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Experimental investigation of a FSFC variable speed pump-turbine prototype - Part1: penstock fatigue reduction and fast active power regulation

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Abstract. The Z'Mutt pumping station is located in Canton Valais-Wallis, in Switzerland and is part of the Grande Dixence hydroelectric scheme. The unit 5 of this station has recently been upgraded with a 5 MW variable speed reversible Francis pump-turbine equipped with Full Size Frequency Converter, FSFC, allowing the unit speed to be adjusted from -100% to +100%. This paper presents the methodology based on 1D numerical simulations including CFD/FEM runner damage hill chart to optimize the turbine start-up sequence to minimize both runner and penstock fatigue by taking advantage of the FSFC variable speed technology. FSFC allows for precise start-up trajectories in the n11-Q11 frame, to avoid runner high damage operating points, while reducing penstock pressure variations as compared to a classical fixed speed technology. This methodology resulted in the definition of 6 different FSFC start-up sequences, as well as the classical fixed speed start-up, which have been successfully implemented and tested on site. Site tests of fast transition from turbine to pump and vice versa are also showcased. Finally, fast active power regulation tests performed in pump mode are presented to show the ability of FSFC variable speed technology to provide ancillary grid service in pump mode.

1. Introduction

One of the key objective of the XFLEX HYDRO H2020 European project is to increase the flexibility of Hydro Power Plants (HPP) with respect to the provision of several Electric Power Systems (EPS) services, [1]. In this context, the XFLEX HYDRO demonstrator of Z'Mutt was selected to showcase that variable speed technology can play an important role by providing a variety of ancillary services through its operational flexibility, enabling quick active power response time and large and efficient energy storage capability, [2], [3], [4]. The Z'Mutt pumping station is part of the Grande Dixence hydroelectric scheme located in Canton Valais-Wallis, in Switzerland. The unit 5 of this station has recently been upgraded with a 5 MW variable speed reversible Francis pump-turbine equipped with Full Size Frequency Converter, FSFC, allowing the unit speed to be adjusted from -100% to +100%. This paper presents the methodology based on 1D numerical simulations including CFD/FEM runner damage hill chart established to optimize the turbine start-up sequence to minimize both runner and penstock fatigue by taking advantage of the FSFC variable speed technology [5], [6], [7], [8]. Since FSFC enables the unit rotational speed to be driven simultaneously with guide vane opening during the turbine start-up sequence, it allows for precise start-up trajectories in N11-Q11 frame, defined to avoid runner high damage operating points, while at the same time reducing penstock pressure variations as compared to a classical fixed speed technology, [9], [10], [11]. This methodology resulted in the definition of 6 different FSFC start-up sequences [8], as well as the classical fixed speed start-up, which have been successfully implemented in the Z'Mutt Unit 5 controller and tested on site. Thanks to the extensive instrumentation deployed during the measurement campaign, including dynamic pressure transducers and strain gauges on both rotating and stationary frame, it was possible to assess and compare dynamic performances of each start-up sequence regarding penstock and runner fatigue. Results of penstock fatigue reduction are presented in part 1 of the paper, while runner fatigue reduction is presented in part 2 of the paper. Site tests of fast transition from turbine to pump and vice versa are also showcased. Finally, fast active power regulation tests performed in pump mode are presented to show the ability of FSFC variable speed technology to provide ancillary grid service in pump mode.

2. Z'Mutt power plant demonstrator

The Z'Mutt Pumping Station (PS) located in Canton Valais-Wallis, in Switzerland. is equipped with two 30 MW pump units (U1, U2), two 14 MW pump units (U3, U4) and one 5 MW reversible pump-turbine unit (U5), see Figure 1,. The new unit U5 is equipped with an asynchronous motor-generator driven by a FSFC. The pump-turbine features a specific speed of Nq = 54 and a mechanical time constant of τ_m=1.3 s, see main characteristics given in Table 1.

