Design Considerations to Optimise Supercapacitor-based Energy Storage Systems for Aerospace Applications

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Abstract—This paper investigates the design optimization of a supercapacitor-based energy storage system for aerospace applications which may be needed to complement the operation of a high power pulsed load such as electromechanical actuators have been proposed. Different designs of a supercapacitor (SC) stack to achieve minimum weight are investigated but this may cause suboptimal operation of the associated converter. To assess the impact on the weight of the converter, the weight of its key elements are assessed and shown that at system level an optimal solution can be found. Thermal stress analysis on the candidate supercapacitor cells is investigated to ensure the design solutions are valid.

Keywords— *Electrical energy storage system, optimization, supercapacitors*

I. INTRODUCTION

It is predicted that in new aircraft designs, significantly more electrical power will be generated and consumed, a trend referred to as “more Electric Aircraft”. Some of this equipment, such as flight actuation is characterised by significant peak power requirement which will cause significant challenges for the power system affecting its ratings and stability. This may cause difficulties to the power system especially when it needs to deliver the peak load power requirement or when the highly dynamic loads cause rapid electrical transients that can cause voltage disturbances[1].

There are two options to address this issue: (i) increasing the rated power for the on-board power generation system in conjunction with decreasing the impedance/resistance of the power bus which requires the increase of the cross-section/weight of the cables or (ii) the use of energy storage to compensate for the high power peaks that are characteristic to an intermittent power consumption.

Employing energy storage may allow changes in the design of the power system for more electric aircrafts. For example, the generation system will be designed to provide the average power consumption of the overall system, while energy storage provides the power peaks and hence reducing the size of the generation units and the engine stress. Also, Local/ distributed energy storage may be

considered to smooth the power demand surges of a specific loads with pulsed power demand nature such as EMAs. This will allow reducing the cross-section of the power cables in accordance to the average power consumption of the EMAs, rather than the peak power/current requirement. Some advantages may be also gained if in new aircraft designs, weight reduction is implemented by adapting the cross-section of the power cables in accordance with the average power consumption, rather than the peak power/current requirement. Different technologies of storing energy exist and their characteristics need to be assessed against the requirement from the application. Aircraft applications are characterised by a need to provide minimum weight which translates in high specific energy (Wh/kg) and specific power (kW/kg), which is needed to minimise system weight and high round-trip efficiency which is needed to minimise fuel consumption, whilst minimising the cost is not a prime concern. It is widely recognised that electrochemical energy storage is the only suitable technology for aircraft use. There are two representative devices that each offer high specific energy (Lithium-ion battery offer approx. 100-300Wh/kg) or high specific power (the Electrochemical Double Layer Capacitor (EDLC) referred also as supercapacitor (SC) which offer 5-20kW/kg but at a specific energy of less than 5-10Wh/kg)[2]. This makes the selection of the suitable electrochemical energy storage device highly dependent on the specific of the applications, with centralised energy storage systems designed to store large amounts of energy can also deliver powers of similar magnitude as the generator ratings and would favour the use of Li-ion batteries whilst distributed energy storage systems needed to compensate for a very particular high peak power/short term loads will favour the use of supercapacitors [3].

This paper will investigate the design of a supercapacitor based local energy storage system for high peak power loads. Based on the technical specification, a set of commercially available supercapacitor devices are selected. It will be shown that there is significant variation in the specific energy offered by the different devices which leads to different implementations that result in a trade-off between supercapacitor weight and the current

rating of the required DC/DC converter. This is caused by the fact that small capacity SC devices that have lower specific energy will result in higher number of series connected cells, higher SC stack voltages and lower maximum current/converter weight whilst some of the largest cells will provide better specific energy/lower weight but due to lower SC string voltage will result in larger current ratings and converter weight. The paper will investigate the weight of the SC-unit and converter components and the resulting losses for the shortlisted designs and will investigate the thermal stress on the SC-cells under these designs based on accurate loss models for the used cells to demonstrate how an optimum energy storage system implementation can be achieved.

II. SUPERCAPACITOR UNIT SIZING

A supercapacitor energy storage system (SC-ESS) shown in Fig. 1, consists of a supercapacitor (SC) unit and a DC-DC converter interfacing the SC unit to the DC-bus.

Fig. 1 supercapacitor energy storage system block diagram

The SC unit can be implemented as series/parallel combinations of supercapacitor cells to provide the required voltage level as well as energy capacity. The design of the SC-unit in this paper should satisfy the energy and power requirements of the given load as listed in TABLE 1.

