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Autonomous emergency LED luminaires powered by supercapacitor

***Abstract**. In this article, the authors are describing possibility of supercapacitor usage for supplying emergency luminaires. Basic facts about modern supercapacitors and fundamental characteristics are provided initially. Analysis of usage of these supercapacitors in emergency lighting and suitable LED luminaires follow. For this purpose authors made capacity calculation and simulation of discharging characteristics. Then results of capacity and consumption are described. Finally pros and cons of supercapacitors usage are summarized, with prediction of the future growth.*

Streszczenie.** W niniejszym artykule autorzy opisują możliwości użycia superkondensatorów do podłączania oświetlenia awaryjnego. Omówiona jest analiza użycia kondensatorów do podłączania awaryjnego oświetlenia, jak również odpowiedniego oświetlenia typu LED. Pod tym kątem autorzy dokonali kalkulacji pod względem żywotności urządzenia na podstawie ogólnej charakterystyki wyładowywania. **Autonomiczne oświetlenie awaryjne zasilane przez superkondensatory

Keywords: Emergency lighting, Luminaire, Supercapacitor, LED
Słowa kluczowe: Oświetlenie awaryjne, lampa, Superkondensator, LED

Introduction

In connection with the development of nanotechnologies in recent years there have been created new possibilities of power accumulation on the principle of electric charge accumulation on the capacitors electrodes. These "capacitors" are called supercapacitors in Czech language (from English SuperCap, UltraCap). Even if the capacitors have been known for a long time they have improved so much in the recent years (especially surfaces of electrodes and dielectric materials) that can be meaningfully used for accumulating energy for a longer period. Mostly they are used currently to back up data in electronic memories and similar devices with low power consumption. The newly found usage is when starting a drive with high currents, in the DC link converters, in the reduction of peak demand and in the traffic engineering in accumulation of vehicles braking energy that will be used in their next moving off (e.g. Mazda6).

In connection with the LED light sources the supercapacitors seem ideal backup power supply for emergency lighting luminaires.

Advantages:

- Lower power consumption by LED
- Long life- time
- Reliable operation at low temperatures

Disadvantages:

- Higher cost than conventional accumulators
- Larger sizes of accumulators

General description of supercapacitor

Supercapacitor, unlike various accumulators (NiCd, Pb, NiMH, Li-Po, Li-Ion, etc.) does not use the electrochemical principle to accumulate the power. It transforms power into electric field energy between two electrodes.

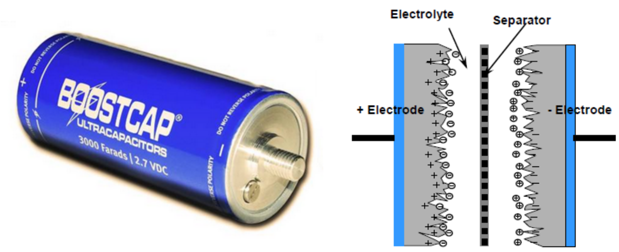

Fig.1. Supercapacitor Maxwell BCAP3000 and supercapacitor inner structure [1]

These are dominantly made of carbon powder coated on aluminum foil. One gram of powdered carbon has a surface area up to 2000 m2. Positive and negative electrodes are separated by a separator consisting of a polypropylene film. Free room is filled with liquid electrolyte. The maximal voltage of supercapacitor depends on it. The operating voltage and the maximal one is about 2-3 V. The large surface of electrodes, the small distance between them and high electric solidity of electrolyte and separator create conditions for the relatively high capacity of the supercapacitors. The capacity is directly proportional to the electrodes surface and inversely proportional to their distance:

(1) $$C = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{S}{d}$$

The amount of energy that can be accumulated:

(2) $$W = \frac{1}{2} \cdot C \cdot U^2$$

It is worth emphasizing that the amount of accumulated energy depends on the square of the voltage. Therefore the voltage has the greater impact on the accumulated energy than the capacity does. For example supercapacitor 2.7 V / 2500 F is able to store the same energy as a supercapacitor 2.5 V/3000 F.

A significant advantage of supercapacitors is that the voltage changes are relatively little during their discharge.

(3) $$\frac{W_{0.5}}{W_1} = \frac{\frac{1}{2} \cdot C \cdot \left(\frac{1}{2} \cdot U\right)^2}{\frac{1}{2} \cdot C \cdot U^2} = \frac{\frac{1}{4} \cdot U^2}{U^2} = \frac{1}{4}$$

Equation 3 shows that the reduction in voltage of the capacitor from the initial voltage by half causes the release 75 % of the accumulated energy. The change of the certain (above described) parameters may occur due to aging. They are affected by time or number of cycles. The comparison of the main energy-technical parameters is shown in Table 1.

