Renewable Energy 88 (2016) 465–473

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Simplified model of offshore Airborne Wind Energy Converters

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ARTICLE INFO

Article history:
Received 28 November 2014
Received in revised form
16 November 2015
Accepted 25 November 2015
Available online 12 December 2015

Keywords:
Floating
AWE
Wave energy
High altitude wind
Offshore renewable
Offshore platform

ABSTRACT

Airborne Wind Energy Converters (AWECs) are promising devices that, thanks to tethered airborne systems, are able to harvest energy of winds blowing at an altitude which is not reachable by traditional wind turbines. This paper is meant to provide an analysis and a preliminary evaluation of an AWEC installed on a floating offshore platform. A minimum complexity dynamic model is developed including a moored heaving platform coupled with the dynamics of an AWEC in steady crosswind flight. A numerical case study is presented through the analysis of different geometrical sizes for the platform and for the airborne components. The results show that offshore AWECs are theoretically viable and they may also be more efficient than grounded devices by taking advantage of a small amount of additionally harvested power from ocean waves.

1. Introduction

The last years have seen a dramatic growth of a new sector in renewable energy technologies which aim at the development of Airborne Wind Energy Converters (AWECs), that are a new kind of wind generators that extract energy from high altitude winds by means of tethered kites or aircraft. The scientific community and the Industry are increasingly focussing their attention on this technology because of its potential to provide low-cost renewable energy [1]. The economics of AWECs is very promising for mainly two reasons. First, winds high above ground level are steadier and typically much more powerful, persistent and globally available than those closer to the ground [2], and second, the structure of AWECs is expected to be orders of magnitude lighter (and thus cheaper) than conventional wind turbines [3].

On the downside, a possible limitation for the global development of AWECs could be the availability of significant land and air spaces required during operation. There are several strategies that are proposed to overcome this issue: (1) for land surfaces, an improvement could be obtained by allowing airborne systems to fly over living or industrial areas but this would raise important Not-In-My-BackYard (NIMBY) issues; (2) optimized use of airspace could be obtained through farm installations where multiple devices share the same volume of air [4].

Recently, there has been an increasing focus on bringing wind turbines offshore because, when compared to conventional onshore systems, they can rely on more powerful winds and they exploit cheaper offshore ‘land’. However, offshore wind farms are expensive because their installation requires costly foundations and maintenance. Today, in Europe, the offshore installed capacity accounts for 6.6 GW out of a total 117.3 GW [5]. All the offshore wind farms are fixed to the seabed in shallow water at depths usually lower than 20 m [6]. However, the global interest is set on offshore deep water floating installations where water depth reaches several hundreds meters, due to the huge availability of sites [7]. A few experimental full scale floating wind turbines have been deployed but unfortunately, they are expensive and require large submerged foundations, for example the Hywind turbine has a submerged structure 100 m deep with a water mass displacement (hereafter simply referred to as ‘displacement’) around 5300 tons [8].

Since floating AWECs may take advantage of both the lightweight design of AWECs and the huge availability of low-cost sites for the installation of floating structures, this work presents a preliminary investigation on the feasibility and on first design issues of offshore AWECs.

Section 2 is an introduction to modelling offshore AWECs. Section 3 introduces a simple dynamic model for an offshore pumping

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http://dx.doi.org/10.1016/j.renene.2015.11.063
0960-1481/

AWEC with catenary mooring. In Section 4, a case study is analysed in order to address first design issues and to estimate the advantage that an offshore AWEC could obtain by exploiting the available wave energy in addition to that of wind.

2. Offshore AWECs

The study and development of offshore AWECs combine different fields of engineering. They are composed of a flying wing (or kite) linked with a tether to a floating platform, which in turn is anchored to the seabed by a mooring system as shown in Fig. 1. All these subsystems involve complex dynamics and can be studied with different degrees of accuracy.

Depending on where the generators are placed, two types of AWECs can be envisioned:

- 'Float-gen' (floating equivalent of ground-gen) in case the generators are placed on the floating platform.
- 'Fly-gen' in case the generators are placed on board the wing.

In float-gen systems, the generation type is traction based and the aircraft performs the pumping cycle. Electricity is generated during the reel-out phase of the cycle when the aircraft generates significant pull and the cables are reeled out from the drums on which they are wound. Then comes the reel-in phase in which the aircraft is controlled in order to generate less tension and the cables are reeled back in. Reeling-in of cables is achieved with the aircraft in a depowered configuration. For current experimental systems, the reel-in phase requires nearly one third of the power produced during the reel-out phase [9,10] but there are several concepts that aim at reducing substantially this power requirement [11].

