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# Power Smoothing of a direct wave energy converter

## Management and sizing of a supercapacitor energy storage system under a flicker constraint

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*ABSTRACT.* This article examines the problem of sizing and managing an Energy Storage System (ESS) composed of supercapacitors for a Direct Wave Energy Converter (DWEC), with the SEAREV project taken as an example. The main objective is to enable grid integration by satisfying the flicker constraint. An original sequentialization is proposed in order to simplify this co-optimization resolution. Then, a rule-based energy management is introduced that depends on both the Energy Storage System and the power produced by the Wave Energy Converter. This management has been optimized for each size in order to reduce electrical losses, while strictly satisfying the flicker criteria. The final design should minimize total system cost, by taking into account both the investment cost (supercapacitors) and the operating cost (losses).

*RÉSUMÉ.* Cet article examine le problème du dimensionnement et de la gestion d'un système de stockage électrique composé de supercondensateurs pour un houlogénérateur direct avec comme exemple le projet SEAREV. L'objectif principal consiste à permettre l'intégration au réseau en respectant les contraintes de flicker. Une séquentialisation originale du problème est proposée afin de simplifier ce problème de co-optimisation. Nous introduisons une gestion dépendant de l'état d'énergie du système de stockage, et de la puissance produite par le houlogénérateur. Cette gestion est optimisée pour chaque dimensionnement afin de réduire les pertes électriques, tout en respectant strictement le critère de flicker. Le dimensionnement final doit minimiser le coût total du système, en prenant en compte à la fois l'investissement (coût des supercondensateurs) et l'exploitation (pertes dans les supercondensateurs).

*KEYWORDS:* electrical energy storage system, power smoothing, direct wave energy converter, supercapacitors, energy quality, flicker, grid integration.

*MOTS-CLÉS :* système de stockage d'énergie électrique, lissage de puissance, houlogénérateur direct, supercondensateurs, qualité de l'énergie, flicker, intégration réseau.

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DOI:10.3166/EJEE.18.243-263 © Lavoisier 2016

## 1. Introduction

Integration to the grid is one of the keys to developing Direct Wave Energy Converters (DWEK). This technology does indeed possess a high potential for reliability, yet it also produces a power that fluctuates at the rate of ocean waves. Without any compensatory action, this production (even in the presence of a farm aggregation effect) can lead to quality problems in the distribution grid. Smoothing the production with an Energy Storage System (ESS) offers one way to solve this grid integration problem. The wave energy converter considered in this study is the SEAREV (Cordonnier *et al.*, 2015) (see Figure 1); it is a completely closed buoy associated with an internal pendular wheel. The buoy is approximately 30 meters wide, 10 meters in diameter and weighs 2,000 tons; moreover, it is mainly constituted of seawater ballast. The excitation wave buoy in mechanical stresses generates a relative oscillating motion of the pendular wheel, whose rotation is damped by an electric generator (electrical Power Take-Off). The hull weighs 200 tons and the pendular wheel 300 tons.

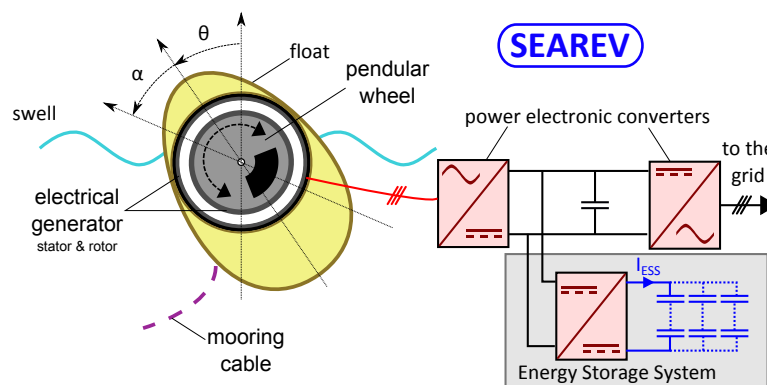


Figure 1. Main diagram of the SEAREV Direct Wave Energy Converter with a supercapacitor power smoothing system

In the present study, pendulum damping is controlled by a simple viscous damping law with a power limitation (see Figure 2). The damping coefficient equals 4 MNm/rad and power is limited to 1.1 MW, regardless of the sea state. With this recovery control, the average power over an hour equals between 0 and 570 kW. Other existing laws (Kovaltchouk *et al.*, 2013; Ringwood *et al.*, 2014) may be more attractive for maximizing recovered energy, although the power fluctuations would then be greater.

Compared to a hydraulic Power Take-Off, the choice of a direct electric chain offers many benefits, including better recovery control and fewer wearing parts, yet it removes the possibility of power smoothing, as is the case with hydro-pneumatic Power Take-Off and accumulators, Oscillating Water Column (in which turbine inertia can be used to smooth production) or over-topping WEC (with gravity storage smoothing production).

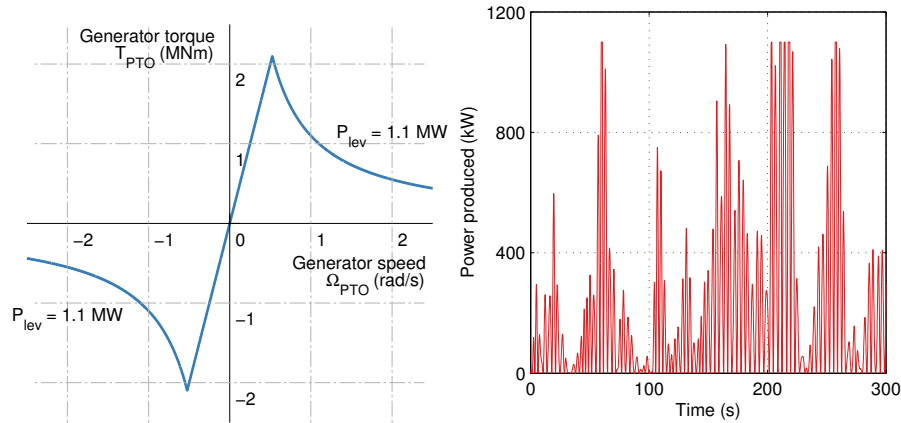


Figure 2. Pendulum damping law: generator torque vs. angular speed (viscous damping law with power leveling) and example of a production power profile vs. time

When production fluctuates at relatively high frequencies (frequency range between 10 mHz and 10 Hz), power quality problems at the grid delivery point may arise. In particular, the flicker has been identified as an important element in distribution networks (Perera *et al.*, 2014), for wind turbines (Ammar, Joós, 2013; Girbau-Llistuella *et al.*, 2014) and wave energy converters (Tedeschi, Santos-Mugica, 2013; Trilla *et al.*, 2015; Blavette *et al.*, 2015). The combination of the weak grid (which is often the case with a near-shore distribution grid) and production fluctuations can actually cause significant flicker non-compliance. The concept of flicker and the procedures for measuring and estimating it will be presented in Section 2.1.

