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First approach for a techno-economic analysis of storage components used for improving energy management strategies in microgrids

A. Ndiaye

AVENUES, Université de Technologie de Compiègne, Compiègne, France
alla.ndiaye@univ-lille.fr

F. Locment

AVENUES, Université de Technologie de Compiègne, Compiègne, France
fabrice.locment@utc.fr

A. De Bernardinis

COSYS / SATIE, Université Gustave Eiffel, Versailles, France
alexandre.de-bernardinis@univ-eiffel.fr

M. Sechilariu

AVENUES, Université de Technologie de Compiègne, Compiègne, France
manuela.sechilariu@utc.fr

E. Redondo-Iglesias

Eco7, Université Gustave Eiffel, Lyon, France
eduardo.redondo@univ-eiffel.fr

ABSTRACT:

Microgrids are essential elements of the energy transition because they allow optimal use of renewable energy sources (photovoltaic panels, wind turbines, etc.) and storage devices (batteries, supercapacitors ...) by connecting them to consumption poles (buildings, charging stations of electric vehicles, etc. ...). Lithium-ion batteries and supercapacitors are the main electrical storage devices usually used by microgrids for the energy and power transient management. In the present paper, microgrid's simulations have been performed. Electrical and aging models of storage components are presented. Strategies and scenarios for the batteries are presented either based on state-of-charge limitation, or towards hybrid association with supercapacitors, in order to extend their lifetime in microgrids operation, while in the meantime searching for minimizing the installation costs. The first approach for a techno-economic study provided in that study enables to improve the strategies by optimizing the use of the battery. The results obtained in this paper demonstrate the key role of the techno-economic approach, and knowledge of the aging processes of storage devices for improving the energy management and global feedback costs of microgrids.

KEYWORDS:

Techno-economic analysis; microgrids; lithium-ion batteries; supercapacitors; aging modeling.

I. INTRODUCTION

The security and reliability of large-scale grids is becoming increasingly problematic due to profound changes in the sector such as market liberalization, increased interconnections, but also economic and environmental constraints [1]. One of the solutions to these problems is the

decentralization of production sites based on renewable energy. Decentralized power generation will on the one hand reduce the investment costs of electricity transmission and distribution. On the other hand, it will facilitate the integration of renewable energies into the public grid via micro-grids. The final objective is to achieve optimized local production-consumption controlled in real time by an intelligent electricity network. The micro-grid framework provides a means of harnessing diverse energy sources, e.g. photovoltaic (PV) panels, wind turbines, engines, in a decentralized manner, while reducing the load on the grid by generating power close to the consumer [2]. Microgrid aggregates local power production, consumption and storage together [3]. Storage systems provide security of supply to the microgrid and address fluctuations of renewable energy sources in the grid (e.g. intermittency and randomness of the power generated by PV) [1]. Lithium-ion batteries and supercapacitors (SCs) are the main electrical storage devices usually used in microgrids for energy and power transient management. Optimized energy management is a key issue for the deployment of microgrids, which will require specific modelling and management tools. In order to improve, or reinforce, management strategies the knowledge of a techno-economic study among different operating cases for the storage components, is mandatory. To achieve such techno-economic analysis, accurate models for the electrical storage components are first required. In particular, aging models should bring key indicators on how to optimize the state-of-health (SoH) of the storage components, predict possible fluctuations, and act to preserve the battery lifetime. For the lithium-ion batteries, combined calendar-cycling aging simulations have been performed. For SCs, calendar aging, as well as a degradation model according to the SoH are investigated. In addition, strategies and scenarios for the batteries are presented either based on state-of-charge (SOC) limitation, or towards hybrid association with SCs, in order to extend their lifetime in microgrids operation, while in the meantime searching for minimizing the installation costs. The first approach for a techno-economic study provided in that study enables to improve the strategies by optimizing the use of the battery. First results for a real-time management for microgrids is achieved by adapting aging models, outputs of the techno-economic study for the battery and SCs towards real-time implementation.

