Integration of Run-of-River/Pumped Hydro with an Energy Storage System Based on Batteries and Supercapacitors for Enabling Ancillary Services and Extending the Lifetime of Generating Equipment

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Abstract This chapter explores the integration of run-of-river and pumped-storage hydroelectric power plants with lithium-ion batteries and supercapacitors to enhance frequency regulation while minimizing mechanical stress on hydropower units. Hydroelectric plants play a key role in grid stability, but frequent power adjustments required for ancillary services accelerate wear and tear on their mechanical components. The proposed hybrid system follows a cascading control approach, where each energy storage element protects the next: lithium-ion batteries handle medium-term power fluctuations, reducing the need for constant hydro unit adjustments, while supercapacitors absorb rapid transients, shielding both the batteries and the hydro units from excessive cycling and mechanical fatigue. This setup improves the efficiency and lifespan of all components while enhancing the plant's ability to participate in ancillary service markets. The chapter reviews state-of-the-art solutions and presents a detailed analysis of technical requirements for hybrid hydropower-storage systems. It also discusses results from simulations and laboratory tests that validate the effectiveness of the proposed configuration. Findings indicate that integrating batteries and supercapacitors with hydropower can significantly improve frequency regulation quality, extend asset lifespan, and facilitate higher penetration of renewable energy sources, making hybrid hydropower systems a crucial component of future power grids.

Keywords Hydroelectric power plant · Lithium-ion battery · Supercapacitor · Frequency regulation · Hybrid energy storage

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1 Case Study Description and State-of-the-Art

Electric power systems have suffered severe changes over the last decades, mainly related to the increasing integration of non-dispatchable renewable generation units, large nondeferrable loads (e.g. fast charge of electric vehicle fleets), and other actors such as energy storage systems. This paradigm, where imbalances between power generation and consumption can happen all of a sudden and are hardly predictable, forces the electric power system (namely the transmission system operator and distribution system operator) to make use of the ancillary services at its disposal in order to keep the power quality within the safe operation range. Among those ancillary services, the ones related to the frequency control are typically provided by the power generation units and energy storage systems.

Hydroelectric power plants have historically taken a strong share in relation to frequency control ancillary services. In this sense, a hydroelectric power plant is forced to adjust its generation power when providing primary and secondary frequency control, causing wear and tear to the different mechanical parts (moving components of the hydro-mechanical governors). In the new paradigm of electric power system, the needs of providing frequency control are continuously growing and, thus, the lifespan of hydroelectric power plants is being compromised.

Several solutions have been proposed in the literature for solving the issues associated with the hydroelectric power plants' frequency control. The most relevant alternatives integrate energy storage systems with the hydroelectric power plant, with the aim of extending the lifetime of the hydropower units, enlarging the plant's active power regulation capacity, enhancing the quality of the frequency control provided by the plant, and increasing the revenue that the plant obtains from the energy and ancillary services markets.

In 2007, the Pacific Northwest National Laboratory (PNNL) started a project for the Bonneville Power Administration (BPA) aimed to address the issue of mitigating additional variability and fast ramps that occur at higher penetration of variable resources, including wind generation in the BPA and California independent system operator (CAISO) control areas, through the energy exchange between the control areas and through the use of energy storage and other generation resources. In Phase 1 of the abovementioned project, the PNNL developed a control algorithm for an aggregate regulating unit (a hydropower unit and a flywheel) to track the area control error (ACE) signal while minimizing the quadratic deviations of the flywheel State of Charge (SOC) and the power generated by the hydropower unit, with respect to a target SOC and the power generated by the hydropower unit at the best efficiency point. The analyzed flywheel had a power rating of 7.5–12.5% of that of the hydropower unit. The algorithm was tested by simulations and provided satisfactory results, which are summarized as follows: the unit provided a robust and accurate signal tracking; the flywheel contributed to operating the hydro unit near its best efficiency; the hydro unit contributed to maintaining the flywheel's SOC within a specific range. In the second phase of the project, the PNNL tested the algorithm by means of hardware-in-the-loop simulations. Findings are detailed in Makarov et al.

