Control Strategies for the Grid Integration of Wave Energy Converters at the BIscay Marine Energy Platform

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***Abstract*— The goal of this paper is to address some of the main issues arising from the grid integration of Wave Farms. The real test case offered by bimep (Biscay Marine Energy Platform) is used to model the grid connection infrastructure and a wave-to-wire model is developed to evaluate the impact of different Power Take-Offs (PTOs) when connecting a 20 MW farm of point absorbers to the local distribution system. The case of Wave Energy Converters (WECs) equipped with direct driven squirrel cage induction machines is considered as a worst case, then electrical generators driven by fully controllable power electronics interfaces are introduced. Different control strategies, aimed both at improving the power extraction from the waves and at controlling the active and reactive power exchange with the power system, are considered and compared. Both steady-state and dynamic analyses are carried out in order to assess the performance of the farm under its nominal operation and also to underline the detrimental effect of the energy source intermittency. Fault analyses are performed to evaluate the effect on the system operation of voltage dips. Finally, the usefulness of WEC inherent energy storage in smoothing the power profile and mitigating the grid impact of the Wave Farm is shown.**

***Keywords*— Wave Energy Converter, grid integration, point absorber, wave farm, control techniques**

I. INTRODUCTION

Among renewable energy sources, Wave Energy is certainly one of the most recently investigated. Despite its consistent estimated potential, [1], a single technology for energy extraction from sea waves has not emerged yet and several different devices are being studied and tested worldwide to prove their technical and economic feasibility. Among such different concepts, one of the most promising is that of point absorbers, due to their low infrastructural cost, good power performance and easy scalability. Such Wave Energy Converters (WECs) have been extensively studied in the past, mostly focusing on hydrodynamic aspects and control strategies implementation, both aimed at the maximization of the power output from the single device.

As long as an increased number of Wave Energy Converters are reaching their prototypal and pre-commercial stage it is fundamental to analyse in detail the issues arising from the grid integration of such devices. This is crucial especially when they are arranged in arrays, since they can affect the operation of the local power system as severely as the penetration level increases. In this paper a medium size wave farm (20MW) composed of point absorbers in heave will be considered. The real test case offered by bimep (Biscay Marine Energy Platform [2]) is used to model the grid connection infrastructure and real wave data from an ocean measuring buoy operating there between 2009 and 2010 will be used as a basis for the investigation.

The goal of the paper is to evaluate how control strategies and storage can improve grid connections issues when connecting to the Distribution System. At first, no storage provisions are included in the system. The analyses focus on the effect and management of the oscillating nature of the extracted power, fluctuating on a time scale of some seconds. The impact of such variations on the electric system will be evaluated both in steady state and in transient conditions. Steady state analyses aim at quantifying the efficiency of the power transmission within the considered wave farm, which is a fundamental factor to assess the economic viability of the project. Transient analyses will follow to underline the

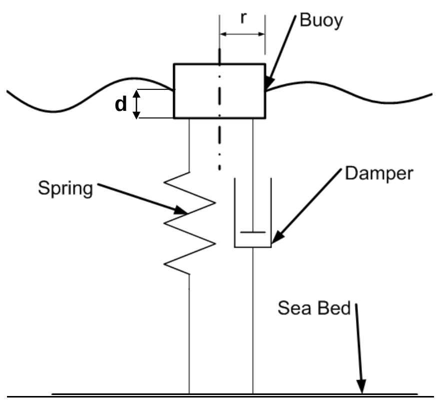

Fig.1. Schematic model of the considered point absorber (buoy)

effect of voltage dips affecting the operation of the considered system. As a starting step, the worst case of WECs equipped with squirrel cage induction generators, whose magnetization requires a reactive power absorption from the main grid will be specifically considered in order to evaluate how active and reactive power consumption mutually affect. Following, less critical cases of WECs equipped with a fully controllable power electronics interface will be analysed and discussed.

II. MODEL OF THE WECS

A. Hydrodynamic model

The basic element of the considered system is a cylindrical point absorber moving only in heave, which is schematically represented in Fig. 1. Its main physical parameters are reported in Tab. I.

Under the assumption of incompressible inviscid fluid and incompressible and irrotational flow, the linear water wave theory is applied to solve the hydrodynamic problem. Thus, the radiated and diffracted components of the velocity potential can be computed by applying boundary element methods and hydrodynamic coefficients can be therefore determined.

A time domain model of the system can be obtained from the Cummins equation [3], that, in the case of a single body floating in heave, can be written as follows:

$$(m+a_{\infty})\ddot{x}(t)+\int_{-\infty}^{t}K_{rad}(t-\tau)\dot{x}(\tau)d\tau+\rho gSx(t)+F_{ext}(x,\dot{x},t)=F_{e}(t) \quad (1)$$

In the above formula, m is the point absorber mass and a_{∞} the corresponding added mass at infinite frequency; x represents the point absorber position and the dot sign indicates time derivation operation. $K_{rad}(t)$ is the radiation impulse response function, representing a memory effect due to the radiation forces originated by the past motion of the body. Furthermore, g is the gravity constant, ρ the water density and S the surface defined by the intersection between the free surface and the buoy. F_{ext}, represents the external forces applied to the system due, for example, to the Power Take-Off (PTO) or to the moorings, while F_e is the waves excitation force. As said, hydrodynamic parameters such as damping and added mass have been obtained by using a boundary element code (ANSYS-AQWA [4]), while the convolution integral accounting for the radiation force has been modelled as a transfer function derived by a frequency-domain identification procedure [5].

