Supercapacitors as elements increasing the efficiency of photovoltaic installation

Sz Rogowski¹, M Sibiński¹, A Kolczyńska¹, and A Kluba¹

¹ Department of Optoelectronics and Semiconductor Devices (DSOD), Łódź University of Technology (LUT)
ul: Wólczanska 211/215, 90-924 Łódź, Poland

corresponding author: szymon.rogowski@dokt.p.lodz.pl

Abstract. The main purpose of the research is to check an influence of supercapacitors as the elements increasing the efficiency of short-period energy storage in photovoltaic installations. Their task will be to substitute the batteries or enhance their performance as the energy bank. For the model storage setup consisting of six supercapacitors, the work charge–discharge characteristics were determined. Additionally, an influence of storage time on the amount of charge accumulated inside the battery was tested. Then the examined setup was coupled with a conventional PV module by the charge regulator system and tested in laboratory and under real operating conditions. Obtained results proved that the use of supercapacitors as buffer elements in energy storage system of photovoltaic installation can significantly increase operation lifetime and reliability.

1. Introduction
An element that has a significant impact on the lifetime of the PV off grid installation is the energy storage bank, which is considered to be the component with the shortest operating period. Therefore, to increase the profitability and efficiency of the entire installation, it is necessary to increase the durability of this element. Nowadays, energy storage banks in off-grid or hybrid solar systems uses lead-acid batteries or less frequently lithium-ion cells [1]. The advantage of lead-acid batteries is the lowest price per unit of power amongst all types of batteries [5-7]. However, this solution has many drawbacks, the largest of which is the limited and relatively small number of charging-discharging cycles. The second disadvantage is sensitivity to high discharge currents and sensitivity to deep discharge level. Elimination of these two biggest drawbacks may result in longer operation time of the energy storage, which will consequently increase the efficiency and profitability of the photovoltaics installation. The use of super capacitor as the energy reservoir or battery support element may reduce or completely eliminate these two defects [3].

The main purpose of the research was to create and test a supercapacitor battery, whose task would be to effectively store energy generated in the off grid type solar installation.
2. Materials and methods

2.1. Parameters of supercapacitors.
Supercapacitors are electronic components that have very large capacitances compared to standard electrolytic capacitors. Thanks to the special technology of producing electrodes, it is possible to achieve very large capacities, eg. 3000 F. and very high energy density of 10,000 Wh/kg in comparison to ordinary batteries, which reach 100 Wh/kg [8-11]. The second unquestionable advantage is that supercapacitors can withstand up to a million full charge / discharge cycles, which is over 400 times more than conventional lead-acid batteries. Supercapacitors are also elements that can operate in a wide range of temperatures from -40°C to +65°C and are also resistant to humidity and environment conditions because they are hermetically sealed, robust and durable.

Supercapacitors are made of two electrodes coated with a material such as activated carbon. By using such material, the electrodes have a very large surface, approximately 100,000 times larger than a smooth surface. The electrodes are separated by an ion-permeable membrane used as an insulator to protect them against short circuits. This structure is then rolled or folded into a cylindrical shape and stacked in an aluminum can. The internal structure is then impregnated with liquid or viscous electrolyte of the organic or water type. Finally, the housing is hermetically sealed to ensure stable behavior for a specified period of use [4].

These elements, however, have some drawbacks that limit the possibility of their direct use in photovoltaic systems. First disadvantage is the low operating voltage, which is less than 3V for a single capacitor. The second problem is the shape of the discharge characteristics of the capacitor, which looks completely different than in the case of conventional batteries. The first problem can be solved by connecting several capacitors in series, but this solution requires the use of voltage equalizing circuits on individual capacitors [2]. The second problem related to the method of the voltage changing during discharge of the supercapacitor is possible to be solved by using a special converter system.

2.2. Supercapacitors in PV system
Very large capacity and up to a million full charge / discharge cycles, makes supercapacitors suitable for energy storage in some PV systems. The biggest limitation in this concept is very low voltage. The easiest way to solve this problem is to connect the capacitors in series, but as a result of this process the capacity of the whole battery is reduced which results from the formula for the serial connection capacity.

System based on supercapacitors can be used in grids with fluctuations in electric power, also supercapacitors as opposed to battery can handle peaks on load without loss of efficiency, therefore that systems will work perfectly at the end of transmission lines in the villages or low-urbanized areas. However, this common method appears not to be simple in practice, demanding devices necessary to realize such connections. In addition, replacing currently used energy storage with supercapacitors could prove to be less efficient and much more expensive solution [13-16].

