DEVELOPMENT OF A NANOSATELLITE ELECTRICAL POWER SYSTEM USING Li-ION SUPERCAPACITORS

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This paper presents an innovative solution for electric power system (EPS) based on supercapacitors, developed for nanosatellites. Considering 3 different configurations of possible redundant systems for EPS, using Li-Ion supercapacitors, with their advantages and faults, it has been chosen the best one which allowed further testing of a nanosatellite model in light and in dark conditions. Testing and analyzing the EPS, it was possible to select the appropriate conversion circuit in order to get the best efficiency. We have proved that there are handy solutions for supercapacitor based EPS as primary source for electrical power system storage.

Keywords: electric power system, Li-Ion supercapacitor, CubeSat, solar panels, DC-DC convertors

1. Introduction

Nowadays, almost all of the electrical power system (EPS) used in satellites or nanosatellites are developed based on rechargeable batteries [1]. The main issues regarding the usage of rechargeable batteries in space refers to: the commonly limited life of the batteries due to numerous continuous charging/discharging cycles in a short period of time; extreme functioning temperatures (from - 40^0C to 70^0C) limiting their performance; capacity to supply larger power for short period of time. Taking into consideration the high number of daily charging/discharging cycles that rechargeable batteries had to support, for instance, at an average of 14-15 cycles for low earth orbit (LEO) [2] rechargeable batteries should support over 1,000 cycles in less of 72 days [3]. As most of the CubeSat missions have an average experimenting term of three months, with a lifetime expectancy of years, the stress on the rechargeable batteries performances, subsequently on the EPS, is very high. In mean time, functioning at low temperatures, these rechargeable batteries determine application of

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unconventional solutions [1]. For instance, an electrical resistance wrapped around the rechargeable batteries can be used for their heating. Such electrical energy is used in order to bring the rechargeable batteries within the functioning temperatures range, although it could also be used for some other practical purposes [4]. Various tasks as: data transmissions, processor or high power sensor testing or an experimental module, could overpass the limits of the present rechargeable batteries. The ability of EPS module inside a CubeSat [5] for supplying in certain situations instantaneous electrical power of over 50W should not be ignored, much more that such task could not be fulfilled by classic Ni-Mh or Li-Ion rechargeable batteries.

Taking into consideration all these aspects, we proposed to use supercapacitors as unique source for viable electrical energy storage. Such devices usually have at least 50,000 charging/discharging cycles and they function within a temperature range from -40^{0}C to +70^{0}C, with even a larger range for EDLC supercapacitors. Another advantage of such devices is the capacity to supply a much higher electrical current for short periods of time.

2. Experimental development of the electrical power system (EPS) with supercapacitors for nanosatellites

The EPS could be designed in various modes according to the conception and function principle considered.

2.1. Solution *A* for EPS

The simplest implementation for EPS is presented in Fig. 1.

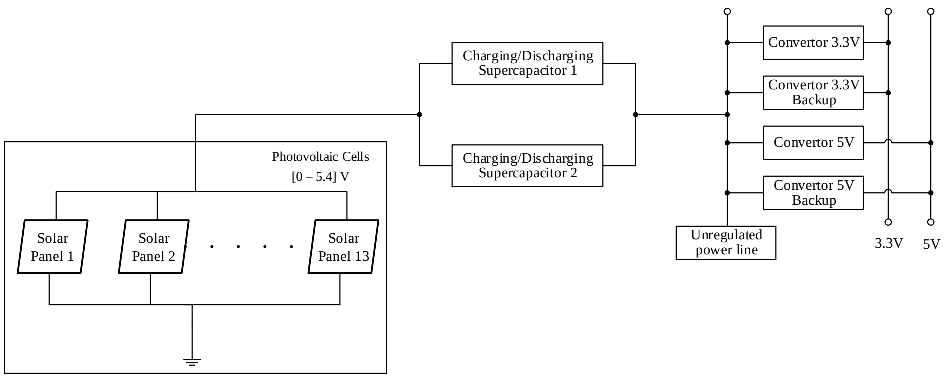

Fig. 1. Functional structure for EPS - Solution *A*.