The rest of the paper is organized as follows: Section II presents the studied microgrid. The modelling of the hybrid energy storage system (HESS) elements is presented as well as the PV panels and the connection to the utility grid. Then the three management strategies used are defined. Section III presents the simulation results. A comparison is performed between strategies 1 and 2 in different SOC scenarios. A techno-economic study is conducted in this section. The simulation results in the case of HESS are presented. Finally, section IV presents the conclusion and perspectives.

II. ENERGY MANAGEMENT STRATEGIES IN MICROGRIDS

Most of renewable power generation is very intermittent and random, especially at a lower scale like in microgrids. If this continuously growing production is injected into the grid without control, it will increase the power mismatching in the utility grid and cause fluctuations in voltage and frequency [1], [2], or even blackout. Thus, the vulnerability of the utility grid could increase.

Within a time horizon, energy management is supposed to manage the power flow in microgrid and power flow exchanged with the utility grid during the grid-connected mode, with the objective of making full use of each source while respecting their constraints on capacity and

power. Thus, that operation can be optimized and the cost can be reduced; nevertheless, data communication by smart grid is required for overall grid performance enhancement. The energy management can be classified into rule-based and optimization-based approaches. Rule-based approach manages the system according to prefixed rules, such as simple rule base, multi-agent system [4] and fuzzy logic approaches[5], [6]. Optimization based approach manages the system by mathematical optimization, carried out with objective function and constraints. The rule-based management strategy is used in this study, as it is simple and provides efficient energy management of the studied microgrid.

A. PRESENTATION OF THE MICROGRID

Microgrids are essential elements of the energy transition as they allow an optimal use of renewable energy sources (PV panels, wind turbines, etc.) by connecting them to loads (buildings, electric vehicle charging stations) or storage systems (batteries, SCs). There are AC, DC and hybrid AC/DC microgrid structures depending on the usage of AC or DC common bus for coupling different elements within microgrid. The microgrid combines local power generation and local consumption, and can operate in grid-connected or in islanded operation mode [3]. A microgrid controller allows the connection to the public grid and provides voltage control, energy and power flow, load sharing, load shedding during islanding and considers the constraints of the public grid transmitted through a communication bus [1]. Figure 1 shows the studied DC microgrid.

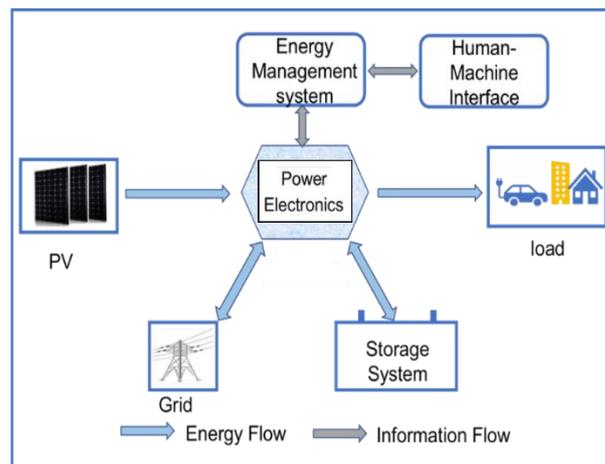


Figure 1. DC microgrid.

A1. Definition of the hybrid energy storage system.

Microgrid storage devices are necessary to manage electric grid peak demand, improve reliability and outage mitigation, compensate for intermittent power generation from distributed generation, provide ancillary services specifically in islanded mode of operation and increase electric grid load factor and utilization via the smart grid [2]. The considered HESS is based on batteries and SCs. The aging of these storage systems due to various stress factors (operating temperature, SOC, current amplitude, etc.) is a major problem in microgrids. As the price per kWh of batteries and SCs is still high today (a few hundred euros depending on the technology), it is essential to extend their life span as long as possible in order to reduce the total cost of the installation. To achieve this objective, better sizing and management are the only solutions. This work focuses on the management part.

All. Li-ion batteries: In this section, the battery aging model used is that developed in [7]. Based on Eyring's law, this semi-empirical model combines calendar and cycled aging and considers the accumulation of three aging mechanisms (calendar, cold cycling and hot cycling) in an independent way. More details on the development of the model can be found in [7].

