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Characterization and Validation of Hybrid Energy Storage Systems formed by Li-ion Batteries and Supercapacitors for their installation in Hydroelectric Power Plants

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***Abstract*—Hydroelectric power plants suffer from wear and tear of the different mechanical parts when participating in frequency control ancillary services. In a paradigm where the needs of providing frequency control are continuously growing, the lifespan of hydroelectric power plants is being compromised. In this sense, hybridizing the hydro with energy storage systems, specifically Li-ion batteries (Li-ion BESS) has been proven to be a good solution. However, Li-BESS suffer from ageing, and a combination of hydro, Li-BESS, and supercapacitors (SCs) seems to be promising for protecting both the hydro and Li-BESS from an excessive aging (Project HYBRIDHYDRO). CIEMAT's facilities account for a Hardware-In-the-Loop (HIL) installation to test this configuration, with prototypes of Li-BESS, SCs and a HIL platform that emulates the hydro.**

This paper presents the models, characterization and validation tests for real prototypes of Li-BESS and SCs. They are needed to develop hybrid control strategies that reduce the aging of Li-BESS and the hydro. Starting from selecting proper semi-empirical models, laboratory tests have been performed for finding the parameters. Then, the models are compared to the manufacturer datasheet, reaching errors below 3% for the voltage/runtime and thermal model of the Li-BESS, as well as for the frequency domain and thermal model of the SCs. In addition, the time delay introduced by the power electronic converters when imposing a reference to the Li-BESS and SCs have been tested in laboratory, and thereby modeled. Hence, the complete behavior of the facility is taken into account when developing hybrid control strategies, resulting in an optimized techno-economical operation which will include both Li-BESS and hydro aging considerations.

***Index Terms*—li-ion batteries, supercapacitors, hydroelectric power plant, characterisation, validation**

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I. Introduction

Electric power systems have suffered severe changes over the last decades, mainly related to the increasing integration of non-dispatchable renewable generation units, large non-deferrable loads, and other actors such as energy storage systems. This paradigm, where imbalances between the power generation and consumption can happen all of a sudden and are hardly predictable, forces the electric power system to make use of the ancillary services at it 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 provided by the power generation units and storage systems.

Hydroelectric power plants have historically taken a strong share in relation with frequency control ancillary services, causing wear and tear to the different mechanical parts. 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 to 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 and increasing the revenue that the plant obtains from the energy and ancillary services markets. The following paragraph includes the most significant works in this topic.

The Project developed in [1] integrated a flywheel with a hydropower unit for mitigating the renewable power generation variability and covering the fast ramps associated to it. The work developed in [2] verses about the coordinated operation of a variable-speed run-of-river hydropower plant and a SC energy storage system for the provision of frequency regulation. The results presented in the paper demonstrated that the combination can help to increase the quality of the system's frequency. The authors in [3] developed two control algorithms for the real-time energy management of a power plant comprising hydropower and a Li-BESS. The power plant is assumed to provide frequency containment reserves for normal operation in a reserve market, concluding that the power plant is able to provide it with a much lower wear and tear. The works published in [4] and [5] presented two optimization algorithms for the hourly power dispatch of a power plant comprising a pumped-storage power plant and a Li-BESS. The power plant is assumed to be connected to an isolated power system which is exclusively fed by non-dispatchable renewable generation. Both articles concluded that, with a proper power dispatch algorithm, the power plant can increase the reliability of the electricity supply in the systems under study. The authors in [6] also 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, resulting in a successful combination.

As seen in the previous paragraph, the solutions studied in the literature integrate a Li-BESS, SC or flywheel with hydropower units for solving the aforementioned issues. Previous references that integrate a fast response energy storage system mention that solutions are valid for specific scenarios, but not as a general solution due to the lack of energy density. Out of the three energy storage technologies, Li- BESS is the one that allows the hydroelectric power plan to expand its lifespan and improve its regulation capacity for a wider range of events and situations. However, it is well known that the Li-BESSs suffer from aging, which depends on the cycling and ambient conditions [7]. Hence, the lifespan of a combined hydropower and Li-BESS plant is not only limited by the wear and tear of the hydro unit, but for the aging of the Li-BESS, which in situations with a high penetration of non-dispatchable renewable generation can severely increase. The present work is framed within two Projects (HYBRIDHYDRO and StoRIES), the first one exploring the combined integration of a Li-BESS and SCs with a hydropower plant working in cascade, i.e. the Li-BESS protects the hydropower from fast fluctuations in the output power, while the SCs protect the Li-BESS from an excessive ageing when cycling.

