Experimental facility for reduced scale model testing of hydraulic machines hybridized with a battery energy storage system

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Abstract. With a continuously growing share of non-dispatchable renewable energy sources in the power mix, flexibility in hydropower provision is becoming fundamental. The major role played by hydropower in frequency regulation in the last years has underlined the possible drawbacks of fast regulation impacting the hydraulic system health. Two of the most promising solutions to address this problem are the hybridisation of hydropower with battery energy storage systems and the variable speed technology. Batteries have already proved to be able to provide multiple services to the power system, and their coupling with hydropower is a possible interdisciplinary solution to increase flexibility provision in power systems. In this respect, one of the main challenges to address is the control of the hybrid system. While research is heading towards this direction, it becomes necessary to have experiment facilities able to test and validate the upcoming solutions. Testing platforms are nowadays decoupling the hydraulic and the electric components, testing them separately, therefore, they are not suitable for the validation of the control strategy under real grid conditions. The scope of this paper is to present an experimental facility where different joint control techniques can be tested on reduced scale models of hydraulic machines hybridized with a battery energy storage system. The presented test-rig combines all the fundamental components, both on the hydraulic and on the electrical side, within the same testing facility. The platform is an adaptation of the already existing laboratory of hydraulic machines at EPFL in Switzerland.
1. Introduction
The integration of Renewable Energy Sources (RES) in the European power mix has long been ascertained as a fundamental step in the EU decarbonisation process [1]. Moving towards this direction raises multiple challenges for the Electrical Power System (EPS), in particular the need for power balancing and flexibility services provision to mitigate the massive integration of non-dispatchable RES. Hydropower plants (HPPs) have been playing a major role in frequency regulation [2]. Nevertheless, some difficulties are encountered when providing flexibility with HPPs, impacting the residual lifetime of the hydroelectric unit components. According to [3], the enhancement of the frequency control action of hydropower plants has a considerable effect on the wear and tear of the hydraulic system. The main problems are encountered with the wear on the guide vane and runner bearings. In particular, the wear on Kaplan turbine runner bearings is critical since they are situated inside the waterway and therefore are costly to maintain. The existing literature [3-7] showed the impact of continuous movement of the guide vanes and blades of Kaplan turbines regulating mechanisms due to FCR provision on the wear and tear of the regulation components of hydroelectric units. Hydraulic turbines are also known for suffering load variations in off-design condition and fast regulation since they are not designed for such operating conditions [4, 8]. In particular, the provision of FCR is responsible for: (i) an increase of wear and fatigue [3-5] and (ii) a decrease in the machine performance, especially in terms of efficiency [9].

Batteries have proved to be able to provide multiple services (i.e. frequency containment reserve, voltage control, etc.) to the EPS [10, 11]. Nevertheless, the main limitation of this technology is the finite amount of energy they can store. The applications of batteries in power systems are becoming of increasing interest thanks to their decreasing cost, particularly lithium-ion technologies, and high ramping duties compared to conventional generation units, such as hydropower. To overcome the limitation of both technologies challenges, hybrid power plants featuring Battery Energy Storage Systems (BESS) are drawing increasing attention as possible solutions by both researchers [12] and industries [13]. This hybridization consists of coupling a grid-connected BESS with an existing HPP. The battery fast response time enables the control of power set-point trajectories for reducing the wear and tear of hydraulic components and minimizing start-and-stop operations, which increases the lifetime of the HPPs and improves their availability by decreasing the outage time due to maintenance. On the other side, the BESS system can overcome the problem of limited capacity, by counting on the hydropower unit support to operate continuously. The hybridisation appears to be particularly suitable for Kaplan turbines due to their slower response compared to Pelton and Francis-type turbines and pump-turbines. Integration of battery Hybrid units is expected to bring a step beyond the state of the art of HPP operation by actuating power set points with a response time of a few seconds, compared to conventional hydroelectric technologies, which are typically slower.

Since each single technology (BESS and HPP) have been developed and improved for years, the main challenge to address is the coupling of the two, and, in particular, the control of the hybrid system. To test and validate the developed control strategy and to study the behaviour of the hydraulic system, an experiment facility to study and validate the upcoming solutions is required. Nowadays, testing platforms are decoupling the hydraulic and the electric components, testing them separately and making difficult the validation of joint control of a hybrid system. The scope of this paper is to present an experimental facility where different joint control techniques can be tested on reduced scale models of hydraulic machines hybridized with an integrated BESS. The presented test-rig combines all the fundamental components, from water to grid, within the same testing facility. It allows for reproducing the grid behaviour under different conditions, to study the dynamic of the hybrid system and to test different control strategies to optimize the operation of both the hydraulic machine and the battery by maximizing the provision of ancillary services. In Section [2], the experiment platform is presented, while the experiments to be conducted are presented in Section [3].
Finally, a summary is given in Section 4.

