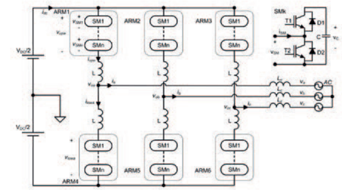
Smoothing of the intermittent power provided by wave power plants using ultracapacitors and a non-linear vector current controlled MMC



Alisado de la energía intermitente proporcionada por las centrales de energía undimotriz utilizando ultracondensadores y un MMC con control vectorial de corriente no lineal

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RESUMEN

- Este artículo se centra en suavizar los grandes picos de potencia que los convertidores de energía undimotriz inyectan en la red eléctrica. El estudio se lleva a cabo para un solo generador donde la energía se entrega a la red por medio de un convertidor electrónico de potencia. Se han estudiado dos estrategias para mejorar la calidad de la energía enviada a la red. En primer lugar, como convertidor electrónico se ha elegido un convertidor modular multinivel (MMC), para permitir la sustitución de los condensadores estándar de alta tensión del enlace de CC por ultracondensadores de baja tensión distribuidos en los módulos del MMC. En segundo lugar, el MMC se controla mediante un control vectorial de corriente no lineal. Los resultados muestran que la potencia entregada a la red se vuelve aproximadamente constante cuando se utilizan ultracondensadores. Además, la fuente de corriente vectorial no lineal proporciona al convertidor de conexión a la red la respuesta dinámica con la rapidez necesaria para evitar grandes variaciones en la tensión de CC.
- Palabras Clave: . convertidor modular multinivel, fuente de corriente vectorial no lineal, energía renovable, ultracondensador, generador undimotriz.

ABSTRACT

This article focuses on smoothing the large power peaks that wave energy converters (WECs) inject into the electrical grid. The study is carried out for a single WEC where the generated power is delivered to the grid by means of a power converter. Two different measures have been considered to improve the power quality of the grid connection. Firstly, the electronic converter has been chosen a modular multilevel converter (MMC) to allow replacing the standard high voltage capacitors of the DC link by low voltage ultracapacitors distributed across the modules of the MMC. Secondly, the MMC is controlled using a non-linear vector current control. The results show that the power delivered to the grid becomes approximately constant when using ultracapacitors. Furthermore, the non-linear vector current source provides the grid connection converter with the necessary fast dynamic response to avoid large variations in the DC voltage.

Key words: modular multilevel converter (MMC), non-linear vector current source, renewable energy, ultracapacitor, wave energy converter (WEC)

NOMENCLATURE

Available in the supplementary material linked at the end of the paper.

1. INTRODUCTION

Renewable energies are, because of their nature, intermittent. For this reason, when the penetration of power plants based on these kind of energy resources is high, it might cause disturbances in the electrical system to which they are connected. Mainly, wind and wave power can lead to a degradation of the quality of the power supplied, especially in weak and isolated grids; giving raise to effects such as flicker and voltage and frequency fluctuations [1][2][3]. To reduce their impact, it is necessary to smooth the profile of the power delivered to the grid, reducing and slowing down the variations of the generated energy. By using energy storage, it is possible to store the excess of generated power during peaks and to deliver it during valleys.

Lead acid-based batteries have been traditionally used in medium power applications such as photovoltaic generation. They are intended to store the non-consumed energy in order to deliver it during the hours when the sun is out or also to take advantage of utility rate plans that charge more for electricity during on-peak hours and less during off-peak hours.

Other technology used to this end is the one based on lithium ions. It provides lighter and more compact batteries as well as longer lifespan than lead acid-based batteries, although they result more expensive. Lithium ion batteries are also common in low power applications such as home and portable electronics.

Ultracapacitors represent a completely different storage technology that is been used in low power applications such as smart meters, emergency radios or flashlights. Nowadays, ultracapacitors have a higher power density and cycle lifetime than lithium ion batteries, although lower energy density but this situation might change because of the fast evolution of both technologies [4]. Also, ultracapacitors cannot be used with high voltage and, like with any other type of capacitor, when several of them are connected in series, it is necessary to equalize the voltages across the individual components.

