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Towards the optimal use of an existing MRE electrical network from an electrothermal perspective

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Abstract—Marine renewable energy (MRE) is an interesting sustainable source of power. However, planning the cost-effective integration of MRE, and in particular of wave energy, in the energy mix remains a challenge as its levelized cost of energy (LCOE) is still greater than these of more conventional energy sources. This paper describes a preliminary study about the energy production management of a simulated point absorber-based WEC farm that could be installed in the vicinity of the SEM-REV site, i.e. the French multi-technology open sea test site. The proposed approach is based on the temporal analysis of the electrothermal behavior of the export cable of the SEM-REV. The models developed under Matlab-Simulink®, are generic and can be easily extended to other WEC types and more sophisticated models and control strategies, as well as to other energy sources (e.g. offshore wind). It is demonstrated in this work that there is room to maximize the utilization of the export cable, which allows to increase wave electricity production during a predetermined sea-state sequence with limited to no curtailment.

I. INTRODUCTION

Marine renewable energy (MRE) is an interesting and sustainable source of power. However, planning the integration of MRE, and in particular of wave energy, in the energy mix remains a challenge as its levelized cost of energy (LCOE) is still greater than these of more conventional energy sources [1], [2], [3]. Many studies have addressed the design optimization of the MRE farms electrical infrastructure. More precisely, they have mainly focused on cable length and rated current [4], [5], [6], [7], [8], and WECs spatial layout [9], [10]. One of the next steps consists in addressing the future challenges regarding the use of the electric infrastructures, such as the existing test sites (e.g. SEM-REV, bimep). In particular, this paper discusses the potential for increasing the number of WECs in a wave farm without grid reinforcement by taking into account less conservative, and more realistic, operational constraints. This approach stems from the observation that highly conservative, and relatively irrelevant, design constraints are generally applied to wave farms. More precisely, the design of a wave farm export cable is based on the maximum value of the electric current profile flowing through the cable, regardless

of the duration during which it is applied to the latter. In other words, this method considers implicitly that a fictive, constant current profile, whose magnitude is equal to the actual maximum current value, is applied to the cable at any time [11], [12], [13]. Based on this observation, and on the potentially highly fluctuating power output of a wave farm, one of our previous studies showed that a submarine power cable can carry, on a temporary basis, significantly more current than its rated value, the latter being evaluated under fictive, constant current conditions [14]. Hence, it was proposed to consider thermal limits rather than current limits, as the latter may be quite irrelevant in the case of a highly fluctuating current output. This approach is similar to the concept of dynamic line rating (DLR) used for transmission lines in that it proposes to consider dynamic thermal limits rather than to rely entirely on a fixed current limit established under worst or near-worst case conditions [15]. However, these two approaches differ as in DLR, several current limits are defined based on varying external meteorological conditions (e.g. wind speed, air temperature). On the contrary, in our approach, the external conditions, such as soil temperature and moisture for instance, are constant but the potential for electric current increase is made possible by 1) the soil large heat capacity, 2) the variable nature of the wave energy resource. This is illustrated in Fig. 1 where a current profile and the corresponding temperature profile are shown: despite large current fluctuations, the environment (soil and sea) acts as a damper with a certain thermal inertia, thus leading to temperature fluctuations of smaller magnitude. In this work, we are going one step further and we present a preliminary study about the optimal energy production management of a wave farm inspired from the SEM-REV test site, i.e. the French multi-technology open sea testing site managed by Ecole Centrale de Nantes [16]. As shown in Fig. 2, it is located near Le Croisic (France). Thanks to the thermal inertia of the overall system, composed of the cable and of its environment (soil and sea), and the fluctuating current generated by a wave farm, a submarine export cable

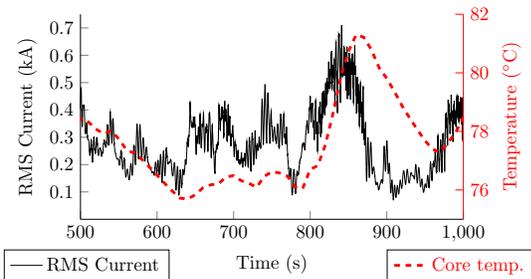


Fig. 1. Example of a RMS current profile generated by a WEC farm composed of 20 WECs considering a $H_s = 6$ m and $T_p = 9$ s sea-state. The current profile is very fluctuating and ranges between 70 A and 700 A while in the same time the temperature varies only from 76°C to 81°C.