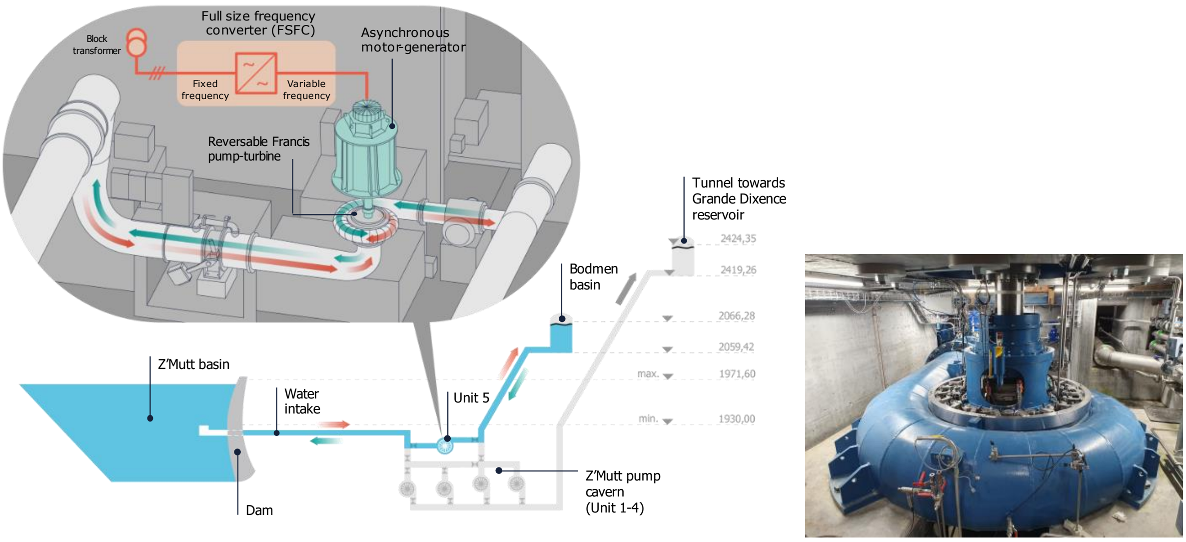

Figure 1: Layout of the Z'Mutt pumping station (left) and new unit 5 photography (right).

Table 1: Hydraulic and mechanical characteristics of unit U5 in pump mode.

Data		Unit	Value
Nominal flow rate	Qn	$m^3 \cdot s^{-1}$	3.6
Nominal head	Hn	mWC	115
Nominal rotational speed	Nn	min^{-1}	1000
Nominal mechanical power	Pn	MW	4.5
Specific speed number	Nq	-	54
Mechanical time constant	τ_m	s	1.3

3. Turbine mode start-up optimization method

3.1. Optimization approach

FSFC technology enables the avoidance of a fixed-speed start-up that typically involves speed-no-load operation which are known to induce significant Francis runner fatigue damage, [10], [11]. Previous research indicates that using a speed controller is more advantageous to ensure unit stability compared to a power controller during turbine mode start-up, [7]. Consequently, a speed controller is employed for the start-up control in this case.

Figure 2 presents the overview of the methodology to perform the optimization of the turbine mode start-up sequence for the Z'Mutt Francis pump-turbine. The optimization process, which is fully described in [8], is utilizing 1D transient simulations, to address several objectives, including optimizing efficiency of the hydraulic machine by following the Best Efficiency Point, BEP, minimizing runner damage, and reducing fatigue on the penstock.

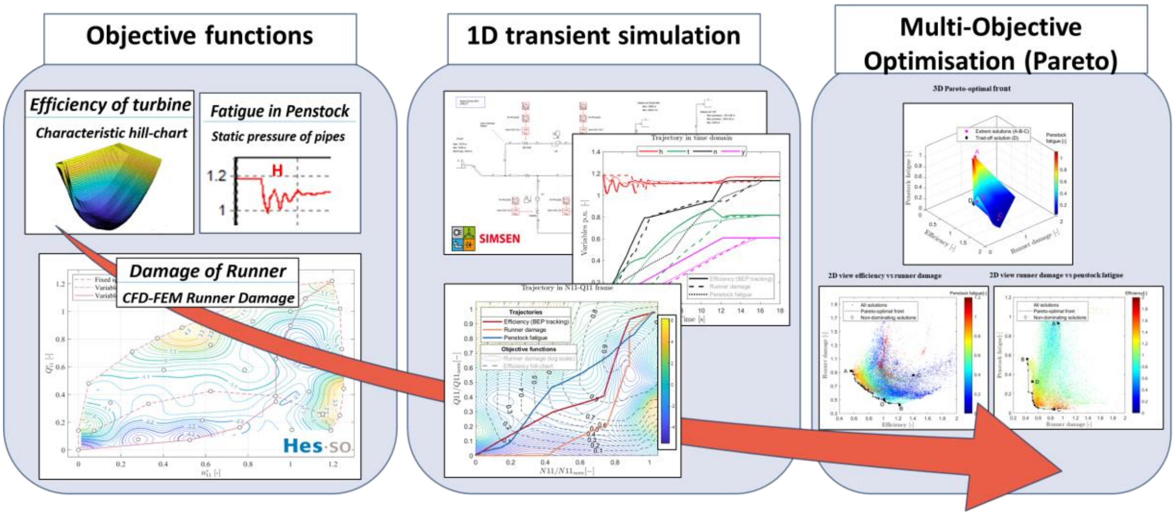

Figure 2: Overview of the methodology for the turbine mode start-up optimization.