Applications such as wind and photovoltaic (PV) generation or electric vehicles (EV) present fast fluctuations of power that make ultracapacitors more suitable than batteries because of its better charging/discharging dynamic capabilities. In large power applications, ultracapacitors are usually used together with batteries; the former cope with fast variations of energy and the latter with slow variations [5]. Some examples of this combination are [6]:

- Recovering of the braking energy in subway trains and the subsequent use to accelerate.
- Smoothing of the power peaks of the cranes of a port.
- Smoothening fluctuations in wind and photovoltaic production.

In the technical literature, many references can be found where renewable energy sources have been integrated with systems with storage capacity in the range of seconds to minutes to smooth the power injected into to the grid.

An active filter connected in parallel with the AC grid made up of one DC/DC and one DC/AC converters as well as ultracapacitors is used in [7] to smooth the intermittent profile of the power generated in renewable energy applications (wind, photovoltaic). In a similar application, a dynamic voltage restorer (DVR) using an ultracapacitor in the DC side is added to the active filter to provide sag/swell compensation in [8].

In [9], an ultracapacitor connected via a DC/DC converter to the DC part of the wind generator is used to improve the wind turbines' dynamic response to frequency disturbances in a remote wind-diesel application.

Among renewable power generators, WECs present the larger power variations as a consequence of the intermittent nature of the waves.

The electric generator driven by a WEC is connected to the grid in [10] using a back-to-back converter, whereas a DC/DC converter made up of ultracapacitors is used to keep constant the DC-link voltage.

In [11], a mixed storage comprising an ultracapacitor and a battery is used for smoothing of oscillating wave energy. The former deals with the higher frequency power variations due to its higher power density whereas the latter deals with lower frequency power variations due to its higher energy density. This topology includes a DC/AC converter for each of the turbines, and a single converter for the grid connection. The battery and the ultracapacitors are independently connected to the DC bus through a DC/DC converter for each of them.

Modular multilevel converters (MMC) are currently been used in high-voltage DC transmission (HVDC) by the most important companies [12][13][14]. In the technical literature, medium voltage applications such as D-STATCOM [15][16] or control of wind generators without gearbox [17] can be found, as well as low voltage applications [18] that is the case of this paper.

Although two-level converters are usually used for low voltage systems, the use of MMC has been proposed in the literature since it present some advantages [18][19]. Its efficiency may be higher when metal-oxide-semiconductor field-effect transistor (MOSFET) instead of Insulated Gate Bipolar Transistor (IGBT) are used in the switching modules (SM), further reducing losses when using synchronous rectification [20]. Recent developments in SiC MOSFETs and MMC promise significant improvements in the performance of low voltage inverters [21]. MOSFET-based MMCs allow to use a low cost and size filter, makes easier redundancy and losses are low [22].

MMCs control systems based on space vectors usually feature two PI controllers in an outer control loop that are responsible for controlling: (1) the DC-link voltage or the active power, and (2) the reactive power or the AC output voltage. These regulators provide the references of the AC currents in axes dq, i_d* and i_q* [22][23]. An inner control loop transform next the references, i_d* and i_q* into voltage references, v_{od}* and v_{oq}*, by means of another two PI regulators and the corresponding decoupling equations [24]. However, the use of PI controllers might reduce the overall dynamic response of the MMC what could lead to a poor control of highly variable systems like wave energy power plants. In such a case it might be advisable to use the faster no linear control systems such as the non-linear vector current source (NLVCS) [25][26], used in this article.

This paper looks into the advantages of replacing the capacitors included in the SM of MMCs by ultracapacitors, aiming to smooth the power profile provided by a wave energy converter (WEC). The profile of power provided by the WEC is used as input to the MMC, that is controlled using a no-linear technique based on current space vectors.

The article is organized as follows. In Section 2, the fundamentals of MMC and the NLVCS control are included for both, two-level and multilevel cases. In Section 3, the simulation of the application is carried out using standard capacitors of standard capacity value. In Section 4, the same simulations are carried out using ultracapacitors, and the results are compared with those of the previous section. Finally, Section 5 presents the conclusions.

