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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

OCV	Open Circuit Voltage
P_t	Electric drive requested power
P_b	Power supplied by battery
P_{sc}	Power supplied by supercapacitor module
R_b	Battery model resistance
SC	Supercapacitor
T	Operation time of the waterbus over a defined pattern
V_b	Battery and dc-link voltage
V_{Sc}	Supercapacitor modules voltage

2. Case study description

The case study of a water bus is considered in this paper, in order to evaluate the convenience of using proper energy management strategies in hybrid energy storage systems for marine applications. In particular, the proposed case study is referred to a member of the fleet for passenger transportation, through waterways, in Venice. This fleet is characterized by repetitive routes, high number of boats and passengers.

The typical ship has an overall length around 23 m and a full load displacement of 55 t with 220 passengers. The propeller is powered by a diesel engine of 130÷140 kW at 1800 rpm.

The allowed speed in the lagoon is strictly ruled to limit channels wall erosion; in the Grand Canal the maximum speed is 7 km/h (3.8 kn), in the Giudecca channel is 11 km/h (6.0 kn) and 20 km/h (10.8 kn) in open waters. As a result of these limitations, the required power for steady state conditions is lower than that installed onboard; navigating along Grand Canal requires 25÷30 kW (~20% of the engine rated power) while during navigation at high speed power is 70÷75 kW. In transient and maneuvering the power demand increases up to 120 kW and it is important to observe that, during these phases, ship propeller is not able to recovery the braking energy that, on the contrary, has to be supplied by the prime mover; the engine maximum power is useful to improve ship safety when sailing in restricted and congested waters.

The power supply profile appears very unsteady and its irregularity is determined by the number of stops and speed limits active along the route.

ACTV, the Venetian public transport company, operates waterbuses on different routes, the most important ones connect the mainland (Piazzale Roma) with very popular and famous sites as Piazza San Marco and Lido, through the Grand Canal or circumnavigating the center through the Giudecca channel.

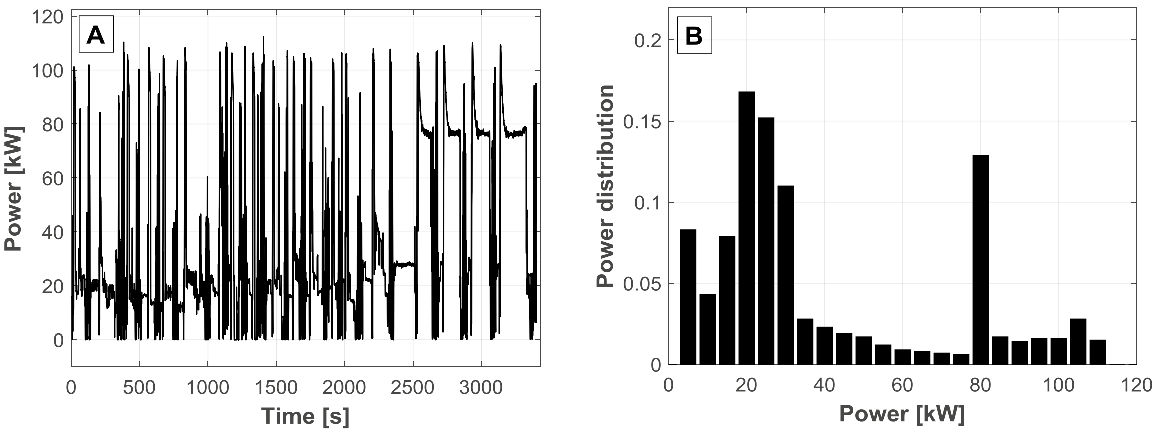

Figure 1 - Shaft power profile (A) and power distribution (B) during a single route from Piazzale Roma to Lido

The route through the Grand Canal has been considered in this paper; it presents a high grade of irregularity due to the numerous stops, which averagely occur every three minutes, so that the boat works in transient conditions for the most part of the time.

