Assessments of hydropower plants start-up sequences and equivalent runner damage under transient operation

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Abstract. With the increasing share of renewables in the electricity market, hydropower plants (HPP) are increasingly operated in off-design conditions including frequent start-up and shut-down maneuvers as well as repeated large variations of power set-points. With specific reference to the HPP start-up sequence, the conventional process requires to operate the runner in a particular operating regime called Speed-No-Load (SNL) that is detrimental for the runner. Thanks to last decade's improvements in MW-class power electronics, new generators' technologies have emerged providing an additional degree of freedom to HPPs control. In this respect, the control of the hydraulic turbine speed can be used to decrease the level of damage induced on the runner by choosing the appropriate trajectory for transient operations such as start-up and stop. Variable speed is a recent technology and its capability to improve the transient operation of hydraulic machines is not fully addressed in literature and, specifically, for start-up sequences. To fully take advantage of such an added degree of freedom, an in-depth experimental study has been performed at EPFL Technology Platform for Hydraulic Machines (PTMH) on a specific speed homologous reduced scale model of the unit 5 of Z'Mutt HPP equipped with a reversible pump-turbine. The paper presents a methodology to (i) investigate different transient sequences to start-up the hydraulic machine, which have been tested on reduced scale model, and to (ii) evaluate the equivalent damage impact on the runner. The results of this study highlight the advantages of leveraging the variable speed technology during the unit start-up in respect to the conventional start-up sequence for synchronous generators.

1. Introduction

Last decades have brought several changes in the electricity market in both production and consumption. Given the European union's objective to feed the global **E**lectrical **P**ower **S**ystem (**EPS**) with at least 32% of energy coming from **R**enewable **E**nergy

Sources (**RES**) major changes in electrical grid supply have been undertaken to move away from conventional fossil fuels and decarbonise the electricity production. However, the inherent stochastic behaviour of non-dispatchable RES, such as wind and solar, challenges the EPS operations and its safety. **H**ydro **P**ower **P**lants (**HPPs**) already play a significant role in the power systems balance due to their large capacity for power regulation, and, therefore, are expected to be a key component for the smooth integration of non-dispatchable RES [1, 2].

1.1. High dynamic load during operation

Francis runners run smoothly at their designed operating point called **B**est **E**fficiency **P**oint (**BEP**) and in its vicinity. Due to head variation over time, power regulation, or ancillary services provision, HPPs have to work in off-designed conditions. When the runner is operating in off-design conditions such as part-load, full-load, speed-no-load or during transient operations such as start-stop sequences, high pressure fluctuations may arise [3]. Those high pressure fluctuations induce mechanical vibrations that could lead to cracks development on the runner's blades. These cracks generally do not affect the integrity of the runner but must remain under control. In order to decrease down time and excessive maintenance costs, plant owners have to minimize damaging operating conditions. In this respect, a detailed knowledge of the damage created during a given operating transient could provide precious insight on how to quantify the accumulated damage and how to extend the mechanical components lifespan.

1.2. Start-up sequences

Among all possible detrimental conditions, the start-up of the unit is well known to be as one of the most critical operating conditions and special care has to be undertaken to mitigate the damage created during this phase [4, 5, 6, 7, 8]. A practical way for HPP end-users to reduce the associated runner's damage is to modify the transient start-up sequence. The main parameters that control HPPs during these sequences is the guide vanes opening and the related adjustable parameters of the speed governor, namely the opening limit, the fold back speed, and fold back opening [6]. Those parameters are easily settable by the HPPs end-user for a limited cost. Unfortunately, the ability of these parameters to act remains limited and is generally at the expense of the start-up time [9] and requires extensive start-up measurement and optimisation campaign.

