Development of a wave-to-wire model to calculate flicker caused by wave energy converters and study power quality

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Abstract—**Power quality is an important issue for wave energy developers, as the wave energy converters output power profile can present fluctuations in the range of seconds, due to the oscillatory nature of the ocean waves. The impact of these devices on the electric grid hence needs to be investigated for wave farms to be connected to the grid.**

In order to emulate an operating direct drive wave energy converter, study power quality improvement and test different control strategies, a wave-to-wire model has been developed using Matlab-Simulink SimpowerSystems toolbox. The case study addressed in this paper is the SEAREV wave energy converter. Simulation results in terms of power quality are presented in the last section.

Index Terms—**Energy management, Voltage regulation, Wave energy**

I. Introduction

Although wave energy presents a significant energetic potential and numerous devices have been developed, it still remains nearly unexploited.

One of the important issues encountered for wave energy converters development is the integration of the devices into the electric grid. Indeed, the output power profile presents a lot of fluctuations due to the oscillatory nature of the resource. As an example, figure 1 shows an output power profile from a wave energy converter, namely the SEAREV, that was developed at Ecole Centrale de Nantes [1]. For direct drive wave energy converters for which the mechanic to electric energy conversion is directly done through a generator (no use of hydraulic part, for example), the electric power is not smoothed at all and presents fluctuations with a frequency of the same order of magnitude than the waves frequency. These fluctuations can lead to disruption into the electric grid.

A single wave energy converter would not influence the frequency or voltage of a large strong grid, but it can create local effects in the distribution grid, such as harmonics, fast voltage fluctuations, flicker or performance fails during grid faults [2]. Furthermore, close to the shore the grid is often considered as a weak grid, which implies that the voltage variations would be larger.

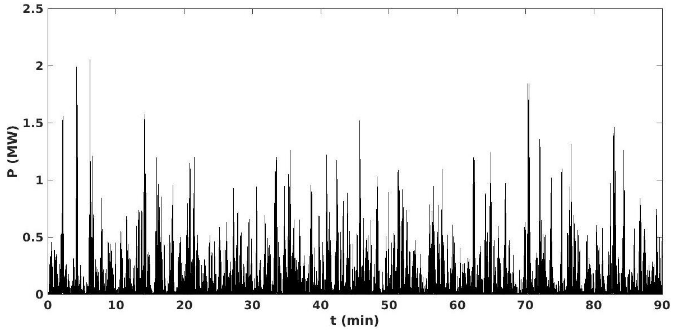

Fig. 1. Power output profile for the SEAREV

A few studies about grid integration of wave energy converters have been published, analyzing power quality especially in terms of flicker.

In [3], flicker has been examined for a farm of oscillating water columns operated under constant speed control for different grid strengths. Data were coming from the deployment of a floating quarter-scale oscillating water column (OWC) in Galway Bay (Ireland) from March to May 2011. The device was connected to an embedded isolated grid composed of a battery, a load to disperse the excess of energy that could not be loaded into the battery and a back-up generator. In [4], different generator control strategies have been tested and the harmonics are also studied, for the same OWC. Data from tank and laboratory testing were used as inputs.

In [5], the aggregation of wave farms is studied in order to simplify wave power systems dynamic models. The conclusion of this paper is that aggregated models can be used for load flow and short term transient stability studies, but it is not sufficient for long term steady-state simulations.

[6] determines tools for early stage flicker assessment and calculates the expected flicker for a Wavebob point absorber.