Supercapacitors can hold a large number of cycles and provide a reduced cost per unit of power, which leads to consider this technology as a solution to smooth wave energy power (Aubry *et al.*, 2010; Murray, Hayes, 2015). The high cost of storage systems necessitates both a design and energy management that minimize costs while reducing the impact on the overall per megawatt-hour cost as much as possible.

The purpose of this study therefore is to minimize the cost of the ESS while guaranteeing respect of an energy quality constraint. The sizing combined with energy management will be optimized under a nonlinear constraint on the power injected into the grid. Only a few authors have used an optimized design and energy management combination (Brekken *et al.*, 2010; Haessig, Multon *et al.*, 2013; Le Goff Latimier *et al.*, 2014) in order to minimize a cost or maximize an income that accounts for penalties. Optimization problems with a constraint on the smoothed power however receive, to the best of our knowledge, only limited attention in the literature (Haessig *et al.*, 2014). In order to simplify this co-optimization under a non-linear constraint, an original sequentialization of the optimization procedure is proposed in subsection 3.3. This work can be useful for other fluctuating energy sources, like photovoltaic panels or wind turbines.

## 2. Modelling and hypotheses

### 2.1. Flicker and flickermeter

To enable grid integration, energy producers must meet some constraints on the quality of injected energy. In the case of DWEC, the limitation of voltage fluctuations (flicker) is a critical constraint. Power-line flicker is a visible change in brightness of a light source due to rapid fluctuations in the power supply voltage. These fluctuations are caused by variations in either active or reactive power to the network (IEC 61000-4-15, 2003). Beyond a certain amplitude, these rapid fluctuations (in a range from 50 mHz to 33 Hz) may cause humans to suffer from fatigue, irritability and epilepsy; they are framed by flicker standards to keep them limited (see Figure 3).

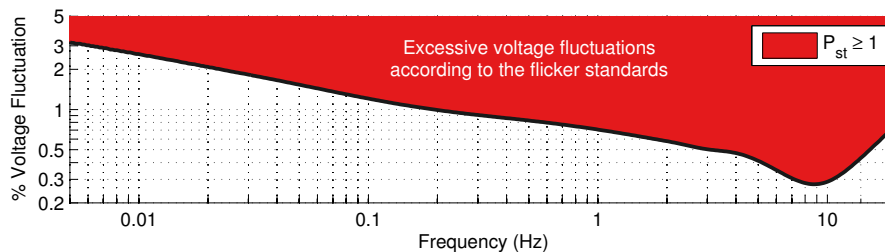


Figure 3. Flicker constraint:  $P_{st} = 1$  curve for regular rectangular voltage changes according to the IEC 61000-4-15 Standard. The zone corresponds to irritation for the consumer

Two flicker severities are typically used in grid codes:

- The short-term flicker severity  $P_{st}$  is measured over a 10-minute period,
- The long-term flicker severity  $P_{lt}$  (long-term) is measured over 1 hour.

A severity equal to 1 corresponds to the acceptable limit that the electricity distributor must provide to its customers. To ensure these levels, the distributor requires consumers and producers to limit their individual flicker to lower levels (due to pollution aggregation).

For French grids, Article 15 of the April 23<sup>rd</sup> 2008 Decree (decree, 2011) states that the flicker level should be limited at the delivery point to 0.35 in  $P_{st}$  and to 0.25 in  $P_{lt}$ , with a reference short-circuit power of 40 MVA. The long-term severity is more stringent and hence is used in this study. Short-term severity is used instead for grid connection/disconnection stages, while the long-term flicker can take into account a more regular pollution. The calculations have thus been conducted over a 1-hour period.

Flicker measurement with a flickermeter is defined in the IEC 61000-4-15 Standard (IEC 61000-4-15, 2003). The four blocks constituting a flickermeter are explained in Figure 4:

– The first process is to separate the waveform producing the voltage change from the continuous mains level signal with a demodulation process that involves squaring and filtering (blocks 1 and 2).

– This waveform then goes through the simulation filters with a maximum at 8.8 Hz that simulates the lamp to eye response, whilst a squaring operation and a sliding mean filter simulate the non-linear memory process in the eye and brain (block 3).

– The extent to which flicker is annoying to the observer depends on its level and its rate of occurrence. This is carried-out by a distribution which relates to the proportion of time each particular level of flicker is exceeded. After 10 minutes of data accumulation, key levels are taken from this distribution to compute the short-term flicker severity  $P_{st}$ .

This device can be implemented in either hardware or software. For these purposes herein, a flickermeter installed on Matlab (Jourdan, 2009) is used.