The advantages of the proposed solution are: it is easily implemented, there are a low number of connections, redundancy in all critical points, in principal for the DC-DC convertors.

However, there are some disadvantages for this solution, specifically on its dependence of the whole system on the supercapacitor block. Even if the supercapacitors configuration is redundant, in case that they are just not functioning in space, or if they present prematurely malfunction, then the power supply of the whole system could be seriously affected.

2.2. Solution *B* for EPS

In Fig. 2 is presented the second solution, which is introducing convertors and stabilizers which could be supplied directly from the photovoltaic panels. The convertors for supercapacitors are bidirectional and independent, and their part in the set configuration could overcome the lack of potential on the unregulated supply line, being supplied by the photovoltaic cells [6].

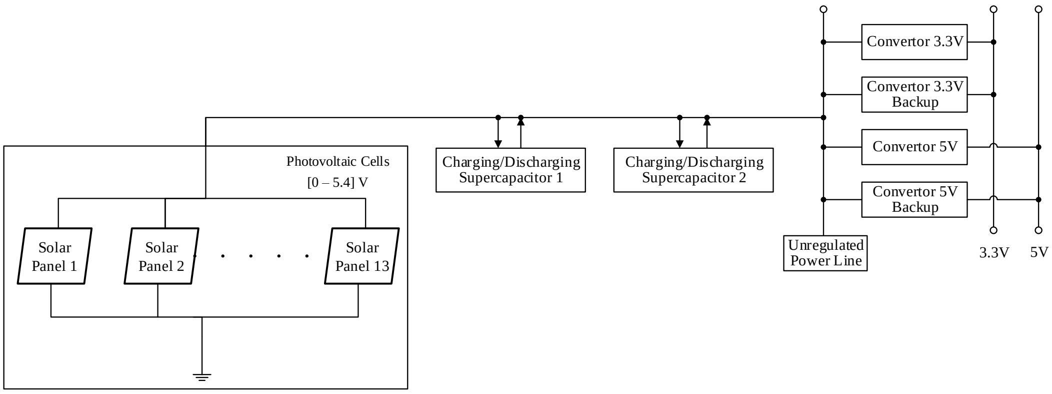

Fig. 2. Functional structure for EPS - Solution *B*.

The main advantage of *B* solution is the maintenance of the simplified configuration related to the 3.3 V and 5 V converters. The specific disadvantage for this proposed solution is found in the difficulty to keep a correct separation for charging/discharging supercapacitors circuits, therefore for implementing this type of configuration it would be necessary a degree of active control, using a microcontroller or otherwise. Without this kind of control, the supercapacitors chargers can power each other when there will be no power input from the solar panels, consuming precious resources. In addition, the supercapacitors could be individually used for short period of time in special cases only through limiting the efficiency of the solar panels.

2.3. Solution *C* for EPS

Following the previous proposed solutions, it was developed a new scheme in which the 3.3V convertors are used in alternation, during the light (illumination) period being used the convertors no.1, while during dark there are used the no.2 convertors.