(2008), Lu et al. (2010) and Jin et al. (2011). For this purpose, the research team of the project used a Beacon Power's flywheel (25 kWh, 100 kW). Some years later, the control algorithm was revised and improved as presented in Jin et al. (2013). The algorithm used a SOC band control to give the flywheel priority to follow the regulation signal and thus further reduce the frequency of the hydro unit output adjustment. As long as the flywheel SOC is within a specific band, the flywheel takes over the responsibility to follow the ACE signal. The hydro unit provides frequency regulation only when the flywheel SOC is outside the band. The original control algorithm required the hydro unit to adjust its output every 4 s, whereas the improved version required less than one adjustment per hour. A patent entitled "Controller for hybrid energy storage" (US 8,754,547 B2), was developed based on this concept.

In 2014, the project's team began working on the control and sizing of a flywheel energy storage system for the frequency control of El Hierro system. A droop-based control strategy, similar to the one implemented in the Rhode hybrid test facility (Ortega and Milano 2016), as well as a nonlinear proportional control strategy which modifies the input/output power set-point signal of the flywheels as a function of the SOC, were tested by means of simulations. The frequency regulation effort was distributed between the flywheels and the pumped-storage power plant thanks to the use of different control dead bands. The results of the study were presented in Sarasúa et al. (2016) and point out that in El Hierro system a small flywheel energy storage system with an installed power capacity of 3% of that of the pumped-storage power plant contributes to notably reduce the amplitude of frequency deviations caused by wind generation variability, and to integrate more wind power in the system at a reasonable cost. The results also highlight the importance of the control strategy of the flywheel energy storage system in order to maximize the effective integration of wind generation.

Moghaddam and Chowdhury (2016) presented a method for the optimal sizing of a hybrid power plant comprising pumped-storage and a sodium sulfur battery so as to reduce the wind power imbalances in the BPA control area. The results presented in the paper showed that the storage capacity required for the hybrid power plant to compensate for the wind power forecast error is smaller than the one required when only one of the storage systems is utilized. Gevorgian et al. (2017) worked on the coordinated operation of a variable-speed run-of-river hydropower plant and a supercapacitor energy storage system for the provision of frequency regulation. The results presented in the paper demonstrated that the suggested coordination strategy between the supercapacitor energy storage system and the hydropower plant can help increase the quality of the system's frequency. Laban (2019) developed two control algorithms for the real-time energy management of a hybrid power plant comprising hydropower and Li-ion batteries. The hybrid power plant is assumed to provide frequency containment reserves for normal operation (FCR-N) in the reserve market operated by Svenska Kraftnät. Laban (2019) concluded that the hybrid power plant is able to provide the same amount of FCR-N as the hydropower plant, with a much lower wear and tear of the hydropower units.

Guezgouz et al. (2019) and Javed et al. (2020) presented two optimization algorithms for the hourly power dispatch of a hybrid power plant comprising a pumped-storage power plant and a Li-ion battery energy storage system (BESS). The hybrid power plant is assumed to be connected to an isolated power system which is exclusively fed by variable renewable generation. Both articles concluded that with a proper power dispatch algorithm the hybrid power plant helps increase the reliability of the electricity supply in the systems under study. Parastegari et al. (2015) developed an optimization model for the generation scheduling of a hybrid power plant comprising a pumped-storage power plant and a BESS. The hybrid power plant is assumed to operate in a coordinated fashion with a set of wind and solar PV power plants. The results presented by Parastegari et al. (2015) demonstrate that with the help of a proper scheduling model the hybrid power plant can contribute to increase the profit of the wind and solar PV plants. Dawn et al. (2018) presented an optimization model for the hourly power dispatch of a hybrid power plant comprising a pumped-storage power plant and a generic converter-interfaced energy storage system. The hybrid power plant is assumed to operate in a coordinated fashion with a thermal power plant and a set of wind and solar PV plants. The results obtained by Dawn et al. (2018) showed that with a proper power dispatch model, the hybrid power plant contributes to increasing the profit of the thermal and renewable power plants. Pérez-Díaz et al. (2020) discussed the benefits of the integration of flywheels in pumped-storage power plants for the enhancement of the quality of the system's frequency in a scenario of high renewable penetration. Román et al. (2019) suggested the possibility of coordinating the operation of a hydropower plant and the batteries of a fleet of electric vehicles to modulate the fluctuation of the flow released by the hydropower plant. Thus, the environmental impact of hydropeaking on the river reach downstream of the hydropower plant is mitigated. Anindito et al. (2019) compared the use of batteries and re-regulation reservoirs for the mitigation of the environmental impact of hydropeaking. Anindito et al. (2019) concluded that batteries can help mitigate the environmental impact of hydropeaking as effectively as a re-regulation reservoir, though their feasibility strongly depends on the prices of the energy and ancillary services markets.