Fig. 2. The SEM-REV open sea test site is located in western France, near Le Croisic. The physical installation of the 24 km export cable studied in this paper follows the dotted path. It connects the SEM-REV offshore hub to an onshore substation and finally to the local network belonging to French DSO Enedis (red and dark green paths). Figure modified, courtesy of École Centrale de Nantes [16].

can temporarily carry more current than its rated value, which is defined under static, (near-)worst case conditions, as mentioned earlier. This paper describes three case studies based on a direct-drive, point absorber-based WEC farm with negligible energy storage, thus presenting a highly variable power output. The point absorbers are controlled passively with a damping factor depending on the sea-state considered. Our approach is two-fold. First, as electric currents greater than the rated value can be safely tolerated in the system on a temporary basis, we analysed whether the wave electricity production during highly energetic sea-states could be increased with limited to no curtailment, thus leading to an increased wave farm capacity factor. Second, a simple farm power production strategy has been applied by (de)activating the WECs with respect to marine weather conditions (i.e. sea-state parameters) in order to maximize the overall energy production while still not exceeding the thermal constraints. The proposed approach, implemented under Matlab-Simulink[®], is generic and can be extended to other WEC types and to more sophisticated models and strategies. The rest of the paper is divided into four sections. Section II describes the electrothermal modeling of the cable that transmits the energy to the onshore network. Then, Section III describes the numerical simulations. Finally, Section IV details the results, followed by the conclusion of the paper.

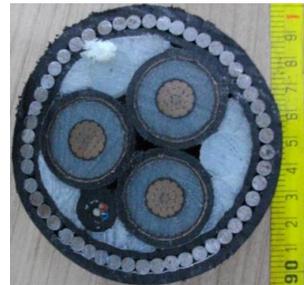


Fig. 3. Cross section picture of the export cable considered for our case studies. This 3×95 mm² copper cores cable (that was designed to carry a constant electric current of 290 A) is currently installed in the SEM-REV test site located off Le Croisic (see Fig. 2), France and is managed by École Centrale de Nantes [16].

II. CABLE ELECTROTHERMAL MODELING

The model used in this study is intended to reproduce the electrothermal behaviour of the 24 km export cable installed in the SEM-REV test site (see Fig. 2). We considered that this 3-phase, 20 kV, XLPE insulation cable is buried at a 1.5 m depth in soil, where thermal properties are deemed to be homogeneous and constant, and where thermal resistivity $\rho_{th} = 0.7$ m·K·W⁻¹ and heat capacity $C_{th} = 2$ MJ·m⁻³·K⁻¹. Also, based on a previous work [18], it was considered necessary that the cable materials consider the temperature dependence of the specific heat $C_p(T)$ in J/(kg·K), of the thermal conductivity $\kappa(T)$ in W/(m·K), and of the electrical resistivity $\rho_e(T)$ in Ω ·m. One can find the materials data we used in [19], [20], [21], [13]. However, compared to our previous models based on the finite element method[14], and which required an important computing time, in this paper a simplified model based on the well-known analogy between electrical and thermal physics [23], [13], and implemented under the Matlab-Simulink[®] software [22], was used for the sake of computing speed.

III. NUMERICAL SIMULATIONS

A. Introduction

All the case studies presented in this paper used the same sea-state sequence shown in Fig. 4. Regarding the initial conditions, we used a predefined sea-state with wave height $H_s = 1$ m and wave period $T_p = 12$ s. It was assumed that at initial time $t=0$ s, the system was in a dynamic steady-state where the cable temperature fluctuates around a constant value which is assumed to be the initial temperature for the simulations considered here. We have also computed the cable current carrying capacity $I_{cc} \approx 330$ A which corresponds to the maximum constant RMS value of the current that can be transmitted in the cable without exceeding the maximum allowed temperature of the cable cores, i.e. $T_{max} = 90$ °C for a XLPE-insulated cable, as it is the case here. The difference between the rated value of 290 A and the calculated current carrying value, i.e. $I_{cc} \approx 330$ A, may be explained by the fact that we do not consider potential hot spots, which could be the case at landfall or at each junction box. Also, a