On the other hand, fly-gen systems extract electricity from on board wind turbines which rotate fast and continuously. With respect to float-gen systems, they can have higher global electrical efficiencies and 100% duty-cycle efficiency (they are not subjected to reel-out reel-in cycles). However, the transmission of electricity from the wing to the floating platform adds a lot more complexity and requires larger-sized cables, thus increasing the aerodynamic drag, which has a detrimental effect on crosswind power output [3]. In this work float-gen systems are analysed.

The aerodynamics of the AWEC can be investigated through different models; for example it can be described by a simple algebraic formula for quick power assessment [12], or can be modelled with a first order non linear dynamic system for controller design [13], or can be thoroughly simulated to investigate how a kite deforms during flight manoeuvres [14]. Also the cable dynamics can be taken into account when modelling the aircraft forces [15,16].

In order to model the displacement of the floating platform and to estimate its effect on the energy production, it is necessary to investigate the hydrodynamics of the system. The hydrodynamics of floating bodies involve highly non-linear phenomena and turbulent flows. Reasonable predictions and simulations can be obtained by means of computationally intensive Computational Fluid Dynamic (CFD) analyses. However, several simplified methods are commonly employed in marine engineering to efficiently perform preliminary design iterations [17–19].

The mooring system cannot be neglected when modelling an offshore AWEC, even though it is only needed to hold the generator in place. Several kinds of mooring systems are available and extensive literature, patents and regulations exist for oil drilling platforms and naval engineering [20,21]. Mooring systems are known to be difficult to model due to their inherent non-linearity and sophisticated fluid structure interaction. For example, simple slack mooring systems have a non linear stiffness that changes significantly with the applied load and other design criteria [22]. In offshore oil platforms, their dynamics are usually deemed to be negligible for non-extreme events. However, it is important to notice that mooring equipment could be the most costly subsystem of a floating platform and could affect substantially the global business plan [23].

In this paper, a preliminary study of offshore AWECs is performed thanks to a simplified model with minimum complexity that allows analysis of the coupling of two main systems, namely a moored floating platform and an airborne device. This model has the important advantage of being computationally fast and easy to use. It is therefore suitable for qualitative analyses and first design iterations. In particular, the next section proposes a model of a 1 Degree of Freedom (DoF) heaving platform coupled with a steady state aerodynamic model of a generic wing flying in the crosswind direction.

The study only focuses on an AWEC in operational conditions, during energy production phase. Although relevant, other aspects and operating modes, such as launching/landing/emergency manoeuvres, optimal control, etc. are not discussed [1].

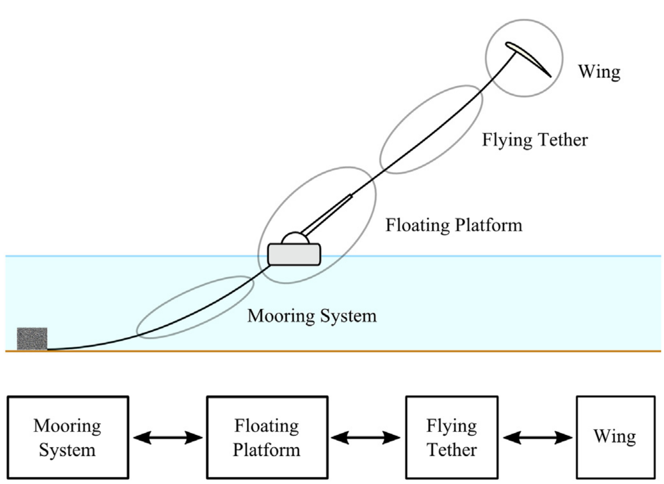

Fig. 1. Schematic layout of an offshore Airborne Wind Energy Converter – The four subsystems composing an offshore AWEC are shown, i.e. wing, tether, floating platform and mooring system. The forces transmitted among the chain of components are indicated in the block diagram.

3. Model

This section describes the simple model shown in Fig. 1 that has been taken as reference for the numerical study provided in the following section.

3.1. Hydrodynamic model

The offshore floating platform is modelled as a heaving rigid body having only 1 DoF. This approximation, often assumed in the preliminary design phases of buoy-like Wave Energy Converters (WECs) [24], limits the capability and accuracy of the model. However, this approach is very useful to provide a first (quick) insight into the global behaviour of the floating dynamic system.

The forces acting on the system are shown in Fig. 2. Under these assumptions, the vertical equilibrium of the platform yields

$$M\ddot{z}(t) = f_{\mathrm{h}}(t) + f_{\mathrm{g}} + f_{\mathrm{m}}(t) + f_{\mathrm{k}}(t) \tag{1}$$

where z is the heaving coordinate and M is the nominal mass, i.e. the actual mass of the floating platform. On the right-hand side of