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Testing and control of a power take-off system for an oscillating-water-column wave energy converter

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ABSTRACT

The paper concerns the development of the PTO (power take-off) control of an OWC (oscillating-water-column) spar-buoy wave energy converter. The OWC spar-buoy is an axisymmetric device consisting of a submerged vertical tail tube open at both ends, rigidly fixed to a floater that moves essentially in heave. The oscillating motion of the internal free surface relative to the floater-tube set, produced by the incident waves, makes the air flow through a novel self-rectifying air turbine: the biradial turbine. To reduce the losses of the PTO system at partial load, an electrical generator with a rated power twice the maximum expected average power conversion of the buoy was adopted. The control of the turbine-generator set under highly energetic sea-state conditions was experimentally investigated by means of tests performed in a PTO test rig. In the reported tests, the hydrodynamics of the OWC spar-buoy and the aerodynamics of the air turbine were numerically simulated in real-time and coupled with the experimental model of the turbine/electrical generator set in a hardware-in-the-loop configuration. The experimental results allowed the dynamic behaviour of the PTO to be characterized and provided validation of the proposed control algorithms that ensure operation within safe limits.

1. Introduction

The ocean waves are an important renewable energy resource that, if extensively exploited, may contribute significantly to the electrical energy supply of countries with coasts facing the ocean [1,2]. A wide variety of technologies has been proposed, studied and in some cases tested at full size in real ocean conditions [3–6]. The oscillating-water column (OWC) is widely regarded as the simplest concept for a wave energy converter (WEC): the only moving part of the power take-off (PTO) mechanism is the rotor of an air turbine directly driving a conventional electrical generator. 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 forces air to flow through a turbine coupled to an electrical generator. Unless rectifying valves are used, which is not practical 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. Several types of such special turbines have been developed. The axial-flow Wells turbine, invented in the mid-1970s, is the best known self-rectifying turbine, but other types have also been proposed, studied and used. Reviews can be found in Refs. [7,8] for OWCs and in Refs. [9–11] for air turbines.

The construction of a full-sized WEC and its deployment, maintenance and testing in sometimes very harsh sea conditions are time-consuming and expensive tasks that usually take place only at a late stage of a long development process. This should be preceded by theoretical/numerical model testing of the whole energy conversion chain from waves to electrical wire, followed by small-scale model testing. Such model testing is usually performed at scales ranging from 1:100th in small wave flumes to about 1:10th in the largest wave tanks, or in sheltered real sea conditions at scales typically between 1:5th and 1:3rd (see Ref. [12]). If the geometrical scale ratio (considering Froude scaling criterion) of the WEC model is denoted by ε, then the scale for the PTO power is $\varepsilon^{7/2}$ (if eventual differences between sea water density and fresh water density in the tank are neglected) [12,13]. This shows that, even at

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the largest scales (about 1:10th) at which WECs can be tested in the large wave tanks, the PTO power scale is about $(1/10)^{7/2} = 1/3162$. At this scale, the rated power of a large WEC (say 1 MW) is simulated, at model scale, as 316 W, which is too small for realistic PTO physical testing. It is usually considered that the smallest geometrical scale ratio for the PTO simulation to be minimally realistic is about 1:4th, for which the power scale is 1:128th, see Ref. [13]. Testing at such a scale must be made in the sea (possibly sheltered sea conditions), as was done in Galway bay (western Ireland) with a 1:4th-scale model of the Backward Bent Duct Buoy (BBDB), a floating OWC wave energy converter that was equipped with a Wells turbine and later with an axial-flow self-rectifying impulse air turbine [14].

Field testing, even at scales less than full scale, is expensive and time consuming, apart from raising problems of reproducibility of conditions. If the main object is to test the response of the electrical equipment and the control of the PTO, then a much less expensive and more expedite alternative is to carry out the testing of the generator and power electronics in a laboratory at a power scale large enough to be realistic. The electrical generator is driven mechanically by a machine simulating the torque and rotational speed of the actual PTO. This can be done by a properly fed and controlled electrical motor coupled to the electrical generator. The energy conversion chain from the waves to the output from the mechanical machine driving the generator is to be simulated numerically in the time domain at the adopted scale. In the case of an OWC converter, this numerical simulation involves the hydrodynamic process of energy absorption from the waves, the thermodynamics of the air compressibility in the chamber and the air turbine aerodynamics. This mixed simulation of the whole energy conversion chain is named hardware-in-the-loop testing.