The manuscript describes the modelling and performs the characterization and validation of real Li-BESS and SCs via laboratory tests. Besides the dynamics of power electronic converters associated to them are also modelled and characterized, which are also needed to size the energy storage systems and develop energy management control strategies to coordinate them with the hydropower plant. The paper describes the ageing, efficiency and dynamic model of a Li-BESS in Section 2, as well as the efficiency and dynamic model of a SC. The complete laboratory facility is described in Section 3, while the modelled Li-BESS and SC are then characterized for representing two real storage systems available in the researchers' laboratory in Section 4, together with the dynamics of power electronic converters associated to the energy storage systems. Conclusions are drawn in Section 5.

II. Li-BESS and SC Modelling

There is a wide variety of modelling approaches in the literature for electrochemical and electric energy storage systems, such as Li-BESS and SC. They can be grouped into three main categories [8]: electrochemical models, intelligent or mathematical models, and equivalent circuit models.

Electrochemical models have a high accuracy and low calculation efficiency, but demand a high computational effort. Two of the most relevant electrochemical models for Li-BESS and SCs can be found in [9] and [10].

Intelligent modelling is commonly associated with stochastic models, such as artificial neural networks or fuzzy logic. These models require a large amount of training data for being accurate. The most relevant models for Li-BESS and SCs can be found in [11] and [12] respectively.

At last, equivalent circuit models substitute the coupled partial differential equations with ordinary differential equations, reducing the computational effort and facilitating their implementation. The most relevant equivalent circuit models for Li-BESS and SCs can be found in [13] and [14].

The equivalent circuit approach has been selected for both the SC and Li-BESS in this work, since it allows for widely applicable models although loses accuracy. Sacrificing accuracy can lead to critical problems when designing in detail a system. However, for the purpose of the Project where this work is framed, the models are needed for pre-dimensioning the systems and for testing the behavior of energy management control strategies, and it suffices with the equivalent circuit modelling approach.

A. Li-BESS Modelling

The Li-BESS model is based on the work developed in [7]. This model is based on the well known Shepherd model and on [15], which describes the electrochemical behavior in terms of voltage, current, internal resistance and SoC.

The voltage/runtime Li-BESS model behaves as follows:

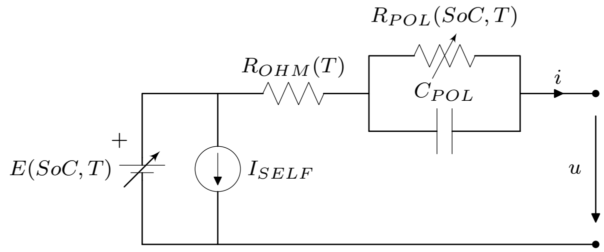

Fig. 1. Li-BESS model proposed in [7].

$$E = E_0 - K \cdot Q_{MAX} \cdot (\frac{100}{SoC} - 1) + A \cdot e^{-B \cdot Q_{MAX}(1 - \frac{SoC}{100})} \quad (1)$$

The Li-BESS thermal model comprises two parts: a heat generation model and a heat evacuation model. For the heat evacuation model the only heat transfer considered is from the cell surface to the ambient (conduction heat inside the cell can be considered constant and uniform, as in [7]).

For the Li-BESS aging model, the combination of cycling and calendar aging is considered, being the former dependent on the cell temperature, rate of charge/discharge (C_{rate}) and Ah throughput, and the latter on the cell temperature, SoC, and time.

Further and detailed information about the model can be found in [7]. Experimental tests performed for characterizing the Li-BESS model include voltage/runtime and thermal tests, and are detailed in Section IV. Aging tests for characterizing the Li-BESS model have been taken from databases [7].

B. SC Modelling

The SC model is based on the work developed in [16]. The model has similarities with the work presented in [17], but implements modifications to include the frequency response of 2 SC cells connected in series and their equalization circuit. The scheme is shown in Fig. 2, where the variable elements are SoC dependent.