The mission profile, in terms of power versus time (A) and power distribution (B), is shown in Figure 1.

In this case, internal combustion engine specific fuel consumption and exhaust emissions values are much higher than the rated ones, because the engine works far from its ideal conditions.

As shown in Figure 1, the considered power profile is characterized by low average values and high peak values, which occur during the acceleration phases. As mentioned in the Introduction, this kind of profile can be efficiently supplied by a hybrid storage system, which combines batteries and supercapacitors.

3. Energy Management Strategy formulation

For the presented case study, a hybrid energy storage system, based on a combination of a ZEBRA battery pack and electric double layer capacitors, is considered. The electric power required by the electric drive has been calculated from mission power profile depicted in Figure 1-A, under the hypothesis of an overall efficiency of 80%.

The number of Zebra Battery cells is sized applying a stochastic procedure in order to guarantee sufficient waterbus cycling tasks and minimizing costs as suggested in [2]. The considered supercapacitor system is a 63 F Maxwell BMOD0063 P125 module with a rated voltage of 125 V and a weight of 61 kg. For the evaluations reported in this paper, the number of supercapacitors modules has been considered as a variable parameter, in order to quantify the combined effects of the EMS for different energy storage system configurations on the considered power distribution profile. In addition, under the hypothesis of fixed DC-link voltage, the electric drive is considered as a variable DC load, which is supplied by the batteries and supercapacitor modules. The water-bus propulsion system can be schematized as reported in Figure 2.

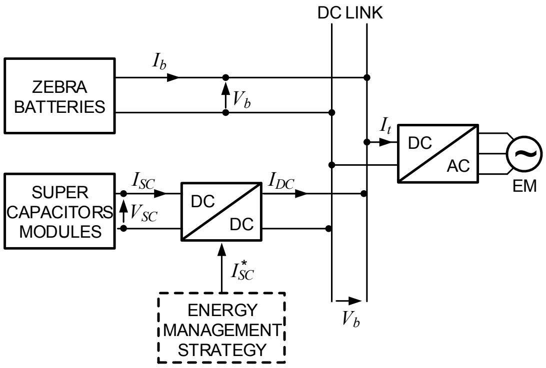

Figure 2–Block scheme of the water-bus propulsion system

The power exchange between the storage units of the HESS is managed by means of a DC/DC bidirectional converter, which can be controlled through the supercapacitor current reference I^*_{SC} [3].On this purpose, a lambda control EMS [4] can be considered as on line EMS. This last EMS considers the following objective function reported in (1):

$$\Phi = \int_0^T i_b^2(t)dt \tag{1}$$

The above function can be considered for a specific working cycle as representative of the battery lifetime reduction, related to peak charging/discharging current values [5]. Lambda control EMS aims to calculate of the optimal value of battery current $i_b(t)$ with the advantage of low computational effort and near-optimal behavior. To obtain the EMS control equation, the following simplified hypotheses are considered.

- The considered battery model is based on the well-known equivalent series resistance model with a voltage source, representing the open circuit voltage, OCV, and a series resistance R_b.As a consequence, battery voltage v_b can be written as reported in the following equation (2):

$$v_b(t) = OCV - R_b i_b(t) \tag{2}$$

- The supercapacitor modules are considered as an ideal equivalent capacitor and are described by the equation (3):

$$i_{sc} = C\dot{v}_{sc} \tag{3}$$

- The DC/DC is modeled as an ideal device without power losses. For this reason, the input/output power balance of the DC/DC converter can be written as in the following equation (4).

