Energy Storage System Sizing for Smoothing Power Generation of Direct Wave Energy Converters

Judicael Aubry, Paul Bydlowski, Bernard Multon, Hamid Ben Ahmed, Bruno Borgarino

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J. Aubry[1], P. Bydlowski[1,2], B. Multon[1], H. Ben Ahmed[1] and B. Borgarino[2]

[1] SATIE, ENS Cachan Bretagne, CNRS, UEB
av Robert Schuman, F-35170 Bruz
E-mail: judicael.aubry@bretagne.ens-cachan.fr

[2] LMF, Ecole Centrale de Nantes, CNRS
1 rue de la Noë, F-44000 Nantes

Abstract

This paper examines the sizing problem of an energy storage system (ESS) for a direct wave energy converter as the SEAREV. The aim of this ESS is to insure a smoothed output power profile. First, the output set point power is considered constant and equal to the average produced power during a sea state representative time (about two hours). Two others causal method of smoothing will be studied in a second part. We introduce two state of charge (SOC) control strategies in order to maintain SOC between two limits and also two power quality criteria in order to quantify the difference of the real output grid power with respect to the desired set point. The life cycle economical cost of the ESS is analyzed according to its storage energy rating in case of supercapacitor technology. The life expectancy is also studied in order to determine a possible replacement of the ESS during its life.

Keywords: Energy Storage System (ESS), power smoothing, Direct Wave Energy Converter, Supercapacitor, Power Quality

1. Introduction

The minimization of power fluctuations is one of the keys for the development of direct electricity production from fluctuating renewable energies [1], especially in the case of direct wave energy conversion where the output power is far from smooth [2]. The smoothing of direct wave energy converter (DWEC) power production due to the summation of the production of each single converter spatially dispersed in a farm has been studied in [3,4]. This smoothing effect could be wisely combined with an individual (WEC scale) or global (farm scale) energy storage system (ESS) in order to improve the quality of the produced energy and also to provide system services for the grid (furniture of reactive power, power system balancing, low voltage ride through capability…).

Here, the studied DWEC is the SEAREV [5, 6]. The SEAREV consists of a completely enclosed floating buoy with an embedded pendular wheel. Excitation forces of the swell on the buoy generate a relative motion between the float and the wheel; this oscillating motion is damped to produce energy through a Power Take Off (PTO). For the PTO, we consider the case of direct-drive energy conversion (all-electric chain) [7], in such a way that the power cannot be smoothed by hydro-pneumatic storage as in the Pelamis, for example. Furthermore, the control strategy of the PTO (ie viscous damping torque with leveling of the recovered power) is not able to produce smoothed power without an important loss of productivity. Because of its high cycling capability, we will study supercapacitor (SC) technology for the ESS. Compared to other electricity storage technologies, SC satisfies better the WEC constraints [8].

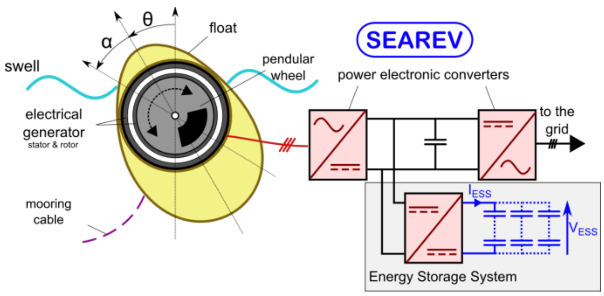

Figure 1: Principle of the SEAREV Wave Energy Converter.

2. Hypotheses

In order to simplify, this study, we make a certain number of hypotheses in this work:

- The sea state is considered to be always the same. The significant height and the pic period are respectively 3m,8s.
- The Energy Storage System is composed of supercapacitors modules. The nominal voltage of

the ESS, corresponding to a State Of Charge (SOC) of 1, is 1200V. SOC is 0 when the voltage is 0V. The electrical characteristics (serial resistance and capacity) are assumed to be constant.

- The only losses considered are those in supercapacitors. The losses in power electronics converters and the grid are not considered because they are second-order in this preliminary study.

