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Multifunctional HIL testbench for hybrid energy storage systems analysis

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Multifunctional HIL Testbench for Hybrid Energy Storage Systems Analysis

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***Abstract*—This paper presents a multifunctional Hardware-in-the-Loop (HIL) testing facility developed by CIEMAT's Unidad de Accionamientos Eléctricos for analyzing and validating hybrid energy storage systems (HESS). The facility integrates lithium-ion battery systems (Li-BESS), supercapacitors (SCs), and flywheel (FW) storage, alongside a real-time emulation platform. Two distinct case studies are discussed: the HYBRIDHYDRO project, which couples hydroelectric generation with Li-BESS and SCs to mitigate mechanical wear and provide frequency regulation, and the POSEIDON project, examining the hybridization of SCs or FWs with existing Li-BESS in maritime vessels to reduce battery aging. Experimental tests demonstrate that appropriately tuned hybrid configurations effectively reduce mechanical stress in hydroelectric systems and battery aging in maritime applications, highlighting significant technical benefits.**

***Index Terms*—Hardware-In-the-Loop, hybrid energy storage, experimental tests, characterization, validation**

I. Introduction

Energy storage systems (ESSs) have become crucial in various energy sectors and activities, enhancing the flexibility of electric power systems, boosting the integration of non-dispatchable renewable generation, and fostering the electrification of transportation, among others. ESSs differ in their main features, from specific power and energy to cyclability and time response. This diversity means that certain applications may struggle to meet technical requirements with a single storage technology. For instance, an ESS might be oversized in terms of energy capacity to satisfy power demands, or a suitable ESS in terms of energy and power may be unsuitable due to slow response times. In such cases, hybridizing ESSs to form hybrid ESSs (HESSs) is a practical solution. Besides, HESSs can also extend the lifespan of individual ESSs, reducing replacement costs over a project's duration [1]–[7].

This paper is framed within two distinct projects concerning HESS integration: the HYBRIDHYDRO project [8], which involves hybridizing a hydroelectric power plant with lithium-ion batteries (Li-BESS) and supercapacitors (SCs) to mitigate wear on hydro-mechanical components during primary and secondary frequency regulation; and the POSEIDON project [9], integrating a combination of flywheels (FWs) and SCs into maritime vessels to address the technical limitations of LiBs in marine transportation.

In these projects, the Unidad de Accionamientos Eléctricos at CIEMAT utilizes a multifunctional hardware-in-the-loop (HIL) test bench in their laboratory to accomplish the technical tasks. This facility comprises, in general terms, a HIL platform, a Li-BESS system, a SCs system, a FW system, a controllable load, an electrolyzer, an AC/AC grid emulator converter, and the remaining power converters associated with the different ESSs. The HIL platform is capable of emulating diverse generation and consumption scenarios, AC grid dynamics, and any other ESS that may be integrated with the real equipment available in the laboratory.

This paper outlines the multifunctional HIL test bench, the specific configuration employed in each project to analyze the hybrid energy storage system, and the preliminary results of the tests conducted within the test bench, where the different

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Project HYBRIDHYDRO (TED2021-132794A-C22), which has received funding from MCIN/AEI/10.13039/501100011033 and from the European Union "NextGenerationEU"/PRTR.
Project StoRIES (ID: 101036910), which has received funding from European Union's Horizon 2020 research and innovation programme under the call H2020-LC-GD-2020 and topic LC-GD-9-1-2020.
Project POSEIDON (ID: 101096457), which has received funding from European Union's Horizon Europe research and innovation programme under the call HORIZON-CL5-2022-D5-01 and topic HORIZON-CL5-2022-D5-01-02.

HESSs combinations offer a versatile approach to meeting the projects' technical requirements while optimizing performance and cost.

II. Laboratory Testing Facility

The experimental testing facility integrates various energy storage devices, specifically a lithium-ion battery energy storage system (Li-BESS), supercapacitors (SC), and a flywheel-based (FW) storage system, combined with a Hardware-in-the-Loop (HIL) platform designed for emulating hydropower generation. The laboratory installation comprises the Li-BESS, the SC system, the FW, dedicated bidirectional DC/DC converters for both the SC and the FW, and two independent inverters interfacing with the electrical grid. Additionally, the facility includes a load emulator, a centralized control platform, and a real-time HIL emulation system. The general configuration is detailed in Fig. 1.