Bucher and Schreider (2017) discussed the benefits of the coordinated operation of a pumped-storage power plant and a BESS for the provision of frequency containment reserves (FCR) in the market currently implemented in Central Europe. Bucher et al. (2018) describe the Li-ion BESS (12.5 MW/13 MWh) that the company ENGIE integrated in 2017 in the Pfreimd pumped storage system. The batteries operate in a coordinated fashion with several ternary pumped-storage units. The latter are used to charge/discharge the batteries when the SOC is lower/higher than 25%/75% so as to meet the requirements for participation in the FCR market. FORTUM company integrated a Li-ion BESS (5 MW/6.2 MWh) in the Forshuvud run-of-river hydropower plant in 2019. The batteries provide FCR-N in the reserve market operated by Fingrid. FORTUM uses the hydropower units as backup reserve when the BESS cannot provide FCR-N as required by Fingrid because of having reached the maximum or minimum SOC.

Eiper et al. (2019) described the advantages of ANDRITZ company Hydro's HyBaTec product (ANDRITZ 2024). It consists in the integration of a Li-ion BESS in a hydropower plant and its control system to extend the lifetime of the hydro units and maximize the plant's revenue. Eiper et al. (2019) illustrate some advantages of the HyBaTec product by simulating the coordinated operation of a run-of-river hydropower plant and a Li-ion BESS for the provision of FCR. The results of the simulations show that the coordinated operation allows reducing the wear and tear of the hydro units. ANDRITZ Hydro is involved in the XFLEX HYDRO H2020 project (https://xflexhydro.net/) in which the coordinated operation of a run-of-river hydropower plant and a Li-ion BESS is being demonstrated in an operational environment. The French Alternative Energies and Atomic Energy Commission (CEA) integrated in 2021 a 600 kW Li-ion BESS in EDF's Vogelgrun run-of-river hydropower plant which is equipped with 4 35.5 MW low head Kaplan turbines. ANDRITZ Hydro has developed the control system of the hybrid power plant and a digital twin of the plant for the real-time assessment of the Kaplan units' wear and tear.

Verbund company integrated in 2020 a Li-ion BESS (8 MW/14 MWh) in the Wallsee run-of-river hydropower plant, which is equipped with 6 Kaplan turbines, of 35 MW each.

As discussed above, the solutions explored in the literature integrate a BESS (Battery Energy Storage System), supercapacitors (SC), or flywheels with hydropower units to address the issues mentioned earlier. Among these energy storage technologies, BESS stands out as the most effective one in extending the lifespan of a hydroelectric power plant and enhances its regulation capacity across a wider range of events and situations, due to its higher energy density. However, it is well known that BESS units experience aging, which is influenced by cycling and environmental conditions. As a result, the lifespan of a combined hydropower and BESS plant is not only constrained by the wear and tear of the hydro unit, but also by the aging of the BESS, which can accelerate significantly in scenarios with high penetration of non-dispatchable renewable energy sources.

Therefore, it is crucial to analyze the combined integration of BESS and fast response energy storage systems (FRESS) with a hydropower plant operating in cascade. In this configuration, the BESS and FRESS protect the hydropower system from rapid power fluctuations, while the FRESS also shields the BESS from excessive aging due to frequent cycling.