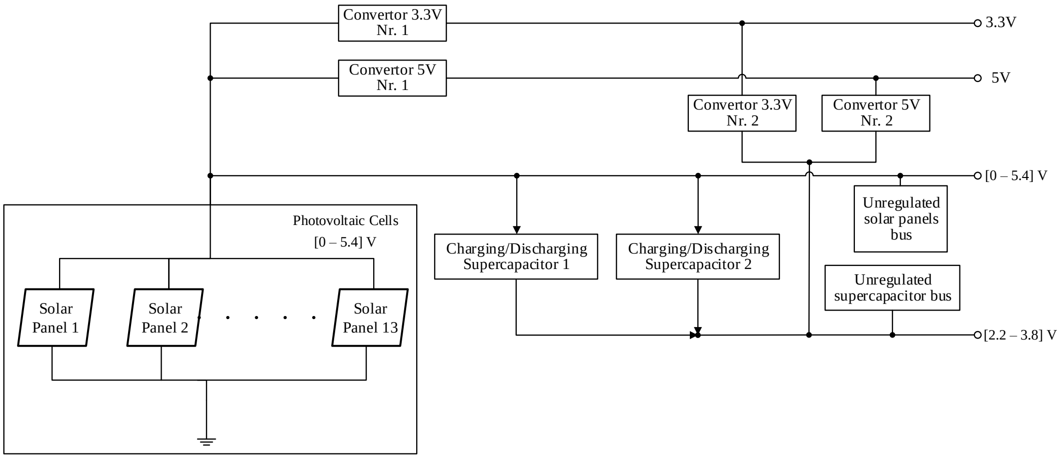

Fig. 3. Functional structure for EPS - Solution *C*.

In such configuration as presented in Fig. 3 it is possible to connect modules with high power requirements separated from the other systems due to the fact that the supercapacitors potential could be accessed on its own bus, independent of the rest of the bus convertors. The redundancy is assured by convertors no.2 if those from no.1 are broken, but not vice versa. Practically, the malfunction of convertors no.2 lead to a power supply for the nanosatellite available only from the supercapacitors bus during the dark period.

The redundancy of the convertors no. 2 could be assured by: supplementing with a parallel convertor each voltage bus; implementing the redundancy at power supply entrance for each bus or subsystem. The presented solutions could be used for any type of supercapacitors available to date.

2.4. Obtaining the test circuit for EPS

The Solution C was chosen for developing the EPS test circuit, as it offers the best redundancy option out of the three. When using Li-Ion supercapacitors there are more restrictions applying for the charging circuits in comparison with EDLC type. One of these restrictions refers to the lower limit of the potential – 2.2V as a decrease under this value will damage irreversibly the Li-Ion supercapacitors. Therefore, in order to choose the most appropriate DC-DC convertor among various types (LTC 3110, LTC 3112, LTC 3127, LTC3129, LTC 3412, LTC 3442, LTC 3536, LTC4425, SPV 1040, MAX 16930, SN6501-Q1) it has been performed the comparison between various parameters as: minimum and maximum input voltage, minimum and maximum output voltage, maximum output current and working temperature. Following such analysis there were selected two DC-DC convertors, namely: LTC3127 and LTC3442. Due to the space limitation and wanting to keep the redundancy available, it has been decided to group by two capacitors parallel connected for each DC-DC convertor.

It can be approximated that 8 Li-Ion supercapacitors occupy an approximate volume of 2 EDLC capacitors.

There are also initial restrictions for the test PCB created due to nanosatellite internal available space, and the supercapacitor positions and connections; the PCB dimension is 83mm x 83mm. The external dimension of the plate was adjusted according to the launching trails of a CubeSat [5] nanosatellite, considering that the rail dimension is 8.5mm in each of its corner. The scheme in Fig.4 shows the grouped capacitors in the lower part of the plate, such configuration being advantageous as a second PCB could have a mirror placement for its own devices.

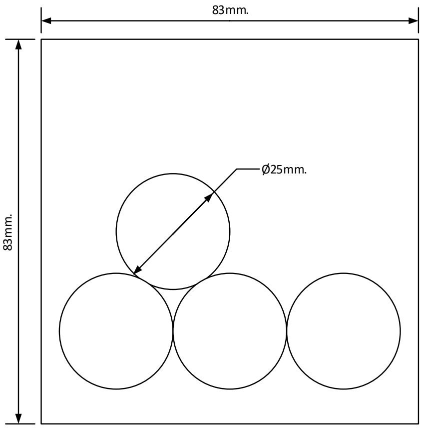

Fig. 4. Planning the supercapacitors placement for developing the test plate.

