Power Collection Array for Improved Wave Farm Output based on Reduced Matrix Converters

Alejandro Garces¹, Elisabeta Tedeschi¹, Guillaume Verez², Marta Molinas¹
¹Department of Electric Power Engineering, Norwegian University of Science and Technology, NTNU, 7491 Trondheim, Norway
²Ecole Nationale de l’Energie, l’Eau et l’Environnement, Grenoble France
[alejan, elisabeta.tedeschi, marta.molinas]@elkraft.ntnu.no, Guillaume.Verez@bvra.etu.grenoble-inp.fr

Abstract—This paper suggests and explores an alternative power electronics interface solution for Wave Energy Converters (WECs) based on series DC power collection. The proposed solution is based on a reduced matrix converter linked to a high frequency transformer and a full bridge rectifier, reducing in this way the conversion stages and switching losses with respect to traditional approaches. The improvement wave farm output is investigated based on both, improved power extraction by the suggested power electronics interface and a smoothing technique. The smoothing technique is based on spatial distribution of the WECs in the sea with respect to the wave front. The improved power extraction is due to the improved efficiency of the direct AC-AC conversion with the reduced matrix converter. In addition, improved reliability and compactness of the equipment can be obtained, which are valuable advantages for offshore applications. Wave farm arrays excited by an ideal sinusoidal sea wave are modelled in PSIM and Matlab to show the consequent pulsating nature of extracted power. The effect of the smoothing technique is investigated and its impact on required energy storage addressed. Simulations results indicating the strengths and weaknesses of the proposed solution are presented to discuss the feasibility of a practical implementation.

Index Terms—Wave Energy Converter, Direct AC link, Series DC Collection System, Power Take Off (PTO), linear PM generator, Wave Farms

I. INTRODUCTION

Electricity production from wave energy is recently gaining increased attention due to its large availability and high energy density and predictability [1]. Now that the first prototypes of Wave Energy Converters (WECs) have shown the technological feasibility of various concepts, the real challenge will soon be that of managing large Wave Farms [2], in the power range of several hundred MW. Thus, issues like plants lay-out, suitable device control strategies and especially connection to the power grid need to be specifically reconsidered, taking into account the harsh operating environment and the inherent limitations imposed by offshore applications. Offshore installations require compact solutions and high reliability. The Power Take Off (PTO) for the WEC should be designed to fit these requirements by reducing the total size and weight and also focusing on reliability by eliminating components that are most prone to failure. The lessons learned from the wind energy sector [3] and the possibility of a profitable integration of wave and wind plants, suggest the opportunity of focusing on far offshore installations, employing HVDC transmission to convey power onshore. In this sense, the power collection array should be selected based on maximum offshore grid efficiency and HVDC transmission efficiency. When such global efficiency is on focus, the collection systems should not be separately analysed from the conversion system as this will strongly affect the overall efficiency. As reported in [3], the choice of electrical conversion system critically influences the overall offshore grid efficiency. It shows that series connection in the case of offshore wind parks leads to less offshore grid losses but to higher losses in the power electronics interfaces compared to parallel connection. Therefore, converter topology and its modulation become the key factors to make series connection viable by reducing the losses in the power electronics interfaces before the HVDC transmission. Upon this consideration, this paper suggests a power electronics interface based on the matrix converter concept. The motivation behind this choice is the potential to increase the efficiency of the power electronics interface. As it is well known, matrix converters reduce the conversion stages by the direct AC-AC conversion, and as it does not require electrolytic capacitor, size and weight of the converter are reduced [12]. Reliability and efficiency will then be improved in this topology as compared to conventional topologies [4][13]. In [18], the authors presented a comparison between a matrix converter based topology and conventional back to back converter topology showing a clear improvement in the efficiency.

Based on the above potential benefits, the paper investigates the operation of the matrix converter based interface presented in [4] when a series connection of WECs is considered. Characteristic behaviour arising from the intrinsic oscillating nature of wave motion is explained and its challenges discussed.

The focus of this paper is put on the mitigation of the most critical of these challenges: the fluctuating nature of
wave power. A power smoothing technique based on spatial distribution of WEC units in the sea is implemented according to [9]. A wave farm with series connection of WEC units as the one indicated in Fig. 1, with the suggested power electronics interface and smoothing technique is investigated by simulations. Operating conditions under ideal sea waves are tested and smoothing technique is investigated by simulations. 