2 Technology Neutral System Requirements

From a technology-neutral perspective, this case study explores the hybridization of a large-scale energy generation system, such as a hydroelectric plant (with a focus on run-of-river and pumped-storage types), with additional elements to reduce the fatigue (wear and tear) of its mechanical components when providing ancillary regulation services. Simultaneously, the integration of new energy storage systems should extend and enhance the regulation capacity of the original technology, potentially opening access to new markets for ancillary services.

Hydroelectric plants are capable of generating substantial amounts of power and energy, and they play a critical role in grid services such as frequency regulation, reactive power provision, and black start capability. However, reducing the mechanical fatigue associated with these services requires smoothing the hydro's response to power set-point changes. To achieve this, another system component must be introduced to provide or absorb the power that the hydro plant cannot manage at the point of common coupling (PCC). This additional element should be an energy storage system (ESS) with sufficient energy and power capacity to smooth the hydro's set-point curve over a desired time window, which could extend over several hours depending on the regulation service. Additionally, the ESS must have a faster response time than the hydro plant, as it needs to act more quickly than the hydro's mechanical components to protect them.

When integrating different technologies into a hybrid plant, the overall performance is constrained by the weakest component. Therefore, to reduce fatigue and extend the lifespan of the hydroelectric plant, the durability of the hybrid system will be limited by the lifespan of the ESS. Energy storage technologies capable of supporting hydro plants in providing ancillary services tend to have shorter lifespans. Devices with low aging rates typically have very low energy densities, while those with sufficient energy density are subject to significant aging. To address this, the case study examines the feasibility of hybridizing with not just one, but two different ESS types, each with complementary characteristics. In this way, the high energy density ESS can be protected by a low-aging ESS, which will also safeguard the other systems in the hybrid plant.

From a technical standpoint, the key requirements of a hybrid system comprising a hydro plant, a high energy density ESS, and a fast-responding ESS (FRESS) for reducing hydro fatigue while expanding its regulation capacity are time response and aging. From a general point of view, the technical requirements for both hybrid pumped hydro plant, and hybrid run-on-river plant are summarized in the next section (aging not included since it is highly dependent on the application and regulation services).

3 Hybrid Energy Storage Capabilities

To date, the most feasible hybrid power plant configuration combining hydro, a high-energy density ESS, and a FRESS consists of a hydro plant, Li-ion batteries, and supercapacitors. Analysing the components individually, their technical characteristics are summarized in the following tables (Tables 1 and 2):

Comparing the performance of the different elements, it is evident that both batteries and supercapacitors (see Tables 5 and 6, respectively) surpass the hydro units in terms of efficiency and response time (see Tables 3 and 4)—two critical factors for enhancing the hydro plant's regulation capacity and reducing mechanical stress.

Table 1 Hybrid pumped hydro plant requirements

Power capacity	50–500 MW
Storage capacity	> 8 h full load
Efficiency	> 80%
Reaction time (50–100%)	< 10 s
Reaction time (0–100%)	< 1 min

Table 2 Hybrid run-on-river plant requirements

Power capacity	10-100 MW
Storage capacity	> 1 h full load
Efficiency	> 80%
Reaction time (50–100%)	< 10 s
Reaction time (0–100%)	< 1 min

Table 3 Pumped hydro

Power capacity	50–500 MW
Storage capacity	> 8 h full load
Efficiency	70-75%
Reaction time (50–100%)	~ 15 s
Reaction time (0–100%)	< 2 min

Additionally, the long lifespan of supercapacitors makes them ideal for protecting both the hydro and the batteries during ramp-up events, preventing excessive aging and mechanical strain.

From the comparison of the technical requirements in Tables 1 and 2, it is clear that the inclusion of both batteries and supercapacitors alongside the hydro plant is sufficient to achieve the desired technical objectives.

