Safe and Flexible Variable Speed Pump-Turbine Operation: Advanced Monitoring Systems at Z'Mutt Hydropower Plant

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Abstract: Predicting the onset of instability in variable-speed pump-turbines during pump mode is inherently challenging, with model tests often yielding results that differ from prototype behavior. This paper presents an advanced in-situ monitoring approach that synchronizes hydraulic operating points with high-frequency vibrations and pressure fluctuations data, enabling precise identification of stable operating zones. The methodology is validated through extensive on-site testing, highlighting the benefits of the deployed monitoring system in ensuring reliable plant operation.

1 Introduction

The Z'Mutt pumping station, located in Switzerland, plays a critical role in feeding water into the main reservoir of the Grande Dixence hydroelectric scheme. Originally commissioned in 1964, the five pumps of the power plant have a combined capacity of 88 MW. In a recent modernization effort, the Unit U5 was replaced with a 5 MW variable-speed reversible Francis pump-turbine. This modernization, which incorporates advanced power electronics and control systems, has significantly improved operational flexibility. The new system allows for adjustable pump power, rapid transitions between turbine and pump modes, fast and smooth start-up sequences [1], enhanced responsiveness and swift active power regulation.

The introduction of variable speed also added a significant layer of complexity, particularly in predicting and managing the onset of instability during pump mode. In centrifugal pumps, the hump region, i.e. where the head-discharge characteristic has a positive slope, presents significant challenges in both design and operation [2]. Strong noise and significant fluctuations are typically observed when pump-turbines operate in the hump region [3]. This region limits the allowable operating range to values above a minimum discharge, below which the system becomes unstable. For a fixed-speed unit, the steady operating point is determined by the intersection of the parabola representing the energy losses in the waterway with the pump's head-discharge characteristic. As this intersection defines the operating head, the pump's characteristics must be designed for this point to remain below a certain threshold to avoid instability with sufficient margin, as illustrated in Figure 1.

The situation becomes more complex with a variable-speed machine, which offers the advantage of adjusting the pump's power and flow at any given head. However, this extended operating range also means that for a given head, reducing the pump discharge by lowering the unit's rotational speed brings the operating point closer to the instability limit, as illustrated in Figure 2. This proximity to the instability threshold necessitates careful monitoring and control to ensure safe and reliable operation under variable-speed conditions. In addition, reversible pump turbines have the ability to adjust the guide vane openings to improve efficiency and stability, introducing an additional degree of freedom that further complicates the operation. Furthermore, there are often discrepancies between model tests and real prototype behaviour regarding the identification of the unstable region. The root cause of unstable discharge characteristics lies in complex 3D flow phenomena and flow separation that develop in the rotor-stator interface and guide vane & stay vane passages [4][5]. These phenomena are notoriously difficult to predict accurately through numerical simulations [6][7], or reduced-scale model testing.

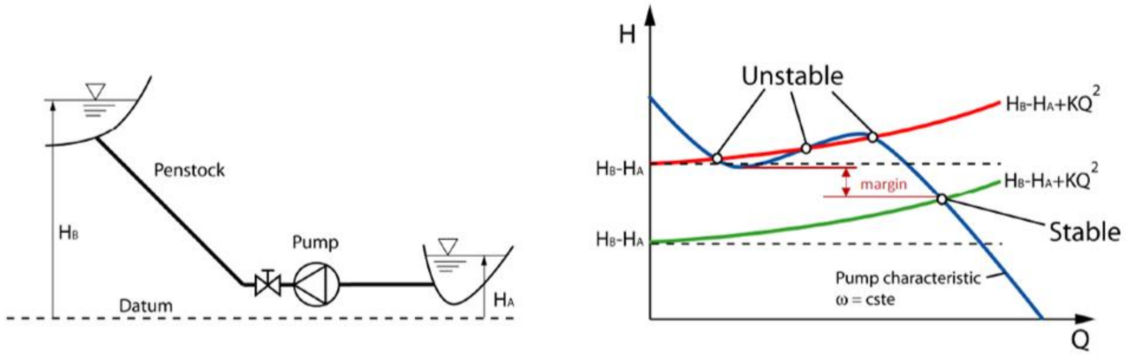

Figure 1 Stability condition of a fixed speed pump system in the presence of a positive slope in the head-discharge characteristic.