B. Power Take-Off

As regards the PTO system, two different options have been considered:

- Static Generator (SG): a generic electrical machine equipped with a fully controlled bi-directional power electronics interface (i.e. a back-to-back converter).
  Such configuration allows a full control of the device, both on the “waves side”, for the maximization of the power extraction from the sea and on the “grid side”, making it possible to control the power factor and the reactive power injection (or voltage level) at the WEC connection point.
- Squirrel Cage (SC): a squirrel cage generator with a direct drive grid connection. In this case control strategies to improve the power extraction from the waves can still be implemented, but the reactive power absorption on the grid side (and consequently the corresponding power factor) cannot be controlled, being dependent, at first, on the magnetization requirement of the machine itself.

C. Storage provisions

Finally, concerning energy storage provisions, two different cases have been analysed.

- The basic case assumes that no energy storage is included in the system. Thus the power extracted from the point absorber is directly injected into the grid, without any smoothing.
- As a second case it is considered that each WEC is equipped with an inherent energy storage. Such storage is assumed to have the capability of smoothing the power profile and it is assumed not to affect the power capture from the waves but only to reduce the variability of the power injected into the electric system. It is modelled as a low-pass filter acting on the instantaneous power profile extracted from the WECs, in a similar way to what was done in [6] for wind energy applications. Three different cases are analysed, ideally corresponding to different storage capability. The considered options correspond to a power smoothing on a time scale of 30 s, 60 s and 180 s respectively.

III. BIMEP LAY OUT

In order to study the grid integration of a 20 MW Wave Farm, the bimep has been selected as a reference test case. bimep is an offshore facility for testing and demonstrating small scale WECs; it is located in Northern Spain, South East of the Bay of Biscay, and it is expected to be in operation by the end of 2011, being the process of obtaining licences underway. bimep accounts for 4 offshore benches, rated 5MW each and composed by subsea cables of different lengths. Once onshore, the subsea cables are replaced by four identical overhead lines up to the substation.

TABLE I
REFERENCE PARAMETERS OF THE SELECTED WEC

Quantity	Symbol	Unit of measure	Value
Buoy radius	r	[m]	5
Buoy draught	d	[m]	5
Buoy mass	m	[kg]	402520
Buoy surface	S	[m^2]	78.6
Buoy added mass at infinite frequency	a_{∞}	[kg]	235635
Water density	ρ	[kg/m^3]	1025

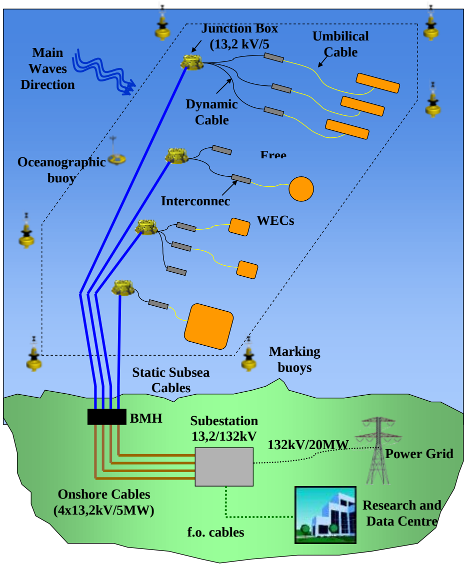

Fig.2. bimep architecture

The substation consists of two 13.2/132 kV transformers, used for the wave farm connection to the Point of Common Coupling (PCC), which is modelled by a Thevenin equivalent, whose parameters were derived by the short circuit power data provided by the local Distribution System Operator, Iberdorla [7].

Several WECs can be connected to the 0.69/13.2 kV transformer of each bench and each WEC is composed of a point absorber and the corresponding electrical generator.

Fig. 2 shows the structure of bimep, according to its present state of development and all the main parameters of the infrastructure can be found in Tab. II.

It is worth noting that the real bimep infrastructure is connected to a strong grid as already shown in [8]. Thus, in order to evaluate the effect of the grid connection of a 20 MW wave farm on a potentially weaker grid, the value of the grid impedance has been modified with respect to the real case. So that the farm corresponds to a 5% of wave energy penetration into the grid. More specifically, the short circuit power at the PCC has been considered to be of 400MVA.