Table 4 Run-on-river hydro

Power capacity	10-100 MW
Storage capacity	–
Efficiency	> 80%
Reaction time (50–100%)	~ 15 s
Reaction time (0–100%)	< 2 min

Table 5 Li-ion batteries

Power density	> 3000 W/kg
Energy density	> 280 Wh/kg
Efficiency	> 95%
Reaction time	< 1 s
Lifetime	> 5000 cycles

Table 6 Supercapacitors

Power density	> 20 kW/kg
Energy density	> 8 Wh/kg
Efficiency	> 98%
Reaction time	< 1 s
Lifetime	> 1 M cycles

4 Techno-economic and Sustainability Analysis

With the help of suitable control algorithms for the real-time energy management and optimization algorithms for the generation scheduling and redispatch, the coordinated operation of a hydropower plant (with or without pumping capability), Li-ion batteries and supercapacitors, can be beneficial from different perspectives.

For a reservoir hydropower plant, the proposed coordinated operation can contribute to the following: extend the lifetime of the hydropower units; enlarge the plant's active power regulation capacity; enhance the quality of the frequency control provided by the plant; increase the revenue the plant obtains from the energy and ancillary services markets; reduce the environmental impact in the river reach downstream of the plant.

For a run-of-river hydropower plant, the proposed coordinated operation can contribute to: extend the lifetime of the hydropower units; allow the plant to provide frequency control ancillary services and participate in the corresponding markets (or enlarge the plant's active power regulation capacity and enhance the quality of the frequency control provided by the plant); increase the revenue the plant obtains from the energy and ancillary services markets.

For a closed- or open-loop pumped storage power plant, the benefits are similar to those described for a reservoir hydropower plant. In addition, the proposed coordinated operation can contribute to increase the plant's energy storage capacity. In all these cases (reservoir, run-of-river and pumped-storage hydropower plant), the proposed coordinated operation can eventually contribute to improve the quality of the system's frequency.

Furthermore, the proposed hybrid power plant can contribute to mitigate the adverse effects of wind and solar generation variability and unpredictability by the coordination with wind and/or solar PV farms. These adverse effects are the imbalance costs and the impact on the system's frequency. To date, this impact has not been a concern in most large, interconnected power systems, but the situation might well change on the way to reach the declared renewable share generation targets.

5 Implementation

Implementing a hybrid power plant to perform the regulation tasks outlined in this case study requires a high-level control (HLC) system, which sets the working references for the various elements, specifically the hydro units, batteries, and supercapacitors. While hybrid power plant controls can cover a wide range of architectures, a feasible approach is proposed in this section. The high-level control scheme is illustrated below in Fig. 1.

According to the scheme depicted in Fig. 1, the HLC provides a power reference for the entire hybrid plant, based on the regulation service that needs to be delivered. This reference passes through a low-pass filter, establishing the power reference for the hydro. This filtering helps to reduce the wear and tear on the hydro's mechanical components, as it follows a smoother and less abrupt reference.

The state of charge (SoC) of both the batteries and supercapacitors is regulated by the hydro units. If either the batteries or supercapacitors reach high or low SoC levels, the hydro units respond by charging or discharging them, ensuring that both systems maintain a SoC that allows the hybrid power plant to remain flexible in responding to different scenarios. SoC control, represented at the top of the scheme, prevents situations where the batteries or supercapacitors would receive charging commands when near 100% SoC, or discharging commands when near 0% SoC. Such scenarios would place an excessive burden on the hydro units, as the hybrid power plant would then operate based solely on the hydro system. To avoid this, the SoC control adjusts the filtered reference power for the hydro units based on the SoC of the batteries and supercapacitors. The final output of the SoC control is the adjusted reference power, which is sent to the hydro units to ensure optimal operation.

The reference power for the lithium-ion batteries is determined by subtracting the filtered reference power from the unfiltered reference provided by the HLC. In this way, the batteries handle the high-frequency component of the unfiltered reference, helping to reduce mechanical stress on the hydro. This reference power is applied to the batteries, and under ideal conditions, the unfiltered reference power would be split between the hydro and battery systems.

