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Supercapacitors, and the Potential to Revolutionize Energy Storage & Power Delivery

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Table of Contents

Introduction

What are Supercapacitors?

Can Supercapacitors Replace Batteries?

Supercapacitor Use Cases and Applications

How do Supercapacitors Work?

Key Parameters of Supercapacitors

Conclusion

Abracon Supercapacitors

Introduction

While batteries have been a mature technology for over a century, the need for energy storage solutions with faster charging and discharging cycles than traditional batteries has led to the search for a new alternative. Although conventional capacitors offer the fastest charging and discharging cycles among energy storage solutions, they lack the high energy densities that batteries feature. Technological research in the domain of energy storage has given birth to a new class of solution that bridges the gap between the properties of both batteries and capacitors: supercapacitors.

The history of supercapacitors, also referred to as “ultracapacitors”, starts in the 1950s with General Electric’s research and development of activated charcoal electrodes. Although they were not known as “supercapacitors” at the time, further research by different entities followed the same trail and aimed to increase the energy densities of capacitors. Early supercapacitors faced challenges such as high ESR, high leakage current, and safety and environmental hazards. However, their evolution continued with the incorporation of different materials such as metal oxides, activated carbon, lithium-ion, graphene, and many others. Today, supercapacitors can reach energy densities up to tens of Wh/kg, which is more than 100 times larger than regular capacitors, as shown in Figure 1.

What are supercapacitors?

And how are they different from batteries and traditional capacitors?

Traditional capacitors are two-terminal passive electrical components that store energy electrostatically in the form of an electric field. They consist of two conductive surfaces, also known as electrodes, separated by a dielectric or an insulator. When a voltage is applied across the capacitor, electrons migrate towards one of the plates, creating a net positive charge on it, and repelling the electrons on the other plate. The positive and negative charges remain on the plates due to the electrostatic attraction between the opposite charges. The insulator between the plates prevents any charge migration due to the electric potential difference, so no current flows through the capacitor. This creates an electric field between the two plates, which is sustained until the external terminals are loaded, shorted, or there is a change in the polarity of the applied voltage on the capacitor. This feature is the essence of the energy storage capability of the capacitor, where the voltage is maintained across it, even if it is disconnected from the voltage source.

Batteries, on the other hand, store energy in a chemical form. Although there are many types of batteries that utilize different materials to achieve certain features, they all operate on the same general principle: storing and converting energy between chemical and electrical forms through chemical reactions between the cathode, anode, and an electrolyte solution. In this case, there is no electrostatic interaction.

Can supercapacitors replace batteries?

Supercapacitors are not intended to replace either batteries or traditional capacitors. Rather, they are an intermediate solution that combines the characteristics of both. This makes them the optimal candidate for applications that require the specific features discussed in the next section.

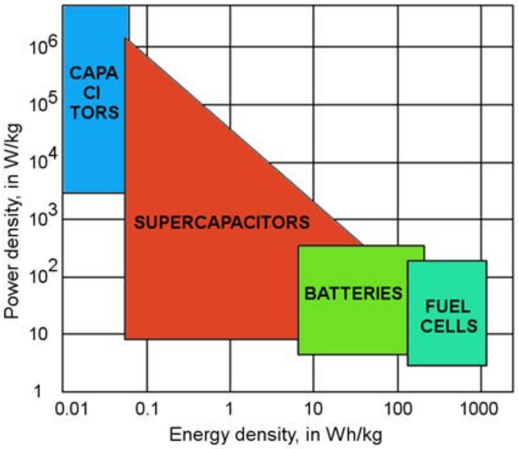


Figure 1: Power and energy densities of different energy storage solutions [1]

Figure 1 shows that batteries and fuel cells excel in one critical aspect compared to other energy storage solutions: they have high energy densities, which enable them to discharge over extended periods. Conversely, capacitors have higher power densities than any other energy storage technology. This directly corresponds to the amount of energy that can be released or stored per unit of time, resulting in faster charging and discharging rates.

The unique characteristics of supercapacitors are attributed to their blend of traits inherited from both capacitors and batteries, effectively filling the gap between the two. Although batteries have a higher power density than capacitors, they lose voltage and capacity over time, and do not have the high-power density required for certain applications. In contrast, capacitors can be charged and discharged at a much faster rate, but the amount of energy they can store is significantly less than batteries. Supercapacitors overcome these limitations, offering energy densities that are comparable to batteries and power densities that are comparable to capacitors.

