Energy 71 (2014) 569–578

Contents lists available at ScienceDirect

Energy

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

Modelling of a synchronous offshore pumping mode airborne wind energy farm

J. Coleman*, H. Ahmad, E. Pican, D. Toal

Mobile & Marine Robotics Research Centre, Department of Electronic & Computer Engineering, University of Limerick, Limerick, Ireland

ARTICLE INFO

Article history:
Received 6 February 2014
Received in revised form
18 April 2014
Accepted 29 April 2014
Available online 2 June 2014

Keywords:
Airborne wind energy
Synchronous
Generator
Modelling
Power take off
Offshore

ABSTRACT

A wind farm for the deployment of pumping mode AWE (airborne wind energy) systems is presented in this paper. The topology presented is suitable for the deployment of such systems in a marine or similarly inaccessible environment. A brief technical description of AWE is provided, outlining the background, motivation and approaches taken by this emerging technology. A method of providing a continuous power supply from a cluster of AWE systems whose individual operation produces a periodic power supply is outlined. This method employs direct drive, directly interconnected permanent magnet synchronous generators on a local bus. A full-scale power converter is located at the point of grid connection, providing compliant power output for the remote cluster. In the case of a marine environment deployment, the power electronics are located onshore where maintenance and repair can be readily performed without the delays and costs associated with offshore maintenance and repair. The direct interconnection of synchronous generators introduces the requirement for a control system to control the connection of offline machines to the energised bus. A mathematical model of the system is outlined and the implementation of this model in Simulink is detailed. Simulation results under varied operating conditions are presented and discussed.

1. Introduction

The use of tethered wings or kites as the prime mover for a new form of wind energy has been under development for several years by a variety of international groups. First suggested in literature by Loyd [1], tethered wings may provide more economical access to wind energy as such systems avoid the large civil & structural requirements of conventional wind turbine systems. This paper presents a description, mathematical model & simulation of a synchronous AWE (airborne wind energy) farm, building on previously reported work of these authors in [2–4].

Conventional wind turbine designs utilise static towers to raise the system above ground level, into smoother, stronger wind; however, the maximum altitude possible is restricted by the trade-off between the structural capacity and the cost of production, transport and erection of large towers. An airborne system is by definition self-lifting; no tower and associated civil engineering are required to elevate the airfoil to the desired altitude. A tethered system is much less restricted in the maximum altitude achievable, limited primarily by the tether mass and drag at large lengths. With increased altitude above ground level, the wind speed increases in a predictable manner as governed by log and power laws within c.1 km of the Earth's surface [5]. With increased altitude, winds are also so more persistent and less turbulent [6,7]. This altitude range is within the operating range of most AWE prototype systems [8]. As no tower is employed, the heavy electromechanical power take off system can be relocated to ground level [8]. The aerodynamic forces act directly on the foundation of the system and not via a lever arm as illustrated in Fig. 1. This results in the elimination of the large moments and a low centre of gravity for the system compared to a floating wind turbine [9]. AWE systems are therefore readily suited to offshore floating platforms as the requirement for large counter balance structures is avoided.

While simplifying the civil and structural requirements the use of AWE systems requires the development of robust, automated control systems. The design of suitable power take off systems must also be undertaken. Consideration must be taken of the requirements of the TSO (transmission system operator) for systems intended for integration on an electricity distribution network [10]. The acceptability of AWE systems and their operating procedures to TSOs is of paramount importance for the successful development of AWE systems on a meaningful utility scale.

* Corresponding author. Tel.: +353 (0)61 202355.
E-mail addresses: joseph.coleman@ul.ie, josephcoleman0@gmail.com (J. Coleman).

