A Hybrid Storage Systems for All Electric Aircraft

G. Bossi, A.Damiano
Dipartimento di Ingegneria Elettrica
Universitá degli Studi di Cagliari
Cagliari,Italy
damiano@unica.it

N. Campagna, V. Castiglia, R. Miceli, A. O. Di Tommaso
Dipartimento di Ingegneria
Universitá degli Studi di Palermo
Palermo, Italy
rosario.miceli@unipa.it

***Abstract*—A hybrid energy storage system specifically designed for a fully electric aircraft is presented in the paper. The analysis of the time evolution of the power demand of the electric propulsion system during a test mission of Maxwell X-57, an all-electric aircraft developed by NASA, has pointed out the presence of significant peak power during take-off and air tack. Considered the issues related to weight and the volume of the energy storage systems (ESSs) in all-electric aircraft, a hybridization of aircraft ESS with a Supercapacitors (SCs) bank, devoted to smooth peak power demand, has been investigated. A comparison between the simulation results of an electrochemical battery and hybrid ESSs, designed on the test mission of Maxwell X-57 power demand, has been developed. The advantage of hybrid configuration with respect to battery-based one in term of volume and weight reduction is finally presented.**

***Index Terms*—Battery, Supercapacitors, all-electric aircraft, hybrid storage system.**

I. INTRODUCTION

The transport sector contributes significantly to CO_2 emissions, which is considered one of the leading causes of current global warming. In 2016, the entire transport sector contributed to the world climate change emission with a share with respect global one of 21.4%; the 2.6% of equivalent CO_2 emissions was due to the air transport sector. A further contribution from the aeronautical sector to the greenhouse effect is the contrails, which double the contribution to global warming caused by this air transport. Considering an expected increase in air traffic of about 4.5% per year, the air transport emissions without any mitigation action will increase significantly [1]. A study carried out by NASA has shown that the use of a more significant share of electricity in a typical 200-seat aircraft could result in a 10% reduction in the unladen weight of the aircraft; a 13% reduction in the thrust required by the engine, and a 9% reduction in fuel consumption [2]. The analysis highlights the present and future impact of the air transport sector, requiring a significant improvement from an environmental and economic perspective. The European Union has defined the target for future aircraft [3]. Specifically, the *European Flightpath 2050* fixes a reduction relative 2020 of CO_2 emissions of 75% per passenger-kilometer and a reduction of NO_x emission of 90%. In this context, the full electrification of aircraft assumed a strategic role in achieving these ambitious targets. The partial electrification [4] promoted through More Electric Aircraft (MEA) cannot be sufficient to attain the reduction fixed by *European Flightpath 2050*. The All-Electric Aircraft (AEA) represents air transport solutions that do not involve fossil fuel during propulsion, removing from the source all polluting emissions during the flight phase, including contrails. The AEAs are characterized by electric propulsion systems that, not being bound by the principles of thermodynamics, can achieve energy efficiencies that are significantly higher than those of fossil-based fuel engines. Moreover, the electric propellers, such as ducted fans, retain high efficiency even for small sizes. This allows the Distributed Electric Propulsion (DEP) system, which can be a remarkably silent, light and efficient. In addition, this system provides greater redundancy to the propulsion system and allows the achievement of the best performance conditions even for off-project flight situations. However, one of the central issues of AEA is the availability of electrical energy and power during the flight path in all possible operative conditions, guaranteeing the safety standards typical of the aeronautic sector. The energy and power supply in AEA is provided by ESS that must ensure the power and energy necessary for air propulsion. Therefore, from the electrical point of view, AEA is comparable to an island power system that requires an electricity supply characterized by high power and energy density. The feasibility studies developed on the original A320 design has defined its AEA optimized version. Under the hypothesis of considering the availability of battery technologies with an energy density of 800 Wh/kg, the flightpath range of A320 AEA version reaches 925 km and maximum take-off weight of 109,5 ton 65% more than conventional. The electrical

Fig. 1. NASA X-57 Maxwell X57 Mod II [8].

