Supercapacitors for space applications: trends and opportunities

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ABSTRACT

Electric Double-Layer Capacitors (EDLC), also known as supercapacitors or ultracapacitors, are being considered as an energy storage option in space applications because they can operate over wider temperature ranges and have longer lifetimes and higher power densities than batteries. Since almost a decade, supercapacitors (SCs) were identified as promising high-power sources as they can bridge the gap between capacitors and batteries. SCs have been found to be potentially attractive for several space power applications. ESA has conducted several activities for developing supercapacitors for space applications. The trends and the opportunities of using supercapacitors in space applications will be discussed.

INTRODUCTION

The European Space agency (ESA) has been interested in the study of supercapacitors since the beginning of the 2000's. Many activities have been released in order to study the benefits of supercapacitors in the energy storage systems of the spacecrafts and the launchers. At the beginning, the strategy was to identify the applications for which the use of supercapacitors could bring benefit compared to other electrochemical energy storage technologies, in terms of performances. Once the most relevant applications have been identified, the second step of the strategy was to qualify in space environment, supercapacitor devices used in terrestrial applications, also known as Commercial-of-the-shelf (COTS), that have demonstrated interesting performances for space applications. These COTS supercapacitors cells enabled to answer partially the high-power supply demands encountered in space applications as introduced in the following sections. Indeed, two factors enabled to explain that: the new requirements at supercapacitors part level in terms of power and energy densities. Following the results obtained in the activity of space qualification of COTS supercapacitors, the third step of the strategy was to cover new requirements at supercapacitors devices level, with the main objective to design, develop and manufacture space qualified supercapacitors cells using innovative electrode materials that cope with the high-power demand not covered by the COTS supercapacitors nor by high power batteries and to replace obsolescent batteries technologies.

WHERE DO BATTERIES END AND SUPERCAPACITORS BEGIN?

Batteries and supercapacitors both rely on electrochemical processes, although separate electrochemical mechanisms determine their relative energy and power densities. During the past decades, the energy storage field has witnessed a dramatic expansion in research directed at materials that might combine the high energy density of batteries with the long life cycle and short charging times of supercapacitors [1].

The figure 1 presents the Ragone plot for various electrochemical devices.

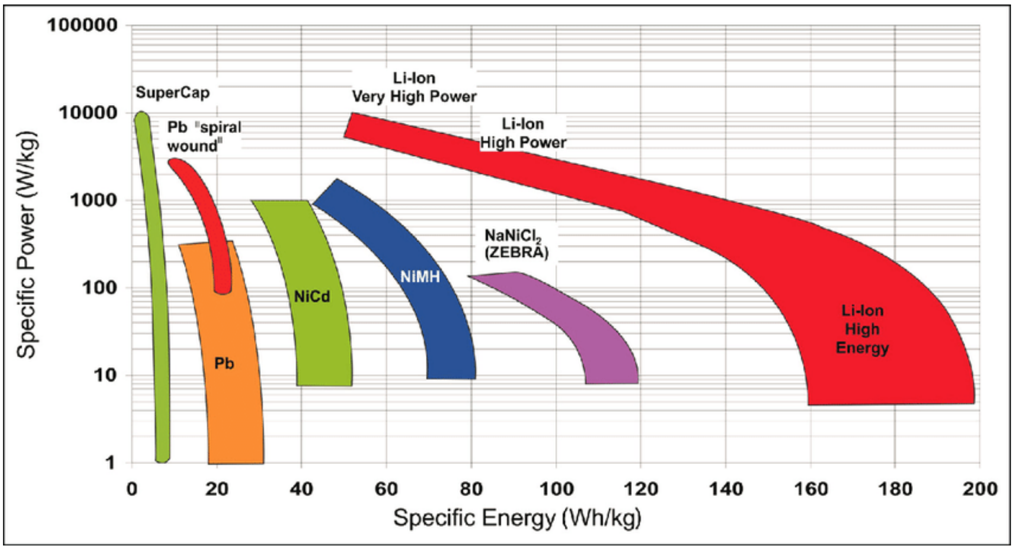


Figure 1: Ragone plot of various battery technologies with specification at cell level SuperCap: supercapacitor; Pb: lead; Li-ion: lithium-ion; NiCd: nickel–cadmium; NiMH: nickel–metal hydride; $NaNiCl_2$: sodium–nickel chloride; ZEBRA: Zero Emission Battery Research Activities.