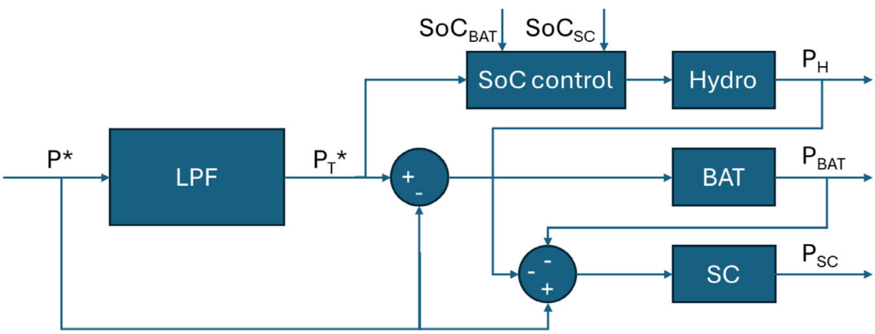

Fig. 1 High-level control scheme for the proposed hybrid power plant

In the proposed HLC, the supercapacitors manage any deviations between the unfiltered reference power and the actual power output of the hydro and battery systems. Therefore, the reference power for the supercapacitors is calculated by subtracting the real power output of the hydro and battery systems from the unfiltered power.

This HLC structure is relatively simple, with the three components of the hybrid power plant operating in a cascade arrangement. It allows for both the reduction of mechanical stress on the hydro plant and the delivery of the desired regulation, with the power reference coming from a higher-level control scheme. Additionally, the supercapacitors protect the batteries from excessive and aggressive cycling, thereby reducing the aging process associated with the batteries.

Proper tuning of the HLC parameters is essential to meet the desired objectives. The selection of parameters for the low-pass filter and SoC control depends on the specific application, the regulation tasks performed by the hybrid plant, and the sizing and characteristics of the actual devices within the plant.

For illustrative purposes, the following paragraphs describe the behaviour of the proposed control system when the hybrid power plant provides primary and secondary frequency regulation services. This example corresponds to a Hardware-In-the-Loop (HIL) system, where the hydro component is emulated on the HIL platform, while the batteries and supercapacitors are real devices. The HLC control is implemented in the laboratory testing facility of the Unidad de Accionamientos Eléctricos at CIEMAT (C/Julián Camarillo 30, 28,037 Madrid, Spain).

The laboratory testing facility includes the following components: a lithium-ion battery energy storage system (Li-BESS), a supercapacitor (SC) storage system, a DC/DC converter connected to the SCs, an inverter linking the facility to the main grid, the HIL platform, and a control platform. The general layout is shown in Fig. 2.

As shown in the layout, the installation connects to the grid on the left via a transformer, an inductive link, and a bidirectional inverter. The Li-BESS is directly connected to the DC bus, with a nominal voltage of 736 V and an energy capacity of 70kWh. The SC system is connected to the DC bus through a bidirectional DC/DC converter, with an energy capacity of 768Wh and a usable voltage range between 691

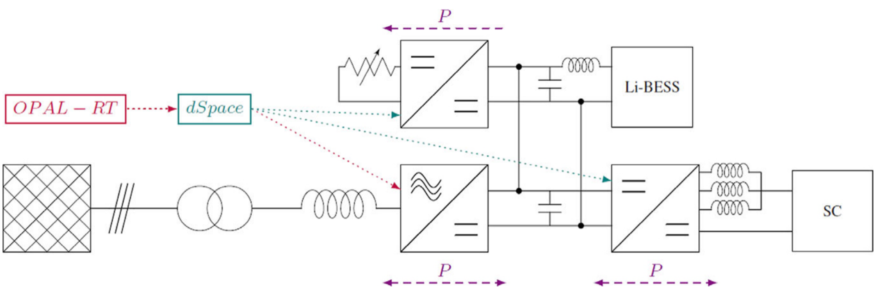

Fig. 2 Laboratory testing facility scheme

and 345 V (half of the maximum voltage, equivalent to 75% of the stored energy). Additionally, there is a controllable load emulator with a 50 kW resistor.

