Static frequency converter for hybrid pumped storage power plant with integrated energy storage system

Florian Errigo, Florent Morel, Hugo Mesnage, Renaud Guillaume

HAL Id: hal-04320201

https://hal.science/hal-04320201v2

Submitted on 12 Dec 2023

Static frequency converter for hybrid pumped storage power plant with integrated energy storage system

F. Errigo, F. Morel, H. Mesnage and R. Guillaume

SuperGrid Institute
23 Rue de Cyprian
69611 Villeurbanne, France
florian.errigo@supergrid-institute.com
https://www.supergrid-institute.com

Abstract

Pumped storage plants (PSPs) are considered as the most mature and reliable technology for bulk storage energy with low CO_2 footprint. With the massive integration of variable renewable energy sources and power electronic devices, transmission system operators (TSOs) need more flexibility to ensure a secure supply of the electrical energy. From an electricity generation company standpoint, this represents a diversification of income sources since new markets as fast frequency services tend to emerge. Although, they can balance the grid power by consuming or providing energy, the main drawbacks of PSPs are their low time response that makes them unable to access to these new remuneration mechanisms. One of the considered solutions to increase the flexibility of PSPs, and unlock the provision of dynamic ancillary services, is to hybridize the hydropower plant with a stand-alone energy storage system (ESS) using technologies like batteries or supercapacitors.

However, the little space available in hydropower stations and environmental constraints can make access difficult to such a solution. Traditionally, reversible PSPs work with fixed-speed machines. A static frequency converter (SFC) is commonly used to start a group in pump mode. In that perspective, the proposed paper presents an innovative concept of enhanced static frequency converter (E-SFC). It consists in integrating the ESS directly in the SFC of the plant to mutualize equipment, with a dual use of the power converter. It also provides an opportunity to reduce the overall capital expenditure in comparison with a conventional ESS connected to the point of coupling of the medium voltage grid of the plant.

The paper is organized as follows. Section 1 presents the need of flexibility from a hydroelectric power plant to fit with the growing needs and new ancillary services emerging worldwide. In Section 2, the innovative solution of SuperGrid Institute to hybridize a PSP, and to keep the existing hydropower fleet with a key role in the future power markets, is presented. In section 3, the need of synergistic control methods to operate hybrid power plant is exposed. Section 4 depicts the experimental results of the hybridization of a PSP on a real time power hardware in the loop (PHIL) test rig. Finally, section 5 concludes and highlights the advantages of the proposed solution.

1. Power system and ancillary services – Future trend

Due to the massive integration of non-dispatchable renewable energy sources and the strong effort to decarbonize the power system, transmission system operators (TSOs) will need more flexibility to ensure a secure supply of the electrical energy. Another expected consequence is the reduction of system inertia. Indeed, most of these new generation units (as solar farms and wind turbines) are decoupled from the grid through a power converter with no kinetic energy buffer for most of them. Thus, they do not intrinsically participate to the system strength contrary to traditional synchronous generators whose rotational speed are directly linked to system frequency. Therefore, power system is more unstable due to more abrupt frequency transient from sub second to second after active power unbalances and the lack of kinetic energy to maintain system stability [1].

Thus, the provision of ancillary services is crucial to mitigate the future lack of inertia. Furthermore, it is needed to adapt system services all over the world to evolve in the upcoming decades to follow these evolutions. The overall trend tends towards a need for fast regulation mechanisms [2, 3]. Note that flexibility is required at all the stages of the value chain of a power system: from the production to the consumers. From the provider standpoint, these services can be considered as an attractive source of income, since new markets tend to emerge, such as fast frequency services. For hydraulic turbines, and pump-turbine installations, this can be translated into opportunities as soon as the behaviour of the plant is in line with the future requirements.

However, conventional hydraulic power plants are currently unable to perform these new services that need a fast activation. Even tough hydraulic power plants are considered as a mature and a reliable technology, they are commonly used for long term services and high energy requirements. This is due to physical constraints as the effect mechanism of water inertia in the penstocks or machine safety. They inherently limit the response time of a hydraulic installation and then cannot provide services requiring fast responses. This is due to low activation time from several dozens of seconds to minutes. Nonetheless, by envisioning synergies with additional systems, new innovative control methods or technological solutions, these shortcomings can be overcome.