The work reported here concerns a floating OWC device of spar-buoy type that has been under development for some years at Instituto Superior Técnico, Lisbon [15–17]. The OWC spar-buoy is a particularly simple concept for a floating OWC. It is an axisymmetric device (and so insensitive to wave direction) consisting basically of a (relatively long) submerged vertical tail tube open at both ends and fixed to a floater that moves essentially in heave, see Fig. 1a. The air flow displaced by the motion of the OWC inner free-surface, relative to the buoy, drives an air turbine. Several types of wave-powered navigation buoys have been based on this concept [18,19], which has also been considered for larger scale energy production [20]. For this kind of application, where relatively large air pressure oscillation amplitudes occur, the single-stage Wells turbine is penalized by its typically high ratio of blade speed to axial-flow speed, which requires unacceptably high rotor blade tip speeds in the more energetic sea states. This limitation is attenuated by the use of several stages, which however introduces other problems, namely higher mechanical complexity and increased cost. A self-rectifying impulse turbine may be a better choice, especially the highly efficient biradial turbine [21], see Fig. 1b and c.

In a given sea state, the aerodynamic efficiency of the air turbine is sensitive to the rotational speed. On the other hand, changes in rotational speed also affect the damping provided by the turbine on the hydrodynamic process of wave energy absorption and so indirectly affect the hydrodynamic efficiency of this process. This effect is known to be more important in Wells turbines than in self-rectifying impulse turbines [13]. Anyway, the instantaneous rotational speed of the turbine-generator should be controlled to maximize the time averaged power output from the plant. A proposed control algorithm consists in establishing a control law, to be implemented on the controller, that relates the electromagnetic torque on the generator to the instantaneous rotational speed. This may take the form of a power law [21,22]. In very energetic sea states, the electrical hardware may be unable to impose the electromagnetic torque specified by the control law, which would have as consequence the rotational speed increasing beyond acceptable limits. In such limiting cases, the air flow rate through the turbine should be decreased by partially or totally closing an high-speed stop valve installed in series with the turbine or opening a relief valve in parallel with it, see Fig. 1. Such procedures should be implemented in the control strategy of the plant.

The present paper aims to establish control strategies for safe operation of the OWC spar-buoy in moderate and highly energetic sea-states, in which the generator was specified to have its rated output power approximately twice the expected annual averaged power output. This is a severe constraint due the large peak-to-average power ratio that can be found in wave climates of interest. The compressibility effects in the air chamber are also taken into account. These effects cannot be neglected in sea states of medium and high energy levels since the compression half-cycles become far from identical to the expansion half-cycles.

Section 2 gives an overview of the Tecnalia PTO laboratory in Bilbao, Spain, where the tests were performed. The modelling of the complete system is presented in Section 3. The electrical hardware in the laboratory, including the generator, is a scaled-down representation of the full-scale PTO. This has to interact with the simulated wave-to-turbine numerical model that represents a full-scale device. The way to implement this interaction is addressed in Section 3. Experimental results are presented in Section 4 for several OWC spar-buoy configurations. Different generator control laws were tested to assess the performance of the system with respect to the mean power and also to the highest power peaks. Finally, conclusions are drawn about the best configuration to keep the generator power within safety limits for the highest energetic sea-states considered.

2. Tecnalia PTO test rig

The present tests were performed on the PTO emulator available at Tecnalia. The test rig can be divided into three main parts: the motor and generator, the hardware-in-the-loop simulator, and the data logging, see Fig. 2. The motor and the generator are coupled through a shaft. A flywheel is rigidly attached to the shaft to increase the system inertia, see Fig. 2.

The motor/generator set with appropriate control can run coupled to a hardware-in-the-loop simulator to test real sea operating conditions. The motor part is composed by the motor and frequency converter which is used to control the output torque via an analogue input signal. The aim of these components is the simulation of the turbine torque under the prescribed sea conditions. The motor torque is an output of the hardware-in-the-loop simulator. The generator part includes the generator, the back-to-back power converter to control the generator and the grid connection, and a PLC (programmable logic controller) which includes the control algorithm.

The hardware-in-the-loop simulator runs on a computer with Matlab xPC target real-time operating system, which links the simulation model to the physical model. In the present implementation, computer simulations of the OWC spar-buoy hydrodynamics and turbine aerodynamics are simulated in real-time for different sea-state conditions. The inputs are the generator/motor (turbine) rotational speed and an analogue signal from a torquemeter. The turbine torque is computed in real-time and supplied as a reference to the frequency variator that drives the motor.

The motor frequency converter is rated at 18 kW and allows power-peaks up to 28 kW. It is suitable to control motors with a maximum speed of 3000 rpm. It can be controlled remotely via external 4/20 mA signals. Both speed and torque control modes are available. The motor is a two-pair-of-poles squirrel cage induction