The vortex effect of Francis turbine in electric power generation

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Received: 23.05.2011 • Accepted: 15.08.2011 • Published Online: 27.12.2012 • Printed: 28.01.2013

Abstract: In this study, the vibration effects of a vortex that occurred in high-head Francis turbines and an alternator are examined. The vortex effect, which directly affects the efficiency and the quality of the energy, was tested at the Darca-1 hydroelectric power plant (HPP) located in Ordu Province, Turkey. Formed by undissolved oxygen in the water, the vortex effect, which is parallel to the alternator load, causes tremendous vibration within the alternator and Francis turbine bearings. This problem, which has a direct negative effect on the alternator capacity, was solved by adding an air-admission system. In doing so, power production was increased by 11.11%, from 44 MW to 49.5 MW. This caused a significant head loss, specifically in the Francis turbines. Vortex optimization was successfully established at the Darca-1 HPP.

Key words: Francis turbine, vortex effect, alternator, hydroelectric power plant

1. Introduction

Hydroplants and various hydromechanisms generally have vibration-related issues. Structural problems are likely to be caused by the extensive amount of water stored in places such as pipelines, tunnels, penstocks, and draft tubes. When the frequency of the oscillations coincide and resonate with the natural frequency of a hydraulic, mechanical, or structural component, the amplitudes of the oscillations are reinforced, and the potential for damage is maximized.

The most damaging cause of excitation is the draft tube vortex core in Francis turbines. The intensity of the air significantly affects the excitation of the natural frequencies of a turbine water passage system and the response of the system. It is crucial to consider the air–water flow through the turbine draft tube. Keeping turbine loads within the optimal operating zone, far from the zone of vortex core resonance, will increase plant profitability and reliability [1].

There are many studies on turbine vortex effect [2,3]. Researchers have proposed various techniques to lessen the impact of vortex and vibrations [4]. Air admission into the draft tube is the most commonly used technique among them [5]. Meanwhile, a new method has been offered by Susan-Resiga et al. [6,7], which uses an axial jet made from the craw tip to reduce the amount of vortex rope.

Empirical studies have looked at the irregularities of the pressure caused by the vortex rope in the draft tube of Francis turbines [8,9]. Another study tested the use of scale model Francis turbines at the EPFL Laboratory for Hydraulic Machines [10]. Another study offered information about the operation of Francis turbines and their complex hydrodynamic system [11].

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At the upper part of load operation under low cavitation numbers, scale models of high-specific-speed Francis turbines may present pressure fluctuation in the range 2 to 4 times $f_n$, the rotating frequency. In the framework of the FLINDT project, pressure measurements on the draft tube wall of a Francis turbine scale model, at 104 locations, revealed such a phenomenon at a frequency of almost 2.5 $f_n$. The phase shift analysis of the measured compression instabilities in the draft tube at this frequency points out a pressure source located in the inner part of the draft tube elbow [12].

An analysis of the dynamic pressures causing danger during operation in the Francis turbine runner was carried out and it was found that the main cause for the damage in the runner blade was the hydraulic forces creating dynamic pressure [13].

In another study, researchers used wavelet analysis to investigate the static pressure pulsation in the cavitated vortex core in the draft tube of a Francis turbine and found that there was a significant correlation between the processes [14].

In order to increase the amount of dissolved oxygen (DO level) in hydroelectric plants, researchers have also used models where they injected air into the Francis turbines [15].

This study presents our ongoing developments of the jet control technique for swirling flows in hydraulic turbines. In order to determine the best jet configuration for mitigating the vortex rope, researchers have developed a special swirling jet apparatus that is able to generate swirling flows similar to the ones downstream from Francis turbine runners operated at partial discharge [16]. In electricity generation, studies of network security, diagnostics, and the alternator are all very important [17,18].

2. Theoretical approach

Because it is in line with the theoretical infrastructure of the optimization at the Darca-1 hydroelectric power plant (HPP), located in Ordu Province, Turkey, one theoretical approach used in a study at the Laboratory for Hydraulic Machines (LMH; Lausanne, Switzerland) is presented here, related to undissolved oxygen-formed vibration [15].

Turbine tests regarding the DO levels were carried out at the LMH laboratory, where knowledge parameters governing gas dissolution in liquids and the analysis of each of the parameters were presented as a prerequisite.

