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Hybrid Storage System Control Strategy for All-Electric Powered Ships

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Abstract

In marine applications all-electric propulsion systems are employed on surface ships that are subjected to particular constraints, generally due to environmental restrictions. The technological advancement of electrochemical batteries, which are today characterized by higher capacity and efficiency, has widened their fields of application, although these storage systems require an accurate design to limit their initial and maintenance costs. In order to reduce battery charge and discharge peak currents, supercapacitor modules are generally adopted with the aim to extend batteries expected life. The proper management of energy fluxes within the hybrid architecture, and in particular among batteries, capacitors and loads requires a specific control, called EMS – Energy Management Strategy. In this paper, a novel EMS, based on constrained minimization problem, is proposed and verified with reference to a case study of a waterbus operating in restricted waterways on different routes. The procedure is based on a preliminary solution of an off-line optimization with respect to a known mission profile. Hence, a real-time control strategy is properly evaluated, in order to guarantee robustness against the unavoidable uncertainties, which occur during the operating conditions. In the last part of the paper, a numerical application is presented with the purpose to emphasize the feasibility of the proposal.

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Keywords: All-electric ship, EDLC, Energy Management Strategy, Hybrid energy storage system, nonlinear programming

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1. Introduction

As a result of the environmental concern about air pollution, more and more are marine applications where traditional thermal engines are not the best option to cope with regulation limits and constraints, as in the case of passenger transportation in coastal cities waterways or in marine protected areas. In such areas Zero Emission Vehicles (ZEV) are desirable or, as in marine protected areas, compulsory, so electric motor is considered as the best candidate to take the place of the internal combustion engine.

Clean electric power can be generated on board by using renewable energy sources (such as solar energy), fuel cells or batteries. In the first case, the peak power is generally limited by on board space constraints, whereas fuel cell applications are still affected by safety issues, related to the on board hydrogen storage, which involve higher management costs and design limitations. On the other hand, recent battery technologies based on lithium compounds are characterized by reduced cost and high performance in terms of energy density. These characteristics justify the growing interest towards the use of all-electric propulsion for surface ships, where the electric motor is supplied only by the on-board battery pack. Moreover, ships are generally less sensitive to weight constraints, in comparison with road applications and for this reason a higher amount of energy can be stored on-board.

Various requirements should be taken into account for the proper design of the on board battery pack. In particular, the number of battery elements to put onboard mainly depends on the amount of energy, which is required to complete the ship mission on an assigned route; the state of charge at the end of the working period should not be lower than a minimum value, that depends on the specific battery technology, as the depth of discharge affects the expected life of the battery. In addition, as widely recognized in the scientific literature [1], the expected battery lifetime is also affected by the number of charging/discharging cycles and high peak current values. As a consequence, the use of hybrid energy storage systems, combining batteries with high power density devices, such as super-capacitors, appears to be an attractive solution to improve the whole energy storage performance in terms of lifetime and efficiency. In fact, peak power values required by the electric drive can be conveniently supplied by supercapacitors, through the proper management of on board power electronics devices.

In the above context, the main contribution of this paper is focused on optimal energy management strategies (EMS) for a hybrid energy storage system, with reference to the case study of an all-electric ship. In particular, off-line and on-line EMS have been evaluated, with the aim of reducing the effects of high charging/discharging current values on the expected battery lifetime. Simulation results have shown the convenience of using the proposed energy management strategies for different energy storage system configurations.

Nomenclature

$d\lambda$	Adaptive term of the adaptive scheme for lambda control EMS
EMS	Energy Management Strategy
$Eff_{\%}$	Efficacy of the Energy Management Strategy
f_0	Cutoff frequency of current filter in adaptive control scheme
Φ	Lambda control EMS objective function
HESS	Hybrid Energy Storage System
I_b	Current supplied by the battery
I_b^*	Battery current reference
$I_{b\lambda}$	Battery current reference provided by Lambda control EMS before SC current-voltage limitation
I_{sc}	Current value in supercapacitors modules
I_{sc}^*	Reference current value of supercapacitors modules
I_{DC}	Current supplied by SC modules to the electric drive
$I_{DC\lambda}$	Reference current supplied by SC provided by Lambda control EMS before SC current-voltage limitation
I_t	Current requested by the electric drive
k_1, k_2	Adaptive scheme parameter for lambda control EMS
k_{lim}	Limitation status variable
λ	Lambda parameter used for lambda control EMS
λ_0	Lambda parameter of lambda control EMS obtained with offline procedure