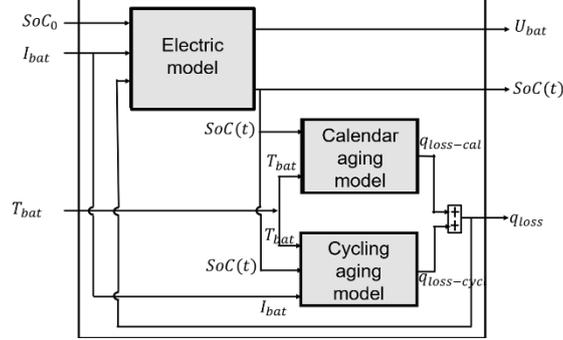


Figure 2. Electric and aging model of the battery.

The Eyring law for an “i” cycling aging mechanism is presented in equation (1).

$$\frac{dq_{\text{loss},i}}{dt} = A_i \times e^{B_i \times \text{SOC}} \times e^{\frac{E_{a,i} - C_i \times I}{R \times (T_{\text{bat}} - T_r)}} \times I \times \left(\frac{1}{1 + b \times q_{\text{loss}}^c} \right) \quad (1)$$

where q_{loss} is the battery capacity loss (p.u), A_1 is the pre-exponential factor (p.u./day), E_a is the activation energy ($\text{J} \cdot \text{mol}^{-1}$), R is the gas constant ($\text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$), I is the battery charging current expressed in C-rate, T_{bat} is the battery temperature (K), B is the SOC influence coefficient C is the current influence coefficient expressed in (h. p.u⁻¹). T_r is the reference temperature where the “i” aging mechanism influence is assumed to be zero (typically $T_r = 0\text{K}$ for calendar and hot cycling aging). b and c are unitless model parameters. C-rate is a measure of charging or discharging current, expressed as a ratio of the rated capacity to the time required to fully charge an energy storage system.

To calibrate the model, a current of $I_0 = \text{C-rate}/12$ is chosen. Any cycling at a current less than or equal to this is considered to be calendar aging. Equation (2) gives the variation of the capacity loss of the complete aging model, where $q_{\text{loss-cal}}$ is the capacity loss due to calendar aging, $q_{\text{loss-cycl-hot}}$ is the capacity loss during hot cycling aging, and $q_{\text{loss-cycl-cold}}$ is the capacity loss during cold cycling aging.

$$\frac{dq_{\text{loss}}}{dt} = \frac{dq_{\text{loss-cal}}}{dt} + \frac{dq_{\text{loss-cycl-hot}}}{dt} + \frac{dq_{\text{loss-cycl-cold}}}{dt} \quad (2)$$

$$\frac{dq_{\text{loss-cal}}}{dt} = \underbrace{A_{\text{cal}} \times e^{B \times \text{SOC}} \times e^{\frac{-E_{a,\text{cal}} + C_{\text{cal}} \times I_0}{R \times T_{\text{bat}}}} \times \left(\frac{1}{1 + b \times q_{\text{loss}}^c} \right)}_{\text{calendar aging}} \quad (3)$$

$$\frac{dq_{\text{loss-cycl-hot}}}{dt} = \underbrace{A_c \times e^{B \times \text{SOC}} \times e^{\frac{-E_{a,c} + C_c \times I}{R \times T_{\text{bat}}}} \times I \times \left(\frac{1}{1 + b \times q_{\text{loss}}^c} \right)}_{\text{hot aging}} \quad (4)$$

$$\frac{dq_{\text{loss-cycl-cold}}}{dt} = \underbrace{A_f \times e^{B \times \text{SOC}} \times e^{\frac{E_{a,f} - C_f \times I}{R \times (T_{\text{bat}} - T_r)}}}_{\text{cold aging}} \times I \times \left(\frac{1}{1 + b \times q_{\text{loss}}^c} \right) \quad (5)$$

A12. Supercapacitors: The SCs, also known as Electrochemical Double-Layer Capacitors or ultra-capacitors are less performant than electrochemical batteries in terms of energy density [8]. However, their cycling lifetimes, power densities and operating temperature ranges make them a storage technology used in many applications, whether vehicle or stationary.

In a microgrid involving a HESS, composed by batteries and SCs, the SCs allow to improve the lifetime of batteries. The high-power density of SCs allows absorbing transient currents due to the numerous power fluxes of the panels. The management of the power flow for these storage components with the other elements of the microgrid is a key point.