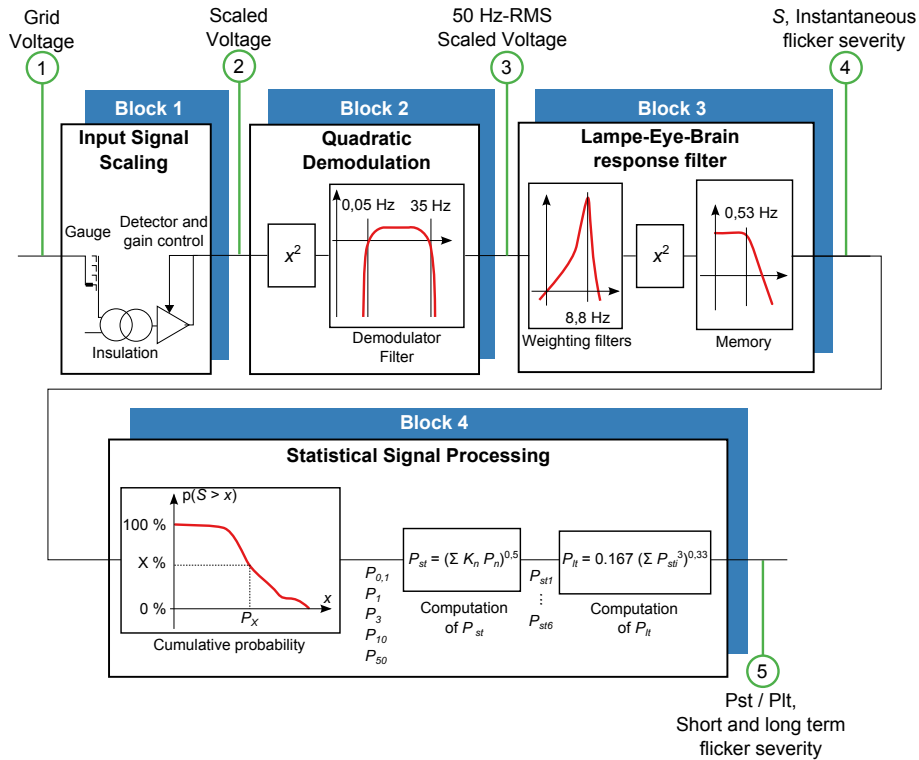


Figure 4. Block Diagram of an IEC Flickermeter, from grid voltage to flicker severity

Since the effective voltage at 50 Hz can be directly computed from production without the need for instantaneous voltage, blocks 1 and 2 of the flickermeter are not being used in this case; consequently, it could be operated at a much higher temporal resolution for the same degree of accuracy (20 ms instead of 400 μs), thus reducing computation time.

## 2.2. Grid impedance and reactive power injection

The voltage drop  $\Delta V$  due to one DWEC at the point of delivery is calculated by following this conventional approximated formula:

$$\frac{\Delta V}{V} = -\frac{P_{Grid} \cdot \cos(\Psi) + Q_{Grid} \cdot \sin(\Psi)}{S_{sc}} \quad (1)$$

with  $P_{Grid}$  and  $Q_{Grid}$  respectively the active and reactive power provided by the DWEC at the delivery point,  $\Psi$  the grid impedance angle (here  $60^\circ$ ) and  $S_{sc}$  the short-circuit apparent power (here 50 MVA). Both values typically correspond to a weak distribution grid in 20 kV Medium Voltage (MV), which is common from near-shore or island grids. Moreover, the short-circuit power is close to the minimum reference value, i.e. 40 MVA.

The injection of reactive power is restricted by the grid operator. In this case, the following requirement is considered:

$$-0,2 \leq \frac{Q_{Grid}}{P_{Grid}} \leq 0 \quad (2)$$

In order to limit the voltage drop, the maximum compensation given this limitation is provided by:

$$Q_{Grid} = -0,2 \cdot P_{Grid} \quad (3)$$

## 2.3. Aggregation effect in a production farm

To account for the aggregation effect in a farm, the assumption is made that the behaviour of several DWEC is similar to the behaviour of several wind turbines, as described in IEC 61400-21 Standard (IEC 61400-21, 2001):

$$P_{ltfarm} = \left( \sum_{i=1}^{N_{WEC}} P_{lti}^2 \right)^{\frac{1}{2}} = \sqrt{N_{WEC}} \cdot P_{lt} \quad (4)$$

with  $N_{WEC}$  the number of production units in the farm: 20 DWEC, corresponding to a power averaged over 1 hour of below 11.4 MW. The maximum power of a Medium-Voltage producer in France is in fact 12 MW (decree, 2011). If severity is limited to 0.25 for the farm, then the maximum severity for a production unit would be 0.056. This limit is therefore considered for both the energy management and sizing of the ESS in each production unit.

## 2.4. Energy and electrical model of the Energy Storage System

The complete system with all power flows is illustrated in Figure 5.

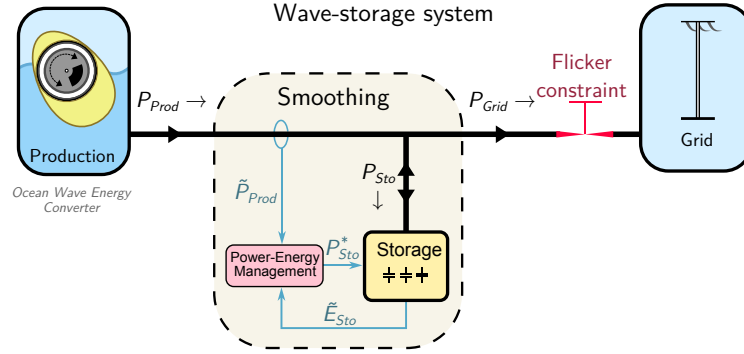


Figure 5. Power smoothing with the ESS in order to satisfy a flicker constraint

The effects of losses on the dynamic behaviour of the storage system are neglected, though this does not imply that losses are completely neglected, but only that the dynamic behaviour does not change significantly by neglecting them. With this assumption, the ESS is considered as a pure integrator; such an assumption is often adopted for this type of problem and can be summarized by the following equations:

$$\frac{dE_{Sto}}{dt} = P_{Sto}(t) \quad (5)$$

$$P_{Sto}(t) = P_{Prod}(t) - P_{Grid}(t) \quad (6)$$

The storage model is based on a reference cell from Maxwell (Maxwell Technologies, 2007). This cell is modelled by a capacitance  $C_{Ref} = 3000$  F in series with an equivalent series resistance  $R_{Ref} = 0.29$  m $\Omega$ . The rated voltage of this element is  $V_{ElementRated} = 2.7$  V. The series and parallel connections of these cells allow adjusting both the rated voltage and total size of the ESS. All cells are assumed to be identical and undergo the same conditions. This assumption is backed up by balancing circuits that are typically used to compensate for voltage deviation between the cells (Linzen *et al.*, 2005) and thus help generate this assumption.

It is now possible to express the total stored energy as a function of voltage on one cell along with the total number of cells:

$$E_{Sto}(t) = \frac{1}{2} \cdot C_{Eq} \cdot V_{ESS}^2(t) \quad (7)$$

$$E_{Sto}(t) = N_{Tot} \cdot \frac{1}{2} \cdot C_{Ref} \cdot V_{Element}^2(t) \quad (8)$$

with  $N_{Tot}$  the total number of supercapacitors,  $V_{ESS}$  the terminal voltage of the set, and  $C_{Eq}$  the equivalent capacitance of the set. The rated energy  $E_{Rated}$  corresponds to the rated voltage; hence, the rated energy of the reference cell is 10.9 kJ or 3 Wh.