1.3. Variable speed power generator

Variable speed capability of power generator is a recent technology and provide an added degree of freedom compared to conventional fixed speed synchronous generators [10, 11]. This technology brings additional flexibility to the HPP while offering a larger capacity for ancillary services provision. The major advantages is the capability to regulate the power consumed in pumping mode but not only. It extends the operating range of the runner, improve the efficiency of HPPs, offer a better capability for load balancing allowing the integration of variable renewable energy (VRE) and offer high power ramping rates. Indeed, high dynamic control can be used to provide a more reliable and fast response to frequency regulation using the fly wheel effect [12, 13, 14, 15]. Two main technologies composing variable speed unit are the **D**oubly **F**ed **I**nduction **M**achine (**DFIM**) and the **F**ull **S**ize **F**requency **C**onverter (**FSFC**). FSFC offers superior performance and freedom even if the cost of the latter is lower. Nevertheless, with the continuous development in power electronics, FSFC is expected to become more and more attractive financially. Note that the current limitation in term of **V**oltage **S**ource **C**onverter (**VSC**) power is above 500 MVA [16]. Only few large HPPs having variable speed are currently under operation. Variable speed generator technology, and more specifically FSFC, offer a full control of the unit speed during both quasi-static and transient conditions. Knowing that the starting-up of the unit is one of the most damageable operation for HPPs, variable speed technology can be leveraged to decrease the transient operation impact on the runner damaging. However, how to make good use of the additional degree of freedom offered by variable speed to reduce the equivalent damage during a start-up is not fully understood [17, 18].

1.4. Problem statement and paper structure

In this context, this paper presents a methodology to investigate the equivalent damage on the runner blades during different start-up sequences and shows the potential of the variable speed technology to increase the lifetime of the unit. This study is framed within the XFLEX HYDRO project which aims to demonstrate how to improve the flexibility of the European hydropower fleet to support the energy transition. The paper is structured as follows: in section 2, the methodology, including the experimental set-up (acquisition devices and sensors), is presented along with the definition of the start-up sequences, and the equivalent damage computation. Section 3 presents the results extracted from the test-rig measurement and compare the damage induced by two considered start-up sequences. Finally, a summary of the results and perspective studies conclude the paper.

2. Methodology

2.1. Modification of reduced scale model test Platform for transient operations

The EPFL PTMH facility used for the test campaign consists of a closed-loop test rig that complies with the IEC-60193 standard and is equipped with a 300 kW electrical machine that can operate in the four quadrants. The hydraulic circuit is fed by two centrifugal pumps driven by 300 kW electric machine which can operate in parallel (higher discharge) or in series (higher head). To perform the test, a maximum head of 100 mWC and a maximum discharge of 1.4 $m^3\,s^{-1}$ can be achieved. Finally, the submergence of the runner can be adjusted by setting the pressure in the lower reservoir,

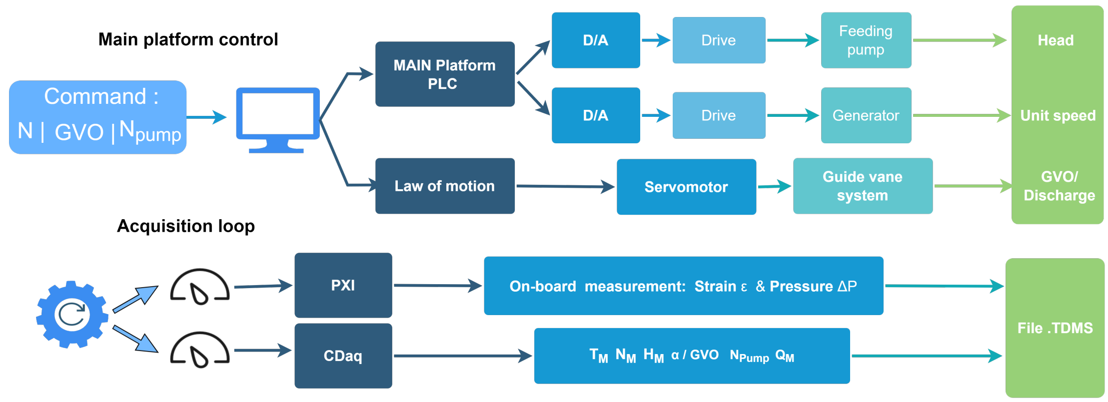


Figure 1: Data flow of the test rig and data acquisition system.

thus reproducing the hydraulic parameters of the dam under test. In order to study transient operations on the existing test-rigs at EPFL PTMH, several modifications have been undertaken. They are described here below.