$$v_{sc} i_{sc} = v_b i_{dc} \tag{4}$$

- The supercapacitors modules are used only as an energy buffer, so the energy supplied by supercapacitors on a considered working cycle is null, as shown in the equation (5)

$$\int_0^T P_{sc}(t)dt = 0 \tag{5}$$

problem can be stated as it follows:

$$\min_{\mathrm{i_b(t)}} \Phi(T)$$

Subject to:

$$\int_0^T \big(OCV - R_b i_b(t)\big)\big(i_b(t) - i_t(t)\big)dt = 0 \tag{6}$$

The above formulation can be seen as an isoperimetric problem, which can be solved through the theory of Calculus of Variations [6]. According with that theory, the Lagrange function can be written as:

$$L(i_b, \lambda) = \int_0^T i_b^2(t)dt + \lambda_0 \int_0^T \big(OCV - R_b i_b(t)\big)\big(i_b(t) - i_t(t)\big)dt \tag{7}$$

Whereas, the optimal reference value of battery current i_b can be obtained solving the system:

$$\begin{cases} \dfrac{\partial}{\partial i_b}\left[i_b^2 + \lambda_0(OCV - R_b i_b(\mathrm{t}))(i_b(\mathrm{t}) - i_t(\mathrm{t}))\right] = 0 \\ \displaystyle\int_0^T (OCV - R_b i_b(\mathrm{t}))(i_b(\mathrm{t}) - i_t(\mathrm{t}))dt = 0 \end{cases} \tag{8}$$

The solution of (8) is a function of the parameter λ:

$$i_b(\mathrm{t}) = \frac{\lambda_0\big(OCV + R_b i_t(\mathrm{t})\big)}{2(\lambda_0 R_b - 1)} \tag{9}$$

This parameter can be calculated through the substitution of (9) in the second equation of (6). For this reason the equation (9) can be reformulated as it follows:

$$G(\lambda) = \int_0^T \left(OCV - R_b \frac{\lambda_0(OCV + R_b i_t)}{2(\lambda_0 R_b - 1)}\right)\left(\frac{\lambda_0(OCV + R_b i_t)}{2(\lambda_0 R_b - 1)} - i_t\right)dt = 0 \tag{10}$$

The integral equation (10) depends only on the traction current over the entire ship operation time. The λ_0 parameter can be evaluated with offline numeric methods using the known-in-advance requested current of the power train. The control scheme of this EMS is reported in Figure 3-A, where safety voltage and current limitations are added in order to guarantee safe operation of the HESS.

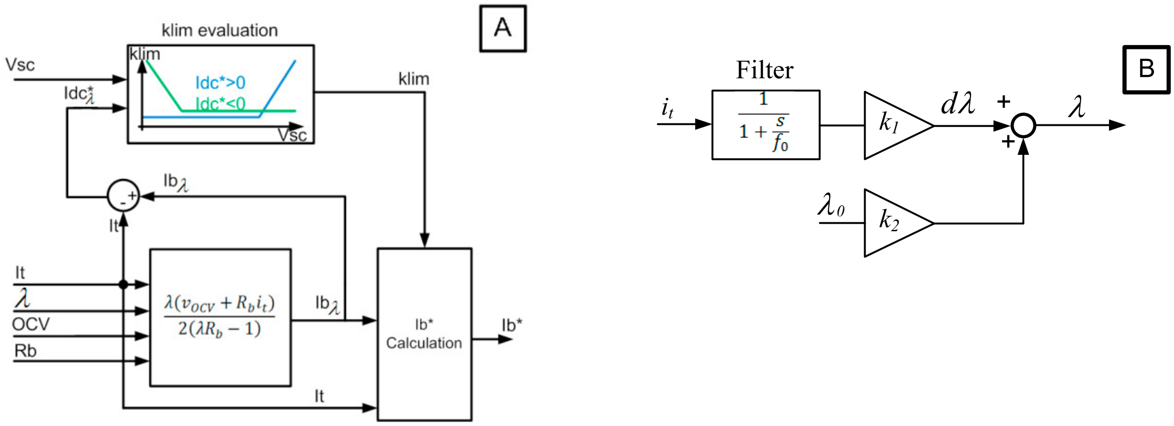

Figure 3 - Control scheme for lambda-control EMS (A) and adaptive λ parameter estimation (B)

The abovementioned limitations, which are contained in "klim evaluation" and "Ib* Calculation" blocks, can ensure safety in variable conditions, as example when variable and not known current profiles are requested over the operation time.