Maximizing the performance with fast ramping operations is one aspect of the provision of flexible services from a hydraulic power plant with increasing its availability or optimizing its maintenance schedule [4]. To provide these technical and economic advantages, a solution considered in the literature consists in hybridizing an installation with an energy storage system (ESS). A typical conceptual hydraulic power plant with an ESS is depicted in Figure 1-1 (left) [5, 6]. Regardless of the energy storage technology, a degree of freedom is brought in terms of power control by adding an additional power source in parallel with the turbine. This asset is further increased since the two systems share the same point of coupling, from a TSO point of view, and transaction cost. Thus, it can not only provide prospects for new operating modes but also offer a suitable solution to the needs of ancillary services expressed by grid operators to enable maintaining the stability of the grid.
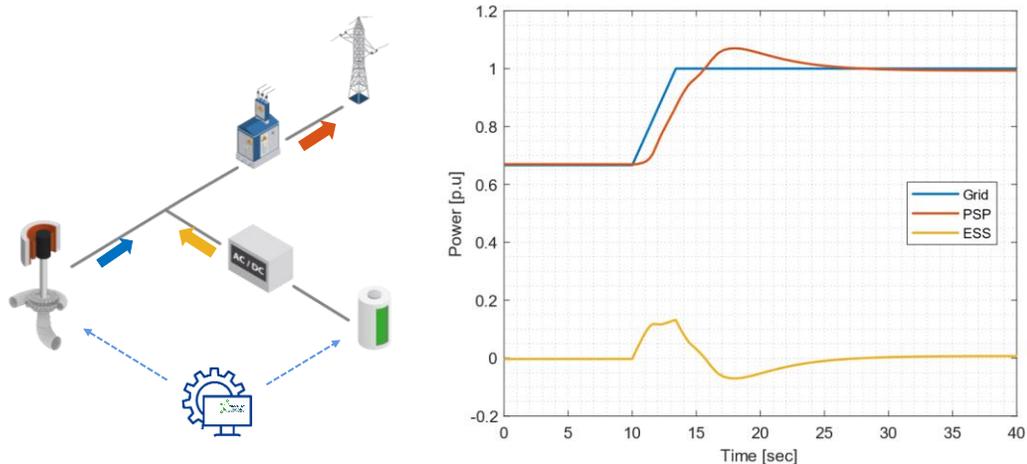

Figure 1-1 Illustration of the concept of the hybridization of a PSP with an ESS (left) Illustration of the general principle of the fast ramp up of a hybridized PSP

2. Enhanced static frequency converter with integrated energy storage system

Even if hybridization is seen as a promising solution to tackle the provision of flexibility to existing hydroelectric machinery, the little space available in the cavern, or the powerhouse, of hydropower stations and the cost can challenge hybridization projects. In that perspective, SuperGrid Institute works on innovative solutions to ease the integration of ESS in conventional pumped storage power plant (PSP). Usually, a static frequency converter (SFC) is used to start the groups in pump mode (cf. Figure 2-1(a)). In that perspective, new concepts are introduced in this paper as in Figure 2-1(b) and Figure 2-2. It consists in integrating the ESS directly in the SFC of the plant. It allows to mutualize equipment with a dual use of the power converters, but also to provide an opportunity to reduce the overall capital expenditure in comparison with a conventional standalone ESS connected to the point of coupling of the medium voltage grid of the plant.
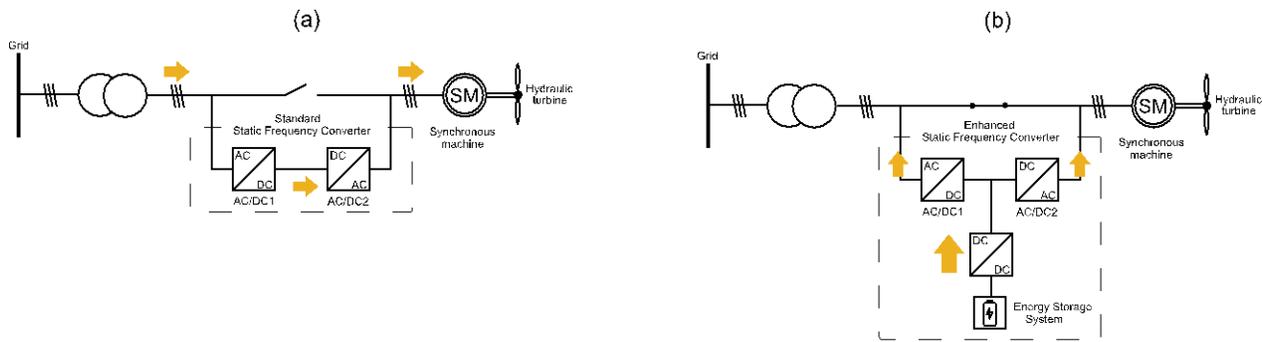
Figure 2-1 (a) Standard SFC in a PSP (b) SFC with embedded energy storage system