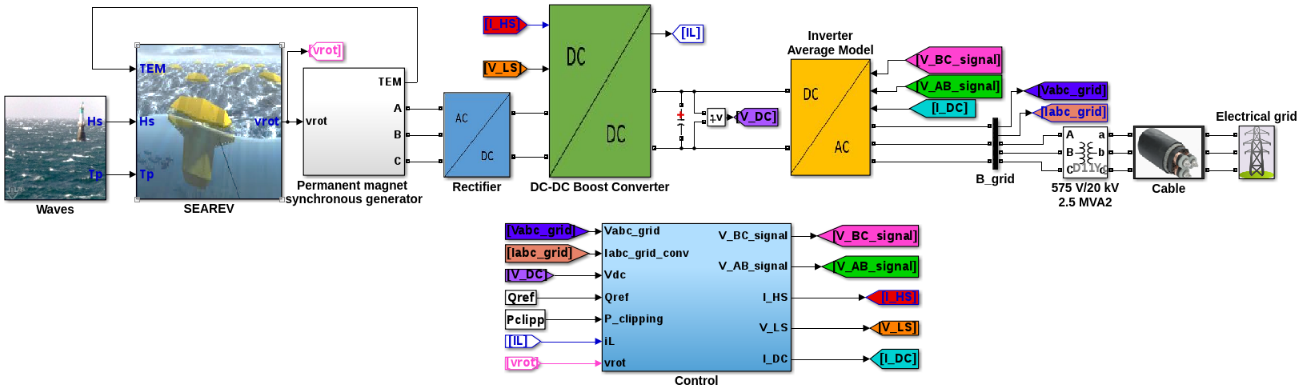

Fig. 2. Simulink scheme of the wave-to-wire model

Three flicker assessment methods (basic flicker assessment, flicker assessment chart and standard flickermeter measures) are compared.

In their study of flicker and voltage levels for an array of point absorbers [7], Tedeschi and Santos-Mugica insist on the fact that it is important to model the whole system, a fragmented approach of the system can lead to economically infeasible solutions.

Considering these previous studies, a model describing the system from the waves to the electric grid (wave-to-wire model), including a flickermeter, has been developed in order to assess power quality and especially flicker caused by a wave energy converter on a local grid and to study its behavior in different conditions and under different control strategies. This model is presented in the first section. Then, the power quality indicators chosen for this study are introduced and simulation results are presented.

II. A WAVE-TO-WIRE MODEL AND ITS ASSOCIATED CONTROL STRATEGIES

The wave-to-wire model is a model representing the wave energy system, from the ocean waves to the electric grid. It has been developed using Matlab-Simulink and the toolboxes Simscape and SimpowerSystems for electronic devices. Figure 2 shows an illustration of the model's simulink scheme.

A. Absorption and generation stages

The wave energy converter used in this study is the SEAREV: a heavy horizontal axis wheel whose center of gravity is off-centered, is completely enclosed in a floating body and behaves like a pendulum with the action of the ocean waves. The rotational motion of the wheel activates a permanent magnets synchronous generator [8]. The generator exerts a damping force on the WEC so the electromagnetic torque created in the generator is also taken into account. Figure 3 gives an illustration of the SEAREV.

The hydromechanical model used for the WEC is a time domain state equation model [10]. It allows, for a given wave profile (or sea-state), the obtaining of a movement profile for the SEAREV and a mechanical power profile. The sea-state is characterized by a significant wave height, Hs (defined as the mean height of the highest third of the waves) and a peak period, Tp defined as the peak period of the energy spectrum [11].

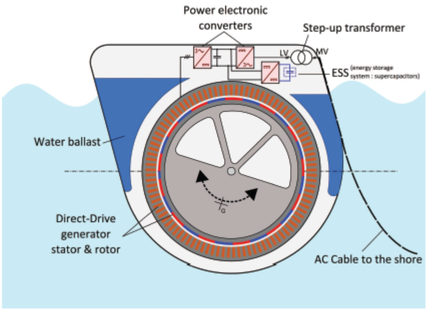

Fig. 3. scheme of the SEAREV wave energy converter (all electric version) [9]

The rotational velocity extracted from the hydrodynamic model is fed into a generator model from the Simulink SimPowerSystems toolbox. Its parameters have been determined according to the optimization realized by J. Aubry in [9]. The feedback electromagnetic torque produced by the generator and applied on the wave energy converter is an input of the hydromechanical model of the SEAREV, together with waves elevation.

B. Conversion stage

The SEAREV is followed by a back-to-back converter (figure 2). The AC voltage generated by the synchronous machine is converted into DC voltage through a diode rectifier. A boost converter is added on the DC bus in order to control the electric machine output. The DC bus can be used to insert an energy storage system (ESS) for power quality enhancement, for example. A PWM inverter is then used for the DC/AC conversion.