The adaptive scheme reported in Figure 3-B calculates adaptively lambda parameter, it has been considered in order to ensure optimal performances over the entire work cycle. For this scheme, the value of λ_0 parameter has been calculated by equation (10) and the term $d\lambda$ is provided by traction current filtering through the block "Filter". The parameter λ_0 has been calculated through the two terms using two weight parameters k_1 and k_2. The parameters f_0, k_1 and k_2 are obtained through an iterative simulation procedure, in order to minimize (1).

The proposed on-line EMS has been compared with an offline EMS, which cannot be considered suitable for real time control schemes due to high computational cost. Anyway, this offline EMS represents can be used as a benchmark to evaluate online EMS performance [7]. The considered offline EMS is based on the following constrained optimization problem, considering the hypotheses of equations (2)-(5):

$$\min_{i_b(t)} \Phi(T)$$

Subject to:

$$\int_0^T P_{sc}dt = 0 \tag{11}$$
$$v_{scmin} < v_{sc}(t) < v_{scmax}$$
$$i_{scmin} < i_{sc}(t) < i_{scmax}$$

Where for the selected SC module, voltage limits are 125-55 V and current limits depends on the number of considered SC modules. The problem (11) has been solved numerically using nonlinear programming through the use of Matlab-Simulink environment.

4. Simulation results

As already mentioned in Section 4, different number of supercapacitors modules are considered in order to evaluate the capacitance effects on EMS performances. In particular, the following three different values of capacitance has been considered: 120 F ("case a"), 500 F ("case b"), 1000 F ("case c"), which respectively correspond to 2, 8 and 16 supercapacitor modules.

The λ parameter value of the EMS has been evaluated for the proposed water-bus with reference to an idealized power profile, by using the equation (10) and adaptive scheme of Figure 3-B After the parameter identification phase, a simulation using an experimental power profile has been carried out. The simulation results in terms of power train and battery current for the "case b" are depicted in Figure 4-A. On the other hand, in Figure 4-B the main results for the "case b" with the offline strategy are reported.

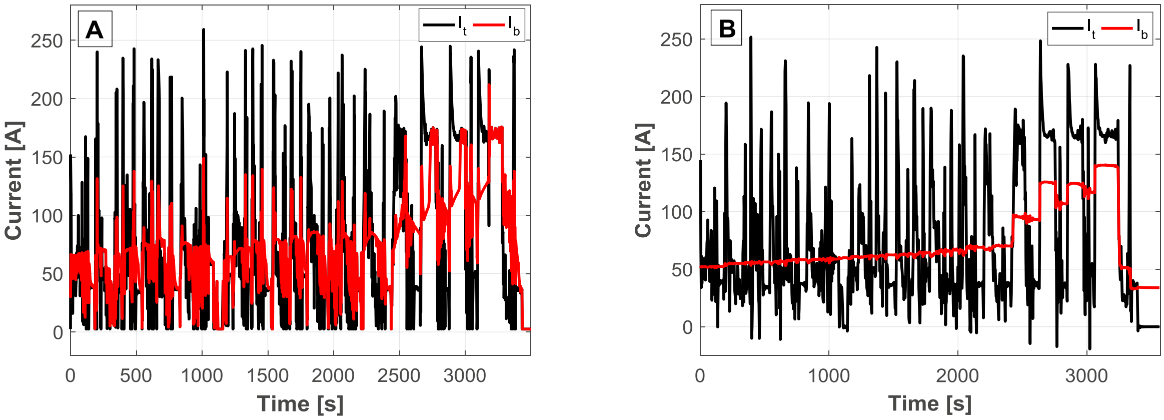

Figure 4– Lambda control EMS (A) and Offline EMS (B) results obtained for the case "b"

From the comparison between Figure 4-A and Figure 4-B, a difference between the two power train current, represented by the black traces, can be observed.