and propulsion system, including ESS, is a factor of four heavier than the conventional one, including fuel [5]. The state of the art of batteries commercially available is characterized by energy density of 450Wh/kg. The reference value of 800 Wh/kg is the expected values achievable by commercial Li-Sulphur batteries [6]. For this reason, the prototyping and the research activities are focused mainly on ultra-light aircraft (ULA) and light-sport aircraft (LSA) because it presents aircraft design parameters in terms of the flight path, maximum take-off weight and required power and energy that can be satisfied by the available ESSs [7]. In this context, the authors develop a project to develop innovative electric power trains and auxiliary electric power systems for horizontal and landing (HTOL) aircraft with flight autonomy of one hundred Km. In the present paper, a hybrid energy storage system specifically designed for an HTOL is presented, referring to a test mission of AEA Maxwell X-57 Mod II whose picture is reported in Fig.1.

II. Electrochemical battery for AEA

The design of the electrochemical batteries for AEA has to consider different aspects. Expressly, the power and energy densities assume a significant impact due to the limited volume availability in the fuselage and wings of an aircraft. Other essential aspects are reliability, safety, the expected life (Calendar life and Cycle life), the costs and the charging time. Hence, the AEA battery design and sizing is a complex task that requires the definition of a set of specification strictly related to the particular application.

State of the art for vehicular applications of electrochemical batteries is represented by lithium-ion (Li-Ion). Their development is supported by very active research. However, this technology is nearing its practical energy density limit, equal to about 250 [Wh⁄kg]. This constraint represents a barrier for their future implementation of AEA because it affects the aircraft significantly with flight autonomy. Presently they are extensively used in horizontal take-off and landing vehicles as small size drones characterised by limited flightpath.

One of the most promising technologies to support the AEA request of increasing the battery energy density are the Lithium-Sulfur (Li-S) batteries. They are characterised by a high practical energy density technological limit of about 800 [Wh⁄kg]. Moreover, the materials used are less expensive and polluting, leading to much cheaper and more sustainable electrochemical energy storage devices. Another very promising electrochemical cell clustered in the class of "Beyond Li-Ion Technologies" is represented by Lithium-Air batteries (Li-air or Li-O_2). They present the highest theoretical limit of energy. However, they are still under development, and there are some open issues as the achievable power density is still under investigation.

The main characteristics of the electrochemical battery suitable for AEA are summarised in Table I

TABLE I
Main Characteristic of Batteries Suitable for AEA.

		Li-Ion	**Li-S**	**Li-Air**
Cell Voltage	[V]	3,4 – 4,1	2,1	3,10
Theoretical limit of gravimetric Capacity	$[\frac{Ah}{kg}]$	160	1165	3829
Theoretical limit of energy density	$[\frac{Wh}{kg}]$	588	2447	11 870
Achievable energy density	$[\frac{Wh}{kg}]$	<250	<800	<1000
Cycle life	cycles	500 - 2000	50	100

III. System-level simulation

The main purpose of the presented work is the sizing of an electric aircraft on-board storage system on the base of the energy required by a typical aircraft mission. In particular, the possibility of the storage system hybridization is investigated, through the utilization of a Supercapacitors (SCs) bank in addition to a traditional li-ion battery pack, in order to examinate the main parameters of interest: weights and volumes. A nominal Maxwell X-57 Mod II mission is evaluated. It is characterized by a cruise altitude equal to 3048 m, a cruise time equal to 5 min, a cruise speed equal to 230 km/h and a climb rate equal to 164.6 m/min. By the implementation of the aircraft dynamic model, reported in [8], the power profile shown in Fig. 2 is considered for the storage sizing.

In order to compare the performances, weight and volume of the storage system, the profile is simulated firstly with a battery-only storage and then with a hybrid battery-SCs storage.