SFCs rely on two AC-DC converters in back-to-back configuration. Thyristor based line commutated converters (LCCs) have dominated this high-power drive application and are still a viable option. However, the remarkable advances in power electronics have made the voltage source converters (VSCs) with IGBTs an attractive solution [7]. Even tough, the scheme proposed in Figure 2-1(b) has a certain potential, it requires an additional DC-DC converter to connect the ESS to the dc bus of the converter. Currently, this latter has a low degree of maturity despite a high level of development expected in the coming years.

Therefore, this paper proposes a second cost attractive solution that consists also in integrating the ESS on the terminals of a VSC drive as in Figure 2-2 to make an enhanced SFC. However, one of the existing AC-DC inverters is reconfigured to be used as an interface element between the dc bus and the ESS. Indeed, this latter is only used few times a day to start a hydraulic machine. Consequently, it is an asset which is switched off most of the time. Moreover, this integration brings a new degree of freedom in the management of the PSP with an extra energy source but without significant additional costs other than the storage. Thus, two modes can be achieved with this enhanced static frequency converter (E-SFC).

- In the first mode, it works as a standard SFC allowing the start of the machine in pump mode or as brake to help the machine to slow down and transfer the kinetic energy to the grid.
- In the second mode, the E-SFC no longer connects the machine to the grid but an ESS for the provision of ancillary services.