This is due to the simplifying hypotheses of the problem (11). In addition, it is clear that the current reference of the Offline EMS has less ripple current than the reference value provided by lambda control strategy. The highlighted difference is due to the non-causality of the offline one, it means that given a fixed time "t", the lambda control EMS calculates its battery current reference using information of the time interval [0,t] while the offline EMS uses the entire operation cycle information [0,T] that are known in advance.

A comparison between the power train, P_t, and battery, P_b, power evaluated from simulation in terms of stochastic parameters, is reported in Table 1.

Table 1. P_t and P_b comparison in terms of stochastic variables

Stochastic parameters	P_t	P_b (case "a")	P_b (case "b")	P_b (case "c")
Mean Value	34	34	34	34
Standard deviation	26	22	17	14
Max Value	114 kW	98 kW	92 kW	77 kW

The considered values are obtained using Matlab Simulink simulation environment. As clear from Table 1, the use of the supercapacitor can significantly reduce battery peak power up to about 32% and battery power standard deviation up to about 46%. From the values presented in Table 1 it can be observed that the correct sizing of SCs capacitance has a positive effect on battery sizing. In fact, the reduction of peak value and standard deviation of power requested to the battery P_b can reduce battery costs, as it can be seen in reference [2].

In order to quantify the stress reduction on battery package provided by the EMS, a simple index called "efficacy" based on objective function (1) has been defined:

$$Eff_{\%} = 100\frac{\Phi_{\mathrm{b}}(T) - \Phi_{\mathrm{bSc}}(T)}{\Phi_{\mathrm{b}}(T)} \tag{12}$$

Where $\Phi_{\mathrm{b}}(T)$ is the objective function of eq.(1) evaluated for battery current values obtained without using the SCs and $\Phi_{\mathrm{bSc}}(T)$ is the same function evaluated in SCs operation case. Towards this index, the optimized offline EMS and lambda control EMS performances are compared in Table 2.

Table 2. Efficacy of the EMS for different capacitor sizes indicated as cases a, b and c.

Efficacy	Lambda control EMS	Offline EMS
Case “a”	13%	17%
Case “b”	24%	29%
Case “c”	28%	32%

As reported in Table 2, the efficacy reached by the lambda control EMS is similar to the benchmark values provided by Offline EMS. It demonstrates the good performances of the control strategy and the advantages of using an HESS in order to reduce battery stress. Although the capacitance value is doubled, the variation of the index (12) between case “b” and case “c” is negligible. This observation highlights the relevance of the sizing process of the SCs modules which has to take into account technical and economical advantages of the use of SCs.

5. Conclusions

In this paper a new hybrid energy storage system has been studied for waterbus application. On the other hand, in order to define a real time EMS, it has been studied a simple EMS based on a reduced optimization problem. Different values of capacitance values have been considered in order to verify the capacitance size effects on the performances of the EMS. The analysis of the online EMS behavior has been carried out by simulation in Matlab/Simulink environment. The simulation results highlighted the battery stress reduction of the efficient use of supercapacitor in naval applications. A quantitative analysis has been carried out using statistic parameters of battery power and introducing an efficacy index of the strategy, used to quantify the battery losses reduction over the operation time. The control strategy proposed in this work obtains a positive value of efficacy due to its optimization based formulation but it still remains under the optimal EMS strategy due to the non-causality of the latter one. Other predictive and adaptive schemes can be further analyzed in order to obtain better values of efficacy for the considered operation cycle. Towards the sizing process of the SCs capacitance, the analyses highlighted the advantages of combined sizing process that involves both battery mass and capacitance value, it is also relevant to consider EMS strategy for sizing process.

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