The evaluation of the objective functions is performed with a numerical model of the Z'Mutt PS, using the SIMSEN software, [12]. The model is implemented, calibrated, and validated with comparison between site measurements and numerical simulations of transient events. The model includes the complete hydraulic circuit comprising reservoirs, pipes, valves and the five units U1-U5. The simulation start-up sequence is driven with rotational speed and guide vanes parameters to reach the power set point.

In the present study, three main objective functions to be minimized are defined as follows: (i) the unit efficiency , (ii) the runner damage and (iii) the penstock fatigue. An additional constraint function is used as penalty, to avoid energy consumption from the grid during the start-up sequence. A runner damage hill-chart deduced from coupled FSI simulations using full CFD and FEM models of the pump-turbine, [13] is used to quantify runner damage. The penstock fatigue functions minimize the penstock pipe wall stress variation induced by the pressure fluctuations in the hydraulic scheme during the transient events. The cumulative damage on the penstock segments is computed with the static pressure thanks to the 1D transient model simulation results. Once the static pressure is converted into a stress according to the hoop stress equation rain flow counting algorithm is applied to determine the cumulative damage is calculated using Palmgren-Miner's rule in accordance with ref. [14] as follows:

$$D = \sum_i \frac{n_i}{N_k}\left(\frac{\sigma_i}{\sigma_f}\right)^m$$

with D the damage tally, n_i the number of cycles accumulated, N_k the endurance limit number of cycles to failure at 2×10^6 cycles, σ_i the stress range, σ_f the corresponding endurance limit stress range at 2×10^6 cycles and the exponent m related to the type of weld between the pipe segments

3.2. Selected start-up sequences for site tests

The projective simulations of the 6 start-up sequences to be tested on site with the variable speed technology, which sequences are generated either from a predefined trajectory or through the optimization process with different targets, are illustrated in Figure 3.