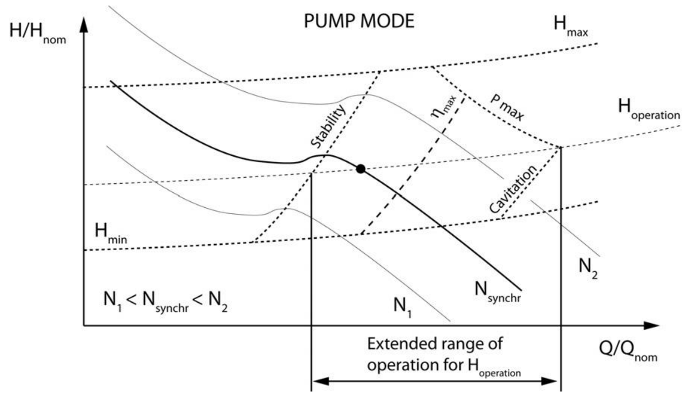

Figure 2 Extended operation in pumping mode for a variable speed machine, from [8].

The Z’Mutt pumping station took the advantage of the advanced in-situ monitoring system implemented as part of the XFLEX HYDRO project [9] to address the challenge of maintaining stable operation of the new variable-speed unit in pumping mode. This system synchronizes hydraulic operating points with high-frequency data of vibrations and pressure fluctuations, providing a comprehensive understanding of the unit's behavior under various operating conditions. This paper presents an overview of the on-site tests conducted during the commissioning phase to identify stable operating points, demonstrating the effectiveness of the monitoring system of the unit U5 in ensuring reliable plant operation and highlighting the benefits of this integrated approach in managing the complexities of variable-speed pump-turbines.

2 Presentation of Z'Mutt PSP

The Z'Mutt Pumping Station (PSP), located in Canton Valais-Wallis, Switzerland, is the most powerful pumping facility within the Grande Dixence complex. It sources water from the Bis and Schali glaciers, which rise above the Visp River, as well as from the Gorner glacier, and pumps approximately 140 million m³ of water each season into the Lac des Dix, the main reservoir of the Grande Dixence hydroelectric scheme, which has a capacity of 400 million m³. The plant is equipped with a range of pumping units, including two 30 MW units (U1, U2), two 14 MW units (U3, U4), and one 5 MW reversible pump-turbine unit (U5), as depicted in Figure 3. The new variable speed unit U5, shown in Figure 4, is equipped with an asynchronous motor-generator driven by a full-sized frequency converter. The pump-turbine features a specific speed of Nq = 54 and a mechanical time constant of τ_m =1.3 s, cf. main characteristics given in Table 1.

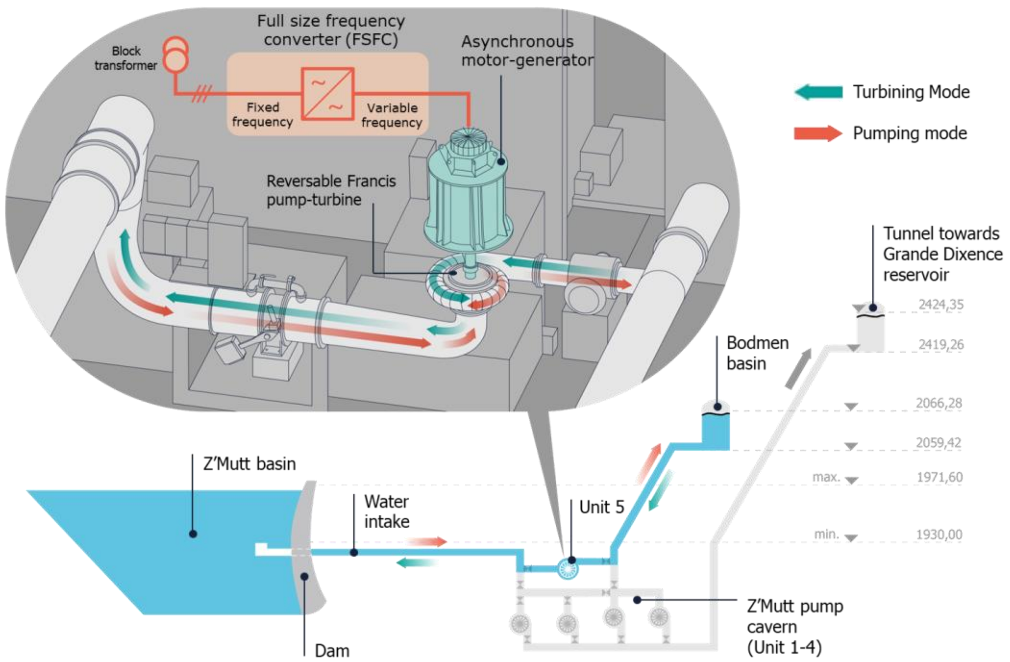

Figure 3 Overview of Z'Mutt pumping station with the new 5 MW reversible variable-speed pump-turbine.