The main difference between Lithium Ion Batteries (LIBs) and SCs lies in the charge storage mechanism: in short, the former involves redox reactions in the bulk of the active materials, while the latter operate through the accumulation of electrons at the surface of the electrode particles. While clearly more electrons can be stored in the bulk, kinetics limitations arise from the slow diffusion of the ions. In addition, LIBs operate in the electrochemical window where electrolyte is thermodynamically unstable. While the formation of passivation Solid Electrolyte Interphase layer on the anode (SEI) and the cathode (typically called CEI) and the use of relatively large active particles (with small surface area in contact with electrolyte) may slow down electrolyte decomposition dramatically and permit 500 to 5000 or more deep cycles, such cycle stability is still very short compared to SCs which typically undergo 1,000,000 or more cycles before degrading to 80% of the initial capacitance [2].

SUPERCAPACITORS FOR SPACE APPLICATIONS: MAIN TRENDS IN THE 2000's

Since the early 2000's, supercapacitors have been identified as interesting high-power sources. Indeed, supercapacitors have been identified as an adequate energy storage technology to ensure the peak power supply of several space applications ordered in function of their peak power requirements:

- Peaks power < 100W, like in robotic instrumentation, energy reserve for On-Board Computer, or Transmit and Receive Modules (TRM) for radar,
- Peaks power in the range of [100 W; 1 kW], as required for spacecraft actuator, pyrotechnics, radar and lidar, and launcher pyrotechnics and safeguard
- Peaks power > 10 kW, as needed for future radar, filtering bus for GEO spacecraft, and launchers Electromechanical Thrust Vector Control (EMTVC).

Several potential applications for telecommunications satellites, flight control and electric propulsion, have been identified in the past decades, with the main objective to use supercapacitors in order to optimise the overall mass and performances of the energy storage system, based on the promising peak power capabilities of these devices.

Some trends regarding each domain are listed below:

- Geostationary Earth Orbit subsystems: the objective is to use supercapacitors to keep a satellite's power supply from fluctuating as the satellite loads change, providing Power Bus voltage regulation (start of electrical propulsion thrusters, eclipse transitions…). Another targeted application is the power supply of the release mechanisms of the spacecraft, used to deploy for example the solar panels, these are triggered after receiving a single pulse signal [3],
- High-power radar supply for small-satellite earth-observation missions ([3],[4]): the objective is to use supercapacitors to provide the necessary power and fulfil the low mass requirements [5],
- Flight control surface, including launch vehicle actuation systems [4]: the supercapacitors can provide the high-power density and energy storage these systems require. A specific example of this hybridization is the Flight Control Actuation Systems (FCAS): these systems require high-power manoeuvres, while maintaining an adequate mission energy density. A USA patented Modular Electric Power Systems (MEPS^{TM}), consisting of parallel strings of batteries supplemented with supercapacitors, complies with this requisite, saving weight and increasing the life of batteries at the same time,
- Hybridization of a bank of supercapacitor (BOSC) with Li-Ion batteries for electrical Thrust Vector Control (TVC) in spacecrafts for collision avoidance purposes, ([3], [5]) and in launchers [6]: the objective is to use the supercapacitors to decrease the amount and duration of power loads on the batteries, and consequently extends the lifetime of the whole energy storage system [6]. In a formation flight frame, emergency collision avoidance within one hour is a necessity. Thrusters need a long pre-warming phase before any manoeuvre can take place.
- Electric propulsion: a resistojet thruster that replaces the cold gas (Xe and Kr) system with supercapacitors managed to improve the specific impulse up to 28% [7],
- Optimization of the power supply of pyrotechnic separation mechanisms during launch phase ([4],[7], [8]): the objective is to replace the battery system by a bank of supercapacitors,
- Mars exploration missions: ultra-low temperature supercapacitors (operating at -70ºC) with porous carbon aerogel and advanced manufacturing technology have been identified as a potential power supply, in order to reduce the current heating needs for batteries [9].

If supercapacitors could be relevant, in order to power supply, the high-power peak demand of each of the applications listed above, their high-power capability is not enough to embed the technology is space applications. Indeed, there are a lot of other key parameters to consider for the optimization of the electrical architectures and the energy storage systems of spacecrafts and launchers.