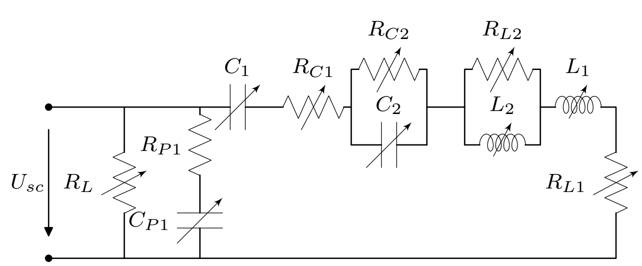

Fig. 2. SC model proposed in [16].

For the thermal model of the SC, a similar approach as the Li-BESS thermal model has been followed, having a generation model which comprises reversible and irreversible heat, and an evacuation model between the cell and the ambient. Further and detailed information about the model can be found in [16].

Notice the reader that both time domain and frequency domain are used when simulating the complete model (Li-BESS and SCs). The laboratory facility with the Li-BESS and SCs to be characterized is described in Section III, while Both Li-BESS and SCs models will be parameterized by experimental tests in Section IV, as well as validated against manufacturer's data.

III. Laboratory Testing Facility

The laboratory testing facility to be used in the Project HYBRIDHYDRO integrates a real Li-BESS and SCs devices with a Hardware-in-The-Loop (HIL) platform where the hydropower plan is emulated. It comprises the following elements: a Li-BESS, SC storage system, a controllable load, a bidirectional DC/DC converter associated to the SCs, an unidirectional DC/DC converter associated to the load, a bidirectional inverter that connects the facility to the main grid, the HIL platform, and a control platform. The general scheme is depicted in Fig. 3.

As seen in Fig. 3, the installation is connected to the grid at the left via a transformer, an inductive link and a bidirectional inverter. The Li-BESS is directly connected to the DC bus, having a nominal voltage of 736V and a nominal energy of 69kWh, while the SC system is connected to the DC bus via a bidirectional DC/DC converter, having 768Wh of energy and usable voltage range between 691V and 345V (half of the maximum voltage, which equals 75% of the stored energy). Besides, there is a controllable load emulator with a 50kW resistor. The laboratory installation is controlled via a dSpace MicroAutoBox III platform [18], which set the references for the power consumed by the load emulator, the power stored or delivered by the SCs (through the DC/DC converter), and the power consumed or delivered to the grid by the inverter. At last, the hydro is emulated in the HIL platform (OPAL-RT 4510 [19]), which is communicated with the dSpace.

The duty is implemented via a PW-SVM in the inverter, while for the DC/DC converters the duty is established via a PWM.

Both the Li-BESS and the SC system need to be characterized, so the parameters of the models presented in Section 3 can be set. As mentioned in Section 1, once the models are parameterized they will be used to develop control strategies for the complete plant (hydropower, Li-BESS, and SCs), aiming to diminish the wear and tear of the hydro and the Li-BESS ageing, while providing frequency control regulation and maximizing the revenue from energy and auxiliary services markets. The Li-BESS is formed by Kokam SLPB100255255HR2 cells [20], while the SC system equips Maxwell BCAP3000 cells [21].

IV. Characterization and Validation Tests

Three set of characterization tests are presented in this section: Li-BESS cell voltage/runtime and thermal tests, SC cell frequency response tests, and power converter time response tests. The Li-BESS ageing parameters have been obtained from [22]. The Li-BESS and SC characterization tests are

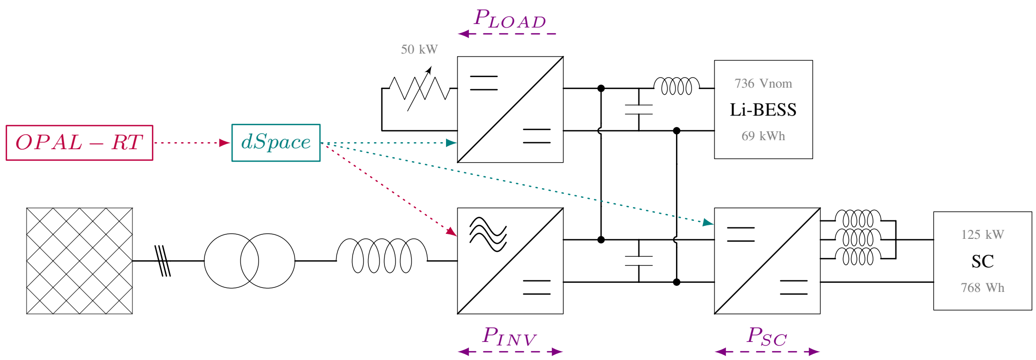

Fig. 3. Laboratory testing facility scheme.