Figure 4 Photography of the new unit U5.

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 Advanced monitoring

An advanced in-situ monitoring approach that synchronizes hydraulic operating points with high-frequency vibration and pressure fluctuations data was implemented on the unit U5 of the Z'Mutt PSP. This monitoring system integrates a digital twin, Hydro-Clone® [10], which uses a SIMSEN numerical model to simulate the plant's dynamic behavior in real-time. This is complemented by a dedicated high-frequency vibrations and pressure fluctuations acquisition system, the PMM-305 Plus, along with condition monitoring software, CMS-500 Orca. This section provides an overview of these key components and their implementation, highlighting how they collectively contribute to the advanced monitoring of the variable-speed unit.

Hydro-Clone is a "Real-Time Numerical Simulation Monitoring" system based on a 1-D numerical model of the hydropower plant. It simulates and replicates the dynamic behaviour of the hydraulic system in real time, effectively serving as a physics-based digital twin for monitoring hydropower plant transients [11][12]. The numerical model is continuously updated with the actual boundary conditions of the power plant at a frequency of 10 Hz to accurately reproduce its transient behaviour, as schematized in Figure 5. This system proved to be very useful for efficient and effective transient monitoring during the transient tests conducted at the Z'Mutt pumping station. Figure 6 shows an example of a sequence monitored in real time during the commissioning phase, showing the emergency shutdown of Unit U5 in pump mode. The simulated pressure at the Main Inlet Valve (MIV) closely matches the measured values, as does the unit speed following the circuit breaker opening.

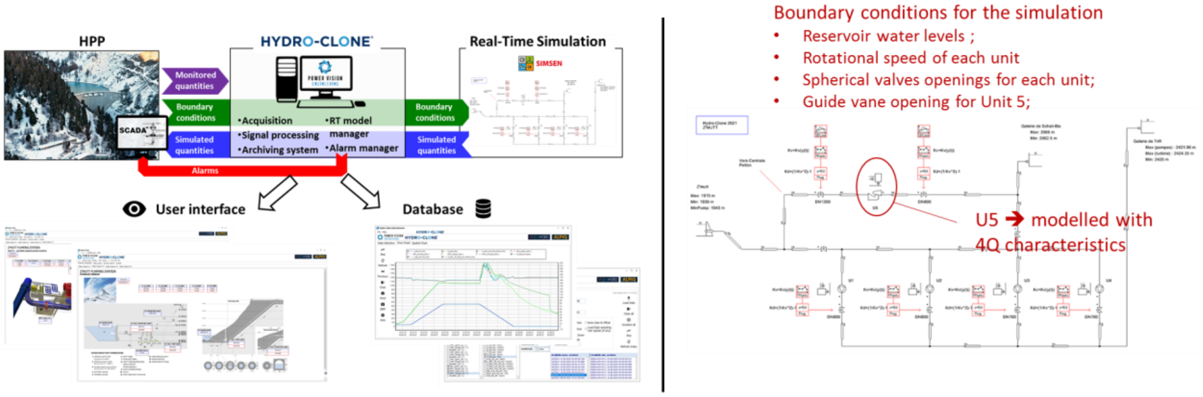

Figure 5 Left: general concept of Hydro-Clone system based on real-time simulation. Right: SIMSEN model of the Z'Mutt PSP comprising the 4 main pumps and the 5 MW reversible pump-turbine unit U5.