3. First ESS requirement estimation

A first order estimation of the storage energy rating for an AWS farm has been studied in [9]. The considered power production profile was simulated with a strong sea state, for a park with 30 AWS. The grid power profile was deduced from the production profile by a low-pass filtering. The energy rating of the ESS was the difference between the maximum and the minimum value of the time-integral of the difference between the production (input) power and the grid (output) power.

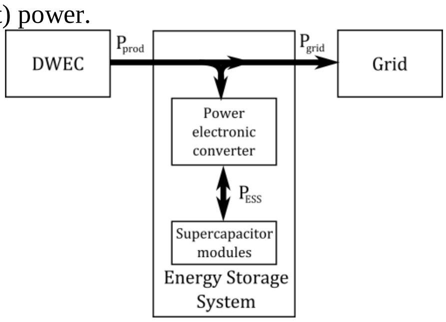

Figure 2: Energetic representation of the ESS.

We can use this method in our case. The Fig. 3 shows one example of production power profile for one SEAREV on a sea state Hs=3m, Tp=8s and with power levelling control (of 1 MW). The average of power profile is equal to 270kW and it is considered as the output grid power. Then, the power in the ESS is equal to the difference of this two power profiles.

$$P_{ESS}(t) = P_{prod}(t) - P_{grid}(t) \qquad (1)$$

$$E_{ESS}(t) - E_{ESS}(t=0) = \int_0^t P_{ESS}(t)dt \qquad (2)$$

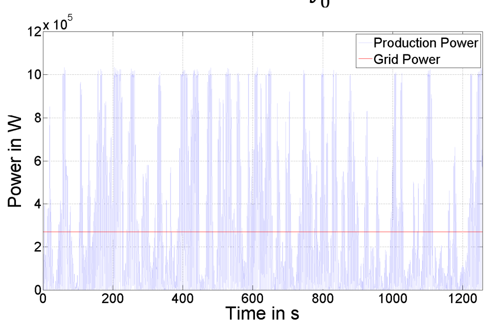

Figure 3: Example of a production power profile for the SEAREV.

As shown in Fig. 4, the difference between the maximum and the minimum value of the integral of the difference between the two power profiles is 45MJ (12.5kWh). It corresponds to the stored energy in a capacitance of 84F between 1200V and 600V (Note: $E = ½C(V_{max}^2 - V_{min}^2)$).

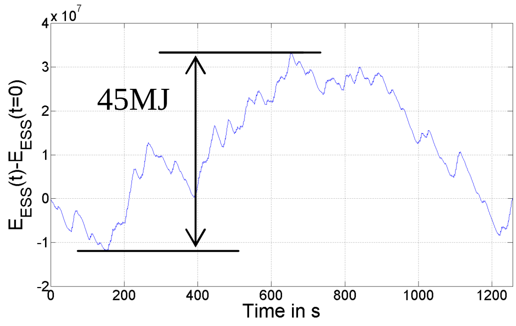

Figure 4: Integral of the ESS power profile $P_{ESS}(t)$.

The power production profile of the Fig. 3 is simulated on the basis of a particular sea elevation profile. This profile is based on the Pierson Moskovitz spectrum [10]. It gives the amplitude of each frequency component while the phase of each component is randomly drawn uniformly between 0 and 2π.Then, on a same sea state (here Hs=3m, Tp=8s), we could have some temporal differences in the power production profile while the average produced power kept relatively constant. Fig. 5 shows for 200 random draws, the sensitivity of the necessary energy rating of the ESS to insure a constant grid power profile equal to the average produced power.

We want to point out the significant influence of the random draw of initial phases for each frequency components, and then the one of the sea elevation and power production temporal profile at the same energy content, on the sizing of the ESS. The minimum value is 5.7kWh (energy stored in 38F between 1200V and 600V) and the maximum is 18.3kWh (energy stored in 122F between 1200V and 600V).