The DC/DC converter and the DC/AC converter have been modeled using average-value models (or medium fidelity

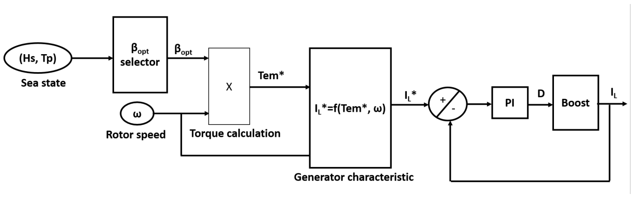

Fig. 4. Torque regulation scheme [14]

models), in order to limit calculation time and effort to the minimum during the simulations of power electronics systems. Average-value models represent the average behavior of the system during two switching events [12]. Average models are slightly less accurate than switching models for steady-state and dynamic performances modeling but they are five times more efficient [13]. Non linear elements are replaced by voltage and current controlled sources, representing the relations between average currents and voltages. Signals for these controlled source are calculated as specified in [14].

Three phase transmission lines are represented with a PI sections.

The electrical grid is modeled with a three-phase voltage source in series with an impedance, that can be changed to test different grid strength.

C. Control strategies

1) Torque regulation: : The electromagnetic torque generated by the synchronous machine is controlled by the boost converter in order to extract the optimal amount of energy for each state encountered by the wave energy converter. The optimal electromagnetic torque for each sea state is calculated using equation (1), where ω is the pendulum rotational velocity (rad/s) and β_{opt} is the viscous damping coefficient (Nm/(rad.s^{-1})). This last coefficient has been determined by maximization of the mechanical mean power using the SEAREV hydromechanical model. The control output is the boost converter duty cycle.

$$C_{ref} = \beta_{opt} * \omega(t) \tag{1}$$

The control scheme is represented in figure 4.

A power clipping is also introduced here (algorithm in figure 5) in order to decrease the output peak power and thus the sizing of the power electronics, whitout loosing too much mean power [9].

2) DC link voltage and reactive power regulation: : For a grid connected inverter, the DC bus voltage can be exposed to variations due to the fluctuations of the mean power going through the DC bus and to oscillations of the instantaneous power because of a fault on the grid.

The DC bus voltage and the reactive power then have to be controlled through the PWM inverter. A Clark-Park transformation is used: in the dq frame, the d-axis current controls the DC-link voltage while the q-axis current controls the grid reactive power. Figure 6 presents the curent control loop.

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if $P_{elec}(t) < P_{clipping}$ then
    $T_{ref}(t) = \beta_{opt} * \omega(t)$
else if $P_{elec}(t) \geq P_{clipping}$ then
    $T_{ref}(t) = \frac{P_{clipping}}{\omega(t)}$
end if
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Fig. 5. Power clipping

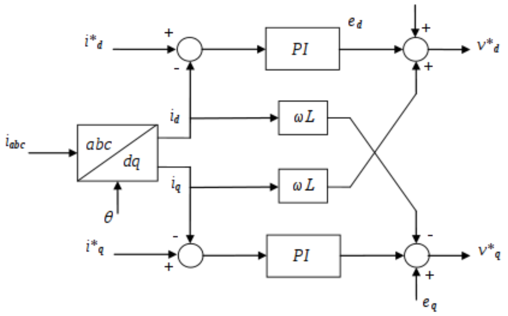

Fig. 6. Grid converter current control loop

The outputs of the controller are the grid side inverter voltages commands Vd and Vq, which are converted into an abc voltage through an inverse Park transformation. The angular position is given by a Phase Locked Loop (PLL) which synchronizes the three-phase sinusoidal signal.

III. Power quality

Grid codes are defined by transmission system operators (TSO). They are currently being adapted in order to take into account the new types of energy converters. Nowadays, wave energy is not yet integrated into these grid codes but in order to assess power quality, one can take inspiration from requirements for wind energy.

A. Flicker

Flicker is the perception of very fast changes in the light intensity, experienced by the human eyes. They are caused by rapid and regular changes of the light source's electrical supply's voltage level [15]. Because of the link with human perception, flicker is not easy to determine and standards have been created in order to unify its calculation. A flickermeter is added to the wave-to-wire model to measure flicker at the point of common coupling (PCC). Flicker is characterized by short term severity, Pst (10 min) and long term severity, Plt (120 min).

The flickermeter design is specified in the IEC 610000-4-15 standard [16]. It consists of five blocks: Block 1 changes the input voltage time series in per-unit time series, block 2 simulates the response in light intensity of an incandescent light bulb to voltage fluctuations, blocks 3 to 4 are for the simulation of the response of a human eye to light intensity variations and block 5 performs a statistical analysis of flicker perceptibility over 10 min (figure 7).