2.1.1. Control of the test rig The parameters to control the start-up sequences are: (i) the speed of the unit; (ii) the **g**uide **v**anes **o**pening (GVO) and (iii) the head. Managing these three parameters allows for the full control of the start-up sequence on the test rig. In Figure 1, the data flow of both the test-rig control and data acquisition are presented. The smallest time discretisation allowing for a smooth control of the test-rig is 400 ms. The definition of the guide vanes opening over time $GVO(t)$ is controlled via the rotational speed of the servo-motor and has to be defined by the law of motion of the guide vanes system. The screw thread pitch, the radius of action on the guide vane pitch circle and the arm rod length are the parameters that have to be considered. A pure feed-forward control has been implemented to manage the model head during transients and has been set to have a purely linear speed increase over time to limit the overlaying hydraulic transient. Indeed, hydrodynamic phenomena of the hydraulic circuit are faster than the control capability of the test rig. Having the full characteristics of the test rig pump allowed for the definition of the required rotational speed of the pump during the start-up sequence. The first target is the speed providing nominal head with closed GVO and the final target is the speed providing the nominal head for the **B**est **E**fficiency **P**oint (**BEP**)'s GVO. As shown in the following section, the tested sequences start with a standstill unit under rated head and end at BEP.

The simulation of the start-up sequences has been realized within the SIMSEN [19] simulation software to ensure that no harmful pressure fluctuations would take place during transient operations, but they are not presented in this paper.

2.2. Instrumentation and experimental campaign

Several instrumentation systems were employed to carry out the measurements and provide a complete quantification of the flow dynamics during transients. On the static frame, five absolute piezo-resistive pressure transducers (UNISENSOR HF900-

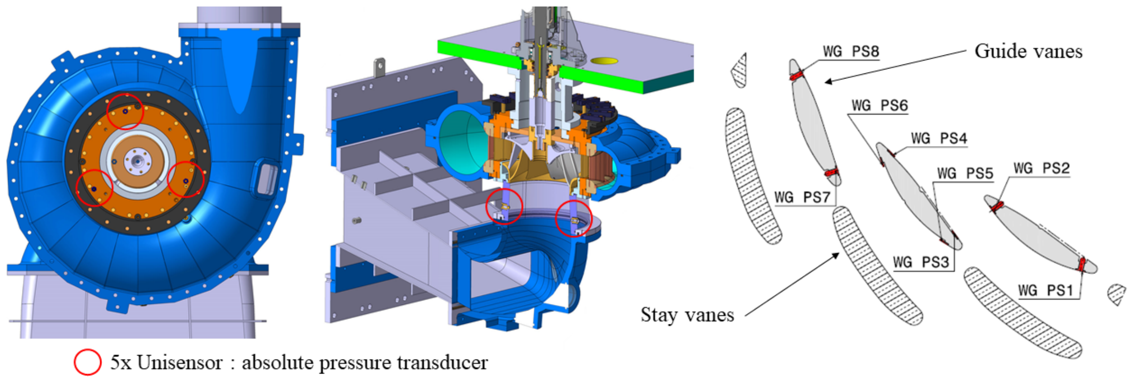


Figure 2: Static frame pressure measurement set-up: positioning of the pressure sensors in the runner's vicinity.