2. Test-rig Characteristics

2.1. State of the Art

The hybrid experimental platform modernizes an existing platform in the Plateforme Technologique Machines Hydrauliques PTMH, at EPFL. The current platform, PTMH-PF3, illustrated in Fig. 1, is a closed-loop test-rig that allows for performance assessments of hydraulic machines in the four-quadrant characteristic curve within an accuracy of 0.2 %, complying with the IEC60153 standard for reduced scale physical model testing. It features a 300-kV DC generator connected to the model runner to regulate the rotational speed up to 2500 min\(^{-1}\). The specific hydraulic energy in the closed-loop test-rig is generated by two 400kV centrifugal pumps which can be connected in parallel or series depending on the required specific energy. They allow for a maximum head of 100 m and a maximum discharge of 1.4 m\(^3\)s\(^{-1}\). Furthermore, the pressure in the draft tube is set by adjusting the pressure in the downstream reservoir by using a vacuum pump.

2.2. Innovative setup

As previously stated in Section 1, the upgrade of the testing facilities consists of the integration of the hydraulic test-rig with a BESS and with an electrical subsystem capable to simulate a realistic grid connection of the system. The novel setup and the differences with the state of the art are presented in Fig. 2. As shown in the figure, the new configuration does not replace the current test-rig but incorporates the existing facility by allowing for switching between the two configurations depending on the experimental tests to be performed. The mechanical coupling of the reduced scale model can be linked with either the 300 KW DC motor-generator for performance assessments of the hydraulic machines, or with the 100 KW AC synchronous generator for testing control strategies.

In the upgraded configuration, the turbine is coupled with a synchronous motor-generator, employed in the large majority of the existing full-size hydropower units. The synchronous machine allows for testing in the reduced scale model facility the provision of ancillary services, such as voltage control, and provides inertia to the system. Moreover, it provides precious insights into the behaviour of the unit facing frequency disturbances generated by the grid emulator. To perform the tests related to variable speed units, the generator has been specially designed to withstand continuous operation around the nominal operating speed (1500 rpm for 50 Hz supply) within 10% of speed variation. A BESS is located in parallel with the synchronous generator so that the power flow at
the grid connection point is dispatched between the hydraulic machine and the battery. To test different control frameworks under the same grid conditions, the platform features a grid emulator (REGATRON). This component can reproduce different grid scenarios, especially frequency and voltage disturbances, to test grid regulation services. It is fundamental to evaluate the performance of different control techniques and to test them under different scenarios. Nevertheless, by operating a system of different switches, it is possible to bypass this grid emulator and connect the hybrid platform directly to the real grid. This allows performing the tests at several power levels which are above the nominal power of the grid emulator. Finally, a full quadrant converter, also known as Full-Size Frequency Converter (FSFC) will be exploited for the variable speed tests. The FSFC is located between the grid-emulator and the motor-generator but it can also be bypassed for testing the hybrid configuration with a fixed speed hydraulic machine. Since the variable speed technology represents one of the most up-to-date technologies in the hydropower sector, it has been chosen as a reference for evaluating the performance of the hybrid HPP control. The characteristics of the electrical components of the new facility are listed in Table 1.
Grid Emulator

| Characteristic                               | Value              |
|----------------------------------------------|--------------------|
| Maximum AC apparent power                    | 100 kVA            |
| Rated AC grid voltage                        | 400 V              |
| Rated grid frequency                         | 50 Hz              |
| Operation on 4 AC quadrants                  | Required           |
| Output voltage range (line to neutral)       | 0-300 Vrms         |
| Output frequency range of the fundamental    | 0-500 Hz           |
| Minimal output frequency range of the harmonics | 0-1500 Hz         |

Synchronous Motor-Generator

| Characteristic                               | Value              |
|----------------------------------------------|--------------------|
| Nominal power                                | 100 kVA            |
| Nominal rotational speed                     | 1500 rpm           |
| Rated speed for continuous operation         | [1350 – 1650] rpm  |
| Critical rotational speed                    | 2200 rpm           |
| Number of poles’ pair                        | 2 pair of poles    |

Battery Energy Storage System

| Characteristic                               | Value              |
|----------------------------------------------|--------------------|
| Nominal Capacity BOL                         | 92.3 kWh           |
| Maximum AC apparent power                    | 100 kVA            |
| Rated AC grid voltage                        | 400 V              |
| Rated grid frequency                         | 50 Hz              |
| Operation on 4 AC P/Q quadrants              | Required           |
| Distortion factor (THD)                      | <5%                |
| Full controllability in CSI and VSI mode     | Required           |

Table 1. Characteristic of the different components of the test-rig

3. Innovative experimental design
The structure of the testing facility allows performing multiple tests, intending to compare different hardware configurations and control techniques under the same grid conditions. In particular, the topology of the test-rig can be modified by maneuvering nine different switches (S1-S8, Sc) and obtaining different testing configurations. The switch combinations, for each test-rig configuration, are presented in Table 1.

