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Operating cycle optimization for a Magnus effect-based airborne wind energy system

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ABSTRACT

The paper presents a control variables optimization study for an airborne wind energy production system. The system comprises an airborne module in the form of a buoyant, rotating cylinder, whose rotation in a wind stream induces the Magnus effect-based aerodynamic lift. Through a tether, the airborne module first drives the generator fixed on the ground, and then the generator becomes a motor that lowers the airborne module. The optimization is aimed at maximizing the average power produced at the generator during a continuously repeatable operating cycle. The control variables are the generator-side rope force and the cylinder rotation speed. The optimization is based on a multi-phase problem formulation, where operation is divided into ascending and descending phases, with free boundary conditions and free cycle duration. The presented simulation results show that significant power increase can be achieved by using the obtained optimal operating cycle instead of the initial, empirically based operation control strategy. A brief analysis is also given to provide a physical interpretation of the optimal cycle results.

1. Introduction

As the ground-based wind turbine systems (see [1] for a concise overview of their design aspects) approach their technological limits, while also suffering from the intermittent nature and relatively low speed of near-surface winds, a number of airborne wind energy (AWE) systems have been proposed within the last decade. The development of AWE systems is motivated by significantly higher available wind power at high elevations. It is shown in [2] that the increase in wind power density with height in the region of 80–500 m is about 0.25 $\mathrm{kW/m^2/m}$ for median winds (present 50% of the time or more), and that there is a several fold potential increase in mean wind power density if the height is increased from 100–150 m to 500–1000 m. The study presented in [3] concentrates on altitudes accessible to the current and planned AWE concepts and finds that locations with particularly strong and relatively steady winds at altitudes below 3000 m are more common than previously thought. The preliminary calculations of the same study indicate that the energy production potential of the AWE systems exploiting such winds can surpass the 2012 global electricity demand by a factor of three.

An extensive overview of the current AWE concepts and present challenges is available in [4], while a summary of the field is given in [5]. One of the main distinctions between the systems is in the location of the generator. There are two basic arrangements: on-board generators (OBG), which are attached to the airborne unit, or ground-level generators (GLG), which are fixed on the ground [5]. For example, the ascending-descending kite-based “Laddermill” [6] and “Kite-Gen” [7] systems are examples of GLG systems, and use flexible wings to generate lift. A rigid stationary tethered rotorcraft system, an example of OBG system, is discussed in [8]. A lighter-than-air flexible stationary system that also uses an OBG is presented in [9]. For an OBG system that uses a rigid, glider-like flying structure that moves in a crosswind direction, see [10].

The airborne wind energy system considered in this paper [11,12], consists of an airborne module (ABM) connected by a single tether (rope) to the winch-generator system located on the ground (Fig. 1a). A wind stream produces the Magnus effect-based aerodynamic lift on a rotating cylindrical balloon, thereby driving the generator in the ascending phase. The generator drives the winch in the motoring mode to pull the ABM down during the recovery phase. The rotation of the cylinder is accomplished using an electric drive attached to the ABM (the tether has a dual function of both the mechanical and the electrical link with the ABM). Previously conducted theoretical studies [12] and, in particular, preliminary proof-of-concept experimental results [11]

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have shown that the energy production based on the proposed concept is viable. To achieve a smooth grid power delivery during the entire operating cycle (Fig. 1b) despite the inherently intermittent power production response of the described system, the ground station unit should be equipped with an electric storage subsystem [13]. The storage subsystem stores the energy produced during the ascending phase, and supplies it to the grid and the generator during the descending phase, thereby providing steady grid power over the whole operating cycle.

An important objective for the overall system development is to design a control system required to facilitate continuous cyclical operation while maximizing the produced mechanical power transferred by the rope to the winch. Based on the ABM control-oriented 2D dynamics model initially outlined in [12], it is useful to conduct open-loop (off-line) control optimization studies, which can be used as an insightful basis and a benchmark for the development of realistic, closed-loop control systems. Such an optimization study is the main subject of this paper, noting that similar studies have thus far been conducted mainly for GBG AWE systems that are kite or wing-based, e.g. [14–17], which are aerodynamically quite different from the Magnus effect-based concept presented herein, and for which it is well known that a crosswind motion is preferable [18].

