water level at atmospheric pressure (p_{amb}) during the measurements.