The obtained results indicate a remarkable power smoothing when the number of WEC units is 10 compared to the case of 2 WEC units. The smoothing attained is however at the cost of large variations in the terminal DC voltage of each of the converters in series connection.

II. WAVE FARM DESCRIPTION

The wave farm under investigation is schematically depicted in Fig. 1. Details of the WEC concept considered in the analysis are beyond the scope of the paper. However, for the sake of understanding it is necessary to state that the heaving body is a floater directly connected to a linear generator as described in [5] for the AWS concept.

A. Power Take Off (PTO)

The Power Take Off system investigated in this paper is an all electric PTO composed of an electrical generator and a power electronics interface.

**Electric Generator:** A linear permanent magnet generator (PM) is suggested for converting the mechanical power from the WEC into electrical power. The PM-machine is one of the most reliable generator alternatives for WECs, since the absence of excitation winding losses helps to reach high efficiency values [14]. A multi-pole PM generator design will also provide the possibility to increase the amplitude of the attainable induced EMF from a primary source of energy of very low frequency as it is typical of sea waves. The equivalent circuit of the PM linear generator as treated in this paper is shown in Fig. 2. The mathematical model of the PM linear machine is discussed in section IV.

**Power Electronics Interface:** Most of the previous contributions in the field of wave farms [6],[8] propose topologies based on AC-DC-AC conversion such as the well known back-to-back topology shown in Fig. 3.a. This paper explores the feasibility of a solution employing a reduced matrix converter (RMC) as the one depicted in Fig. 3.b. The concept has been first suggested in [4] for application in offshore wind turbines. According to the scheme proposed, the EMF induced in the linear electric generator is transformed into an alternate square wave by the three-phase to single-phase AC/AC converter using a specially designed switching logic obtained by carrier based modulation [18]. The square wave supplies the transformer which provides galvanic insulation and ensures a suitable voltage level at the secondary side. Then, a single phase full-bridge active rectifier (FB) is used for the final AC/DC conversion. The power electronics interface will then be able to convert from the AC input voltage of the electrical generator into a DC output voltage. This output voltage can be connected in series or in parallel to collect the power from all the WEC units in the farm. When connected in series, the transmission voltage level will be reached by a suitable number of series connected WEC units in the offshore farm.

The RMC proposed here has potential for reducing losses and improving the reliability in the AC/AC conversion since fewer elements are required. A higher
enhancement is achieved if the bidirectional switches are implemented with reverse-blocking IGBTs (RB-IGBT). RB-IGBTs do not need any anti parallel diodes for reverse voltage blocking and present a better behaviour in the state changes, especially for the reverse-recovery [16]. In a conventional matrix converter efficiency is 1.3 points higher compared with a voltage source PWM converter [16]. This comes as a result of the use of RB-IGBTs.

The main advantages of the RMC with respect to traditional back-to-back solutions are in the reduction of the conversion stages, resulting in reduced power losses. Moreover the intermediate DC link of the traditional configuration is here avoided and replaced by small filtering capacitors at the output of the single phase rectifiers. As this capacitor has a filter function and not an energy storage function, its size will not compromise the size reduction gained with the RMC. A medium to high frequency transformer is also used. All of these technical provisions lead to a reduction in the weight and size of the power electronics equipment onboard, which is a major advantage for offshore applications [17].

B. Wave Farm Power Collection

Although several grid arrays have been proposed for offshore wind and wave farms, series or parallel connections are the two main well defined alternatives [6][7]. According to Meyer [3], series collection leads to high losses in the power electronics. To make series connection a viable option, the efficiency of the power electronics interface should then be improved. Converter topology and modulation are then the critical factors that will enable reduction of losses. From that, the RMC described in previous section, is suggested in this paper for the farm collection array. The series connection of all the WECs units ensures a suitably high value for the common DC bus in order to allow the HVDC power transmission, with no need for offshore substation. Fig. 4 shows a wave farm in which 10 WEC units are connected in a series array to investigate the smoothing technique described in previous section, is implemented for the distribution of the WEC units in the sea and its effect on converter voltage and DC power is investigated.