2. MODULAR MULTILEVEL CONVERTER: STRUCTURE AND CONTROL

2.1 MODULAR MULTILEVEL CONVERTER

MMC (Figure 1) is formed by several switching modules (SM) in each arm, whose usual topology is half-bridge (HBSM) or full bridge (FBSM), and is constituted by IGBTs, diodes and a capacitor. The aim of the capacitor is to maintain a constant voltage $v_C=V_{DC}/n$, where n is the number of SM of each arm, in order to form a multilevel voltage waveform v_{oabc} at the output of the MMC. The SM is called to be in ON state when the T1 and T2 transistors are in ON and OFF states respectively, while the SM is called to be in OFF state in the opposite case. The voltage of the SM v_{SM} is not obtained from an external source but from the voltage of the SM capacitor. When the SM is ON, the voltage of the SM is equal to the voltage of the capacitor, $v_{SM}= v_C$; while when the SM is OFF, the voltage of the SM is zero, $v_{SM}= 0$. During the SM ON state, the current i_{SM} modifies the charge state of the capacitor, increasing its voltage ($\Delta v_C>0$) when i_{SM} is positive and reducing its voltage ($\Delta v_C<0$) when i_{SM} is negative. During the SM OFF state, the capacitor voltage remains constant [27][28].

Equations involving DC voltage V_{DC}, AC voltage v_{oa}, arm currents, i_{upa} and i_{lowa}, and voltages for upper v_{upa} and lower v_{lowa} arms are (Figure 1):

$$v_{oa} = \frac{V_{DC}}{2} - v_{upa} - L\frac{di_{upa}}{dt} \quad [1]$$

$$v_{oa} = -\frac{V_{DC}}{2} + v_{lowa} + L\frac{di_{lowa}}{dt} \quad [2]$$

The voltages of the k-order capacitors of the upper and lower arms of phase a are called v_{cupak} and v_{clowak}, respectively.

The variables s_{upak} and s_{lowak} k take the values 1/0 according to the ON/OFF state of the k-order SM of the upper and lower arms of phase a, respectively. Voltages of the upper and lower arms, v_{upa} and v_{lowa}, are the sum of the products of the capacitor voltages, v_{cupak} and v_{clowak}, multiplied by the SM states, S_{upak} and S_{lowak}.

$$v_{upa} = \sum_{k=1}^{n} S_{upak}\, v_{Cupak} \quad [3]$$

$$v_{lowa} = \sum_{k=1}^{n} S_{lowak}\, v_{Clowak} \quad [4]$$

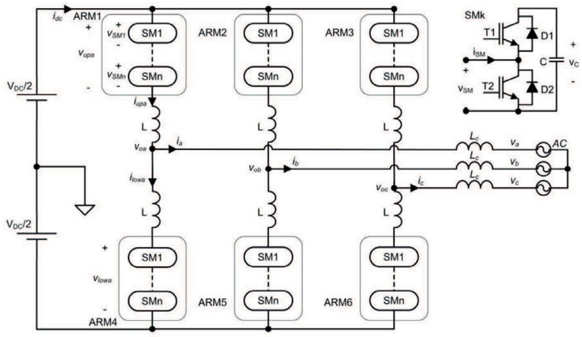

Fig. 1 Schematic of a modular multilevel converter (MMC), including the detail of a switching module (SM) with half-bridge (HB) topology.

As the capacitor voltages v_{cupak} and v_{clowak} have a value of approximately V_{DC}/n, the arm voltages v_{upa} and v_{lowa} will have values at approximately {0,VV_{DC}/n, 2 V_{DC}/n,...,(n-1) V_{DC}/n, V_{DC} }, and they will be responsible for obtaining the n+1 levels of the output voltage (the voltages in the arm inductances L usually have a very small value): {$-V_{DC}/2$,$-V_{DC}/2 +V_{DC}/n$,$-V_{DC}/2+ 2V_{DC}/n$,...,$-V_{DC}/2$+(n-1) V_{DC}/n, $V_{DC}/2$}.

Upper and lower arm currents, i_upa and i_{lowa}, are the sum of half the phase current i_a, third the DC current i_{dc} plus the circulating current *i* [27] [28].

$$i_{upa} = \frac{i_a}{2} + \frac{i_{dc}}{3} + i_{za} \quad [5]$$

$$i_{lowa} = -\frac{i_a}{2} + \frac{i_{dc}}{3} + i_{za} \quad [6]$$

Circulating current, included in (5) and (6) .is a 100Hz current that has the same value in the upper and lower arms of each phase, so it does not appear in the output current i_{abc}.