3.1. Baseline Setup
In the existing platform configuration, reduced scale model tests of the hydraulic machine can be performed for several purposes. This baseline configuration of the platform allows for performance tests, suitable to measure the efficiency hillchart, the cavitation limits, and the critical pressure fluctuations in the hydraulic machine over the full operating range of the hydraulic machine. These tests can be performed in both steady conditions and during transient operations. Furthermore, a dedicated shaft allows for on-board measurements on the runner to perform experiments on the structural loads on the runner blades. All these features and capabilities of the baseline setup will be integrated into the new configuration.

3.2. BESS Setup
The BESS setup represents the hybridization scenario, where the BESS is connected in parallel with the synchronous generator as shown in Fig. 3(a). Particular attention will be paid to this
configuration. The objective of the tests run in this setup is to investigate the upgraded potential of a battery storage system integration in HPPs and the performances of the control strategy. These tests are essential to validate the best control framework which defines the optimal sizing of the battery storage system to increase the potential and benefits of the hybridisation. In order to study the optimal BESS sizing based on the developed control algorithms, the BESS of the test-rig is oversized in respect to the power of the reduced scale model hydraulic machines: the power ratio of the two components is equal to 1. During tests, the battery size can be modified via software depending on the needs, by shrinking the capability curve of the BESS and constraining the maximum and minimum state of charge to different values within the available range. Furthermore, this configuration will allow quantifying the benefits of the hybridization by measuring the wear and tear reduction on the components of the hydraulic machines by measuring the components mileage and fatigue. These tests can be performed for both the steady operations and during transients. Therefore, the joint control of the hybrid system will be a multi-objectives control strategy expected to fulfill the following expectations:

- The system is expected to increase the promptness of the hydropower plant for frequency support thanks to the storage battery system
- Improve the time response for FCR of the system
- The number of turbine governor maneuvers is expected to be reduced
- The reduction of outage time due to battery hybridisation is expected to increase the generation.

For experiments where the power exceeds the nominal power of the grid emulator, or to test the hybrid unit directly connected to the grid, the grid emulator can be bypassed (acting on S1, S2, S3). This variation of the BESS setup is named "BESS Setup - grid".

### Table 2. Switches configuration for the different testing setups

| Switch | Baseline Setup | BESS Setup | FSFC Setup | BESS Setup - grid | FSFC Setup - grid | Black start |
|--------|----------------|------------|------------|-------------------|-------------------|-------------|
| S1     | OFF            | ON         | ON         | ON                | OFF               | OFF         |
| S2     | OFF            | ON         | ON         | OFF               | OFF               | OFF         |
| S3     | OFF            | OFF        | OFF        | ON                | OFF               | OFF         |
| S4     | OFF            | ON         | ON         | OFF               | OFF               | OFF         |
| S5     | OFF            | OFF        | ON         | OFF               | ON                | OFF         |
| S6     | OFF            | ON         | OFF        | ON                | OFF               | OFF         |
| S7     | OFF            | OFF        | ON         | ON                | OFF               | OFF         |
| S8     | OFF            | ON         | OFF        | ON                | OFF               | ON          |
| Sc     | OFF            | ON         | ON         | ON                | ON                | ON          |

3.3. FCFC Setup

The FSFC Setup represent the variable speed scenario, where the BESS is disconnected, and the synchronous generator is connected to the full-size frequency converter as shown in Fig. 3(b). This setup will allow developing the optimal control framework for variable speed hydroelectric units, and as a benchmark to compare the performance of the hybrid setup with the state of the art. Similarly to the BESS setup, the benefits of the variable speed technology will be evaluated by quantifying the hydraulic component's fatigue during both steady operation and transients sequences, such as start-up and stops. As for the BESS Setup, the grid emulator can be bypassed. This variation of the FSFC setup is named "FSFC Setup - grid".
3.4. Black start
Finally, the Black Start setup considers the synchronous generator only connected with the BESS. The ability of the system to start-up off-grid will be tested. The BESS will be therefore tested in grid-forming mode, to provide the synchronous generator with the power supply required in the start-up process.

![Diagram](image)

**Figure 3.** Innovative experimental facility for reduced scale model testing of hydraulic machines (a) hybridized with a battery energy storage system (b) with full size frequency converter.
4. Conclusions
In this paper, the design of an experimental facility for reduced scale model testing of hydraulic machines hybridized with a battery energy storage system is introduced. The capabilities of this upgraded platform and the type of tests that can be performed are also detailed. The presented test-rig combines all the fundamental components on a hydroelectric unit, both the hydraulic and the electrical components, within the same testing facility. In such a facility, several testing conditions can be performed to investigate the behaviour of hydroelectric units providing ancillary services to the power system under different control frameworks. Furthermore, it will be possible to validate and quantify the benefits of the hybridization of a hydraulic unit with battery energy storage systems, as well as the advantages of the variable speed technology. Particular attention will be paid to the joint control strategy of hybrid systems, expected to increase the promptness of the hydropower plant for frequency support while maximizing the residual lifetime of the hydraulic machine. Finally, a high level of versatility of the platform allows testing different turbine types, therefore investigating the potential of the hybridization solutions for several types of hydropower plants.

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