Table 1. Comparison of supercapacitor and a typical accumulator for emergency lighting luminaires

	NiCd high-temperature acumulator	Supercapacitor MAXWELL BCAP 3000
Density of energy	32 Wh/kg	6 Wh/kg
Specific power	100 W/kg	6 kW/kg
Lifetime	4 years	1 000 000 cycles

Self-discharge of a capacitor is a phenomenon which is very fast when comes to the classical capacitors. The manufacturers try to reduce the self-discharge as much as possible when producing the supercapacitors. Despite this effort the self-discharge is striking. The biggest impact of self-discharge is noticeable immediately after disconnecting of supercapacitor from the power supply. However, as demonstrated below, the typical self-discharge supercapacitor loses approximately 3 % of its accumulated energy in the first hour (see the relations 4 and 5). There is also the temperature dependence of the supercapacitor self-discharge. The minimal self-discharge is during low operating or storage temperatures.

(4) $$\Delta U_{1h} = \frac{V_0 - V_{1h}}{V_0} \times 100\% \qquad \Delta U_{1h} = \frac{2{,}67 - 2{,}63}{2{,}67} \times 100\% = 1{,}5\%$$

(5) $$\Delta W_{1h} = \frac{W_0 - W_{1h}}{W_0} \times 100\% \qquad \Delta W_{1h} = \frac{2{,}67^2 - 2{,}63^2}{2{,}67^2} \times 100\% = 3\%$$

From the above mentioned characteristics it is clear that the self-discharge at the expected operating temperature is important. However, in terms of the emergency lighting it is considered for the supercapacitors only the state of charging or discharging, and the emergency luminaires standard in emergency mode work only for one hour and 3 %, then loss of accumulated energy is almost negligible.

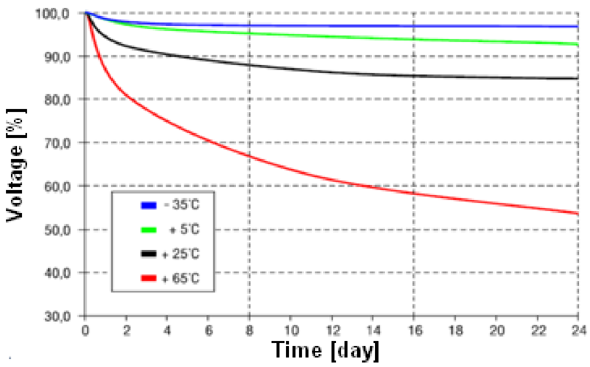

Fig.2. Supercapacitor self-discharging [1]

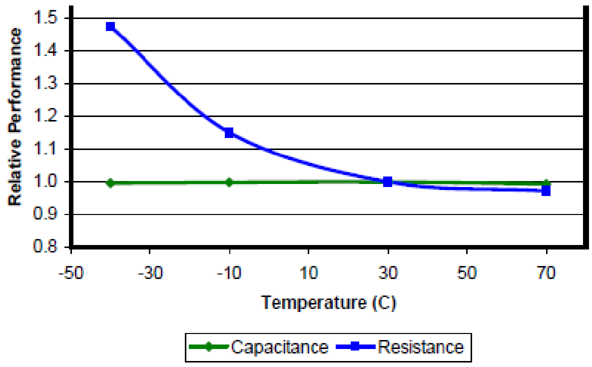

Fig.3. Supercapacitors parameters temperature dependence [1]

Due to the very low temperature solidification of the electrolyte the supercapacitors can operate at temperatures as low as -40 °C and even higher working temperatures do not have a marked influence on capacity. There is only a change of a value of the replacement series resistance (Resr). However, this resistance is not an important parameter for emergency lighting due to low labor currents, since it arises only minimal voltage drop (see Fig. 3) and therefore its warming is negligible too. Maximal operating temperature of supercapacitors is 65 °C so it is higher than at the conventional battery cells.

Supercapacitors´ lifetime is influenced by applied voltage and by ambient temperature. For example, at rated voltage and temperature 25 °C there is after 88 000 hours (about 10 years of operation) the loss of capacity about 15 %. With increasing of temperature by every 10 °C the loss of the capacity is multiplied. At 35 °C, which is considered as maximal when the device is being installed, the loss of capacity after ten years of operation is the maximum up to 30 %. Number of cycles has the impact on the capacity reduction as well (1 million cycles cause a loss of capacity by about 20 %). However, when using to supply emergency luminaires the number of cycles for the expected lifetime is less than one thousand. Supercapacitors are permanently under the supply voltage and the discharging occurs only when there is a voltage failure. This mode will have only a minimal effect on the capacity loss. Due to the high lifetime of supercapacitors it will not be necessary to change them during all time when the emergency luminaires are being used. This provides the advantages of enabling permanent installation into luminaires and especially in reducing the cost of maintenance (replacing the standard accumulators).