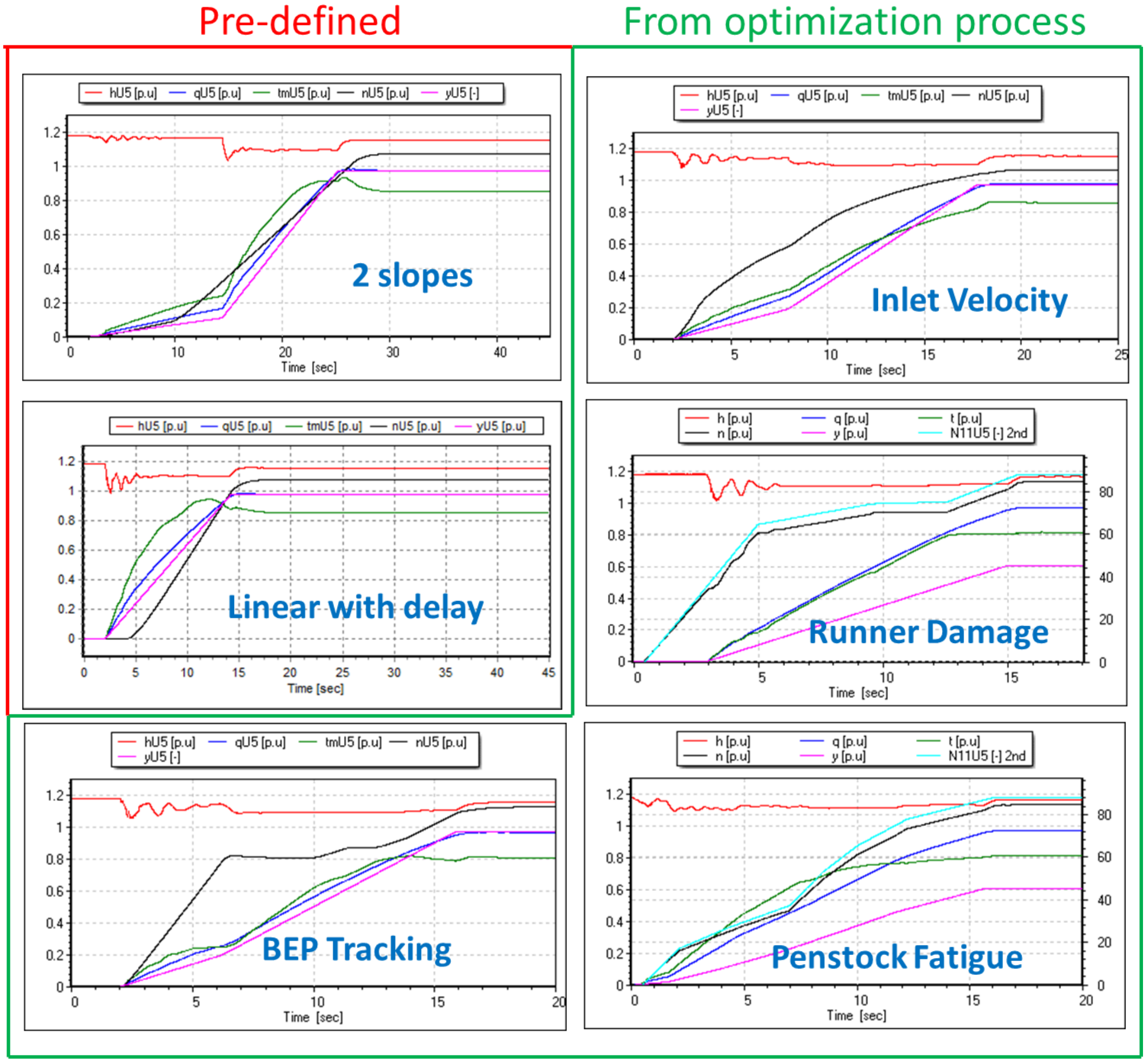

Figure 3: Simulation results of the 6 different FSFC driven variable speed turbine mode start-up and loading sequences (where h: head, q: discharge, t: torque, n: speed, y: GVO).

The denomination of the start-up sequence is selected in accordance with the specific objective function employed during the optimization process:

- The **"2-slope"** sequence, made of two linear speed increases and two linear GVO increases, is a predefined trajectory that is implemented for the commissioning of the unit with the aim to approximate the BEP tracking trajectory, with a simplified implementation;
- The **"Linear"** sequence corresponds to a linear GVO increase and speed increase. This is a predefined trajectory which has the advantage of being easy to implement and enable very fast start-up;

- The **“BEP Tracking”** sequence is the results of the optimization using the efficiency as objective function. It aims to find the trajectory passing through the local best operating point;
- For the **"Inlet velocity"** trajectory, the rotational speed of the unit is adjusted to maintain optimal angle of attack at the blade leading edge;
- The **“Runner damage”** sequence is the result of the optimization aiming to minimize the runner’s damage induced by the start-up sequence and is based on runner CFD/FEM damage hill-chart;
- The **“Penstock fatigue”** sequence is the result of the optimization aiming to reduce water hammer-induced penstock fatigue.

Figure 4 presents the **“Fixed speed”** sequence of the start-up of the unit 5 of Z’Mutt that would correspond to the case where the unit 5 of Z’Mutt would have been equipped with a conventional fixed-speed motor-generator, which serves here as a baseline sequence to be compared with the optimised variable speed sequences. In this fixed speed unit start-up sequence, the unit is accelerated up to the nominal speed, followed by a synchronisation phase assumed to last only 15 s, which is rather an optimistic hypothesis, followed by load acceptance.

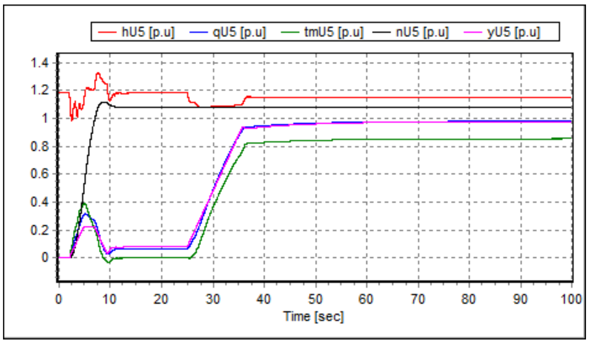

Figure 4: Simulated classical fixed speed turbine mode start-up.

4. Experimental on-site test results

4.1. 1D numerical model validation

Hydro-Clone® is a "Real-Time Numerical simulation Monitoring" system, which is built on a numerical SIMSEN model of the hydropower plant to simulate and replicate in real time the dynamic behaviour of the hydraulic scheme, *i.e.*, a physics based digital twin for hydro power plant transients monitoring, [15]. The numerical model is updated in real time with the power plant's actual boundary conditions to reproduce its transient behaviour. This system was used for an efficient and effective transient monitoring during the transient tests performed at the Z’Mutt pumping station. An example of a sequence monitored in real time during the commissioning phase is shown in Figure 5, with turbine mode start-up of unit 5, followed by an emergency shutdown. As it can be seen, the pressure simulated at the Main Inlet Valve (MIV) corresponds very well with the measurement, as well as the evolution of the rotational speed of the unit when the circuit breaker opens. The start-up sequence considered during the commissioning phase was a simplified version of the 2 slopes sequence which was originally achieved within 30 s from standstill to full load, which is already remarkable start-up performance significantly faster than any synchronous unit start-up.

