

Expanding the Frontiers of Hydropower Innovation



A selection of experimental & numerical approaches developed and applied by
SuperGrid Institute Hydropower team to support innovation.

Hydropower is entering a phase of **accelerated transformation**. As power systems integrate higher shares of variable renewable energy, hydropower plants are expected to provide faster response, wider operating ranges and improved reliability.

This shift increases the need for accurate testing, robust modelling and advanced validation methods capable of reducing uncertainty across design, operation and refurbishment processes.



Who is this white paper for?

This white paper is intended for turbine manufacturers, hydropower innovation teams and asset managers seeking to reduce uncertainty, improve operational flexibility and make evidence-based decisions for new designs, refurbishments or fleet optimisation.

Turbine manufacturers

Validate performance, stability and control strategies before prototype deployment.

Innovation leaders

Assess emerging technologies and priorities solutions with industrial potential.

Asset managers

Evaluate operating limits, refurbishment options and opportunities to safely increase flexibility and capacity.

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1. Context & challenges for flexible hydropower

Hydropower is increasingly relied upon to balance power systems with high shares of variable renewable energy. Plants are therefore expected to respond faster, operate more frequently at part-load, undergo more frequent start-stop cycles and withstand increasingly demanding transients. These new operating patterns can increase hydraulic instabilities, mechanical stresses and uncertainty regarding equipment behaviour outside historically validated operating conditions.

For ageing assets, the challenge is even greater, as refurbishment and life-extension decisions require a reliable understanding of behaviour across wider operating ranges. Many existing plants were not originally designed or validated for these requirements. The challenge is therefore to determine how far their operating envelope can be safely extended while preserving equipment lifetime, operational safety and economic performance.

Testing and modelling are essential to address these challenges. They help characterise unsteady multiphases flow phenomena, validate design choices, assess dynamic response and quantify the flexibility potential of hydropower assets.

SuperGrid Institute helps utilities, turbine manufacturers, EPC (Engineering, Procurement & Construction) contractors and developers assess and enhance the flexibility potential of hydropower assets through advanced testing, simulation and engineering studies.

Key business benefits

- Reduce uncertainty before refurbishment and investment decisions
- Extend operating ranges safely
- Improve grid-support capabilities and operational flexibility
- Increase renewable energy integration
- Prepare assets for future flexibility and ancillary services markets

Unlocking flexibility & greater capacity

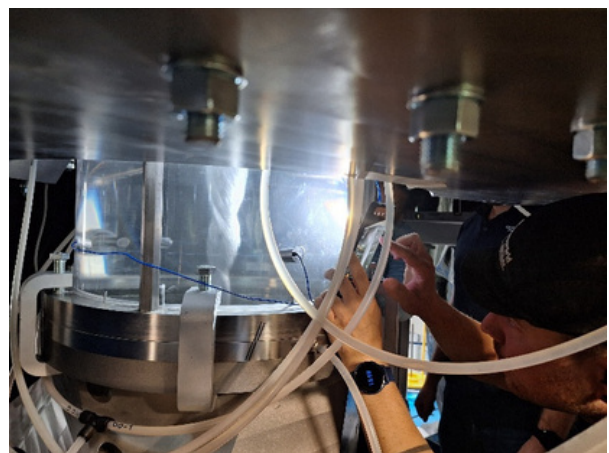
A comprehensive flexibility assessment provides a clear understanding of an asset's operational limits, dynamic behaviour and upgrade opportunities. To unlock additional value from existing hydropower assets, SuperGrid Institute supports:

- Flexibility assessment studies,
- Dynamic simulations and Hardware-in-the-Loop validation,
- Hybridization with Battery Energy Storage Systems (BESS) or supercapacitors for extended operating range and enhanced dynamic performance
- Energy Management System (EMS) design and validation.

These approaches help stakeholders identify technical limitations, quantify flexibility potential and prioritise the most effective upgrade pathways.

2. Validating turbine design with model testing (IEC 60193)

Scale model testing remains a key step in turbine development and qualification. It provides controlled, repeatable data to validate performance predictions, assess hydraulic stability and refine design choices before prototype manufacturing. For existing turbines, model testing can also be used to assess and validate the extension of the operating range beyond the original design conditions. IEC 60193 ensures that measurements follow recognized similarity and uncertainty criteria (*efficiency accuracy: $\leq 0,3 \%$*).



