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

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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.

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

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Nomenclature

Abbreviations

ABM	airborne module
DC	direct current
ESS	energy storage system
HAWE	high-altitude wind energy
LCL	inductive-capacitive-inductive
PI	proportional-integral
PLL	phase-locked loop
PMSM	permanent-magnet synchronous machine
PWM	pulse-width modulation
SRF	synchronous reference frame
d-q	direct-quadrature

Dynamic variables

ˆ	estimated value
$A_c(s)$	closed-loop characteristic polynomial
F_r, F_R	rope pulling force and rope force reference [N]
i_a, i_b, i_c	instantaneous phase currents [A]
i_{uc}	ultracapacitor current [A]
i_{ESS}	storage system current [A]
i_1, i_2, i_f	LCL filter current components [A]
i_d, i_q	direct and quadrature current components
l_r	unwound rope length [m]
P_c	ultracapacitor power [W]
$P_{dc,mg}$	motor/generator power [W]
P_{dcR}	DC link power reference [W]
P_{ESS}	energy storage system power [W]
P_{grid}	grid inverter active power [W]
P_g	generator/motor mechanical power [W]
P_{loss}	power losses map [W]
P_L	grid inverter load [W]
$P_{m,asc}$	power at winch during ABM ascending [W]
$\|P_{m,des}\|$	power at winch during ABM descending [W]
Q_{grid}	grid inverter active power [VAr]
S_{grid}	grid inverter apparent power [VA]
s	Laplace operator [s^{-1}]
u_1, u_2	LCL filter input and output voltage [V]
u_a, u_b, u_c	instantaneous phase voltages [V]
u_{dc}, U_{dc}	instantaneous and average DC link voltage [V]
u_d, u_q	direct and quadrature voltage components [V]
Δu_d, Δu_q	d-q axis cross-coupling terms [V]
u_{uc}	ultracapacitor terminal voltage [V]
U_{c0}	ultracapacitor stack idle voltage [V]
v_{asc}, v_{des}	ABM ascending and descending speed [m/s]
W_{dc}, W_{uc}	DC link and ultracapacitor energy [J], [kW h]
τ_g, τ_w	generator and winch torque [Nm]
ξ	ultracapacitor state-of-charge
θ	grid voltage phase angle [rad]

Parameters

C_{3f}	LCL filter capacitance [F]
C_{dc}	DC link capacitance [F]
C_{uc}	ultracapacitor ESS capacitance [F]
D_i	damping optimum characteristic ratios ($i = 2 \dots n$)
f_{grid}	grid voltage frequency [Hz]
J_{tot}	total inertia at winch side [kg m^2]
J_w, J_m	winch and generator inertia [kgm^2]
$K_{c\omega}$	PI speed controller proportional gain
K_{ci}	current controller proportional gain
$K_{e\omega}$, K_{eF}	Luenberger observer correction gains
K_{pll}	PLL proportional gain
K_{Rdc}	DC link PI controller proportional gain
K_{RP}, K_{RQ}	grid inverter power controller proportional gains
K_ξ	state-of-charge controller proportional gain
L_{1f}, L_{2f}	LCL filter reactor inductances [H]
L_{dc}	storage system inductances [H]
m_{ABM}	airborne module mass [kg]
Q_{max}	ultracapacitor charge capacity [As]
r_W	winch radius [m]
R_{3f}	LCL filter capacitive branch resistance [Ω]
R_{1f}, R_{2f}	LCL filter reactor Ohmic resistances [Ω]
R_s	ultracapacitor ESS series resistance [Ω]
T_{asc}, T_{des}	duration of ABM ascending and descending [s]
$T_{c\omega}$	PI speed controller integral time constant [s]
T_{ci}	current controller integral time constant [s]
T_e	damping optimum equivalent time constant [s]
T_{Idc}	DC link PI controller integral time constant [s]
T_{IP}, T_{IQ}	grid inverter power controller time constants [s]
W_{st},	ESS energy storage requirement [J], [kW h]
$W_{st,adj}$	ultracapacitor energy storage capacity [J], [kW h]
Δh	ABM altitude range [m]
η_W	winch system mechanical efficiency
η_{MG}	generator/motor efficiency
η_{FC}	generator/motor power converter efficiency
η_{ESS}	energy storage system efficiency
η_{grid}	grid inverter efficiency
η_g	generator/motor and power converter efficiency
κ_{os}	energy storage over-sizing factor
ζ	closed-loop damping ratio
ω_g, ω_w	generator and winch angular velocity [rad/s]
ω_R	generator angular velocity reference [rad/s]
ω_{grid}	grid voltage frequency [rad/s]

airborne module system and its interaction vs. ground station winch system through the compliant tether have been transformed in [8] into a spatially-discretized grid based on polynomial approximations suitable for NLP optimization problem by using the so-called pseudo-spectral collocation method. Finally, ABM trajectory profiles may also be used for the assessment and subsequent selection and optimization of ABM monitoring and control hardware based on the overall system performance requirements [9].

An interesting avenue of research in this field has been dedicated to investigation of novel airborne unit designs, such as lighter-than-air turbine systems for fixed-altitude power production [10]. These types of fixed-position high-altitude turbine systems may, in turn, feature 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