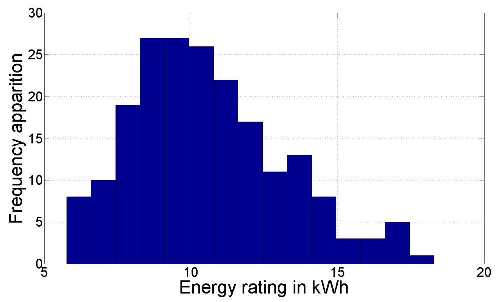

Figure 5: Sensitivity of the random draw of phases for a same sea state on the minimum needed energy storage rating of the ESS to insure a constant grid power.

4. SOC control strategies

In the previous paragraph, the energy rating of the ESS is determined to insure every time the set point of the grid power (here our power set point is firstly considered as constant equal to the average produced power).

Another way to tackle this problem of ESS sizing is to introduce a State Of Charge (SOC) control strategy. Indeed, for a given value of storage energy rating, it may not be possible to insure every time the power set point P_{set} especially when the SOC is equal to 0 (0V) or 1 (here 1200V). Then the grid power must dissent from the power set point according a SOC control strategy.

4.1 First SOC control strategy

Teleke [11] has introduced a rule based control of the SOC.

$$P_{grid} = P_{set} \quad if \begin{cases} SOC & \in]0.3;1[\\ SOC = 1 & \& \quad P_{prod} < P_{set} \\ SOC = 0.3 & \& \quad P_{prod} > P_{set} \end{cases}$$

$$P_{grid} = P_{prod} \; if \begin{cases} SOC = 1 & \& \quad P_{prod} > P_{set} \\ SOC = 0.3 & \& \quad P_{prod} < P_{set} \end{cases}$$

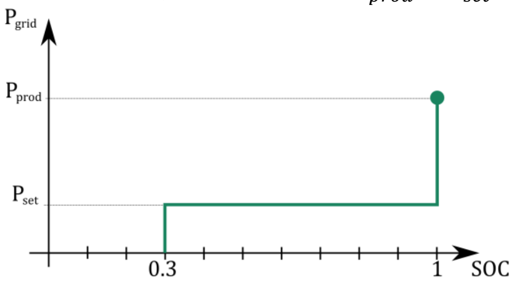

Figure 6: Rules and diagram of the first SOC control strategy.

The idea of this strategy is to insure the set point during the maximum of time. We illustrate this strategy on Fig. 7 and Fig. 8. The grid power is kept constant equal to the set point during the maximum of time. But when SOC limitations are reached, the grid power becomes equal to the produced power and then its large fluctuations are not smoothed. In this example the production power profile is this one of Fig. 3. The energy rating of the ESS is 6.3kWh and the initial SOC is 65%.

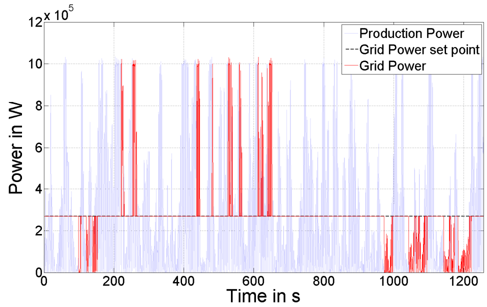

Figure 7: Example of the first SOC control strategy.

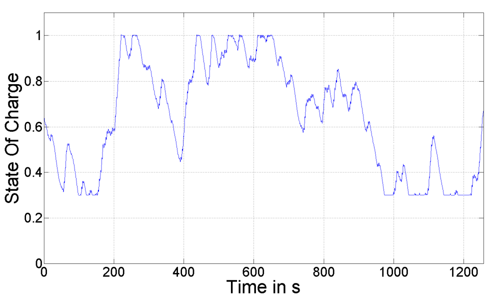

Figure 8: SOC profile corresponding to the Fig. 7.

4.2 Power quality criteria

In order to quantify the difference of the grid power with respect to the set point, we introduce power quality criteria. The first one is equivalent to the one used by Teleke. We denote it Δ_{abs}

$$\Delta_{abs} = \frac{1}{T}\int_T \left|P_{set} - P_{grid}\right| dt \qquad (3)$$

The second that we will use is based on the rms value of the error between the power set point and the power fed to the grid. We denote it Δ_{rms} :

$$\Delta_{rms} = \sqrt{\frac{1}{T}\int_T \left(P_{set} - P_{grid}\right)^2 dt} \qquad (4)$$

This second criterion penalizes more strongly, the important deviations from the set point. Values of these two criteria in the presented example are respectively 47kW and 143kW.