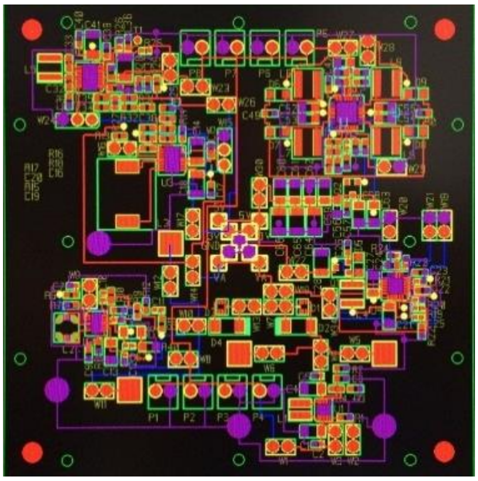

Fig.5. Printed Circuit Board (PCB) [8] designed by Mihai Totu for the new EPS

Mounting half of the capacitors on a second plate is beneficial for the general dynamic at the launching stage. Also, grouping the capacitors towards the plate's center allowed lateral space to be available for other requirements. The obtained design is presented in Fig.5. In the middle of the PCB there are grouped the main electric buses of EPS, namely: input voltage from solar panels, grouped output voltage from supercapacitors, output voltage of 3.3V, output voltage of 5V and the circuit ground.

3. Testing set up for the implemented EPS circuit

For testing the created EPS circuit, it was developed a testing system using a nanosatellite model with 13 solar panels mounted, a distribution board with the generated voltages from each solar panel grouped, an Arduino Mega platform and a transmitting module composed of two APC220 units [7]. Exploiting the microcontroller ability to measure analogic voltages and the ADC convertor, there have been performed measurements from distance for the voltages in the key points of the EPS circuit – Fig.6.

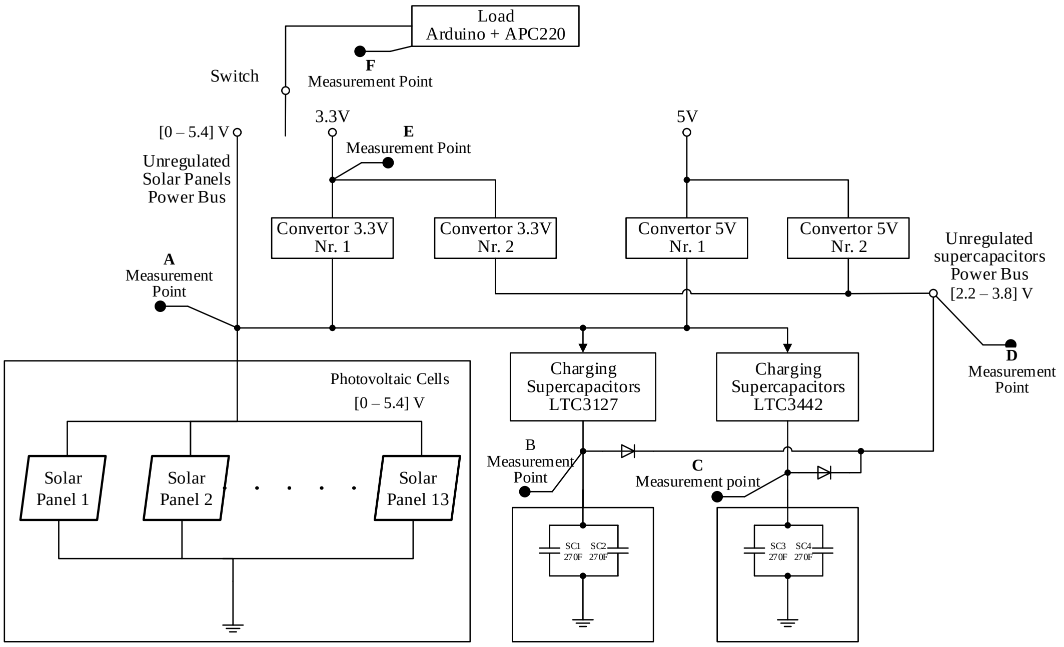

Fig.6. Scheme for the EPS platform test.

The whole system functioned generating its own electrical power, without being necessary external power supply. The ambient temperature recorded during the testing system was 34°C, as it was a sunny day. The maximum recorded solar intensity during the measurements was about 93.000lx – Fig.7.

There have been installed 5 solar panels (silicon based) which were directed towards sun and the nanosatellite model has been moved manually aiming to obtain the peak voltage at each charging cycle, Fig.7.