http://dx.doi.org/10.1016/j.energy.2014.04.110
0360-5442/

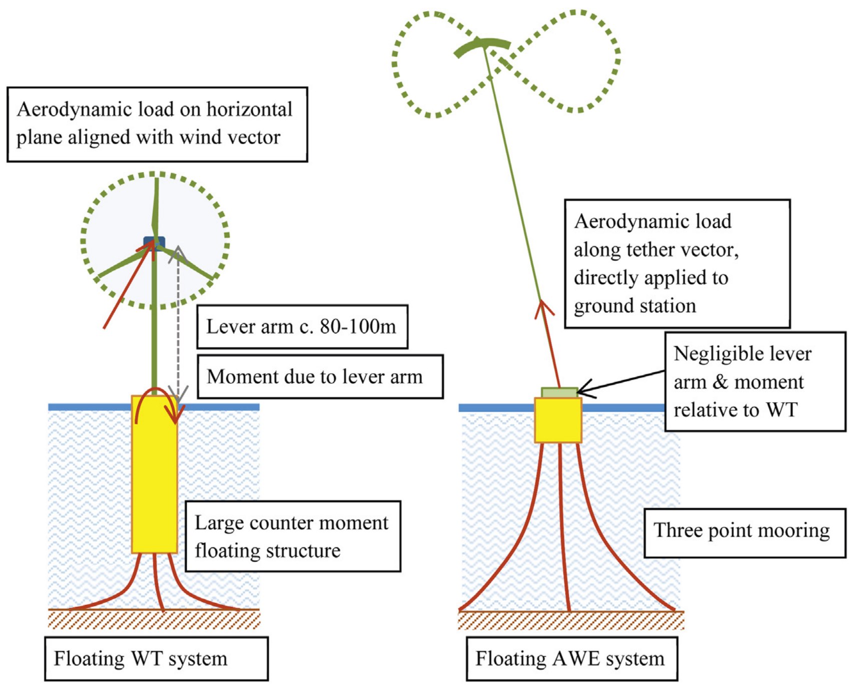

Fig. 1. Simplification of floating structure requirements for AWE system relative to wind turbine (WT).

Proposed designs and prototypes to date have taken several diverse approaches [11,8,12]. The common feature of these systems is a tethered wing flying in a crosswind flight path, while the major difference is whether the power take off occurs on board the airborne wing or on the ground. The airborne generation systems must carry the mass of the electrical machines and transmit the power produced using a medium voltage conductor within the tether [13]. The ground generation systems deliver mechanical power to ground level where the electrical power take off occurs. In such systems, the tether must only transmit mechanical loads and the wing is unburdened by electrical machines and propellers. A clear leader amongst these systems has not yet been established. Within ground based generation, there is further variety in how the mechanical power is delivered to the generator. The simplest and currently prevailing amongst these strategies is the pumping mode method, which is the focus of this paper. This implementation typically consists of an airborne wing, which is tethered to a winch anchored at ground level. A long high strength, lightweight tether connects the wing to the winch tether drum. The tether is typically a braided rope of ultra-high molecular weight polyethylene fibre, which offers excellent tensile strength to weight ratios; e.g. Dyneema [14]. The tether drum is mechanically connected to an electrical generator. The wing may consist of a rigid glider like structure or a quasi-rigid high strength polymer kite. A trade-off exists between the aerodynamic efficiency, wing loading and construction costs of the wing; hence, these differing topologies remain under development without a clear wining technology having yet emerged. The operation of a single pumping-mode cycle takes the following sequential form:

1. Following launch or a recovery phase, a power phase begins. The wing is flown by a controller in a periodic orbit (either a figure of eight helix or circular helix) about the wind vector in a high lift configuration. This produces a large tensile force in the tether, which unwinds from the drum at a regulated velocity. Mechanical power is delivered to the ground winch as the product of the tether tension and velocity. The power phase continues, with the wing gaining altitude as the tether unwinds until the maximum tether length is reached.
2. At the maximum tether length, the tether must be recovered onto the tether drum to facilitate a further power phase. The tether is recovered to the initial tether length by the recovery motor on the winch. To minimise the power consumption during this manoeuvre, the wing enters a minimum lift configuration by altering the wing profile and by ceasing crosswind manoeuvres. The recovery phase readies the system for the following power phase.

A single pumping-mode AWE system thus produces power in a reciprocating cycle, somewhat analogous to a slow, long stroke, single cylinder combustion engine. The power used during the recovery stroke of the airborne system is a small fraction of the power produced during the power stroke, resulting in a net positive power cycle as demonstrated in Refs. [15–17]. The wing may also be recovered at a greater tether velocity than during the power phase, minimising the time where power is not produced. Many pumping mode AWE designs call for the generator to be reversed to provide the recovery function (step 2). The authors propose an alternative method where the generator is not reversed, rather through the use of clutching mechanisms the reel out and reel in functions are separated [4,18].

As seen in the above sequence, the electrical power produced by any individual generator is periodic with the system consuming power for a portion of the cycle. To provide a continuous power output from an AWE unit, the recovery phase must be buffered by an additional power source, removing the periodic nature of its operation. Small-scale implementations of AWE may be able to supplement the power output with an auxiliary power source or storage methods. For larger scale implementations, storage methods may become uneconomical. To enable standalone operation from an individual unit, an energy storage method is required if the system power output is to remain at nominal during the recovery phase. Power exported during the production phase will be