IV. WAVE FARM SIMULATION MODEL

A. Electrical Generator modelling

The single phase equivalent circuit of the PM linear generator is shown in Fig. 2 with respective generator inductance and resistance L and R. In this figure, the PM linear generator appears connected to the power electronics interface, isolating transformer, and full bridge with its DC output. For the purpose of the investigation, the PM linear generator assumed in this paper is modelled considering its equivalent circuit as schematically shown in Fig. 2. In order to understand the linear machine behaviour under sea waves excitation, the characteristic induced electromotive force is derived starting from the position x of the translator of the linear machine expressed in equation (1) [10][11]. In (1), \( \dot{x} \) is the amplitude of the motion and \( \Omega \) the angular frequency of the translator.

\[
x(t) = \dot{x} \sin(\Omega \cdot t) \tag{1}
\]

From the derivation of (1) the translator speed can be obtained; hence the electrical angular frequency, \( \omega_e \), can be expressed as:

\[
\omega_e(t) = \frac{2\pi}{w_p} \frac{\dot{x}}{w_p} = \frac{2\pi \dot{x}}{w_p \cos(\Omega \cdot t)} \tag{2}
\]

where, \( w_p \) is the distance between one north pole to the next. From this, the electric position \( \theta \) is given by the

![Fig. 5. No load electromotive forces (EMFs) induced under ideal conditions in the three phases of each linear generator](image-url)
using the carrier based technique as reported in [18].

DC output voltage fluctuations. The RMC is modulated
by a high frequency sine wave modulated by a second sine
wave farm composed of 10 WEC units. In order to
investigate the influence of the smoothing technique in a
WEC units connected in series. An average model of the
simulated with PSIM for the case of one WEC and two

implement the smoothing technique, a displaced voltage,
for the RMC, an ideal transformer and IGBTs with
antiparallel diodes for the full bridge rectifier. A capacitor
for the RMC, an ideal transformer and IGBTs with

Fig. 3b is modelled by using ideal bidirectional switches
for the RMC, an ideal transformer and IGBTs with
antiparallel diodes for the full bridge rectifier. A capacitor
is placed at the DC output of the full bridge to reduce the
DC output voltage fluctuations. The RMC is modulated
using the carrier based technique as reported in [18].

B. Power electronics interface modelling

as indicated in Fig. 4.

V. SIMULATION RESULTS

Three selected test cases are investigated by simulations.
One single WEC unit, series connection of two WEC
units, and series connection of 10 WEC units connected
to a stiff voltage source representing the inverter onshore.
All WEC units are assumed to be identically rated to
produce an output power of 60 kW each, and excited by
perfectly sinusoidal incident sea waves. The main
parameters are listed in Table I. Matlab and PSIM
simulations under steady state conditions have been
carried out especially focusing on the operation of the
matrix converter and on the resulting DC voltage at the
converter terminal with and without smoothing.

In all cases the matrix converter is controlled to obtain
input currents that are proportional to the corresponding
no load EMFs

A. Case I: Single WEC operation

This case is run in order to illustrate the most critical
operating condition of a WEC unit when excited by an
ideal sinusoidal wave. The no load electromotive force
induced in the PM linear generator is shown in Fig. 5.
When the matrix converter is controlled so as to obtain
input currents that are proportional to the corresponding
no load EMFs, the line voltages at the matrix input
section result as the one shown in Fig. 7 for phase a. The
alternating voltage square wave of Fig. 6a can be
obtained at the secondary transformer terminals (turn

C. Wave Farm and DC transmission modelling

The equivalent wave farm model shown in Fig. 4 has
been first implemented with a detailed model and
simulated with PSIM for the case of one WEC and two
WEC units connected in series. An average model of the
system shown in Fig. 4 was implemented in Matlab to
investigate the influence of the smoothing technique in a
wave farm composed of 10 WEC units. In order to
implement the smoothing technique, a displaced voltage,
$e_{PM}$, coming from the linear PM generator was imposed
in the equivalent circuit of Fig. 4, so that this displaced
induced voltage reduced by the linear machine internal

integral of (2), which will give the flux $\phi$, known as a
sinusoidal function of the electric position $\theta$ as expressed
in (3).

$$\phi(t) = \phi \cos(\theta - \delta) = \phi \cos \left( \frac{2\pi}{w_p} (\Omega t - \delta) \right)$$

(3)

where $\phi$ is the flux amplitude and $\delta$ the load angle. From
Faraday’s law, the final expression for the induced
electromotive force (EMF) in a PM linear generator
excited by a sinusoidal sea wave is given by:

$$e_{PM}(t) = -\frac{d\phi(t)}{dt} = \frac{2\pi\phi\Omega}{w_p} \cos(\Omega t) \sin \left( \frac{2\pi}{w_p} (\Omega t - \delta) \right)$$

(4)

In the PSIM and Matlab simulation models, the PM
linear generator was modelled based on the EMF
corresponding to the AWS device extracted from [8], and
that could in principle be obtained for any PM linear
generator by equation (4), with knowledge of the design
parameters and the position, $x$, of the translator.