ESS losses are not considered in the dynamic model (see section 2.4) but instead computed a posteriori in order to take them into account in the design process.  $R_{Eq}$  is

the equivalent series resistance of the set, just as  $C_{Eq}$  is the equivalent capacitance of the set. Losses are calculated as follows:

$$P_{Loss}(t) = R_{Eq} \cdot I_{ESS}(t)^2 \quad (9)$$

$$= R_{Eq} \cdot \left( \frac{P_{Sto}(t)}{V_{ESS}(t)} \right)^2 \quad (10)$$

$$= R_{Ref} \cdot C_{Ref} \cdot \frac{P_{Sto}^2(t)}{2 \cdot E_{Sto}(t)} \quad (11)$$

with  $I_{ESS}$  the current through the ESS (see Figure 1). It is noticeable that ESS size must be increased in order to reduce losses. With this instantaneous power of losses, the computing of the energy loss during a cycle using an integral is possible.

### 3. Energy Management

#### 3.1. Rule-based control

The energy management discussed herein is a rule-based control with adjustment parameters. This set-up allows optimizing the parameters (hence the management) according to the constraints and costs. The rule applied is that the stored power depends linearly on both the power produced and the state of ESS energy. This type of law is inspired by fuzzy logic management (Caux *et al.*, 2005; Muyeen *et al.*, 2009; Suvire, Mercado, 2012).

$$P_{Sto}(t) = \alpha \left[ (P_{Prod}(t) - P_{Min}) - (P_{Max} - P_{Min}) \frac{E_{Sto}(t) - E_{Min}}{E_{Max} - E_{Min}} \right] \quad (12)$$

The power produced by the wave energy converter is bounded (here between 0 and 1.1 MW):  $P_{Min} \leq P_{Prod}(t) \leq P_{Max}$ , with  $P_{Min}$  and  $P_{Max}$  the minimum and maximum values of the power produced. Three adjustment parameters are associated with this management law:  $E_{Min}$ ,  $E_{Max}$  and  $\alpha$  the minimum and maximum stored energy, and  $\alpha$  a ratio bounded between 0 and 1. This management rule is illustrated in Figure 6.

The parameter  $\alpha$  modulates the smoothed power thanks to the ESS in the injected power. For example, from the equations (6), (12) and  $\alpha = 1$ , the following result can be found:

$$P_{Grid} = P_{Min} + (P_{Max} - P_{Min}) \frac{E_{Sto}(t) - E_{Min}}{E_{Max} - E_{Min}} \quad (13)$$

The power injected into the grid thus depends solely on the ESS State of Energy. This special case was studied in (Aubry, 2011). On the contrary, for  $\alpha = 0$ :

$$P_{Grid} = P_{Prod} \quad (14)$$

Here, the power injected into the grid depends solely on the power produced (i.e. smoothing is no longer taking place).



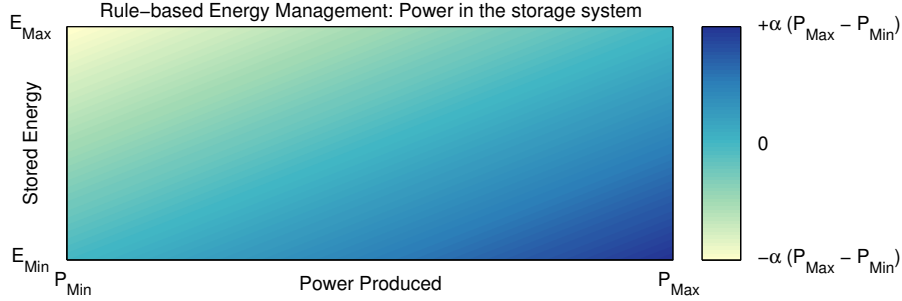


Figure 6. Rule-based management: Stored power vs. both the power produced by the Wave Energy Converter and the ESS State of Energy.  $\alpha$  is a parameter bounded between 0 and 1

This law is extremely simple to implement with measurements or approximations of the stored energy and power produced; it requires, among other things, considerably fewer parameters than the controls relying on fuzzy logic (Caux *et al.*, 2005; Muyeen *et al.*, 2009; Suvire, Mercado, 2012), dynamic programming (Haessig, Kovaltchouk *et al.*, 2013) or pseudo-dynamic programming (Kim, Peng, 2007).

### 3.2. Power and energy level limitations in the Energy Storage System

When energy in the ESS is minimum (i.e.  $E_{Sto} = E_{Min}$ ), it becomes obvious that:

$$P_{Sto}(E_{Sto} = E_{Min}) = \alpha [P_{Prod} - P_{Min}] \geq 0 \quad (15)$$

The storage system necessarily fills up whenever it is empty. Similarly, when the storage system is full ( $E_{Sto} = E_{Max}$ ), it then empties:

$$P_{Sto}(E_{Sto} = E_{Max}) = \alpha [P_{Prod} - P_{Max}] \leq 0 \quad (16)$$

This situation intrinsically prevents saturations thanks to application of the management rule.

Moreover, the stored power limitation is naturally symmetric:

$$\alpha \cdot (P_{Min} - P_{Max}) \leq P_{Sto}(t) \leq \alpha \cdot (P_{Max} - P_{Min}) \quad (17)$$

This condition can be summarized in the following equation:

$$|P_{Sto}(t)| \leq P_{StoMax} = \alpha \cdot (P_{Max} - P_{Min}) \quad (18)$$

It is therefore possible to define a storage time constant, which is the minimum time for a full charge or discharge; this constant is defined as the ratio of available energy to maximum power in the storage:

$$\tau = \frac{\Delta E}{P_{StoMax}} = \frac{E_{Max} - E_{Min}}{\alpha \cdot (P_{Max} - P_{Min})} \quad (19)$$

In this conditions, the energy management result ( $P_{Grid}$  temporal profile) depends only on the power produced and these two parameters:  $\alpha$  and  $\tau$ .