As stated in Fick’s law [19], gas dissolution is mainly affected by the following parameters: exchange area $A$, control volume $V$, contact time $t$, saturation concentration $C_s$, and initial and final concentrations $C_1$ and $C_2$, stating a coefficient of diffusion $K_L$ and meeting the requirements of the differential equation below.

$$\frac{\partial C}{\partial t} = K_L \frac{A}{V}(C_s - C)$$  \hspace{1cm} (1)

Presuming a continuous coefficient of diffusion, Eq. (1) can be incorporated as follows:

$$\ln \left( \frac{C_s - C_2}{C_s - C_1} \right) = K_L \frac{A}{V} t.$$  \hspace{1cm} (2)

The final concentration is reached as follows:

$$C_2 = C_s - (C_s - C_1) e^{(K_L \frac{A}{V} t)}.$$  \hspace{1cm} (3)

Eq. (3) can be used to find the final concentration in the river downstream from the power plants.
In Henry’s law [20], the increase in the liquid temperature decreases saturation concentration $C_s$ of gas in liquids, while it increases with pressure. In a study by Thompson and Gulliver [21], the relationship between the prototype ($p$) and the model ($m$) about the exchange area $A$ is stated as follows:

$$\frac{A_p}{A_m} = \left( \frac{\Phi_p}{\Phi_m} \right) \left( \frac{\rho_p}{\rho_m} \right)^{3/5} \left( \frac{\sigma_m}{\sigma_p} \right)^{3/5} \left( \frac{n_p}{n_m} \right)^{6/5} \left( \frac{D_p}{D_m} \right)^{4/5},$$

(4)

where $\Phi$ = the gas volume ratio, $\rho$ = the water density, $\sigma$ = the surface tension, $n$ = the rotational speed, and $D$ = the runner diameter. The existing experiments have used various volumes of gas during the tests; however, with $\Phi_p = \Phi_m$ and $\Phi_p / \Phi_m$, the ratio continues and equals unity. Moreover, because the water temperature will be similar between the model and the prototype, Eq. (4) can be reduced as follows:

$$\frac{A_p}{A_m} = \left( \frac{n_p}{n_m} \right) \left( \frac{D_p}{D_m} \right)^{4/5}.$$  

(5)

According to Fick’s law, the oxygenated water is represented by volume $V$, which is the through flow in a turbine. In terms of volumes, there is a proportion between the ratio of the prototype ($p$) and the model ($m$) to the square of the ratio of the 2 diameters ($D$) and the square root of the corresponding heads ($H$):

$$\frac{V_p}{V_m} = \left( \frac{D_p}{D_m} \right)^2 \sqrt{\frac{H_p}{H_m}}.$$  

(6)

As with the contact time and the pressure, the 2 phases of dissolution must be differentiated from each other, the diffuser being the first and the exit channel or tail race the second. Approximations need to be done in accordance with the difference between a model’s section downstream and the prototype’s tail. For the current test, the coefficient of diffusion has been assumed to be the same as in the diffuser and the exit channel. The ratio of the proportion between the contact time and the geometric scale and the square root of the heads is as follows:

$$\frac{t_p}{t_m} = \frac{D_p}{D_m} \sqrt{\frac{H_m}{H_p}} = \frac{n_m}{n_p}.$$  

(7)

Because only the decrease in the speed of the bubbles has significance in the tail race, the contact time is determined by the geometric scale and the level of upstream water. Similarly, there is a proportion between the pressure ratio with an impact on the saturation concentration level, $C_s$, and the geometric scale and the level of upstream, and the square root of the heads in the turbine, as well as the geometric scale and the level of water upstream in the exit channel or tail race, which is as follows:

$$\frac{P_p}{P_m} = \frac{D_p}{D_m} \sqrt{\frac{H_m}{H_p}} \frac{Z_{2p}}{Z_{2m}} = \frac{n_m}{n_p} \frac{Z_{2p}}{Z_{2m}}.$$  

(8)

Figure 1 shows a simulation of the vortex rope motion in the draft tube.
3. Materials and methods

3.1. Vibration measurement

To measure the vibration, a DTM10 distributed-vibration transmitter-monitor, as shown in Figure 2, is used. With proximity probes and a Modbus interface to a programmable logic controller or distributed control system, it is recommended to use a DTM10 distributed-vibration transmitter-monitor to check the vibration in the machine via integration. Redundant power supplies and redundant 4–20 mA transmissions are also provided with the DTM10. It is possible to create an interface between the DTM10 and any other proximity probe system, which can be done with the existing hardware.

In order for the DTM10 vibration sensor to perceive the vibrations, as shown in Figure 3, TM180 proximity
probe transducers check the static and dynamic distance between the target and the probe. The architecture of the TM series proximity probe system is in line with the standards of API 670. There are probes, extension cables, and drivers in every system. Figure 4 shows the DTM10 system installation.

![Diagram of DTM10 system installation]

**Figure 4.** DTM10 system installation [22].

### 3.2. Air-admission system

Figure 5 shows the air-admission system used to prevent the vortex effect at the Darca-1 HPP. With part 3 of the slip ring cover valve, shown in the upper section of Figure 5, the amount of air is admitted through the shaft. Normally, this valve is left fully open for maximum air admission.

