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Test of a Francis turbine with variable speed operation

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Abstract. The paper present the plan of procedure a model test of a Francis turbine runner designed for variable-speed operation (VSO). The new turbine is designed for having it operated more flexible and thus meet the increasing demand for off-design load at the European grid system. The purpose of the model test is to compare the results and verify numerical simulation related to the turbine. The model test will take place at the Waterpower Laboratory at NTNU, Trondheim, and the standard for model acceptance tests, *Hydraulic turbines, storage pumps and pump-turbines - Model acceptance tests*, will carefully be followed. Measurements included in the test are hydraulic efficiency, pressure pulsations, axial load and runaway speed. Raw data from the logging will be post-processed and results presented in Hill-chart and different contour plots related to the Hill-chart. Finally, the results will be compared with numerical simulations, and the design will be discussed based on this.

1. Introduction

The proportion of renewable energy entering the European grid system is growing, especially the amount of intermittent production from solar, wind, and wave energy. This type of energy leads to challenges as they are dependent on uncontrollable external factors, does not provide reserve capacity and therefore not contributes to maintaining the grid systems frequency [1]. Flexible energy resources have for a long time been understood in terms of balancing the system. In Norway, hydropower is the core of the power system and contributes to the balancing of the European grid system, but to a certain extent. When the demand for frequency response is increasing, the grid experience higher imbalance and forces the turbines more often to be operated at off-design, and the runners experience increasing load changes. For a Francis turbine, this can lead to fatigue and cracks of the runner, and unwanted phenomena as vortex shedding, cavitation or swirl can occur and influence the lifetime and thus reduce the hydraulic efficiency.[2]

A potential method of meeting this problem is the introduction of variable speed technology. Utilizing optimized methods for the runner to have it operated at variable speed, are maybe the key to future electricity production and favourable for the grid. At NTNU a new Francis runner has been developed with optimizing methods for having it operated at variable speed condition. To verify numerical simulations a model test has to be conducted, and necessary arrangements and plans for this test have to be carried out according to the model acceptance test standard *Hydraulic turbines, storage pumps and pump-turbines - Model acceptance tests*, IEC60193. This paper presents the preliminary work for conducting the model test at the Waterpower Laboratory at NTNU. In the model test measurements regarding hydraulic efficiency, pressure pulsations, axial load and runaway speed are included.

2. Previous work

Both numerical and experimental investigations on the Francis turbine has been conducted over the past decades. In recent times the focus has been shifted from not only looking at the traditionally Francis turbine with synchronous speed but also include variable speed operation with introducing double fed induction machine or converter-fed synchronous machine. Already in the 1990s, the first implementation of this technology was utilized for the reversible pump-turbines (RPT)[3].

Iliev, Trivedi and Dahlhaug[3] performed a review study with a focus on the flexible operation of Francis turbines using frequency converter or induction machine, a technology that allows one to adjust the speed of the runner. They concluded that variable-speed turbines could have improved efficiency for almost 10% at off-design for larger head variations. They also found that such turbines give a precise, faster, and smoother response to load variations, but very dependant on the hydraulic design of the runner. From the same review study, it was found that the hill-charts seem to be "stretched" towards constant guide vane opening. This means that the turbine can be operated at high efficiency over a broader range of runner speed and thus avoid the most severe pressure pulsations and flow instabilities. Despite this, one found a gap for the variable-speed technology for Francis turbines as there were little or nothing much published. However, it seemed like researchers just had started paying attention to that technology as a solution for today's challenges in the hydropower industry.

Trivedi, Agnalt and Dahlhaug[4] investigated the unsteady pressure loading in a Francis turbine operated at variable speed. For this study, 12 sensors were integrated in the turbine, four operating conditions were used, and the guide vane opening was fixed. They found that amplitudes of unsteady pressure fluctuations increase when the angular speed of the runner increases. In terms of designing a runner based on variable-speed technology, they concluded that the design needed to have a balance between the induced fatigue loading and the efficiency for the benefit of longer runner life.