### 3.3. Transfer function of the equivalent filter

With this management rule, the differential power balance equation (6) can now be rewritten:

$$\frac{d(E_{Sto} - E_{Min})}{dt} + \frac{E_{Sto} - E_{Min}}{\tau} = \alpha \cdot (P_{Prod} - P_{Min}) \quad (20)$$

Next, the following variables are used in order to simplify the dynamic study:

$$\tilde{E}_{Sto} = E_{Sto} - E_{Min} \quad (21)$$

$$\tilde{P}_{Prod} = P_{Prod} - P_{Min} \quad (22)$$

$$\tilde{P}_{Grid} = P_{Grid} - P_{Min} \quad (23)$$

The following system of equations is then obtained:

$$\frac{d\tilde{E}_{Sto}}{dt} + \frac{\tilde{E}_{Sto}}{\tau} = \alpha \cdot \tilde{P}_{Prod} \quad (24)$$

$$\tilde{P}_{Grid} = \tilde{P}_{Prod} - \frac{d\tilde{E}_{Sto}}{dt} \quad (25)$$

Working in the Laplace space (with the Laplace variable denoted  $s$ ), the expression of this dynamic system become:

$$(\tau \cdot s + 1) \cdot \tilde{E}_{Sto}(s) = \alpha \cdot \tau \cdot \tilde{P}_{Prod}(s) \quad (26)$$

$$\tilde{P}_{Grid} = \tilde{P}_{Prod} - s \cdot \tilde{E}_{Sto}(s) \quad (27)$$

The power injected into the grid can thus be written in the Laplace domain as the sum of two terms: a power part that remains unchanged, and another part that gets smoothed:

$$\frac{\tilde{P}_{Grid}(s)}{\tilde{P}_{Prod}(s)} = (1 - \alpha) + \frac{\alpha}{1 + \tau \cdot s} \quad (28)$$

$$\frac{\tilde{P}_{Grid}(s)}{\tilde{P}_{Prod}(s)} = \frac{1 + (1 - \alpha) \cdot \tau \cdot s}{1 + \tau \cdot s} \quad (29)$$

Moreover, the transfer function between power at the delivery point and the power produced is a first-order function. Bear in mind that the management law defines more than the transfer function, which is a consequence of the management law. The implementation of this transfer function in an alternative way would not secure the energy and power limitation properties described in section 3.2.

One advantage of this management is to ensure linearity between the input (power produced by the DWEC) and output (power injected into the grid); it yields a very simple behaviour and enables a rapid resolution of the dynamic model. For the sizing process, multiple successive resolutions are required, so it is essential that the dynamic model not require a lengthy resolution. The filter function of Matlab (*filter()*) is thus used to simulate storage.

The two parameters  $\alpha$  and  $\tau$  are chosen in order to satisfy the grid quality constraint and minimize the ESS operating cost for each sea-state (management dependent on the production profile). An infinite number of couples ( $\alpha; \tau$ ) allows for compliance with the flicker criterion with a given production profile.

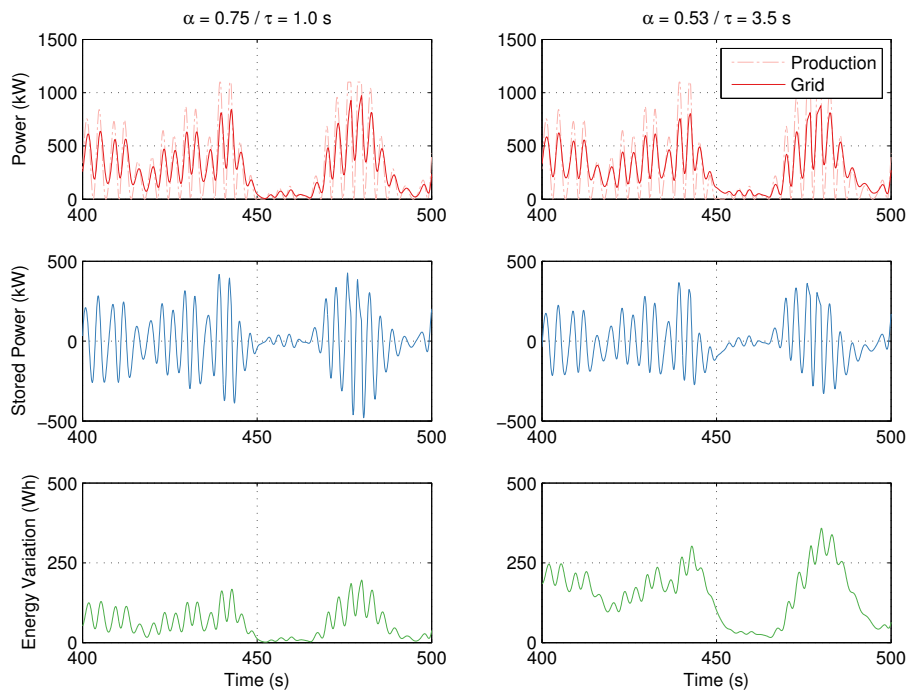


Figure 7. Smoothing of a Wave Energy Converter power production with two energy management parameters ( $\alpha, \tau$ ): sea-state ( $H_s = 2.5\text{ m}$ ,  $T_p = 8\text{ s}$ ); mean power production: 190 kW, flicker severity constraint  $P_{lt} = 0.056$  (met in both cases)

Figure 7 shows how two pairs of different parameters can yield the same respect of the flicker constraints (long-term severity  $P_{lt} = 0.056$ , as explained in section

2.3). The top figures correspond to the power produced by a unit ( $P_{Prod}$ ) and the power injected into the grid by this unit ( $P_{Grid}$ ). The central figures correspond to the exchanged power in the ESS. Finally, the bottom figures correspond to the energy variation inside the ESS. The left figures correspond to the management with  $\alpha = 0.75$  and  $\tau = 1.0$  s while the right figures correspond to the management with  $\alpha = 0.53$  and  $\tau = 3.5$  s. It is noticeable that the ESS is solicited more in power when  $\alpha$  is large and more in energy when  $\tau$  is large.

#### 4. Sequential procedure of management and sizing co-optimization

##### 4.1. Principle

The co-optimization problem consists of determining an optimized energy capacity for the ESS  $E_{rated}$  and an optimized energy management in order to minimize the cycle cost  $C_{cycle}$ . The classical way to solve this problem consists in a management optimization embedded within a global sizing optimization. This is illustrated by the part (a) of the Figure 8.