Normalization of these criteria

In the following, we will normalize these criteria with respect to the ones calculated without energy storage. Without storage, values of Δ_{abs} and Δ_{rms} would have been respectively 247kW and 310kW. This normalization allows quantifying the gain of use of an ESS on these criteria. For the example above, these two normalized criteria are respectively 19% and 46%.

4.3 Second SOC control strategy

We introduced another strategy for the control of the SOC.

$$P_{grid} = P_{set} \qquad if\ SOC \in]0.5; 0.8[$$

$$P_{grid} = P_{set}\frac{SOC - 0.3}{0.5 - 0.3} \qquad if\ SOC \leq 0.5$$

$$P_{grid} = P_{set}\left(1 + \frac{SOC - 0.8}{1 - 0.8}\right) \qquad if\ SOC \geq 0.8$$

$$P_{grid} = P_{prod} \qquad if\ SOC = 1\ and\ P_{prod} > 2P_{set}$$

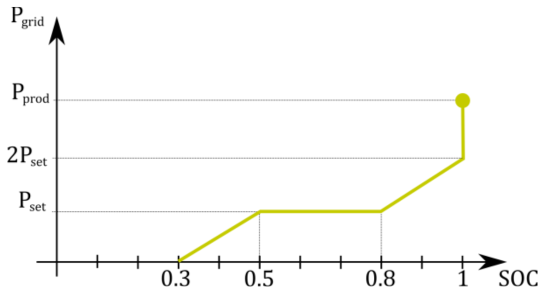

Figure 9: Rules and diagram of the second SOC control strategy.

This strategy avoids so far as possible large and quick fluctuations of the grid power from the set point thanks to the direct relation between the grid power and the SOC. We illustrate this strategy on Fig. 10 and Fig. 11. For this second example, the two criteria are respectively 25% (61kW) and 35% (107kW) for the same energy rating of the ESS (6.3kWh). The power quality is worse according to Δ_{abs} criterion but better by the second Δ_{rms}.

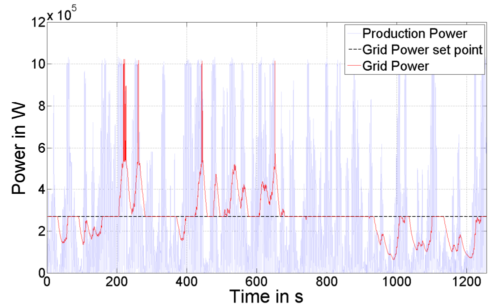

Figure 10: Example of the second SOC control strategy.

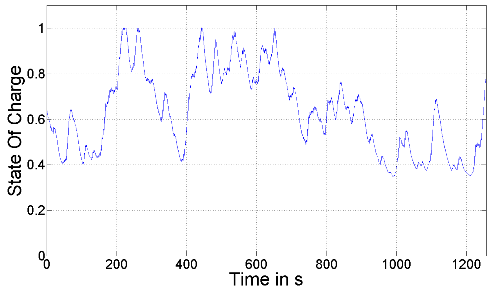

Figure 11: SOC profile corresponding to the Fig. 10.

The calculation of the power quality criteria Δ_{abs} and Δ_{rms} must be done with care. As in the previous chapter, there is an important influence of the random draw of initial phases for each frequency components of the sea elevation profile. There is also an influence of the initial SOC. That is the reason why in the following, Δ_{abs} and Δ_{rms} will always be the average of 50 production power profile random draws and 11 initial states of charge.

4.4 Power quality criteria versus storage energy rating

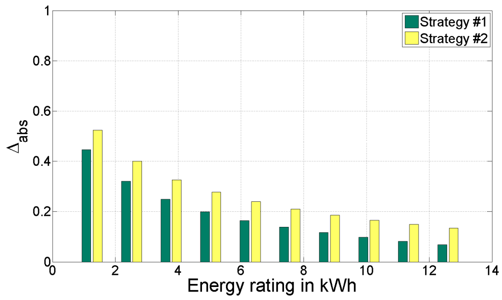

Figure 12: Δ_{abs} vs energy rating of the ESS.