SUPERCAPACITORS FOR SPACE APPLICATIONS: THE HIGH-POWER CHARACTERISTICS ARE NOT ENOUGH TO MAKE THE DIFFERENCE

The studies on supercapacitors, funded by ESA in the 2010's have shown interesting results with regards to the capabilities and limitations of COTS supercapacitors. In one of these studies, entitled « high power battery-supercapacitor study » in 2010, carried out by EADS Space Transportation, the demonstration that the high power characteristics of COTS supercapacitors are not enough to make the difference in order to ensure the power supply of the various electrical functions of a spacecraft and of launcher with an hybrid power system composed of COTS supercapacitors and secondary batteries has been performed [10].

Indeed, there are several key parameters to consider:

- the range of energy, that is also quite broad depending on the targeted application, from few Joules for pyrotechnics function or Laser Imaging Detection and Ranging (LIDAR) to several hundred kilojoules for the power supply of large actuator such EMTVC for new launchers. So, it seems not feasible to cover such range of energy by a same high-power storage system. In some cases, as it is done in state-of-the-art for energy storage solutions, the energy requirements could be covered with the parallelization of the high-power storage units. In such a case the knowledge of the failure modes of the unit is mandatory to cope with adequate “high power” system sizing.
- the range of operating voltage, with operating voltage requirements for spacecraft platforms from 28V up to 100V. For future launchers EMTVC is up to 400V. As it is observed in the state-of-the-art of the energy storage solutions, the series connection of high-power storage cells will be mandatory. Indeed, with respect to maximum operating voltage of such units of 4.10V for lithium-ion battery cells. and of the order of magnitude of 2.85V for carbon/carbon supercapacitors, the design and the sizing of “high power” storage systems with several high-power cells in series shall be done in order to avoid stress on the single cells. It means that the overcharge or overdischarge of the single cells shall not occur or shall be limited during the mission life. Several solutions have been used in the state-of-the-art of energy storage solutions up to now: adequate matching of the single cells in series, use of passive or active “balancing system”, system oversizing.
- the range of temperature, with operating temperature requirements comprised in the range - 50°C and +70°C. As for any electrochemical power sources, the operational temperature has a strong influence on the electrochemical system performances.
- the mission duration range is between few hours (launchers) to several years with a maximum of around 20 years for telecom satellites (including 5 years storage), and an observed increase of mission duration for observation satellites up to 17 years (including 5 years storage). We can expect in the future the same trend with longer mission durations. Such mission durations mean high power storage sources must be compatible with such long mission duration. Such increase in mission durations will have an impact in term of qualification of this “high power storage sources”.
- And the number of cycles which covers a very broad range from some cycles to several millions cycling (bus filtering or actuator powering) depending on the targeted application. The cycling number will be one of key driver in the choice of the high-power storage power sources. For example, it is known that several millions cycling on a battery can be achieved only by using low Depth of discharge (DoD), meaning oversizing the electrochemical power system, and extra mass at system level. Supercapacitors are devices where the processes used to store and deliver the energy have been identified more suitable for very high number of cycles. Nevertheless, such device can compete to batteries only for very low energy requirements.

Finally, the results of the study have shown that the use of supercapacitors and/or of hybrid power sources instead of primary or secondary batteries could be particularly strategic for the following applications:

- spacecraft applications: high-power LIDAR, radars and high-power actuators. For each application, it has been demonstrated that the use of 10 F supercapacitor cells in hybrid power systems could be a decisive advantage by contributing to the limitation of the main bus perturbations due to peak power.
- launcher applications: Electro-Mechanical Thrust Vector Control and pyrotechnics functions. Drastic gain in mass are expected by using 10 F to 100 F supercapacitor cells assembled in packs and used as single power source or combined with a battery pack to build a hybrid power system.

Indeed, the use of supercapacitors for space applications is still limited to some very specific applications. It's mainly since in the meantime, the development and qualification of improved electrochemical storage devices such as lithium-ion batteries were achieved. The explanation for such differences in development between both technologies can be explained by the impact and the improvement of new technology on the spacecraft mainly in term of mass, cost, power, size, management for a given set of mission requirements: strong impacts and improvements were found for lithium batteries technologies and strong efforts were made by satellite equipment manufacturers to develop and qualify this technology.