As 3 level VSC converters are well suited for SFCs in PSPs, this work considers the use of neutral point clamped (NPC) arms to build the needed dc/dc between the ESS and the VSC dc terminals [8]. To switch from one mode to the other, only mechanical switches and additional inductors, less expensive than a complete DC-DC converter, are required as described in Figure 2-2.
As observed, each arm of the three phase three-level NPC inverter is connected to two ESSs, one on the lower arm and the other on the upper arm. This results in two bidirectional dc-dc converters per arm, each of them being connected to a dc bus capacitor. In the same way, each arm of the upper part (similarly for the lower arm) of the converter is connected to the same storage using an interleaved approach (i.e., multiple converter arms in parallel). This configuration allows to have two ESSs at lower voltage and a reduced current ripple within them to ease its integration. Furthermore, only two voltage sensors for both ESSs and six currents sensors to track the current flowing within the inductors are needed. This won't necessitate significant changes on the control board. Obviously, new control principles are requested to operate as a DC-DC converter with these arms which are normally only used in AC-DC converters. SuperGrid Institute has been developed such a control scheme as well as earthing strategies, protection elements to ensure a safe operation of the converter.
An approach to optimise the coordinated operation of the PSP and the E-SFC is presented in the following section.
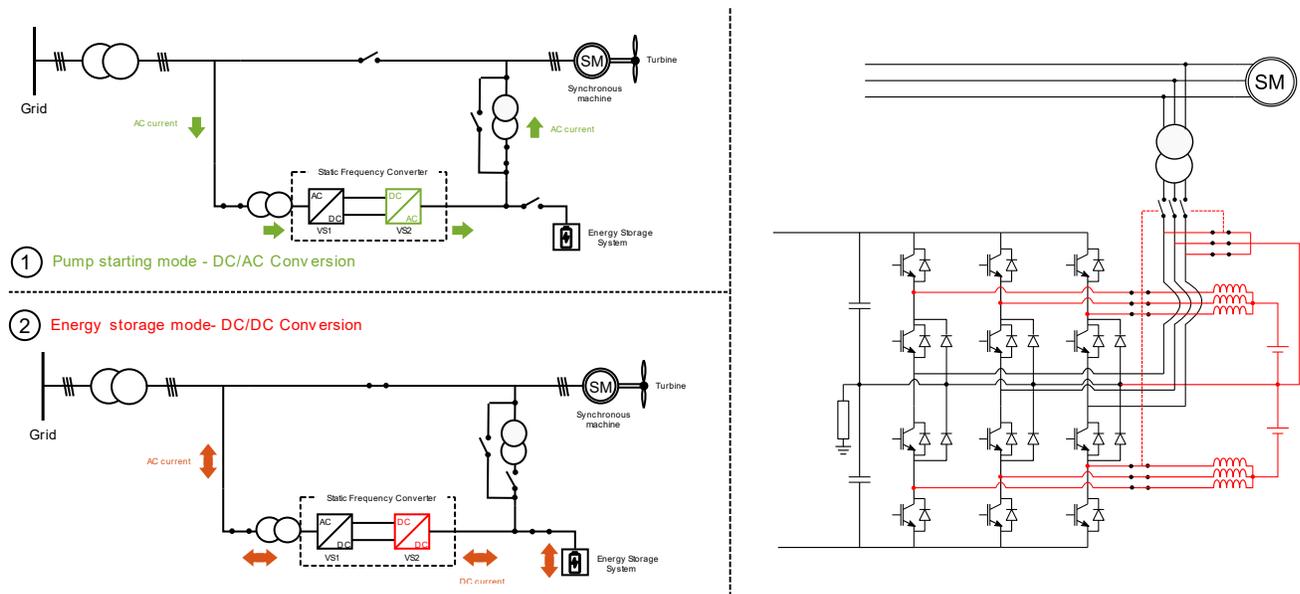
Figure 2-2 E-SFC proposed by SuperGrid Institute with (left) The general principle of the E-SFC (right) A topology of E-SFC based on a three level NPC inverter.

3. Supervisor development to improve the synergistic operation

Complementing the working operation of a PSP with an ESS, will reinforce and make the overall operation of the plant more flexible. Different purposes can be pursued with this extra energy source as reducing the wear and tears of the mechanical elements or increasing system performances with faster ramp rates. Regarding this last topic, the principle is quite simple to understand as depicted in Figure 1-1 (right). As observed, during a setpoint change from the grid, the ESS starts quickly before being replaced overtime by the hydraulic system which keeps its usual dynamic with low ramp rate and minimize constraints on its mechanical elements.
However, the major drivers of ESS are its cost and footprint. They are directly related to the energy stored. For the power conversion system, the cost is linked to the power of the system [9]. Thus, one can remark that for an installation of a hundred megawatts, making a fast ramp from speed no load to full power is not relevant. In fact, it would raise the question of why not install an equivalent means of production nearby on the grid. This would make no sense and lead to a bulk system. So, one of the main challenges for hybridizing a hydraulic power plant relies in a technical-economic balance of the system. Therefore, the development of smart supervisors that considers cleverly system requirements and the technical-economical aspects of the plants is as necessary as an innovative conversion system. Thus, it can manage adequately the power flow within the installation, while allowing the hybrid system to provide a wide range of services.

In that perspective, SuperGrid Institute has also developed supervisors based on digital twin. It permits to monitor the ESS and the hydraulic machine in real time, according to their state of charge and their physical limits, to ensure an optimal power flow between both systems. Note that the approach includes the optimization of the PID gains of the hydraulic power plant and the ESS. This concept is illustrated on Figure 3-1 that shows the benefits of the control method proposed by SuperGrid Institute. The example describes a 10% step-up for a hydraulic power plant of 8 MW. As observed, the proposed algorithm allows to reduce by 30% the energy that needs to be provided by the ESS in comparison to standard control methods.