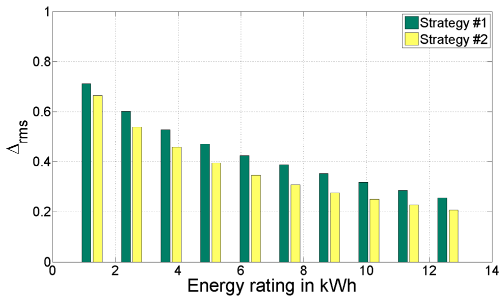

Figure 13: Δ_{rms} vs energy rating of the ESS.

Fig. 12 and 13 show the decrease of the two power quality criteria with respect to the ESS energy rating. According to the criterion, one of two strategies is better than the other. The second strategy leads to lower values of Δ_{rms}.

4.5 Energy losses versus storage energy rating

Another interesting aspect is to calculate average losses due to the serial resistance of the supercapacitor ESS. We consider here that the ESS is composed of several BMOD0063 P125 Maxwell modules (63F 125V). The serial resistance of one module is 18mΩ [12]. The total serial resistance of the ESS is :

$$R_{serial} = 18.10^{-3} \frac{N_{series}}{N_{parallel}} \quad (5)$$

Where N_{series} is 10 because we consider 1200V as the maximum voltage of the ESS. $N_{parallel}$ depends on the desired storage energy rating. Fig. 14 represents the evolution of average losses with respect to the storage energy rating.

$$P_{ESS}(t) = V_{ESS}(t) I_{ESS}(t) \quad (6)$$

$$P_{loss}(t) = R_{serial} I_{ESS}(t)^2 \quad (7)$$

With an average produced power of 270kW, the efficiency on cycle of the supercapacitor ESS varies between 96% and 99% according to the storage energy rating ($\propto N_{parallel}$).

$$\eta = 1 - \frac{\langle P_{losses} \rangle}{\langle P_{prod} \rangle} \quad (8)$$

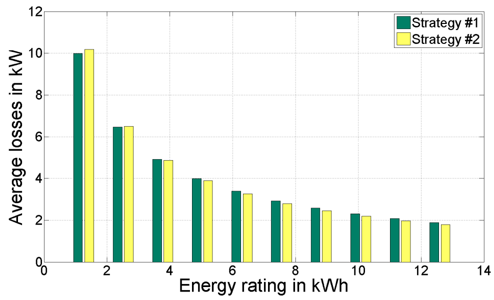

Figure 14: Average losses vs energy rating of the ESS.

5. Cost analysis on life cycle with taking into account of energy losses

With an expected life of 20 years, the cost of these losses must be compared to the initial cost of the ESS. We consider an initial cost of the ESS of about 20k€/kWh (actual price for small serie production). The feed-in tariff of the produced energy is supposed to be fixed at 15c€/kWh (French value). Fig. 15 shows the cost on life cycle with taking into account of energy losses in storage device.

$$C_{life}(k€) = 20.E_{rat}(kWh) + 15.10^{-5}.P_{loss}(kW).20(y).8760(h) \quad (9)$$

On life cycle of 20 years, there is a minimum cost for about 5kWh of storage energy rating (corresponding to $N_{parallel} = 4$). It means that all the solutions below this value (except 0kWh which has no cost) are not interesting because they exhibit a higher cost) and higher power quality criteria (Δ_{abs} and Δ_{eff}). It may be noted that the two strategies are equivalent in terms of economic cost on life cycle. Their differences are mainly on the two power quality criteria.

The optimal energy value is dependent of the feed-in tariff of the electrical energy and the initial cost (€/kWh) of the ESS.

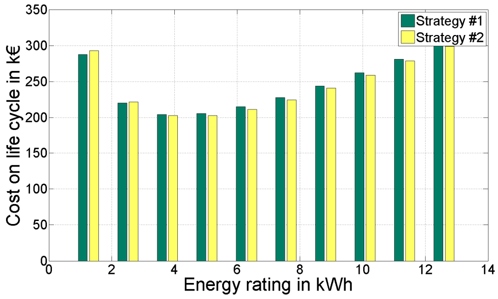

Figure 15: Cost on life cycle of the ESS versus its energy rating.