As depicted in Fig. 1, the experimental facility interfaces with the electrical grid on the left-hand side through two parallel pathways. The upper pathway includes a transformer, an inductive link, and a bidirectional inverter, directly linking the DC bus to the main grid. The Li-BESS, featuring a nominal energy capacity of 69 kWh, is directly connected to this DC bus. The SC system, characterized by a power rating of 125 kW, interfaces with the DC bus through its respective bidirectional DC/DC converter, enabling efficient power flow control and energy buffering.

The lower pathway provides additional flexibility and is used to emulate diverse generation scenarios. It incorporates another inductive connection and an independent bidirectional inverter, which can emulate different generation technologies dynamically. This second inverter is also directly linked to the common DC bus. The flywheel energy storage device, rated at 25 kW, is integrated into the DC bus via its dedicated bidirectional DC/DC converter, enhancing the facility's capability for short-term energy storage and rapid power exchange.

Control and coordination of the overall system are managed through a centralized control platform, marked as "Control" in Fig. 1, which defines operational setpoints and dynamically manages energy flows among all components. This platform communicates bidirectionally with the HIL emulation system (labelled as HIL), allowing real-time emulation and validation of hydropower generation conditions. The control system sets the power references for the grid-tied inverter, the emulated generation inverter, the SCs, and the flywheel storage, thus indirectly defining the Li-BESS power flow by ensuring the overall energy balance on the DC bus.

III. Case Study 1

The first case study discussed in this paper focuses on integrating run-of-river/pumped hydroelectric generation with an energy storage system composed of Li-BESS and SCs to provide ancillary services and extend equipment lifespan. Hydropower plants typically face mechanical component degradation when delivering frequency control ancillary services. To mitigate this issue, coupling hydro plants with energy storage systems, specifically Li-BESS, has proven effective. However, Li-BESS also suffer from aging processes, making a combined solution of hydro, Li-BESS, and SCs a promising approach to minimize excessive degradation for both hydro and Li-BESS units, while ensuring continuous provision of frequency regulation. This case study is part of the HYBRIDHYDRO Project. The CIEMAT facilities have been modified accordingly, removing the lower branch that includes the inverter and the FW.

Implementing a hybrid power plant to execute the regulatory tasks described requires establishing a high-level control (HLC) system, which provides reference signals to each element, specifically the hydro unit, Li-BESS, and SCs. Although control architectures for hybrid plants can vary widely, this section proposes a practical and effective approach applied within this project. The overall high-level control structure is presented in Fig. 2.

According to this arrangement, the HLC generates a power reference for the hybrid plant based on the specific regulation service required. This reference passes through a low-pass filter to establish the target power for the hydro unit, smoothing rapid fluctuations and consequently reducing mechanical stress on the hydro plant components.

The hydroelectric plant actively regulates the state of charge (SoC) for both Li-BESS and SCs. Should either energy storage system reach critical SoC limits (high or low), the hydro unit adjusts its operation, charging or discharging as necessary to maintain SoC within a suitable operating range. This mechanism, indicated at the top of the control scheme, prevents situations in which the battery or supercapacitor would receive inappropriate charging instructions near full charge or discharge commands near complete depletion. Such scenarios would overburden the hydro unit, compelling it to meet all demands alone. To avoid this, the SoC controller modifies the filtered hydro reference according to the storage units' SoC. Ultimately, this adjusted power reference ensures optimal operation conditions for the hydro system.

The Li-ion batteries' power reference is computed by subtracting the filtered hydro reference from the original unfiltered HLC reference. This approach assigns the high-frequency power demands to the batteries, alleviating mechanical stress on the hydro components. Ideally, this allocation splits the reference power between hydro and battery systems, with batteries addressing rapid variations.

Within the proposed HLC scheme, SCs absorb any residual differences between the initial unfiltered power reference and the actual combined outputs of the hydro and battery systems. Consequently, the SC reference power is calculated by subtracting the real-time power outputs of the hydro and battery from the original unfiltered reference.

