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Control of Hydrodynamic Parameters of Wave Energy Point Absorbers using Linear Generators and VSC-based Power Converters Connected to the Grid

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Abstract. The use of linear generators in offshore wave energy plants is one of the most promising technologies for such facilities. The first power converter stage consists of rectifying the electricity generated by the linear generator. Lower cost and easy of assembly are the main diode rectifier advantages, but these devices are not able to control the power extracted from waves. The use of power converters allows control over the instantaneous power flow, and in turn enables both power flow directions. This paper focuses on the control of the first power conversion stage using Voltage Source Converters, in order to modify the characteristics of the hydrodynamic buoy-translator system and thus, optimize the extracted energy from the waves. Simulation results are presented showing the features and advantages of the use of controlled power converters.

Key words

Wave energy converters, linear generators, WEC control, renewable energy, modelling.

1. Introduction

Among the emerging electrical power generation choices from renewable sources of energy, the energy contained in the seas and oceans is one of the most promising. Research and industry have begun considering Wave Energy Converters (WEC) as the next new alternative energy. A diversity of prototypes has been developed during the last decades. Oscillating buoy systems are one of the systems currently in testing stage [1]. These devices use the vertical motion produced by waves on a buoy.

This paper focuses in oscillating point absorber. This device consists of a buoy which is directly connected to a permanent magnet linear generator (LPMG) via a rope placed on the seabed, where storms are not dangerous. To extract energy, springs are attached between the alternator and the foundation to pull the alternator downwards in wave troughs. The direct conversion power take-off (PTO) system provides a simple and robust way of increasing the survival possibilities, reduces the maintenance costs and may reduce the cost of electricity produced from wave energy [2].

The electric energy should be properly injected in the grid. This condition implies to keep the right wave quality at the connection point. The available primary energy features are pulsing and thus, it is necessary to use WEC systems that incorporate intermediate energy storage, to reduce the oscillations in the injected power. For this purpose, several systems have been used, such as oil or air pressure circuits.

One of the most interesting proposals about connecting the electricity generated by buoy oscillating systems to the power grid, is based on using linear generators and full-scale back-to-back Voltage Source Converters (VSC) jointly [3,4,5].

Linear generators do not require mechanical linkages to convert the buoy oscillating motion into rotative generator motion [6]. Besides, the power converter enables the use of DC Link capacitor as an intermediate stage of storage. It also enables to adapt electric power output for proper grid connection [3,4].

The hydrodynamic characteristics of the WEC system made up of the buoy and the generator moving parts, largely determine the amount of energy extractable from waves. For regular waves, it is possible to calculate the optimal hydrodynamic characteristics that enable to extract the maximum amount of energy, for each type of WEC and for incident wave [7]. Controlling the auxiliary mechanical systems enables to achieve these optimal hydrodynamic conditions. However, these systems entail more complexity in the design of the WEC and slow response times.

In references [3,4] control techniques are applied to a VSC back-to-back converter using the *dq* frame transformation of the electrical parameters. The one used in [4] acts on the generator side converter, in order to extract the maximum power from the wave within the Archimedes Wave Swing device.

This paper proposes a generalized strategy that allows optimization of energy extraction from regular waves in an oscillating system using VSC-based power converters. The WEC hydrodynamic conditions are matched to the instantaneous wave conditions in regular waves, via the electromagnetic force exerted by the generator. Controlling the first power conversion stage in the converter will be the way to implement this type of control.

The optimum conditions require that during certain periods of time energy is delivered to the oscillating device [8]. It implies that the generator switches to work as motor during some periods of time. Under this operating condition, it is necessary to use a powered conversion to enable both instantaneous power flux directions.

Finally, the overall balance of energy extracted using different sub-optimal control strategies have been analyzed.

2. Hydrodynamic control

Hydrodynamic control in case of single oscillation frequency regular wave, aims to match the movement of the floating device to the characteristics of incident waves. Hydrodynamic control optimal strategy aims to find both elements (wave-buoy) in resonance in order to extract the maximum amount of wave energy.