The considered model for the battery simulation is the Thevenin model, or RC model, shown in Fig. 3 and composed of a controlled voltage source $E(SoC)$, a series resistor $R_0(SoC)$ and an RC branch with

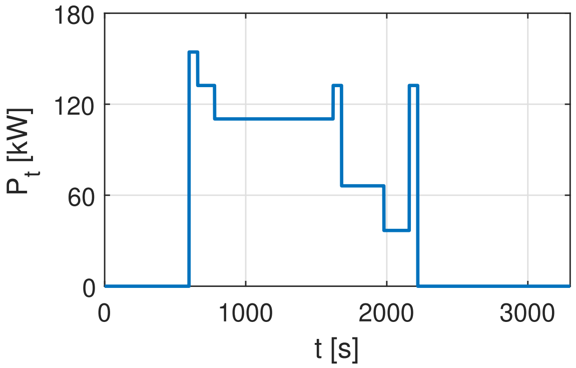

Fig. 2. Power Profile of the Maxwell X57 Mod II.

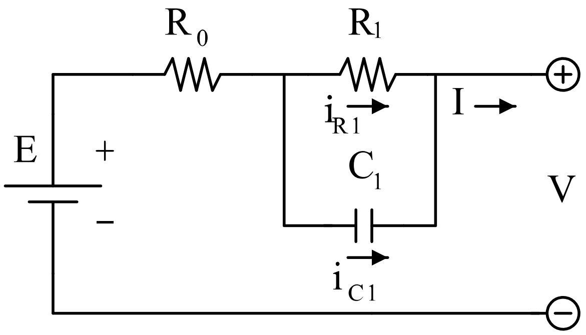

Fig. 3. Thevenin equivalent circuit model of a Li-ion battery.

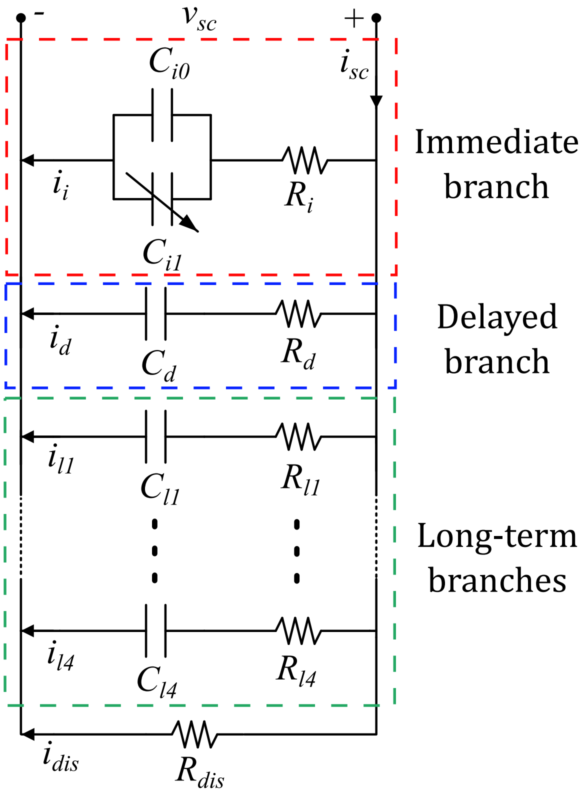

Fig. 4. SC six-branches equivalent circuit model.

$R_1(SoC)$ and $C_1(SoC)$. All the parameters are State of Charge (SoC) dependent and they are obtained though a parameters estimation procedure [9]. In particular, the battery cell LG HG2 is characterized [10], and the resulting parameters are reported in Table II. Other useful datasheet information are summarized in Table III.

For the SCs behavior simulation [11], a six-branches model, shown in Fig. 4, is considered. It is composed of:

- a first branch, called immediate branch, with a series resistor R_i, a fixed capacitor C_{i0} and a voltage dependant capacitor C_{i1};
- a second branch, called delayed branch, with a series resistor R_d and a fixed capacitor C_d;
- four other branches, called long-term branches, with a series resistor $R_{l1...4}$ and a fixed capacitor $C_{l1...4}$;
- a last branch with a parallel resistor R_{dis}.

Each branch has a different time constant, from seconds to several days. Also in this case, the parameters are obtained through a parameters estimation procedure [12]. A TPLC-3R8 hybrid SC is considered [13], and the resulting parameters are reported in Table IV. Other useful datasheet information are summarized in Table V.

A nominal voltage equal to 480 V is chosen for the battery pack. The maximum current value reachable is calculated as the ratio between the maximum power required by the aircraft and the minimum voltage reachable by the battery pack. It is equal to 393 A. The number of series cells N_s is calculated considering the nominal voltage of the battery pack. The number of parallel cells N_p is calculated considering the energy required for the flying cycle and the maximum current per cell.