Another interesting option is the energy storage unit, made of a battery and supercapacitor connected in parallel. In this case, a supercapacitor or a supercapacitor battery due to its very low resistance would transfer energy to the load during periodic instantaneous high-power pulses. As a result, the lead-acid battery would not be exposed to the hazard of short-circuits and may serve with extended lifetime. Such cooperation requires the use of appropriate coupling and monitoring systems that will be responsible for the protection and proper charging and discharging of both elements.

2.3. Architecture of the measurement system
The measurements were divided into two stages:

- measurements of the basic characteristics of the supercapacitors and battery
- measurements of a mini photovoltaic system equipped with a supercapacitor battery
The first part of the research was carried out in laboratory stand equipped with: current and voltage meters, regulated power supply and regulated load. Figure 1 shows the schematic of the measurement system.

![Figure 1. Diagram of the supercapacitors measurement system](image)

Using the data obtained in the first part of the measurements, a mini photovoltaic system was created, consisting of:

- solar module SL080-12P95,
- typical charging regulator system RBL30A,
- energy bank consisting of six Maxwell supercapacitors BCAP3000P connected in series

Figure 2 shows a diagram of the mini solar installation used for measurements.

![Figure 2. Diagram of the mini PV installation](image)

Elements used to build mini PV installation are characterized by the parameters presented in Table 1. The construction of supercapacitor batteries requires to use of one more element - balancers. They are the elements whose task is to connect supercapacitors in pairs and then equalize the voltage on each of them during charging and discharging. Balancers are necessary because omitting them could damage the supercapacitors.
### Table 1. Basic parameters of the elements used in mini PV installation [9]

| Parameter                  | Supercapacitors BCAP3000P |
|----------------------------|---------------------------|
|                            | Capacitance | Maximum charge | Specific energy | Recharge cycles | Efficiency | Internal resistance |
| Unit                       | F           | V               | Wh/kg           | times          | %          | mΩ                  |
| Value                      | 3000        | 2.7-2.8         | 10              | 1000000        | >95        | <0.3                |

| Parameter                  | Charging regulator system RBL30A |
|----------------------------|----------------------------------|
|                            | Standard charging voltage | Max output current | Discharge voltage | Max panel voltage | Efficiency | Current consumption |
| Unit                       | V       | A                | V                | V                | %          | mA                  |
| Value                      | 13.7    | 30               | 10.7             | 48               | >99        | <10                 |

| Parameter                  | Solar module SL080-12P95 |
|----------------------------|-------------------------|
|                            | Rated max power | Current at Pmax | Voltage at Pmax | Short – Circuit current | Open – Circuit voltage | Efficiency |
| Unit                       | W       | A                | V                | A                 | V                 | %          |
| Value                      | 95      | 5.52             | 17.2             | 6.11              | 21.6              | 10         |

### 3. Results

#### 3.1. Supercapacitors parameters

At the beginning, the basic characteristics of supercapacitors was measured during the standard charging and discharging cycle. Such measurements made it possible to predict how the battery system consisting of several supercapacitors connected in series operate. Measurements were made for many different supercapacitor configurations. As the loading element was used resistor, which has an adjustable resistance in the range of 0÷3 Ω, a maximum power of 100 W, and a maximum current of 30 A.

In figure 3 and in figure 4, the characteristics obtained for two and four BCAP3000P type supercapacitors connected in series are presented.
Figure 4. Charging and discharging characteristics of the four BCAP3000P supercapacitor

As can be seen in the characteristics, the measurements were carried out for different load values, which is associated with different values of time constants and different values of charging and discharging currents. The maximum of which are:

- maximum charging current 16 A
- maximum discharging current 18 A

Such current values allow to use the supercapacitors in photovoltaic installations.

The next step was to determine the discharge characteristics of a conventional battery CTM CT65-12i and compare it with the typical characteristics of a supercapacitor BCAP3000P. Battery and supercapacitors were discharged by constant value resistances which in the first case should cause constant current and voltage. Both types of energy storage were unloaded using a charge controller system. The parameters of the battery used are shown in Table 2.

| Parameter                  | Rated Capacity | Rated Voltage | Operating Temperature | Stand by time | Efficiency after 6 months (20°C) | Internal resistance |
|----------------------------|----------------|---------------|-----------------------|---------------|----------------------------------|---------------------|
| Unit                       | Ah             | V             | °C                    | Years         | %                                | mΩ                  |
| Value                      | 65             | 12            | -20 to 50             | 5             | 86                               | 6.0                 |

The result of the comparison is shown in Figure 5.

Figure 5. Comparison of BCAP3000P and CTM CT65-12i discharging characteristics.
As can be seen by analyzing the above characteristics, the shapes of both curves are completely different. With a conventional battery, the voltage remains constant as a function of time. Only a significant discharge will reduce the voltage. For a supercapacitor, the shape of the voltage curve resembles a linear decreasing function. Such a significant difference in the shape of the discharge curves is the biggest problem with the use of supercapacitors in energy storage systems [16].