In order to ensure performance over the life of the system, the reliability of SCs has to be quantified through accelerated aging tests and/or the use of aging models. To this purpose, manufacturers and several laboratories have conducted numerous calendar and cycling aging tests. In this study, we use the electrical and aging models developed in T. Kovaltchouk's thesis (see [8] and [9] for more details).

- Electrical model of SCs

The electrical model used in this study, basically consists in a Thevenin model with a capacitor C in series with the internal resistance (ESR equivalent series resistance) in function of time (t), as shown in Figure 3.

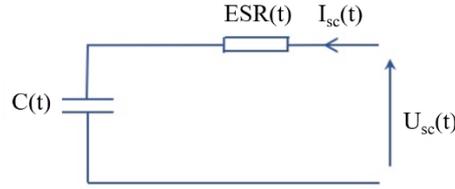


Figure 3. Thevenin electrical model of the SC.

-SC calendar aging model

The classical aging model of SC concerns only calendar effects, it is based on the use of an Eyring's law, which gives the lifetime [10]. The SoH variation is then given by the equation (6), where θ_c is the temperature of the case and V the voltage at the terminals of the component. V_0 and θ_0 correspond respectively to the voltage and temperature drop required to double the lifetime. $t_{\text{Life-Ref}}$ is the reference lifetime in hours, for a reference package temperature $\theta_{c-\text{Ref}}$ (here, the maximum operating temperature is 65°C) and a reference voltage V_{Ref} (here, the nominal voltage is 2.7V).

$$\frac{d\text{SoH}}{dt} = \frac{1}{t_{\text{Life-Ref}}} \times e^{\ln(2) \frac{\theta_c - \theta_{c-\text{Ref}}}{\theta_0}} \times \left[e^{\ln(2) \frac{V - V_{\text{Ref}}}{V_0}} + K \right] \quad (6)$$

The coefficient K enables to take into account the aging in high temperatures and low voltages [8].

Degradation model of electrical characteristics as a function of SoH

The electrical parameters, the capacitor C and ESR, vary as a function of aging. According to [11], two different phases can be observed during SC aging: an initial burning phase, and a linear degradation phase. The model presented in [8] considers only the latter phase considering a linear variation of the capacitance and conductance parameters. Hence, the capacity is equal

to 95% of the initial capacity at $\text{SoH} = 1$ as in equation (7). Equation (8) gives the conductance (i.e. the inverse of the ESR) as a function of SoH . C_0 and ESR_0 are the initial values of C and ESR respectively.

$$C = C_0 \times (0.8 + 0.15 \times \text{SoH}) \quad (7)$$

$$\text{ESR}^{-1} = \text{ESR}_0^{-1} \times (0.7 + \text{SoH}) \quad (8)$$

A2. Photovoltaic panel system

The renewable energy source in a microgrid can be PV panels, wind turbines or both combined. In this study, the renewable energy source considered is based on PVpanels. The solar irradiation data used in the simulation are from the PV installation of the Centre Pierre Guillaumat of the Université de Technologie de Compiègne (UTC), which consists of 16 panels in series of 130 W nominal (reference SolarFabrik SF 130/2) as shown in Figure 4.



Figure 4. PV installation of the Centre Pierre Guillaumat of UTC [12].

Regarding the experimental platform including the PV installation of the Centre Pierre Guillaumat of UTC more details can be found in [12].

A3. Connection to the utility grid

The connection to the public grid is a security element that ensures the safety of the system in case of insufficient power transferable to the load, or excess power [1]. It is assumed that there are no constraints to connect to the grid.

B. DEVELOPMENT OF CONTROL STRATEGIES

The objective of this section is to present the energy management strategies of the microgrid that allow to extend the battery lifetime and consequently to lower the cost of the installation. First, the classical microgrid management strategy is presented. In a second step, two management strategies allowing to reduce the battery aging are presented. Simulation results are given and discussed.