Nevertheless, these main findings have paved the way to more than 10 years of research and development activities conducted by space industry in cooperation with supercapacitors manufacturers, under ESA funding. The most interesting findings are presented in the next sections.

GENERIC SPACE QUALIFICATION OF 10F NESSCAP SUPERCAPACITORS

This ESA funded study has been carried out by Airbus Defence and Space in collaboration with EGGO. The activity was focusing on small size supercapacitors enhancing power densities ≤ 15 kW/kg. At supercapacitor component level, 3000 samples were procured and submitted to screening, in order to rule out infant mortality. the main objective was to make available at space grade a COTS supercapacitor (10F) manufactured by Nesscap (part reference ESHSR-0010C0-002R7UC), in order to prepare the entry of this part into the EPPL part 2. The samples were submitted to a qualification test campaign, taking as a reference the chart F4 in ESCC standards, including vacuum testing, vibration and shock, fast temperature transient tests, seal tests and calendar life tests as well as life cycle tests ([8],[11].

At equipment level, the main objective was to develop a Bank of Supercapacitors (BOSC), composed of 33 components (Nesscap 10 F - 11 in series and 3 strings in parallel. A passive balancing system was implemented in order to make sure the cells voltages remained in the safe areas. Some test points were foreseen in order to check the correct operating of the balancing system. Finally, some thermistors were attached to the BOSC in order to monitor the thermal response of the unit. The figure 2 hereafter presents a generic view of a BOSC of 10F Nesscap supercapacitors cells.

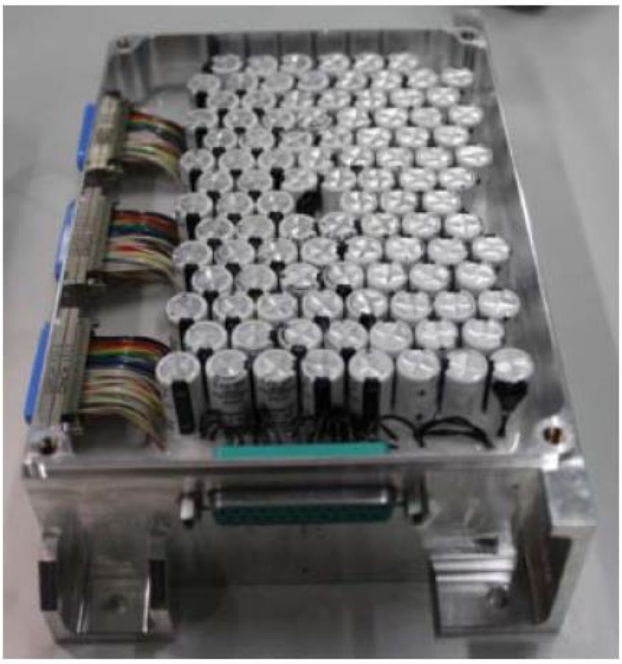


Figure 2: generic view of a BOSC of 10F Nesscap supercapacitor cells.

The testing at equipment level included mechanical inspections (dimensions, mass, flatness and roughness), electrical inspections (bonding, electrical continuity, isolation and electrical characterization), vibration and shock, thermal vacuum tests, and long-life testing (([8],[11]).

The result of the space grade qualification of the 10F Nesscap supercapacitor was successful. A large amount of qualification tests was performed, and all the electrical and mechanical parameters of this supercapacitor stayed in the specified range.

The assembly of these supercapacitors in a BOSC was electrically, mechanically and thermally designed and confirmed by analysis. Then a complete space grade qualification campaign of the BOSC was performed. All the tests were completed and successful. The Nesscap 10F at component and BOSC levels were ready for flight, the Technology Readiness Level (TRL) reached after this activity was 6 for radars and pyrotechnics applications. However, the major drawback for the supercapacitor cells and BOSC was a calendar deterministic ageing which depends on the temperature and the charging voltage. This drawback could also be observed for batteries. It could be maintained in the expected levels by applying derating in voltage and limiting the use temperature to 40°C.

