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Energy storage systems sizing study for a high-altitude wind energy application

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ABSTRACT

As the ground-based wind-turbine systems have steadily reached their performance peak due to turbine blade size limitations, generator size constraints, high investment costs, and relatively unpredictable nature of near-surface winds, the possibility of harnessing the energy of steady, high-altitude/high-speed winds has become increasingly attractive within the last decade. However, due to the intermittent nature of power production of a considered high-altitude wind energy system utilizing an airborne module tethered to a ground station, sufficiently large energy storage is required in order to provide steady power supply to the electrical power grid. This paper focuses on the sizing of typical low-to-medium scale energy storage systems (up to 10 MW), such as those based on flywheels, compressed air, batteries and ultracapacitors, considering the intermittent power production cycle, airborne module altitude range and ground-station generator power ratings. The assessment results are summarized in terms of investment/running costs, storage system size, and durability, thus providing practical guidelines for the selection of appropriate energy storage system.

1. Introduction

Even though the possibility of harnessing the energy of steady, high-altitude/high-speed winds has been studied since the early 1980's [1], it has become increasingly attractive in recent years [2] due to inherent limiting factors of ground-based wind-turbine systems such as the turbine blade size and generator size constraints, high costs, and relatively unpredictable nature of near-surface winds. As a result, a number of HAWE (high-altitude wind energy) concepts have been proposed within the last decade [3–10], including operational small-scale prototypes [3,4]. All these concepts include an airborne module for power production, such as a single kite or a parasail [3,4,8], a multi-tier kite/sail configuration [5], or a rotating-balloon airborne module configuration [6,7,9]. The airborne module is typically tethered via cable to the winch system coupled to an electrical machine (generator/motor) located at the ground level (see Ref. [4]), or on an off-shore platform (e.g. on a marine vessel [10]). Therefore, the electrical machine size and power ratings are less prone to limitations encountered in traditional wind-turbine systems. However, such high-altitude wind energy harvesting concepts are characterized by inherently intermittent power production due to the limited lengths of tethering cables which mandate periodic cable winding and unwinding. In order to mitigate the intermittence issues and to provide continuous grid power delivery, a sufficiently large energy storage system may be required.

In order to gain good insights into the energy storage systems suitable for HAWE applications, this paper first reviews and compares the typical energy storage systems suitable for low-to-medium scale (e.g. up to 10 MW) renewable (wind-based) energy applications, such as flywheels [11], compressed air (hydropneumatic accumulators) [12,13], batteries [14,15] and ultracapacitors (supercapacitors) [16,17]. The design (sizing) of energy storage system starts with an analysis of the HAWE system power profile (see e.g. Refs. [18,19]) aimed at finding the required energy storage system capacity. The sizing study is first performed for a hypothetical 250 kW peak power HAWE system, in order to develop a unified energy storage system sizing technique based only on the anticipated HAWE system power cycle and related energy storage (capacity) requirement. The results are then individually applied to flywheel, hydropneumatic accumulator, battery and ultracapacitor storage systems sizing, including their comparison with respect to investment/running costs, storage system size, and durability. The proposed approach is further broadened based on a more detailed study covering a rather wide HAWE system

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power production and airborne module altitude range, thus resulting in a systematic approach to selection of viable energy storage system solutions for realistic HAWE system ground station arrangements. The proposed methodology could then be used for the sizing and selection of energy storage system and related ancillary equipment of the HAWE ground station system prototype, thus providing a useful tool for the minimization of prototype initial and running costs in preparation for the experimental verification of the anticipated HAWE system functionality.

The paper is organized as follows. In Section 2, the operation of the aimed HAWE system is outlined and a steady-state power flow analysis is performed for a characteristic power–generation cycle. Flywheels, compressed air energy storage systems, batteries and ultracapacitors are surveyed in Section 3. Section 4 illustrates the energy storage sizing methodology on the example of a 250 kW peak power HAWE system, while Section 5 presents the results of energy storage system sizing for a wider range of HAWE ground station peak power production and airborne module altitude range. Concluding remarks and discussion on future research directions are given in Section 6.

2. Concept of HAWE system

This section outlines the HAWE (high-altitude wind energy) system concept proposed in Refs. [6,7,9], including the steady-state energy flow analysis of its intermittent power generation cycle.

