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Rotational speed control and electrical rated power of an oscillating-water-column wave energy converter

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ABSTRACT

The oscillating-water-column device equipped with an air turbine is regarded by many researchers and developers as the simplest and most reliable wave energy converter. It has been object of extensive development effort, including the deployment of prototypes into the sea. The maximization of the produced electrical energy involves the control of the rotational speed, which affects the hydrodynamic process of wave energy absorption, the turbine aerodynamics and the performance of the electrical equipment. In the paper, the overall performance of the plant is modelled as an integrated process, with the hydrodynamic modelling based on linear water wave theory. Special account is taken of the electrical efficiency dependence on the load factor and of the constraint introduced by electrical rated power as a power level that should not be exceeded. A case study was selected to investigate these issues: the existing bottom-standing plant on the shoreline of the island of Pico, in the Azores Archipelago. Results are presented for the control of the self-rectifying air turbine of biradial type and for the annually produced electrical energy as affected by turbine size and by electrical rated power.

1. Introduction

Wind and sea waves are abundant renewable energy resources that are characterized by very large variations in the power level available for conversion. Wind and wave energy plants are mostly used for electrical energy production. It is well known that conventional electrical generators are very efficient machines over a wide range of loads. However their efficiency decays markedly for loads less than about one-third of the rated power. On the other hand, the electrical equipment, especially the power electronics, cannot be subjected to overloads. For these reasons, the specification of the electrical generator rated power has important implications in the amount of electrical energy produced annually and in the control of the plant. In large wind turbines, the control involves rotor blade pitch, rotational speed and yaw. In the case of wave energy, the type of power control depends on converter and power take-off (PTO) types. Here we are concerned with wave energy converters of oscillating-water-column (OWC) type, a major class of wave energy devices.

In an OWC, there is a fixed or floating hollow structure, open to the sea below the water surface, that traps air above the inner free-surface. Wave action alternately compresses and decompresses the trapped air which is forced to flow through a turbine coupled to an electrical generator. Unless rectifying valves are used, which is widely regarded as unpractical except possibly in small devices like navigation buoys, the turbines are self-rectifying, i.e. their rotational direction remains unchanged regardless of the direction of the air flow. Recent reviews of OWC wave energy converters can be found in Refs. [1,2] ([1] also includes a review of self-rectifying air turbines).

In an OWC wave energy converter, there are three energy conversion processes: (i) the hydrodynamic process of wave energy conversion into pneumatic energy in the air chamber that takes place below the water free-surface; (ii) the aerodynamic process of pneumatic energy conversion into mechanical energy at generator shaft that takes place in the turbine; and (iii) the electrical process of shaft power conversion into electrical power supplied to the grid that takes place in the electrical equipment (especially in the electrical generator). Hydrodynamic, aerodynamic and electrical efficiencies may be defined for these three processes. Variations in rotational speed affect the three energy conversion processes.

The control of OWC converters through the control of the air turbine rotational speed was addressed by several authors [3–11]. Here we mention especially a study [12] based on a stochastic

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Nomenclature

Roman letters

a	Coefficient in rotational speed control law
B	Radiation susceptance
D	Turbine rotor diameter
G	Radiation conductance
H_s	Significant wave height
I	Rotational inertia
k	Polytropic exponent
L	Torque
$\dot{m}$	Mass flow rate of air
p	Pressure oscillation in air chamber
p_a	Atmospheric pressure
P	Power
$\overline{P}_{\mathrm{wave}}$	Time-averaged wave power per unit crest length
$S_p(\omega)$	Spectral distribution of p
$S_\zeta(\omega)$	Variance density spectrum of waves
t	Time
T_e	Energy period of waves
V_0	Air chamber volume

Greek letters

β	Exponent in rotational speed control law
Γ	Excitation flow rate coefficient
η	Efficiency
Θ	Electrical generator load factor
Λ	See Eq. (6)
$\Xi = \Phi/\Psi$	Dimensionless damping coefficient of turbine
Π_t	Dimensionless power of turbine
ρ_w	Water density
ρ_a	Density of air in atmosphere
σ_Ψ	Standard deviation of Ψ
φ	Frequency of occurrence of sea state
Φ	Dimensionless flow rate of turbine
Ψ	Dimensionless pressure head of turbine
ω	Radian frequency of waves
Ω	Rotational speed (radians per unit time)