It is considered the simple case of a body oscillating in heave. The governing equation for the body oscillations is:

$$M \cdot \ddot{z} = f_h + f_g + f_s \tag{1}$$

where M is the mass of the buoy-traslator system, $\ddot{z}$ is the acceleration, f_h is the vertical component of the force due to water pressure on the wetted surface of the body, f_g is the vertical component of the force applied on the buoy by the PTO mechanism and f_s is the restoring force due to the spring attached to the translator.

If the amplitudes of the waves and body motions are small, it could be introduced the usual decomposition [9]:

$$f_h = f_d + f_r + f_{hs} \tag{2}$$

where f_d is the force produced by the incident waves on the assumedly fixed body (excitation force), f_r is the hydrodynamic force due to the body oscillation in otherwise calm water (radiation force), and f_{hs} is the hydrostatic force.

The hydrostatic force may be written as:

$$f_{hs} = \rho \cdot g \cdot S \cdot z \tag{3}$$

where ρ is water density, g is acceleration of gravity and S is the buoy cross-sectional area defined by the undisturbed water free-surface.

The spring force that anchors the device to the seabed is defined by the following expression:

$$f_s = -k \cdot z \tag{4}$$

where k is the spring constant.

In case of regular waves, it is convenient to decompose the radiation force as

$$f_r = -m_{add} \cdot \ddot{z} - B \cdot \dot{z} \tag{5}$$

here m_{add} is the added mass and B is the radiation damping coefficient. These parameters depend on the frequency of the waves and define the hydrodynamic characteristics of the buoy.

In case of regular waves of frequency ω_w, the excitation force is a simple-harmonic function of time t

$$f_d = \mathrm{Re}\left(F_d \cdot e^{i \cdot \omega_w \cdot t}\right) \tag{6}$$

here ω_w is the regular wave frequency. The amplitude of this force can be obtained by [7,9]

$$F_d = \sqrt{\frac{2 \cdot g^3 \cdot \rho \cdot B}{\omega^3}} \cdot A_w \tag{7}$$

where A_w is the incident wave amplitude.

If linear PTO system is assumed, it follows:

$$f_g = -\gamma \cdot \dot{z} - k_g \cdot z \tag{8}$$

where γ and k_g are constants. The first term represents the damping effect associated with the energy extraction, while the second is a spring effect (which may exist or not). This term represents energy exchange between the PTO and the oscillating system, similar to the one done by a spring. If spring effect exists, there will be bidirectional energy exchange between the generator and the buoy. Thus, the electrical machine will operate as motor and generator alternatively.

Taking account the above considerations, the system is completely lineal and equation (1) may be written as:

$$(M+m_{add})\cdot\ddot{z}+(B+\gamma)\cdot\dot{z}+ \\ +(\rho\cdot g\cdot S+k_g+k)\cdot z=\mathrm{Re}\left(F_d\cdot e^{i\cdot\omega_w\cdot t}\right) \quad (9)$$

Note the similarity between equation (9) and the one regarding to RLC series circuit fed by sinusoidal voltage.

The resonant frequency of the oscillating system is

$$\omega_0=\sqrt{\frac{\rho\cdot g\cdot S+k+k_g}{M+m_{add}}} \quad (10)$$

To extract the maximum wave energy amount, two conditions must fulfill [7]:

1. The natural oscillation frequency of the oscillating system must match the wave frequency (resonance).
2. The damping force constant from the LPMG should be controlled equaling to the radiation damping coefficient.

$$\omega_0=\omega_w \quad (11)$$

$$\gamma=B \quad (12)$$

A. Optimal strategy to extract wave energy

The optimum conditions may be obtained by controlling the force that the generator applies to the oscillating system. Matching the constants k_g and γ in equation (8), the two conditions for optimization may be fulfilled. If the power converter allows bidirectional power flow, the resonant frequency of the oscillating device can be modified and will depend on the control strategy applied to the generator. Thus, to extract the maximum wave energy, the force exerted by the PTO must be calculated by the constants:

$$\gamma_{op}=B \quad (13)$$

$$k_{g\_op}=\omega_0^2(M+m_{add})-\rho\cdot g\cdot S-k \quad (14)$$

In the system discussed in this article, the force exerted by the PTO on the oscillating system is developed by the linear generator. Its value will depend on the type of power converter and control strategy.