The last type of measurements was to check the losses associated with the leakage of capacitors, which is considered to be their greatest disadvantage. The measurement consisted of charging two capacitors to a certain voltage and then leaving them for a specified time. After this time, the voltage was again measured and the load losses were calculated. The obtained results are presented in Table 3.

| Unit | Voltage [V] | Capacity [F] | Load [C] |
|------|-------------|--------------|----------|
| Day 1 | 5.47        | 1500         | 8205     |
| Day 7 | 5.20        | 1500         | 7800     |

For a system of two supercapacitors, losses after 7 days storage cycle were no higher than 5% of stored energy, which is quite satisfactory and will not affect the operation of the supercapacitors batteries. However, if we compare losses for supercapacitors with losses for typical lead-acid batteries, this value is already significant. For the second one, typical losses are around 5% per month.

### 3.2. Measurements of supercapacitor batteries

Using the data obtained in the first part of the measurements, battery consisting of six BCAP3000P supercapacitors connected in series was created. The energy storage prepared in this way allows to work with the voltages typical for the photovoltaic DC off grid installation and allows to accumulate a maximum of 2.25 Ah.

The energy storage prepared in this way was connected to the PV installation, consisting of one 95Wp SL080-12P95 c-Si module and a standard charging regulator system. The installation prepared in this way was tested in real environmental conditions. The first measurements were related to charging the energy bank by the charging regulator, which unfortunately required the initial charging of batteries to about 9 V, because below this value of the charging regulator could not detect the storage. The entire charging process has been completed at the maximum voltage at which the regulator works, i.e. 14.5 V. Below, in Figure 6 two typical characteristics of charging process of constructed mini photovoltaic installation are presented.

![Figure 6](image-url)
The graph shows the basic battery charging parameters, i.e. current and voltage supplied from the module, and current and voltage for supercapacitors. The energy bank was charged with constant current for most of the time. The characteristics show the moment when the charging was completed, as a result of which the flowing current dropped to a very low value, and the module voltage reached the value of the open circuit voltage. Other charging characteristics had a similar shape only differ in the values of the charging current, which depended on the illuminance[8,13].

The battery charged in this way has been discharged by means of a DC load using a charging regulator connected to the solar module. The result of this process is shown in Figure 7 as the exemplary characteristics.

![Figure 7. An exemplary characteristic of discharging energy storage using the charging regulator system with varied load value.](image)

The characteristics show currents and voltages at the supercapacitor and the load terminals. The current consumed by the load is the sum of the current drawn from the energy bank and supplied from the solar module. During discharging, is visible a change in load causing an increase in absorbed current, and then after some time the load has been reduced again.

The final stage of testing the supercapacitor batteries was connecting the DC / AC converter as a receiver and using a real load source. As a result of these tests an example characteristics presented in Figure 8 was created.

![Figure 8. An exemplary characteristic of working mini installation with DC/AC converter.](image)
The characteristics above show the currents and voltages of working photovoltaic installation equipped with the energy storage in the form of supercapacitors and a DC/AC converter. The current consumed by the load is the sum of the currents supplied from the module and supercapacitors. If the current consumption by the load is less than that supplied from the module, the supercapacitors are recharged. On the graph, the fact of charging capacitors is visible when the current flowing from them is negative. In fact, it means that electricity is supplied to them, and the load is powered only by energy from the solar module. In the case of operation with a small load generated by the converter, the supercapacitors battery voltage remains constant. Only small changes are visible when the load changes significantly.

The process of loading and discharging the energy store is supervised by the standard PV charging system. As a result of the research, it turned out that the whole process is characterized by high efficiency at the level of 99%. Unfortunately it is also visible, that the use of a standard charging regulator system significantly reduces the amount of energy that can be used by the receiver. This is related to the minimum and maximum voltage considered safe for standard lead-acid batteries. As a result, the minimum operating voltage of the energy storage is 9 V, while the maximum value is limited to 14.5 V, which in consequence allows to use only about 0.75 Ah of energy stored in supercapacitors.

In summary, to use the properties of energy storage in the form of supercapacitors, it is necessary to construct a new charge regulator. Its task will be completed in the near future to effectively use voltages below 9 V and to maintain a constant voltage at the output with decreasing battery voltage.

4. Conclusions
The use of supercapacitors as the energy storage can significantly increase the efficiency of the entire installation due to the very short charging times and a very large number of charging and discharging cycles. However, using them with commercially available charger systems significantly reduces the amount of energy they can deliver to the load, because from previous research it appears that only about 33%. In order to meet this effect, it will be necessary to replace typical charging systems specially dedicated for this type of energy storage, which will work with voltages lower than current systems. In addition, such a system must be equipped with a voltage boost converter that would maintain a constant output voltage.