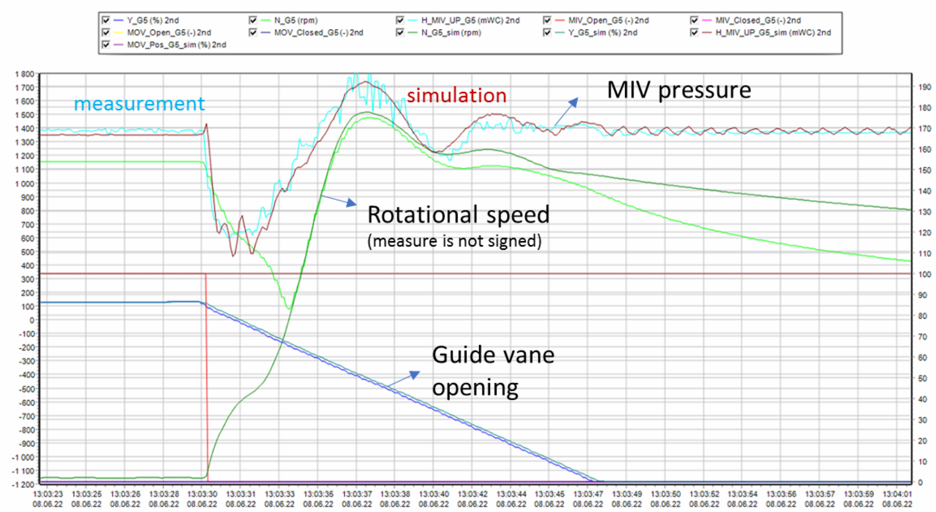

Figure 6 Real-time comparison of measured and simulated pressure upstream of the MIV during Unit U5 emergency shutdown in pump mode, as recorded during the commissioning test.

While Hydro-Clone provides valuable insights into the system's hydraulic behavior, it monitors key parameters— such as unit pressure, head, discharge, torque and power— at a frequency of 10 Hz. However, pump-turbines can experience high-frequency pressure fluctuations induced by the reversible pump-turbine itself, which are not captured in the 1-D simulation. These fluctuations can arise from rotor-stator interaction (RSI), rotating stall, broadband disturbances due to stochastic phenomena, flow separations, and potential cavitation. Therefore, a specialized monitoring approach is necessary to ensure a comprehensive understanding of the unit's behavior.

To address this, a dedicated high-frequency vibrations and pressure fluctuations monitoring system was implemented. This system includes the PMM-305 Plus process monitoring module, which captures pressure and vibration data at frequencies up to 4 kHz, paired with the CMS-500 Orca condition monitoring software. The PMM-305P is equipped with five channels, four for dynamic signals and one for reference, allowing for seamless integration with existing systems via +/-24V differential BNC inputs. Specifically for the Unit U5 at Z'Mutt, three PMM-305P modules are used to monitor eight vibration signals—covering relative shaft displacement at the upper and lower generator bearings and turbine bearing, as well as absolute vibrations—and four dynamic pressure signals, including one in the spiral case and three in the draft tube, as indicated in Figure 7. Additionally, the PMM-305P computes key data trends, such as mean value, RMS, and peak-to-peak 97%.

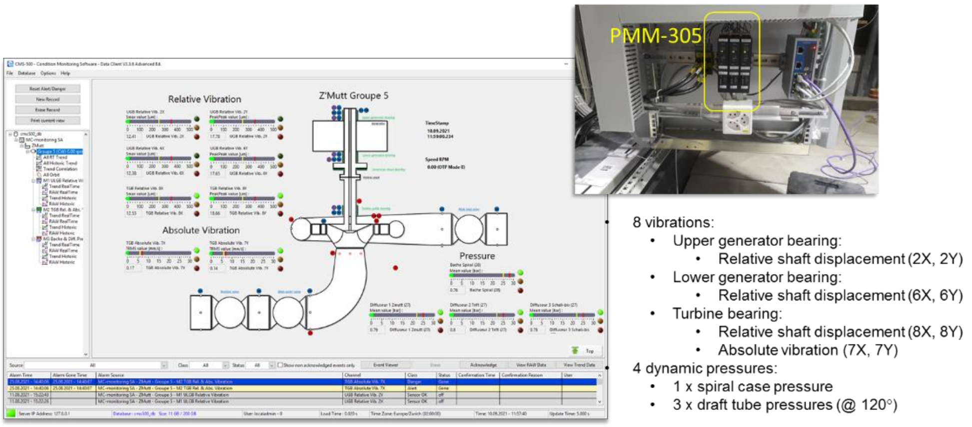

Figure 7 Left: Overview of the ORCA interface, used for monitoring unit vibrations and high-frequency pressure within the unit's spiral case and draft tube. Right: photo of the three PMM-305 Plus device, utilized for high-frequency vibrations and pressure fluctuations data acquisition.