Therefore, beyond performance optimization, advanced control methods also enable to optimize the sizing during the design phase. This element is crucial since the little space available on a hydraulic site is an important issue. Thus, the ESS can be tailored to customer needs, while ensuring an optimized tradeoff between the maximization of revenues (i.e., considering capital and operation costs) and the volume of the system. This solution can be seen as an add-on to enable faster power ramp-up at low capex for hydraulic operators. The following section describes an important step between the concept and the final implementation: power hardware-in-the-loop validation.
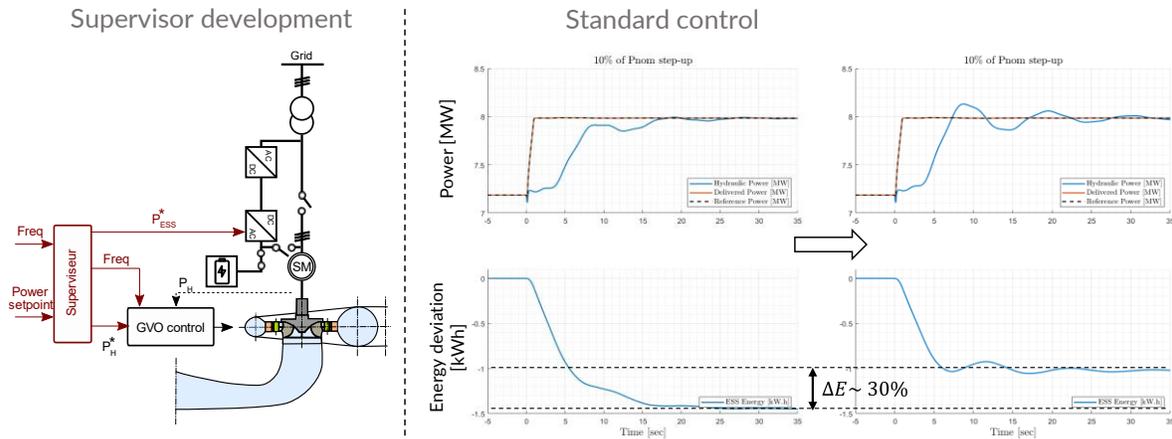
Figure 3-1 General principle of fast power ramp up of an hybrid hydraulic power plant with advanced control methods.

4. Hybridization of a PSP from concept to implementation

4.1 HydroPHIL an unique test rig in the world

To validate the proposed concept and control methods in a relevant environment, a downscaled prototype is required. However, most hydraulic test rigs are usually designed to make hydraulic acceptance tests, in all four quadrants, in steady state operating point according to standards (i.e., IEC 60193). Thus, they are more focussed to validate mechanical components as runners or investigate hydraulic phenomena as hump zone or cavitation. Nevertheless, with emerging hydro power technologies as hybridized PSP, with improved performances, innovative test platforms must be developed.

In that context, SuperGrid Institute has developed a real-time hydraulic pump storage test-rig called HydroPHIL. It enables to replicate pump storage plant's dynamic behaviour in a relevant environment. It enables to validate advanced control strategies, hydraulic response, and dynamic behaviour during transients, while mitigating the risks of implementing innovative solutions. It is thus possible to make closed-loop testing of innovative hydraulic machines and control systems, with added value in unstable operations, in an environment representative of an industrial PSP and its power system. The current overview of HydroPHIL is shown in Figure 4-1.

The installation is composed of the following elements as depicted in Figure 4-2.
- The device under test (DUT) that replicates a PSP includes the hydraulic geometry of the turbine, mechanical starting time, actuators performances, electrical machine topology (either synchronous or asynchronous), power electronics, automation, and instrumentation. Note that fixed-speed machine is represented on the figure, but the platform can be also used for variable-speed tests.
- A grid emulator to reproduce the different grid events and thus study the grid code compliance of the proposed hybridized system. It is made with a four quadrants amplifier.
- A hydraulic circuit emulator that allows to replicate the transient behaviour of the plant's penstock system: it is composed of a virtual reservoir and virtual penstocks physically connected to the reduced scale model of the turbine. It emulates the influence of physical phenomena inherent to these structures such as water hammer, surge tanks oscillations, or basin filling. It takes the form of a pump by-passed by a needle valve, both controlled to dynamically enslave the net head viewed by the turbine.
- An ESS connected to the common point of coupling of the DUT through a power converter to achieve hybridization tests. In this paper, a supercapacitor module is used with a 2 quadrants DC amplifier. Even if supercapacitors are used here, tests can be performed with other technologies like batteries.