A very big advantage of using supercapacitors as an energy storage is the very high dynamics of this solution. With a sufficiently large installation, such an energy bank could be charged in a very short time. The situation is similar with a discharge which, thanks to the very low internal resistance of the supercapacitors, can occur in a very short time, providing to the load very high current at the level of hundreds or thousands of amperes.

The use of a special charging regulator system and increasing the capacity of supercapacitor batteries can significantly increase the efficiency and lifetime of off grid or hybrid photovoltaics installations. The biggest problem using supercapacitors as energy storage is the relatively high cost of building an energy store compared to conventional batteries. Very interesting option is the energy storage unit, made of a battery and supercapacitor connected in parallel. In this case, a supercapacitor or a supercapacitor battery due to its very low resistance would transfer energy to the load during periodic instantaneous high-power pulses. As a result, the lead-acid battery would not be exposed to the hazard of short-circuits and may serve with extended lifetime.

In the future additional measurements are planned, including:
• connecting of supercapacitors as a support for conventional batteries,
• connecting the whole system with a PV installation and long-term testing,
• measurements parameters of supercapacitors after several hundred charging and discharging cycles

To sum up, it can be stated that the use of supercapacitors in solar installations can significantly increase their efficiency and lifetime. This is mainly due to the possibility of fast charging and discharging of energy storage and a large number of charging and discharging cycles. In addition, this solution is characterized by very high efficiency of the entire process, which is about 99%. Such a high
efficiency affects greatly the amount of energy generated by the installation. However, losses associated
with leakage of supercapacitors at 5% per week seem quite large compared to conventional storage for
which it is about 5% per month. Nevertheless, in daily use of the installation, this will not affect the
performance of the entire installation.

References

[1] International Energy Agency 2008 Trends in photovoltaic applications: Survey report of
selected IEA countries between 1992 and 2007 [accessed on 08.2008]
[2] Barrade P 2002 Series connection of supercapacitors: comparative study of solutions for the
active equalization of the voltages Electrimacs 2002 (Montréal, Canada) 18-21
[3] Jaszczur M, Hassan Q and Teneta J 2018 Temporal load resolution impact on PV/grid system
energy flows MATEC Web of Conf. 240 6 [accessed on 11.2018]
[4] Stević Z, Rajčić-Vujasinović M, Bugarinović S and Dekanski A 2009 Construction and
Characterisation of Double Layer Capacitors Proc. of the International Workshop “Oxide
Materials for Electronic Engineering” (OMEE-2009) (Lviv, Ukraine)
[5] Szymański B 2013 Instalacje Fotowoltaiczne 2nd Edition (Geosystem Burek, Kotyza S.C).
[6] Lewandowski W M 2007 Proekologiczne odnawialne źródła energii (Warsaw: Wydawnictwo
Naukowo-Techniczne)
[7] IEC 60904-1 Photovoltaic devices – Part 1: Measurement of PV current-voltage characteristics
[8] Lisowska-Oleksiak A, Nowak A P and Wilamowska M 2010 Superkondensatory jako materiały
do magazynowania energii Acta Energetica 71-79
[9] Datasheet K2 series 650 F - 3,000F ultracapacitors
[10] Poonama, Sharmab K, Arora A and Tripathia S K 2019 Review of supercapacitors: Materials
and devices Journal of Energy Storage Volume 21 801-825
[11] Raza W, Ali F, Raza N, Luo Y, Kim K H, Yang J, Kumar S, Mehmood A and Kwon E E 2018
Recent advancements in supercapacitor technology Nano Energy 52 441-473
[12] Głuchy D, Kasprzyk L and Tomczewski A 2017 Modelowanie superkondensatorów na potrzeby
współpracy z OZE Poznan University of Technology Academic Journals. Electrical
Engineering 335-345
[13] Fahmi M I, Rajkumar R, Arelhi R, Rajkumar R and Isa D 2004 The performance of a solar PV
system using supercapacitor and varying loads IEEE Student Conf. on Research and
Development 2004, (Batu Ferringhi, Malaysia)
[14] Fahmi M I, Rajkumar R, Arelhi R, Rajkumar R and Isa D 2015 Study on the effect of
supercapacitors in solar PV system for rural application in Malaysia 50th Int. Universities
Power Engineering Conf. (UPEC), (Stoke on Trent, UK)
[15] Glavin M E and Hurley W G 2007 Ultracapacitor/ battery hybrid for solar energy storage 42nd
International Universities Power Engineering Conf., 2007 UPEC 2007 (Brighton, UK)
[16] Burzyński D and Kasprzyk L 2017 Modelling and simulation of lead-acid battery pack
powering electric vehicle, E3S Web of Conferences [accessed in 2017]