B. Optimal strategy setting null the PTO stiffness force

In this case, the value of the constant k_g is set null. There will be no energy transfer from the generator to the oscillating buoy system. Therefore, it would not be possible to change the resonant frequency of the oscillating device by acting on the generator control.

Systems where the value of the constant γ may be controlled, the maximum wave energy extraction from equation (9) is achieved for:

$$\gamma_{so}=\sqrt{B^2+\left(\omega\cdot(M+m_{add})-\frac{\rho\cdot g\cdot S+k}{\omega}\right)^2} \quad (15)$$

Systems where unidirectional power converters are implemented, work under these conditions. For instance, the ones based on uncontrolled diode rectifiers. The power extracted using this strategy is an upper limit for the power that can be obtained from systems that use non-controlled rectifiers.

3. Linear generator

An important aspect of survivability is the complexity and longevity of the technology. The more complex a system is and the more moving parts it is composed of, the more likely it is that some part will fail. Furthermore, to improve the prospects of becoming commercially interesting, the need for maintenance should be kept at a minimum. To meet these requirements, the wave energy converter may use a directly driven longitudinal flux, three-phase, synchronous permanent magnet linear generator.

A directly driven generator also circumvents the need of gearboxes, a component in need of regular maintenance and with a relatively high risk of failure. The generator consists of insulated cables, Nd-Fe-B permanent magnets, electroplate, structural steel, and springs. The springs are fastened underneath the translator and serve as a retracting force in wave troughs after the buoy and translator have been lifted by wave crests. Furthermore, the generator is fitted with upper and lower end stops consisting of powerful springs, whose purpose is to limit the mechanical impact on the generator in extreme sea states [2].

The voltage output varies in both amplitude and frequency parameters. Thus, conversion is necessary through a power electronic converter prior to deliver energy to grid. The *dq* components regarding to the linear generator model used in this paper can be expressed as follows [10]:

$$v_{sd}=R_s\cdot i_{sd}+L_s\frac{di_{sd}}{dt}-\omega_m\cdot L_s\cdot i_{sq} \quad (16)$$

$$v_{sq}=R_s\cdot i_{sq}+L_s\frac{di_{sq}}{dt}+\omega_m\cdot L_s\cdot i_{sd}+\omega_m\cdot\phi_{fd} \quad (17)$$

$$\omega_m=\frac{2\cdot\pi\cdot v}{\lambda} \quad (18)$$

where λ is the pole width of the LPMG, R_s is the stator resistance, L_s is the stator inductance and v is the linear speed of the buoy. Further Φ_{fd} is the flux linkage of the stator d-winding due to the flux produced by the permanent magnets. v_{sd}, v_{sq}, i_{sq} and i_{sd} are the voltage induced and the stator current, in the *dq* reference frame.

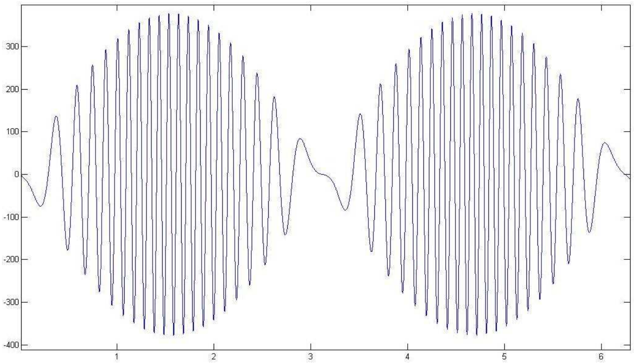

Fig. 1: Single phase output voltage from linear generator.

Figure 1 shows the three-phase linear permanent magnet generator voltages output, which vary in both amplitude and frequency parameters.

The active power at the generator output [3] may be written as:

$$p_s = \frac{3}{2} \cdot \omega_m \cdot \phi_{fd} \cdot i_{sq} \tag{19}$$

The force applied on the buoy by the generator, may be calculated by the following expression [4]:

$$f_g = \frac{p_s}{v} = \frac{3 \cdot \pi \cdot \phi_{fd} \cdot i_{sq}}{\lambda} \tag{20}$$

4. Power conversion electronics

Between the different options considered in this paper, the electronics power selected includes two power converters linked by a DC link [3,4,5]. The configuration considered in this paper includes two PWM controlled VSC.