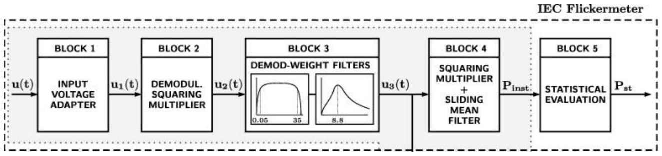

Fig. 7. Block diagram of IEC flickermeter

Table I specify the limits for maximum allowed short term flicker severity as enforced by different grid operators and recommended by the IEC 61000-3-7 standard.

TABLE I
SHORT TERM FLICKER SEVERITY LIMITS

Region/code	Limit
IEC standard 61000-3-7	0.35 (individual contribution)
France - distribution code	0.35 (individual contribution)
Ireland - distribution code	0.35 (individual contribution)
Great Britain - Grid code	1.0 (total level at the PCC)

B. Voltage level

In order to respect grid code requirements, wave farm voltage levels must be maintained between 0.95 pu and 1.05 pu. Reactive power compensation allows to keep the voltages inside this range.

C. short circuit faults

The wave farm must be able to perform low voltage ride through (LVRT): it must remain connected to the grid over specified ranges of voltage drops. Figure 8 [17] gives an example of LVRT curves for different codes. If the voltage sag is above the curve, the wave energy converter must stay connected.

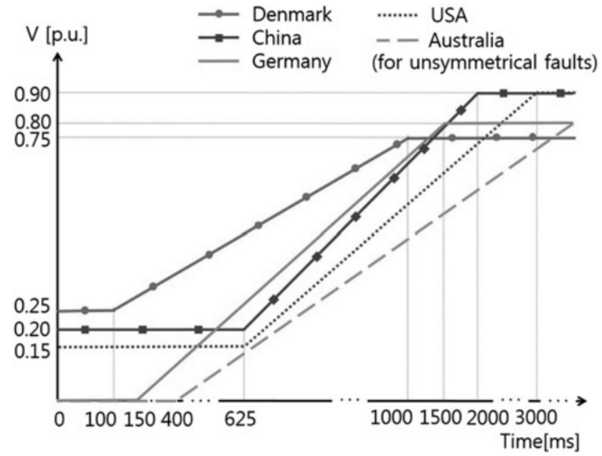

Fig. 8. Low voltage ride through curves for different countries in terms of voltage magnitude and duration [17]

D. Power fluctuations

Grid codes also define requirements about power gradient rates $\frac{dP}{dt}_{limite}$, in MW/min. This gradient is averaged over 1 minute or 10 minutes. Table II presents the constraints imposed by different TSO in Europe [18], [19] [20].

TABLE II
REQUIREMENTS ON POWER GRADIENT IMPOSED BY DIFFERENT TSO

TSO	**Power gradient** $\frac{dP}{dt}_{limit}$
E.On (Germany)	10% Pnom /min
Eltra (Denmark)	10% Pnom/min
Mexico	1-5% Pnom/min
Entso.E (Nordic Grid Code Sweden, Denmark, Finland and Norway)	10% Pnom /min

Power fluctuations can impact other grid-connected equipments and in particular conventional generators' stability (rotor angle stability, referring to the angle between the rotor and the stator magnetic fields) [21].

IV. SIMULATION RESULTS

In this section, the power quality from a SEAREV wave energy converter is investigated. Flicker, voltage levels and LVRT are analyzed for different sea-state (Hs, Tp) and different electric grid strength. Power quality was assessed for the five following values of the grid impedance angle ($\Psi_k = arctan(\frac{X}{R})$), as recommended by by IEC standard 61400-21 [22] for wind turbines: 30°, 50°, 70°and 85°. An intermediate value has been simulated for an impedance angle of 82°(X/R ratio=7).
Each simulation represents 10 minutes.

A. Flicker measurement

Short term flicker (P_{st}) has been calculated at the point of common coupling (PCC), for a grid with a 3-phase short-circuit level at base voltage(20kV) of 500MVA and for different grid impedance angles. The ses-state for thses simulations was (H_s, T_p)=(3m, 6s). For each simulation the SEAREV rotational velocity is the same (represented as curve (H_s, T_p)=(3m, 6s) in figure 9).

Maximum P_{st} measured during the 600s are presented in table III.