Testing protocols and expert insights

Scale model tests follow IEC 60193 procedures for stabilisation, measurement and uncertainty evaluation. Operating points are selected to cover the full range of discharge, head and guide vane openings. Measurements typically include torque, discharge, head, pressure fluctuations and cavitation inception.

Beyond the standard, expert judgement is essential to tailor the test protocol to the phenomena under investigation. Part-load operation, draft-tube instabilities and cavitation dynamics, for example, require dedicated unsteady measurements and specific test conditions.



Model testing goes beyond efficiency: it reveals critical turbine behaviour and reduces risk before prototype manufacturing."

Elise MAZAURIC, Senior hydraulic engineer



We have just completed the reduced-scale Model Test of a Francis Turbine at SuperGrid Institute Hydropower lab. The tests were conducted in accordance with the IEC 60193 standards, with high-quality measurements and reliable hydraulic characterization. We are very satisfied with the results and the hydraulic expertise provided, which enabled us to validate the design and extrapolate to the prototype."

Lorenz NEURURER, Team Leader HydroLab - Global Hydro



Key business benefits

- Reduce uncertainty before committing to prototype manufacturing,
- Strengthen performance guarantees with independently validated data,
- Compare design options on a consistent and measurable basis,
- Anticipate risks before refurbishment or operating range extension.

Case study: hydraulic scale model test for Global Hydro

From concept to validated performance prediction

A scale model test campaign was conducted for a Francis turbine developed by Global Hydro. The objective was to validate performance predictions and assess hydraulic behaviour across an extended operating range.

Test protocol

The model was tested according to **IEC 60193**. The protocol included:

- Systematic exploration of discharge and guide vane openings,
- Steady-state performance measurements,
- Cavitation inception tests,
- Unsteady pressure recordings in the draft tube and in the inlet pipe,
- Targeted investigations in the suspected instability zone.

The results validated the turbine design. This testing campaign reduced uncertainties regarding performance guarantees and provided a solid foundation for the prototype's implementation.

3. Extending operating ranges with air injection



Air injection is used to mitigate hydraulic instabilities and improve turbine behaviour under extended operating ranges. It helps reduce pressure pulsations, limit vortex rope development and stabilise draft-tube flow during part-load operation.

The method consists of introducing a controlled air flow into the draft tube or runner environment. The injected air modifies the density distribution and alters the structure of unsteady vortices. This can reduce the amplitude of pressure fluctuations and improve overall flow stability.

Air injection tests are typically performed on scale models or prototype units equipped with dedicated air supply systems. Key parameters include injection location, air flow rate and operating point.

Measurements focus on:

- Pressure pulsations in the draft tube,
- Vibration and acoustic levels,
- Cavitation behaviour,
- Efficiency impact.

The objective is to identify the injection conditions that provide the best compromise between stability improvement and performance loss. Global Hydro trusted us on this method.

Key findings and insights

Research and industrial experience show that air injection can:

- Significantly reduce draft-tube pressure pulsations at part-load,
- Limit the development of the vortex rope, and Inter-blade vortex
- Improve operational stability during rapid load changes,
- Reduce mechanical stress on the turbine structure.

However, the effect on efficiency must be carefully evaluated, as excessive air flow can lead to performance penalties.

Key business benefits

- Extended operating range with reduced risk of instability
- Improved part-load behaviour for flexible operation
- Lower mechanical stress on runner, bearings and draft-tube structures
- Better alignment with grid flexibility requirements

Case study: R&D project to reduce pressure pulsations

During a recent R&D project, a dedicated system was developed to inject air through the distributor head cover at up to 20 azimuthal locations, either simultaneously or selectively

The experiments showed that the effectiveness of air injection in reducing pressure pulsations depends not only on the injected air flow rate, but also strongly on the specific part-load operating condition, including head and load level.

This highlights the need to optimise air-injection strategies across the operating range rather than applying a single injection configuration.



4. Managing extreme transients with HydroPHIL

Hydropower flexibility exposes assets to increasingly demanding transient conditions. Rapid load changes, emergency shutdowns and fast guide-vane closures can generate severe hydraulic phenomena that are difficult to reproduce and investigate at full scale.