The generator side converter controller match the force exerted by the generator and minimize the power losses in the generator, using the *dq* frame transformation. The generator force is controlled via the quadrature component of the current i_{sq} according to equation (20). Thus, the control reference of the *q* axis current is:

$$i_{sq\_ref} = \frac{\lambda \cdot \left(-\gamma_1 \cdot \dot{z} - k_{g1} \cdot z\right)}{3 \cdot \pi \cdot \phi_{fd}}. \tag{21}$$

The power losses in the generator can be reduced, equaling to zero the direct component of the current i_{sd} produced by the generator. Thus, the control reference of the *d* axis current is set null ($i_{sd\_ref}=0$).

The grid side converter controllers are the output active power to the power grid and the power factor. The first is controlled via the direct component of the current sent to grid i_{Dg}, and its reference is taken as the average value of the power delivered by the generator [3,4]. The second is controlled via the quadrature component of the current sent to grid i_{Qg}, taking account a unity power factor as reference.

5. Results

A. Case study

A wave power device has been developed at the Swedish Centre for Renewable Electric Energy Conversion in Uppsala. The 10 kW power point absorber combined with linear generator has been deployed in Lysekil [1]. Data regarding to oscillant system and generator concerning to this real facility, have been used in the simulations.

The hydrodynamic parameters have been taken from [11]. The most important of them are shown in table I. Table II includes the main linear generator features [12].

Table I. - Main features of the point absorber

Buoy shape	cylindrical
Buoy radius	1.5 m
Buoy height	0.8 m
Buoy mass	850 kg
Spring constant	7064 N/m

Table II. - Main generator features

Nominal output power	10 kW
Nominal speed	0.7 m/s
Phase-to-phase voltage r.m.s.	200 V
Pole width	50 mm
Synchronous reactance	7.8 mH
Stator winding resistance	0.45 ohms

The DC link nominal voltage is 1.100 V and its capacitance is 1 F. Energy is fed into the 20 kV distribution system and the connection to grid consists of 0.69/20 kV transformer and a line whose equivalent total impedance is 0.01+0.04j Ω.

To perform the simulations, several typical wave states, according with the localization, have been considered and are shown in table III [13]. The chosen scenarios are characterized by an energy period T_e and a significant height H_s.

For each state, an equivalent regular wave state has been chosen. This equivalent scenario has the same wave power level, and its parameters are the period T_e and the wave height H, which is $\sqrt{2}$ times smaller than H_s.

Table III. - Parameters for the sea states used to foce the model

Scenario	T_e	H_s	H	J (kW/m)
A	3.89	0.51	0.36	484
B	5.07	0.93	0.66	2099
C	7.34	2.36	1.67	19567

B. Power transfer between oscillant and PTO systems

This section discusses the characteristics of the power extracted from waves, when different references are applied to the force exerted by the electric machine according to the expression (8). The values of the constants for each strategy are defined in Table IV.

Table IV. – Control strategies

Strategy	Description	k_q	γ
1	optimum	-60665	2800
2	p_{max}=20 kW	-46032	13332
3	suboptimum	0	49031

The wave state considered in this section corresponds to scenario B. The average power extracted and the maximum instantaneous power values are listed in Table IV.

Table V. –Average and maximum power (kW) for different control strategies in scenario B

Strategy	Average power	Max. power
1	13.5	250
2	5.1	20
3	1.5	2.9

In the first strategy, the optimal conditions were adopted. They were obtained from expressions (13) and (14). The oscillating system came into resonance through these conditions. The average power transfered to the PTO system (13.5 kW) is the maximum that can be extracted in this wave state.

However, the operating conditions obtained are not feasible because the maximum oscillations (2.5 m/s) and the translator speed (3.1 m/s) are too large; and so does the instantaneous peak power exchanged with the PTO (250 kW). A large amount of power exchanged produces a significant increase in the electrical machine losses, and may lead to negative balances regarding to the power delivered to the grid by the system.