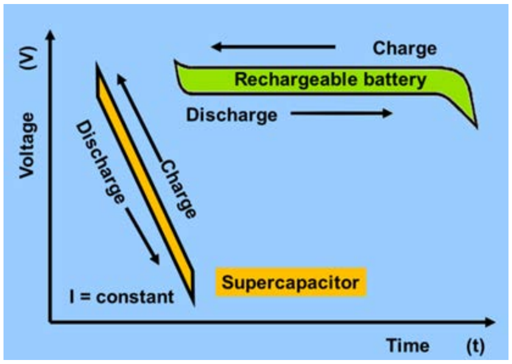


Figure 3: Comparison between supercapacitors and batteries cycles [2]

Compared to batteries, supercapacitors can withstand a lot more iterations of the charging-discharging cycle (100K vs. 1K of Li-Ion batteries). Moreover, they provide safer and more environmentally friendly solutions over a wider temperature range.

It is important to note that supercapacitors have a lower voltage rating compared to batteries and regular capacitors. To achieve higher voltages, a series combination of supercapacitors is necessary, which may require additional circuits for balancing and overvoltage/undervoltage protection.

Supercapacitor Use Cases and Applications

Supercapacitors, with their unique properties and capabilities, are being increasingly adopted across different industries for a variety of applications. They are rapidly emerging as a supplement or alternative to traditional batteries. In the automotive industry, supercapacitors are being utilized in hybrid and electric vehicles (EVs) to provide high power bursts for acceleration, and regenerative braking systems where energy generated from braking is fed into supercapacitors and then utilized to power up the on-board electronics.

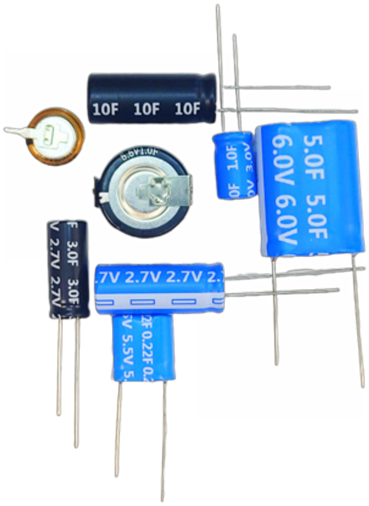


Figure 2: Radial and coin-type supercapacitors

In the renewable energy sector, supercapacitors are increasingly being utilized in DC link systems to store and release energy from solar panels and wind turbines, effectively enhancing their efficiency and reliability. They are also being employed in backup and last-gasp circuits for consumer electronics, enterprise servers, switching, and base stations. Additionally, in industrial applications such as servos and motors, they are used to provide high bursts of power during startup.

Moreover, they are being explored in emerging fields like wearables, IIoT devices, aerospace, and robotics. As technology continues to advance, it is expected that supercapacitors will find new and innovative applications across various industries in the future.

How do Supercapacitors Work?

Supercapacitors have a middle ground composition that possesses features from both regular capacitors and batteries. They contain two electrodes, an electrolyte solution of positively and negatively charged ions, and an electrolyte-porous membrane separator that allows charged ions to travel through while isolating the two electrodes. When voltage is applied across the supercapacitor during the charging process, negatively charged ions in the electrolyte mixture are attracted towards the anode. The ions cannot migrate outside the solution, which results in creating a layer of equal but opposite charge on the surface between the electrode and the electrolyte known as the Helmholtz layer. A similar layer is formed on the surface of the other electrode, hence the name “ electric double-layer capacitors” (EDLCs).