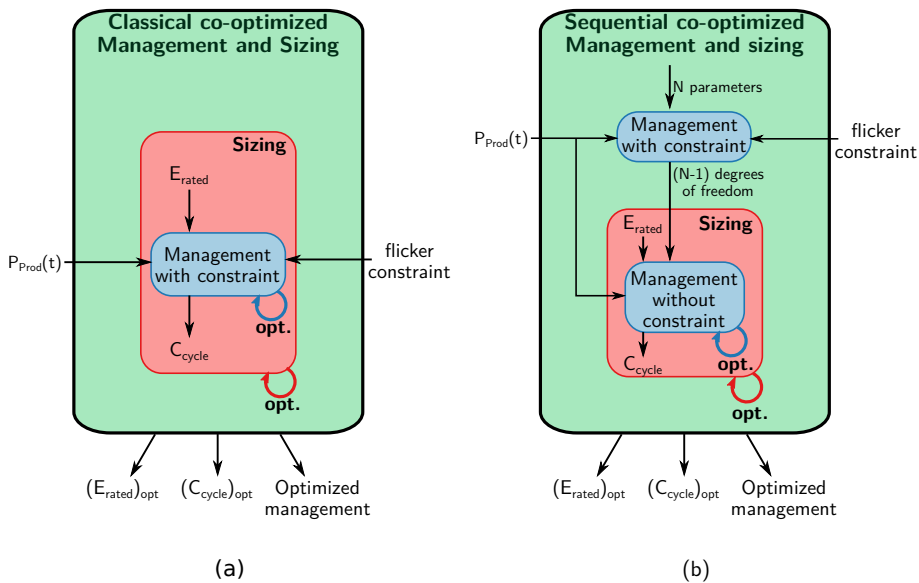


Figure 8. Classical (a) and sequential (b) procedures for co-optimization of the energy management and the ESS sizing

The difficulty with the classical method is that the constraint (flicker) is hard to take into account. In order to remove the constraint from the co-optimization, a sequentialization is used in order to separate the management problem in two different

problems: first, a search for all the managements that meet exactly the constraint and, secondly, the management optimization embedded within the sizing optimization, but without the non-linear constraint (because all the used management respect the constraint). This second method is illustrated by the part (b) of the Figure 8.

One important implication from this method is that the management need to be a rule-based management with a finite number  $N$  of adjustment parameters as the management previously described.

#### 4.2. Cost model

The cost is calculated by taking into account the investment and cost of losses in the ESS. Indeed, **the assumption is made** that the ESS does not require replacement.

$$C_{cycle} = c_{Energy} \cdot E_{rated} + c_{Feed-in} \cdot \overline{P_{Loss}} \cdot \Delta t \quad (30)$$

with  $C_{cycle}$  the life cycle cost of the ESS;  $c_{Energy}$  the supercapacitor cost per unit of energy, set at 15 k€/kWh in this study (see Figure 9);  $c_{Feed-in}$  the feed-in tariff for wave energy, set at 150 €/MWh; and  $\Delta t$  the presumed lifetime of the DWEC system, set at 20 years.

Figure 9 shows a cost analysis performed with 3 electronic component suppliers and 5 manufacturers. The variability naturally conceals many aspects: the packaging of multiple cells in series for larger solutions (employing balancing circuits and heat transfer solutions), a different behaviour in terms of losses, and ageing or specific energy depending on the manufacturer.

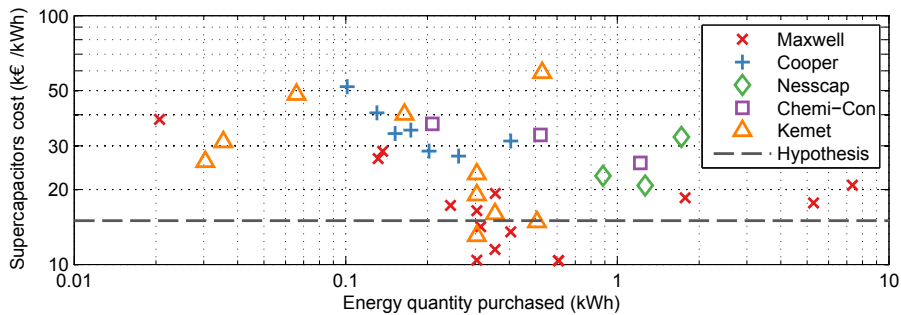


Figure 9. Supercapacitor cost per unit of energy for various manufacturers and suppliers vs. total energy quantity purchased (e.g. 400 Wh can be achieved with 3 modules (125 V, 63 F) or 1,200 cells (2.7 V, 350 F)). Both x- and y-axes are in logarithmic scale

The feed-in tariff for electricity (150 €/MWh) for a 20-year contract is governed by the French decree enacted on March 1<sup>st</sup> 2007 (decree, 2007). Given the maturity of marine renewable energy, this price seems pretty low, although it is the desirable horizon for future grid parity.

106 sea-states are taken into account, whose probability of occurrence corresponds to the site of Yeu Island, France (see Figure 10). This site is of potential interest for wave energy. A sea-state, whose main characteristics are a significant wave height  $H_s$  and peak period  $T_p$ , constitutes the general condition of the free surface on a large body of water. During a sea-state, the waves are in steady state for approximately one hour; thus, the power produced by a DWEC is also in steady state during this time interval.

In order to propose a simplified method, a single sea-state is used for the sizing instead of the 106 different states. The selected sea-state has the following characteristics:  $H_s = 2.5$  m and  $T_p = 8$  s. The average power produced by the DWEC during this sea-state is: 190 kW. On the other hand, the average power produced over a year with all 106 sea-states equals 125 kW. The study with a single sea-state is therefore performed with a shorter reference lifetime, i.e. equal to 13 years, so that the DWEC provides the same energy to the grid during its lifetime, making the study energetically equivalent. Results in section 4.2 will show that the optimal energy capacities found in both cases are very similar.