TABLE III
FLICKER MEASUREMENTS AT THE PCC FOR DIFFERENT GRIDS

Grid impedance angle	Flicker calculated (P_{st})
30°	0.57
50°	0.29
70°	0.14
82°	0.07
85°	0.06

It can be noticed that for the weaker grid, the P_{st} coefficient for one SEAREV exceeds the limit defined by the most restrictive grid codes.

P_{st} has also been calculated for different sea-states with an impedance angle of 50, as presented in table IV. (H_s,

T_p)=(3m, 9s) is considered as the reference sea-state and (H_s, T_p)=(1m, 11s) is the most frequent sea-state at the SEMREV test site, a French test site operated by the LHEEA laboratory.

TABLE IV
FLICKER MEASUREMENTS AT THE PCC FOR DIFFERENT SEA-STATES

Sea-state (H_s, T_p)	Flicker calculated (P_{st})
(3m, 6s)	0.29
(3m, 9s)	0.07
(1m, 11s)	0.06

Figure 9 shows the rotational velocity profile for each sea-state. It can be noticed that the higher the velocity is, the higher the flicker coefficient P_{st} seems to be, especially when the velocity reaches values superior to 1 rad/s.

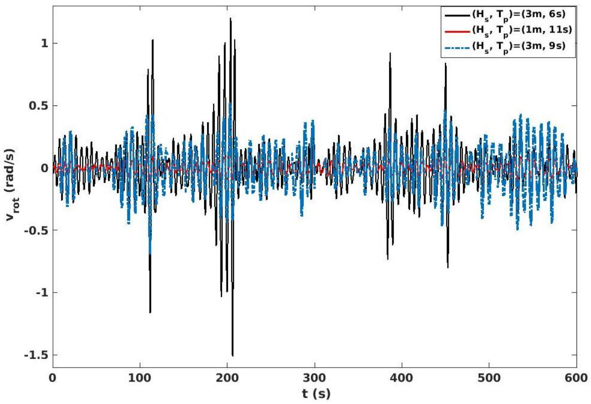

Fig. 9. SEAREV velocity during the simulations

B. Voltage fluctuations

Figure 10 shows the positive envelope of a voltage profile at the point of common coupling. It can be observed that there is very little voltage deviation. The minimum voltage is 0.998 and the maximum 1.014, which fits in the range imposed by TSOs. This low deviation is due to the voltage regulation imposed by the inverter.

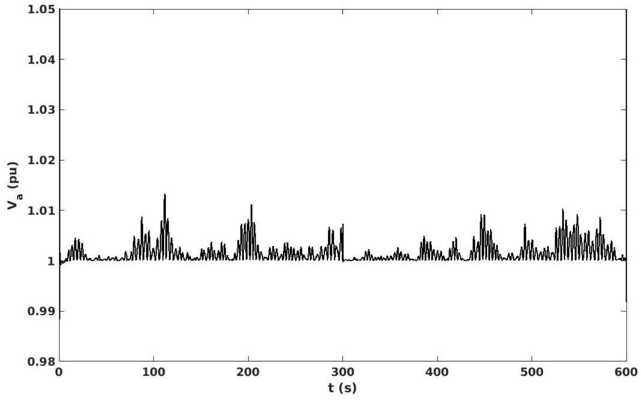

Fig. 10. Envelope of the voltage curve for phase A at the PCC

C. Low voltage ride through

The response of the wave energy converter to a short circuit fault occurring at t=10s during 100ms in terms of voltage at the point of connexion is shown in figure 11. It appears that the generator stays connected during the fault as it is required by the TSO (example of the German curve in figure 8).

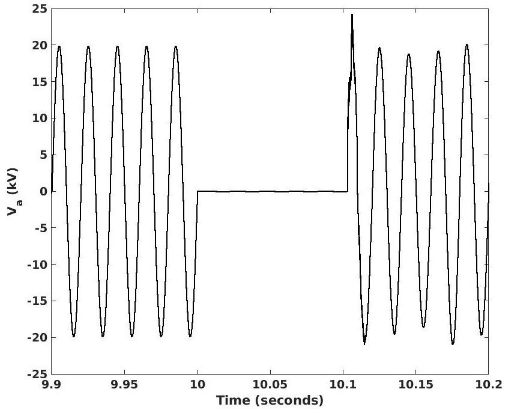

Fig. 11. Voltage (phase to ground) for phase A at the PCC during a fault

D. Power fluctuations

The electrical power profile obtained at the PCC for a sea state (H_s, T_p)=(3m, 6s) and a grid impedance angle of 50 degrees is illustrated in figure 12, together with the mechanical power profile extracted from the permanent magnets generator. It can be seen that it presents a lot of fluctuations, similar to the mechanical power profile extracted from the generator.