needed to parameterize the models presented in Section 3 and, in order to use the models for designing control strategies, the time response of the power converters becomes crucial, specially when the authors aim to develop frequency control, which require actions in the range of milliseconds. Given that the delay between the frequency event and the Li-BESS or SCs response does not depend on the technology but on the power converters and control, it is necessary to add a delay in the simulation models, emulating the time needed by the power converters to impose the power reference that comes from the control platform.

In order to find the dynamic and thermal parameters for the Li-BESS models, tests at different C_{rate} and different temperatures have been performed. A bidirectional DC power supply and a climatic chamber available at the laboratory facilities have been used for performing these tests. A summary of the tests is shown in Fig. 4, with discharge curves for 3 different C_{rate} (0.2C, 0.5C, and 1C) and 3 different temperatures (-10ºC, 0ºC, and 23ºC). The dynamic and thermal parameters are calculated via a least square algorithm. Detailed information about the algorithm can be found in [7] and [22]. Then, once the Li-BESS model is parameterized, the model is validated by comparing its behavior against the manufacturer discharge curves at different C_{rate}, as shown in Fig. 5. The relative error is kept below 3% for all C_{rate}.

The Li-BESS model parameters are listed as follows: $E_0 = 3.3V$, $Q_{MAX} = 55Ah$, $K = 0.00077$, $R_{ohm} = 0.0006\Omega$, $Alpha = 525.43$, $Beta = 8969.86$, $A = 0.51V$, $B = 0.073Ah^{-1}$, $dE/dT = 0.000002V/K$, $dq/dT = 0.316Ah/K$, $R_{out} = 0.06K/W$, $T_{th} = 900s$. Aging model parameters are obtained from [7].

For the SC parameters, capacity, resistance and inductance test have been performed with cells at different voltages, and measured via electrochemical impedance spectroscopy (EIS). The test sample is formed by four cells connected in series (nominal voltage of 10.8V). A summary of the tests is shown in Fig. 6 and Fig. 7, where the capacity and resistance of the SCs are measured for different frequencies ranging from 10^{-3}Hz to 10^{3}Hz, and voltages ranging from nominal voltage to 2V. Following the same methodology, the SC model parameters are calculated via a least square algorithm, which

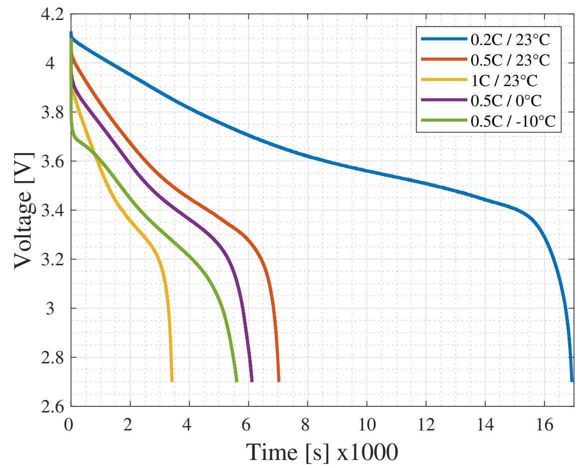

Fig. 4. Characterization tests for the Li-BESS cell.

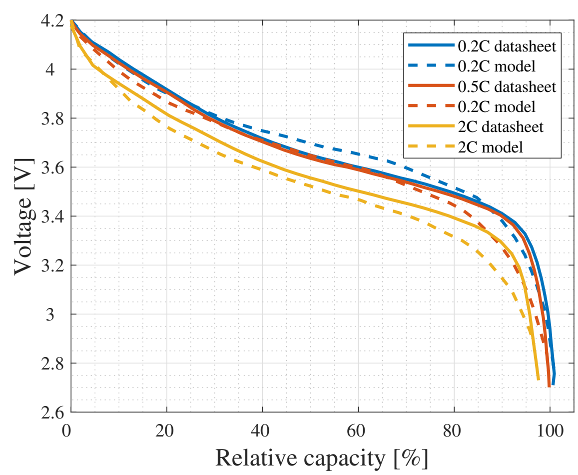

Fig. 5. Li-BESS model behavior comparison with manufacturer data.

is detailed in [16]. Then, the model is also validated by comparing the capacity and resistance against the manufacturer data, as in Fig. 8 and Fig. 9, where errors below 2% are achieved when comparing the model behavior (parameterized with the measured data) with the Manufacturer's data.