The laboratory setup is controlled by a dSPACE MicroAutoBox III platform (dSPACE 2024), which sets the power references for the load emulator, the power stored or delivered by the SCs (through the DC/DC converter), and the power exchanged with the grid via the inverter. The power managed by the Li-BESS is indirectly controlled as the difference between the inverter's power and the combined power of the SCs and the load emulator. The DC bus voltage is regulated by the Li-BESS since it is directly connected to the bus. Finally, the hydropower plant is emulated on an OPAL-RT 4510 HIL platform (OPAL-RT 2018), which communicates with the dSpace system. The emulated hydroelectric plant consists of two units, each with a rated power of 10.24 MWe, a nominal flow rate of 10 m^3/s, and a nominal head of 113 m.

As previously mentioned, the hybrid power plant has been tested for its ability to provide primary and secondary frequency regulation. The HLC is designed to reduce the wear and tear on the hydro system when performing correction actions. A selection of historical time-series data from real measurements of the UK power system was used to evaluate the difference in hydro valve (wicket gate movement) operation when the hydro operates alone versus when it operates alongside batteries and supercapacitors.

The behaviour of the hybrid solution, combined with the proposed control system, is illustrated through two examples: a non-aggressive frequency event (see upper graph of Fig. 3) and an aggressive frequency event (upper graph of Fig. 4). In both cases, the power reference for the plant, which dictates the correction action required, is processed by the HLC.

Figure 3 presents the results for the non-aggressive event. The upper portion of the figure shows a frequency time-series with an over-frequency event ranging between 50.06 Hz and 50.13 Hz. This results in a power reference for the hydro, prompting the plant to take corrective action for frequency regulation. The lower part of Fig. 3 compares the behavior of the hydro valve in two scenarios: one where the hydro handles the entire correction by itself (blue curve), and another where the hydro operates as part of the hybrid system with batteries and supercapacitors (red curve).

As shown in the figure, when the hydro operates without the hybrid system, the valve's movement is somewhat abrupt and exhibits high-frequency fluctuations, which contribute to mechanical stress. In contrast, when the hybrid system is implemented, the valve's operation is much smoother, reducing stress and allowing the hydro to provide correction while being protected from excessive wear.

The results for the aggressive event are shown in Fig. 4. The upper part of the figure displays an extreme over-frequency event ranging between 49.9 Hz and 50.3 Hz, which triggers a significant correction action for the hydro. The lower part of the figure compares the hydro valve's behavior in the same scenarios as before.

In this case, it is evident that operating with the hybrid power plant significantly reduces the steepness of the valve's movement, thereby lessening the mechanical stress on the system. Additionally, the overall valve operation is smoother. As in the