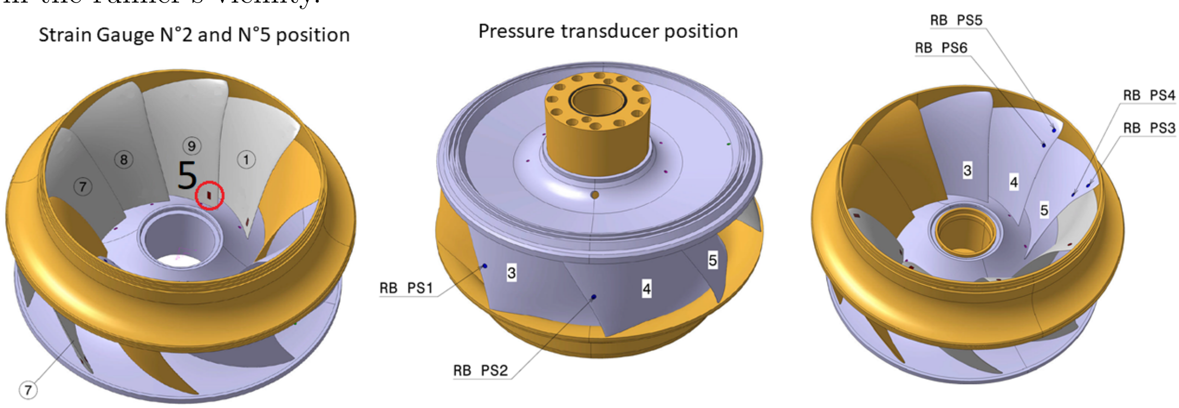
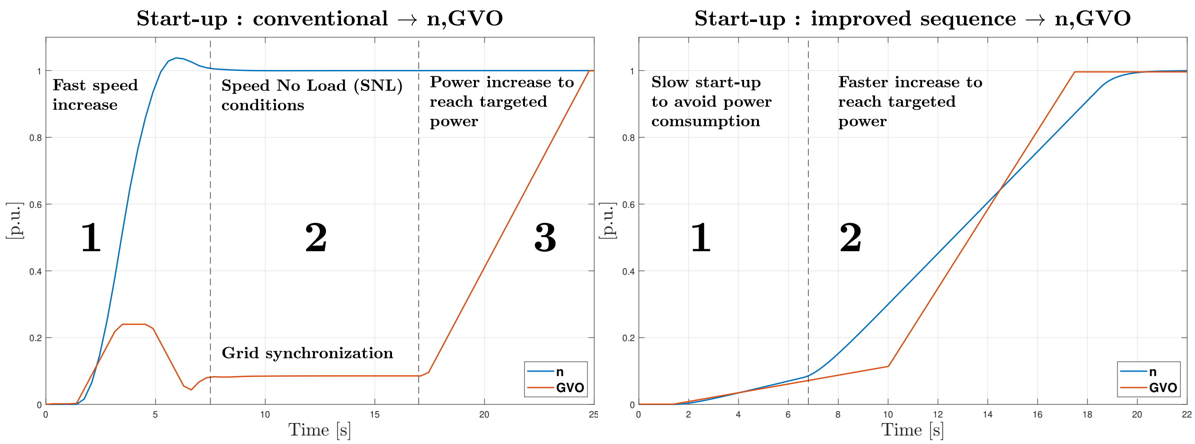


Figure 3: On-board measurements set-up and location of the pressure transducers and strain gauges.

03291.500) have been flush-mounted in the runner vicinity. Three over five were placed in the vaneless gap and two in the draft tube cone on the same section, as shown in Figure 2. They have a measurement uncertainty of 0.7% in a measurement range of 2 MPa. The acquisition frequency of the measurement system is 1 000 Hz.

2.2.1. Runner on-board measurement On-board runner measurements were performed by using a modular sensor telemetry system that allows for on-board measurements on the runner via a multi-channel amplifier. It supports simultaneously eight channels with a 16 bits resolution for a bandwidth of 40 kHz. Both pressure transducers and strain gauges were mounted on the runner to provide measurements of the pressure fluctuations and stresses occurring during the transient sequences. As shown in Figure 3,the runner was equipped with 6 Kyowa PS-10KC pressure transducers placed at mid-height on the pressure side of the leading edge (RB PS1 & RB PS2). The remaining four sensors (RB PS3-6) are located close to the trailing edge of the suction side and near the bend. Both rosettes and uni-axial strain gauges were implemented on the runner's blade allowing a complete assessment of the principal stresses magnitude and direction.



(a) Classical start-up for HHPs

(b) Two-slopes start-up

Figure 4: Comparison between two-slopes and classical start-up sequences.

2.2.2. Guide vanes instrumentation Four guide vanes axles were equipped with full Wheatstone bridge strain gauges for torque measurement, and were placed axis-symmetrically over the unit's axles. Furthermore, two water passages of the guide vanes system were instrumented with eights Kyowa PS-10KC/PS-10KD sensors with a rated capacity of 1 MPa allowing for pressure fluctuations measurement.

2.2.3. Acquisition system The on-board measurement of the telemetry system, the five pressure transducers, the eight pressure transducers placed in the guide vanes water passage and the four full bridge torque measurement gauges were acquired via a National Instrument PXI-4472 acquisition module.