Fig.7. The physical model of the testing nanosatellite with the solar panels extended towards sun.

The testing system is also equipped with an acquisition module of the supplied voltage from the solar panels, therefore it was possible to monitor individually each solar panel. The received data by help of the radio transmission module APC220 have been displayed in real time, so the voltage values were easily monitored in two locations: exterior and inside place at 50m distance between them. Also, the information has been recorded in real time for further subsequent works.

4. Results for EPS testing assisted by solar panels

The experimental results were processed following the data acquisition. The calculated values for the voltage have been calibrated using as reference a voltage generated by a 3.159V battery. This value was measured and confirmed at the beginning, during and at the end of the experimental testing. There were taken into account and measured 3 complete charging – discharging cycles for supercapacitors.

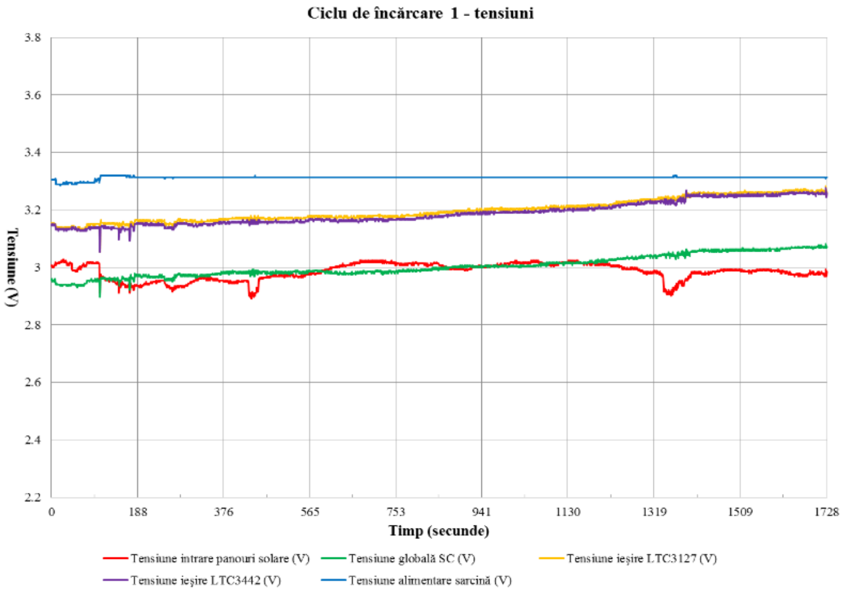

Fig. 8. First charging cycle – voltage variation

The first charging cycle started from supercapacitors voltage of 3.1V, and after 30min it reached 3.25V – Fig.8. The voltage supplied by solar panels varied around 3V. The electrical current for the first cycle varied significantly – Fig.9, as the DC-DC convertors put a lot of stress over the power which could be generated by the solar panels.