B1. Strategy 1: classical microgrid energy management

In this part, the strategy is defined to distribute the extra power between the battery and the public grid considering the SOC of the battery. It is assumed that the extra power can be drained to the grid at any time. The extra power, P_{tot} , is the difference between the generated power and the required power to supply the load, as given in equation (9).

$$P_{\text{tot}} = P_c - P_{\text{pv}} \quad (9)$$

with P_c the power of the load and P_{pv} the power of the PV panels.

To distribute the extra power between the grid and the battery, a distribution coefficient K_D is defined as shown in equations (10) and (11):

$$P_{\text{bat}} = K_D \times P_{\text{tot}} \quad (10)$$

$$P_G = P_{\text{tot}} - P_{\text{bat}} = (1 - K_D) \times P_{\text{tot}} \quad (11)$$

$$\text{With: } \begin{cases} K_D = 1 \Rightarrow P_{\text{bat}} = P_{\text{tot}} \\ K_D = 0 \Rightarrow P_{\text{bat}} = 0 \end{cases}$$

where P_G is utility grid power.

The flowchart of this strategy is presented in Figure 5.

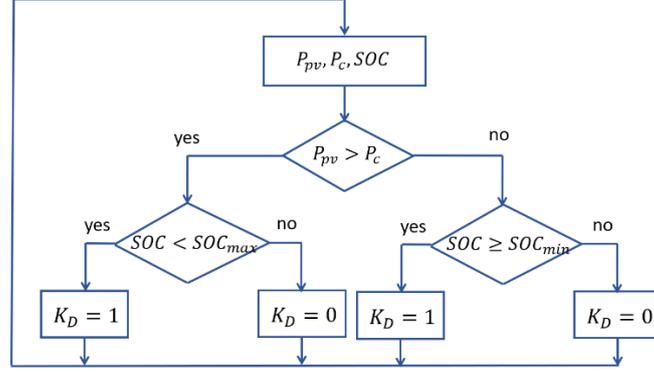


Figure 5. Flowchart of classic management of microgrid.

B2. Control strategy considering battery aging

B2.1. Strategy 2: improvement of strategy 1 considering battery aging: The classical strategy is improved. If the generated power is insufficient, the battery is not automatically used to supply the load. The price per kWh from the grid is compared to the price per kWh from the battery. A cost related to the use of the battery is defined. This price includes cost of battery, power electronics, cost of installation, step-up transformer, smart-grid communication and controls, grid interconnection to utility [2], the replacement costs, repair and maintenance costs, and the discounted purchase price of the battery [3]. To simplify the calculations, the price per kWh battery (C_{bat}) is chosen arbitrarily [3]. The grid kWh price (C_G) varies by time of day:

-During peak hours, the price per kWh from the grid is higher than the battery's one. The load is supplied from the battery.

-During off-peak hours, the grid kWh cost is cheaper than the battery's one. Extra power is purchased from the grid. Table 1 shows the prices per kWh for the grid and battery.

Table 1: Price per kWh for grid and battery

	Grid	Battery
Peak hours	0.7	0.3
Off-peak hours	0.1	

The flowchart for strategy 2 is shown in Figure 6. The influence of the maximum SOC, SOC_{max} , on the battery life is also considered.

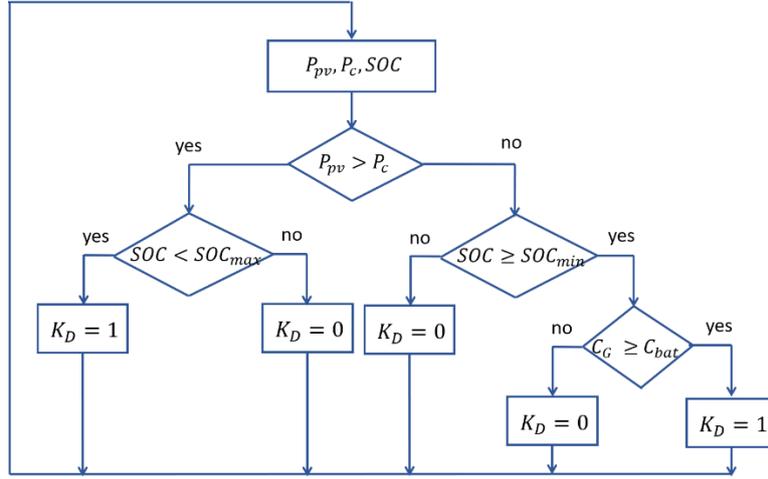


Figure 6. Flowchart of the strategy 2.