Having the trio of information—operating point, vibration, and pressure fluctuations—within the same environment allows for comprehensive monitoring of the unit's operational limits, enabling precise identification of vibration sources linked to hydrodynamic phenomena. The synchronization of these data streams within the Hydro-Clone system ensures that all relevant information is available in real-time. Figure 8 provides an overview of the Hydro-Clone system integrated with the high-frequency vibrations and pressure fluctuations monitoring setup for Unit U5, illustrating the data exchange between these components. Efficient data trend transmission is achieved via dual Modbus TCP/RTU interfaces, ensuring continuous and reliable monitoring, while high-frequency raw data acquired by the PMM-305P can be accessed through FTP for detailed analysis.

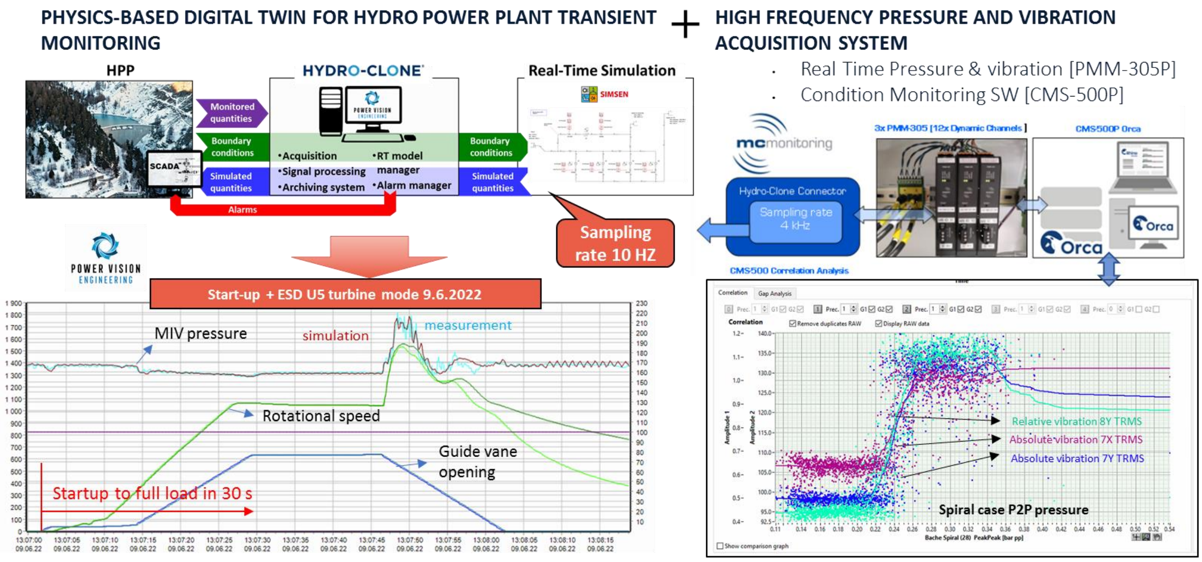

Figure 8 Overview of the Hydro-Clone system integrated with the high-frequency vibrations and pressure fluctuations monitoring setup for Unit U5, including the data shared by the processes.

4 Examples of commissioning tests

4.1 Overspeed test

Figure 9 shows the results of an overspeed test carried out on Unit U5, illustrating the relationship between unit speed, vibration and pressure fluctuations. Starting from a low speed, no-load condition, the unit speed is gradually increased under runaway conditions by opening the guide vanes until a critical overspeed is reached, at which point the unit trips. This process is characterized by a significant increase in both vibration and pressure fluctuations. As the speed and flow rate increase, the pressure fluctuations intensify, with a notable peak around 30 seconds into the test at maximum speed. The high-frequency vibration data recorded at 4 kHz show significant oscillations, indicating the hydraulic origin of these dynamic stresses. These observations underscore the benefit of combining high-frequency monitoring with operating parameters to better understand the unit's behavior during transient conditions, which are believed to be linked to rotating stall.