TABLE 1 SC-ESS REQUIREMENTS

Maximum power	2kW
Bus voltage	270 V
Energy capacity	10 Wh

Based on these requirements, the equivalent capacitance of the SC-unit can be estimated as:

$$C_{eq} = \frac{2E_{str}}{(V_{max}^2 - V_{min}^2)} \quad (1)$$

Where E_{str} is the targeted energy capacity (Joules), V_{max} and V_{min} are the maximum and minimum voltage for the SC-unit. The minimum voltage is usually selected to be around 50% of the maximum voltage to limit the SC-unit current for the required power which has direct impact on size/weight of magnetics/semiconductors. Accordingly, the required capacitance of a single SC-cell in the string can be estimated as:

$$C_{cell} = \frac{C_{eq} \cdot V_{max}}{V_{cell,max}} \quad (2)$$

Where $V_{cell,max}$ is the maximum operating voltage of the SC-cell that should be slightly lower than the specified maximum value from manufacturer (2.7V for most SC cells) to allow a safety margin in the design. This capacitance can be achieved either directly using single cell or by parallel combination of two or more cells based on the available standard capacitances.

Ideally, the design of SC-unit is to select V_{max} to be as high as the bus voltage (in this case 270V) to minimize the converter current ratings, then as the SC-unit discharges and its voltage decreases, the DC-DC converter adapts its duty cycle to maintain SC-ESS power at the designated value [4-6].

By applying (1)-(2) to the design requirements in Table 1, the desired SC-cell capacity is determined to be 150F but as the converter could accommodate lower stack voltages which would require less series connected cells of higher capacitance. This means that the 150F cell represents the lowest cell capacitance (although this could be implemented as parallel connection of multiple cells). In order to identify the best SC device, the characteristics of commercially available SC cells within a capacity range of 100-400F is evaluated from the point of view of specific energy (Wh/kg) as it will reflect the overall weight of the SC-unit. As it can be observed from Fig. 2, the specific energy varies quite a lot due to manufacturing/cost saving limitations. The actual 150F SC-cell that matches the design calculations based on (1)-(2) is not the most energy dense device in the considered range as it has low specific energy (4.7Wh/kg) compared to the Maxwell 350F cell that has a significantly higher specific energy of 5.9Wh/kg (+25%) but using a larger cell will require fewer series connected devices that will lower the stack voltage and will increase the converter current/weight..

Fig. 2 Specific energy vs actual cell capacity for a range of SC cells

Alternatively, designing the SC-unit with ($V_{max}=220V$) results in utilization of 180F capacity SC-cell with better specific energy (+13%) compared to the 150F capacity SC-cell which results in weight reduction of the SC-unit. Fig. 3 shows the utilized SC-cell's capacity and accordingly the overall SC-unit's weight for different designs of SC-unit's maximum voltage. It can be observed that the overall weight of the SC-unit based on the 150F cell design ($V_{max}=270V$) is 3.4kg. However, when designing the SC-

unit with the 350F cells ($V_{max}=110V$), the overall weight of the SC-unit is 2.7kg which is 25% less compared to the previous design. On the other hand, reducing SC-unit's voltage under the same power requirement results in increasing the current requirements which in turns may increase power losses inside SC-cells and the thermal stress which are attenuated by the fact that larger devices have lower resistance and capability to dissipate more losses. Also, reduced voltage of the SC-unit adds more challenges for the interfacing DC-DC converter in terms of lower efficiency at minimum voltage of SC-unit (V_{min})/maximum boosting ratio (gain) as well as needing larger current capability which increases the converter weight.

Fig. 3 Comparison of SC-cell capacitance and SC-unit mass at different designs of SC-unit voltage

Fig. 4 shows the maximum current of the SC-unit and the maximum voltage gain requirements for the converter for different designs of SC-unit. As can be observed, for the weight minimized design of the SC-unit with ($V_{max}=110V$), the converter gain at $V_{min}=55V$ should be 5 which leads to a significant increased converter weight which in turn may undermine the weight savings obtained in the SC-unit design. For this reason, it is necessary to estimate the impact on system weight of the design of the interfacing converter.