B22. Hybrid energy storage system: As mentioned above, the HESS consists of a battery coupled with a SC. The strategy used to distribute energy between the battery and the SC is presented along with the simulation results. The energy management between the battery and SC is a filtering-based strategy.

To distribute the power between the battery and the SC, the filtering-based strategy was used as shown in Figure 77. The strategy based on filtering consists in distributing the power between the low and high frequency dynamics using a low pass filter [13]. The battery power P_{Bat} is the low frequency part of the P_{HESS} power which is the total power of the hybrid storage system, while the high frequency part is the SCs power P_{SC} .

The battery power is the output of the low pass filter and its value is directly related to the cut-off frequency of the low pass filter f_0 [14]. The value of this frequency is chosen so as to minimize the battery current. Figure 7Figure 7 shows filtering-based strategy principle.

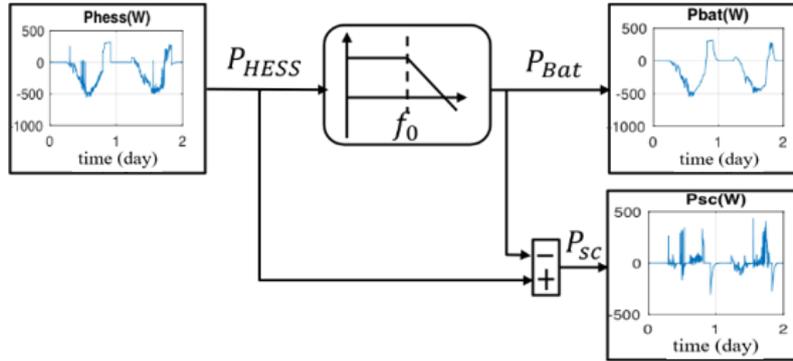


Figure 7. Filtering-based strategy.

III. SIMULATION RESULTS

Simulations were carried out with each of the strategies defined above. The simulations last for 10 days with a time step of one minute. The generated power profile is a real profile of the UTC PV panel platform, from 1st to 10th of June 2019. The load profile is a profile of the lighting consumption of a floor of the Laboratory for Analysis and Architecture of Systems (LAAS) building in Toulouse, from 1st to 10th of June 2017. The load profile is assumed to be constant between 2017 and 2019. The temperature is constant at 25°C for all simulations presented in this section. Two scenarios of SOC are considered: $SOC_{max} = 100\%$ and $SOC_{max} = 80\%$.

Models for the components of the microgrid have been developed using the Matlab/Simulink software (Simulink models). Analytical models are based on common pre-defined HESS component's blocks selected on the Simulink interface, for which the internal and input parameters for aging and dynamic behaviour models are calculated using analytical equations and routines implemented on the Matlab Workspace.

A. COMPARISON OF STRATEGIES 1 AND 2 REGARDING BATTERY AGING

The loss of battery capacity is much greater for strategy 1 as shown in Figure 8 (the values are presented in the following Table 2). In the first case, where the SOC_{max} is set to 100%, the lifetime is equal to 7 years for strategy 2 against 5.5 years for strategy 1, i.e. one and a half years longer (see Table 2). Other simulations were carried out with a maximum SOC of 80%. These simulation results show that the gap increases to 2.2 years when the SOC_{max} is set to 80%. The higher is the SOC, the greater is the capacity loss [15], [16]. According to the model chosen in equations (2) to (5), extreme temperatures (very cold or very hot) and high SOC's favor battery degradation.

In Figure 8, it can be seen that strategy 2 tends towards higher SOC's than strategy 1. This would normally lead to more aging for strategy 2. On the other hand, we observe a very high SOC recharge (from 70 to 100%) for strategy 1 in day 1 that does not exist in strategy 2. This recharge is reflected in the aging curves and is responsible for the main difference in aging between strategy 1 and strategy 2. These simulations were done with a temperature of 25°C (northern France in June), with other more extreme scenarios, for example 0 or 40°C, the differences between strategy 1 and 2 could become even more important.