As for the SC bank, a nominal voltage equal to 400 V is considered. The sizing criterion is similar to the battery pack one, but in this case, for a proper operation, SCs are discharged between the maximum and the half of the maximum voltage [14].

For the hybridization of the storage system, the battery pack is designed to ensure a constant power equal to 110 kW from $t = 600$ s to $t = 1680$ s, 67 kW from $t = 1681$ s to $t = 1979$ s, 37 kW from $t = 1980$ s to $t = 2159$ s and 110 kW from $t = 2160$ s to $t = 2220$ s. The residual power amount required by the mission profile is supplied by the SCs bank. In this case, the number of series and parallel cells and SCs are reported in Table VI and compared to the case of the battery-only storage.

IV. SIMULATION RESULTS

To verify the performances of the system, simulations have been carried out in Matlab/Simulink environment.

Fig. 5 shows the results of the system simulation in which the battery pack is the unique storage system employed. In particular, from top to bottom, the battery

TABLE II
BATTERY MODEL PARAMETERS FOR DIFFERENT SoC VALUES.

SoC	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0
E (V)	4.20	4.08	4.01	3.89	3.80	3.70	3.63	3.55	3.46	3.22	2.5
R_0 (mΩ)	25.6	23.9	22.4	22.0	21.9	21.9	22.0	22.1	22.7	26.2	28.7
R_1 (mΩ)	16.9	20.0	25.2	22.3	22.1	25.0	30.0	25.7	29.9	43.3	56.7
C_1 (kF)	2.05	2.00	1.59	1.79	1.81	1.60	1.31	1.55	1.33	0.92	0.51

TABLE III
BATTERY DATASHEET SPECIFICATIONS.

Specification	**Unit**	**Value**
Volume	ml	16.54
Weight	g	48
Nominal Voltage	V	3.7
Max Voltage	V	4.2
Min. Voltage	V	3
Charge current	A	4
Discharge current	A	3
Capacity	Ah	3

TABLE IV
SUPERCAPACITOR MODEL PARAMETERS.

R_i	R_d	R_{l1}	R_{l2}	R_{l3}	R_{l4}	R_{dis}
(mΩ)	(Ω)	(Ω)	(Ω)	(Ω)	(Ω)	(Ω)
11.9	1.4	5.26	43.01	423.7	572.31	510
C_{i0}	C_{i1}	C_d	C_{l1}	C_{l2}	C_{l3}	C_{l4}
(F)	(F/V)	(F)	(F)	(F)	(F)	(F)
82.63	10.2	39.07	46.61	29.27	52.14	55.6

TABLE V
SUPERCAPACITOR DATASHEET SPECIFICATIONS.

Specification	**Unit**	**Value**
Volume	ml	10.18
Weight	g	18
Nominal Voltage	V	3.8
Charge current	A	14.1
Discharge current	A	14.1
Capacity	F	450

TABLE VI
STORAGE SYSTEM SIZING RESULTS.

Type	**Storage**	N_s	N_p	N_{tot}
Normal	Battery	131	79	10349
Hybrid	Battery	131	57	7467
	Supercapacitors	106	16	1696

power, obviously identical to that required by the load and the trends of voltage, current and SoC are shown.