Finally, in order to perform realistic simulations, real wave data obtained from the measuring buoy deployed in bimep have been used. The sea spectra derived from the hourly measurements for the years 2009 to 2010 were available [9]. Data from March 2009 (Fig.3) have been selected as a basis for the generation of the time series used in the following simulation, and an energetic sea condition at the bimep site was considered. Thus, the sea state reference parameters are: significant wave height H_s = 3.5 m and energy period T_e =12.9 s.

IV. Control Strategy

Control issues related to the considered system present a twofold nature. On one hand they pertain to the control of the single WECs, which is related to the goal of maximizing the power extraction from the waves. On the other hand they refer to the control that must be performed on the grid side

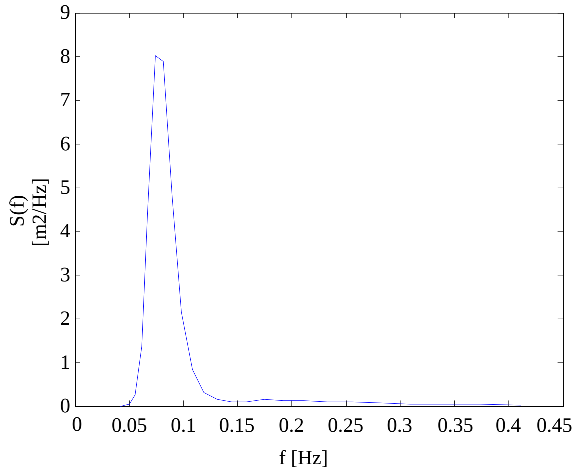

Fig.3 Selected reference sea spectrum for the bimep site

and potentially coordinated at farm level, in order to mitigate the impact of the Wave Farm connection to the PCC, in terms of voltage drop, reactive consumption etc.

If the WECs are equipped with a fully controlled bi-directional converter, (case: SG) both the WECs control and the grid side control can be performed independently, as explained in the following.

A. WEC Control Strategy

As regards control strategies applied to the single WEC, several different options are considered in the following.

The first one is to apply a traditional passive loading [10] to the point absorber, with a constant control parameter, so that the force exerted by the PTO is always proportional to the actual velocity of the point absorber according to the same control coefficient, irrespective of the incoming waves. According to the hydrodynamic analysis performed in the reference sea state, the peak power extracted from the sea with a constant control parameter equal to R = 248076 Kg/s, is 1446 kW, providing an average power extraction of 116.21 kW.

The second considered control strategy is derived from the passive loading, but it behaves as an equivalent saturation control [11], so that the control coefficient is conveniently reduced compared to the aforementioned value, whenever the instantaneous power is reaching an established power limit.

TABLE II
Main Parameters of the BIMEP Installation

BIMEP parameter	Unit of measur	Value
Installed power	[MW]	20
Approx. surface	[km]	4*2
Number of berths	-	4
Length of subsea cables:		
berth 1	[km]	3.386
berth 2	[km]	3.678
berth 3	[km]	4.994
berth 4	[km]	5.933
Nominal voltage at the PCC	[kV]	132
Water depth	[m]	50-90
Closest point to the grid	[m]	750

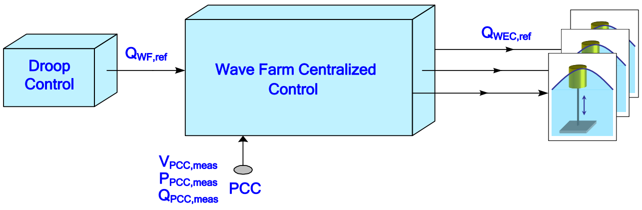

Fig.4. Scheme of the centralized (coordinated) control of the wave farm

The effect is that of exactly limiting the peak power into the system, thus allowing a reduced rating of the PTO. In the following, the limit of the power saturation has been set to 500 kW.

The third control strategy modifies the previous one by introducing a "WEC reactive control component" (here set to X = 65841 N/m), meaning that the torque/force profile applied by the generator has sometimes opposite sign with respect to the velocity waveform. This results in a negative instantaneous power in the system in some instants of the period, but potentially allows, on average, a higher power extraction from the waves, as shown in [12]. The instantaneous power saturation is still applied.

B. Grid Side Control

The impact of the wave farm on the local power system is strongly affected by the grid side control that the WECs perform, if any.

On this respect three possible cases have been evaluated.

If SC generators are considered, no control can be performed on the grid side. This means that the active power injected into the grid directly depends on the power extraction from the waves, while the reactive power exchange is mostly affected by the magnetization requirements of the generators and by the reactive power on the cables and transformers of the bimep infrastructure, that are, in turn, affected by their loading factor.

If SG generators equipped with fully controlled power electronics interfaces are considered a higher flexibility can be reached. One of the options considered in the following is to control the WECs on the grid side so that they inject power into the grid with an unity power factor (PF=1) at the point of connection of each WEC.

The second option is to apply a voltage control at the WECs connection point, so that the local voltage is kept constant to 1 p.u.