The sum of the circulating currents of the three phases is zero, $i_{za}+i_{zb}+i_{zc}=0$, so they do not appear in the direct current *i*. It can be calculated as:

$$i_{za} = \frac{i_{upa}+i_{lowa}}{2} - \frac{i_{dc}}{3} \quad [7]$$

2.2. NON-LINEAR VECTOR CURRENT SOURCE

Available in the supplementary material linked at the end of article.

2.3. CONTROL DEL CONVERTIDOR DEL LADO DE LA RED

Available in the supplementary material linked at the end of paper.

3. SIMULATION OF ONE WEC WITH STANDARD CAPACITORS

The power provided by WECs typically presents large and fast variations (upper graph of Figure 5). If there is no energy storage, the intermittent power is transmitted to the grid, what leads to power quality problems. The main problems that power fluctuations can cause in the grid are voltage and frequency oscillations. Voltage fluctuations are usually caused by large current variations in the line, and are greater on low voltage lines, which are not designed to handle oscillating/intermitting power, resulting in reduced quality supply [1]. The frequency oscillations are caused by variations in the injected active power, and can lead to interruptions and stress in the line [5]. All these problems can be mitigated by installing ultra-capacitors, avoiding the need to install higher power lines [6]. Another problem caused by power oscillations is that the grid connection converter needs to be overrated, due to the power peaks they must handle; that can be solved by using storage devices such as ultra-capacitors [10].

In order to compare the power variations produced by a WEC with those produced by a solar panel and a wind turbine, examples of each one have been searched.

The oscillation range of the power of a WEC can be seen in the upper graph of Figure 5, where power oscillations of 100% every 2.5 seconds appear. These oscillations are much more frequent and intense than in the case of photovoltaic and wind energy, due to the nature of the waves themselves.

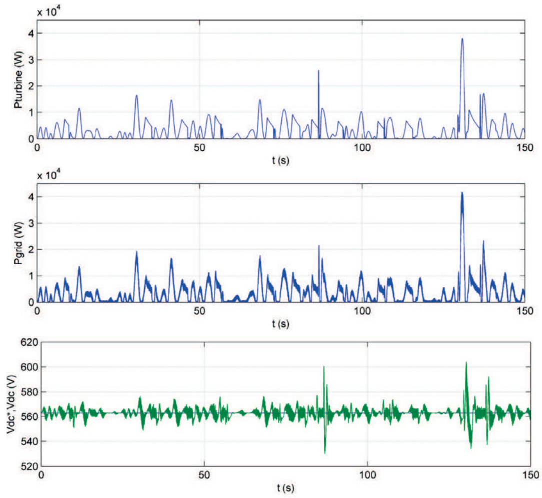

Fig. 5: Figure 5: Power of the WEC (upper graph), power delivered to the grid (middle graph), and reference and measured DC voltages (lower graph).

According to [30], in photovoltaic energy, power variations present an average frequency of 26 minutes and an intensity of around 50%. In the case of wind energy, variations of 15% approximately every 8 seconds are reported in [6].

Sections and address the improvement of the profile of the power delivered to the grid by the MMC when ultracapacitors are used in the SMs. First (Section), the power delivered to the grid is simulated when standard capacitors are used in the SMs, then (Section), the MMC is simulated with ultracapacitors in the SMs. For each case, simulations are performed for one turbine. Commercial capacity values have been chosen for standard capacitors and ultracapacitors.

The WEC used in this paper is a point absorber with one degree of freedom (heave) where a cylindrical buoy is connected, by means of a stiff rope, to a linear permanent magnet synchronous generator located on the seabed. The source of WEC's power data is the wave-to-wire model of a point absorber described in [26].

The grid-connected converter is an NLVCS-controlled MMC (see Section). The MMC integrates into the converter structure a large number of capacitors which, in this paper, are replaced by ultracapacitors. In addition, the converter allows quick control of power variations due to the use of NLVCS.

In the simulation, the input power to the converter is introduced via a controlled current source of value equal to the quotient between power and input voltage. Simulations are carried out using MATLAB/SIMULINK.