6. Taking into account of aging effect

In the precedent section, the cost on life cycle has been calculated without taking account of possible replacements during the life duration of the ESS. In order to verify this assumption, we examine the aging effects on life cycle. We calculate this aging on the basis of a life expectancy law depending on temperature and voltage [14].

$$L_{ex} = C_1 \exp\left(\frac{U}{C_2} + \frac{\Delta T + T_{amb}}{C_3}\right) \quad (10)$$

The constants C1, C2 and C3 are deduced from Fig. 16. $C_1 = 1{,}8.10^{10}\ (years)$; $C_2 = -0{,}1278\ V^{-1}$; $C_3 = 13{,}55°C^{-1}$

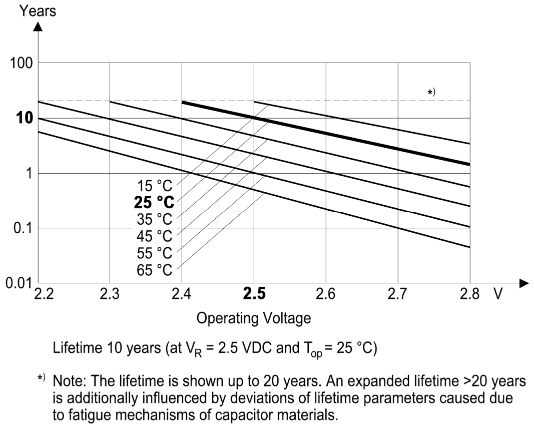

Figure 16: Lifetime of a supercapacitor versus voltage and temperature [13].

We assume that the thermal time constant of supercapacitor modules is such that the temperature rise is equal to average losses multiplied by the thermal resistance (the thermal capacitance is such that the thermal inertia of modules is assumed infinite). According to Maxwell's datasheet, the thermal resistance of a 63F 125V module is equal to $0{,}032°K.W^{-1}$. The temperature rise is:

$$\Delta T = 0{,}032.\frac{< R_{serial} I_{ESS}^2 >}{N_{series} N_{parallel}}\ (°K) \quad (11)$$

A degradation factor γ can be used to compute the aging on an operation cycle. The variation of this factor over a cycle is

$$d\gamma = \int_T \frac{1}{L_{ex}(U(t), T)} dt \quad (12)$$

In our case we calculate this degradation factor over one year and then apply this degradation on the capacitance and serial resistance according to the following equations:

$$R_{serial} = (1 + \gamma) R_{serial,init} \quad (13)$$

$$C = (1 - 0{,}2\gamma) C_{init} \quad (14)$$

Every year, the degradation factor is the average of 50 production power profile (depending on the random draw of phases cf Sec. 4.3) and 11 initial states of charge. The process is iterated every year until the degradation factor becomes one or the life duration reaches 20 years.

Fig. 17 shows life expectancy calculated for the two SOC control strategies. Above $N_{parallel} = 3$, the life expectancy exceeds 20 years. The ambient temperature T_{amb} is fixed at 30°C (Note that it plays a very important role). Fig. 18 shows the degradation factor after the end of life (or after 20 years). We can see that the second SOC control strategy deteriorate less the ESS than the first strategy.

The calculation of cost on life cycle made in the previous section is the valid when $N_{parallel} > 3$. Below this value, we should have introduce the additional cost due to one or more replacements of the ESS.

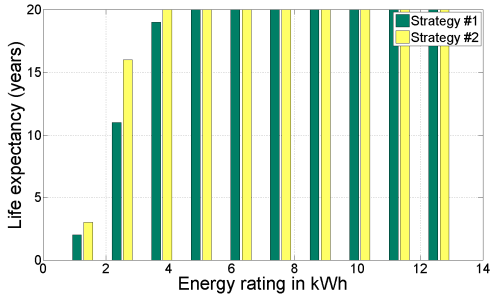

Figure 17: Life expectancy versus energy rating of the ESS.