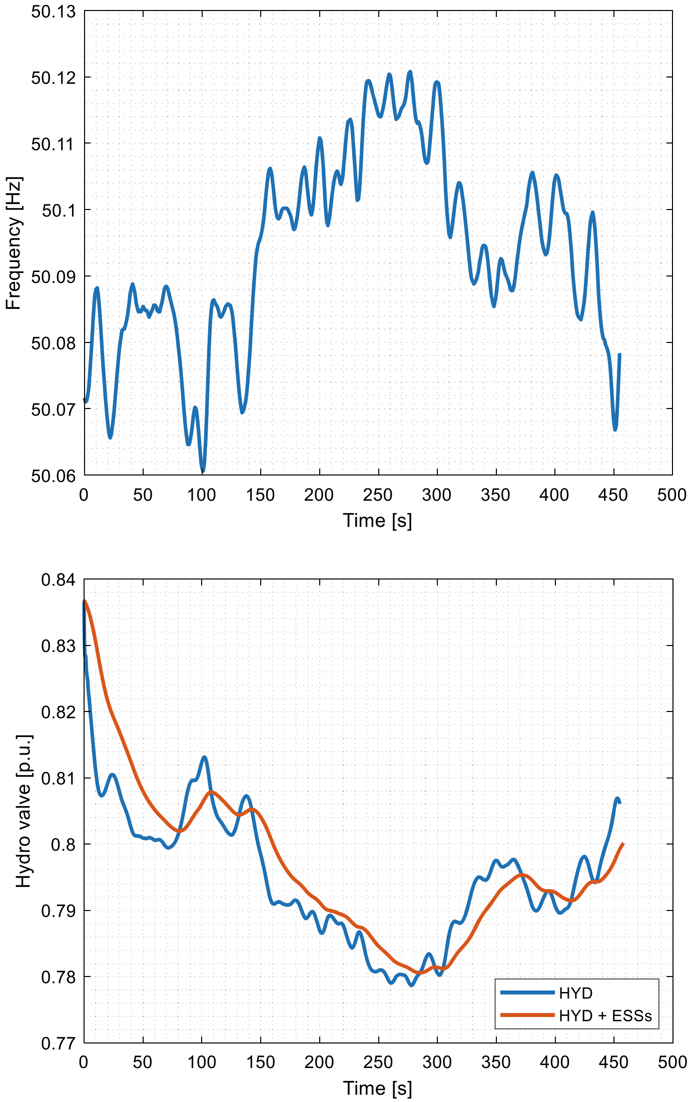

Fig. 3 Non-aggressive event. Frequency time-series and hydro valve evolution

non-aggressive event, the hydro's operation is much more stable when part of the hybrid system compared to when it operates alone.

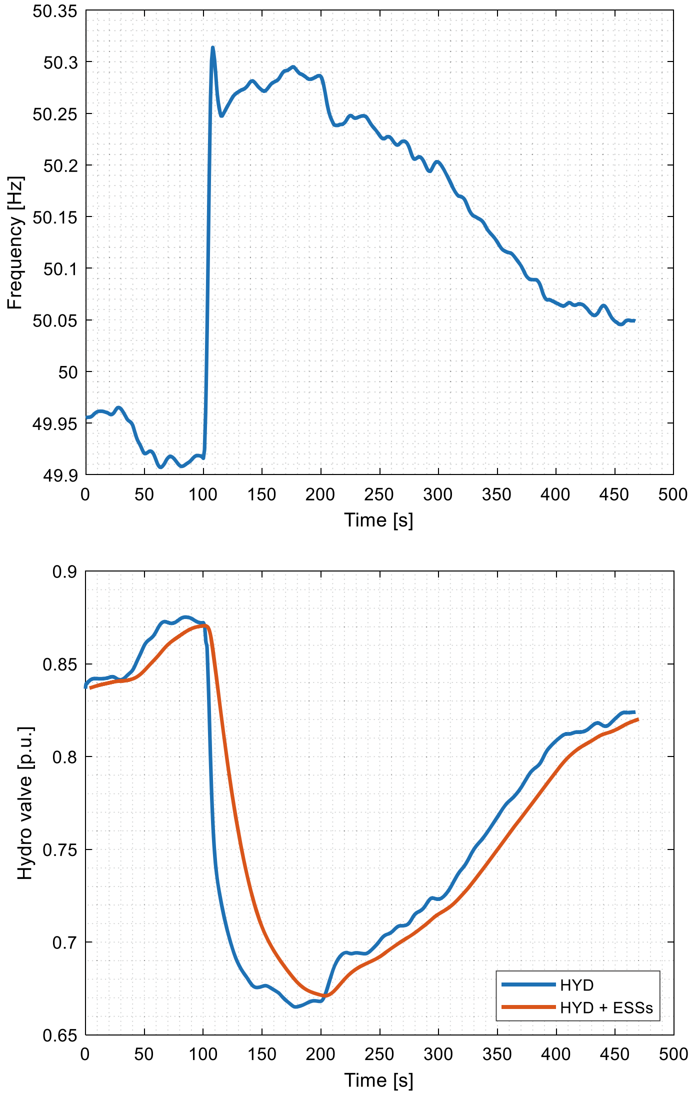

Fig. 4 Aggressive event. Frequency time-series and hydro valve evolution

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