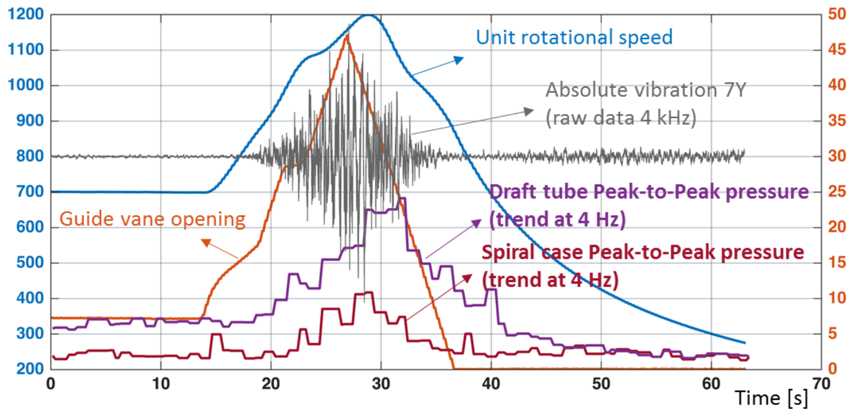

Figure 9. Unit U5 overspeed test highlighting the increased of unit vibration and pressure fluctuation as the speed is increased at runaway points.

4.2 Tests of stability limits in pump mode

An example of the discrepancies between the pump instability threshold predicted by model tests and the actual behavior observed in the prototype is evidenced on Figure 10. Initially, the simulated operating point — derived from 4-quadrant characteristics based on model tests — aligns well with the measured data. However, as the unit speed is slightly reduced, significant differences between the measured and simulated MIV pressures and discharge become apparent. Notably, the measured MIV pressure begins to exhibit high pressure fluctuations that are not replicated in the simulation. This disparity highlights that the prototype enters instability at a different threshold than predicted by the simulation, which is based on the 4-quadrant characteristics measured during model tests.

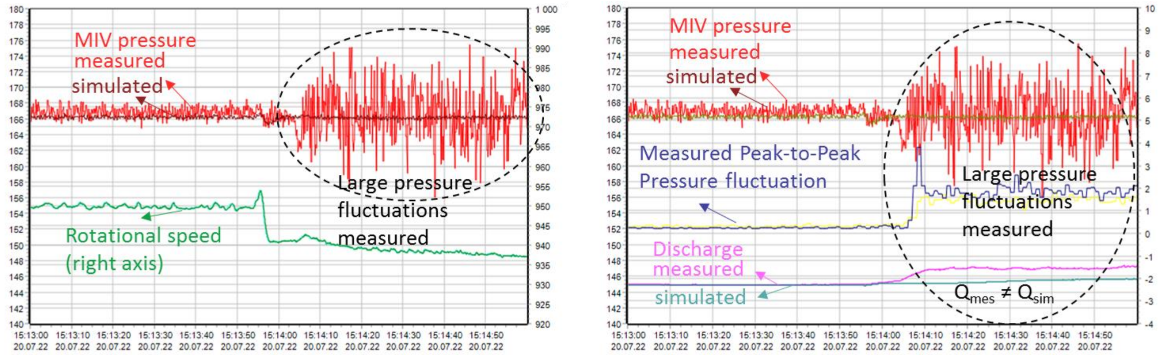

Figure 10. Example of discrepancy between the pump instability threshold predicted by model tests and the actual behavior observed in the prototype

Given the observed discrepancies in the pump hump region prediction between model tests and prototype operation, a dedicated measurement campaign was undertaken to redefine the stability limits for each guide vane opening. As illustrated in Figure 11, the testing strategy involved varying the rotational speed while maintaining a fixed guide vane position, with high-frequency recording of vibrations and pressures throughout the process. In tandem, the Hydro-Clone digital twin was employed to accurately identify the tested operating point based on the calculated net head, discharge, speed and torque of the pump-turbine.