The use of 10F Nesscap supercapacitors and BOSC, enables to optimise the energy storage system for radars and pyrotechnics applications. However, the COTS supercapacitors have limited performances in terms of energy density, implying that for several applications they were in competition with the high-power batteries which were considered as a most relevant and reliable solution. Indeed, there were several space applications with high power peak demands for which there wasn’t any solution to optimize the mass and the volume of some obsolescent battery technologies (e.g: NiCd batteries used for pyrotechnics needs).

Finally, The European Space Agency (ESA) has been involved since more than a decade in the development of new components by supporting several European actors.

CARBIDE-DERIVED CARBON (CDC) SPACECAP SUPERCAPACITORS

This ESA funded on carbide-derived carbon (CDC) electrode materials, carried out by Skeleton technologies. They have been developed and manufactured Electric Double Layer Capacitors (EDLC), also known as supercapacitors, for more than 10 years. The first CDC supercapacitor-related R&D activity with ESA was the research into CDC technology for the supercapacitor electrode. It is known that the double-layer capacitance and inner resistance of carbon EDLC devices follow opposite trends:

- On the one hand, the high amount of smaller the pores at the surface of the electrodes lead to the higher the capacitance (i.e. energy density).
- On the other hand, the high number of small pores at the surface of the electrodes increase the steric restrictions inside pores, which slows down the response of electrolyte ions to the changes of external potential field. Therefore, this increases the inner resistance and worsens the power characteristics of EDLC.

Therefore, to meet requirements of a wide range of applications, the selection of the electrode materials and the balancing of the electrodes, has been released in parallel for 3 different electrochemical systems:

- nanoporous or ultra-microporous CDC electrodes for the development of the high-energy supercapacitors,
- microporous and mesoporous carbon electrodes for the development of high-power supercapacitors,
- microporous carbon electrodes with slightly modified pore size distribution for the better access of micropores for classical supercapacitors.

Different test campaigns were carried out, in order to assess the influence of the specific CDC type, the electrode thickness, the separator materials, and the specific DC-current and ambient temperature.

The 100F SpaceCap prototypes were designed with prismatic shape and are presented in the figure 3 below.

Figure 3: SpaceCap supercapacitors prototypes.

The casing was made from stainless steel (SS304), with dimensions 27×32×16 mm (H×L×W) and wall-thickness of 0.3mm, which assures the mechanical strength of the capacitor and possibly gives better radiation resistance compared to aluminium casings.

As a result of optimizing the selection of these parameters, it was concluded that the high energy supercapacitors prototypes developed presented a power density of 5.8 kW/kg, which exceeded by around 50% the capabilities of the commercially available devices with similar energy capacity at the time of the study. The high-power supercapacitors prototypes developed exhibited a power density of the order of magnitude of 44.9kW/kg, which exceeded by 4 times the power density of the commercially available devices with similar energy capacity at the time of the study. This research enabled Skeleton technologies to develop CDC synthesis and post-treatment research for achieving higher power and energy densities. It was also possible to control the temperature behaviour of the CDC-based electrode.

63 SpaceCap supercapacitor cells (100F) were submitted to a set of tests, taking as a reference the F4 chart of the draft ESCC Generic Specification “Supercapacitors, EDLC”, including mechanical testing (vibration and shock), thermal shock, electrical measurements, life test and life cycle test. The test results supported the objective of achieving power and energy densities beyond the state-of-the-art in the supercapacitor domain ([11], [12]).

However, the testing campaign also revealed several weaknesses:

- relatively large variance in electrical performance: around 20% for capacitance, and 25% for Equivalent Serie Resistance (ESR),
- high variance in life test performance and life test failures: 2 out of 15 cells failed the voltage hold tests, 3 out of 6 cells did not pass the life cycle test. The ones that passed the test showed a variance of the order of magnitude of 40%.

The results obtained in those studies indicated that if CDC based electrodes supercapacitors presented promising results during initial electrical characterization, some improvements at electrode material level were required in order to improve the stability of the electrical performances during life test. Some others promising carbon materials, graphene and Vertically Aligned Carbon Nanotubes (VACNTs) have been studied in order to improve the electrical performances of the supercapacitors compared to the State-of-the-art, and with the objective to improve the life test performances.