3. Theory

3.1. Hydraulic efficiency and Hill-chart

In Francis turbines, the energy transfer happens due to two effects; the drop in pressure from inlet to outlet of the runner and the velocity vectors changes of direction through the channels between the runner blades[5].

Through the turbine and the generator, not all the hydraulic energy is converted to mechanical energy, and the term *turbine efficiency* is expressed as the produced power divided by the hydraulic power[6].

$$\eta = \frac{P}{P_h} = \eta_h \eta_m \tag{1}$$

The hydraulic efficiency of the turbine is defined as the ratio of mechanical power of the runner to the hydraulic power[7],

$$\eta_h = \frac{P_m}{P_h} \tag{2}$$

The mechanical efficiency is defined as the ratio of mechanical power of the machine to the runner [7],

$$\eta_m = \frac{P}{P_m} \tag{3}$$

Specific energy multiplied with mass flow gives the hydraulic power available,

$$P = E\rho Q \eta_h \eta_m = Hg\rho\eta_h\eta_m \tag{4}$$

Q is the discharge through the turbine, g is the gravitational acceleration, and ρ is the fluid density. The net head H in equation 4 is defined in IEC 60193[7],

$$H = \frac{\Delta P}{\rho g} + \frac{v_1^2 - v_2^2}{2g} + (z_1 - z_2) \tag{5}$$

The differential pressure, ΔP, is between the inlet of the turbine and outlet of the draft tube. The velocities are from the inlet and outlet, respectively, and the last term is the difference in elevation from inlet to outlet. At the rotating shaft, the power is transformed into mechanical power and can be written in terms of torque on the runner's hub and angular velocity of the turbine runner.

$$P_m = T\omega \tag{6}$$

3.1.1. Hill-chart The hydraulic efficiency can be illustrated in a Hill-chart, a diagram that provides useful information about the performance of the turbine. The IEC 60193 standard provides the procedure of how to construct the Hill-chart for a single-regulated Francis turbine and the dimensionless parameters plotted against each other at constant guide vane lines opening are given as,

$$n_{ED} = \frac{nD_2}{\sqrt{gH}} \tag{7}$$

$$Q_{ED} = \frac{Q}{D_2^2\sqrt{E}} = \frac{Q}{D_2^2\sqrt{gH}} \tag{8}$$

, where n is the rotational speed and D_2 is the outlet diameter of the runner. There is also a possibility to use the energy coefficient versus the discharge coefficient. The hydraulic energy is calculated, according to IEC,

$$E_h = g \cdot H = \frac{\Delta p}{\rho} + \frac{Q_1/A_1^2 - Q_2/A_2^2}{2} \tag{9}$$

The hydraulic efficiency is then calculated as,

$$\eta_h = \frac{\omega(T_f + T_g)}{E_h \rho_w Q} \tag{10}$$

where T_f and T_g are the friction torque and generator torque.[7]

A runaway curve is normal to include in a Hill-chart At runaway, the torque factor is equal to zero, and the efficiency therefore also is zero. Turbines are not expected to experience runaway conditions often, only a few times in their lifetime, but since it influences the lifetime significantly, one includes the curve in the Hill-chart for safety factors.[8] With all the necessary parameters, the speed factor, discharge factor, efficiency and know guide vane opening, the Hill-chart can be constructed with interpolation the values.