HydroPHIL (Hydro Power Hardware In the Loop) provides a controlled and repeatable environment combining **physical hydraulic testing** with real-time numerical simulation to reproduce representative plant dynamics and investigate critical transient behaviour.

The platform can also operate in Hardware-in-the-Loop (HIL) configuration, coupling a **real control system** with real-time models of the hydraulic and electrical systems. This enables control strategies and controller behaviour to be tested and validated under realistic dynamic conditions before implementation on the actual plant.



Depending on the configuration, the HydroPHIL platform can therefore be used to investigate:

- Rapid load changes and load rejection,
- Start-up and shutdown sequences,
- Water hammer, cavitation and water column separation,
- Grid-turbine interactions and frequency support,
- Control-system validation, controller tuning and stability margins.

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HydroPHIL turns extreme transient phenomena into measurable data, helping define how far operating limits can safely be extended.”

Hugo MESNAGE, Power Storage & Balancing R&D engineer



Key business benefits

- Identify critical transient risks before field implementation,
- Safely investigate extreme hydraulic scenarios without exposing a full-scale asset,
- Pre-validate control systems and advanced control strategies using HIL,
- Generate experimental data to validate and improve numerical models,
- Support the definition of safe operating limits for more flexible operation.

How does this translate into practice?

See case studies on the next page



Case study: investigate water column separation with Andritz



Increasing the power output of existing hydropower units can require higher flow rates, potentially reach the conditions for water column separation during load rejection.



Understanding this phenomenon and evaluating mitigation measures is therefore critical to control pressure surges and safely extend plant operating limits.

SuperGrid Institute worked with Andritz to investigate water column separation using the HydroPHIL test platform.

Tests were conducted on a Francis-type model-scale hydraulic circuit without a runner, combined with a long tailrace section to reproduce the inertia of the downstream water column.

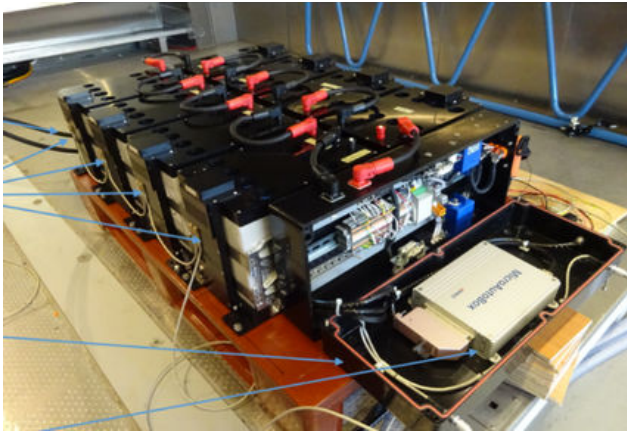
The campaign investigated the influence of key parameters — including initial flow rate, guide-vane closing rate, Thoma number and injected air quantity — on the resulting pressure surges, providing experimental evidence to better understand the phenomenon, assess mitigation strategies and support safer uprating decisions.

Case study: Validating hybrid control strategies with LOLABAT



As part of the European LOLABAT project, SuperGrid Institute investigated how battery hybridisation could extend the operating range of hydropower plants and provide greater flexibility to the grid.

Using the HydroPHIL Hardware-in-the-Loop environment, a 10 kW / 10 kWh Nickel-Zinc battery system was integrated with a simulated hydropower plant and coordinated through an Energy Management System. This configuration enabled the control logic, power-sharing strategy and dynamic response of the hybrid asset to be tested and validated under representative operating conditions before field implementation.



The demonstrated strategy alternated the turbine between **minimum-power operation and shutdown**, while the battery compensated for the resulting power variations. From the grid perspective, the combined system could therefore provide **continuous power delivery between zero and the turbine's minimum operating power**, effectively extending the usable operating range of the hydropower plant.