The great advantage of supercapacitors is their high efficiency. There are not electrochemical reactions as at the conventional accumulators. In applications with low operating current, the total efficiency of the cycle (charging / discharging) is up to 98 %. This allows us to achieve a very high efficiency of the device operation.

The behaviour of supercapacitors for power LED lighting

When calculating the required capacity and the number of articles we start from the substitute scheme and the supercapacitor discharge characteristics (see Fig. 4).

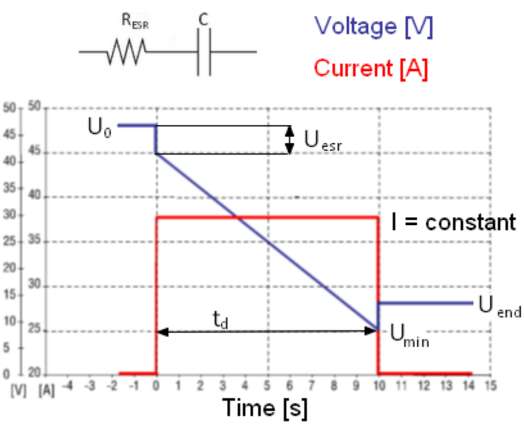

Fig.4. Substitute scheme of the supercapacitor and discharge characteristics of supercapacitor [4]

U_0... the initial voltage of charged capacitor
U_{esr}... voltage drop at the equivalent series resistance
U_{min}... the minimal usable voltage
U_{end}... voltage after load disconnection
t_d... the discharge time
I... constant discharge current#
Besides its capacity the supercapacitor has its spare internal resistance Resr that causes a voltage loss Uesr while discharging.

(6) $$U_{esr} = R_{esr} \cdot I$$

This loss reduces the amount of usable energy from the capacitor:

(7) $$\Delta W = \frac{1}{2} \cdot C \cdot \left[U_0^2 - \left(U_{min} + U_{esr}\right)^2\right]$$

The amount of resistance depends on the type of supercapacitor, number of supercapacitors and their connections:

(8) $$R_{total} = R_{1\,piece} \cdot \frac{\#\text{piece in series connection}}{\#\text{piece in paralell connection}}$$

The maximal voltage loss Uesr occurs at the maximal current that will flow through the circuit at the minimal voltage of the capacitor. The calculation takes into account the effect of the converter (see equation 10). Internal resistance Resr is bigger in cells with lower capacity. For the calculation we have chosen the supercapacitor with capacity of only 2000 F:

(10) $$U_{esr\max} = R_{esr} \cdot I_{\max} = R_{esr} \cdot \frac{P}{U_{\min} \cdot \eta}$$

(11) $$U_{esr\max} = 0.58 \cdot 10^{-3} \cdot \frac{1}{0.8 \cdot 0.7} = 0.001V$$

In applications for charging of the emergency LED lighting, because of low operating currents, Uesr will not be taken into account due to its small size.

Design of power connection of the emergency LED luminaire with supercapacitor

Theoretical calculation of the supercapacitor capacity was done for LED light source of power 1 W, supplied by a constant operating current 350 mA and voltage of 3.3 V. The LED of 1 W power and high luminous efficacy (e.g. 125 lm/W) is an adequate light source in combination with good-quality optics designed for the lighting of emergency exits. The effectiveness of optical parts of such a good-quality luminaire is more than 70 %. Due to the exact distribution of the luminous flux and its sufficient quantity (over 90 lm), such luminaires (when meeting the standard values for emergency lighting) can illuminate the standard corridor with an emergency exit of length longer than 10 m. The lifetime of LED modules is not limiting in case of emergency lighting, because it is considered a lighting period of maximum of 1000 hours in the lifetime of the luminaire.

