1D simulation of pump-turbine transition

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Abstract. Variable speed motor-generators based on full size converter offer new options for operation of reversible pump-turbines. To explore the challenges related with this new technology a specific test rig configuration is developed to perform such transition with a PT reduced scale model. Transition from pump to turbine and vice versa are performed with various guide vanes opening and transition time. In order to extrapolate the results obtained at model scale to prototype, it is important to understand the system behaviour including the waterways and its influence on the flow in the pump-turbine. For this purpose, a 1D model of the test rig is realised. After validation with measurement results, the 1D model has been used to test the influence of the waterway on the pump-turbine transition.

1. Introduction
Variable speed motor-generators based on full converter solutions offer new options for operation of reversible pump-turbines (PT) [1], including fast transition from pump to turbine mode, where the pump is operating in pump-brake mode for a while. To explore the challenges related with this new technology a specific test rig configuration is developed to perform such transition with a PT reduced scale model. Transition from pump to turbine and vice versa are performed with various guide vanes opening and transition time. Dynamic pressure sensors have been installed to capture transient flow phenomena and various mechanical components have been instrumented to evaluate their loadings. In order to extrapolate the results obtained at model scale to prototype, it is important to understand the system behaviour and its influence on the results. For this purpose, a 1D model of the test rig is realised. After validation with measurement results, the 1D model can be used to verify the influence of various parameters on the transition [3].

2. Experimental setup and results
The measurements have been carried out on the universal test rig at ANDRITZ Hydro GmbH in May 2015. A PT model of specific speed NQE=0.17 (nSQ=207) with Zs=24 guide vanes and Zr=7 runner blades was selected for the test. At prototype scale, the machine head is determined by the level difference between upstream and downstream reservoir, the losses in the hydraulic circuit and the fluid acceleration during transitions. For the reduced scale model, a pump is used to deliver the head. The available head is therefore strongly dependent on the discharge through the pump-turbine. For this reason, a specific test rig configuration, see Figure 1, is used in order to perform the full transition with realistic head.
Figure 1. Test rig configuration for pump-turbine transition

The pump-turbine reduced scale model is mounted in parallel with a pump and a diaphragm made of a perforated plate. The head losses through the diaphragm are proportional to the discharge. In pump mode, the discharge of both pump and pump-turbine flows through the diaphragm. In turbine mode, part of pump discharge flows through the pump-turbine, the other part through the diaphragm. The head is adjusted by varying the pump rotating speed. During transitions, linear speed ramps are imposed to both the pump-turbine and the pump using variable speed electric motor-generator. With this alternative test rig configuration, the transition as seen from the pump-turbine is close to the transition at prototype scale. The head variation is mainly driven by the fluid acceleration within the pump turbine branch of the circuit.

In addition to the standard model test instrumentation, dynamic pressure transducers are installed in the rotating and stationary parts of the turbine. Strain gauges are installed on guide vanes stems and turbine shaft for torque measurement. A dynamic flow meter is used to record the discharge variation. Measurements have been performed at constant guide vane opening for various transition time, guide vane opening, cavitation level and head. More details regarding the experimental setup and results can be found in [2].

The transition tests have been performed for the following guide vanes and transition times:
- Guide vanes openings: 5°, 15° and 25°;
- Transition time: 4 s, 8 s, 12 s, 20 s.

In this paper the focus is placed on the integral quantities which are considered in the 1D model. The head is computed using the pressure difference between turbine inlet and outlet. Dynamic pressure sensors are used to capture the transient pressure as well as the fluctuation related to turbulence.

The mechanical torque is measured using an instrumented shaft equipped with strain gauges. Due to instrumentation failure during the measurement campaign, torque records are not available for the final measurements. Fortunately torque records from preliminary measurements are available for most of the operating conditions.

The discharge is measured using a MID flow meter. The nominal time constant of the instrument is 0.07s; preliminary measurements shown that the actual time constant is much larger. Additionally the high frequency flow meter shows drop-outs from a few tenths of seconds to seconds, it was found that this was related to small quantities of air being convected in the test rig. The presence of those bubbles in the flow meter stopped the acquisition of valuable values. In this case, the analogue output of the flow meter that was connected to the acquisition system remains at a constant value until the flow meter goes to normal operation again.

Using pressure difference between sensors located in the discharge measurement section, it is possible to estimate the time constant of flow meter. According to the momentum equation, the time derivative of discharge is proportional with the pressure difference along a pipe section. The best fit between measured discharge (using flow meter, red line) and computed discharge (using pressure sensors, blue line) is obtained assuming a delay of the flow meter of 0.5-0.6s. Example is given in Figure 2 for a 4s transition.
To facilitate the comparison of the simulations with the measurements, all measured signals have been resampled at 100Hz.