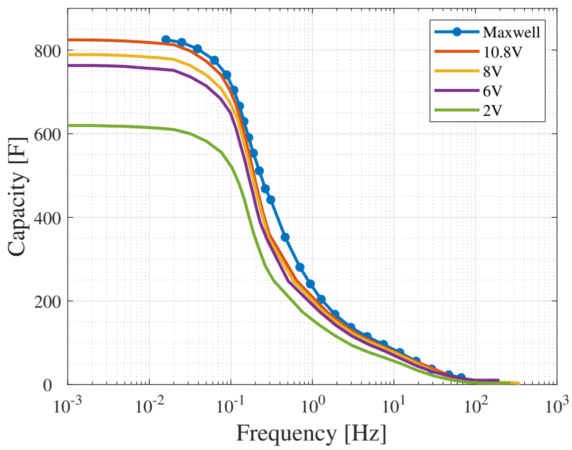

Fig. 6. Capacity characterization tests for the SC cell.

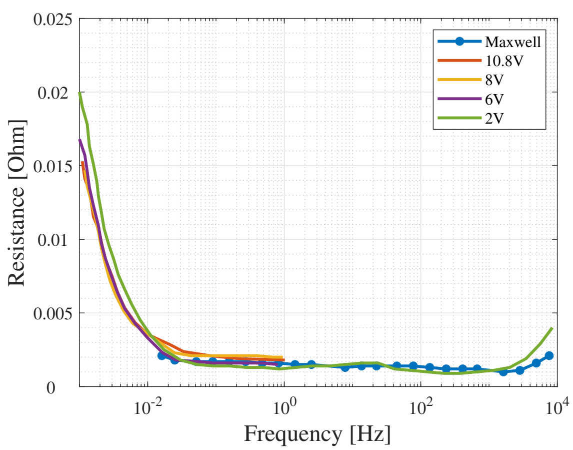

Fig. 7. Resistance characterization tests for the SC cell.

The SC model parameters are listed as follows: $R_L = 500\Omega$, $R_{p1} = 5.286\Omega$, $C_{p1} = 264.3F$, $R_{p2} = 0.5\Omega$, $C_{p2} = 40F$, $C_1 = 1487F$, $R_1 = 0.223m\Omega$, $C_2 = 1116F$, $R_{C2} = 0.0636m\Omega$, $L_2 = 67.3nH$, $R_{L2} = 0.247m\Omega$, $L_1 = 270nH$.

At last, the delay introduced by the power converters is characterized with a straightforward test, consisting on imposing a power reference in form of a step and measuring the dynamic response curve until the converter is able to match the reference. For the inverter test, the SCs are disconnected and the inverter sets the charge/discharge power reference for the Li-BESS, while for the DC/DC converter test, the inverter keeps a constant DC bus voltage so the DC/DC converter sets the charge/discharge power reference for the SCs. The tests for both power converters are shown in Fig. 10.

The converters behavior can be translated into a transfer function that can be added to the complete laboratory model,

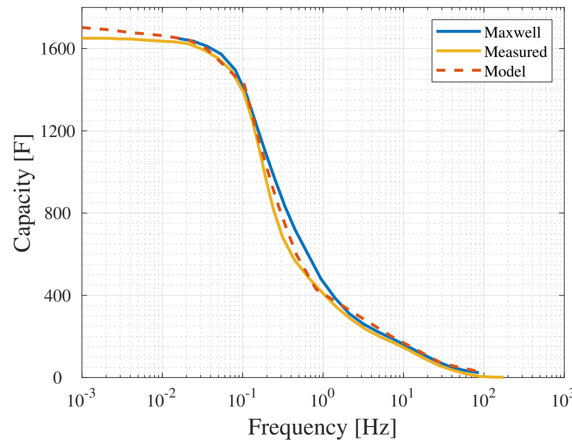

Fig. 8. SC model behavior comparison in terms of capacity.