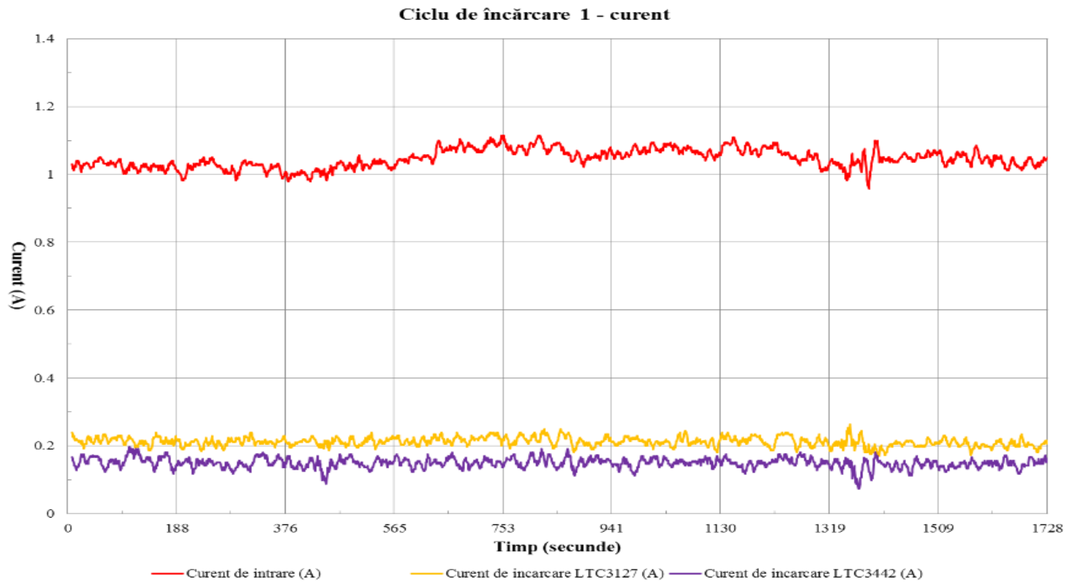

Fig. 9. First charging cycle – electrical current variation

The average value over 1A consumed from the solar panels power is closed to the theoretical maximum of 1.22A which could be supplied by the 5 solar panels under direct sun.

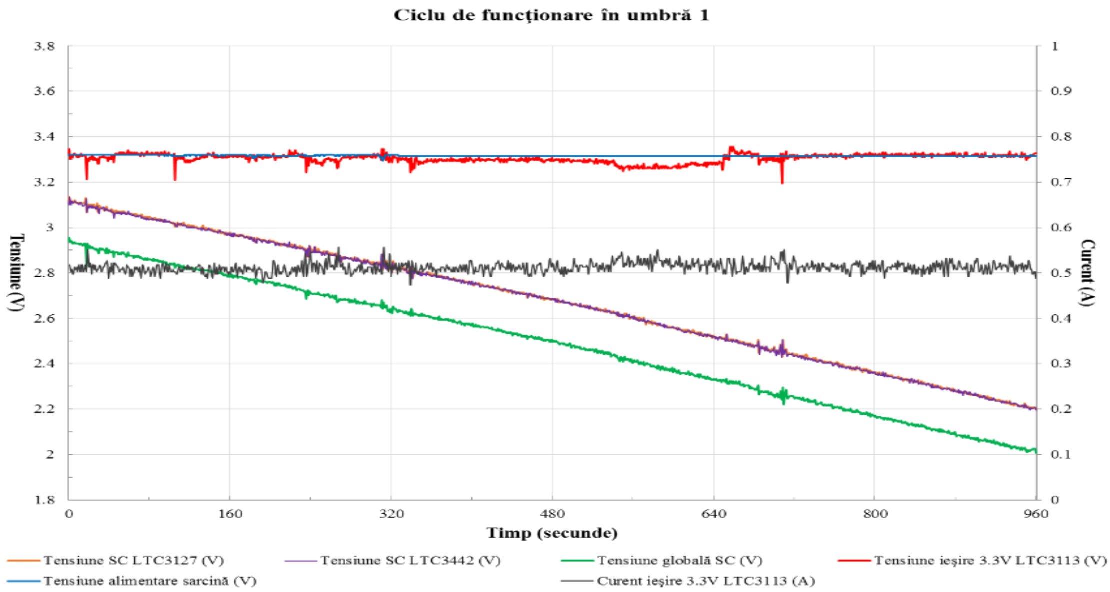

Fig.10. First cycle for functioning in dark conditions

As shown in Fig.10 for the first functioning cycle in dark conditions it was recorded a system functioning for 16min without using solar energy. Considering a double number of supercapacitors for a final application, the circuits and consumption optimization it was possible to prove the viability of the proposed EPS system.

During the second charging cycle, starting the supercapacitors charging from the minimum voltage, 2.2V, to 3.1V after 52min of solar charging. The output voltage variations were higher than those from the first charging cycle, the input voltage also presenting important fluctuations. Similar to the voltage behavior, during the second charging cycle, the input current presented high fluctuations which were reflected in an important variation of the output currents for charging the supercapacitors. For the second discharging cycle it was simulated a dark period of 7 min and 15 sec. During this period, the supercapacitors' voltage decreased from 2.75V to 2.25V while they were supplying continuously an average current of 0.5A to the testing circuit. The supply voltage at the load was constant at 3.3V.