C. Coordinated Control of the Wave Farm

Both WEC control strategy and grid side control represent a "localized" form of control, based on local needs and measures. For a better management of the whole wave farm, however, a system level approach can be also implemented. It represents a centralized control (Fig. 4), whose goal it is, for instance, to increase the voltage level or the power factor at the PCC through a cooperative action of all the WECs. This requires a remote and coordinated control applied to the local WEC grid controllers. It must take into account the actual capability of the equipment and it requires real time communication and duty-sharing among involved devices.

V. Simulation Results

As regards the simulation tests, at first the hydrodynamic model of the single WEC was developed in Matlab Simulink®, through the implementation of the Cummins equation in (1). This allows the preliminary evaluation of the power extraction from the WECs. Subsequently, in order to analyse the issues related to the grid connection of the wave farm, such model has been integrated into a detailed model of the bimep, developed with the specific electric simulation tool DIgSILENT PowerFactory [13].

A. Steady-state analyses

The first set of simulations considers the wave farm working under its nominal conditions and it is used to perform a power flow analysis of the system.

In this case the attention is focused on the impact of the grid side control strategy from the WECs to the PCC.

It is worth noting, however, that the application of a control

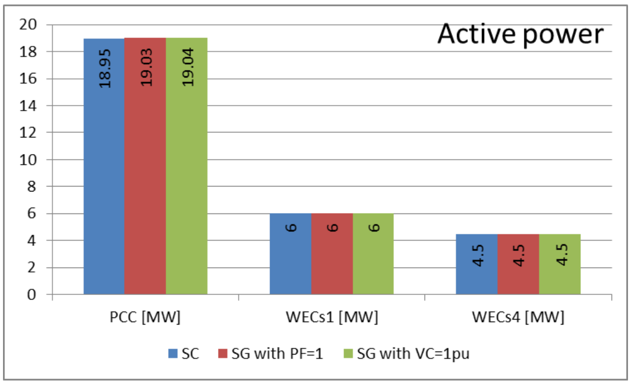

Fig.5. Active power exchange at different grid sections, comparing the cases of no grid side control, localized control to have PF=1 at WEC sections and localized control to have voltage=1 p.u. at WEC sections.

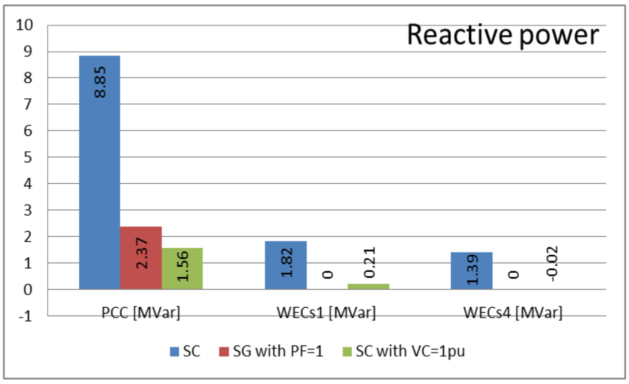

Fig.6. Reactive power exchange at different grid sections, comparing the cases of no grid side control, localized control to have PF=1 at WEC sections and localized control to have voltage=1 p.u. at WEC sections

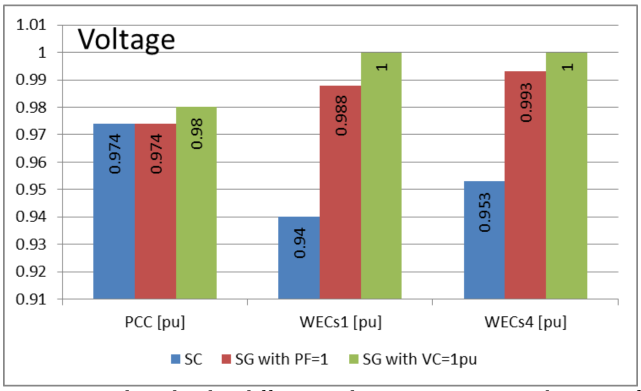

Fig.7. Voltage level at different grid sections, comparing the cases of no grid side control, localized control to have PF=1 at WEC sections and localized control to have voltage=1 p.u. at WEC sections.

applying an equivalent saturation (with or without a reactive component), modifies the number of connected WECs that are required to reach the wave farm nominal power.

In the passive loading case (no saturation), 4 WECs are connected to the transformer of the first bench of bimep and 3 WECs to each of the transformers in the other benches.
If a power saturation is present, the number of connected WECs is: 12 on the first bench and 9 in each of the others.

The active power exchange at the PCC and at the transformers of WECs1 and WECs4 (where the number indicates the bench to which the WECs are connected) are calculated and compared for the three cases mentioned in IV.B and they are reported in Fig.5. Corresponding comparisons have been made for reactive power exchange and voltage variations, which are reported in Figs 6 and 7, respectively. As regards active power, each WEC connected to both bench 1 and bench 4 produces the same active power, as requested under nominal conditions. However the total active power at the PCC is decreased due to the power losses in the infrastructure.

The main differences between the three grid control strategies can be better appreciated considering the reactive power exchange.

