Supercapacitors as storage of modern energy systems

Introduction

In the recent years there have been an increasing interest growth in renewable energy sources (RES), both in transportation and stationary systems. They are no longer an object of scientific researches but play an important role in the energy system and cover significant part of the energy demand. The amount of energy produced by many RES like wind turbines or photovoltaic farms varies depending on the meteorological conditions which causes serious problems in energy management. The currently available technologies include [2]: L/A battery, Li-ion battery, NaS battery, VRB flow battery, supercapacitors, SMES-es (Superconducting Magnetic Energy Storage), high-powered flywheels, pumped hydro and CAES (Compressed Air Energy Storage).

Supercapacitors offer short charge, discharge and response times (in seconds), high power capacity (up to 100 kW/L), high roundtrip efficiency (above 90 %), long lifetime (up to 20 years) and high resistance to deep cycling. The main disadvantages are: low energy density and low storage capacity [2].

Operating principles of supercapacitors

Typical supercapacitor consists of the following parts [6]:
- two electrodes made of high surface area porous material,
- electrolyte,
- separating material,
- electrical connection,
- sealing

The electrodes can be made of conducting carbon (graphene), metal oxides and conducting polymers. Electrolyte can be in form of aqueous electrolyte, nonaqueous electrolytes in aprotic solvents or ionic liquids [9].

A simple Hemholz equation for electrical capacitance is [5]:

\[ C = \frac{\varepsilon_0 \varepsilon_r A}{d}, \]  

where \( \varepsilon_0 \) is dielectric constant of vacuum, \( \varepsilon_r \) - dielectric constant of the dielectric material used, \( A \) – active surface area of the electrode and \( d \) – distance between the electrodes.

The electrodes have high surface area – over 1500 m²g⁻¹ and the distance between the electrodes is small. As a result the capacitance is high.

EDLCs (electric double layer capacitors) operate on the phenomenon of accumulation of electrical charges within the electrical double layer, which is formed at the electrode - electrolyte medium boundary. The ions move under the influence of an applied voltage. In the discharged state are randomly distributed throughout the volume of electrolyte, if the applied voltage is lower than the limit voltage, they start to move in the directions of the respective electrodes - anions toward the anode and cations toward the cathode.
However, no current flows through the capacitor, since the ions are not transferred to, and do not react with the electrodes, and only accumulate near them. In this way the border of the electrolyte - electrode produces two electric layers in which the current carriers accumulate the same value as the charge on the electrode surface, but of opposite sign. The quantity of stored charge is dependent on the applied voltage.

**Operation layouts**

The voltage applied to the capacitor (single capacitor cell) cannot be higher than the limit value for a given electrolyte, otherwise an electrolysis can occur and ions will enter the electrodes which can lead to excessive gas emanation resulting in the capacitor explosion. Exceeding the voltage limit of the supercapacitor will decrease their lifetime and deteriorate the electrical properties [20]. The typical limit for a supercapacitor cell is 3 V [12]. For practical applications they have to be connected in series forming a battery so it is possible to apply a higher voltage. In such case, the voltage on each individual cell will be different because of slightly different properties of each cell (capacitance, leakage current, internal impedance). Thus voltage on a single cell may be higher than the voltage on the battery divided by the number of cells.

To diminish the danger of an overvoltage conditions and increase lifetime, the batteries are connected applying layouts which are supposed to equalize the voltage. Fig. 1 presents various layouts of dissipative shunting equalizers. Fig. 1 a) shows a solution with shunting resistors, which are used to equalize the voltage by means of a (preferably) small current flowing through them. This current, however, will also be increasing the self-discharge of the capacitor block. In Fig. 1 b) Zener diodes are used to equalize the voltage and in Fig. 1 c) the current flowing through the resistors is limited by transistors which are controlled by differential amplifiers with a reference voltage supplied by Zener diodes.

Some authors in [19] and [7] present layouts of active equalizers which offer better performance but on the other hand have higher cost.

![Dissipative shunting equalizers](image)

**Figure 1.** Dissipative shunting equalizers [18]
*Source: Author’s artwork after [18]*

**Equivalent diagrams**

The phenomena involved in charging and discharging of the capacitors are complex, therefore for the purpose of electrical modelling of the device often equivalent diagrams are used. They consist of simple electronic components which connected according to the diagram behave similarly to the modelled device.
Figure 2 presents a five-branch circuit according to [21]. The branch with $R_A$ models an fast response (in range of seconds), branch with $R_B$ – in the range of minutes, $R_C$ – in the range of over 10 minutes. Capacitance $C_A$ reflects the double – layer effect and resistance $R_D$ models the leakage current [13].