Fig. 4 SC-unit current and Conv. gain at diff. designs

III. INTERFACING DC-DC CONVERTER ANALYSIS

First, the use of a traditional half bridge DC/DC converter configuration is considered, to get an indication of how the SC-unit design will influence the weight of the inductor. Then a more complex converter arrangements

such as paralleled interleaved that offer the possibility to further reduction of the overall weight of passive components is considered. As the interfacing DC-DC converter works in boost mode, the inductance of the inductor can be estimated at worst operating point (50% duty cycle):

$$L = \frac{V_{bus}}{4 \cdot \Delta I \cdot f_s} \quad (3)$$

Where V_{bus} is the bus voltage (270V), ΔI is the inductor current ripple and f_s is the switching frequency. As V_{bus} and f_s are same for all SC unit designs, it is clear that the required inductance is determined by the maximum ripple current that is usually specified as proportion of rated/maximum current, which is inverse proportional to the maximum/minimum SC unit voltage. On the other hand, in order to maintain the copper power losses at designated level at the increased average inductor current a thicker winding wire may be required in order to reduce the DC resistance which increases the inductor weight as shown hereafter.

A. Inductor size

As the inductor is one of the main contributors to the converter weight, the estimation of the inductor weight will be used in this investigations as an indicator for the overall converter's weight. Inductor design for the interfacing DC-DC converter under SC-unit with maximum voltage of 270V (higher voltage (HV) design) and 110V (lower voltage (LV) design) are shown in TABLE 2. The inductor designs are based on Kool M μ ® Cores with the shown part numbers and all the designs are based on using 100 kHz switching frequency; faster switching would allow further weight reduction but that will influence all SC unit designs in the same proportion. For the converter interfacing the HV SC-unit, the maximum DC current of the inductor (I_{DC-max}) is 14.8A, and the required inductance is 244 μ H. Accordingly, the core weight of the inductor is 120g and the weight of the copper winding is 180g giving an overall inductor weight of 300g. On the other hand, reducing the maximum voltage for the LV SC-unit to 110V increased I_{DC-max} to 36.4A, although this increase in the inductor current reduces the required inductance to 93 μ H to maintain the same current ripple percentage of I_{DC-max} , the wire diameter for winding increased significantly to keep copper losses constant. As a result, the copper weight become the main contributor of the inductor weight (344g) compared to the core mas of (140g) resulting in an overall inductor weight of 484g which results in an increased inductor weight of 60% compared to HV SC-unit design.

Although the LV SC-unit design saved 700g in terms of SC-unit's weight compared to HV SC-unit as described in § II, it will require an inductor that is 184g heavier but overall, the LV SC-unit design is still providing weight reduction, although the impact of having higher losses on added weight has not been considered.

In order retain as much of the SC-unit weight savings, a superior interfaced converter topology need to be considered that will facilitate smaller magnetics. Compared to the standard topology, the two channel interleaved converter (Fig. 5) for interfacing the LV SC-unit needs two inductors but rated at half the SC current

which means thinner conductor used in the winding. The interleaving between the two channels results in ripple cancelation seen in the SC current and this allows for significantly higher inductor current ripple to be used which means the inductance $L1/2$ can be relatively small. TABLE 2 shows the input and output design parameters for the converter inductors for three SC&converter configurations: single channel HV and LV SC units and LV-2ch interleaved. The weight reduction offered by the two channel interleaved converter is very clear: the core weight of each inductor is 63g so the overall core weight is 126g compared to 140g for the single channel converter. Similarly, the overall copper weight for the two inductors in the interleaved converter is 236g compared to 344g in the single channel converter. This gives an overall weight for the inductors for the interleaved converter of 364g (-25%) compared to 484g for the single channel one. When comparing weight of the two channel interleaved converter designed for LV SC-unit with the single channel HV SC-unit, it could be concluded that it results in only 64g extra weight which means the power density degradation of the converter due to higher load current is significantly reduced by using interleaving (although it is true, that using an interleaved converter for the HV-SC unit could further improve its power density as well). It can be concluded that these weight predictions for the inductor weight are confirming that the savings in the weight of SC cells (-700g) in the LV design is more significant than the added inductor weight which means that the system optimisation will be driven mainly by the need to utilise the 350F cells.