In the second strategy, a suboptimal method is applied: the maximum instantaneous power does not have to exceed a certain value (20 kW). Figure 2 shows the instantaneous power exchanged with the PTO. It can be seen periods where the machine is operating as motor.

Under these conditions, the average power extracted from waves is 5.1 kW, oscillations are around 0.7 m. and the maximum speed is 0.87 m/s, which can be considered acceptable values.

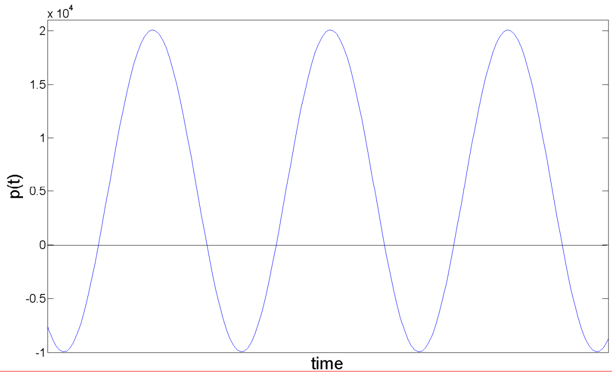

Fig. 2: Power (W) exchanged between the oscillating system and generator applying the strategy 2 in scenario B

Finally, in the third strategy, the optimal conditions for zero stiffness, as shown in equation (15), are used. Figure 3 shows the instantaneous power exchanged with the PTO. This time, the power always flows from generator to the PTO, and the average power extracted is reduced to 1.5 kW.

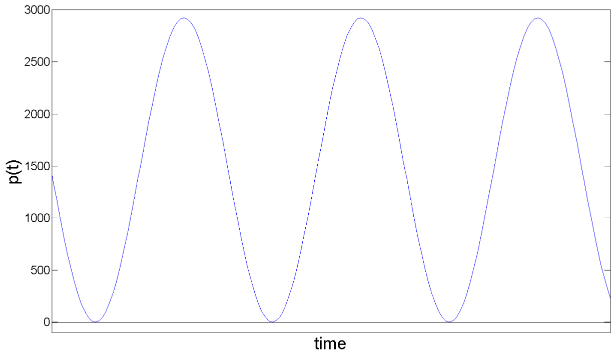

Fig. 3: Power (W) exchanged between the oscillating system and generator applying the strategy 3 in scenario B

To implement the three strategies described above, the power converter configuration has to allow the control over the force developed by the electrical machine. The first and second strategies also require bidirectional power flow.

The results in the third strategy are an upper limit for the power that can be obtained from systems that use uncontrolled rectifiers.

C. Power fed into the grid.

This section presents the results of simulations carried out incorporating models PTO made up by the linear generator and the power converter, according to the configuration described above. Simulations have been developed taking account the wave scenarios shown in Table III.

Table VI shows the average power delivered to the PTO and the average power fed into the grid when control strategies 2 and 3 are applied.

Table VI. – Powers (kW) fed into the grid

	Strategy 2		Strategy 3	
scenario	P_{av} to PTO	P_{av} to grid	P_{av} to PTO	P_{av} to grid
A	1.0	0.9	0.5	0.4
B	5.1	2.5	1.5	1.1
C	9.7	6.9	7.1	4.6

Comparing results in Table VI, it is clear the advantage of applying a suboptimal strategy which lies in incorporating the effect stiffness.

Scenarios A and B show that through the proposed strategy, the average power fed into the grid could double. Thus, the energy extracted by a power converter which incorporates proposed control in the first stage is larger than systems using non-controlled rectifiers.

6. Conclusions

This paper focuses on the way to improve the hydrodynamic features of the WEC by controlling rightly the power converters.

It has been taken into account that the force applied to the oscillant system by the PTO depends, not only on its velocity, but also on its position. Using this control strategy, it has been shown how to reach resonance and extract the maximum power from the wave. Simulations show that applying optimal control strategy is not feasible.

Suboptimal strategies are compared. Results indicate that strategies including stiffness effects controlled in the first conversion stage, increase the energy extracted from waves.

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