As expected, the SC is the worst case, due to the required magnetization of the machines. This results in a lower efficiency of the power conversion (97.2%) evaluated at the

TABLE III
TOTAL LOSSES (AT THE PCC)

Grid Side Control	Type of power	No load losses	Load losses	Total losses
SC	P [MW]	0.01	0.54	0.55
	Q [MVar]	-0.2	3.07	2.87
SG with PF=1	P [MW]	0.01	0.46	0.47
	Q [MVar]	-0.21	2.58	2.37
SG with VC =1pu	P [MW]	0.01	0.45	0.46
	Q [MVar]	-0.21	2.53	2.31

PCC, compared to the case of SG with reactive power and voltage control, whose efficiencies are of 97.5% and 97.7% respectively.

The power losses experienced in the above mentioned cases are reported in detail in Tab. III, where P and Q indicate active and reactive power, respectively.

From the graph of the voltage drop at the PCC the worse performance of the of the SC case can be also understood, which results in a much higher voltage drop both at the PCC and at the WECs connection points (up to 0.94 p.u.). It can also be seen that the PF=1 control strategy actually guarantees a unity power factor at WECs connection points, while producing a reduced voltage drop (0.98 p.u.) at the PCC. By controlling the power factor at WECs level (PF=1), intermediate performances in terms of voltage drop at the PCC are obtained compared to the previous cases.

B. Dynamic analyses

Dynamic simulations have been performed, with the aim of evaluating the effect of the extreme variability of the wave energy source and of the impact of the different WEC control strategies described in IV.A when it comes to the grid connection of the Wave Farm. As regards the grid side control, the two cases of SC and SG with unity power factor at the WEC connection point are analysed.

Such time domain analyses focus on the performance at the PCC and they allow the determination of the local voltage drop, the average, maximum and minimum active and reactive power exchange. The ratio between peak and average instantaneous power is also calculated as an indicator of the required rating of the WECs Power Take-Off.

TABLE IV
RESULTS OF THE DYNAMIC ANALYSIS

	SC with constant passive loading	SC with equivalent saturation control	SC with WEC re-active (sat.) control	SG with constant passive loading	SG with equivalent saturation control	SG with WEC re-active (sat.) control
ΔV_{max} at PCC [pu]	-0.012	-0.012	-0.012	0.001	0.001	0.001
ΔV_{min} at PCC [pu]	-0.024	-0.024	-0.024	-0.008	-0.008	-0.008
P_{max} at PCC [MW]	17.853	17.927	17.983	19.179	19.183	19.183
P_{mean} at PCC [MW]	1.469	4.067	4.582	1.552	4.222	4.853
P_{min} at PCC [MW]	0	0	-2.903	0	0	-2.828
P_{max}/P_{mean} at PCC	12.156	4.408	3.925	12.362	4.544	3.953
Q_{max} at PCC [MVar]	-4.573	-4.573	-4.507	0.218	0.218	0.218
Q_{min} at PCC [MVar]	-8.361	-8.390	-8.404	-2.300	-2.302	-2.302

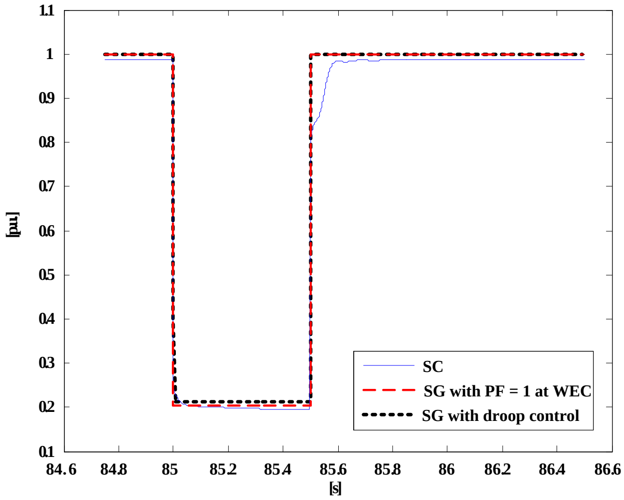

Fig.8 Normalized voltage profile at the PCC, when a 80% voltage dip occurs at the PCC

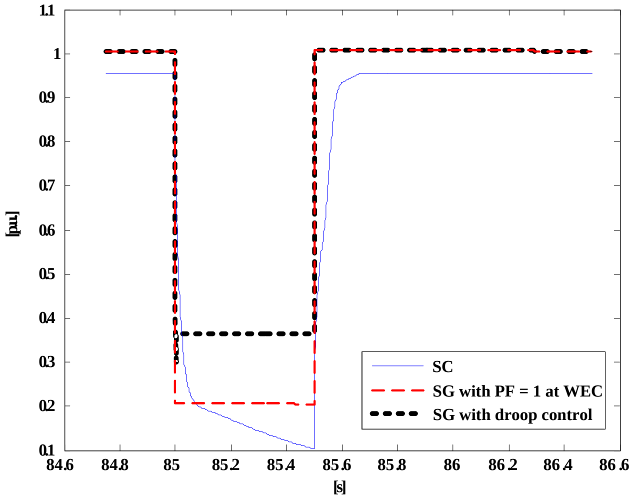

Fig.9 Normalized voltage profile at WEC1 point of connection, when a 80% voltage dip occurs at the PCC

The results are reported in Tab. IV. It can be noted that the implementation of the equivalent saturation consistently increases the average power extracted from the farm, for the same total installed power, even more in the case of a WEC reactive control component included.