TABLE 2 INDUCTOR DESIGN FOR INTERFACING CONVERTER

Inductor parameters	SC-Unit design		
	HV-1ch	LV - 1ch	LV 2ch-interl.
I_{DC-max} (A)	14.8	36.4	18.2
Current Ripple % (I_{DC-max})	20	20	50
Inductance(μ H)	244	93	75
Core part No.	00k5528e026	00k7228e026	00k4022e026
Core weight	120g	140g	63g
No. of turns	54	34	31
Wire Size(AWG)	12	8	11
DCR (m Ω)	32	9.5	13.8
Copper losses	6.4W	12W	4.5W
Copper weight	180g	344g	118.7g
Overall weight	300g	484g	363.5g

Fig. 5 Two channels interleaved converter

B. Converter efficiency

The efficiency of the converter can be estimated based on the calculation of the losses for each key system component which are inductor copper losses and semiconductor switching and conduction losses. The inductor core losses are neglected in this study assuming

that the best core material is used and that the inductor DC current component imposes a permanent bias on the B-H curve and that the current ripple causes only minor hysteresis losses.

The inductor copper losses can be approximated by neglecting the AC-component of the losses as:

$$P_{copper} = I_{rms}^2 \cdot DCR \quad (4)$$

Where DCR is the DC-resistance of the inductor windings and I_{rms} is the inductor RMS current which can be calculated as:

$$I_{rms} = \sqrt{I^2 + \frac{\Delta I^2}{12}} \quad (5)$$

Where I is the DC inductor current and ΔI is the peak-to-peak value of ripple current. The second part of the losses is the switches (MOSFETs) losses which is divided into the conduction and switching losses that can be estimated according to [7] as follows:

$$P_{cond} = I_{rms}^2 \cdot R_{ds-on} \quad (6)$$

Where R_{ds-on} is the drain-source resistance during ON-state of the switch, same for both the upper or lower switch in the converter leg as identical devices are used. The switching energy loss reaches a significant level during the commutation as current through device (I) and voltage across it (V_{bus}) overlap. An average power loss can be determined as:

$$P_{sw} = \frac{V_{bus} \cdot I}{2} (t_{d-on} + t_{d-off}) f_s \quad (7)$$

Where V_{bus} is the bus voltage, t_{d-on} and t_{d-off} represent the ON and OFF delay times of the switch respectively, and f_s is the switching frequency.

TABLE 3 shows the efficiency calculation for the interfacing converter for three different designs of SC-unit. The voltage stress for the switches for all converters is 270V (V_{bus}) and the switching frequency considered for all design is 100kHz. For the HV SC-unit, inductor peak current is $\approx 17A$. The best switch matching this rating has been selected and the efficiency has been calculated under maximum current condition as 95.9%. The second option is the single channel converter interfacing the LV SC-unit and the inductor peak current this case is $\approx 43A$ and accordingly the best switch for this range has been selected and the efficiency at maximum load estimated but at a significantly lower level of 86.6% due to the high current stress of the converter under low voltage. The third option is the two channel interleaved converter interfacing the LV SC-unit for which a better switch technology (GaN) actually exists. It is true that two of these devices could have been used in parallel for option 2 to improve its efficiency but having to use same semiconductors (type, number) would make inductor size as an undeniable advantage and this is why this has not been evaluated. The current rating of the devices is reduced compared to the single channel converter, also due to the significantly

better performance of the GaN devices, both in conduction loss (20W compared to 117W) and switching (6W compared to 99W), the efficiency of the two channel interleaved converter reached 95.3% which is very close to the efficiency of the converter interface for the HV SC-unit. This means that the cooling requirement for option 1 and 3 converters is very similar and an assumption that these will offer similar power density is valid. This means combining the benefits of the LV SC-unit weight reduction without paying any penalties in terms of converter weight or efficiency. However, the thermal stress on the SC-cells due to the high current under low voltage design would be higher and this is investigated in the following section.

TABLE 3 CONVERTER EFFICIENCY AT DIFFERENT DESINGS

parameters	SC-Unit design		
	HV-1ch	LV 1ch	LV 2ch-interleaved
Switch-part number	IXFH 30N40Q	APT40M90JN	GS66508B
Switch-technology	Si MOSFET	Si MOSFET	eGAN FET
$V_{DS}(V)$	400	400	650
$I_{ds}(A)$	30	51	30
$R_{DS-ON}(m\Omega)$	160	90	63
$t_{d-on}(nSec)$	25	32	4.3
$t_{d-off}(nSec)$	51	70	8.2
$P_{cond}(W)$	31	117	20
$P_{sw}(W)$	28	99	6
Efficiency %	95.9	86.6	95.3

IV. EVALUATION OF SUPERCAPACITOR CELLS

In order to accurately evaluate the thermal stress on the SC-cells, accurate electrical and thermal models are required to accurately estimate the power losses inside the candidate SC cells and accordingly the thermal stresses.