Figure 4-1 (top left and bottom left) SuperGrid Institute's HydroPHIL platform architecture dedicated to real time simulations. (upper right) Actuator of the PSP: namely the guide vane operating ring, and inside of the turbine, runner, and wicket gates (bottom centre) ESS on the right and grid emulator on the left
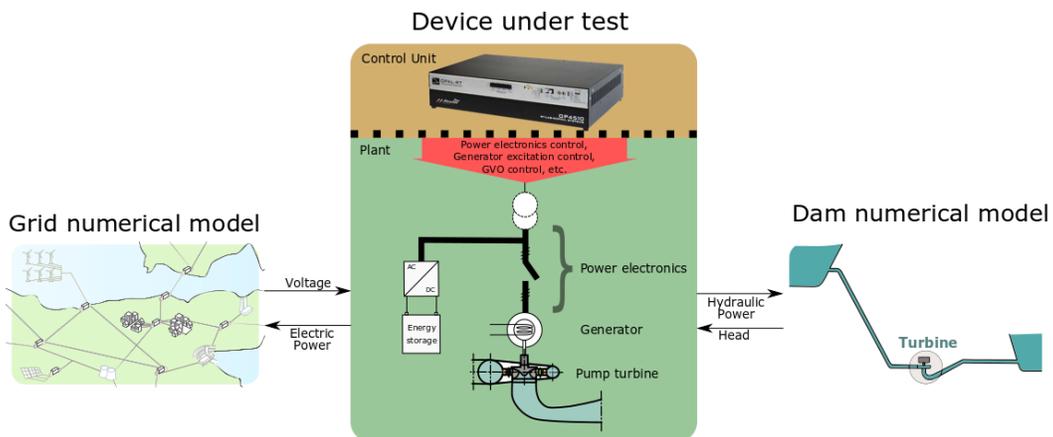

Figure 4-2 General principle of the HydroPHIL test ring

Finally, a real time HIL simulator retrieves all the system measurements, while all the control algorithms are developed under MATLAB/Simulink environment before being imported in the FPGA to perform rapid control prototyping operations.

Note that it has been decided to first implement a standard ESS directly coupled to the common AC point of coupling of the plant. This configuration allows to currently test advanced control methods and energy management strategies, while it is planned to integrate a downscale prototype of the E-SFC within the real test ring to validate the concept in a relevant environment. In the next subsection, the first experimental results of a hybrid power plant, with an ESS connected at the same point of coupling of the turbine, are presented. This is used to validate the supervisor introduced in section 3.