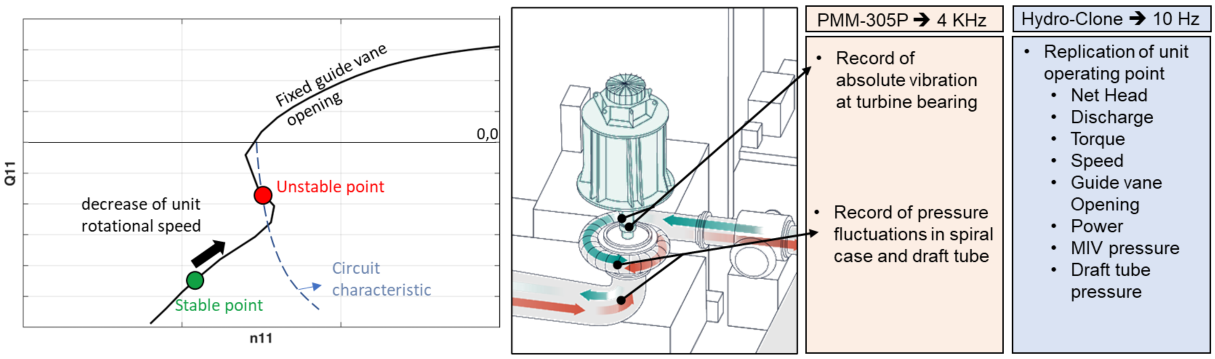

Figure 11. Strategy used in the measurement campaign to define stability limits in pump mode operation

Figure 12 shows an example of the measurement campaign implemented on the prototype. In this test, the speed of the unit is gradually reduced, while maintaining a fixed guide vane opening, until a critical point is reached where both vibration and pressure fluctuations increase significantly, indicating the onset of instability. This behaviour is characteristic of the pump hump region, where dynamic instability is known to occur. After identifying the critical speed, the unit's speed is increased again to exit the unstable region, which is subject to hysteresis. The speed at which the pump exits the unstable region is then designated as the new speed limit for stable operation in pump mode, together with an additional stability margin. This test procedure was repeated for each guide vane opening defined in the 4-quadrant characteristic. The comprehensive measurement campaign allowed for the creation of a detailed fingerprint of the unit U5 operating points, enabling the refinement and updating of look-up tables for pump mode operation based on the test results.

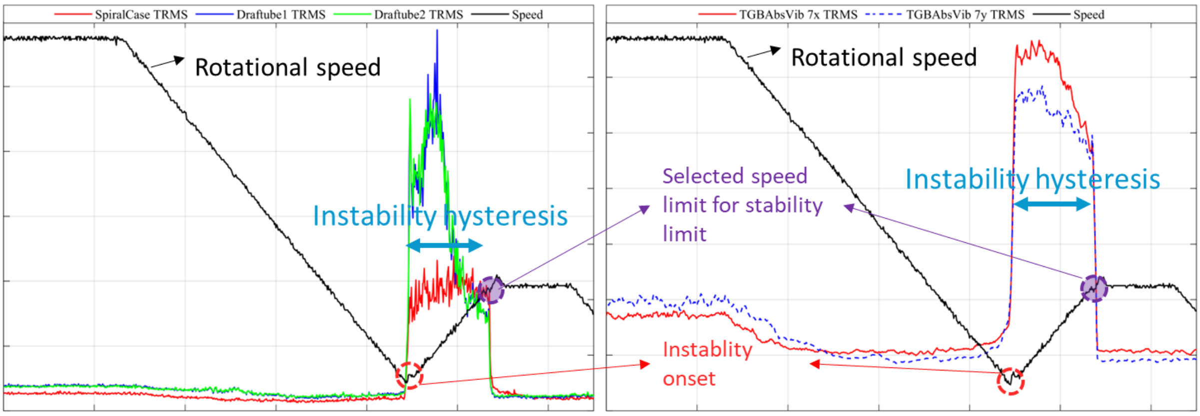

Figure 12. Example of results obtained during the measurement campaign, showing the increase in pressure fluctuations and vibration amplitude at the onset of pump instability.

5 Conclusions

The modernization of the Z’Mutt pumping station, with the integration of Unit U5 variable-speed reversible pump-turbine, has introduced both enhanced operational flexibility and significant challenges in managing operating limits during pump mode. The implementation of an advanced in-situ monitoring system that synchronizes hydraulic operating points with high-frequency vibrations and pressure fluctuations data, has proven extremely useful in accurately identifying stable operating zones. Extensive on-site testing, including the systematic exploration of stability limits across various guide vane openings, facilitated the development of a refined and updated look-up table for stable pump mode operation. Although this methodology was tested on a relatively small 5 MW unit, it demonstrated significant effectiveness and versatility, making it applicable to larger pump-turbine units as well. This approach serves as a valuable tool for ensuring safe and flexible operation of variable-speed pump-turbines.

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