4.2. Turbine start-up sequences

The new start-up sequences implement on-site in the unit controller were closely monitored by Hydro-Clone, as shown in Figure 6 for variable speed start-up and in Figure 7 for the fixed speed start-up. As it can be seen, all the planned trajectories have been successfully implemented and tested on the prototype. The start-up sequences are represented using the speed and opening of the guide vanes, together with the corresponding pressure measured and simulated upstream of the MIV valve. It is noticeable that some of the start-up sequences measured on-site presented in Figure 6 differ to the predictive start-up sequence presented in Figure 3. Indeed, the temporal evolution of opening and rotational speed parameters can vary in their implementation due to technical constraints of the electromechanical equipment. Nevertheless, it was possible to ensure the trajectory in the n11-Q11 reference frame thanks to the start-up sequence implementation in the unit controller using a GVO/rotational speed/net head look-up table. Moreover, it could be highlighted that the linear start-up sequence was performed within 16 s from standstill to full load which is again remarkable start-up performance. A comparison of the start-up trajectories in the n11-Q11 reference frame, comparing the predictions of the 1D model on the left with the actual performance on site on the right is given in Figure 8. This comparison provides an overview of the good concordance between the simulated and start-up trajectories measured on-site, demonstrating that the different trajectories implemented pass through different areas of the n11-Q11 map, depending on the optimisation objective being pursued.

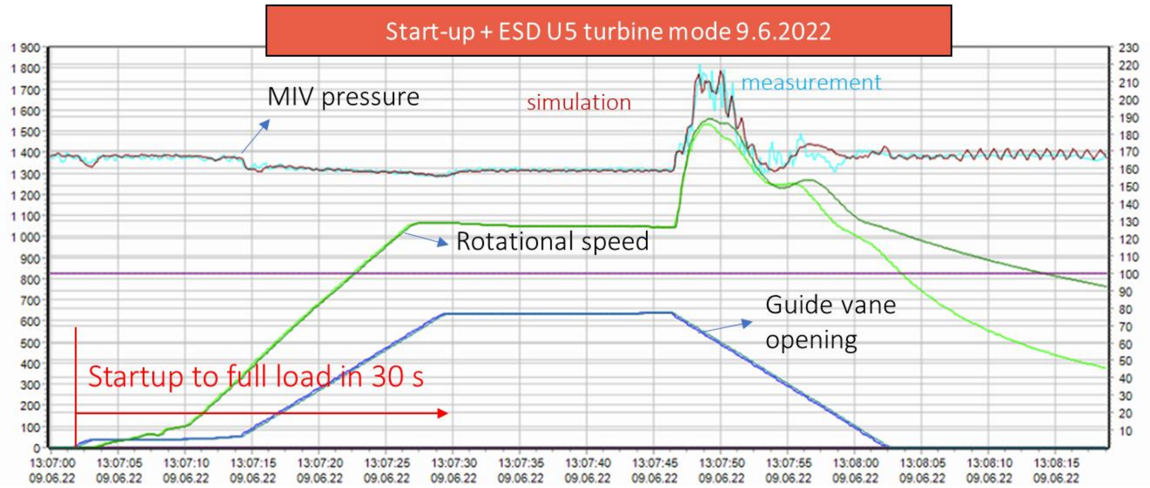

Figure 5: Comparison of experimental on-site test results with numerical simulation performed in real-time during turbine mode transient test of 2 slopes variable speed start-up and loading performed in 30 s followed by emergency shutdown.

The primary outcome from the field tests, illustrated in Figure 9, presents the cumulative relative damage at the penstock upstream of the MIV of the unit 5, comparing simulation and measurement of the various start-ups sequences. The first observation is that the comparison highlights a close alignment between the simulations and the measurements of cumulative damage at the MIV. While the overall trend of the observed relative cumulated damage is alike between the measurement and simulation, the simulation tends to slightly overestimate the damage in most of the start-up sequences.

The significant finding highlights that the conventional start-up scenario, using a fixed-speed technology, yields notably greater relative cumulative damage compared to all variable-speed start-up scenarios. In terms of the pressure fluctuation measurements, the use of variable-speed technology significantly decreases the penstock damage by factor of 4 in contrast to the conventional fixed-speed start-up. The cumulative damage using measured signals shows very close equivalence for all variable-speed sequences. It should be mentioned that the boundary conditions of the simulations are the on-site parameters, i.e. the simulations diverge slightly from the target optimization prediction. In particular, small and slow guide vane position movements were difficult to achieve experimentally, and thus represent a potential for improvement and further penstock fatigue damage reduction. This explains why the optimized fatigue trajectory is not the best of the different trajectories, according to the small divergences explained above.