2.3. Comparison of sequences : conventional start-up vs improved sequence

This section focuses on the comparison between two considered start-up sequences which have been developed in the framework of XFLEX HYDRO project [17]. The former is the conventional sequence commonly used in fixed speed unit. Starting at standstill, the GVO are linearly open up to 22-25% of the nominal stroke with maneuvering speed. Due to the wicket gate opening, the runner speed start increasing and tend to reach synchronous speed. At this moment, a PID controller override GVO control to realize the synchronization with the electrical grid and keep the unit at Speed-No-Load conditions. Once the synchronization is completed, the GVO is suitably controlled to reach the targeted power (BEP conditions). In the second sequence, called two-slopes, the guide vane system is linearly open from completely closed to BEP's opening while unit's speed is increased following a two linear slopes pattern. The first slope, being less steep, avoids power consumption from the grid while the second, is more steep, provides fast turbine start-up. This sequence has been design to be close to BEP of each GVO encounter during transient. Both sequences are represented in Figure 4.

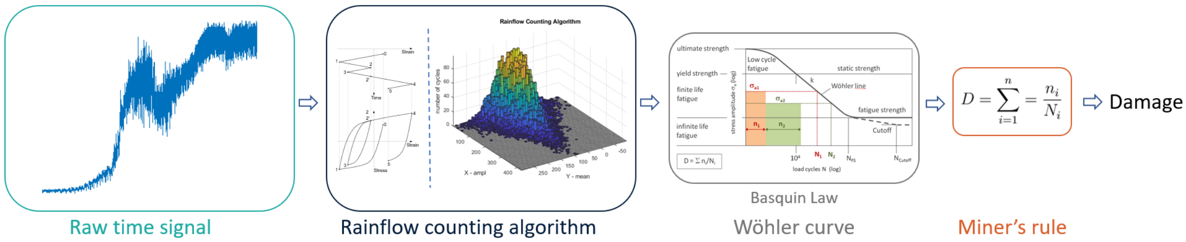


Figure 5: Damage computation methodology.

2.4. Evaluation of equivalent damage

The number of fatigue cycles contained in the load-time history of a sequence is determined by applying a rain flow cycle counting algorithm following ASTM [20]. The signal recorded by the strain gauges is firstly analyzed to extract the local extrema and identify the number of cycles per strain level. These stresses are then corrected via Goodman's relation to account for the mean and alternating stresses in the fatigue assessment. The cumulative damage for each sequence is then calculated using Miner's rule in combination with the appropriate Wöhler curve, whose central part is approximated by a power law following Basquin's law [21]. This procedure allows deriving a global equivalent damage for a given start-up sequence, as shown in Figure 5. The computed damage only considers the start-up sequence and is then compared to the damaging rated occurring at BEP condition, providing an equivalent time that the HPP unit has to be operated at BEP to produce the same damage as the start-up.

2.5. Validation on Z'Mutt pumped-storage power plant

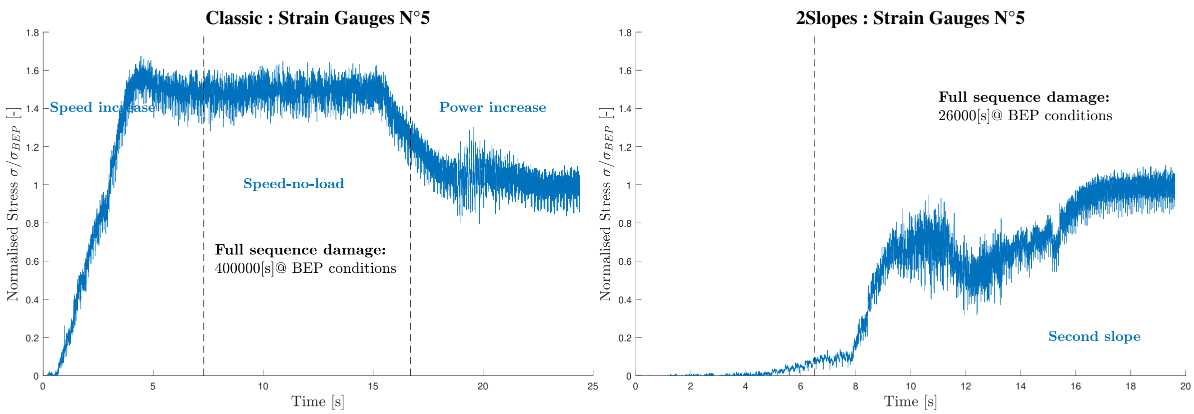
Z'Mutt HPP was commissioned in 1964 and allows pumping water in the main reservoir of the Grande Dixence hydroelectric scheme. Among the five units showing a 88MW pumping capacity, one of the unit is under refurbishment and is replaced by a new 5MW variable speed reversible pump-turbine equipped with FSFC. The goal of the demonstrator is to prove the added operational flexibility of such a unit and to enhanced the start-up process by minimizing the units wear during start-up sequence. The FSFC is adding a degree of freedom that is used to control the unit's speed during start and stop sequences that could be used to minimize the sequence impact on the runner lifespan. The main features of the HPP are provided in Table 1. The test campaign has been realised on a reduced scale model with the same specific speed as the Z'Mutt prototype. In particular, the two-slopes sequence corresponds to a new start-up sequence for the Z'Mutt power plant.