The Francis turbine section of the air-admission system is presented in Figure 6. Here, owing to the check valve in the lower part, airflow is directed upwardly in a one-way manner. Using a check valve in the lower section, pressured water is not permitted to flow through the turbines–generator shaft to the HPP building for any reason. Due to centrally injected air, the vortex oscillation amplitude is decreased; thus, hitting the draft tube is prevented. As a result, the turbine–generator group can operate more efficiently.

Figure 7 shows the data from the turbine and generators used at the Darca-1 HPP. Either of the 2 units was operating while the vibration was being measured.
Figure 5. Generator section [courtesy of Voith Hydro GmbH & Co. KG, Austria].

Figure 6. Francis turbine section [courtesy of Voith Hydro GmbH & Co. KG, Austria].

Figure 7. Darca-1 hydropower turbine and generator data.

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<td>- Runaway speed:</td>
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<td>- Rated current:</td>
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<td>- Rated power:</td>
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<td>- Rated discharge:</td>
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Figure 8. Water flow computer monitoring.

Figure 8 presents the HPP SCADA system, software that was developed by Voith. The immediate turbine regulator controls, power, voltage, current, frequency, power factor, source water level control, main suction hatch controls, and check valve controls of the respective units (unit 1 and unit 2) can be seen and performed by the monitor.

Figure 9. Francis turbine computer monitoring.
In Figure 9, functions such as the monitoring and control of the spherical valve, tracking of the helix pressure, measuring of the turbine flow, positioning of the turbine hatch, speed check, and general monitoring can be performed.

In Figure 10, the control and monitoring of the generator’s upper and lower bearings, turbine bearings, and stator temperature can be observed.

Figure 11 shows the upper section of a generator without an air-admission system. Figure 12 shows the upper section of a generator with an air-admission system mounted onto it. With the valve located on the top, the air-admission rate can be adjusted manually. Based on the experiments performed, this valve is adjusted to the fully open position in the case of the Darca-1 HPP.

Figure 10. Francis turbine upper and lower bearings.

Figure 11. Generator without an air-admission system.

Figure 12. Generator with air admission system.
4. Results

As in Darca-1, a generator that operates without an air-admission system can produce only 44 MW of power despite the fact that its capacity in the safe-vibration range is 49.5 MW. However, after installation of the air-admission system, the generator is now able to produce power under 49.5 MW at full load, within the safe vibration range.

Figure 13 shows the power production of a generator without an air-admission system and bearing vibrations.

Figure 14 shows the measured rates of a system without an air-admission tool. These rates were obtained from the Darca-1 HPP databank, during a period of 3 min and 14 s, on 17.11.2009 at 1050 hours. Here, the significant rates shown in the cursor 1 and cursor 2 columns are circled. In the case of the system without air
admission, for the turbine bearing’s relative radial vibration, cursor 1 = 551.8519 ym and cursor 2 = 533.3333 ym; for the actual power, cursor 1 = 47.3047 MW and cursor 2 = 49.7583 MW. The steady-state actual power was measured as 44.0837 MW and the turbine bearing’s relative radial vibration was 475.9259 ym.

Figure 15 shows the vibration rates of the turbine–generator group with an air-admission system and the actual power produced by the generator. The data used in the study was obtained from the Darca-1 HPP databank during a period of 3 min and 42 s, on 07.05.2010 at 0845 hours. Based on the results, for the turbine bearing’s relative radial vibration, cursor 1 = 355.5555 ym and cursor 2 = 370.3704 ym; for the actual power, cursor 1 = 49.4023 MW and cursor 2 = 49.3393 MW. The steady-state actual power was measured as 49.5406 MW and the turbine bearing’s relative radial vibration was 372.2224 ym.

Figure 16 shows the measured rates of a system with an air-admission tool.

Figure 15. Power production of a generator with an air-admission system and bearing vibrations.

Figure 16. Measurement panel with air admission.
5. Conclusion

In this study, the effect of the Francis turbine air-admission system on both the efficiency of the generator’s power production and the vibration of the turbine has been investigated. Due to the air-admission system, it was determined that the actual power production increased by 11.11% and reached 49.5 MW, and the relative radial vibration of the Francis turbine decreased by 27.68%. Because the generator operates at full capacity, the power production was increased about 4,752,000 KWh annually. Considering that the vibration of the Francis turbine decreased by 27.68%, its contribution to the life cycle of the turbine is clear. This improvement will decrease power cutoffs and positively affect the periodic maintenance of the turbine. One of the most important parts of the turbines is their bearings; the lower the amplitude, the better the operating time of the bearings. It is obvious that the decrease in vibration will improve the operating time of the bearings for both the generator and the turbines.

Acknowledgments

The author would like to express his gratitude to Voith Hydro for granting permission to study the Darca-1 air-admission system and for sharing the technical photos of the system. Thanks are also given to Yapsan Enerji A.. for allowing the author to conduct a study at the Darca-1 HPP facilities and for their contributions and valuable information.

References