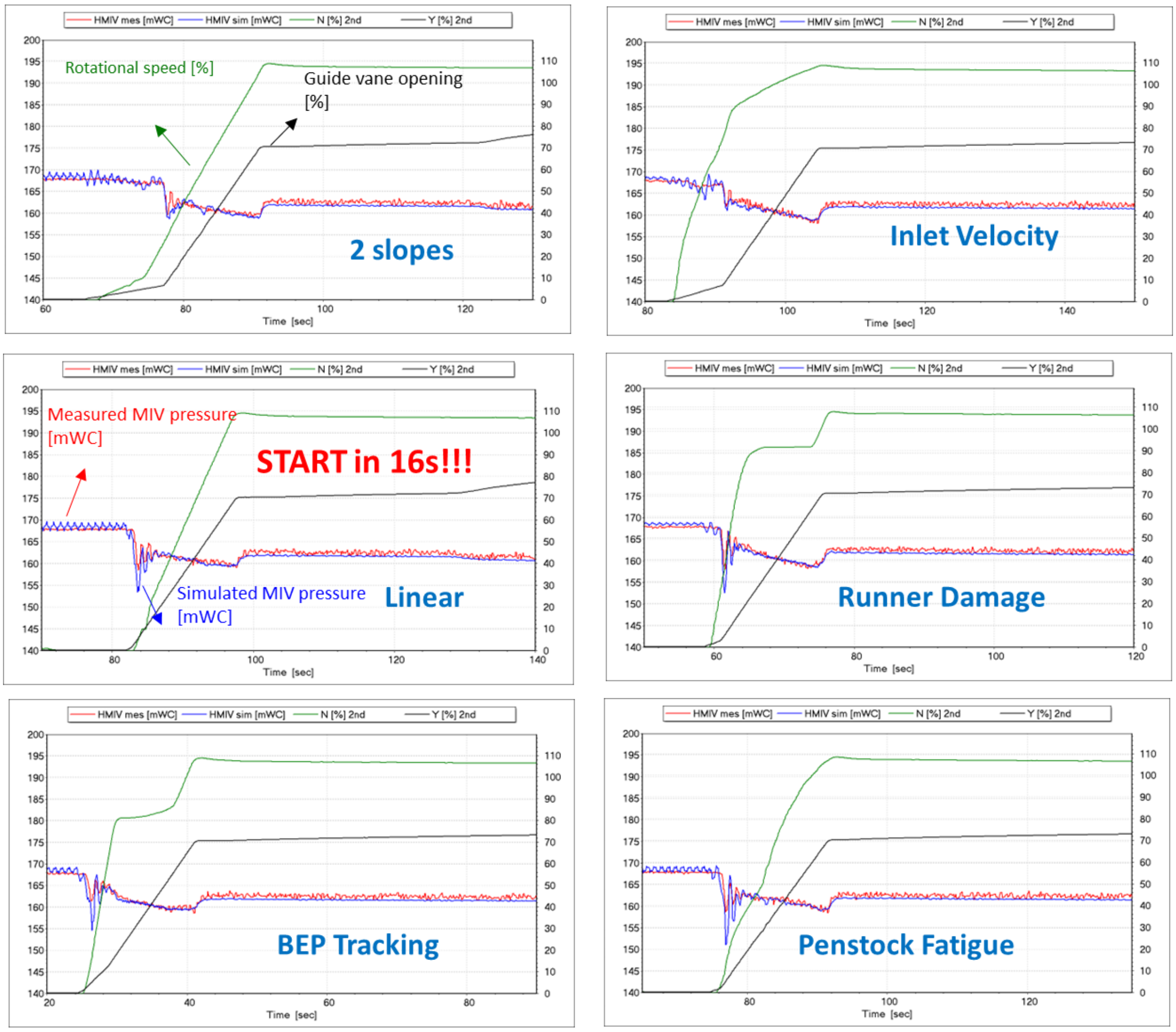

Figure 6: Comparison of experimental on-site test results with numerical simulation during turbine mode transient tests of the 6 different FSFC driven turbine mode start-up and loading sequences.

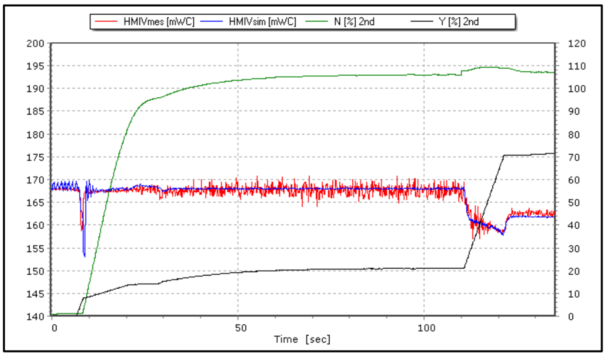

Figure 7: Comparison of experimental on-site test results with numerical simulation performed in real-time during turbine mode transient test of classical fixed speed start-up and loading sequence.