This is related to the increased number of deployed WECs and to the specific control strategy, assuming equivalent performance for PTOs of different ratings.

Saturation adoption also contributes to the reduction of the peak to average power ratio, by imposing a constraint on the instantaneous peak power in each WEC. From the presented data it can be also noted how the introduction of a WEC reactive control component implies a reversed active power flow, in some instants, requiring the electrical machines to operate also as motors and not only as generators.

As expected, the SC cases are much more critical implying a reactive power exchange at the PCC, that can be more than 3.5 times that of the SG cases.

Again, voltage variations at the PCC is much higher in the case of SC generators, although still well below the limits imposed by the Proposal of Operating Procedure [14], issued by the Spanish National Energy Commission (CNE). This proposal accepts voltage variations of ± 7% of the nominal voltage level.

- *Faults analyses*

Due to the lack of a specific legislation for wave energy applications, reference is made to the requirements imposed to wind installations in case of faults [15], due to the similar characteristics and arising problems.

Thus, in order to analyse the system behaviour under faults conditions and evaluating its Fault Ride Through capability as related to the applied grid control strategy, an 80% voltage dip has been applied to the PCC.

Three different cases are here analysed and compared:

- SC generator (without grid side control).
- SG with local control to have PF=1 at WECs connection point, as described in IV.B.
- SG with coordinated control of WEC controlling the reactive power exchanged at the PCC depending on the voltage variation (droop control) [16].

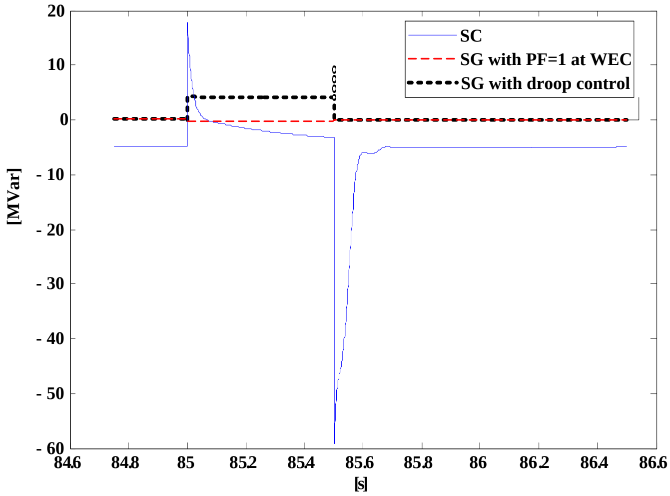

Fig.10 Reactive power exchange at the PCC, when a 80% voltage dip occurs at the PCC

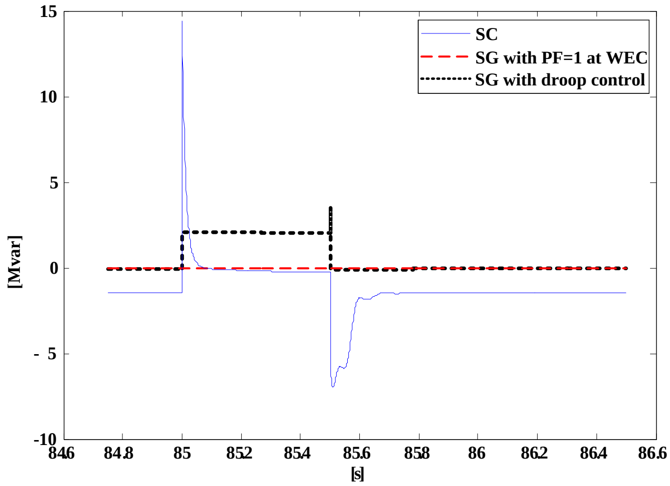

Fig.11 Reactive power exchange at the WEC1 point of connection, when a 80% voltage dip occurs at the PCC

