Hydro Power Plant Hybridization with Battery Energy Storage System for Primary Frequency Control

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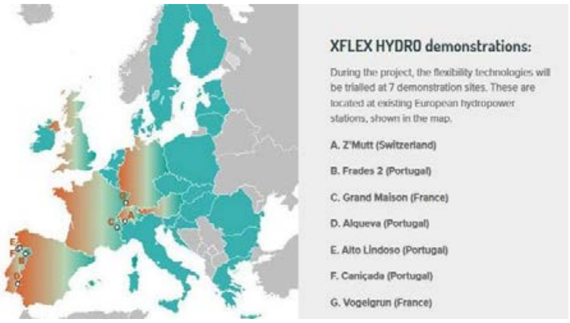
***Abstract*—This article presents the methodology used to size the battery energy storage system in terms of power and energy in order to participate to the frequency control together with the hydro generating unit and considering specific requirements defined by the transmission system operator**

Keywords: Energy Storage System, Power Conversion System, Hydro Power Plant, Primary Control, Battery SOH

I. CONTEXT

XFLEX HYDRO European project is a consortium of 19 partners funded by the EU. It aims at demonstrating, through industrial scale demonstrators across Europe, new hydropower technologies such as smart controls, enhanced variable and fixed-speed turbine systems, as well as a battery-turbine hybrid system. Supporting the EU's 2030 targets, the project will showcase how modern hydropower plants can provide the vital power grid flexibility services required by any country investing in variable renewables such as solar and wind power. During the project, the flexibility technologies will be trialed at 6 demonstration sites (Fig. 1). These are located at existing European hydropower stations such as Vogelgrun location. This is a 142 MW run-of-river Hydro Power Plant (HPP) in France, situated near the border with Germany along the Rhine river. The plant has four low head Kaplan turbines, in service since 1959, and during XFLEX HYDRO one of the units will be hybridized with a battery system for a duration of 2 years. Complementing the turbine's operations, the battery system will add energy storage to share response capability with the hydraulic unit, and use a master control to optimize both flexibility and wear and tear effects.



During the project, the flexibility technologies will be trialled at 7 demonstration sites. These are located at existing European hydropower stations, shown in the map.

Figure 1: XFLEX project demonstrator locations

II. SIZING METHODOLOGY OVERVIEW

The main objective of the Volgelgrun demonstrator is to hybridize the HPP with the installation and operation of a BESS in order to achieve dynamic frequency response on the french primary energy market while reducing wear and tear in the run-of-river turbine operating mechanism.

The frequency parameter is the main input of the primary control in order to fulfil the TSO requirements [1]. On the Vogelgrun demonstrator 10% of nominal power of the production unit has been dedicated for the primary control regarding a frequency deviation of 200 mHz. In our study case, this HPP could produce 40 MW in nominal using that means the 4 MW should be operate once a frequency deviation appears.

From these technical considerations, the methodology presented in this article consists:

1. To assess the regulating power needed to balance frequency deviation from a yearlong frequency data recording. Next, the power profile applied to BESS helps us to determine the capacity of the Energy Storage System (ESS) and maximum power of the inverter.
2. To compute performance and ageing indicators from different battery's technologies and for different manufacturers. These indicators help us to compare and select the solution regarding economic and technical constraints.

III. BATTERY ENERGY STORAGE SYSTEM SIZING

The methodology to size BESS as shown in Fig 2, consists of three main steps explained in the following sub-sections:

- Sub-section A (red selection in Fig. 2) presents how to assess the BESS power profile.
- Sub-section B (blue selection in Fig. 2) presents how to size the system in term of maximum power.
- Sub-section C (yellow selection in Fig. 2) presents how to size the capacity of the battery

A. Power profile applied to BESS

The first step of this study was to obtain the power profile applied to the battery in order to sizing the maximum power