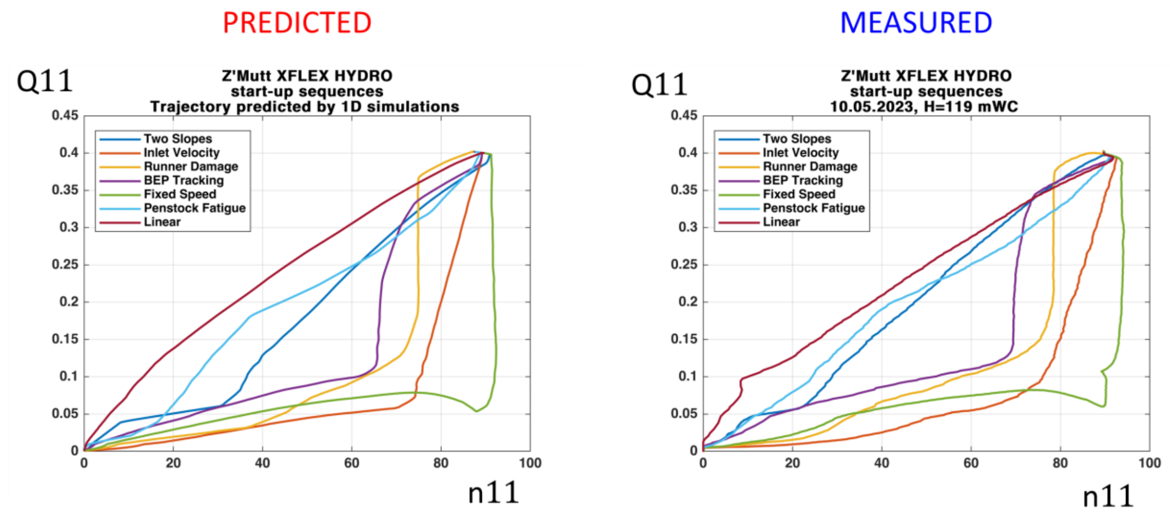

Figure 8: Comparison of start-up trajectories in the n11-Q11 reference frame as predicted by the 1D model (left) and performed on-site (right).

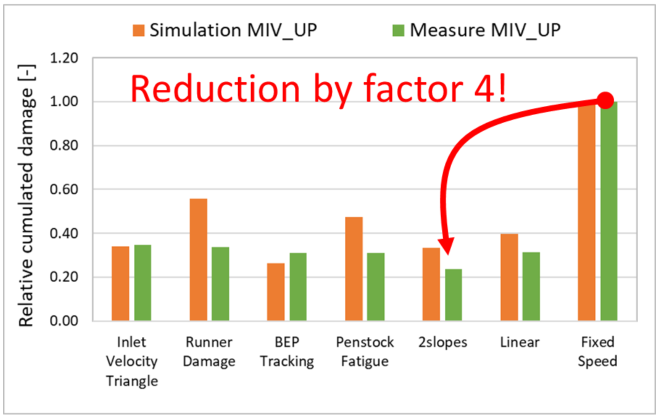

Figure 9: Comparison of the relative cumulated damage in the penstock at the upper position of the MIV between the simulation and the measurement of the on-site test start-ups. The value is normalized by the maximum value obtained with the fixed-speed technology.

4.3. Fast mode transitions

The Full-Size Frequency Converter enables a swift transition from turbine to pump mode, optimizing operational flexibility and responsiveness. Whereas in the case of a transition from pump to turbine, the natural flow direction of the water supports the transition, the case of a transition from turbine to pump is more demanding and requires all the flexibility offered by the FSFC.

A fast pump-turbine transition sequence, showcasing the time evolution of the pump-turbine transient during on-site testing monitored with Hydro-Clone, is depicted in Figure 10 left. The corresponding trajectory of the operating point in the n11-Q11 reference frame is depicted on the right, providing a comprehensive visual representation of the operating point during transitions between turbine and pump modes. In this case, the rapid transition simply consisted of combining a normal stop sequence with a normal start. A 70-second transition can be achieved without difficulty for both transitions. It's worth mentioning that, similarly to the turbine start-ups that are optimised, this type of transition could be further improved to find the fastest and least load-intensive sequence for the unit.