The no load EMF expression of the PM linear
generator (Fig. 5) used hereafter is derived from (4) by
assuming a maximum EMF of 1050 V, according to [8].
A high frequency sine wave modulated by a second sine
wave with low frequency can be observed.

### Table I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM Linear Generator</td>
<td>Maximum EMF 1050 V</td>
</tr>
</tbody>
</table>

### Wave Farm

The power electronics interface was modelled in PSIM
using a detailed switching model. The interface shown in
Fig. 3b is modelled by using ideal bidirectional switches
for the RMC, an ideal transformer and IGBTs with
antiparallel diodes for the full bridge rectifier. A capacitor
is placed at the DC output of the full bridge to reduce the
DC output voltage fluctuations. The RMC is modulated
using the carrier based technique as reported in [18].

### Wave Farm and DC transmission modelling

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### Wave Farm and DC transmission modelling

The equivalent wave farm model shown in Fig. 4 has
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simulated with PSIM for the case of one WEC and two
WEC units connected in series. An average model of the
system shown in Fig. 4 was implemented in Matlab to
investigate the influence of the smoothing technique in a
wave farm composed of 10 WEC units. In order to
implement the smoothing technique, a displaced voltage,
$e_{PM}$, coming from the linear PM generator was imposed
in the equivalent circuit of Fig. 4, so that this displaced
induced voltage reduced by the linear machine internal
go to zero thus avoiding the instability problem. From the doing so, the DC voltage at the other WEC unit will not voltage rise up to 4000 V as can be seen in Fig. 9. By threshold voltage control is imposed to the FB to limit the controlling the corresponding WEC unit. To avoid this, a with the lower voltage due to the impossibility of not regulated will introduce instability in the converter voltage excursions remains as in the case of 2 WEC units, and it is observed in the upper plot of Fig. 9. By doing so, the DC voltage at the other WEC unit will not go to zero thus avoiding the instability problem. From the inspection of Fig. 8, it is clear that under series connection without displacement, the WEC DC power output is subjected to larger variations ($P_{peak}/P_{av}=2$), compared to the case in which displacement is implemented, as can be seen by comparing figures 8 and 9. The evident drawback of series connection is that the total power output cannot be the maximum attainable, as maximum power tracking is not possible to implement under the constraints of threshold voltage control of the DC terminals.

## B. Case II: Two WEC in proposed array

This case is run in order to see the effect of the smoothing technique suggested in this paper when 2 WEC units are connected in series. A 90° displacement in the induced voltage is fed in the second WEC unit with respect to the first one. The resulting converter DC voltage and DC power is compared with the case of series connection of two WECs without implementation of smoothing. The plots shown in Fig. 9 illustrate the influence of the displacement introduced in the induced voltages compared to the case without displacement shown in Fig. 8. Worth noticing is that as a consequence of the displacement imposed, the DC voltage terminal of each full bridge will experience large excursions that if not regulated will introduce instability in the converter with the lower voltage due to the impossibility of controlling the corresponding WEC unit. To avoid this, a threshold voltage control is imposed to the FB to limit the voltage rise up to 4000 V as can be seen in Fig. 9. By doing so, the DC voltage at the other WEC unit will not go to zero thus avoiding the instability problem.

### C. Case III: Ten WEC in proposed array

This case is simulated in order to draw the attention to the condition under which the real beneficial effect of the smoothing technique is seen. When the number of WEC units is increased to 10, the DC voltage at one converter and the total DC power out of the 10 WEC units are shown in Fig. 10 and 11 for the cases without and with smoothing technique implemented. It is evident that a much better smoothing is achieved for 10 WEC ($P_{peak}/P_{av}=1.1$) units compared to 2 WEC units ($P_{peak}/P_{av}=1.7$ in Fig. 9). When comparing 10 WEC units with and without the smoothing technique, it is noticed however that the smoothing is achieved at the cost of a reduced obtainable average power, which is limited by the value of the voltage threshold, as seen in Fig. 11. The issue of the DC voltage excursions remains as in the case of 2 WEC units, and it is observed in the upper plot of Fig. 7. The main strength of the smoothing lies however on the fact that the PTO system rating can be reduced, storage requirements can be reduced and efficiency can be increased ($P_{peak}/P_{av}$ is reduced); all at the cost of a lowered average power.