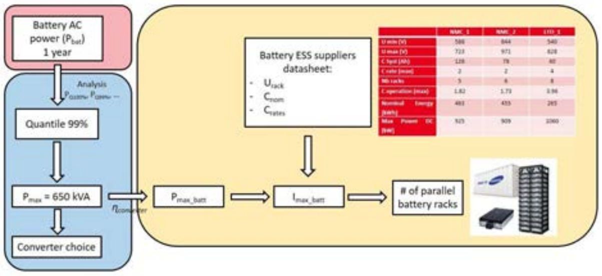


Figure 2: Battery sizing methodology

and the capacity of the storage system. This profile is computed from frequency measurement provided by EDF and composed of data over 1 year at sampling rate of 1 second and 1 mHz accuracy.

Three powers are computed as described in (Fig. 3):

- The first, in black color, is the power expected by the TSO regarding the frequency deviation (denoted P_{FCR}). It's just the frequency deviation from 50Hz multiplied by the FCR ratio (4MW/200mHz) dealt between EDF (French energy provider) and RTE (French TSO).
- The second, in blue color, is the power provided by the Hydro Power Plant (denoted P_{hydro}). This power is computed by using a simple model of the Vogelgrun HPP based on the first order model system. From qualification test and based on time step response of minus 200mHz frequency deviation, time constant response and static gain are identified.
- The third, in pink, is the power expected by the battery to respect for the hybrid system the expected power required by the TSO. This power is the difference between P_{FCR} and P_{hydro}.

These 3 power signals over 1 year at sampling rate of 1 second will be used to compute indicators to help us to size the BESS.

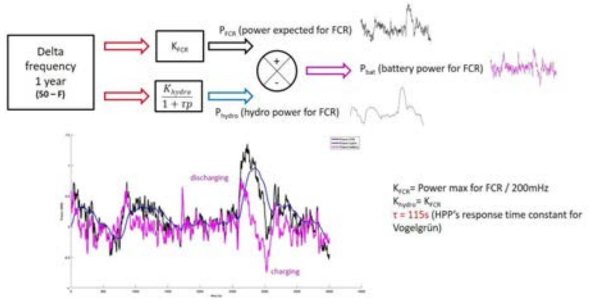


Figure 3: Power extraction methodology

B. Power controller system sizing

The second step consists by determining the optimum power size of the BESS regarding some indicators.

Firstly, a "Quantile" approach has been included in order to optimize the BESS parameters in term of power and energy, down to reasonable values. The quantile 100% means that the BESS can fulfil the power requirement with taken into account 1 year of frequency data. While a quantile 90% means that 10% of time, the BESS cannot fulfil the set point due to power limitation (inverter and/or battery) and HPP has to substitute.

Secondly, several Key Performance Indicator (KPI) have been computed (as shown on Table 1) in order to compare first BESS power size, second the BESS energy capacity, third the power ramp up ability.

Regarding the BESS power feature, we compute the yearlong maximum power in charge and in discharge mode. Battery is charged when the power is negative and is discharged when power is positive.

Regarding the energy feature, we compute for every day the cumulative total of energy in charge and in discharge mode and the daily energy balance ΔEnergy of the battery. If during a day, we start to discharge the battery with 100kWh and after we charge it with 120kWh and finally we discharge it with 30kWh, daily charge energy KPI corresponds to 120kWh, daily discharge energy corresponds to 130kWh and finally daily ΔEnergy corresponds to 10kWh. For each energy KPI the maximum value among the 365 values is retained and displayed.

Another indicator interesting to follow is the power gradient above 15 kW/s, meaning too fast power ramp up that HPP unit cannot follow. This KPI is the time percent over 1 year where the hydro power gradient exceed this threshold and could be considered as an indicator of HPP mechanical stress.

Considering the wear and tear improvement due to hybridization, the quantile 100% shows in Table 1, that the power gradient over 15 kW/s that HPP is not be able to follow, are almost all taken into account by the BESS. Indeed, without hybridization this KPI is about 55.2%.