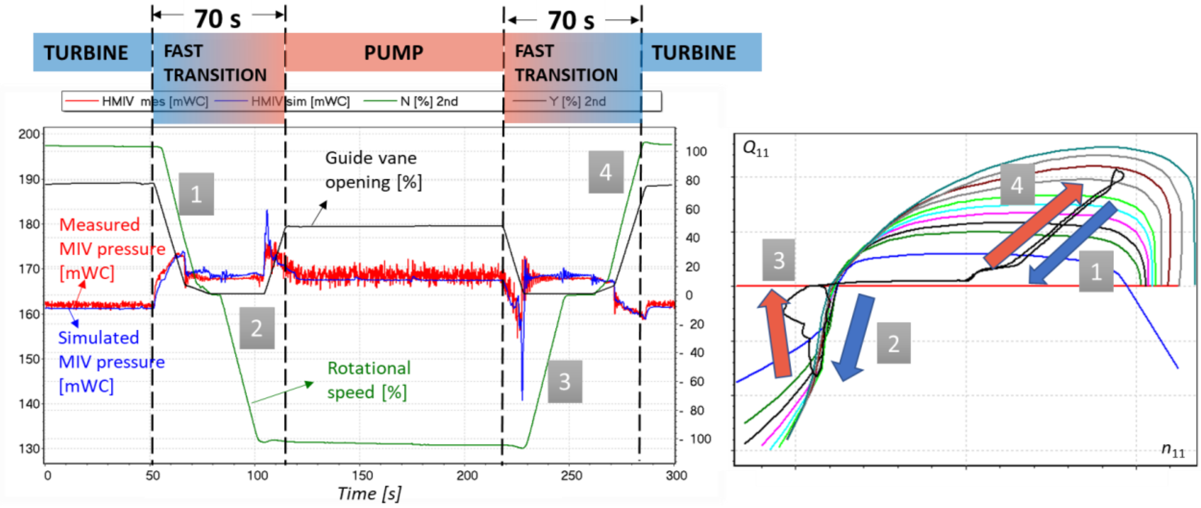

Figure 10: Fast pump-turbine transition sequence from turbine mode to pump mode and vice versa. Left: time evolution of the pump-turbine transient as tested on site and monitored with Hydro-Clone. Right: Corresponding trajectory of the operating point in the n11-Q11 reference frame.

4.4. *Fast active power control in pump mode*

To perform fast active power control variations in pump mode, the FSFC is set in speed regulation mode, which setpoint results from the speed optimizer lookup table. The input power is mainly driven by the rotational speed of the unit which is quickly driven by the FSFC. The change of guide vane opening to respond to an input power set point change is aiming to maximise the pump's efficiency.

The on-site tests of fast power regulation in pump mode monitored by Hydro-Clone are shown in Figure 11. As it can be seen, with the FSFC, the pumping power can be adapted quickly with two jumps of ± 0.18 MW, representing 4% of Pref, followed by a jump of 0.465 MW and 0.33 MW, representing variations of respectively 10.3% and 7.3% of the reference power. It should also be noted that the measured power is subject to noise, so that for small jumps in power, the value simulated by Hydro-Clone is a valuable aid to understanding the behaviour of the unit.

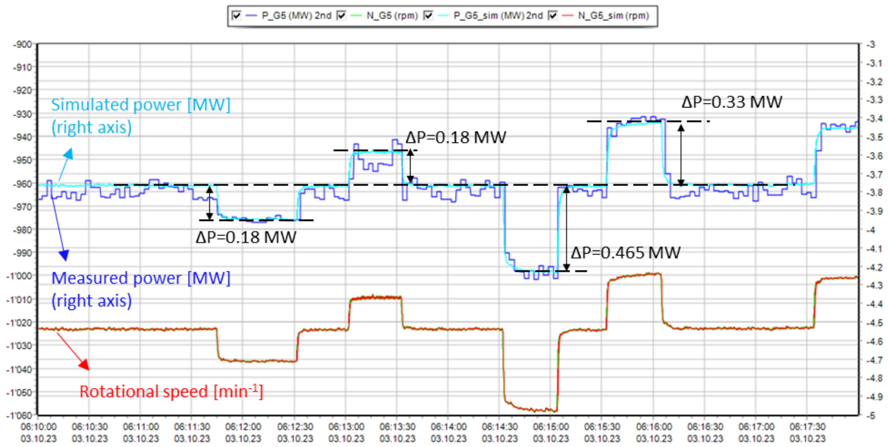

Figure 11: On-site test of fast power regulation in pump mode and monitored by Hydro-Clone.

5. Conclusion

Six variable-speed start-up sequences have been determined by 1D and 3D numerical simulations and multi-objective function optimization, then implemented and tested on-site and compared with a fixed-speed sequence. All the 6 variable speed turbine mode start-up sequences measured enable to significantly reduce the penstock fatigue with a maximum reduction of factor of 4. Fast transition between pump and turbine mode, and vice versa are successfully implemented and tested at site and evidence the possibility to perform such a transition in 70 s thanks to the FSFC technology for both directions. Finally, the tests also confirmed the capability of the variable speed technology to regulate pump power efficiently. The results indicate a significant reduction in both runner damage that is detailed in part 2 of the paper, see [16], and penstock fatigue. The methodologies developed here on a 5 MW variable speed reversible pump-turbine are directly applicable to other large variable speed reversible pump-turbines equipped with Full Size Frequency Converter. The use of FSFC technology leads to an increased operational flexibility through (i) an increased number of unit starts and stops thanks to optimised start-up sequences minimizing runner and penstock fatigue, (ii) fast turbine to pump mode transitions and vice-versa, and (iii) fast power regulation capability and the possibility to provide new ancillary services such as Fast Frequency Response (FFR) and Inertia Emulation (IE), [17].

6. Acknowledgements

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