GRAPHENE ENABLED SUPERCAPACITORS CELL (GRACE) [13]

This ESA funded study related to the development of graphene electrodes for high-energy supercapacitors, has been carried out by Pleione. The objectives of the de-risk GRACE activity ([3], [13]) were to develop a supercapacitor cell with proven capabilities of increased specific energy and life test stability while maintaining satisfactory power density by exploiting the promising properties of graphene. Furthermore, to meet space application requirements and maintain clear competitive advantages as a product, the goal was to achieve broad operating conditions for the cell (-40 to 70ºC).

The main objective of GRACE was to select, manufacture, test and benchmark graphene-based supercapacitor electrodes by testing different graphene commercially available products in different compositions, as well as establishing a supercapacitor cell manufacturing process with all the necessary Quality Assurance and Product Assurance measures.

The results obtained for optimised electrodes are promising, with specific capacitances of 323 F/g and 356 F/g, performed by using high content of graphene nanoplatelets in combination with other materials. These values measured indicate a significant improvement compared to commercial activated carbon, which presented a maximum specific capacitance of 120 F/g at electrode level.

The results in large scale pouch cell level indicated a transfer ratio of the electrode property around of the order of magnitude of 45%. The cells were designed to perform approximately a capacitance of the order of magnitude of 80 F. However, the results showed a maximum capacitance value of 37 F.

The targeted value of energy density was achieved (around 30 Wh /kg, so higher than 10 Wh/kg). The life cycle of the cells was lower than expected. A more comprehensive study shall be performed on the combination and suitable pairing of electrolyte/electrode system. Upon the completion of the de-risk GRACE activity the TRL of technology was 4.

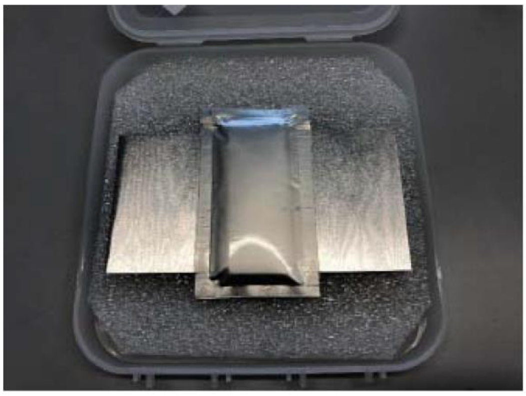
VACNTs BASED SUPERCAPACITORS FOR LAUNCHERS APPLICATIONS

This ESA funded study carried out by NawaTechnologies involved in the development of Vertically Aligned Carbon Nanotubes and related applications, in collaboration with Almatech, a, in charge of the design of the BOSC, and ArianeGroup as end-user for launcher applications. The main objective of the study was to develop high-energy supercapacitors (15 Wh/kg) in order to power supply, the pyrotechnics functions of the launchers.

Even if supercapacitors are not currently used in launchers, they hold a tremendous potential that has been investigated for more than10 years, mostly because of their high-power density, which fit with power supply needs of pyrotechnics applications and/or EMTVC. Indeed, the use of supercapacitors, in replacement or in combination of secondary batteries, will enable to obtain interesting mass savings. Vertically Aligned Carbon Nanotubes (VACNT) electrode materials, developed by NawaTechnologies were selected for this ESA R&D activity, since VACNT supercapacitors performances were expected to be better than classical carbon supercapacitors, in terms of specific power and energy capabilities ([11],[13]).

NawaTechnologies designed, built, assembled and tested about 20 preliminary prototypes of VACNTs supercapacitors pouch cells, and in the meanwhile, Almatech designed, built, assembled and tested the Bank of Supercapacitors (BOSC), using the VACNTs supercapacitors pouch cells developed by NawaTechnologies.

The figure 4 presents supercapacitor pouch cell and the BOSC.



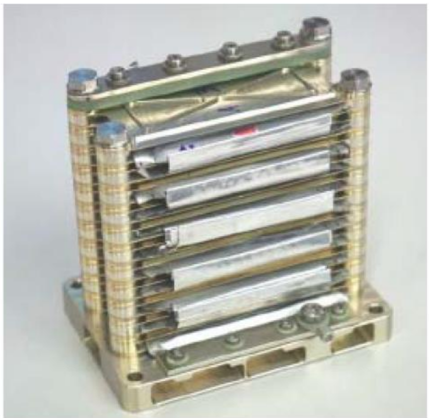


Figure 4: a VACNT pouch on the left (manufactured by NawaTechnologies) and on the right ALMATECH Bank of Supercapacitors.