3. Results

The measurements performed during the experimental campaign are analysed to quantify the equivalent damage of the two tested start-up sequences. Each sequence has been repeated and recorded at least 5 times to ensure the repeatability of the

Francis-type pump-turbine nominal values		
Turbine type	Reversible single stage pump turbine	[-]
Head H_n	115	[m]
Discharge Q_n	3.6	[$\mathrm{m^3\,s^{-1}}$]
Rotationnal speed n_n	1 000	[rpm]
Power P_n	4.5	[MW]
Specific speed n_q	54	[-]
Reference diameter D_{ref}	0.9	[m]

Table 1: Nominal values of the Z'Mutt pumped-storage power plant.



(a) Classical start-up for HHPs

(b) Two-slopes start-up

Figure 6: Stress comparison between the two-slopes start-up and the classical sequence.

measurements.

Figure 6 shows the time history of the stress for both types of start-up scheme. For the classical sequence, the speed-no-load regime reveals a high dynamic load causing higher degree of damage, as expected. Thanks to the FSFC, the speed-no-load regime is avoided during the two slopes start-up sequence, by significantly decreasing the stresses range. Furthermore, the generator is directly connected to the grid allowing for faster start-up and, hence, decreasing the damage caused to the runner. To ensure a normalisation of the results, the stress has been divided by the average stress occurring at BEP conditions. Moreover, the equivalent damage is expressed through the equivalent time that the unit must be operated at BEP conditions to produce the same amount of damage as during the start-up. The equivalent time is calculated based on the signal of the strain gauge placed near the crown and the trailing edge on the suction side of the blade, as shown in Figure 2. The results of this calculation is presented in Table 2: the equivalent damage magnitude is up to an order of magnitude lower for the two slopes sequences in respect to the classical sequence.

Most of the stress is due to centrifugal acceleration and it is directly proportional to the square of the speed and proportional to the density of the runner material. The runner reduced scale model is made out of bronze with a density of 8 800 $\mathrm{kg\,m^-3}$, therefore, the component of the stress due to the centrifugal acceleration is

Sensor	Type of sequence	Equivalent time @BEP
SG n°5	Classic	400 000 s
SG n°5	two-slopes	26 000 s

Table 2: Equivalent damage statistics.

approximately 12.8% higher than for a stainless steel runner (steel density being $\simeq 7\,800$ kg m^{-}3). Furthermore, the measurement realised for this study are performed close to the four corners of a pump-turbine's blade commonly known as hot-spots of maximal strain. The exact location of the hot-spot must be determined by FEM analysis and depends on the operating point, so this location changes over time during transient operation. These results can be used to compare the damage at these specific locations between different sequences. This is not a complete map of stresses, but an evaluation of the dynamic loading during transient operation, where accumulated damage is expected to be the greatest. Strain gauge N°5 was selected for results presentation because it performed consistent measurements for all tested sequences and persisted throughout the campaign.