For this 100% quantile, the nominal power of Power Converter System (PCS) is close to 3MW. The quantile 99% was studied to reduce this power, and shows that the PCS power requirement drops to 650 kW – almost 5 times smaller power sizing. In other words and regarding this nominal power, the converter does not cover statically 1% of the powers that occur during 1 year because just 1% of powers exceed the maximum power provided by the PCS.

Considering the energy side, the overall energy exchanged per day is close to 2MWh, however the difference of energy parameter between a charge and discharge case per day is very small, which means the energy tank could be much lower than 2 MWh – and is discussed in the following section.

Quantile	100%	99%	97%	95%	90%
BESS Pmax charge (MW)	1.96	0.65	0.49	0.43	0.35
BESS Pmax discharge (MW)	2.89	0.65	0.49	0.43	0.35
Daily charge energy (MWh)	2.05	2.04	2.02	1.99	1.93
Daily discharge energy (MWh)	2.05	2.01	1.96	1.93	1.85
Daily ΔEnergy (MWh)	0.05	0.08	0.1	0.11	0.12
Over 15 kW/s (%)	0.008	0.604	1.76	2.9	5.73

TABLE I. KPI ACCORING TO QUANTILE

C. *BESS capacity sizing*

Considering the power of PCS set at 650 kW as described in sub-section B, the study now focuses on the required optimal energy to embed in the DC part, and the choice of electrochemical technology and its provider. In this sense, two technologies of battery have been compared coming from three different providers as presented in Table 2. Regarding confidentiality clauses the name of providers are anonymized.

Technology (Cathode / Anode)	NMC/C	NMC/C	LMO/LTO
Cell Provider	NMC_1	NMC_2	LTO_1

TABLE II. BATTERY PROVIDER & TECHNOLOGY

One important parameter to take into account for the sizing of BESS, is the maximum current that the system has to provide. The calculation of the maximum current parameter (I_{max}) depends on the maximum power of the PCS evaluated to 650 kW (P_{max}), the efficiency of PCS close to 95% (η) and the minimum value of the battery voltage (U_{min}). The formula presented in (1).

$$I_{max} = \frac{\frac{Pmax}{\eta}}{Umin} \tag{1}$$

The cell provider through the datasheet indicates the maximum current that batteries can supply without harm, known as C_{rate}. Up to now, all providers supply and install the DC part in racks (assembly of battery modules). Considering the maximum current calculated previously (I_{max}) and the allowed maximum current rating from the battery provider (C_rate) and the capacity of each rack (C_{syst}), the number of racks to be installed inside the container can be calculated. The formula presented in (2)

$$N_{Racks} = \frac{Imax}{Csyst * Crate} \tag{2}$$

According to those parameters calculation, the energy for each BESS technology can be calculated as described in Table 3. This table shows that the NMC technology choice for the BESS integration needs to embed 500kWh of energy instead of 265 kWh for LTO technology. Indeed, the LTO technology allows to perform the battery with high power rate (4C versus 2C for NMC technology).

However the price (€/kWh) of LTO technology is more expensive, this is the reason why the energy sizing need to be optimized. Another indicator would be introduced regarding BESS cost which take into account the most relevant cost components during the entire operation of the system. In [2] it concludes that maintenance and disposal represent significant costs hence we introduce an ageing indicator.

IV. AGEING SIMULATION APPROACH

Considering that the BESS sizing and technology are defined according to methodology presented in section 3, ageing evaluation of the battery can be performed: known as State Of Health (SOH) parameter and corresponds to the ratio between the actual capacity and the nominal capacity of the battery cell (3).

$$SOH = 100 * \frac{Q_{nom} - Q_{loss}}{Q_{nom}} \tag{3}$$

	NMC_1	**NMC_2**	**LTO_1**
U min (V)	588	844	540
U max (V)	723	971	828
C Syst (Ah)	128	78	40
C rate (max)	2	2	4
Nb racks	5	6	8
C operation (max)	1.82	1.73	3.96
Nominal Energy (kWh)	463	455	265
Max Power DC (kW)	925	909	1060