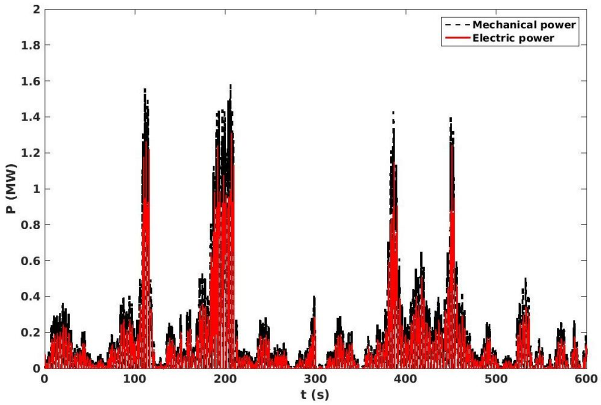

Fig. 12. Electrical power at the point of connexion and mechanical power output from the generator for a sea-state (H_s, T_p)=(3m, 6s)

Considering these rapid power fluctuations, it can be concluded that considering ramp rates over a minute is not relevant for wave energy. Requirements more adapted to these types of fluctuations would need to be developed. The aggregation of devices in arrays allows a smoothing of the power [23] but it is not sufficient. In order to obtain an appropriate quality for the output power, the aggregation effect must be combined with an energy storage system.

Figure 13 presents the peak-to-average ratio for the same simulation as figure 12. This ratio can go up to 12, which is an important peak for the grid connected equipments to integrate.

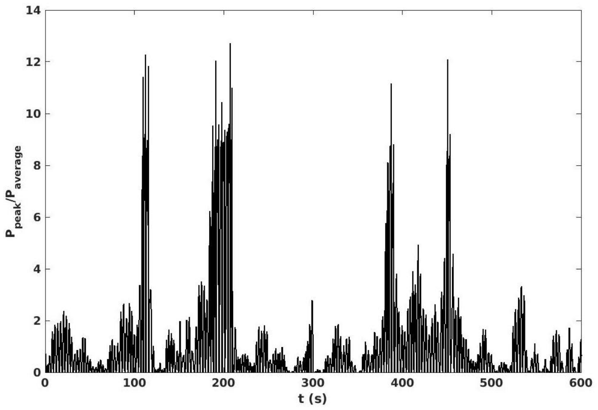

Fig. 13. Peak-to-average power ratio at the point of connexion for a sea-state (H_s, T_p)=(3m, 6s)

V. CONCLUSION

A wave-to-wire model has been developed in order to analyze power quality from wave energy converters and test control strategies. Using the SEAREV wave energy converter as a case study, simulations performed with this model show that, for weak grids, wave energy converters grid code requirements may not me respected. Furthermore, the power profile at the point of common coupling presents very fast fluctuations, that can not be estimated with ramp rates over a minute as expected by grid codes. This fluctuations can be smoothed with the help of energy storage systems, for example. Other grid code requirements, as harmonics for example, have not been investigated.

Furthermore, it has to be pointed out that wave energy converters would not be used as single devices but would be gathered in farms. Farm effects can be important, especially in term of power quality at the point of connection. It, among others, allows a first smoothing of the power profile.
The wave-to-wire model will then be used in order to investigate this farm effects. Moreover, energy storage systems and energy management strategies will be studied in order to improve wave farm power quality.

REFERENCES

[1] Cordonnier J.; Gorintin, F.; Cagny, A. D.; Clément, A. and Babarit, A., SEAREV: Case study of the development of a wave energy converter *Renewable Energy, Elsevier BV*, 2015, 80, 40-52

[2] Polinder H. and Scuotto M., ”Wave energy converters and their impact on power systems” *2005 International Conference on Future Power Systems*, 2005, 9 pp.-9

[3] Blavette A., O’Sullivan D. L., Alcorn R., Lewis T. W. and Egan M. G.; ”Impact of a Medium-Size Wave Farm on Grids of Different Strength Levels” *IEEE Transactions on Power Systems*, vol. 29, pp. 917-923, 2014

[4] Armstrong S. and Lewis A. W. ”Power Quality Analysis of a Wave Farm under Different Generator Control Strategies” in *Proceedings of the 11th European Wave and Tidal Energy Conference 6-11th Sept 2015, Nantes, France*, Sept. 2015

[5] S. Armstrong, D. Mollaghan, and R. Alcorn, Effect of wave farm aggregation on power system stability, in *2014 IEEE 5th Int. Symp. Power Electron. Distrib. Gener. Syst.*, pp. 16, Jun. 2014.

