Modeling, parameterization and damping optimum-based control system design for an airborne wind energy ground station power plant

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\begin{abstract}
This paper presents the results of modeling and parameterization of the high-altitude wind energy system ground station power-plant equipped with a generator/motor unit as a primary power source tethered to the airborne module via a winch system, an ultracapacitor energy storage system, and grid inverter connected to the common direct-current link. Consequently, a suitable ground station power plant control strategy is designed, comprising the generator/motor speed control and cable tension control system, direct-current link power flow coordination control, and grid-side inverter control strategy. Control system design is exclusively based on the damping optimum criterion which provides a straightforward way of closed-loop damping tuning. The effectiveness of the proposed ground station control strategy is verified by means of comprehensive computer simulations. These have pointed out to precise coordination of the winch electrical servodrive with the airborne module-related rope force control system and sustained power production during the airborne module ascending phase in the presence of high-altitude wind disturbances, and continuous power delivery to the grid-side inverter, facilitated by the utilization of ultracapacitor energy storage. This indicates rather robust behavior of the overall ground station control system under anticipated external disturbance conditions.
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1. Introduction

Even though the possibility of harnessing of the relatively steady high-altitude/high-speed wind power has been continually studied since the early 1980s (see e.g. [1]), it has become increasingly attractive over the last decade. This is primarily due to inherent limiting factors of ground-based wind-turbine systems related to the size constraints of the turbine blade and the generator, high investment costs, and relatively unpredictable nature of near-surface winds. One of the key advantages of high-altitude wind energy (HAWE) systems over traditional wind turbine-based systems is that the HAWE system power-plant is located at the ground level, so that the winch machine size and power ratings are no longer an issue. Hence, a number of studies have been carried out up to date, concerning many theoretical aspects of high-altitude wind power system modeling and airborne module (ABM) control, and various practical aspects of airborne module vs. ground station interaction and airborne module trajectory optimization.

In particular, Ref. [2] has shown that detailed modeling of airborne module aerodynamic behavior represents the key prerequisite for the development of suitable ABM guidance strategies and flight control trajectory optimization based on nonlinear model predictive control (MPC) approach. The effectiveness of MPC-based trajectory optimization approach has been subsequently verified in [2] by means of detailed computer simulations and experiments based on a scaled-down high-altitude wind energy system prototype. The airborne module, typically being tethered to the ground station via a winch system and a suitable generator/motor unit, interacts with the ground station through tether tension force, which also mandates a detailed analysis of ABM/tether/winch system, as outlined in [3]. To this end, Ref. [4] has proposed a multi-segment tether model in order to model the spatially-distributed (so called catenary) shape of the rope in a systematic and straightforward manner, which also inherently includes the tether dynamic behavior and compliance effects. Based on such ABM dynamic models, the airborne unit flight-path-related cycle energy production can be analyzed, as shown in [5], and the energy efficiency of the prospective flight trajectories can be calculated, as illustrated in [6]. Naturally, ABM trajectory (flight path) optimization may also be used for the purpose of on-line maximization of net energy gain [7]. In order to gain the theoretical limit of net energy production, off-line optimization of the airborne module trajectory and the energy production can be based on the solving of the non-linear programming (NLP) problem, as shown in [8]. In particular, the dynamic state equations of the
highly-specialized turbine configurations and turbine blade designs [11]. Different variable-altitude systems that produce upward lift force by using a parasail-based flying wing configuration have also been considered, either in the form of a single unit [12], or a multiple parasail-unit system [13]. In the latter case, multiple units may provide additional control authority, and continuity of resulting tether pulling force. An alternative approach has been considered in [14], based on positive-buoyancy rotating airborne balloons aimed at exploiting the so-called Magnus’ effect between high-altitude winds and airborne unit rotating body. Alternative uses of high-altitude wind energy harvesting systems, such as those for wind-assisted marine propulsion have been investigated in [15], and their power production potential has been investigated with respect to high-altitude parasail vs. ship’s course and speed. Note also that suitable geographical locations need to be identified before high-altitude wind energy systems are fielded, which suggests certain limitations to the breadth of their implementation.
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