3.2. Pressure Pulsations

High-pressure oscillations in fluid flow is often a phenomenon that emerges when running a Francis turbine outside best efficiency point (BEP). The most common phenomena are Rotor-Stator Interactions, rotating vortex rope and von Karman vortex shedding. Rotor-Stator Interactions (RSI) cause pressure pulsation in the runner as the guide vanes create spatially varying pressure field[9]. Two phenomena are related to the RSI, blade passing frequency and guide vane frequency. Every time a runner blade passes a guide vane, a pressure pulse is generated, and the amplitude of this pulse is predominant during steady operations[10]. Pulsation with this frequency can also cause an intense sound around the turbine[11]. Pressure distribution varies from the pressure to the suction side of the runner blades, creating wakes. Pressure pulsations occur when the runner blades passing these wakes. The amplitude of this guide vane frequency is dependent on the distance between the guide vane and the runner blade, and with increasing distance, the amplitude is decreasing.[12] To find the blade passing frequency the number of runner blades and the runner rotation frequency has to be known,

$$f = \frac{n}{60} \tag{11}$$

$$f_{bp} = f \cdot Z_{bp} \cdot m \tag{12}$$

, where n are the rotational speed of the runner and Z_{bp} are numbers of runner blades. m represents the harmonic order, m = 1,2,3... The frequency of the guide vane passing is found as

$$f_{gv} = f \cdot Z_{gv} \cdot m \tag{13}$$

, where Z_{gv} are numbers of guide vanes.

In the draft tube of the Francis turbine, two velocity components are found, depending on the turbine operation, axial and tangential[13]. During steady operation conditions, there is no tangential velocity component and therefore no swirl. When the turbine is running at part load, a swirling component will move in the same directions as the runner due to a coupling between the tangential and axial velocity components. An increasing swirl number leads to a vortex rope that is visible as a swirl of vapour inside the draft tube. The amplitude of this generated frequency, when the swirl becomes visible, is known as Rheingans frequency[10],

$$f_R \cong \frac{f}{3.6} \tag{14}$$

Rheingans frequency can also be found at other operation points, but then with lower amplitude. If the swirl becomes quite intense, a negative axial velocity can be present in the centre stalled region, and a vortex breakdown may occur.

When flow separates at the trailing edge, the circulating fluid structure of vortices occurs in the wake region, also called vortex shedding. The flow will alternate between two sides of the separation point, and a swirling component will occur. Pressure pulsations with the same frequency as the formation of the swirling component is then prominent. In the Francis turbine, such phenomena occur at the trailing edge of the stay vanes, guide vanes and the runner blades. The high-frequency phenomena can be damaging over time as it leads to fatigue of the vanes and blades.[10]

4. Experimental overview

4.1. Francis Model Test Rig at NTNU

The model test is planned performed at the Waterpower Laboratory at NTNU, where the Francis model test rig is located. The test rig is installed in agreement to the international standards for model testing and consist of a pipe system, two pumps, frequency converters, motors, low-pressure tank and high-pressure tank, the turbine part itself with a generator, and upper and lower reservoir.

The turbine runner is designed for high head, and therefore a closed-loop configuration for the test rig must be used to achieve this. In this configuration, the water is pumped from the reservoir in the basement into the high-pressure tank before it is entering the turbine. Downstream of the turbine, the water flows through the draft tube and into the low-pressure tank before it goes back to the pump, without forming any free surfaces. With this configuration, the upstream pressure can be regulated to a great extent, and the downstream pressure can be regulated between atmospheric pressure and down to about 9 meters below ambient pressure. In the turbine part of the rig, the unit consists of a spiral casing with 10 stay vanes and 28 guide vanes. On the top of the turbine, a DC generator with a vertical shaft is installed, and a DC converter is connected to the generator and the power grid.

4.2. Equipment for the Model Test

Several sensors with different purposes are connected to the Francis turbine rig, making it possible to measure generator torque, friction torque, axial load, rotational speed, inlet pressure, differential pressure, dissolved oxygen content and temperature of the water, atmospheric pressure and discharge. Most of the sensors do not measure fundamental quantities like length, mass and time, and therefore requires calibration to meet the requirements for having the model test accepted, the needed level of accuracy and uncertainty.[7] The location of the sensors can be seen in figure 1 below.