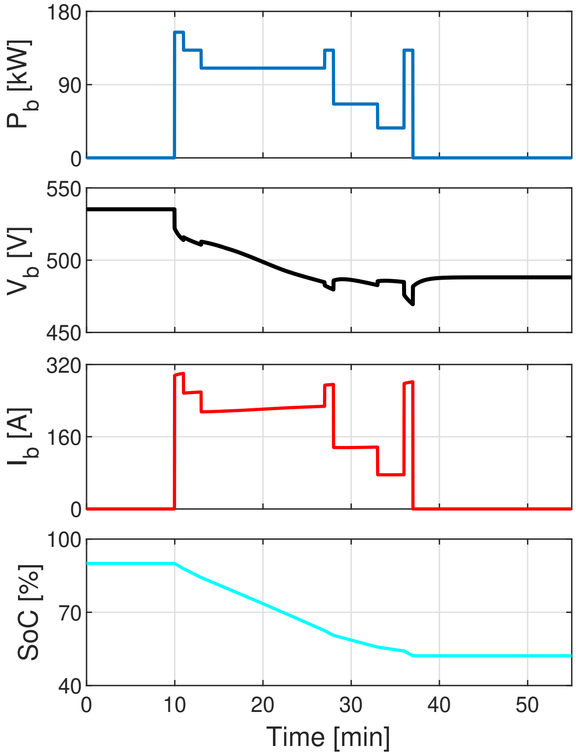

Fig. 5. Simulation results of the battery-only storage system.

Fig. 6 shows the results of the system simulation in which the hybrid storage system is considered. From top to bottom, the battery pack and the SCs bank power, the battery pack and the SCs bank voltages and currents and the battery pack SoC are reported.

As it can be noticed, using SCs allows the reduction the amount of current delivered by the battery, thus reducing possible battery overheats. Furthermore, in the case of using the battery-only storage, due to the high power demand during the takeoff, phase and the climbout phase, the number of parallel cells would be higher and it would result in an excessive oversizing of the battery pack in terms of energy. In addition, an analysis on weights and volumes is carried out. Table VII shows the weights and volumes of the storage system in both configurations: battery-only and hybrid. As it can be clearly noticed, with the employment of SCs in addition to traditional Li-ion battery packs, a significant reduction of both weight and volume is possible.

TABLE VII
WEIGHT AND VOLUME COMPARISON.

Type	**Storage**	**Weight** [kg]	**Volume** [l]	**Tot. weight** [kg]	**Tot. volume** [l]	**Weight reduction** [%]	**Volume reduction** [%]
Normal	Battery	497	172	497	172	-	-
Hybrid	Battery SCs	359 31	124 18	390	192	21.53	17.44

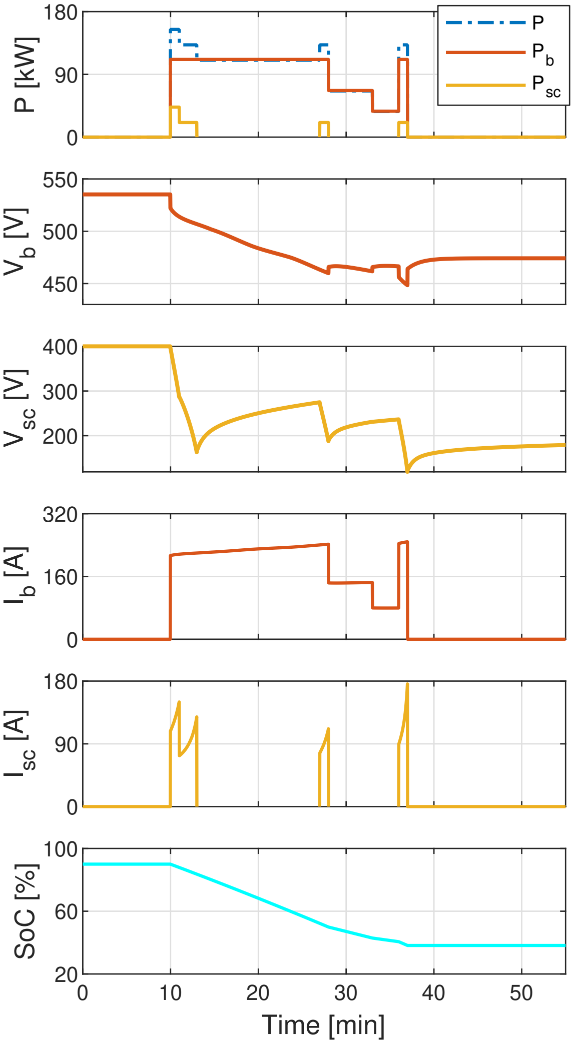

Fig. 6. Simulation results of the hybrid storage system.