For the third charging cycle, the average supplied voltage by the solar panels was over 3V, and at the final of the charging cycle the supercapacitors' voltage from 2.25V reached 2.9V. During the third charging cycle the current varied constantly around 1A over the entire test. Towards the end of the 54min of cycle time, the current presented a bit lower variations, directly correlated with a lower variation of the output voltages for supercapacitors charging.

The last cycle for EPS power supply using only supercapacitors during the dark period put in evidence that for 500s the supercapacitors' voltage decreased linear from 2.9 V to 2.3V while the circuit was supplying a 0.55A current. The output voltage of the DC-DC convertor was 3.3V having a ripple current lower than in the first two cycles.

5. Results for EPS testing in ideal conditions

Testing the EPS for general ideal efficiency was done using several multimeters and oscilloscopes. The power was constant supplied using a constant power source. There were measured the efficiency and capabilities of the 6 implemented modules. The efficiency for the supercapacitor circuit charger were measured between 86 and 96% efficiency. Considering the LTC3127 manufacture specifications, the DC-DC integrated circuit convertor used in this application, we can consider the implementation almost ideal. The efficiency graph was drawn in Fig. 11, based on extensive data measurement. To be noted, that the general current input was limited to 0.28A, in this way keeping under control the main total power consumption of the circuit. The general temperature rise was less than 5°C in all testing conditions, which shows a good thermal design for the PCB passive cooling.

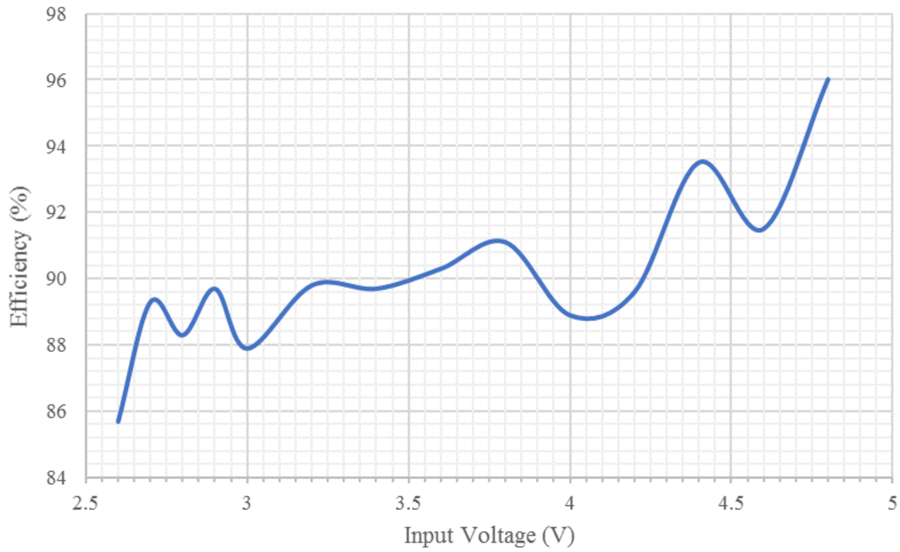

Fig. 11. First supercapacitor charging circuit efficiency

The 5V convertors had a lower energy efficiency than the supercapacitors chargers, although they could provide higher power conversion. In Fig. 12, it can be observed the efficiency of the second DC-DC 5V convertor, developed using LTC3421. The efficiency drop at higher power requirement could be created by PCB design limitation in passive cooling. The ΔT increase in temperature of more than 20°C in less than 5 minutes of 4.4W demand, shows that thermal dissipation and management should be improved for the proposed design and PCB.