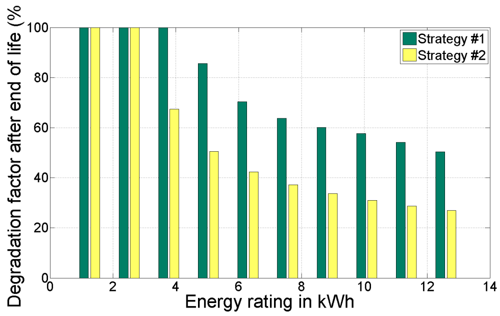

Figure 18: Degradation factor after the end of life.

In this calculation, voltage has been limited to 1200V (2,5V per supercapacitor cells). If this voltage would have been limited to 1250V, the life expectancy would have been less of 20 years for most values of the storage energy rating (cf. Fig. 19) except for the second strategy which exhibits a life expectancy of 20 years for values of $N_{parallel}$ higher than 5.

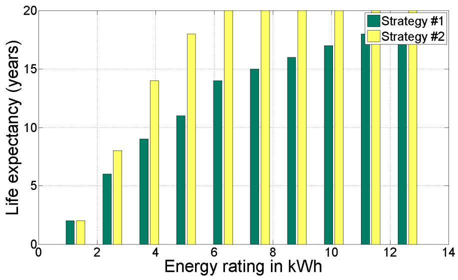

Figure 19: Life expectancy versus energy rating of the ESS for a maximum voltage of 1250V.

7. Influence of the grid power set point

Up to there, the set point of the output power fed to the grid was the the average produced power. Actually, this set point cannot be known precisely even with a sea state forecast. Teleke has introduced in his simulations a prediction error of 10% around the real average power for the set point of each dispatch hour [11]. In the following, we will see the influence, in terms of power quality criteria and economical life cycle cost, of a causal determination of the grid power set point (i.e. without prediction of the incoming power thanks to a sea state forecast).

7.1 Low-pass filtering

Firstly, the set point can be deduced from a low-pass filtering of the instantaneous production power profile. Fig. 20 illustrates this set point. In this example the time constant of the low pass filter is fixed at 200s and the initial SOC is 0.5 for a storage energy rating of 6.3kWh. The second SOC control strategy is used. In order to compare with the previous values of power quality criteria, we calculate in the following Δ_{abs} and Δ_{eff} according to the average power (in the formulas we replace P_{set} by P_{mean}). Then for this example, the criteria are respectively 30% and 34%.

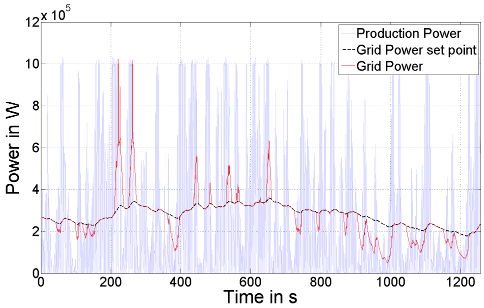

Figure 20: Example of low-pass filtering for the determination of the grid output power set point for a filter time constant of 200s.

Fig. 21 to Fig. 23 represents the evolution of the power quality criteria and losses versus the storage energy rating for different values of the filter time constant, only for the second SOC control strategy. For values of time constant greater than 500s, the performance of the ESS and his SOC control strategy are relatively similar.

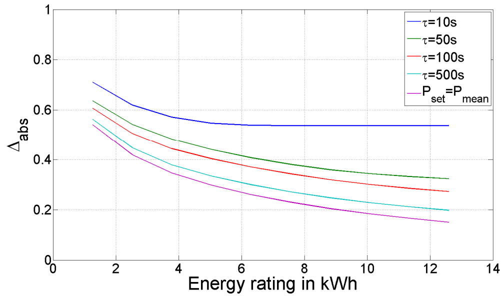

Figure 21: Evolution of Δ_{abs} for different value of filter time constant and the second SOC control strategy.