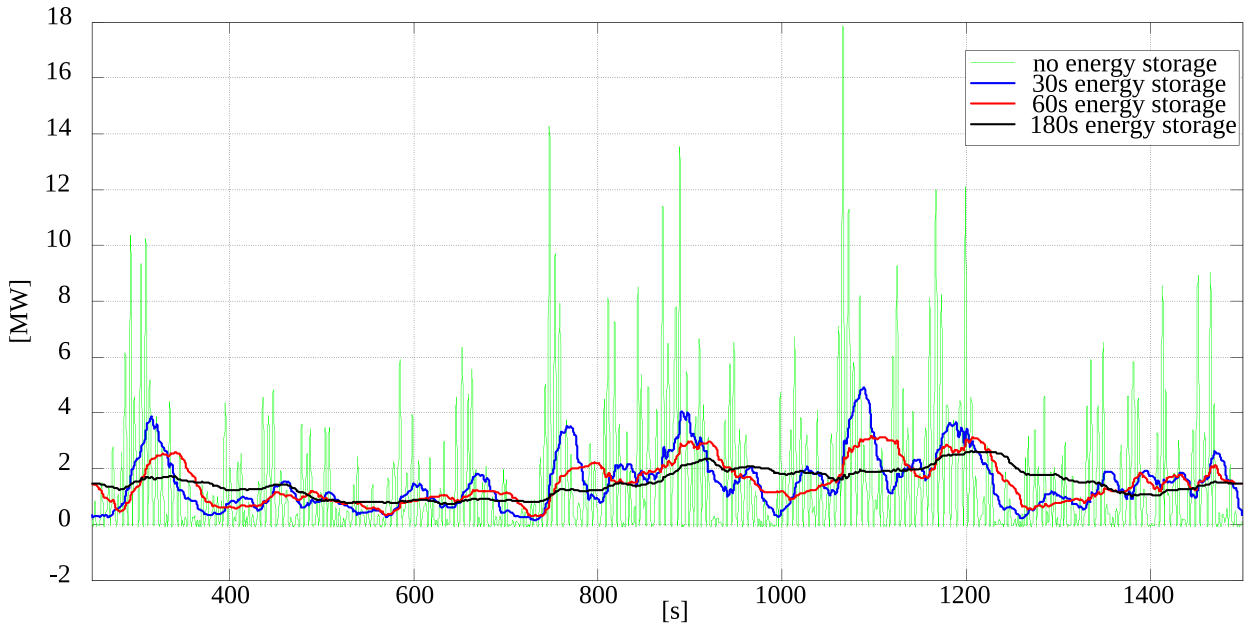

Fig.12. Instantaneous power at the PCC, with and without inherent energy storage

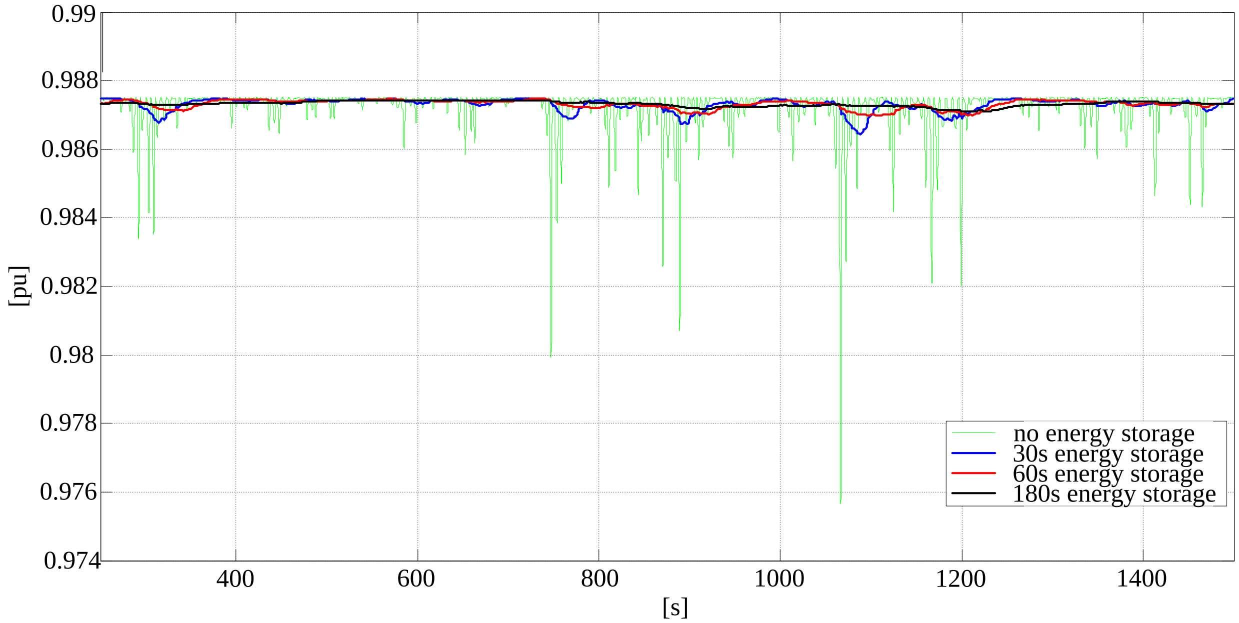

Fig.13 Voltage level at the PCC, with and without inherent energy storage

Normalized voltage profiles for all the considered cases are reported in Fig. 8 for the PCC and in Fig. 9 for the connection point of WEC1. It can be noted that, when no grid side control is possible (SC case) the fault behaviour is completely determined by the active power generated. Thus the SC case is the worst one, producing a higher voltage drop at both sections and longer recovery time. At the PCC, where the voltage drop occurs, the local control and coordinated control can only slightly increase the voltage with respect to the SC uncontrolled case. However the positive action of local and coordinated droop control can be better understood by considering the voltage drop at WEC1 connection point. When attempting to keep the unity power factor at WECs connection point, local control leads to increase the local voltage of 10% and if the coordinated control is applied, the voltage drop can be reduced of 27% compared to the SC case. Such action of support to the local grid is performed by the different controllers by changing the reactive exchange at the WEC sections.