Subscripts

annual	Annual average
avai	Available to turbine
e	Electrical
in	Electrical input
opt	Optimal
out	Electrical output
rated	Rated
t	Turbine

Superscript

Overbar	Time average

method: a control algorithm of type $L_e = a\Omega^{\beta-1}$ which was found to be adequate for the instantaneous electromagnetic torque L_e on the generator rotor versus the instantaneous rotational speed Ω, a and β being constants for given OWC converter and air turbine that are independent of sea state. This type of control based on a power law, which does not account for turbine or electrical equipment constraints (like maximum allowable rotational speed or power), was later adopted in other studies [11–13].

An investigation is presented here on the optimization of the turbine size and rotational speed, for various values of the electrical generator rated power, having in view the maximization of the annual production of electrical energy by a given OWC plant. In particular, it is shown how the rated power of the electrical equipment affects the choice of the turbine, its rotational speed control and the amount of electrical energy produced annually in a given wave climate. Numerical results are presented for a case study: the existing bottom-standing OWC plant constructed on the shoreline of the island of Pico, in the Azores Archipelago, northern Atlantic Ocean. Use is made of results from numerical simulations of the same plant recently published in Ref. [12]. Those results are based on a stochastic approach that yields probability density functions and time-averaged values, not time series. This approach is complemented by a simplified time-domain analysis in which time-variations in rotational speed and electrical power output are investigated.

The implications of electrical rated power on the rotational speed control are analysed in Section 2. Numerical results are presented in Section 3 for the Pico OWC plant assumed to be equipped with an air turbine of biradial impulse type (rather than the existing Wells turbine) in a given wave climate. This illustrates the application of the rotational speed control and shows the effects of varying turbine size and rated electrical power upon the annual-averaged electrical power output. Results in the time domain show how oscillations in rotational speed and electrical power output are affected by the rated electrical power and by the rotational inertia of the rotating elements. Conclusions are drawn in Section 4.

2. Control for maximum produced electrical energy

In an OWC plant, the air turbine is subjected to a pressure head $p(t)$, alternately positive and negative, given by the chamber pressure oscillation with respect to the atmospheric pressure. The torque $L_t(t)$ induced by the flow of air on the turbine rotor depends on $p(t)$ and on the instantaneous rotational speed $\Omega(t)$ (radians per unit time). We define the turbine aerodynamic power as $P_t(t) = \Omega(t) L_t(t)$. Likewise, we introduce the electromagnetic torque on the generator rotor $L_e(t)$ and the generator input power $P_{e,in}(t) = \Omega(t) L_e(t)$. If the bearing friction losses and the generator windage losses are neglected, then, over a time interval much longer than the typical wave period, the time-averaged values (denoted by an overbar) of $P_t(t)$ and $P_{e,in}(t)$ are approximately equal: $\overline{P}_t = \overline{P}_{e,in}$.

We denote by $P_{e,out}(t)$ the electrical power supplied to the grid. The electrical conversion is a complex process; the electrical efficiency $\eta_e = P_{e,out}/P_{e,in}$ is affected by several factors, such as the loading conditions and the rotational speed. Here, as in Refs. [14,15], we assume that η_e is a function of only the load factor $\Theta = P_{e,out}/P_{\mathrm{rated}}$, where P_{rated} is the rated (or nominal) electrical power, and write $\eta_e = f(\Theta)$.

We assume first that the rotational inertia of the rotating elements is large, so that, in a given sea state, the oscillations in rotational speed Ω and in the generator input power $P_{e,in}$ are relatively small. We write

$$\overline{P}_t = \overline{P}_{e,in} = \overline{P}_{e,out} / f\left(\overline{P}_{e,out}/P_{\mathrm{rated}}\right). \tag{1}$$

Variations in turbine rotational speed affect the hydrodynamic process of wave energy absorption (indirectly through changes in