4.2 Experimental results

The general concept of the hybridization of a PSP for fast ramping operation and the proposed control described in section 3 have been successfully verified upon commissioning. This section shows some results. It aims at highlighting the feasibility of such innovative solution. Figure 4-3 shows the results for a step-up and a step-down of the operating point of the PSP. Note that results are presented in per unit. The base power is 6.3 kW in this case.
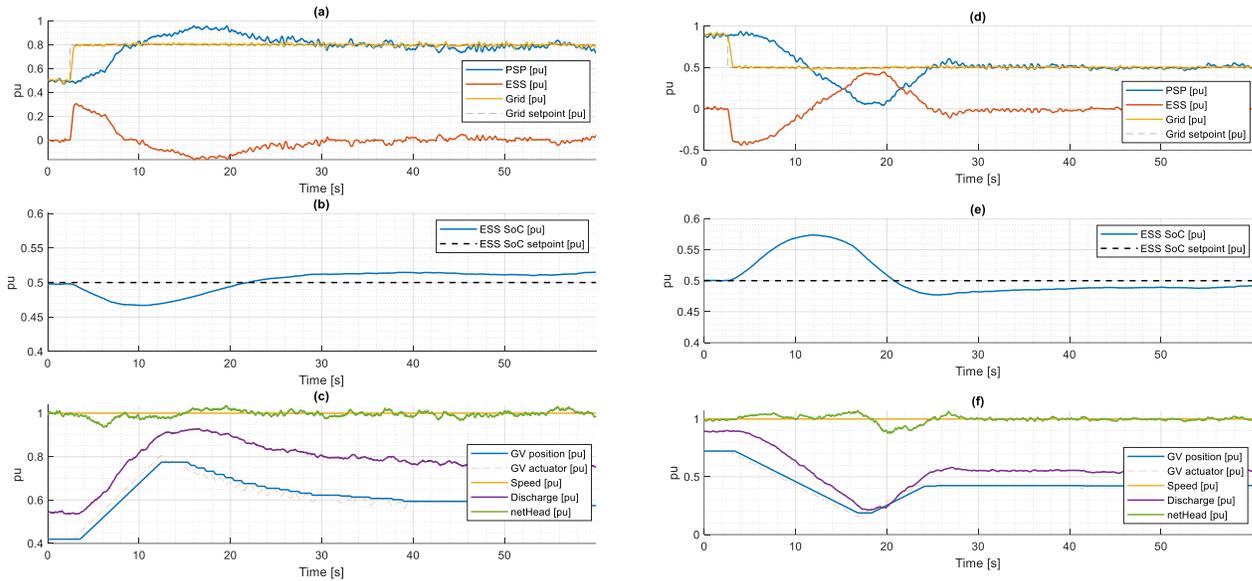

Figure 4-3 Experimental results of fast ramping operation on HydroPHIL with (a) and (d) The power flow within the system (b) and (e) The state of charge of the energy storage system (c) and (f) The guide vane position, the speed of the machine, the flowrate and net head of the system

Figure 4-3(a) and Figure 4-3(d) outline the power flow within the test platform. As observed, the hybrid system shows a fast reaction. The power response provided to the grid is almost instantaneous once a change in power is requested. However, the operating point change of the PSP is not affected by this abrupt rise. The difference between the grid setpoint and the hydraulic response is well compensated by the energy storage system. This confirms the suitability of the proposed solution. Fast response can be provided without disturbing the standard behaviour of the plant. In the same way, the opening and closing of the wicket gates are smooth enough to avoid water hammer, while the variation in flowrate (i.e "Discharge") within the test rig is reasonable.
Finally, Figure 4-3(b) and Figure 4-3(c) highlight the state of charge of the system. It can be seen that after reaching the new power setpoint, the supervisor anticipates to charge/discharge smoothly the ESS to attain the reference state of charge through the help of the hydraulic system without disturbing the grid.

5. Conclusion

This paper introduces innovative concepts for the development of flexible hydro-electric power plants. It is often stated in the literature that hydropower will be a key player in power system transformation and the growing needs of flexibility at different time scales. The paper focuses on the benefits of the hybridization of a hydropower plant through the implementation of an energy storage system. It shows how this hybrid system can allow PSPs to address the emerging need of fast response services which require fast ramp operation, which cannot be traditionally achieved by a standard hydraulic power plant.

In that perspective, pioneering power electronics have been presented to integrate smartly an energy storage system using the SFC of a PSP. This E-SFC is based on existing VSC converters. Thanks to some additional components, the AC-DC inverter of an SFC can be used in a second mode that allows to connect an ESS. This means that no additional converter is required to integrate the energy storage elements lowering the cost of the solution and its

footprint in the plant. To conclude, this E-SFC can, in addition to start a machine in motor mode, connect an ESS for the provision of ancillary services in operation, and also at stand still.

Furthermore, SuperGrid Institute elaborates groundbreaking solutions that aim to support the maturation and the development of hybridization system within the hydropower fleet. Thus, smart supervisor, based on predictive control, are carried out to permit cost effective solutions that address customers needs while minimizing the footprint of the solution.

Finally, SuperGrid has conceived a real-time power hardware-in-the-loop test-rig of a hybrid PSP to demonstrate the performances of the solution in a relevant environment. Experimental results show the feasibility and the interest, while the industrialization is the next step.