[6] F. Sharkey, K. Gaughan, E. Bannon, M. Conlon, and J. MacEnri, Resource-induced voltage flicker for wave energy converters assessment tools, *IET Renewable Power Generation*, vol. 7, no. 6, pp. 623630, Nov. 2013.

[7] Tedeschi E. and Santos-Mugica M., ”Modeling and Control of a Wave Energy Farm Including Energy Storage for Power Quality Enhancement: the Bimep Case Study”,*IEEE Transactions on Power Systems*, vol. 29, pp. 1489-1497, 2014

[8] Ruellan M., PhD. thesis Méthodologie de dimensionnement d’un système de récupération de l’énergie des vagues, *Ecole normale supérieure de Cachan*, 2007

[9] Aubry J., PhD. thesis ”Optimisation du dimensionnement d’une chane de conversion électrique directe incluant un système de lissage de production par supercondensateurs.Application au houlogénérateur SEAREV”, *Ecole normale supérieure de Cachan*, 2011

[10] Babarit, A.; Clement, A. H. and Gilloteaux, J.-C., ”Optimization and Time-Domain Simulation of the SEAREV Wave Energy Converter”, *24th International Conference on Offshore Mechanics and Arctic Engineering: Volume 2, ASME*, 2005

[11] Falnes J., *Ocean Waves and Oscillating Systems*, Cambridge University Press (CUP), 2002

[12] Middlebrook R. D. and Cuk S., ”A general unified approach to modelling switching-converter power stages”, *Power Electronics Specialists Conference, 1976 IEEE*, 1976, 18-34

[13] Peralta J., Saad H. and Dennetiere S., ”Dynamic performance of average-value models for multi-terminal VSC-HVDC systems” *2012 IEEE Power and Energy Society General Meeting, Institute of Electrical and Electronics Engineers (IEEE)*, 2012

[14] Clemot H., Dupriez-Robin F., Babarit A. and Tran Q. T., “A wave-to-wire chain modeling and command for a direct drive wave energy converter” *2017 Twelfth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, Apr. 2017., in press.

[15] Baggini A., ”Handbook of power quality” (John Wiley and Sons, 2008)

[16] *Electromagnetic Compatibility (EMC)Part 415: Testing and Measurement TechniquesFlickermeterFunctional and Design Specifications*, IEC 61000-4-15, 2010, TC/SC 77A, ed. 2.0.

[17] Park C.-H. and Jang G., ”Voltage quality assessment considering low voltage ride-through requirement for wind turbines”, *IET Generation, Transmission and Distribution*, vol. 10, no. 16, pp. 42054212, Dec. 2016.

[18] Ikni D., PhD thesis ”Production d énergie marine: Intégration de la production éolienne offshore dans un bouquet énergétique décentralisé” *Université du Havre*, 2014

[19] Kasem A. H., El-Saadany E. F., El-Tamaly H. H. and Wahab M. A. A., ”Ramp rate control and voltage regulation for grid directly connected wind turbines” *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, 2008, pp. 1-6

[20] De la Parra I., Marcos J., Garca M. and Marroyo L., ”Control strategies to use the minimum energy storage requirement for PV power ramp-rate control” *Solar Energy* vol. 111, pp. 332 - 343, 2015

[21] Blavette A., OSullivan D. L., Lewis A. W. and Egan M. G., Impact of a wave farm on its local grid: Voltage limits, flicker level and power fluctuations, *2012 Oceans - Yeosu Institute of Electrical and Electronics Engineers (IEEE)*, May 2012.

[22] *Wind Turbines Part 21: Measurement and Assessment of Power Quality Characteristics of Grid Connected Wind Turbines*,IEC 61400-21, 2008, TC/SC 88, ed. 2.0

[23] Tissandier J., Babarit A. and Clément A., ”Study of the smoothing effect on the power production in an array of SEAREV wave energy converters”, *18th International Offshore and Polar Engineering, International Society of Offshore and Polar Engineers*, pp. 374-381, 2008