Abstract—Power generation from ocean wave energy conversion is the subject of this paper, namely directly driven converters. The associated generators induced electromotive force (emf) is characterized. Issues on grid interaction are also brought up and a connection scheme is proposed deriving from the spatial configuration of simple converters in a wave farm.

Keywords—wave energy converters, direct drive, grid connection

I. INTRODUCTION

The energetic potential of ocean waves is well documented and, foreseeably, a valuable resource in the renewable energies context. Waves are due to the interaction of wind with the ocean surface, concentrating the energy carried in a higher density fluid. Power per wave crest can typically reach 40 kW/m on the Portuguese coast [1], depending mostly on coastal distance. Such value is more favorable than those of most European countries, whence projects like the Pelamis and the Archimedes Wave Swing (AWS) have chosen it for experimental purposes.

The main technological problem facing wave energy conversion is that of incident waves varying in amplitude and frequency (which has typical values of 0,1 Hz). Some type of power take-off is needed to transform this low speed and shifting movement into a revolving one with hundreds of rpm’s proper of common electrical generators. Such approach comprises hydraulic systems (Pelamis), oscillating water columns (Pico) or overtopping devices (WaveDragon) [2]. All these devices but the Pelamis drive variable speed generators, whence a power electronic converter is indispensable for grid connection.

The intermediate energy storage mechanisms cited above have losses associated, spoiling the global process’s efficiency. To avoid it, direct drive could be an alternative, and, for instance, the AWS is a converter where a linear permanent-magnets generator is directly submitted to wave swing [2]. This makes it possible to couple the generator motion directly to the reciprocating, vertical motion of the ocean waves, which eliminates the need of complex power take-off schemes and gearboxes.

The costs of operating offshore devices under an aggressive environment like the sea have, above all, prevented the dissemination of wave conversion technologies. The straightforwardness of direct drive can lead to economical benefits, thus making it a valid research subject. In this paper, general aspects of it are discussed and a grid connection scheme investigated.

II. DIRECTLY DRIVEN CONVERTERS

Wave fluctuation is applied on a generator in order to produce relative motion between a stator and a rotor. Machine topology can either be linear or rotary, as long as both are able to oscillate with the incidence of ocean waves.

Fig. 1 depicts a wave energy converter consisting of a buoy, floating on the surface of the ocean, connected with a rope to the rotor of a linear generator. Such is the design of the AWS, where the rotor is a piston with permanent magnets moving in a coil where electricity is induced. The force exerted on the piston is a sum of the gravitational lift force on the buoy, the response of the generator due to electromechanical conversion and a mechanical spring-like force which, in the case of the AWS, is associated with air compression inside the piston.

This system is modeled by (1) and if a sinusoidal excitation – the incident wave – is considered, it is evident that resonating frequencies can be determined for it in terms of the mechanical parameters. Moreover, these could be adjusted to the wave spectrum at a given site (for instance, by constraining the air pressure inside the piston) thus optimizing power extraction.
\[
(M_{\text{buoy}} + M_{\text{water}}) \frac{d^2y}{dt^2} + \beta \frac{dy}{dt} + C_{\text{spring}}y = F_{\text{wave}} \quad (1)
\]

If a rotary machine were to be directly driven, wave motion would have to be transformed into an oscillating, pendulum type movement. Straightforwardly, having the machines on top of a floater would suffice, however, the oscillating speed could improved by also tuning the structural mechanical frequencies with those of marine fluctuation. An alternative approach is that of the Wave Rotor, where submerged vertical axis turbines are driven by ocean waves and currents [3].

III. GENERATED EMF

A permanent-magnet linear synchronous generator with magnets on the translator has been chosen for the AWS because of its efficiency at low speeds, comprising high force densities and avoiding any electrical contact with the moving part. Since the magnetic attractive forces between stator and rotor form a dangerous load for the bearings, a double-sided, symmetrical generator is of benefit. Alternative configurations are being studied, such as transverse flux machines [4].

As the rotor progresses along with the waves, the coils wound on the stator will undergo a varying magnetic flux and electromotive induction will take place under Faraday’s law. If a sinusoidal magnetic distribution is considered for the air-gap, the induced emf on a generator can be expressed as by (2), where \( E_m \) is a constant depending on the secondary coil’s number of turns and effective area, the winding factor and the magnetic flux density due to the magnets.

\[
e = -\frac{d\psi}{dt} = E_m \sin (2\pi f_s t) \frac{dy}{dt} \quad (2)
\]

The sinusoidal behavior associated with the coil pitch (\( \tau \)) and the motion of the magnets with velocity \( v \) is evidenced by the frequency \( f_s = v/\tau \). Magnetic flux harmonics should exist in the air-gap and would naturally have repercussion in the emf, however, this analysis isn’t weakened and their effect can even be canceled.

In (2) the speed voltage characteristic is attested by the rotor position’s time variation (\( dy/dt \)). In a conventional machine driven at constant speed like a synchronous generator, a regular sinusoidal voltage is thus produced. Yet, in a wave energy converter such as the one on Fig. 1, speed will very much depend on the incident wave characteristics, and from (2) if a sinusoidal regime with a frequency \( f_w \) is assumed, the induced emf must exhibit a likewise modulation. This is conveyed by (3), where \( f_w \) will typically be smaller than \( f_s \) because of the latter’s determination by the converter’s mechanics through (1) and the pole pitch.

\[
e = (2\pi f_w) E_m \sin (2\pi f_s t) \sin (2\pi f_w t) \quad (3)
\]

A more complex behavior might be expected, for the sea is assigned to a spectrum of wave frequencies rather than a monochromatic description. However, the variable frequency and magnitude of the voltage produced by a directly driven generator stands out, whence a power electronic converter becomes imperative for grid connection. Such devices process the output converting it to DC by a rectifier and subsequently to AC by an inverter. The intermediate DC link will undoubtedly have a filtering capacitor installed, which can be seen as an energy storage, but at an electrical level and therefore less expensive than a power take-off mechanism.