<table>
<thead>
<tr>
<th>SINGLE WEC</th>
<th>TWO WECs SERIES</th>
<th>PARAMETER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{wave}=6.25$ s</td>
<td></td>
<td>Sea wave period</td>
</tr>
<tr>
<td>$EMF_{peak}=1050$ V</td>
<td></td>
<td>Gen. peak EMF</td>
</tr>
<tr>
<td>$L =31$ mH</td>
<td></td>
<td>Gen. inductance</td>
</tr>
<tr>
<td>$R = 0.29$ Ω</td>
<td></td>
<td>Gen. resistance</td>
</tr>
<tr>
<td>$V_{DC}=3175$ V</td>
<td></td>
<td>Output DC voltage</td>
</tr>
<tr>
<td>$C_1 =1$ mF</td>
<td></td>
<td>Output capacitor</td>
</tr>
<tr>
<td>$\Delta V_{DC}=11%$</td>
<td></td>
<td>% Voltage ripple</td>
</tr>
<tr>
<td>$L_{HVDC}=0.128$ H</td>
<td></td>
<td>HVDC inductance</td>
</tr>
<tr>
<td>$R_{HVDC}=9.6$ Ω</td>
<td></td>
<td>HVDC resistance</td>
</tr>
<tr>
<td>$C_{HVDC}=34$ µF</td>
<td></td>
<td>HVDC capacitance</td>
</tr>
<tr>
<td>$P_{OUT} = 60$ kW</td>
<td></td>
<td>Rated power</td>
</tr>
</tbody>
</table>

### Table I: MAIN PARAMETERS OF THE SIMULATION SYSTEM

![Fig. 9. DC voltage, DC current and total DC power for series connection of two WEC units with 90° spatial displacement with respect to wave front](image)

![Fig. 10. DC voltage at one converter, DC current and total DC power out of 10 WEC units connected in series without phase displacement with respect to wave front](image)

![Fig. 11. DC voltage at two first converters, DC current and total DC power out of 10 WEC units connected in series with phase displacement with respect to wave front](image)
VI. DISCUSSION

Series connection of WEC units poses technological challenges which need to be further investigated. Practical considerations that have to be made before applying this concept to a conversion and collection system in a real application were not yet thoroughly analyzed. Among such practical considerations, it will be important to face the technical challenge of DC circuit breakers, the HF transformer, and the floating voltage in the series connection that will require special consideration of the insulation system. Some authors have presented some advances related to this [15],[19], but it remains an open problem for the research and development community. It will further be relevant to investigate control issues for optimisation, to keep the minimum DC current and to regulate the wide excursions of voltages of each WEC unit when one is out of service, under short circuit conditions, or when implementing the smoothing technique. Variation in the incoming wave groups will cause variations in the output power and therefore in the output voltage of each WEC. Consequently, a wide voltage variation capability and coordinated control is required in the output voltage of the full bridges.

Although series connection of WEC units at high voltage level (as in HVDC) is arguable from the technical feasibility point of view, its advantages are highlighted in this paper in an attempt to rescue the opportunities for research while technological advancements in the industry sector would eventually enable the practical realisation of the technology.

VII. CONCLUSION

In this paper, power smoothing and improved global efficiency have been brought into the discussion of wave energy conversion. From that, a power electronics interface and a power collection array based on DC series connection were proposed. The feasibility of the series connection of Wave Energy Converters equipped with a power electronics interface composed of RMC, high frequency transformer and full bridge rectifier has been investigated. The RMC is evaluated as candidate solution for improving the power electronics interface to make series connection a competitive option for offshore grids. It is worth noting that the proposed power electronics interface can also be used in parallel arrays favourably influencing the global offshore grid efficiency as well.

Simulations results of the operation of a wave farm composed with 2 and 10 WEC units have been presented to evaluate the performance of the smoothing technique. An improved power output profile has been achieved by implementing a smoothing technique based on the spatial distribution of WEC units in the sea. It should be remarked that the analysis presented in this paper is entirely based on the assumption of ideal sinusoidal sea waves, which will not occur in reality. The deviation of performance of the smoothing technique under irregular wave conditions will be investigated and reported in a further work.

The results shown in this paper and the discussion presented, provides elements to assess the strengths and weaknesses of series DC collection array presented here as an option for the future wave farms offshore grids.

REFERENCES