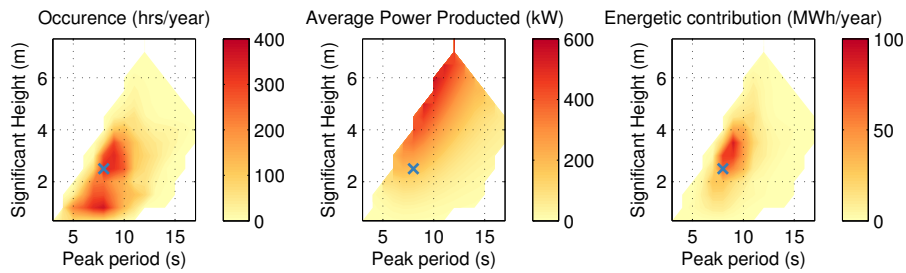


Figure 10. Sea-state occurrence for the Yeu Island site, SEAREV average power and energy contribution for each sea-state ( $H_s$ ,  $T_p$ ); the cross indicates the sea-state considered as representative (8 s; 2.5 m)

### 4.3. Management with constraint

As explained in Figure 8, the first management optimization is to find all the parameters combination that respect strictly the constraint.

For each sea-state, a series of parameter pairs  $(\alpha, \tau)$  is determined by scanning  $\alpha$  from 0 to 1 and seeking  $\tau$  corresponding to a flicker severity equal to the constraint.

For each sea-state, a space  $\Omega(H_s, T_p) \subset \mathbb{R}^2$  of parameters are obtained corresponding to the following property:

$$\forall (\alpha, \tau) \in \Omega(H_s, T_p) : P_{lt}(H_s, T_p, \alpha, \tau) = 0.056 \quad (31)$$

For each sea-state, 500 parameter pairs belonging to the space  $\Omega(H_s, T_p)$ , and thus corresponding to the strict compliance with the flicker constraint, are found through the *fminbnd()* Matlab function applied to the function  $|P_{lt} - 0.056|$ .

#### 4.4. Management without constraint

As explained in Figure 8, the second management optimization is to find the parameters that correspond to cost minimization inside the space  $\Omega(H_s, T_p)$  corresponding to constraint respect. According to the cost model, at a given storage capacity, losses have to be minimized in order to minimize cycle cost. For this purpose, three parameters need to be optimized:  $E_{Min}$ ,  $E_{Max}$ , and  $\alpha$ . The obvious technical constraints on  $E_{Min}$  and  $E_{Max}$  are:  $E_{Min} \geq 0$  and  $E_{Max} \leq E_{Rated}$ . To minimize losses, according to equation (11), the energy state must be maximized, leading to the following choices:

$$E_{Max} = E_{Rated} \quad (32)$$

$$E_{Min} = E_{Max} - \Delta E \quad (33)$$

$$E_{Min} = E_{Rated} - \alpha \cdot \tau \cdot (P_{Max} - P_{Min}) \quad (34)$$

If after this computation  $E_{Min}$  is negative, the considered storage system would be considered too small to allow this energy management. For a size  $E_{Rated}$  large enough for management to be feasible, the losses can be computed for all pairs of values  $\alpha$  and  $\tau$ . Therefore, the following problem has to be solved:

$$\min_{(\alpha, \tau) \in \Omega(H_s, T_p)} \overline{P_{Loss}}(E_{Rated}, H_s, T_p, \alpha, \tau) \quad (35)$$

This research is exhaustive within each parameter space and for each size (500 pairs of parameters tested). The loss minimization condition is illustrated in Figure 11 for a storage size of 1.2 kWh and two different sea-states. This loss minimization effort is shown with a specific design but is then repeated with several storage sizes.

Each point in Figure 11 corresponds to a pair of parameters whose energy management satisfies the flicker constraint (long-term severity  $P_{lt} = 0.056$ , as explained in section 2.3). The point corresponding to the minimum losses is a square, while the point corresponding to the minimum quadratic mean (Root Mean Square value) of the power in ESS is a circle. In these two examples, a very general rule is being displayed: the minimization of losses in storage corresponds approximately to the minimized power RMS-value in the ESS. In seeking to minimize the RMS power in storage instead of minimizing losses, the parameters  $\alpha$  and  $\tau$  would no longer depend on the storage size, but merely on the sea-state. This may be worthwhile to note for the purpose of decoupling the energy management problem from the sizing problem. In the following discussion, the management rule that minimizes losses is still used for this study.

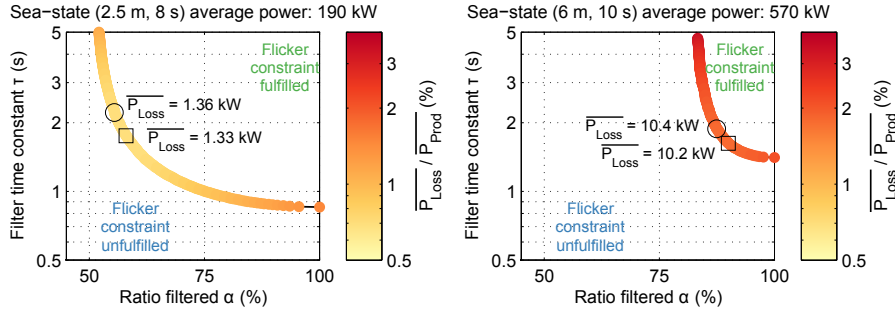


Figure 11. Ratio of average losses over the average production for a 1.2 kWh storage system in the management parameter space ( $\alpha$ ;  $\tau$ )

Energy management parameters differ for each sea-state at a given size, which may be viewed in Figure 12; this figure can provide a graph for selecting energy management as a function of the sea-state. When  $\alpha = 0$ , the ESS is not used because for some sea-states, the flicker constraint is satisfied without the need for energy storage.

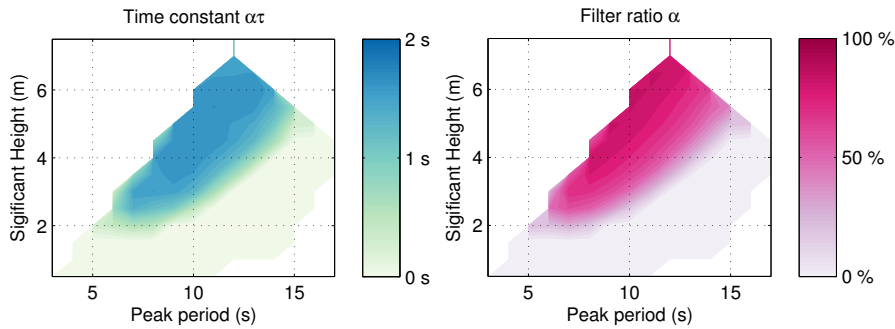


Figure 12. Energy management parameters that minimize losses for each sea-state in the case of a 1.2 kWh ESS

An even simpler chart can be produced by using only information that is precisely known: the average value of power produced. This value is in fact directly correlated with the fluctuations in the power produced. The corresponding chart is shown in Figure 13. It is worth noting that the higher this value, the greater the need for filtering.