V. CONCLUSION

In this paper, the possibility of hybridization of an aircraft storage system was investigated. In particular, a Maxwell X-57 Mod II typical mission was analysed. The power profile and the energy required by the mission were considered for the sizing of the storage system. A comparison between a battery-only storage system and a hybrid storage system composed of a battery pack and a SC bank was reported. In particular, a description of the employed models for both battery and SC was provided and the system level simulation results were examined. They have shown how the employment of SCs results in better performances and lower weights and volumes.

ACKNOWLEDGMENT

This work was financially supported by Prin 2017-Settore /Ambito di intervento: PE7 linea C - Advanced powertrains and systems for full electric aircrafts.

REFERENCES

[1] A. Schafer, S. Barrett, K. Doyme, and alter, “Technological, economic and environmental prospect of all electric aircraft,” *Nature Energy*, vol. 4, pp. 160–166, 2018.

[2] A. Hoffman, I. Hansen, R. Beach, R. Plencner, R. Dengler, K. Jefferies, and R. Frye, “Advanced secondary power system for transport aircraft, nasa technical paper 2463,” 1985.

[3] M. Darecki, C. Edelstenne, T. Enders, E. Fernandez, P. Hartman, J.-P. Herteman, M. Kerkloh, I. King, P. Ky, M. Mathieu, G. Orsi, G. Schotman, C. Smith, and J.-D. Wörner, “Flightpath 2050: Europe’s vision for aviation,» publications office of the european union, luxembourg,” 2011.

[4] M. Longo, F. Viola, R. Miceli, D. Zaninelli, and P. Romano, “Replacement of vehicle fleet with evs using pv energy,” *International Journal of Renewable Energy Research*, vol. 5, no. 4, pp. 1146–1153, 2015.

[5] A. R. Raymond, L. Speth, J. S. Sabnis, and S. Barrett, “Technical and environmental assessment of all-electric 180-passenger commercial aircraft,” *Progress in Aerospace Sciences*, vol. 105, pp. 1–30, 2019.

[6] A. Damiano, M. Porru, A. Salimbeni, A. Serpi, V. Castiglia, A. O. Di Tommaso, R. Miceli, and G. Schettino, “Batteries for aerospace: a brief review,” in *2018 AEIT International Annual Conference*, 2018, pp. 1–6.

[7] V. Boscaino, R. Miceli, and G. Capponi, “Matlab-based simulator of a 5 kw fuel cell for power electronics design,” *International Journal of Hydrogen Energy*, vol. 38, no. 19, pp. 7924–7934, 2013.

[8] S. L. Schnulo, J. Chin, R. D. Falck, J. S. Gray, K. V. Papathakis, S. C. Clarke, N. Reid, and N. K. Borer, *Development of a Multi-Segment Mission Planning Tool for SCEPTOR X-57*. [Online]. Available: "https://arc.aiaa.org/doi/abs/10.2514/6.2018-3738"

[9] N. Campagna, V. Castiglia, R. Miceli, R. Mastromauro, C. Spataro, M. Trapanese, and F. Viola, “Battery models for battery powered applications: A comparative study,” *Energies*, vol. 13, no. 15, 2020.

[10] LG. (2014) LG HG2. [Online]. Available: https://www.nkon.nl/sk/k/hg2.pdf.

[11] A. Berrueta, A. Ursua, I. S. Martin, A. Eftekhari, and P. Sanchis, “Supercapacitors: Electrical characteristics, modeling, applications, and future trends,” *IEEE Access*, vol. 7, pp. 50 869–50 896, 2019.

[12] V. Musolino, L. Piegari, and E. Tironi, “New full-frequency-range supercapacitor model with easy identification procedure,” *IEEE Transactions on Industrial Electronics*, vol. 60, no. 1, pp. 112–120, 2013.

[13] Tecate Group, “TPLC-3R8,” 2020. [Online]. Available: "https://www.tecategroup.com/products/data_sheet.php?i=TPLC-3R8/450MR18X40"

[14] V. Castiglia, N. Campagna, A. O. Di Tommaso, R. Miceli, F. Pellitteri, C. Puccio, and F. Viola, “Modelling, simulation and characterization of a supercapacitor in automotive applications,” in *2020 Fifteenth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, 2020, pp. 1–6.