In this section, the power profile of a single WEC (upper graph of Figure 5 is simulated as the input power for the MMC (Figure 4) connected to the grid. The simulation parameters are included in Table I. Note that the SM capacitors have a relatively high value (50*mF*) but much lower than that of the ultracapacitor (5F in Section. Parameter T_S is the sampling frequency of the simulation.

n	*5*
T_s	$8_{\mu s}$
T_{PWM}	$50_{\mu s}$
$V_{DC}{}^*$	*563V*
C	*50mF*
L	*23.44μH*
$v_{ph,ph}$	$219.9V_{RMS}$
L_C	*3mH*
C_{DC}	*9mF*
ε	*0.1A*
$k_{p,VDC}$	*1*
$k_{i,VDC}$	*10*
$k_{p,PLL}$	*0.025*
$k_{i,PLL}$	*1*
$i_q{}^*$	*0*

Table 1: Simulation parameters

When choosing the components of this application, the following things must be taken into account. High frequency ripple appears in the current of the three phases, which depends on the switching period $T_{PWM}$and the grid coupling inductance L_C The ripple of the power delivered to the grid is high frequency and consequence of the ripple of the currents. Increasing L_C reduces the phase current ripple, however, the variation of the arm inductance L has no influence on the phase current ripple. If the coupling inductance L_C is very large, the ripple of current and power is small, but the amplitude of the current is limited and the current can be delayed, limiting the power to be injected into the grid. Reducing T_{PWM} also reduces the ripple of power injected to the grid and the ripple of the grid current.

The simulation results show that the power generated by the WEC (upper graph of Figure 5) is equal to the power delivered to the grid by the MMC (middle graph of Figure 5), although the second one has a superimposed ripple of approximately 2000W. This is a consequence of the low energy storage capacity of the capacitors of the SMs. The current reference i_d*has the same profile as the power delivered to the grid P_{grid}, since both variables are proportional [33]:

$$P_{grid} = \frac{3}{2} v_d i_d \qquad [12]$$

Finally, the lower graph of Figure 5 shows that the DC voltage presents variations of less than 7.5% around its reference value $V_{DC}{}^*$

4. SIMULATION OF ONE WEC WITH ULTRACAPACITORS IN THE SM

The characteristics of the ultracapacitors make them very suitable for filtering the power peaks generated in WECs. The following list shows the main differences between the main types of storage [4]:

- Lithium-ion battery. Energy density (Wh/Kg): 10 to 100. Power density (W/Kg): <1000. Charging/discharging time: 0.3 to 5 hours. Cycle Life: <1000.
- Conventional capacitor. Energy density (Wh/Kg): <0.1. Power density (W/Kg): <100000. Charging/discharging time: 10-3 to 10-6 seconds. Cycle Life: <500000.
- Ultracapacitor. Energy density (Wh/Kg): 1 to 10. Power density (W/Kg): <10000. Charging/discharging time: 0.3 to 30 seconds. Cycle Life: <500000.

In order to smooth the power profile delivered to the grid, this paper proposes to replace the capacitors of the SMs of the MMC with ultracapacitors. Their capacity has to be high enough to store the energy of a wave without experiencing appreciable voltage variations.

In this section, first, the capacity of the ultracapacitors is calculated, and then the simulations are carried out for the case of one WEC.

4.1 CALCULATION OF THE CAPACITY OF THE ULTRACAPACITORS FOR THE SM

To calculate the capacity of the ultracapacitors, the graph of the generated power (upper graph of Figure 5) is used. The condition is that the ultracapacitors are capable of storing the energy of the most powerful waves without producing a large variation in their voltage. Another way to size the capacitor is based on considering that the generated power has a sinusoidal shape [11].