This cascade-based HLC architecture is straightforward yet effective. It simultaneously reduces mechanical wear on hydro components and reliably delivers the required regulatory functions determined by the overarching control system. Additionally, the SC system protects the Li-ion batteries from aggressive cycling, significantly reducing battery aging effects.

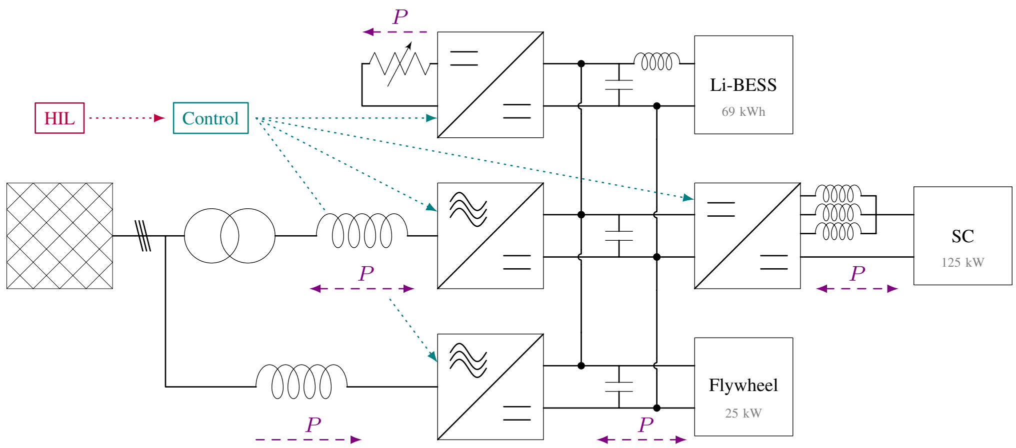

Fig. 1. Laboratory testing facility scheme of the Unidad de Accionamientos Eléctricos - CIEMAT.

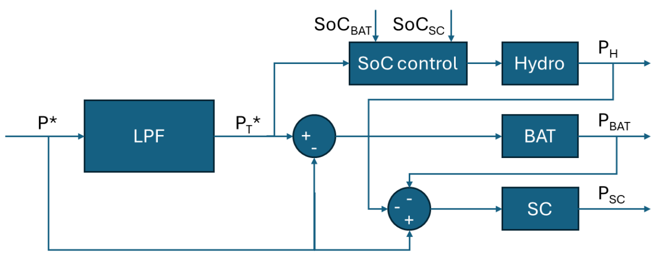

Fig. 2. HLC implemented for Hybtidhydro Ptoject.

Proper parameter tuning within the HLC is crucial for achieving optimal outcomes. Parameters for the low-pass filter and SoC controller depend on the specific regulation tasks assigned to the hybrid power plant, as well as the sizing and technical characteristics of the installed devices.

To illustrate the effectiveness of the proposed control system, the following paragraphs detail its behavior in delivering primary and secondary frequency regulation. As previously stated, the hybrid plant's capability to provide these regulation services was evaluated through simulations using historical time-series data from the UK power grid. Specifically, differences in hydro valve operation were analyzed comparing scenarios where the hydro system operates independently versus integrated with Li-BESS and SC units.

Two representative examples are used to demonstrate the hybrid solution's response: a moderate frequency event and an aggressive frequency event. In each scenario, the control system processes the required corrective power actions through the HLC.

Fig. 3 illustrates results for the moderate event. The upper graph depicts a frequency event with fluctuations between 50.06Hz and 50.13Hz, necessitating corrective measures. The lower graph compares hydro valve behavior under two operating modes: standalone hydro operation (blue curve), and hybrid operation with batteries and SCs integrated (red curve).