5. Exploring future efficiency pathways with riblet surfaces

Understanding force behaviour and scale effects (Bilasurf project)



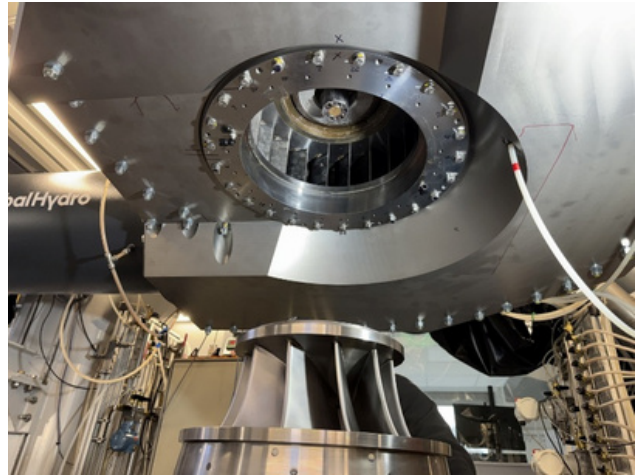
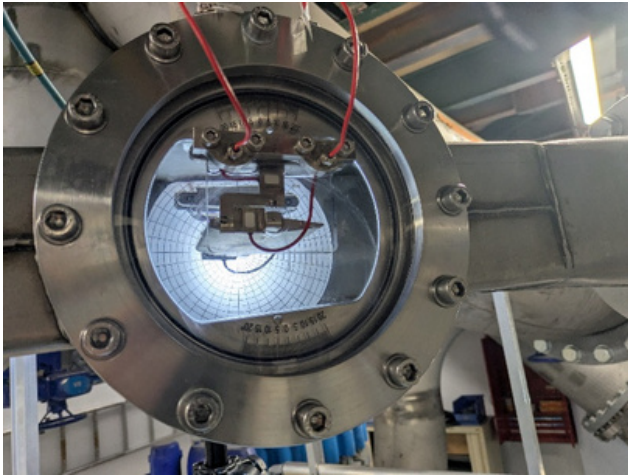
Within the BILASURF project (Bio-inspired Laser functionalisation of complex 3D industrial SURfaces), SuperGrid Institute and its partners investigated bio-inspired riblet surfaces to improve the hydraulic performance of turbine components.

Inspired by shark skin, microscopic grooves are applied to hydrodynamic surfaces to modify near-wall turbulence and potentially reduce friction losses and improve efficiency.

The technology was experimentally evaluated on smooth and ribleted hydrofoils at two different scales, under flow velocities up to 12 m/s and incidence angles from -15° to $+15^\circ$. Drag and lift measurements were compared with CFD (Computational Fluid Dynamics) predictions to quantify performance gains, investigate scale effects and assess the robustness of numerical optimization.

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Experimental & numerical approaches developed and applied by SuperGrid Institute Hydropower team



The methodology is now being extended towards turbine-relevant geometries, including guide vanes, supporting the transfer of the technology from experimental validation towards industrial application.

Low-flow duct measurement section

The low-flow section of SuperGrid Institute's IEC 60193 platform enables accurate characterisation of components at reduced discharge without affecting the main loop. It provides dual flow measurement with 0.2% precision. This setup was used to evaluate the Bilasurf guide vane profiles under controlled low-flow conditions. The experimental results revealed a strong scale effect, showing that riblet performance depends significantly on the relative size of the riblets compared with the guide vane profile.

“

Innovation creates value when experimental testing turns promising concepts into proven performance.”

Jean-Pierre PAYRE, Senior Project Management Advisor



Key business benefits

- Assess emerging efficiency-improvement technologies,
- Quantify performance gains before industrial deployment,
- Prioritize innovations supported by experimental evidence,
- Explore long-term pathways to increase asset value.

6. Hybrid hydro-storage solutions

Combining hydropower plants with Battery Energy Storage Systems (BESS) creates a highly flexible hybrid asset able to respond to grid requirements across multiple timescales.

While batteries provide fast-response power and high-performance grid support, hydropower contributes long-duration storage, energy shifting capabilities and proven reliability. Coordinated through an advanced Energy Management System (EMS), both technologies operate as a single flexible asset.

This hybrid approach can:

- Improve frequency response and grid stability,
- Facilitate the integration of variable renewable energy,
- Optimise water resource utilisation,
- Reduce stress on hydraulic equipment during rapid operating changes,
- Increase the value and flexibility of existing assets.