The cost function to be minimized relates to the negative value of the average power produced at the generator during a single, repeatable operating cycle. The control variables are the rope force at the winch and the cylinder rotation speed. The problem formulation and related optimization results are presented in a gradually refined form. The results of simpler formulation stages serve as a guide on how the optimization problem formulation could be improved to better suit the goal of maximizing energy production during continuous operation, i.e. over an arbitrary number of consecutive, repeatable operating cycles. Between different stages of problem formulation, the constraints, boundary conditions and even the cost function were readjusted according to this goal. The final formulation is based on multi-phase optimization, by dividing the time horizon into ascending and descending phases, with free initial and final conditions on ABM state and control variables, as well as free cycle duration. Periodicity constraints are imposed to ensure repeatability of the obtained cycle. The problem is solved numerically using the TOMLAB/PROPT software tool [19], which is an optimal control platform intended for integration with the Matlab package.

The results obtained in Tomlab have been verified by means of numerical simulations, using the optimized control variables as inputs of the ABM simulation model. The optimal cycle power production results are compared with those obtained by the existing heuristic control system [12] to analyse the potential for future improvements by means of control strategy enhancement. An algebraic analysis of the optimal operating cycle is also presented, in order to provide its physical interpretation. This knowledge provides insight into the optimal system behaviour and is required to determine a control strategy aimed to approach the optimization results in a robust manner. Therefore, the main contribution of the paper is in determining considerably different and more productive operation compared to that obtained by the existing control strategy [12], as well as a better understanding of optimal behaviour of the novel Magnus effect-based AWE system.

Even though the presented optimization study has been applied to the particular airborne wind energy system, it illustrates how advanced numerical optimization methods and tools, combining control variable and parameter optimization, can be used to gain insights into optimal behaviour of complex energy conversion and management systems in general, such as those considered in [20], where power production of a conventional wind turbine was maximized by means of appropriate turbine speed control, and [21], where overall efficiency of an IC engine-powered vehicle was maximized by optimizing the energy management of its electric energy storage system.

2. Process model

A model used for the purpose of ABM control system design, and in particular for numerical optimization of control variables, should be as simple as possible. At the same time, it should reflect the basic dynamics of the system. To satisfy these requirements, a simple 2D ABM state-space dynamics model based on the approach introduced in [12] is used throughout this paper. The presented model has been refined into a more complete model in [22], to account for many effects that were disregarded here for the sake of computational efficiency, such as elasticity and inertia of the rope, inertia of the winch and aerodynamic drag of the rope. Such a model would be suitable for final control system design and simulation purposes.

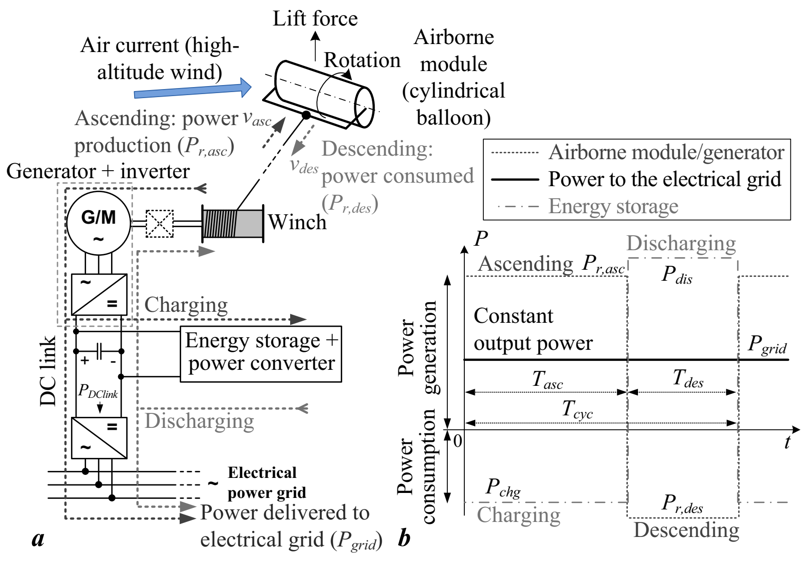

Fig. 1. Schematic of the system (a) and illustration of its idealized power cycle (b).