The VACNTs supercapacitors pouch cells developed by NawaTechnologies presented some limitations in terms of electrical performances for the targeted application:

- Capacitance of the cells of the order of magnitude of 60F, versus the 200F required,
- Specific energy at cell level of the order of magnitude of 4.80Wh/kg, versus the 15 Wh/kg required.

Furthermore, the VACNTs supercapacitors cells developed by NawaTechnologies presented some limitations in terms of cell design:

- Lack of electrical performances at the temperature of -30°C,
- Poor behaviour of the cells assembled in BOSC under vacuum conditions.

Upon the completion of the activity the TRL of technology was 4. In conclusion, the design and the performances of the preliminary VACNTs pouch cell supercapacitors developed by NawaTechnologies need to be improved, in order to cope with the energy densities required for launchers, to use the supercapacitors for pyrotechnics, in replacement of existing secondary batteries, or in hybrid power systems in order to power supply EMTVC.

SUPERCAPACITORS FOR SPACE APPLICATIONS: OPPORTUNITIES

These last years, with the growth market of the small spacecrafts, weighting between 100 kg and 200 kg, facing with constraints in the allowable on-board battery volume, new opportunities appear for the use of supercapacitors in space. Indeed, this volume constraint has an impact on the maximum power supply capability of small spacecrafts, which is generally limited in ranges between 70 W to 200 W. This relatively low maximum power limits the capabilities of small satellites in terms of payload design and selection. In order to enhance these satellites' power performance, the implementation of supercapacitors as practical rechargeable energy storage medium, and as an alternative to chemical batteries is foreseen. Furthermore, as small spacecrafts programs are deployed beyond Low-Earth Orbit (LEO), their energy storage system will have to operate at lower temperatures and under wider ranges of load capabilities.

The figure 5 hereafter presents the number of Small satellites by mass class, for the period 2012 – 2021.

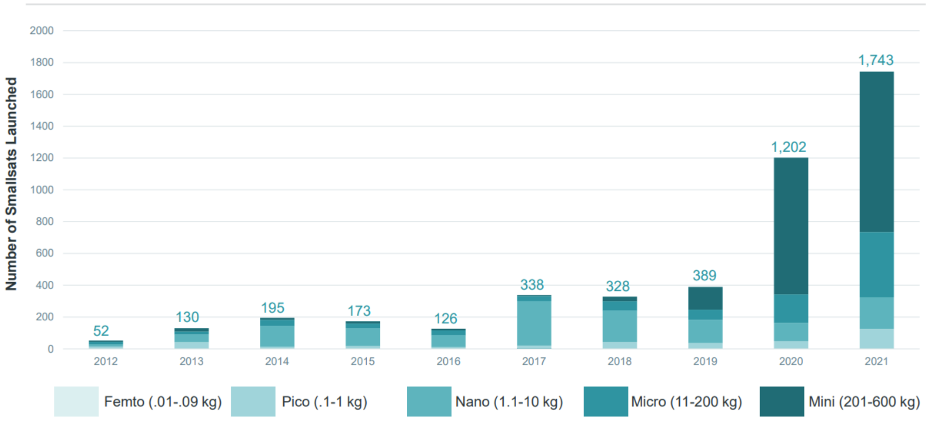


Figure 5: number of small satellites launched each year by mass class [14].

Many studies related to the use of supercapacitors in small satellites have been released these last years. The most interesting are listed hereafter:

- High power capabilities: researchers of the University of Surrey carried out a study in order to determine the feasibility and effectiveness of using supercapacitors-based power systems. For that purpose, the basic operation methods and several topologies were proposed and examined through the simulation and analysed against surveys. In addition, a simple and easy to use formula for estimating discharge efficiency was derived. Both the simulations and the formula were validated by cross-checking. The results suggest that the supercapacitor can replace an on-board battery and provide high power capability to small satellites. However, current supercapacitor technology cannot practically store a whole orbit's worth of average payload power at once, due to its low specific energy density. Current COTS very low ESR EDLCs have some potential to be used to supplement a battery for supplying very high power at high energy efficiency, for very short periods. However, LICs have advantages in terms of having higher energy capacity. indeed, the provision of this high-power capability would considerably widen the range of small satellite applications, enabling to reach 1 kW peak power capabilities and overpass the 200W peak power limitation [5].
- Hybrid power supply: in a NASA funded work, carried out at the Jet Propulsion Laboratory in 2013, a hybrid energy storage system consisting of a low temperature Li-ion cell (26 650 Li-ion battery cell – 2.3 Ah) and a bank of supercapacitors (310F Maxwell Technologies Inc.) was evaluated for performances enhancements at high power and low-temperature for future deep-space CubeSat applications (CSUN Cubesat). Although no significant improvements are observed in terms of the energy storage as compared to a CubeSat polymer battery, the hybrid power system exhibited substantial gains in power with high current (15A) pulse testing. The minimum discharger voltage is about 2.0V higher than the standalone Li-ion cell at the worst case initial 50% State-of-Charge. Finally, another benefit, is the low impedance of the hybrid system which is responsible for the observed performance improvement is about 5mOhm at a -40 ^{o}C operating temperature and is substantially lower than the CubeSat baseline polymer battery of about 1000 mOhm [15].
- 1U CubeSat Electrical Power System: a new EDLC-based EPS board was developed and tested in this study for its electrical performance and robustness in space environments, including launch environments and thermal environments. The total EDLC capacitance was 1600 F, the Electrical Power System occupying a volume of 90 × 87.3 × 64.6 mm. The functionality of the board was tested, assuming

realistic power, voltage, and current profiles based on actual orbital periods, and assuming release of the satellite from the International Space Station (ISS). The CubeSat power consumption profile was assumed to be from 920 mW to 2.67 W, and the photovoltaic power generation output to be 2.93 W, at its peak. The board was proven to withstand space environments, and to provide the power to operate a CubeSat in orbit, with a remaining energy level of 52% at the end of eclipse [16].

- In-orbit demonstration of COTS supercapacitors: in this study, a commercially available (COTS) supercapacitor (400 F supercapacitor cell manufactured by PowerStor/Eaton, XV series) was selected to power supply one of the payloads of the spacecraft Ten-Koh and wasn't used as an energy storage medium for the spacecraft electrical power system. Indeed, the supercapacitor was considered a part of the spacecraft payload and, because it did not serve as primary energy storage for the spacecraft, any potential failure was considered acceptable to the mission as whole. Ten-Koh was launched on October 2018 and remained operational until mid-March 2019. To contribute to studies that support the feasibility of using supercapacitors in small spacecraft, two goals are pursued: First, to demonstrate that a supercapacitor can survive the launch. Second, to prove that charging and discharging a supercapacitor in Low Earth Orbit (LEO) is possible. Three charge-discharge cycles of the supercapacitor in LEO have been recorded over the timespan of five months from the launch and are compared to ground results. In addition, self-discharge over two days in orbit has been calculated as less than 2.5%. These results show that the COTS supercapacitor can withstand the launch and space environment with capacitance loss lower than 1% and, therefore, is a viable energy storage device for LEO satellites. However, degradation of the supercapacitor over longer stays in orbit and repeated cycling is yet to be characterised [17].

CONCLUSIONS

The studies reported in this paper have demonstrated the successful use of supercapacitors, in the power supply and/or the hybrid power supply of several classical spacecrafts' applications (high-power LIDAR, radars and high-power actuators) and of two functions of launchers (pyrotechnics and EMTVC). Furthermore, the studies have shown the limitations and constraints related to the use of COTS supercapacitors. Indeed, enhancement of the performances of existing supercapacitors is an innovative field where new materials (VACNTs, graphene…) are going to play a determinant role in order to develop high-energy supercapacitors (> 15 Wh/kg) and hybrid supercapacitors (e.g Lithium Carbon capacitors with 50 Wh/kg energy density). With the proliferation of small satellites in recent years, the use of COTS supercapacitors that have not been developed for space applications is of interest to the space community. The use of COTS supercapacitors is interesting in more than one way as shown in the paper. Indeed, COTS supercapacitors have demonstrated their capability to be used: as the electrical power system of 1U CubeSat, as a payload power supply, as an electrical performances enhancer in a hybrid-power supply of small spacecraft. Finally, innovative supercapacitors based on graphene could be an enabler for the small satellites market, enabling to propose improved and/or new services and extended life duration.

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