Where hydro-BESS hybridisation creates value

Context	Challenge	Value of Hydro + BESS
Isolated or island grids	Low inertia, renewable variability and power quality issues	Improve frequency stability, maximize renewable penetration and reduce reliance on diesel or gas generation
Renewable-rich power systems	Increasing solar and wind variability	Smooth fluctuations and improve dispatchability
Hydropower plants with operating constraints	Dead bands and ramp-rate limitations	Extend the effective operating range while preserving equipment
Ancillary services markets	Fast response requirements	Combine battery responsiveness with the long-duration capability of hydropower
Refurbishment and flexibility upgrades	Need for greater flexibility without major asset replacement	Unlock additional flexibility while leveraging existing infrastructure
Mini-PSP and distributed energy systems	Local balancing and renewable integration challenges	Improve local flexibility and project economics

Expanding the usable operating range

Many hydropower plants include operating restrictions or dead bands caused by hydraulic, mechanical or control-system limitations.

Through advanced control solutions validated using dedicated simulation and testing platforms such as HydroPHIL, SuperGrid Institute helps operators identify and safely expand their usable operating range.

The result is a more responsive and flexible asset, capable of delivering additional services to the grid while maintaining reliable operation and preserving equipment lifetime.

From assessment to implementation

Whether the objective is to extend the operating range of an existing hydropower plant, evaluate a refurbishment program or assess the value of a hydro-BESS hybrid solution, SuperGrid Institute provides the technical evidence required to support strategic decisions. By combining experimental testing, dynamic simulations and engineering expertise, we help stakeholders identify safe operating zones, quantify risks and priorities the most effective flexibility upgrade pathways.

Key business benefits

- Unlock additional flexibility and value from existing hydropower assets
- Improve participation in ancillary services and flexibility markets
- Support higher renewable energy penetration while maintaining grid stability
- Enable evidence-based refurbishment and upgrade decisions

Case study: Meridiam | Hybrid pumped-storage and battery system for Martinique



Meridiam developed a pumped-storage hydropower project in Martinique featuring **7 MW generating capacity, 4.6 MW pumping capacity and 4-hour storage capability**. The project was designed to support a power system characterized by low inertia and increasing shares of renewable generation.

A standalone pumped-storage plant could not fully address the stringent grid-code requirement for very fast frequency response. To meet these requirements, the project evaluated the hybridization of the pumped-storage facility with a Battery Energy Storage System (BESS).

In this configuration, the battery delivers the immediate response required by the grid, while the pumped-storage plant provides long-duration storage and energy shifting capabilities. Coordinated through an advanced control architecture, both assets operate as a single flexibility resource.

This approach demonstrates how hybrid hydro-storage solutions can enhance grid stability, facilitate renewable energy integration and maximize the value of hydropower assets in isolated and renewable-rich power systems.

Use case: Mini-PSP using existing snowmaking reservoirs in the Alps

Mountain areas face growing electricity needs, increasing renewable generation and constrained grid infrastructure, creating a need for local flexibility and energy storage.

SuperGrid Institute is assessing Mini-PSP (Pumped Storage Plant) solutions using existing snowmaking reservoirs and hydraulic infrastructure to provide energy storage and grid support while preserving other water uses such as snowmaking, irrigation and firefighting.



Several projects in the French Alps are being evaluated to optimise system design, coordinate multiple water uses and assess technical feasibility, grid services and economic value.

The objective is to turn existing mountain infrastructure into a multi-purpose flexibility asset with limited additional environmental impact.