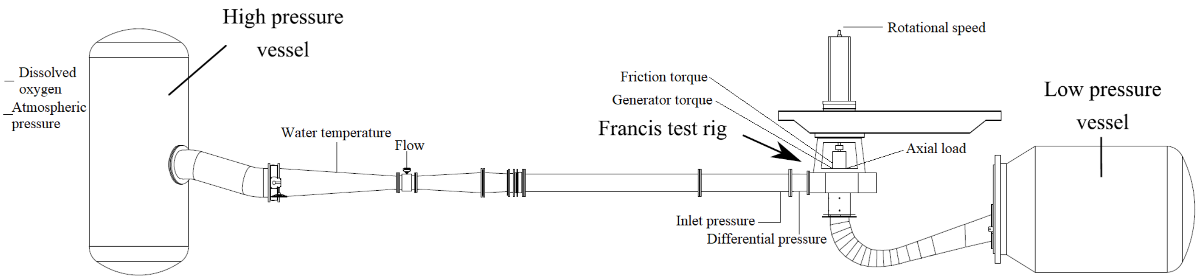

Figure 1. Francis test rig with all sensor marked, pumps and pipeline into the basement not included.

For the measurements regarding generator torque, friction torque and axial load, the bearing block plays an important role. The bearing block is where the rotating shaft and the stationary part of the rig are connected, and the main feature is to absorb radial and axial forces in the turbine. The block contains a lower and upper bearing, where the lower bearing is a double roller bearing, and the upper bearing is a double ball bearing. Oil from a hydraulic system is lubricating the bearing, controlled by a pump. Generator torque is measured with the use of the hydraulic bearing, a load cell and an arm mounted on the generator. Friction torque is important to measure despite its low impact on the total torque, and can be found in the bearings and seals. The friction torque is measured with a similar system as the generator torque, where a load cell connected to the hydraulic bearing unit absorbs all the friction in the two bearings connected to the generator axle. The axial load is measured with the use of differential pressure transducer inside the bearing block, where oil is supplied to the transducers from the two sections of the axial thrust bearing.

The rotational speed is measured by a magnetic rotary encoder located at the top of the generator. A differential pressure transducer measures the inlet pipe pressure. At the high-pressure side, the water is fed in, and at the low-pressure side, it is open to the atmosphere. In that way, one measures pressure at the inlet and removes the pressure given by the height of sensor placement. The differential pressure is measured by a differential pressure transducer connected to the inlet pipe and the draft tube. The atmospheric pressure is measured with the use of a barometer with an absolute output. Pressure pulsations are measured by using pressure transducers mounted where one expects different phenomena related to pressure pulsations to occur. For the Francis turbine, this means at the inlet, in the vaneless space and in the draft tube, respectively.

Dissolved oxygen content in the water has to be measured as it plays a major role in travelling cavitation [7]. To measure the oxygen content, an oxygen probe is mounted at the inlet of the main pump in the basement, where this probe also is connected to a digital signal converter. The efficiency of a turbine depends on the water temperature as the calculation requires the mass density of the water. The temperature is measured using a temperature probe with an internal amplifier/signal converter. The probe is mounted downstream of the high-pressure tank.

The discharge is measured between the inlet at the turbine and the pressure tank with an electromagnetic flow-meter. The working principle is that the conductive fluid moves across the magnetic field resulting in an induced voltage in the conductor. The velocity of the fluid is proportional to the magnitude of the voltage. An electromagnetic flow-meter is very sensitive to gas in the flow and extra attention should be paid to venting the pipes before tests.

All the sensor for use in the model test is connected to a general logging program in LabVIEW. The raw data will be logged, also the ones for the calibration, and saved into TDMS-files or HTML-files which easily can be imported in Matlab and processed.