Results for the aggressive event are presented in Fig. 4. The

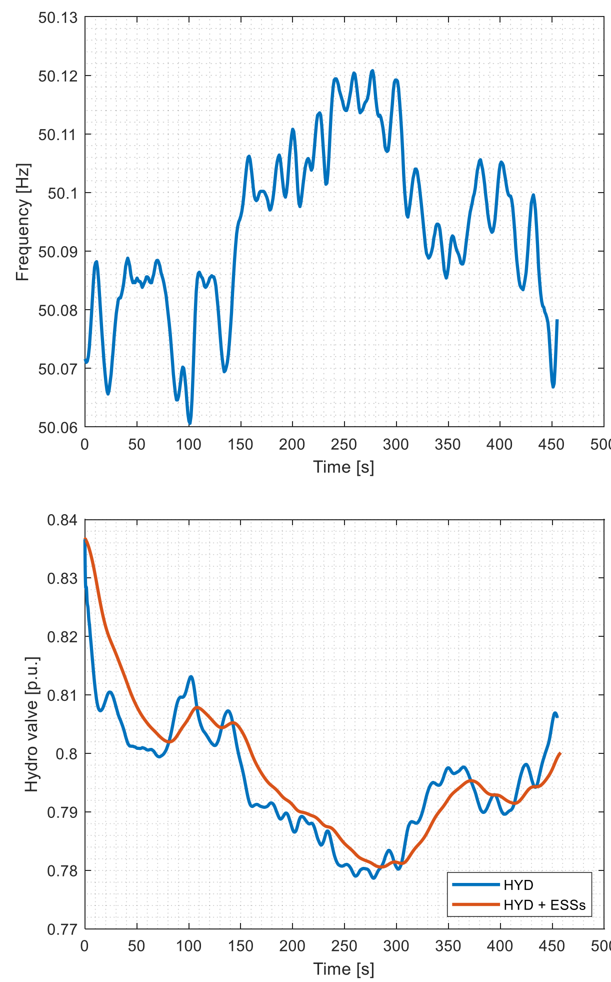

Fig. 3. Moderate event. Frequency time-series and hydro valve evolution.

upper graph shows a pronounced frequency event ranging from 49.9Hz to 50.3Hz, demanding substantial corrective actions. Similarly, the lower graph contrasts valve behavior in the two operating conditions described previously.

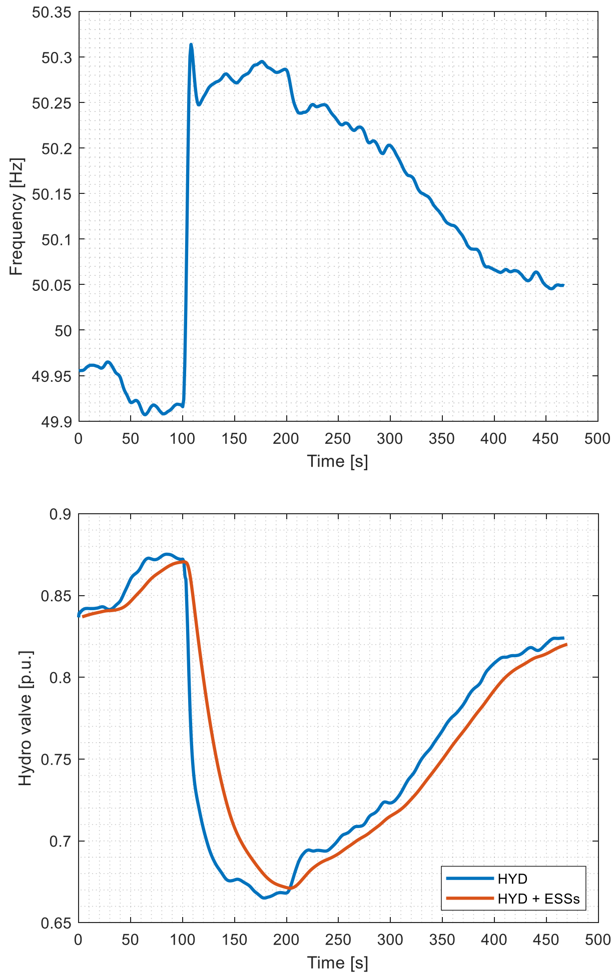

Fig. 4. Aggressive event. Frequency time-series and hydro valve evolution.

In this aggressive scenario, the hybrid configuration clearly reduces abrupt valve movements, thereby decreasing mechanical stress and promoting smoother operation. As with the moderate event, valve movements become notably more stable when utilizing the hybrid system. Fig. 4 highlights that standalone hydro operation results in abrupt and frequent valve adjustments, increasing mechanical strain.

Conversely, integrating the hybrid system smooths these operations, effectively minimizing mechanical wear and enabling the hydro unit to contribute significantly to frequency regulation tasks without incurring excessive component stress.