Acknowledgement

References

1. **P. Tielens and D. Van Hertem,** « The relevance of inertia in power systems," Renewable and Sustainable Energy Reviews, vol. 55, pp. 999-1009, 2016.
2. **ENTSO-E**, «Technical Requirements for Fast Frequency Reserves Provision in the Nordic Synchronous Area », august 2020.
3. **L. Meng and al**, « Fast Frequency Response From Energy Storage Systems: A review of Grid Standards, Projects and Technical Issues », IEEE Transaction on Smart Grids, vol. 11, no. 2, pp. 1566-1581, 2020.
4. **XFLEX HYDRO**, « D2.1 Flexibility technologies and scenarios for hydropower », august 2021.
5. **Fortum**., « New Fortum batteries enhance renewable energy capacity », 2019. https://www.fortum.com/media/2019/05/new-fortum-batteries-enhance-renewable-energy-capacity
6. **XFLEX HYDRO**, « Major step forward as Vogelgrun battery system arrives », 2021. https://www.xflexhydro.com/news/major-step-forward-as-vogelgrun-battery-system-arrives
7. **A. Holopainen**, « Multilevel voltage source inverters in medium voltage drives », Bachelor's thesis of LUT University, February 2019.
8. **GE Power Conversion,** "MV7000 Reliable, High Performance medium Voltage Drive. Commercial Brochure." https://www.gepowerconversion.com/sites/gepc/files/product/MV7000%20Brochure_EN.pdf
9. **U.S Department of Energy**, « Energy Storage Technology and Cost Characterization Report », july. 2019.

The Authors

Florian Errigo received the M.Sc degree in electrical engineering from the Energy Department in University of Technology of Belfort-Montbéliard (UTBM), France, in 2017 and the PhD in electrical engineering from the University of Lyon in 2020 working with the SuperGrid Institute, Villeurbanne, and the Ampère laboratory, Lyon. His PhD research was focused on power converters with integrated energy storage for high voltage DC networks. He is currently working as an R&D engineer at the SuperGrid Institute, where he is conducting research on power electronics and energy storage systems for high and medium voltage applications and the flexibility of hydropower plants. He is also an active member of the CIGRE working group B4.84 on integration of energy storage in HVDC applications.

Florent Morel is an alumnus of École normale supérieure (ENS) de Cachan, France. In 2002, he obtained the "agrégation" in Electrical Engineering and he received an MSc in Electrical Engineering from INSA de Lyon, France in 2004. He pursued his PhD at INSA de Lyon on the control of electrical drives. He considered especially the association of a permanent magnet synchronous machine with a three-phase matrix converter. From 2007 to 2019, he was Associate Professor at École Centrale de Lyon and the Ampère Laboratory. He taught electrical engineering and power electronics. His research activities focused on power electronics converter design. He especially considered electromagnetic compatibility (EMC), use of silicon carbide devices, power supply of circuits with a high-voltage insulation and converters for high voltage grids (including railway). He is currently with Supergrid Institute, Villeurbanne, France. He is working on converters for HVDC applications, especially power flow controllers (also known as current flow controller), dc/dc converters and integration of energy storage in HVDC applications. He is IEEE senior member and CIGRE member. He is an active member of the CIGRE working group B4.84 on integration of energy storage in HVDC applications.

Hugo MESNAGE has joined Supergrid Institute in 2019 after 2 years working in the automotive industry. He received his Ph.D. degree in Automatic Control from UGA (University Grenoble Alpes) in 2017 on the topic of modeling & control of pump storage plants. His PhD took place in a collaboration between General Electric Renewables & Gipsa-lab. He is responsible for the development and exploitation of the experimental hydraulic test rig in CREMHyG laboratory on which P-HIL tests is held.

Renaud GUILLAUME graduated as an engineer from the Ecole Polytechnique (France) in 2007. He joined the R&D department of an important hydraulic turbine manufacturer in 2009, first in mechanical department where he dealt with numerical simulations and measurement and after in the hydraulic department to handle transverse subjects, in particular concerning pump-turbines. He then took over responsibility for the "flexibility program" to increase the operating range of Francis and pump turbines and improve the response time of hydro powerplants. He has contributed to the commissioning of variable speed projects in Europe. He joined the SuperGrid Institute in 2018 as director of the research program " Power Storage & Balancing ".