In Figure 7, the comparison of the two start-up sequences on a N_{11}/Q_{11} map is presented and provides insights on the discrepancies between the tested sequences. The black curves represent the theoretical path that the runner should follow to respect the defined sequences and the coloured lines indicate how the test rig manages to follow the command. The theoretical curve has been extracted from 1D simulation realised prior to the campaign on SIMSEN simulation software. The discrepancy between the theoretical curve and the measured curve can be explained on the one hand by the command refresh rate of the test rig automaton, which is limited to 2.5 Hz. This causes the speed to wobble when rapid speed changes are required. On the other hand, the sudden change in discharge caused by the rapid opening of the guide vanes leads to a reduction in head, which is balanced by the increase of the feeding pump speed, resulting in a shift of the curve.

4. Conclusion

The study presented in this paper has shown the benefits to use the variable speed technology to mitigate the impact of a start-up on the runner lifespan. In particular, a method to quantify the equivalent damage based on the measurements of strain gauge directly mounted on a reduced scale model runner of a reversible Francis-type pump-turbine has been presented. The results have highlighted that the equivalent damage of a start-up can be significantly decreased, up to 15 times, thanks to the capacity to control the speed of the unit along the sequence and, therefore, avoiding the higher stresses of the conventional synchronous generator start-up sequence. This shows the added value of such technology and how it can be use to mitigate fatigue related problem on Francis runners. Nevertheless, a study of the complete hydropower plant response

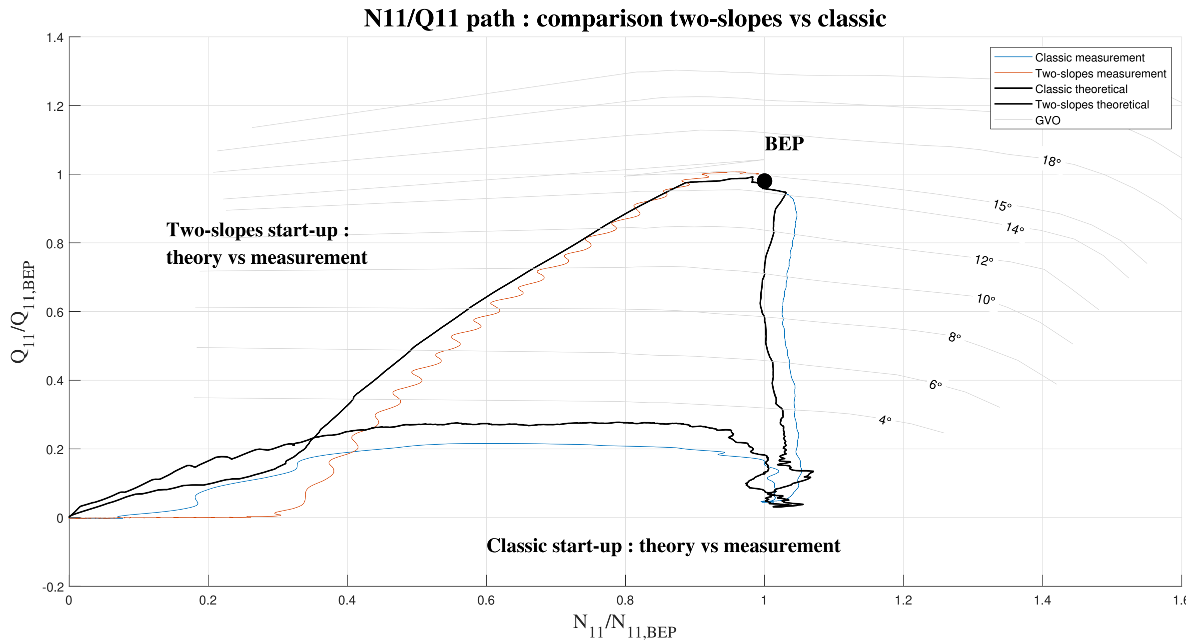


Figure 7: Comparison between start-up sequences.

has to be undertaken to evaluate the impact of the start-up sequence on the different parts of the hydraulic circuit to obtain a comprehensive evaluation of the components lifetime. Furthermore, additional investigations with several different start-up schemes should take place to define the optimal sequences. The damage minimisation during start-up enables to increase the number of start-ups and stops of hydroelectric units and, therefore, brings a gain in flexibility allowing for a more advantageous economic-technical operation of the unit for increasing the profitability.

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