IV. Case Study 2

The second case study analyzed in this paper is developed within the framework of the POSEIDON Project, and addresses the utilization of SCs or FW to mitigate aging effects on existing Li-BESS installed in maritime vessels.

For the specific use case considered, the vessel's consumption profile selected corresponds to data recorded on September 29th, 2023, by the Battery Management System (BMS) of a Li-BESS onboard a Balearia ferry. According to Balearia's internal operational guidelines, diesel engines must remain inactive during port maneuvers, meaning that the Li-BESS is responsible for supplying all onboard energy needs. During sailing, however, the diesel engine powers the vessel and simultaneously recharges the Li-BESS. At nighttime, no power flows into or out of the Li-BESS. Fig. 5 depicts the measured Li-BESS power profile.

Fig. 5 illustrates power delivered (negative values) and charged (positive values) during a sequence of eight trips. The Li-BESS discharges primarily during port maneuvers, with docking and undocking operations clearly identifiable by pronounced discharge peaks. Additionally, the Li-BESS experiences constant-current charging once the vessel departs the port, resulting in a slight increase in charging power as battery voltage rises. To facilitate quicker simulation analysis, the cycle highlighted in red has been identified as the most representative and selected for further study.

As previously mentioned, the primary objective of this case study is to explore the hybridization of the existing Li-BESS with SCs onboard the Balearia ferry, aiming to cover the vessel's energy demands during port stays while reducing battery aging. The incorporation of SCs is expected to significantly decrease Li-BESS aging relative to scenarios without hybrid energy storage systems (HESS). However, the economic viability of this technical improvement remains uncertain, given that prolonging the battery lifetime delays replacement costs and potentially enhances overall economic returns over the project's lifespan.

To evaluate these effects, a series of simulations have been performed, varying the filter's time constant. Lower time constants result in a higher energy throughput from the Li-BESS with minimal participation of the SCs, while larger time constants shift more energy-handling responsibility to the SCs. Additionally, the simulations explored different quantities of SC stacks, as fewer stacks cannot sustain high energy throughput for extended durations. With insufficient stacks, SCs would become rapidly discharged, forcing the Li-BESS to fulfill the entire power demand and thus deviating significantly from the filtered reference.

Fig. 6 shows the examined combinations of SC stack numbers and filter time constants. In each scenario, the deviation between the vessel's actual power demand and the combined output from SCs and Li-BESS (represented by the filtered power profile) is calculated and indicated in red in the figure. Combinations with deviations lower than 1e-05, situated to the right of the solid red line in Figure 5, are considered acceptable since the HESS can adequately fulfill the vessel's demand. As anticipated, configurations with few SC stacks and high time constants exhibit deviations above 1e-05 and thus are excluded from further analysis.

From a purely technical standpoint, increasing the filter's time constant enhances the contribution of SCs, which reach

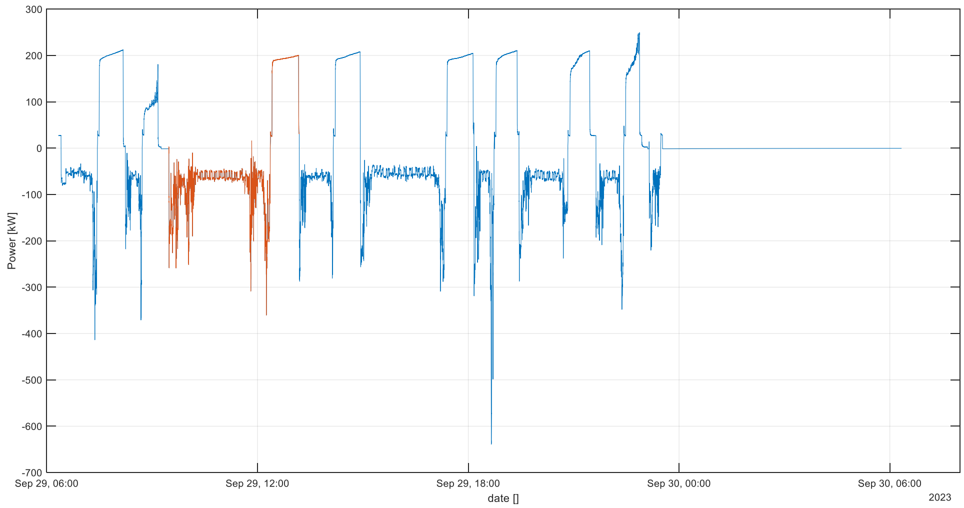

Fig. 5. Power profile of the Li-BESS for the Balearia's ferry ship.

a maximum power contribution of approximately 45%.