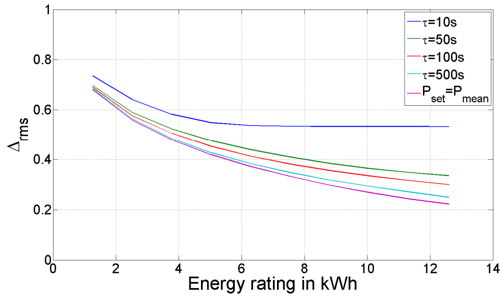

Figure 22: Evolution of Δ_{rms} for different value of filter time constant and the second SOC control strategy.

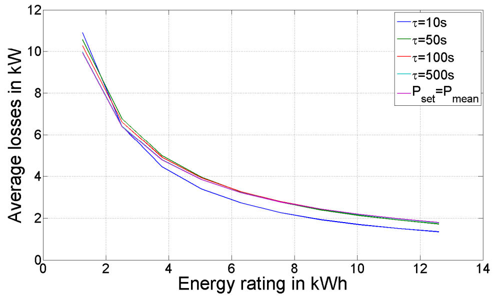

Figure 23: Evolution of average losses for different value of filter time constant and the second SOC control strategy.

7.2 Piecewise constant power

Another method to determine the set point for the grid power is to set a constant power during a certain period. This power set point is equal to the average production power during the preceding period. This method is causal. We illustrate this on Fig. 24. The period is equal to 314s. All others parameters are the same as the previous example.

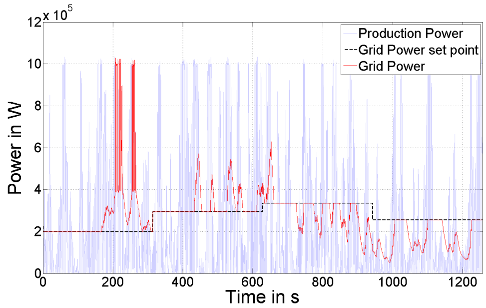

Figure 24: Example of piecewise average for the determination of the grid output power set point for a step period of 314s.

Fig. 25 and Fig. 26 represent the evolution of the power quality criteria versus the storage energy rating for different values of the step period, only for the second SOC control strategy.

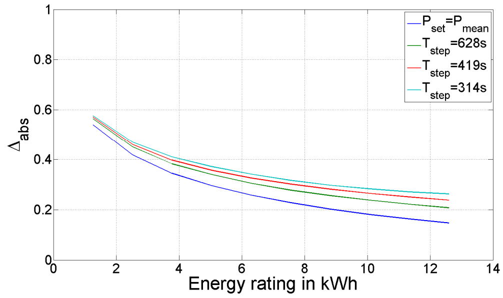

Figure 25: Evolution of Δ_{abs} for different value of step period and the second SOC control strategy.

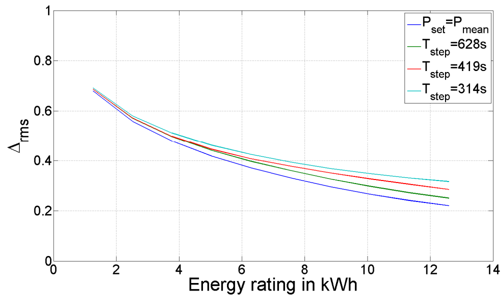

Figure 26: Evolution of Δ_{rms} for different value of step period and the second SOC control strategy.

8. Conclusion

In this paper we presented and reviewed methods for the sizing of an Energy Storage System with two SOC control strategy and two power quality criteria. It was applied to the smoothing of the power produced by a Direct Wave Energy Converter (as the SEAREV).

A cost analysis on life-cycle was conducted in order to find the best values of storage energy rating. Storage energy losses and ageing effect has been analysed on a life cycle of 20 years. According to the power quality criterion, one or the other of the strategies is the best.

We observe that the smoothing performances are relatively the same with or without short-term (~hour) prediction of the power production.

Further work can be done for a farm of wave energy converters. In this context, the smoothing due to the ESS can be wisely combine with the aggregating effect due to the summation of the production of each single DWEC spatially dispersed.

Another aspect that could be in-depth is the influence of the leveling of the produced power on the sizing of the ESS. This problem will be more important if the cost of power electronic converter is taken into account.

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