TABLE III. BESS ENERGY SIZING ACCORDING THE PROVIDER

For this purpose, a power profile regarding the DC side and cell level have been extracted from the AC power profile requested (Fig. 2 & section 3). An operating range of SOC has been included from 10% to 90% because outside this range, the Battery Management System (BMS) of the BESS generally limits the power in charge and discharge for Li-ion technologies. The preliminary simulation results highlight that the DC power profile is not symmetrical in terms of energy, and the BESS reaches quickly low value of SOC. To address this case, a Power Management System (PMS) has been designed in order to operate the BESS around a SOC target. Indeed, the idea is to use energy provided by HPP to charge the BESS according to the SOC level when the HPP is over the reference power set point calculated.

Three different ageing models have been used to simulate the capacity loss of the 3 different providers presented in Table 2. These ageing models are empirical models based on ageing tests performed at cell level for different conditions. Although the results of the ageing tests are different regarding the technologies, the architecture of the models follows the same principle for the 3 models. The objective of the battery ageing models developed at CEA is to be able to predict the loss of capacity of a cell subjected to a given power profile (calendar storage or charge / discharge cycles) over a certain period of time. For this, the degradation law described below is defined and the parameters of this law are best adjusted to the available experimental data (loss of capacity as a function of time or of Ah transited) by the method of least squares.

The capacity loss of a battery cell, which degrades in calendar and / or cycling, can be partly explained by the growth of the layer of Solid Electrolyte Interphase (SEI) at the negative electrode. This growth is limited by ionic diffusion in the SEI [3].

In this approach, the rate of decrease in capacity can be expressed, in the case of calendar storage, by calendar capacity loss rate expression (4) With Q_{loss}, the capacity loss in Ah, J_{cal}, kinetic factor depending on cell's SOC level and cell's temperature and A, a constant factor.

$$\frac{\partial Q_{loss}}{\partial t} = \frac{J_{cal}}{1 + A.Q_{loss}} \tag{4}$$

$$\frac{\partial Q_{loss}}{\partial Q_{th}} = J_{cyc} \tag{5}$$

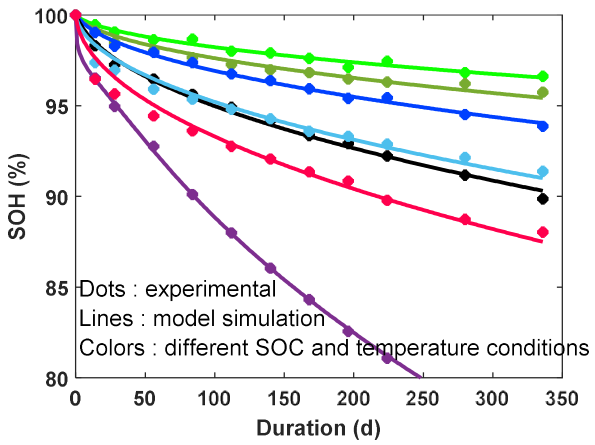


Figure 4: Example of calendar ageing test campaign results and model simulation

For cycling ageing, the degradation rate depends on the cell's charge quantity Q_{th} transited during battery use (5).

It is considered that during cycling periods, there is still a calendar contribution, which depends on the time spent. The capacity degradation law is then expressed as the sum of the calendar and cycling contributions (6).

Depending on experimental results, these degradation laws could be adapted. Figure 4 show an example of model

$$dQ_{loss} = \frac{\partial Q_{loss}}{\partial t} dt + \frac{\partial Q_{loss}}{\partial Q_{th}} dQ_{th} \qquad (6)$$

parameters calibration for calendar tests. In our case, the models parameters have been determined for the 3 different Li-ion cell's technologies. The profiles described in the next section have then been simulated to determine the ageing regarding each cell's reference.

V. AGEING RESUTS

Considering the different sizing described in section 4 according to the technology and the provider, it seems to be useful to simulate the operation during 2 years and evaluate the SOH of the BESS in terms of energy with taken into account chemical degradation process explained previously.