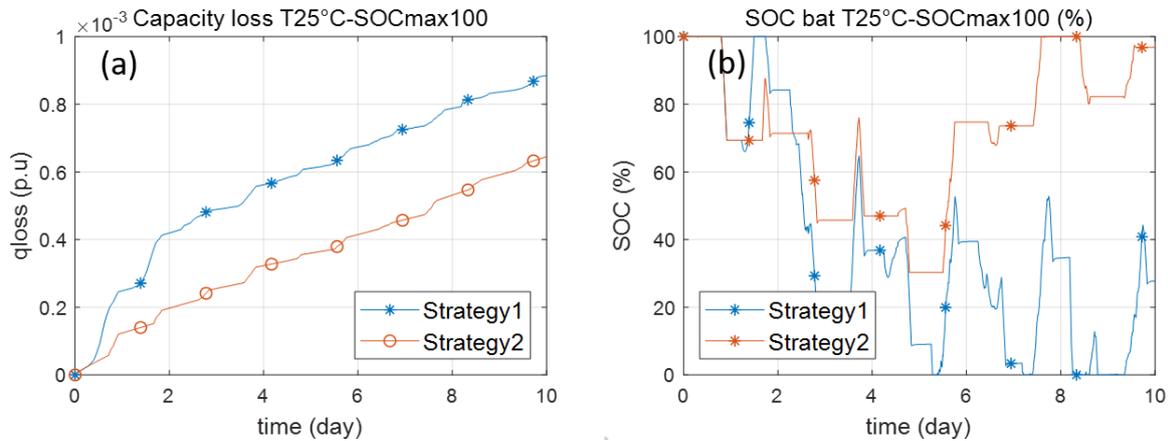


Figure 8. Capacity loss (a) and SOC of the battery (b) for strategies 1 and 2.

B. TECHNO-ECONOMIC STUDY

The Table 2 above shows the total cost (battery price + cost of energy purchased from the utility grid) in a 20-year microgrid project. The total cost of energy purchased from the utility grid over a year is higher in strategy 2. This is due to the fact that strategy 2 favours the purchase of energy over the use of the battery (especially when the cost of grid energy is cheaper) to improve the lifetime of the battery. However, the total cost over the life of the project (here 20 years), including the price of the batteries multiplied by the number of times they are replaced, for each strategy, strategy 2 becomes much cheaper. At the end of the project, strategy 2 will have cost €16688 compared to €18921 for strategy 1. The batteries are replaced 3 times in strategy 2 against 4 times in strategy 1. In conclusion, strategy 2 is much more advantageous

than strategy 1. Considering the aging aspect in the real time management allowed to extend the life of the batteries and to reduce the total cost of the installation by reducing the cost of the batteries.

Table 2: Total cost of strategies 1 and 2 for a 20-year microgrid project with $SOC_{max} = 100$ and $T = 25^{\circ}C$

Strategies	1	2
Q_{loss} (p.u. $\times 10^{-4}$)	10	7.84
Battery life (years)	5.5	7
Total cost of energy purchased for 20 years (€)	720	2380
Number of battery replacement over 20 years	4	3
Battery cost over 10 years (€)	18201	14308
Total project cost over 10 years (€)	18921	16688

C. SIMULATION RESULTS OF THE HESS

The total power of the HESS, P_{HESS} , the powers of battery P_{bat} and SCs P_{sc} are presented in Figure 9 below. One notes that the coupling between the battery and the SCs through filtering has resulted in a much smoother current at the battery. The HESS avoids applying high frequency currents directly to the battery. These currents are largely responsible for the premature aging of batteries.