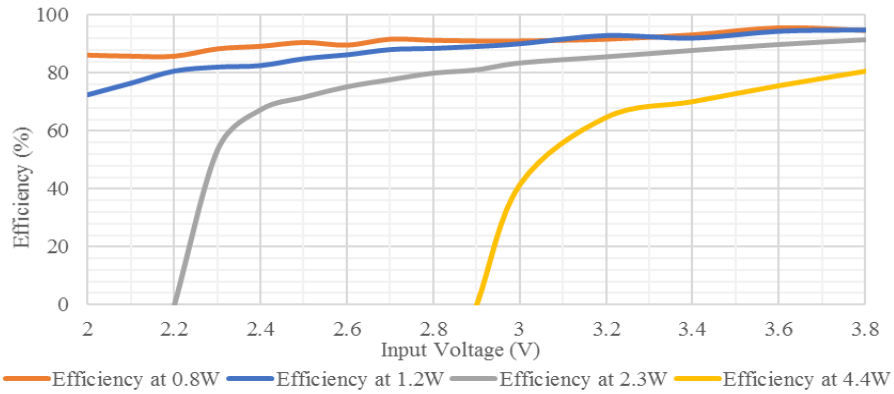

Fig. 12. Second 5V DC-DC convertor efficiency

The ideal efficiency of the 3.3V DC-DC converter is shown here for the first 3.3V convertor, which converts power directly from the solar panels. This circuit was developed using the LTC3112 as the central piece. As it can be seen, for an output higher than 1A, so a power larger than 3.3W, the efficiency drops significantly, and the regulated output is lost at a voltage of 3.3V input, consequently the converter cannot work in boosting mode any longer. Although, it is difficult to believe that a nanosatellite would consume such a high power only by using the 3.3V rail, this experiment proves that a very small power source to be implemented in a satellite, capable of supplying power for any type of application.

Modifying different components of the implementation, such as the inductor for the circuit, or the caps size, could improve the circuit efficiency at specific functioning regimes, though differences from the drawn graphic show in Fig. 13 will not be higher than 10% for the high load cases.

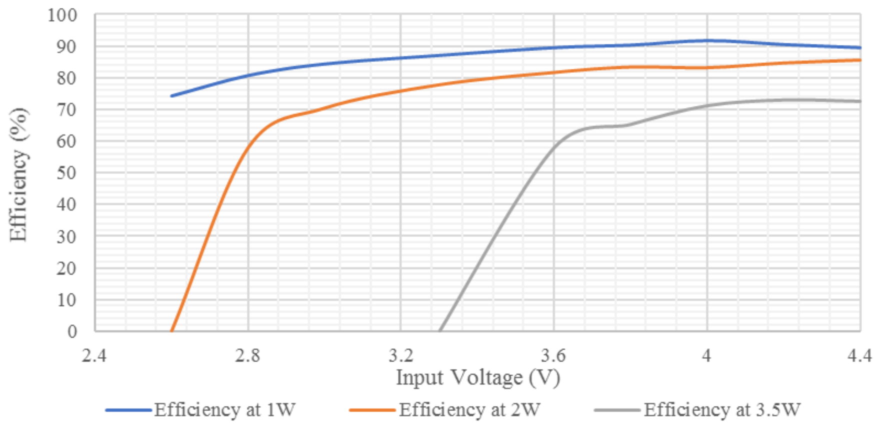

Fig. 13. First 3.3V DC-DC converter efficiency

6. Conclusions

According to the performed experiments, the proposed EPS design using supercapacitors (8) compactly placed on PCBs is a good option for powering a nanosatellite. The design did not imply any MPPT or other active power management, and through several optimizations, this solution could be implemented as working solution for CubeSats and other type of nanosatellites. Mounting the supercapacitors on a single PCB or on two PCBs could be done according to the application requirements. Our experimental data proved that it is feasible to develop a new EPS using supercapacitors as primary and only source for the electrical power storage. The EPS developed proved that is possible to use 3.5W by the 3.3V rail, 4.4W by the 5V rail, and twice 1.3W for supercapacitors charging, for a total of 10.5W. Considering a good case of 5.5W power generated by a 1U CubeSat solar panels (in case we use good quality expensive solar panels), the power supply will never be overloaded, and together with the redundancy implemented, it offers a complete solution that could be implemented directly in a CubeSat nanosatellite structure.

Acknowledgements

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R E F E R E N C E S

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