As expected, the enhanced role of SCs corresponds to reduced aging of the Li-BESS due to lower cycling-induced degradation resulting from decreased C rates. However, it is notable that the Li-BESS experiences substantial aging in all tested scenarios, independent of the SC stacks or filtering time constant. This consistent aging is primarily driven by calendar aging, which remains constant across all simulations. In this specific scenario, calendar aging dominates, as the Li-BESS is maintained near 100% state of charge (SoC) throughout most of the day, exacerbating battery degradation. This additional aging could be mitigated through alternative operational strategies that keep the battery at a different SoC, though implementing such strategies falls outside the scope of the current control approach. Simulation results, shown in Fig. 7, indicate that differences in Li-BESS aging across various filter time constants do not surpass 15%, highlighting the potential reduction achievable by integrating SCs to limit cycling-induced aging.

Considering these results, integrating SCs into a hybrid storage system alongside Li-BESS appears technically beneficial but economically questionable. Although reduced aging could extend the interval between battery replacements, the associated investment in SC technology currently does not appear economically justifiable for this particular use case.

V. Conclusions

The presented multifunctional HIL testing facility demonstrated its capability to comprehensively evaluate and validate hybrid energy storage systems under realistic operational conditions. The first case study, HYBRIDHYDRO, clearly illustrated the technical benefits of integrating lithium-ion batteries and supercapacitors with hydroelectric plants, significantly smoothing out rapid fluctuations and reducing mechanical wear during frequency regulation events. The effectiveness of the proposed high-level control (HLC) architecture was confirmed through simulation scenarios, where substantial reductions in mechanical stress and improved operational stability of hydro components were achieved.

In the second case study, within the POSEIDON project, the technical analysis highlighted the capability of SCs or FWs to significantly mitigate cycling-induced aging of Li-BESS systems onboard maritime vessels. Results showed a noteworthy SC power contribution of up to 45%, resulting in lower C rates and subsequently reduced cycling-induced battery degradation. The findings underscore that the hybridization effectively manages the demanding power dynamics during vessel port maneuvers.

Overall, this study underlines the multifunctional HIL platform's potential to replicate diverse energy scenarios accurately, validating hybrid storage solutions that enhance system reliability, extend asset lifespans, and optimize energy management strategies. Future research should address further optimization of control parameters and explore operational strategies such as state-of-charge management to maximize the technical effectiveness and durability of hybrid storage configurations across various practical applications.

References

[1] European Union, "Regulation (EU) 2023/1805 of the European Parliament and of the Council," EUR-Lex, 2023.

[2] European Union, "Regulation (EU) 2015/757 of the European Parliament and of the Council," EUR-Lex, 2015.

[3] Y. V. Makarov, B. Yang, J. G. DeSteese, S. Lu, C. H. Miller, P. Nyeng, J. Ma, D. J. Hammerstrom, and V. V. Vishwanathan, "Wide-area energy storage and management system to balance intermittent resources in the Bonneville Power Administration and California ISO control areas," Pacific Northwest National Laboratory (PNNL), Richland, WA, USA, Tech. Rep., 2008.

[4] V. Gevorgian, E. Muljadi, Y. Luo, M. Mohanpurkar, R. Hovsapian, and V. Koritarov, "Supercapacitor to provide ancillary services," in *Proc. IEEE Energy Conversion Congress and Exposition (ECCE)*, 2017, pp. 1030–1036.