When the average power is greater than 200 kW, the compromise to minimize losses consists of increasing  $\alpha$  while keeping  $\alpha\tau$  nearly constant. Yet the available energy  $\Delta E$  is proportional to  $\alpha\tau$  and nearly constant in these sea-states.

The energy management parameters are now set for each sea-state and each storage size (see Figure 12 and Figure 13). The next subsection examines the sizing in order to find the storage size that minimizes the cycle cost of this smoothing function.



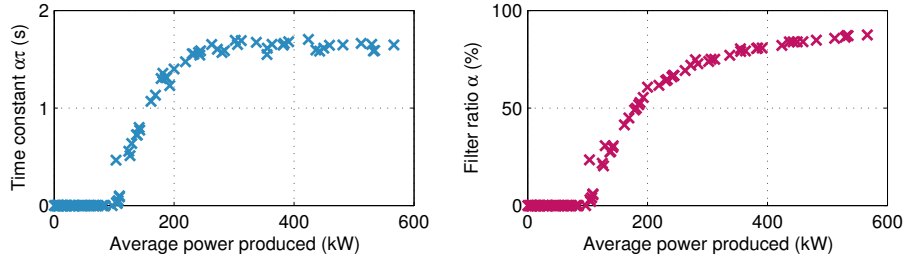


Figure 13. Energy management parameters that minimize losses for each sea-state in the case of a 1.2 kWh ESS vs. average power produced

4.5. Sizing optimization and results

200 different storage sizes, ranging from 10 Wh to 5 kWh, are considered below. Energy management parameters have been optimized in order to satisfy the flicker constraint and minimize the cost for each storage size, as explained above (see Figure 11, Figure 12 and Figure 13).

Two hypotheses have been tested (see section 4.2): sizing and predict the cost of the ESS from modelling 106 sea-states, or else model a single sea-state (with this state being considered as representative, here,  $H_s = 2.5$  m and  $T_p = 8$  s). Results are shown in Figure 14. The optimal point is marked by a cross. The brown area corresponds to an impossibility to sufficiently filter in order to satisfy the flicker constraint given that the ESS is too small in this area.

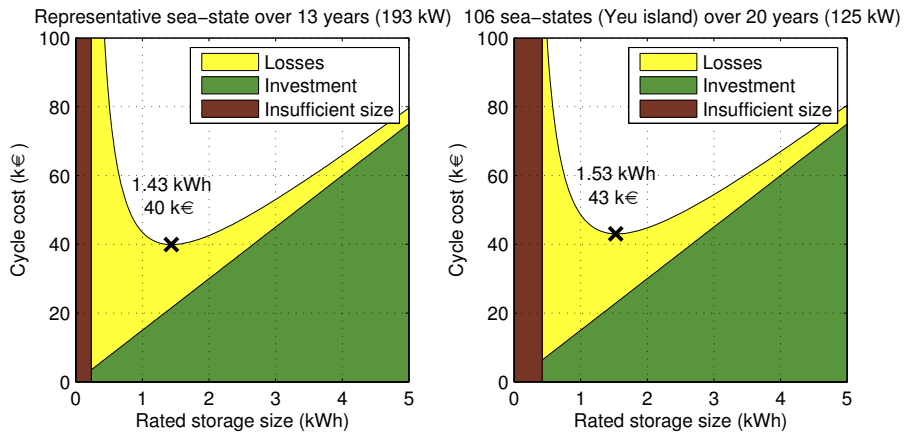


Figure 14. Cycle cost vs. Energy Storage Size, in taking both investment and losses into account

It is worthwhile to note that the result in terms of sizing is very close with a simplified consideration of the sea-states (error of 7% on the energy capacity and system cycle cost). Otherwise, the minimum capacity needed to meet the flicker constraint on

all sea-state conditions has not been predicted. From an overall standpoint, the results are close enough to conclude that a simplified approach would seem to be sufficient.

Note that around the optimum, supercapacitor capacity is significantly underutilized: with the optimal storage size, only 21% of the available energy is used on the representative sea-state and only 30% in an extreme sea-state. The need for power is greater than the need for energy in this application and with this technology. Consequently, if change had to be introduced relative to the technology, the successor would need to demonstrate a lower cost per unit of power.

Changes in voltage across the ESS are low enough to question the need for a converter between the DC bus and supercapacitors, as the extra cost of a floating DC bus (DC voltage slightly and slowly variable) can be beneficial compared to the absence of chopper.

Taking as references a 125 V module (Maxwell Technologies, 2013) (140 Wh for 64 kg and a dedicated volume of 0.13 m<sup>3</sup>), the mass of this ESS would be 700 kg for a dedicated volume of 1.4 m<sup>3</sup>. These values are not problematic in view of the size and mass of the complete production system (500 tons without ballast and 2400 m<sup>3</sup>). The investment cost would be around 23 k€ on the total of 43 k€, considering losses.

## 5. Conclusion

A methodology for managing and sizing an electrical Energy Storage System was set up and used in the context of the power quality (flicker constraint) of a Direct Wave Energy Converter farm on a weak grid.

A rule-based management approach was introduced to allow for compliance with the flicker constraint by means of smoothing the electrical power produced. The parameters of this management law were then optimized to reduce the use time cost, in taking into account the investment and losses of generating capacity due to Joule effects in the supercapacitors.

This methodology was applied with two assumptions: the consideration of 106 different sea-states, or the use of a single representative sea-state. Despite very different conditions, the optimal storage capacity and estimated cost of smoothing were very close for both approaches.

In this example, the system cost would be about 43 k€, an impact of 2 €/MWh, to be compared with the French feed-in tariff for wave energy, i.e. 150 €/MWh. The impact therefore seems to be reasonable.

To confirm these results, aging models of supercapacitors that take into account cycling effects (Kovaltchouk *et al.*, 2015) should be used to conduct a proper study on the life cycle cost in order to ensure that replacements **do not play a prominent role**.

### Acknowledgements

*This work has been supported by the French National Research Agency (ANR) within the scope of the project QUALIPHE (power quality and grid integration of Direct Wave Energy Converters), which is part of the PROGELEC program.*

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