A. Deriving the electrical model

The equivalent circuit model (ECM) is used here to represent the behaviour of the SC cell giving more importance to extracting the correct internal resistances and neglecting the leakage current as the scope of the model is to evaluate the thermal stress during charge/discharge cycling. In order to identify the behaviour of the SC-cell, an experimental characterization through electrochemical impedance spectroscopy (EIS) has been performed on the selected cells using the Biologic® SP-150 potentiostat. EIS testing results for the Maxwell 350F SC-cell within a frequency range of 50mHz to 10kHz and at different bias voltages are shown in Fig. 6. It can be seen that the cell resistance is changing with frequency as well as bias voltage (equivalent to state of charge). The changing in SC-cell resistance with bias voltage is less significant, so a good approximation can be achieved by considering the operating voltage range of the SC cell (1.25V to 2.5V in this design), so resistance at 2V which is close to cycle average can be used leading to ESR errors of max 5%. On the other hand, changing of SC-cell's resistance with frequency is significant, the resistance at 50 mHz is 100% more compared to the resistance at 50Hz, so it cannot be approximated accurately by a single average value. Thus, the simplified ECM consisting of a resistor (ESR) in series with the bulk capacitor shown in Fig. 7 (a) is not accurate for detailed loss estimations where the particularities of the load cycle are available [8].

Modelling the observed behaviour of the SC cell resistance accurately requires a dynamic model with n number of R/C branches as shown in Fig. 7 (b). Increasing the number of R/C branches increases the accuracy of the model but increases the model complexity, Fig. 8 shows the accuracy of fitting the SC-cell EIS with 5th order ECM.

Fig. 6 Electrochemical impedance spectroscopy of SC cell

In order to obtain an accurate model with reasonable complexity, the methodology proposed in [9] has been used by fitting SC-cell's EIS data within a defined targeted frequency range (TFR) selected based on the possible load profiles

Fig. 7 Equivalent circuit modelling of SC cell (a) simplified series RC model (b) higher order model

Fig. 8 Fitting SC-cell impedance spectroscopy with 5th order model

Fig. 9 Fitting SC-cell impedance spectroscopy with 3rd order model

Fig. 9 shows the accuracy of fitting SC-cell EIS with 3rd order ECM within TFR. A similar process has been carried out also for the 150F cell which is the choice for the HV-SC unit configuration.

B. Thermal model of SC cells

The thermal model of the SC-cell can be developed considering the losses due to the ionic and electronic transport and neglecting the losses caused by the thermodynamic phenomena taking place inside the cell [10]. The simplified equivalent circuit (EC) based thermal model can be adapted as in [11] and are illustrated in Fig. 10, with R_{cond} representing the resistance for heat transfer by means of conduction inside the SC-cell and R_{conv} representing the resistance for heat transfer by means of convection between the cell and ambient air and C_{th} is the thermal capacitance of the SC-cell. To identify the parameters of the thermal model, cycling experiments for the Maxwell 150F cell (used in the HV SC-unit) and 350F cell (used in the LV SC-unit) by constant charge/discharge current under constant ambient temperature were performed followed by a rest period.

Fig. 10 EC based thermal model of supercapacitor cell

The temperatures of the SC-cells were measured at the electrode terminal (assuming that the thick metal enables fast transfer of internal heat) as an indication of the internal temperature and at surface of the SC-cell by means of thermocouples. The cycling of the SC-cell were performed for sufficient time to allow reaching a steady state temperature as seen in Fig. 11, where charge/discharge current amplitude was set to 18A to produce significant power loss that will result in a sufficient/precisely measurable temperature rise as seen in

Fig. 12. At steady state temperature during cycling, the model parameters R_{cond} and R_{conv} can be obtained as:

Fig. 11 350F SC-cell electrode and surface temperatures during cycling

$$R_{cond} = \frac{T_{elec} - T_{surf}}{P_{loss}} \quad (8)$$

$$R_{conv} = \frac{T_{surf} - T_{amb}}{P_{loss}} \quad (9)$$

The thermal capacitance can be estimated after identifying the thermal time constant (τ) of the SC-cell during the rest period as:

$$C_{th} = \frac{\tau}{R_{cond} + R_{conv}} \quad (10)$$

Fig. 12 350F SC-cell current and voltage during charge/discharge cycling

V. SIMULATION RESULTS

By using the methodology described in §4A, the model parameters of the 3rd order ECM have been identified for the Maxwell BCAP0150 (150F) cell as well as Maxwell BCAP0350 (350F) cell by means of curve fitting with the EIS experimental data. The model parameters of both

candidate SC cells are shown in TABLE 4. Also, thermal model parameters have been obtained for both SC-cells based on cycling experiments as discussed in §4B. For the 150F cell, the thermal conduction resistance (R_{cond}), the thermal convection resistance (R_{conv}) and thermal capacitance are 3.8 °C/W, 14.5 °C/W and 30 J/°C respectively and for the 350F cell, the values of the parameter are 2.5 °K/W, 7.5°C/W and 60 J/°C

TABLE 4 3RD ORDER MODEL PARAMTERS FOR SC-CELLS

Model parameter	BCAP0150	BCAP0350
Cs (F)	150	350
Rs (mΩ)	5.4	1.7
C1 (F)	66	202
R1(mΩ)	1.67	0.9
C2 (F)	48.8	89
R2(mΩ)	0.7	0.3
C3(F)	3000	3000
R3(mΩ)	1	2

A simulation model consisted of the 3rd order ECM and thermal model (Fig. 13) with the identified parameters has been built using Simulink® and a load power pulse per cell, equivalent to the 2kW system load with duration of 18 seconds has been considered.

Fig. 13 Block diagram of the developed SC-cell stress model

In order to simulate the performance at the SC-cell level, the load has been scaled down to a single SC-cell according to each SC unit configuration and specific stress. For the LV SC-unit ($V_{max}=110V$) which utilizes 44 series connected SC-cells of BCAP0350 (350F), each cell is to handle $\approx 45W$ constant power pulses during this loading condition. Simulation results from the SC stress model are shown in Fig. 14. The electrical model estimates the power loss of the cell, cell voltage, cell current, instantaneous power loss and cumulated cell energy contribution. It can be noticed that the maximum power loss of the SC-cell is 3.8W.

Similarly, for the HV SC-unit with ($V_{max}=270V$) which utilizes 104 series connected SC-cells of BCAP0150 (150F), each cell is to handle $\approx 19W$ constant power pulses during this loading condition.

Fig. 14 BCAP0350 SC-cell loss simulation during 2kW power loading of the SC-unit

Simulation results from the SC stress model are shown in Fig. 15, with maximum power losses of 2.2W for each SC-cell.

Fig. 15 BCAP0150 SC-cell simulation during 2kW power loading of the SC-unit

It can be observed that the power losses of the 350F SC-cell in the LV SC-unit design is twice the power loss of the 150F cell in the HV SC-unit design.

Fig. 16 Temperatures of both 350F and 150F SC-cell during 2kW power loading of the SC-unit

The thermal stresses on both SC-cells are almost same at the end of a single 2kW charge/discharge as can be seen in Fig. 16. When designing the cooling, the heating of the

SC devices during a continuous power cycling may be more relevant. Fig 17 shows that the thermal stress models are able to predict the steady state temperatures of the two SC unit designs: 32°C for the internal and 30°C for the SC capsule surface for the 150F cell and 43°C for internal and 39°C for surface temperature of the 350F cell. Even though the exposure to a continuous power cycle is theoretically possible, it's not to be expected from a real MEA loading but the heating up of both SC devices in this extreme situation is still within the limit which leads to the conclusions that both designs are technically feasible.

Fig. 17 Temperatures of both 350F and 150F SC-cell during continues power cycling of the SC-unit

CONCLUSIONS

The proposed design technique for a supercapacitor (SC) unit to minimise weight as needed in aircraft applications, achieved 20% weight reduction compared to a common design technique that would choose SC devices to maximise converter capability.. Reduction of the SC-unit voltage as a result of having available a significantly energy dense SC device requires an interfacing converter with high boosting ratio which in turns add more weight and results in a reduced system efficiency. However the use of an interleaved topology with superior GaN switches resulted in an insignificant weight penalty for the converter and similar efficiency compared to a converter interfacing with a HV SC-unit which gives best converter design. The thermal stress on the SC-cells due to the higher current requirements under reduced voltage in the LV SC-unit has been investigated.

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