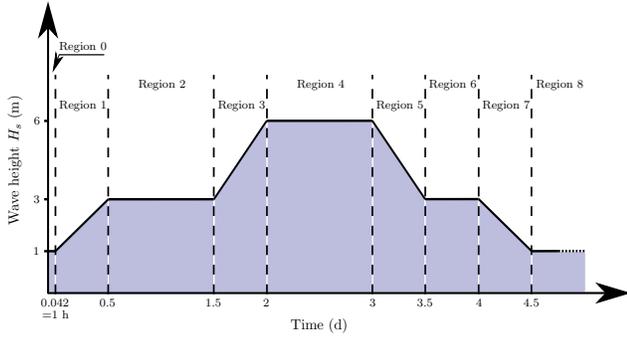


Fig. 4. Sequence of sea-states that has been used for all simulation cases (see Table I). Note that it is a completely fictitious sequence but based on plausible durations and transitions between each sea-states based on Fig. E2 and E3 of [17].

TABLE I
DESCRIPTION OF THE SEA-STATE SEQUENCE⁺.

Region	Wave height H_s (m)	Duration (h)
0	1	1
1	1 to 3	12 ^a
2	3	24
3	3 to 6	12 ^b
4	6	24
5	6 to 3	12 ^b
6	3	12
7	3 to 1	12 ^a
8	1	12

⁺ The sea-states sequence is based on a single peak period $T_p = 12$ s, for all wave heights H_s .

^b Increase or decrease by step of $\Delta H_s = 0.2$ m distributed uniformly over the region duration.

^c Increase or decrease by step of $\Delta H_s = 0.25$ m distributed uniformly over the region duration.

security margin, unknown to the authors of this paper, may have been taken into account in the initial design studies, thus decreasing the value of the rated current. Without more information on these specific points, we deliberately chose to use the highest value, i.e. $I_{cc} \approx 330$ A, as a reference. This constitutes a worst-case scenario leading to a minimal margin for current increase. However, it is important to note that the goal of this paper is to assess the potential for current increase on a submerged, continuous section of an export cable, independently of the influence of other cable elements and parts for which specific actions, such as replacement, may be undertaken.

B. Current profile generated by a WEC farm

In order to model the wave farm, we used a wave-to-wire model implemented under Matlab-Simulink[®], as described in [24]. The farm was composed of up to 36 identical 1 MVA heaving buoys controlled passively, as modelled in [25]. Note that a single peak period $T_p = 12$ s is considered, i.e. the value of the damping factor B_{pto} is constant and equal to $B_{pto} = 680 \times 10^3$ Nms. Due to the random nature of wave

power, the power generated by a WEC farm, especially when it is based on direct-drive point absorbers with little to no storage, can be extremely fluctuating. This is reflected in the current that flows in the export cable as shown in [26], [14] and as illustrated in Fig. 1.

C. Case studies description

The main objective of this paper is to determine the number of additional WECs which could be installed in the farm without exceeding the cable cores temperature constraints. To do so, three different scenarios are considered:

- Case 1 : The number of WEC is kept constant with $N_{WEC} = N_{WEC}^i$. N_{WEC}^i corresponds to the maximum number of WECs which can be connected to the wave farm without exceeding I_{cc} , i.e.

$$\max(I_{farm}(t))|_{N_{WEC}} \leq I_{cc} \quad (1)$$

- Case 2 : N_{WEC} is also kept constant with $N_{WEC} = N_{WEC}^+$. N_{WEC}^+ corresponds to the maximum number of WECs which can be connected to the wave farm without exceeding the cable cores temperature constraints, i.e.

$$\max(T_{core}(t))|_{N_{WEC}} \leq T_{max} \quad (2)$$

- Case 3 : The number of WECs $N_{WEC} = N_{WEC}^v$ is allowed to vary. This can be achieved by (de)activating WECs between different sea-states. However, the cable cores temperature constraints must still be satisfied, i.e.