The current profiles has been sized regarding cell's capacity. During these simulations, SOC profile is calculated taken into account the cell's degradation. Also cell's temperature is assumed constant at 25°C because there is no electro thermal model available for this study. Figure 5 shows an overview of the ageing simulation results with the current, SOC and temperature profiles at cell level, but also capacity losses results due to calendar part and cycling part. Considering these losses, the SOH profiles is estimated by the model.

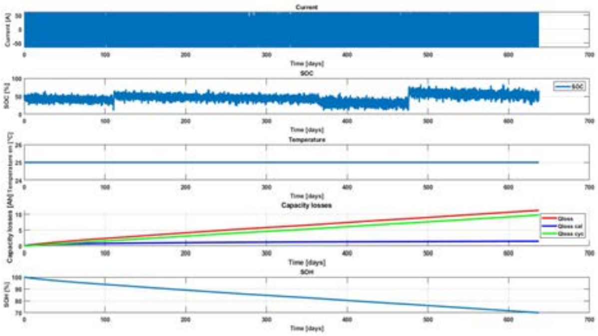


Figure 5: Example of ageing simulation results

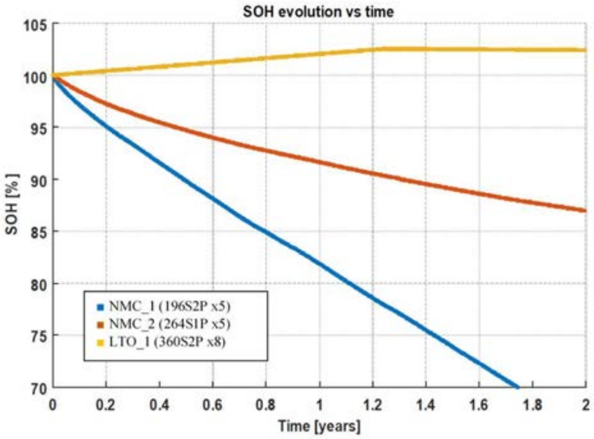


Figure 6: Ageing simulations comparison of 3 li-ion technologies

In figure 6, the difference between the 3 different references can be observed for SOC target of 50%. A significant difference can be noticed between each cell's references with the lowest performances expected to be with NMC_1's reference. As it can be observed, the LTO_1's models presents a running-in phase that can be usually found on this type of technology before starting a low-speed capacity fade. This technology is known as achieving one of the best endurance of li-ion technologies.

VI. CONCLUSION

The battery energy storage system sizing is complete both considering methodology and specific application to Vogelgrun demonstrator. BESS parameters have been computed such as power rating for the PCS side and energy storage regarding the battery side. For this demonstrator, results highlight that a power of 650 kW seems to be the best compromise between rating and required grid frequency support. In the same time, the Titanate battery technology shows very good ageing behavior regarding to this application. However, the price per kWh is rather expensive. As an alternative, the Manganese battery technology and especially rack system provided by NMC_2 manufacturer should be an interesting selection due to the fact that it is cheaper and the ageing simulated over 2 years remains acceptable (87% of SOH) with an initial energy tank close to 500 kWh in total.

ACKNOWLEDGMENT

This work has been realized in association with INES.2S and received funding from the European project XFLEX Hydro (Grant agreement ID: 857832)

REFERENCES

[1] Frequency Ancillary Services Terms and Conditions, version 01/09/2020 – RTE – France.

[2] B. Marchi, M. Pasetti, S. Zanoni., "Life Cycle Cost Analysis for BESS Optimal Sizing", in Energy Procedia, vol. 113, pp. 127-134, 2017.

[3] A. Barré, B. Deguilhem, S. Grolleau, M. Gérard, F. Suard, et al., "A review on lithium-ion battery ageing mechanisms and estimations for automotive applications". Journal of Power Sources, Elsevier, 241, pp. 680 – 689, 2013.