7. Conclusion

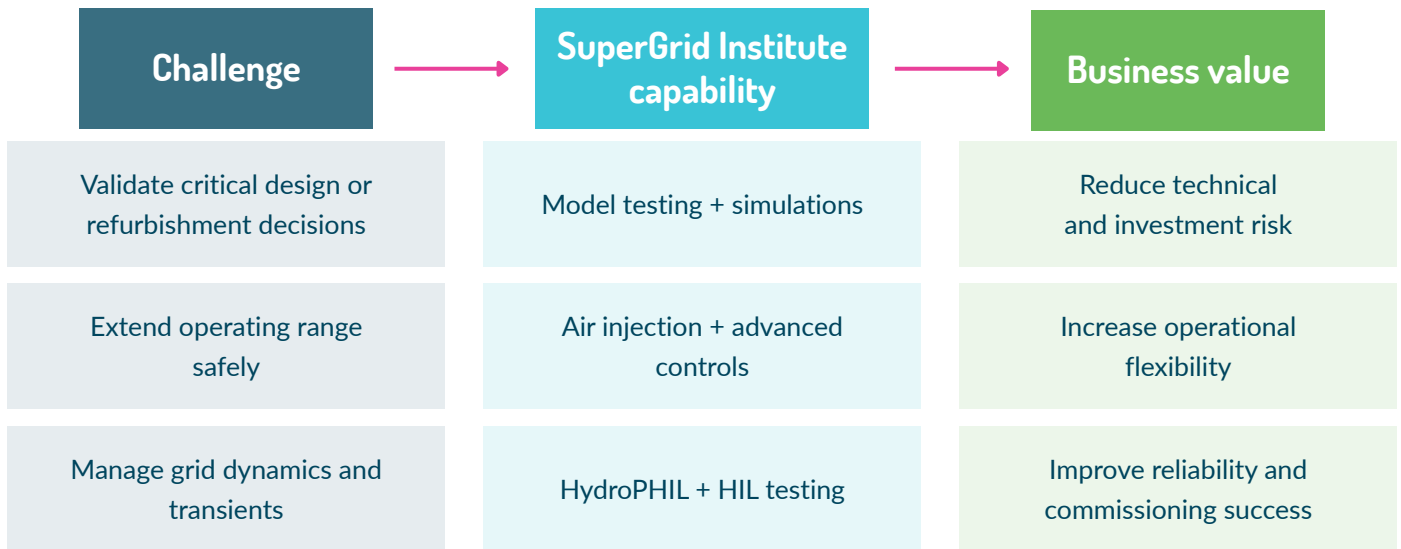
Hydropower is no longer evaluated solely on efficiency. Asset owners increasingly need to understand how far flexibility can be extended without compromising reliability, lifetime or profitability.

Combining testing, modelling and system-level analysis enables stakeholders to make informed decisions, reduce uncertainty and unlock new sources of value from existing and future hydropower assets.

As flexibility becomes a key requirement of modern power systems, hydropower will remain a strategic enabler of the energy transition.

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Discuss your hydropower challenge with our experts

We would be very interested to hear your feedback on the ideas in this paper and about your own related experiences.

Whether you are designing a new turbine, assessing an innovation pathway or evaluating the flexibility potential of an existing asset, our team can help you identify the right testing and modelling approach.

Contact us

Contact our hydro power expert

Camille Prud'Homme, Business Development Manager

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About the author

Sylvain Grillet is Director of the Hydropower Department at SuperGrid Institute. With more than 15 years of experience in hydropower, energy storage and power system flexibility, he supports utilities, manufacturers and project developers in addressing the challenges of the energy transition.



Before joining SuperGrid Institute, Sylvain held several technical and leadership positions within General Electric, covering power electronics, rotating machines, battery energy storage systems and hydropower digitalisation. He notably led the development and deployment of predictive maintenance and flexibility solutions for hydropower producers worldwide.

Today, his work focuses on hydropower flexibility assessment, hydro-storage hybridisation, dynamic simulation and advanced testing methods that help operators optimise asset performance, extend operating ranges and increase renewable energy integration.

About SuperGrid Institute

SuperGrid Institute is an independent research and innovation center dedicated to the development of technologies supporting the future of electrical systems. Within this framework, the Hydropower team focuses on the performance, flexibility and reliability of hydraulic assets across their full operating range.

Our activities cover experimental testing, numerical modelling and system-level analysis. We operate IEC 60193-compliant hydraulic test platforms, low-flow measurement facilities and hardware-in-the-loop environments for dynamic behaviour assessment. These capabilities support the study of hydraulic performance, unsteady phenomena, control strategies and flexibility enhancement.

We collaborate with utilities, manufacturers, EPC contractors and project developers to evaluate and optimise hydropower units, whether associated with renewable integration, storage applications or conventional operation. Our work contributes to improving the operational range, responsiveness and long-term reliability of hydropower assets in an evolving energy landscape.

SuperGrid Institute Hydropower test platforms

HydroPHIL: real-time & transient testing

www.supergrid-institute.com/test-platforms/hydrophil/



Independent hydraulic machines test rig

www.supergrid-institute.com/test-platforms/hydraulic-machine/



Let's tackle your hydropower challenges together.