This can be understood by considering the reactive power exchange at the PCC and at WEC1 connection points, which are plotted in Fig. 10 and Fig. 11, respectively. It can be noted that in the case of WECs based on SC generators there is a first uncontrolled reactive power injection for 120 ms; after that the machine starts consuming reactive power making the voltage fall down. Once the fault is cleared the figures 10 and 11 show a peak in the reactive power consumption which makes the voltage recovery to take longer than in the case of

TABLE V
ANALYSIS OF INHERENT ENERGY STORAGE EFFECT (SQUIRREL CAGE CASE, SC)

	SC without inherent storage	SC with 30s smoothing storage	SC with 60s smoothing storage	SC with 180s smoothing storage
ΔV_{max} at PCC [pu]	-0.0125	-0.0125	-0.0125	-0.0126
ΔV_{min} at PCC [pu]	-0.0243	-0.0136	-0.0130	-0.0129
P_{max} at PCC [MW]	17.85	4.90	3.1662	2.614
P_{mean} at PCC [MW]	1.469	1.485	1.4864	1.4878
P_{min} at PCC [MW]	0	0.135	0.2939	0.7356
P_{max}/P_{mean} at PCC	12.156	3.30	1.4864	1.757
Q_{max} at PCC [MVar]	-4.573	-4.582	-4.5865	-4.6012
Q_{min} at PCC [MVar]	-8.361	-4.93	-4.7512	-4.7068

SG generators.

The differences between the reactive power at PCC and at the WECs are due to the reactive exchange of cables and transformers.

In the case of SG generators, the results show that when a droop control is used the WECs inject reactive power into the grid. This reactive power injection at the PCC results in a voltage increase compared to other cases.

C. Analysis of Energy Storage Effect

As part of the dynamic simulations, the effect of inherent energy storage into the wave farm has been analysed. The case of WECs all equipped with SC generator has been selected as most meaningful for this analysis and the main goal is to compare the case of no energy storage to those of energy storage corresponding to a power smoothing over a time scale of 30 s, 60 s and 180 s. In Fig. 12 corresponding instantaneous power profiles are reported, which are derived by using a moving average filter on the original (no storage) power profile, as in [4]. They clearly show the increasing storage effect on the instantaneous power which is injected into the PCC. From Fig. 13 the voltage drop at PCC can be seen, too. It can be noted as the maximum voltage drop exceeds 2.4% when no storage is included, while it's always lower than 1.4% with the analysed storage provisions. Detailed analyses on the obtained performance at the PCC have been performed and corresponding results are shown in Tab V. It can be observed that, as expected, storage provisions do not affect the average power extraction form the farm, but they strongly reduce the higher and lower peaks of the instantaneous power, thus also reducing the peak to average power ratio. Also in terms of reactive power much smoothing is achieved. Finally, comparing the performance in terms of both power smoothing and voltage drop in the case of 180 s to that of 60 s, the limited improvement observed in the 180 s solution is reached at the expense of a much larger storage system, which would not be thus recommended. The discussion about the specific type and size of the energy storage equipment is outside the scope of this paper. It is however important to highlight a substantial difference in the approaches underlying the analyses of the SC case to evaluate the effect of different control techniques (in Tab IV) and of energy storage (in Tab V). Independently of the specific results, application of saturated control strategies to an increased number of point absorbers would potentially allow a reduction of the rating on the PTO of each WEC, while improving the active power extraction and leaving almost unaffected the reactive power consumption. Adoption of storage provisions actually reduces the active and reactive power oscillation, but, assuming to leave the power capture from the WECs unaffected, it does not reduce the sizing of the electrical machines and power electronics equipment, being aimed only to the mitigation of the farm connection to the local power system.

VI. CONCLUSIONS

The goal of this paper is to analyze the effect of the grid integration of a 20 MW wave farm into a 400 MVA power system. In order to develop realistic simulations the wave farm infrastructure has been modeled as the bimep (Biscay Marine Energy Platform) and real wave data from the corresponding location have been used as a basis for the study. The analyses confirmed the higher criticality of a direct driven connection of induction generators, compared to all the solutions employing fully-controllable power electronics converters.

It has also been proved that the impact of the wave intermittency on the power system can be mitigated by applying suitable control strategies both on the WEC and on the grid side. More specifically by saturation and reactive control component on the WEC side the active power absorption can be improved, while potentially reducing the PTO size on each WEC. On the other hand it has been also shown how a properly rated energy storage can reduce the oscillation of active and reactive power, without affecting the average power extraction.

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