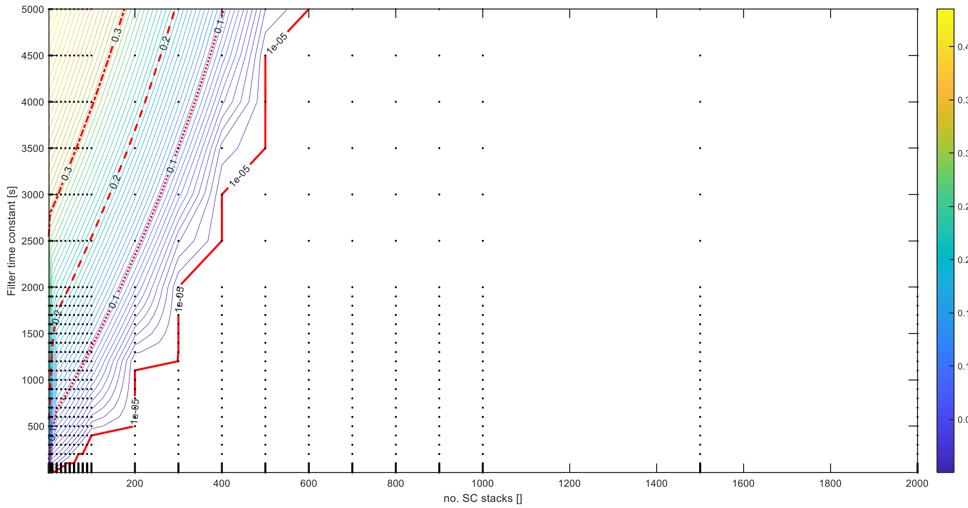

Fig. 6. Power error (P required vs. P delivered).

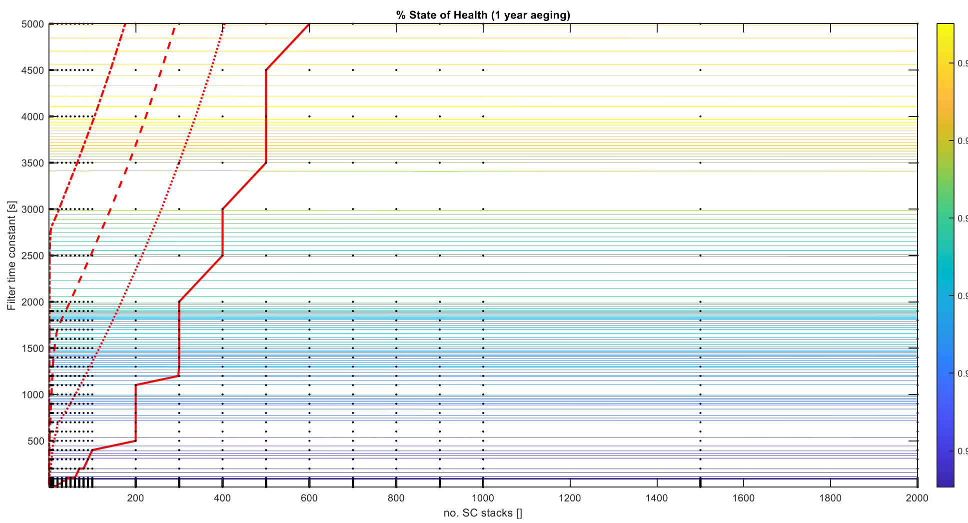

Fig. 7. Li-BESS SoH after 1 year.

[5] D. Laban, “Hydro/battery hybrid systems for frequency regulation,” M.S. thesis, Universitat Politècnica de Catalunya, 2019.

[6] M. Guezgouz, J. Jurasz, B. Bekkouche, T. Ma, M. S. Javed, and A. Kies, “Optimal hybrid pumped hydro-battery storage scheme for off-grid renewable energy systems,” *Energy Conversion and Management*, vol. 199, p. 112046, 2019.

[7] M. S. Javed, D. Zhong, T. Ma, A. Song, and S. Ahmed, “Hybrid pumped hydro and battery storage for renewable energy based power supply system,” *Applied Energy*, vol. 257, p. 114026, 2020.

[8] Project HYBRIDHYDRO (TED2021-132794A-C22), funded by MCIN/AEI/10.13039/501100011033 and the European Union “NextGenerationEU”/PRTR, 2021.

[9] Project POSEIDON (ID: 101096457), funded by the European Union’s Horizon Europe research and innovation programme under call HORIZON-CL5-2022-D5-01, topic HORIZON-CL5-2022-D5-01-02, 2022.