$$\max(T_{core}(t))|_{N_{WEC}(t)} \leq T_{max} \quad (3)$$

Case 1 can be seen as corresponding to an initial and existing WEC farm where the conservative approach considering only maximum current constraints. Case 2 can be envisaged as improvement over Case 1 where temperature constraints are considered instead of current constraints. In this case, N_{WEC} is constant throughout the sea-state sequence. Finally, Case 3 is deemed to represent a further enhancement compared to Case 2, as N_{WEC} is allowed to vary. It is important to note that in this preliminary study, economical considerations were not taken into account. In other words, the number of additional WECs (either N_{WEC}^+ or N_{WEC}^v) was not limited due to economical reasons, but only due to technical constraints. This was meant to assess, at a first stage, the theoretical potential for farm expansion. This paper can therefore be considered as presenting a proof-of-concept study. Once this step is validated, further work will include additional constraints, including economical ones.

IV. RESULTS

A. Case 1

As we can see in Fig 5, the temperature of the cable cores is far below the limit of 90 °C that is suggested in IEC standards and is used by many power cables manufacturers. Such results confirm, as shown in a previous study [14], [18], that eq. (1) was not suitable for sizing power cables in the case of a WEC farm generating highly fluctuating currents. A

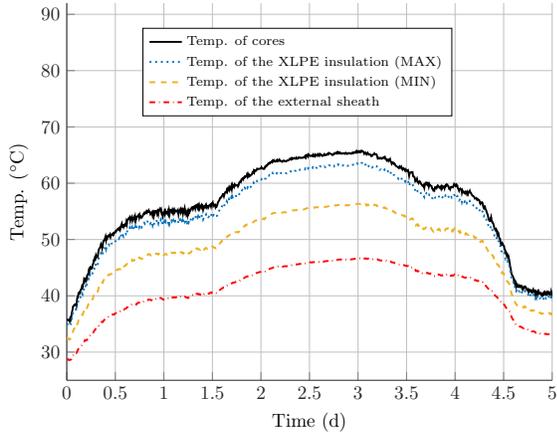


Fig. 5. Temperature calculated in different locations of the cable for Case 1, i.e. with a wave farm composed of 11 WECs. As we can see, the cable cores temperature are far from $T_{max} = 90$ °C, as allowed by the manufacturer and suggested in IEC standards.

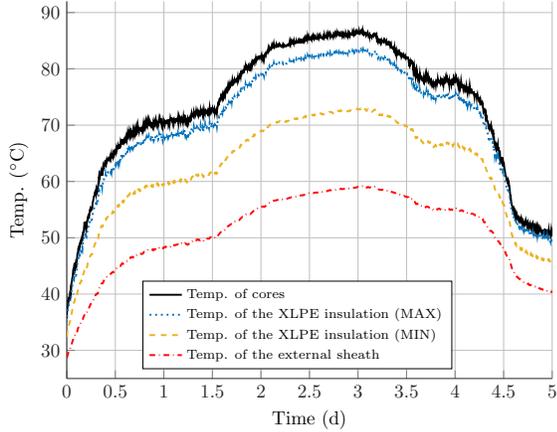


Fig. 6. Temperature calculated in different locations of the cable for Case 2, i.e. with a wave farm composed of 13 WECs. As we can see, the cable cores temperature is close to $T_{max} = 90$ °C.

number of 11 WECs has been found ($N_{WEC}^i = 11$). This number corresponds to the number defined based on the most conservative approach taking into account maximum current constraints only. It will be used as the baseline to compare the results for the two other case studies.

B. Case 2

The results of Case 2 are presented in Fig. 6. In this case, 2 more WECs could be installed in the farm permanently, i.e. ($N_{WEC}^+ = N_{WEC}^i + 2$). This represents an increase of 18.2%, both in terms of WEC number and in terms of harnessed energy compared to Case 1 (see Table II). It is also worth mentioning that the temperature of the cable external sheath, which is in direct contact with the soil, is close to the maximum limit that is generally recommended to prevent the soil from drying out. A maximum value of 60°C may be allowed, considering that the soil is sufficiently humid [27], which is supposed to be the case in a sea water environment.