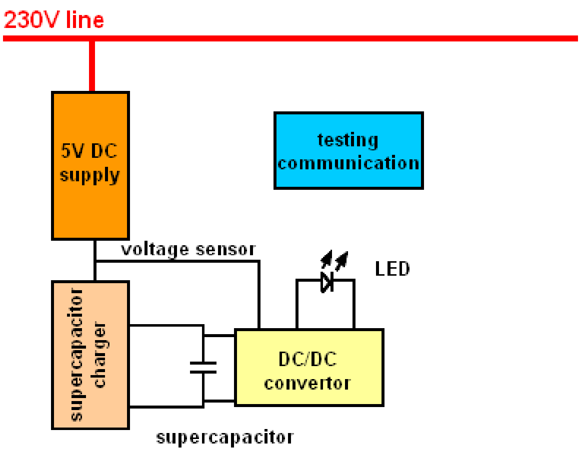

Fig.5. Block scheme of a supercapacitor powered luminaire

Table 2. Parameters of supercapacitor Maxwell BCAP3000

Capacity	3000 F
Voltage	2.7 V
Production tolerance	-0% up to +20%
Operation temperature	-40°C up to +60°C
Available power	3.04 Wh
Lifetime	1 million cycles
Proportions	length 138 mm diameter 60.7 mm
Weight	0.51 kg

The design of a power connection and the choice of appropriate circuit converters as well as power supplies for LED are essential for the functionality and efficiency of the whole system. For the circuit it is necessary to use DC / DC converter, because supercapacitor voltage decreases when discharging. When choosing a suitable circuit it is important to monitor the minimal operating voltage of the converter Umin, which will set the amount of usable energy from the capacitor. Used converter must have the highest efficiency possible at the required output current in the range of input voltage.

To ensure a constant luminous flux coming from LED it is the best if the circuit keeps a constant output current. As it is apparent from the volt-ampere characteristics of the power LED it is neccesary to choose the current source, not the voltage source for the power supply.

Based on the knowledge of LED module power and used circuit we must decide whether to use one or more supercapacitors. Using multiple supercapacitors leads to increased voltage, therefore to reduction of current flowing through the circuit, and also to the reduction of internal losses. On the contrary, there is a higher price of supercapacitors (even if they are of half capacity) and the need to use a voltage balancer, which will be in charge of balancing the voltage on the capacitors so that there is no exceed working voltage, which could damage the supercapacitor. Based on the survey of the present converter circuits and supercapacitors offer the suitable solution seems to be to use a supercapacitor for 1W LED or more pieces for more efficient light sources. The Fig. 4 shows a block scheme of the designed emergency luminaires.

Calculation of a supercapacitor capacity

The calculation of a suitable supercapacitor size comes after the circuit and sources design. From the above mentioned the following quantities will be relevant for the calculation:

The minimal operating voltage converters:

$$U_{\min} = 1V$$

The initial voltage of the charged supercapacitor:

$$U_0 = 2.7V$$

Permitted voltage loss of the supercapacitor::

(12) $$\Delta U = U_0 - U_{\min} = 2.7 - 1 = 1.7V$$

Supplied constant power:

$$P = 1W$$

Efficiency of DC / DC converters and power supply:

$$\eta = 0.8$$

Average current consumption:

(13) $$I_{avg} = \frac{I_{\max} + I_{\min}}{2} = \frac{\frac{1}{1 \cdot 0.8} + \frac{1}{2.7 \cdot 0.8}}{2} = 0.86A$$

Supercapacitor aging factor (capacity decline in 10 years):

$$k = 0.7$$

Required time of luminaire lighting:

$$t = 3600$$

Discharged characteristics of the supercapacitor:

(14) $$dU = i \cdot \frac{dt}{C} + i \cdot R_{esr}$$

According to the above mentioned explanation (see equation 11) there will be neglected a component of the voltage loss at the internal resistance (Uesr). Since the current increases almost linearly during discharging, the instantaneous current can be replaced by and average current Iavg and express the required capacity of the supercapacitor:

(15) $$C = \frac{I_{avg} \cdot t}{\Delta U} = \frac{0.86 \cdot 3600}{1.7} = 1821F$$

The following equation takes into account the capacity loss during the projected lifetime of a luminaire (10 years):

(16) $$C_{final} = \frac{C}{k} = \frac{1821}{0.7} = 2602F$$

From the supercapacitors offer there was chosen the closest higher capacity 3000 F. For an example of such a supercapacitor it was chosen the type Maxwell BCAP3000 with the parameters listed in figure 4.

Conclusion

From above mentioned it is clear that the supercapacitor is fully usable in practice for supplying the autonomous emergency lighting luminaires equipped with LEDs.

Emergency lights supplied by the supercapacitors will be applicable for:

- emergency escape lights and anti-panic luminaires with a operation period of one hour,
- luminaires with LED light sources and with a good directing of luminous flux,
- autonomous supplying.

The biggest disadvantages of this solution are:

- higher investment cost,
- bigger dimensions of supercapacitor and then the whole luminaire,
- unavailability of higher capacity for longer operation time or for the usage of LED higher power consumption.

With the increasing specific power of LED this solution has a great potential for the future.

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