The energy stored in each SM of the MMC is:

$$E_C = \frac{1}{2} C v_C{}^2 \qquad [13]$$

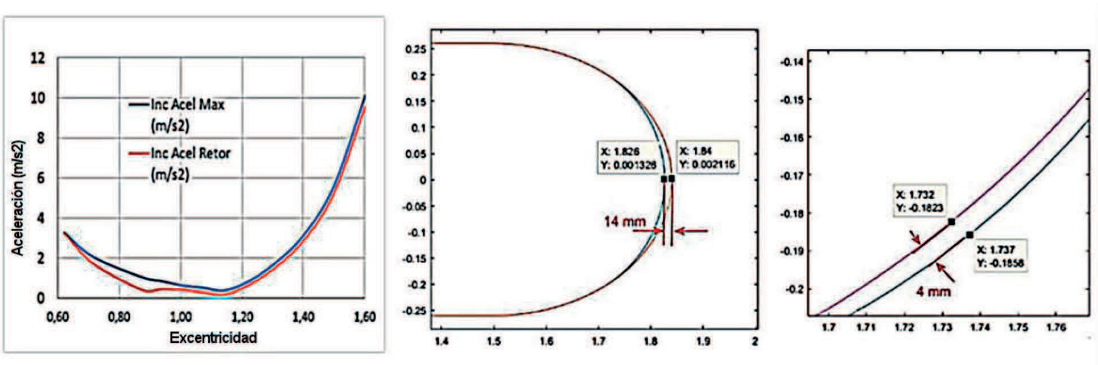

Fig. 6: Relationship between eccentricity and acceleration, left. Similarity between an elliptical and a pulse-free profile, center. Approximation to a pulse-free profile by an elliptical one.

When the capacitor voltage changes from an initial value v_{C1} to a final value $v_{C2}=xv_{C1}$, the capacitor energy variation is:

$$\Delta E_C = E_{C2} - E_{C1} = \frac{1}{2}Cv_{C2}{}^2 - \frac{1}{2}Cv_{C1}{}^2 = \frac{1}{2}Cv_{C1}{}^2(x^2-1) \quad [14]$$

From, the capacity necessary for an amount of energy ΔE_C to produce a variation x (in per unit) of the capacitor voltage v is

$$C = \frac{2\Delta E_C}{v_{C1}{}^2(x^2-1)} \quad [15]$$

To choose the capacity of the ultracapacitor, the power profile generated by a medium wave (upper Figure 6) and by the largest wave (lower Figure 6) are taken into account, both obtained from the power profile of 150 s (upper Figure 5).
The energy of a medium wave (upper Figure 6), calculated approximately as the area of a triangle is:
E_{wave_max}=½ 3 9·10³ =1,35·10⁴*jul.*
The energy of the largest wave (lower Figure 6), calculated as the area of a triangle is:
E_{wave_max}=½ 2 3,8·10³ =3,8·10⁴*jul.*

In the case of a medium wave, to change the voltage of the ultracapacitor by 1%, and taking into account that there are 30 capacitors and each one has to store a thirtieth of wave energy, the capacity of each SM has to be, according to,

$$C = \frac{2\Delta E_C}{v_{C1}{}^2(x^2-1)} = \frac{2(1.35\cdot10^4/30)}{(563/5)^2(1.01^2-1)} = 3.53F \quad [16]$$

And for the largest wave:

$$C = \frac{2\Delta E_C}{v_{C1}{}^2(x^2-1)} = \frac{2(3.8\cdot10^4/30)}{(563/5)^2(1.01^2-1)} = 9.95F \quad [17]$$

$$x = \sqrt{\frac{2\Delta E_C}{Cv_{C1}{}^2}+1} = \sqrt{\frac{2\cdot(3.8\cdot10^4/30)}{5\cdot(563/5)^2}+1} = 1.020 \quad [18]$$

For example, Maxwell's BMOD0006 E160 B02 model could be used, which is an ultracapacitor of rated capacity and voltage 5.8F and 160V, respectively. This ultracapacitor consists of 60 individual 350F cells with resistive balancing. The weight is 5.2Kg, the specific power is 2500W/Kg and the specific energy is 4Wh/Kg.

4.2 SIMULATION OF ONE WEC WITH ULTRACAPACITORS IN THE SM

In the simulation of a turbine using ultracapacitor in the SMs, the parameters of Table I are used except $k_{(P,DC)}$*=0.3125,* $k_{(I,DC)}$*=0.125 and C=5F.*

The intermittent turbine power profile (upper graph in Figure 7) is completely smoothed by the ultracapacitors of the MMC, delivering to the grid a much more stable power (middle graph of Figure 7) than when standard capacitors are used (Figure 5). Because of the limited voltage range of ultracapacitors, a key point is that the voltage of the ultracapacitors presents very moderate variations (lower graph of Figure 7).