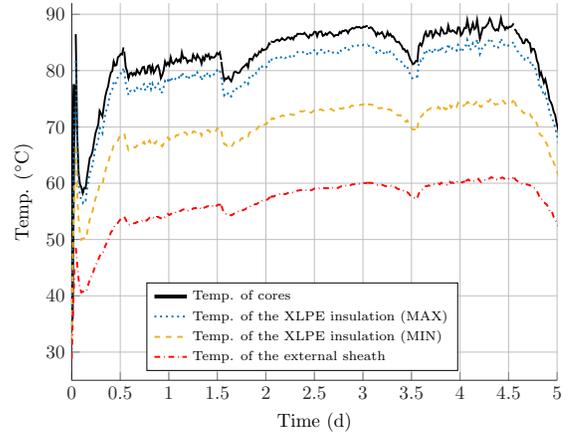


Fig. 7. Temperature calculated in different locations of the cable for Case 3, i.e. with a wave farm composed of 12 to 15 WECs. As we can see, the cable cores temperature is very close to $T_{max} = 90$ °C.

TABLE II
SUMMARY RESULTS OF CASE STUDIES

Case	N_{WEC}	Energy (MWh)	Gain ^a
1	11	1113	0% ^b
2	13	1315	+18.2%
3	13 to 25 ^c	1414	+27%

^a Considering the sequence of sea-states given in Fig. 4 and neglecting the Region 0 that is irrelevant in Case 3.

^b Considered as the reference case.

^c See Table III for more details.

C. Case 3

The results of Case 3, where N_{WEC}^v was varying between 13 to 15, are presented in Fig. 7. Note that we neglect the Region 0, which represents the first step for the computation of the temperature, where initial conditions and short duration of the period lead to an irrelevant number of WECs. One can see that the temperature calculated in Case 3 is closer to $T_{max} = 90$ °C over the total duration of the simulation, which means that the cable utilization is approaching its maximum. However, considering that the calculated temperature remains below 90 °C over the entire sea-state sequence, there is still room for improvement in terms of energy production with finer tuning and more comprehensive control of the WECs. Excluding Region 0, the expected energy production of Case 3 is between 12.7% and 33.5% more than this of Case 1 and is up to 12.8% more than this of Case 2 (see Table III). If we consider the entire duration of the simulation, Case 3 generates 27.0% more energy than this of Case 1, which is significant (see Table II). In Case 3, the external sheath temperature reaches and finally exceeds slightly the value of 60°C, and may thus require to lower the number of WECs. It is worth mentioning that, in this sense, the temperature of the external sheath can be a bottleneck and may require further studies as we discussed in Section IV-B (Case 2).

TABLE III
DETAILED RESULTS AND ENERGY PRODUCTION GAIN FOR CASE 3.

Region	N_{WEC}^v	Gain 1 ^a	Gain 2 ^b
0 ^c	25	+224.2%	+189.2%
1	15	+33.5%	+12.8%
2	14	+25.9%	+6.7%
3	13	+24.3%	+0%
4	13	+28.7%	+0%
5	13	+24.3%	+0%
6	14	+25.8%	+6.6%
7	14	+26%	+6.6%
8	14	+12.7%	+4.8 %

^a Compared to Case 1.

^b Compared to Case 2.

^c First step of the simulation. Due to the initial temperatures and the short duration of Region 0, the number of WECs is irrelevant.

V. CONCLUSION

The study described in this paper, that can be seen as a proof-of-concept analysis, deals with the optimal use of an existing MRE farm and is focused on the thermal response of the export cable to the fluctuating current of a wave farm in a sea-state sequence that considers different wave heights. It is shown that the combination of a wave farm fluctuating current and the thermal inertia of the cable and of its direct environment, composed of the soil and of the sea, may allow an increase of the number of WECs in the existing farm, which could lead to an increase of the energy production of up to 27%. This is an interesting option that could be considered to maximize the utilization of the MRE farms electrical infrastructure. The study also highlights some potential bottlenecks such a slightly excessive external sheath temperature, which could lead the soil to dry out. Future work will consider nearly a year of real sea-state data from the SEM-REV test site, which will allows us to perform a more comprehensive study with the use of a realistic and longer sea-state sequence.

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