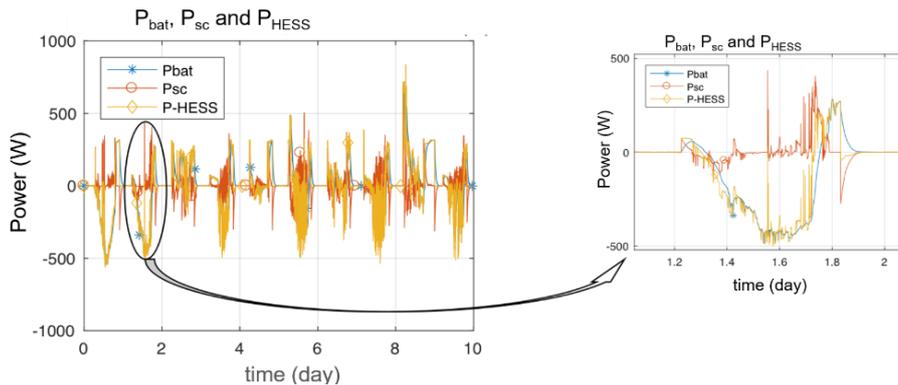


Figure 9. Total unfiltered HESS power, filtered SC and battery power.

In Figure 10 below, it can be seen that filtering the current has a positive influence on the capacity loss of the battery.

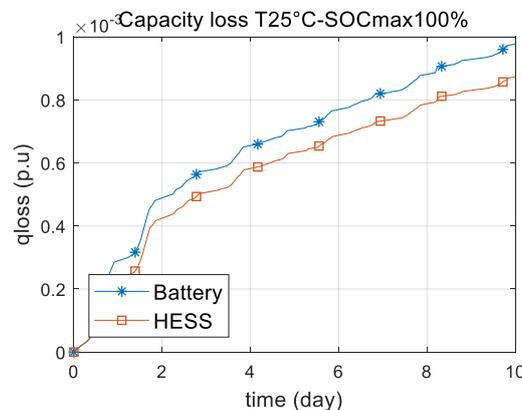


Figure 10. Battery capacity loss in HESS versus classical strategy 1.

The loss of battery capacity increased from 0.1% for 10 days of simulation with the battery alone to 0.085% with the hybrid storage system. This corresponds to a gain of 10 months in battery life. Figure 11 shows the capacitor C and ESR of the SCs. The capacity of the SCs lost over the 10 days simulation is 0.0119% corresponding to a theoretical lifetime (by extrapolation) of "34 years". This large value could be explained by the low values of currents flowing through the SCs. A comparative cost study is not performed in this section. This is one of the perspectives of this work.

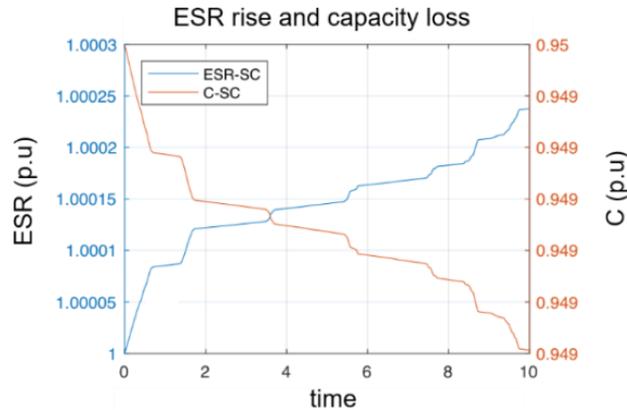


Figure 11. Capacity loss and ESR rise of the SCs.

IV. CONCLUSION AND PERSPECTIVES

Strategies and scenarios for the batteries are presented either based on SOC limitation, or towards hybrid association with SCs, in order to extend their lifetime in microgrids operation, while in the meantime searching for minimizing the installation costs. In the first part, strategy consists of improving the conventional energy management by considering the battery aging. The results show that energy management allows to extend the lifetime of the batteries and to lower the costs of the micro-grid project depending on the chosen strategy. In the second part, the battery is coupled with SCs. The filtering strategy is used to distribute the energy between the battery and the SCs. Results show that high frequency currents are eliminated and battery life is improved. The results obtained in this paper demonstrate the key role of the techno-economic approach, and knowledge of the aging processes of storage devices for improving the energy management and global feedback costs of microgrids. In the future, other scenario will be considered: extreme temperatures, longer simulations over time. Battery and SC models will be performed by adding thermal models. The power performance degradation due to the battery aging will be considered. The SCs will be dimensioned to further the techno-economic study in the case of the hybrid energy storage system. This study would allow to know if it is advantageous or not to couple the batteries with SCs. Finally, the energy management will be improved through more elaborate optimization algorithms.

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