When standard capacitors are used (Figure 5) the oscillations of the power delivered to the grid are the same as those of the input power. In this case the maximum oscillation is presented in the highest wave and it is of about 40000W; the power delivered to the grid has a ripple of about 2000W. When ultracapacitors are used (Figure 7), the oscillations disappear and the ripple of the power delivered to the grid is reduced to just about 600W.

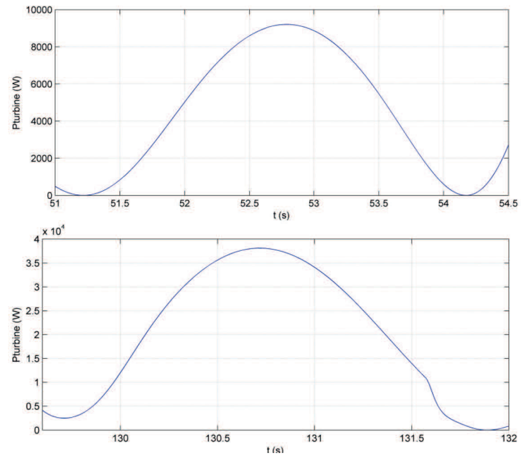

Fig.6 : Power generated by a medium wave (upper graph) and the largest wave (lower graph).

Due to the intermittent nature of the waves, the power generated by a WEC features an intermittent profile. In a park with high number of turbines, the power profile is smoothed out due to the distance at which they are located and the relative location of the WECs one another. Therefore, the higher the number of used turbines, the smoother is the profile of the generated power. For example, in figure 16a of [26], where 200 WECs have been used in the simulation, the power profile features much smaller variations. In fact, the lower number of turbines used, the more evident is the effect of using ultracapacitors.

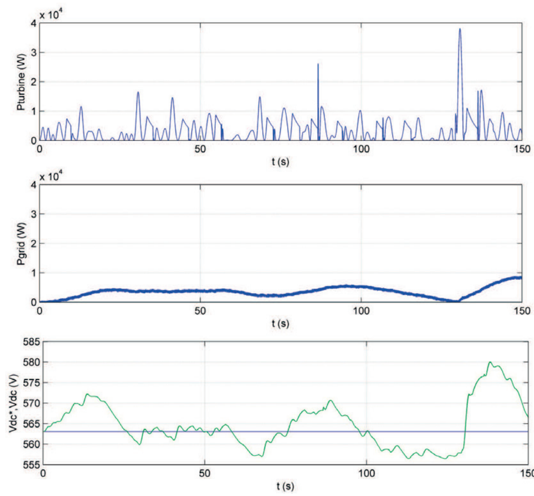

Fig. 7: Power generated by a WEC (upper graph), active power delivered to the grid (middle graph), and reference and measured DC voltages (lower graph).

5. CONCLUSIONS

The power generated by one WEC is shaped like peaks with fast power variations, which greatly reduces its quality. Therefore, from the power quality point of view, it is advisable to eliminate those peaks, delivering a smoother profile power to the grid.

This paper analyzes the use of ultracapacitors to store the power peaks produced by arriving waves and to return energy during the time between waves. The problem that arises is how to integrate low voltage ultracapacitors in the high voltage DC bus of the grid connection power converter. A first contribution is the use of an MMC as grid connection converter since this topology allows distributing the ultracapacitors across the low voltage SMs of the MMC.

The simulations have shown that using standard capacitors with very high capacitance values it is not enough to store the power of the wave and, consequently, the power delivered to the grid has the same profile (same peaks) as the power generated by the WEC. Conversely, by using ultracapacitors integrated in the SM of the MMC, the power injected into the grid features a smooth profile which benefits the power quality of the distribution grid.

Another contribution is the use of the control technique named NLVCS to improve the DC bus control. This technique is a multilevel current control developed from a previous version for two level converters adapted now for MMCs. In wave energy applications, its fast dynamic response allows the MMC to follow the fast changing power references needed to keep the DC voltage constant. In addition, the use of MMCs provides low ripple grid currents due to its multi-level topology.

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