Figure 2. Evaluation of flowmeter delay based on pressure difference

3. 1D simulation model
An equivalent 1D model of the test rig has been prepared using the simulation software SIMSEN, see Figure 3. The model includes:
- The water inertia of the entire circuit;
- The PT (FTURB);
- The pump (PUMP02) characteristics.

Due to the complexity of the junctions, the head losses have been determined a posteriori to fit with the measurements. All head losses are aggregated per branch; LOSS_PT for the PT branch, LOSS_P for the pump branch; DLOSS for the perforated plate branch. Analysis of the measurements shows that the losses are influenced by the cavitation level in the circuit. Most probably, the cavitation level in the wake of the perforated plate is the major driver of this phenomenon.

Figure 3. 1D equivalent model of the test rig

3.1. Validation of 1D model
Simulation is compared with measurement for 8s transition in Figure 4. Fair agreement is found for all variables. The pressure peak amplitude and timing is well predicted, as shown later the amplitude depends mainly on the water inertia. Considering a delay of 0.5s for the measured discharge, good agreement is observed between simulation and measurement. The flow meter drop-out is clearly visible at 21-22s, the measurement is not relevant during this period of time. The predicted torque is also in good agreement with the measurement except at the end of the transition from turbine to pump. From ~22s when the nominal rotating speed is reached the torque is over predicted in the simulation. This effect is observed for all transition time. The strong torque fluctuation observed during the transition is due to the stepwise rotating speed induced by the frequency converter. This effect is not considered in the simulation. The imposed rotating speed is used to synchronize the simulations with the measurements.
3.2. Parameter study on water inertia

Various circuit configurations have been simulated in order to assess the influence of the different elements of the circuit on the pump-turbine transition. To isolate the effect of the pump, a simulation is performed assuming constant pressure at both end of the pump-turbine branch, see Figure 5. This situation corresponds to an ideal pump providing constant pressure independently of the discharge.

To evaluate the influence of the water inertia in the circuit, Setup3 corresponds to Setup 2 as shown in Figure 5, but the lengths of all pipes are divided by 2; the inertia of water inside the turbine remains unchanged. Finally during transient, the pressure difference between inlet and outlet of the pump-turbine or head is due to the quasi-static head on one hand and to the fluid inertia inside the turbine on the other hand. This inertia component induces a deviation from the characteristic curve especially during fast transient, the quasi-static head being the head measured during steady state operation.

To evaluate the influence of the different parameters, the results of the 3 setups are compared in Figure 6 for the head, discharge, torque and trajectory in the n11-Q11 diagram.

The influence of the pump is clearly visible in the head. In the pump turbine, the flow inversion takes place at the beginning of the transition from pump to turbine. Inversely for the transition from turbine to pump, the flow inversion takes place at the end of the transition. On the pump side, the rotating speed and resulting head changes continuously during the 12s transition leading to low head at the end of the transition from pump to turbine and at the beginning of the transition from turbine to pump. The water inertia has a direct influence on the transition speed; this is visible in the discharge. The flow inversion for shorter circuit (green line) is faster than for longer circuit (blue line).

The influence of water inertia in the turbine is visible in the n11-Q11 diagram. For fast transition, deviation from the quasi-static characteristic curve (black line) is observed; this deviation is due the influence of water inertia inside the turbine on the turbine head. In this study, this inertia is estimated based on the turbine geometry.
Figure 6. Discharge, Torque, Head and trajectory in n11-Q11 diagram during 12s transitions, influence of water inertia

4. Conclusion and outlook
1D transient simulation has been performed for a speed controlled transition from turbine to pump and vice-versa. The results are compared with experimental results obtained on reduced scale model. The 1D model help to better understand the relation between experimental results obtained at model scale and actual prototype behaviour. The influence of the specific test rig configuration on the transient head is clearly shown. The influence of the water inertia in the pump-turbine branch is analysed. Its effect on the transition speed is enhanced. The water inertia limits the transition speed and increases the pressure spike during transition.

In the present experiment, the head varies quasi-linearly with the pump speed during the entire transition. This leads to some deviation with respect to the theoretical case with constant head at circuit boundaries. For future work an interesting improvement would be to control the pump speed with the measured pump-turbine head in order to achieve a more realistic transition such as load rejection with surge tank oscillations expected on the prototype.

5. References
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