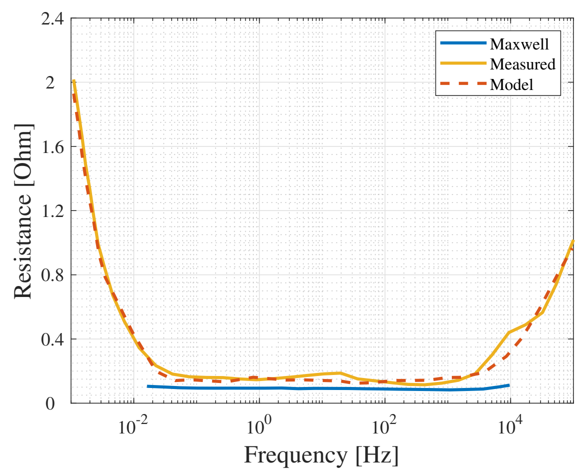

Fig. 9. SC model behavior comparison in terms of resistance.

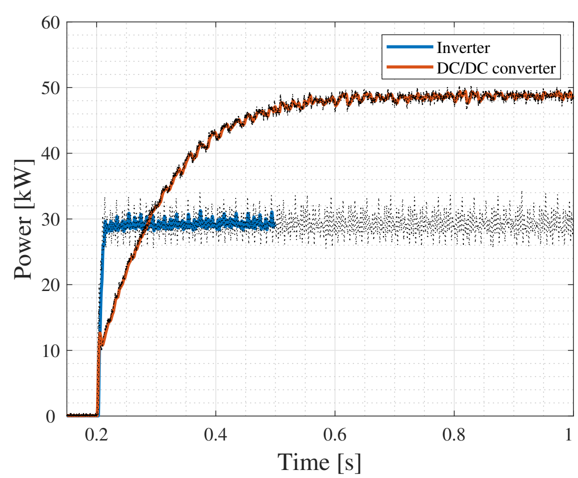

Fig. 10. Dynamic response characterization tests for the power converters associated to the Li-BESS and SCs.

so the time responses when imposing control references is implemented.Black lines in Fig. 10 are raw data, while colored lines are the data used for obtaining the transfer functions. For the inverter, the DC gain equals 250.4 and the time constant 248s, while for the DC/DC converter the DC gain equals 10.68 and the time constant 10.74s.

The results and parameters presented in this section will be used to size the energy storage systems and, in a further stage, to develop energy management control strategies so the coordinated operation between the hydro, Li-BESS and SCs is achieved. The dynamic response is relevant since it will help when tuning control strategies in the experimental facility.

V. CONCLUSIONS

The paper presents the models, laboratory characterization tests, and validation tests for a Li-BESS and a SC storage system that are part of a complete HIL installation. This laboratory facility, in use for Project HYBRIDHYDRO, is dedicated to test the combined integration of Li-BESS and SCs with a hydropower plant when providing frequency control and participating in energy markets, so the different elements are working in cascade expanding the lifespan of the installation (Li-BESS protecting the hydro while the SCs protect the Li-BESS). In this sense, the hydro plant is emulated in the HIL platform, whereas a 736V and 70kWh Li-BESS and 691V and 768Wh SCs are real devices located at CIEMAT's laboratories in Madrid, which need to be modelled, characterized and validated to develop and implement control strategies.

Semi-empirical models for the dynamic, thermal and ageing behavior have been selected for representing the Li-BESS and SCs, based on previous works. In order to parameterize those models, a set of laboratory tests have been performed to real cells to fit the dynamic and thermal parameters of the models. Once the models have been parameterized, they have been validated by comparing their behavior against the manufacturer datasheet, reaching a maximum error of 3% for the voltage/runtime and thermal model of the Li-BESS, and below 2% for SCs well as for the frequency domain and thermal model of the SCs.

Moreover, and given that the response time of Li-BESS and SCs are governed by the power electronic converters associated to it, a set of laboratory tests for modelling the time response of the converters have been performed.They behave a first order circuit, so the corresponding transfer functions have been finally added to the complete facility model so the installation is accurately represented. Thereby, the controls developed at a simulation level will be easily adapted to the laboratory facility in a further stage.

Both the models and power electronic converters characterization and validation will be used for developing frequency control strategies for the complete hydro, Li-BESS and SCs power plant in future works. Those controls will also include aging considerations for the Li-BESS and the hydro, resulting in an optimized techno-economical operation.

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