![Five-branch circuit diagram](image)

Figure 2. Five-branch model [21].  
*Source: Authors’ artwork after [21].*

For simple modelling applications an uncomplicated model can be used. It consists of capacitance $C$, series resistance $R_S$ and shunt resistance $R_{SH}$. The parameters of this model can be easily acquired by measuring charging and discharging process of the supercapacitor. $R_S$ can be calculated according to the following formula [13]:

$$R_S = \frac{\Delta V}{\Delta I},$$  \hspace{1cm} (2)

in which $\Delta V$ and $\Delta I$ are voltage and current change during charging.

The capacitance can be estimated by measuring charge or discharge process from time $t_1$ to $t_2$ and applying equation (3) [13]:

$$C = \frac{2 \int_{t_1}^{t_2} u i dt}{(U_1^2 - U_2^2)},$$  \hspace{1cm} (3)

in which $u$ and $i$ are instantaneous voltage and current, $U_1$ and $U_2$ are voltages at $t_1$ and $t_2$ respectively.

The shunt resistance $R_{SH}$ can be obtained by connecting the charged supercapacitor to a constant voltage source with terminal voltage $V$. After some time, the current will become constant – this is the leakage current $I_{leak}$. The resistance is than:

$$R_{SH} = \frac{V}{I_{leak}},$$  \hspace{1cm} (4)

**Charge and discharge curves and parameter estimation**

As an example of the operation of supercapacitors and in order to obtain the basic parameters of a sample device the charge and discharge curves have been measured. The supercapacitor under examination was a BMOD0058 E016 B02 type by Maxwell [10]. The diagrams of the charging and discharging circuit are presented in Figure 4. The capacitor was charged with a constant-current source and discharged with a programmable load controller set to constant current mode. In both cases the current was 1 A. The charts are shown in Figure 5 and 6.
Figure 4. Diagrams of the a) charging and b) discharging circuits. Source: Authors’ artwork

Figure 5. Charging curve of the capacitor Source: Authors’ artwork

Figure 6. Discharging curve of the capacitor
Source: Authors’ artwork

From the charge and discharge curves the capacitance has been calculated according to eq. 3. The result was 58,7 F, when nominal value from manufacturer datasheet is 58 F [11]. The result of the series resistance measurement was 0.1 Ω. The leakage current after 180 minutes under voltage equal to 15,26 V was equal to 0,026 A so the shunt resistance is 586,9 Ω.
Supercapacitors can be used in applications where the electrical current needs to be supplied for a short time. Often they are a part of a hybrid system which includes other electrical power sources. In [8], a hybrid supercapacitor/fuel cell system is designed to decrease a voltage sag in power distribution system. In [16], a supercapacitor is also used in a fuel cell power supply system to smooth-out the characteristics of the fuel cell powered vehicle. In these kinds of systems they are used to improve the performance of other sources of energy like fuel cells or chemical batteries.

An interesting design has been presented under a trade name “UltraBattery”. It is a hybrid power source which combines lead-acid battery technology with supercapacitor. Its advantage is that it can operate in a partially discharged state, can accept and deliver the charge faster and is well suitable for variable power applications, especially transportation [17].

Another direction which benefits from high specific power of the supercapacitors is regenerative breaking – instead of dissipating the kinetic energy in the form of heat, electrical energy is produced and stored in a supercapacitor energy system for future use. There are experimental solutions for trains [14, 15] and cars [1, 4].

**Summary**

The supercapacitors present high potential for the future energy storing systems. They are especially useful when combined with other energy sources. The hybrid devices can benefit both from high power density of the supercapacitor and high energy density of the complementary device.

The transportation of the future will benefit from the possibilities provided by large capacitance, especially in the electrical vehicles. Also in the renewable energy sector there is a need for efficient energy storing devices. Due to their properties, the supercapacitors are able to provide short-term high-power demand.

**Abstract**

The paper presents supercapacitors as energy storing devices for renewable energy and transportation systems. Basic principles of operation are presented, as well as operation layouts and equivalent circuits of various accuracy. Example charging and discharging curves of the investigated supercapacitors are given along with the main capacitor parameters derived from them.

**SUPERKONDENSATORY JAKO MAGAZYN ENERGII W NOWOCZESNYCH SYSTEMACH ENERGETYCZNYCH**

**Streszczenie**

Artykuł przedstawia superkondensatory jako urządzenia magazynujące energię w systemach energetycznych, wykorzystujących energie odnawialne, oraz w systemach transportowych. Przedstawiono zasadę działania, jak również układy pracy oraz schematy zastępcze o różnym stopniu dokładności. Zamieszczono krzywe ładowania i rozładowania badanego kondensatora oraz na ich podstawie obliczono jego parametry elektryczne.

**References**