2.1. HAWE system overview

The HAWE system concept, shown in Fig. 1a, includes an airborne module shaped as a cylinder (balloon), which is aimed at exploiting the so-called Magnus effect on a rotating body in an air current, wherein a notable lift force can be generated [6,7,9]. This lift force can then be used for electrical power production, where the airborne unit connected to a winch system via a cable (tether) drives an electrical machine M/G (motor/generator). The ground station system is equipped with a regenerative power converter in a so-called back-to-back dual-converter configuration (see e.g. Ref. [20] and references therein) comprising a dedicated M/G machine inverter and a grid inverter connected to a common DC link (Fig. 1a), along with an energy storage system. The energy storage system should also be equipped with a power converter, wherein the power converter type depends on the type of energy storage system used (an inverter in the case of flywheel and hydro-pneumatic system, and a DC/DC power converter in the case of battery and ultracapacitor system).

During the power production cycle (ascending time interval T_{asc}, Fig. 1b), the airborne module increases the lift force in order to ascend and unwind the cable, thus resulting in power generation. In that case the electrical machine feeds the power grid and the energy storage system equipped with its dedicated power converter through the common DC link. After the maximum altitude is reached (dependent on the cable length), the airborne module substantially reduces the rotational speed and lift force, thus allowing for relatively low-power cable winding. The electrical machine now operates as a motor (over a time interval T_{des}), wherein the motor electrical power and the grid power are supplied from the energy storage system through the common DC link. Since it is generally desirable that the grid is supplied by constant power (no output power fluctuations), the proposed ground station system needs to be equipped with an appropriate energy storage system and a related energy management control strategy.

2.2. HAWE system grid power delivery and energy storage requirements

The available power to the grid and the energy storage requirement of the HAWE system in Fig. 1 are determined based on

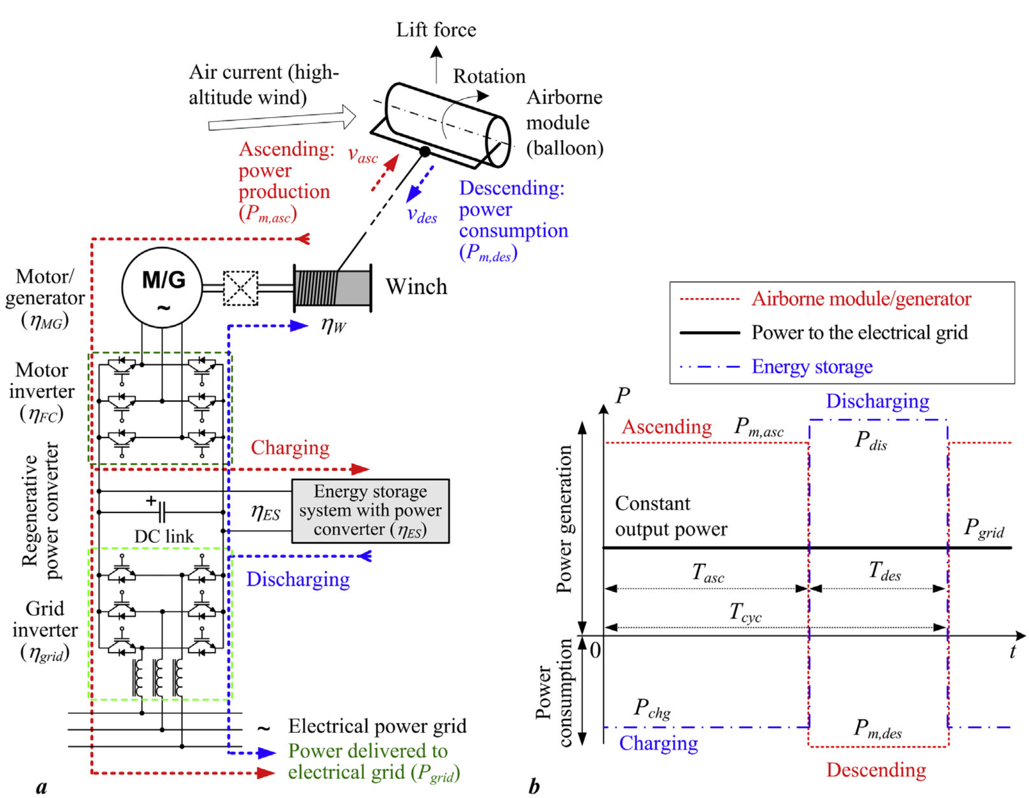

Fig. 1. Simplified representation of HAWE system (a) and illustration of its power cycle (b).