IV. GRID CONNECTION

It can be seen from (3) that the phase voltage becomes zero every half-wave period, therefore a low DC output at these instants will result from a diode rectifier. The voltage waveform across the DC link capacitor will therefore be highly fluctuating, making it impossible for the inverter to supply the grid with constant real power.

This issue is rather common on electrical production from renewable resources and has a growing relevance within distributed production. In fact, the following problems currently arise:

- Delivery of variable active power troubles frequency control and compromises power balance.
- Uncontrollable production of reactive power disturbs voltage regulation and increases transmission losses.
- Change of the power flow in the distribution system corrupts the existing protection system.
- Injection of harmonics in the grid, reducing power quality.

It can be seen that the problems brought up depend on grid strength at the connection point. Besides, with proper electronic filtering and control of the inverter, the impact on power systems can be minimized, however it is crucial that the DC link voltage suffers the least variation possible.

V. SPATIALLY DISTRIBUTED GENERATORS

The set up of a large number of wave energy converters in offshore wave farms has been promoted as a cost-effective solution as well as a way of smoothing active power fluctuation. This can be achieved by combining the rectifiers associated with each generator, managing to compensate the low frequency \( f_w \) dip on the rectified voltages.

Such solution has been presented in [5] complemented by an algorithm to regulate DC voltage at the inverter input through a DC/DC converter. The problems facing this approach is the complexity of the power electronics involved, the control devices’ fragility in a marine environment and the losses concurring in a parallel operation of the rectifiers.

Following the simplicity of direct drive schemes, we investigate the distribution of generators over a wave length, as illustrated in Fig. 2. A basic point-absorber electromechanical converter is assumed, with a single voltage sinusoid being generated over a wave period, that is, a kind of monopolar single phase oscillating machine is idealized. Relatively to (2), the induced voltage can now be defined as (4) for each \( i \) generator from a set of \( n \).

\[
V_i = V_M \sin (2\pi f_w t - \alpha_i) \quad (4)
\]
The phase shift $\alpha_i$ is introduced by the physical distribution of generators which are aligned in a row perpendicular to the wave front having, for a given wave length $L_w$, an equal spacing of $L_w/n$. As the wave continuously sweeps the row, the generators' output will thus be lagging by $\frac{2\pi}{n} i$, the exact phase shift needed to produce an $n$-phasic system.

Nonetheless, the transposal of a spatial distribution into the time domain can be affected by the varying length of the incident wave. This is expected to occur as wave length strongly depends on wave velocity and frequency [3], therefore, phase shift $\alpha_i$ is rather obtained by (5).

$$\alpha_i = \frac{2\pi}{n} \frac{L_{sync}}{L_w} (i - 1), \ i = 1, ..., n \tag{5}$$

The relation between the length for which the generators were firstly positioned ($L_{sync}$) and the actual wave length ($L_w$) is thus accounted for. Only if $L_w = L_{sync}$ can it be said that the generators are synchronized, for otherwise an unbalanced $n$-phasic system will subsist.

Taking advantage of this simple $n$-phasic system created, a bridge rectifier can be used with natural commutation. Fig. 3 illustrates such situation over a wave period, in the cases where $L_w = L_{sync}$ and $L_w = 1.1 L_{sync}$. In both experiences six generators were considered along the wave length, arranged in a polygon connection which produces a higher average output voltage than a star connection, for a number of supplying generators greater than six.

From Fig. 3 it becomes evident that a non-synchronous operation results in a DC link voltage fluctuation with the wave frequency. Subsequently, a variation of the power delivered is expected having a frequency double of the incident waves and, because this ranges typically at 0.2 Hz, a flickering phenomenon may emerge.

The same average output voltage can be gathered from synchronous and non-synchronous performance; the difference dwells instead on the voltage fluctuation, a critical factor in the sizing of the DC link capacitor.

Voltage ripple rate can be defined as (6), where the voltage measurements indicated refer to the rectifier’s output root mean square ($U_{rms}$), average ($U_{av}$) and maximum ($U_{max}$) values.

$$W = \frac{\sqrt{U_{rms}^2 - U_{av}^2}}{U_{max}} \tag{6}$$

Calculations of the ripple rate show it is proportional to the percentual divergence of lengths $L_w$ and $L_{sync}$. This is a natural consequence of a larger unbalance of the $n$-phasic system generated.

VI. Conclusion

Direct drive energy conversion results in variable frequency variable magnitude voltage waveforms. The connection scheme proposed meant to assure a reasonable rectification of a set of such generators.

Spatial distribution will work best when the incident wave’s length fits the established distance between generators. Otherwise voltage ripple will tend to increase, stressing the DC link operation.

A wave farm such as this might be conceptually simple in terms of each generator’s design and maintaining and could be compared to a $n$-phasic machine which windings are wound over wave length distances. However, the typical wave lengths of 100 m could be a more important constraint than slight variations of this value, because submarine cables would have to be deposited over rather long distance to interconnect the generators.
Fig. 4. Voltage ripple rate comparison

REFERENCES