4.3. Measurement Procedure and Processing

Measurements will be done for guide vane opening from 1 degree to 14 degree opening, which is the maximum allowable opening at the Waterpower Laboratory. The rotational speed and discharge will be adjusted for each guide vane opening, making an unstructured grid with all the raw data. For the runaway curve, the turbine will be decoupled from the generator to obtain zero torque. The Hill-chart will be constructed by interpolating the unstructured grid, preferable is a bi-harmonic spline interpolation not based on triangulation. This will make smooth ISO-curves and an easily seen top-hill. By increasing the number of measurements around the seen top-hill, one can manage to have a higher resolution of the BEP. A VSO-curve is desired to implement in the Hill-chart for the purpose of illustrating the highest possible efficiency for any operating condition. For synchronous speed, this will be seen as a straight line from BEP at the associated speed factor. This is illustrated in figure 2, where the Francis99-runner have been used in the experiment. For this figure, the speed has been optimized to achieve the red VSO-curve.

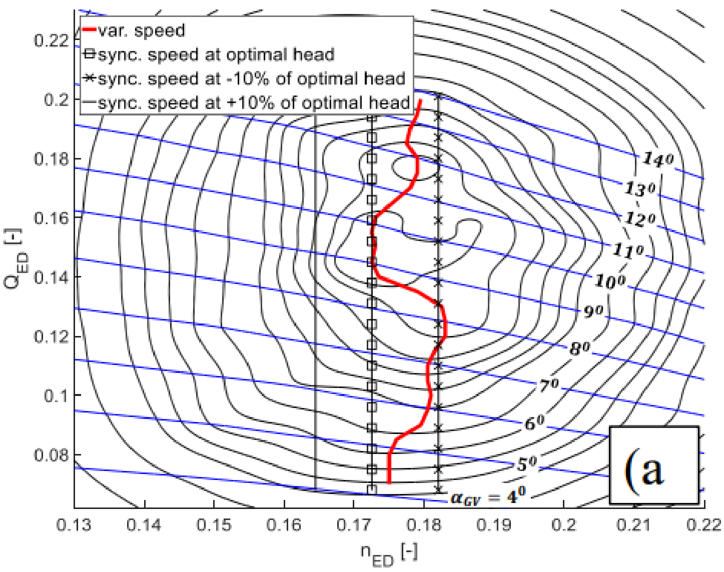

Figure 2. Hill-chart for Francis99 [14].

Analyses of the pressure pulsations data will be conducted in Matlab with the built-in function Power Welch method. The working principle for that function is to use a Discrete Fourier Transform (DFT), meaning that the periodic signal will be transported from the time domain to the frequency domain. The transformation makes it possible to identify the different frequency components of a time signal and represent complicated functions by sine and cosine expressions. For the reason to avoid spectral leakages, the Power Welch method with the use of Hann windows is preferably to use as it is splitting the series into several smaller windows and makes the windows overlapping. For each of the window, a DFT is conducted and the overlapping windows are averaged.[10]

The results from the pressure pulsations analyses can be combined with the Hill-chart to illustrate the pressure distribution for each of the operating points, and also with the axial load towards the n_{ED} and Q_{ED}.

5. Discussion and conclusion

The model test of the new Francis turbine runner is planned performed for the purpose of comparing the results with the numerical simulations and verify them. For that to happen, the model test has to follow the international standard for model acceptance tests *Hydraulic turbines, storage pumps and pump-turbines - Model acceptance tests* and the uncertainty has to be in between certain limits. To see the impact of designing a turbine runner to accommodate variable-speed operation it can be useful to compare the results with existing results for synchronous-speed operated turbines, as the Francis99-runner where the Hill-chart in fig 2 also includes the VSO-curve.

In the process of constructing the Hill-chart and to implement the VSO-curve, perhaps more measurements must be performed to have high enough resolution around where the curve will fit in. The curve will demonstrate the highest efficiency for the different operation points, and increasing the measurements around where these are expected perhaps will give a more presentable curve.

Conclusively, the plan for the model test is in accordance to the IEC60193 standard. The limits for accuracy and uncertainty need to be fulfilled to have the model test accepted. When completed, the results can be compared to the numerical simulations and perhaps be verified. For the interest to see how a Francis turbine designed for VSO behaves compared to a synchronous one, the results also can be compared to for example the Francis-99 runner. Finally, the results from the model test should be discussed with the interest of the design.

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