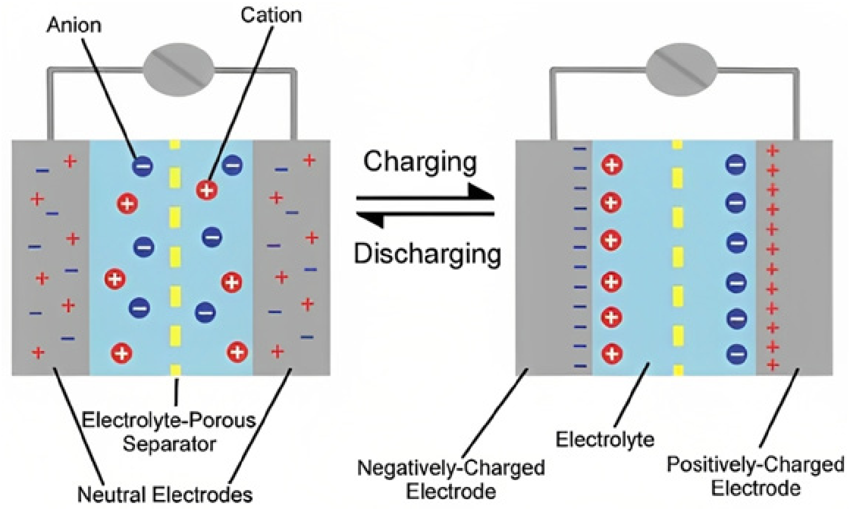


Figure 3: charging and discharging of EDLCs [3]

The various types of supercapacitors are differentiated by factors such as fabrication technology, materials, and physical construction. However, they can generally be categorized into three main groups: electric double-layer capacitors (EDLCs), pseudocapacitors, and hybrid capacitors. The primary distinction between these categories lies in the mechanism by which energy is stored in the capacitor. As mentioned earlier, EDLCs store energy as an electric field in the Helmholtz layer. Pseudocapacitors have a similar structure, but both electrodes employ materials like conducting polymers and metal oxides. This allows for intercalation between the charged ions in the electrolyte and the electrode material surface through reduction-oxidation reactions. Hybrid capacitors take a slightly asymmetric approach to energy storage. The cathode is designed similarly to EDLCs, storing energy electrostatically between the surface of the electrode (typically made of activated carbon material) and the electrolyte. Conversely, the anode is structured to store energy electrochemically through reversible redox reactions and ion intercalation. An example of this type is the lithium-ion capacitor (LiC).

Key Parameters of Supercapacitors

Capacitance (F):

Refers to a capacitor's ability to store electrical energy, or the amount of charge it can hold per unit potential difference. Capacitors come with a specified tolerance range for capacitance, which varies depending on the materials and type of capacitor. However, other operating conditions like temperature, frequency, and voltage can also affect the capacitance of a capacitor.

Rated Voltage (V):

The maximum continuous voltage that a capacitor can handle without risking breakdown of the dielectric or insulation between the two electrodes, which can lead to permanent damage. Supercapacitors are usually rated for a lower voltage range compared to traditional capacitors. While EDLCs can be discharged down to zero volts, some types of supercapacitors, typically hybrids, have a minimum operating voltage below which they may suffer damage and rapidly lose capacity. To prevent voltage from dropping below the minimum limit, circuitry is required for voltage balancing when used in series and protection.

Rated Temperature:

Supercapacitors have a specific temperature range in which they can safely operate without failing. The operating temperature varies based on the type of materials used in their construction. However, most have temperature ratings between -40 and 70°C. Temperature affects the properties of supercapacitors, including capacitance and ESR. Additionally, high currents can increase the body temperature of the supercapacitor above the ambient temperature.

Leakage Current (DCL) (uA):

Due to the non-infinite resistance of the supercapacitor's dielectric or electrolyte, some charge will migrate between the two electrodes, causing a current flow through the capacitor, which can be in the microamps range. This process gradually reduces the electric field and the potential difference across the capacitor, leading to a slow discharge over time. The self-discharge rate of a supercapacitor is typically specified by the manufacturer and is measured by keeping the supercapacitor at the rated voltage for a specified period, usually 72 hours, and then measuring the current through it. This rate can be affected by factors such as temperature and humidity. This period has been chosen such that the supercapacitor is as close as possible to its full capacity where the current flows due leakage rather than the process of charging.

Equivalent Series Resistance (ESR):

Equivalent series resistance (ESR) is measured in ohms and is the inherent internal resistance exhibited by a capacitor to the current passing through it. While ideal capacitors have zero ESR, real-world capacitors have ESR due to the physical and chemical properties of the dielectric and electrode materials. Designers must be careful when choosing a capacitor for high-current applications as losses are directly proportional to ESR. These losses can manifest as an increase in the temperature of the capacitor over time, and high ESR can cause voltage drop, leading to voltage regulation issues in applications that require minimum voltage, such as DC converters and last-gasp circuits. ESR is typically measured at a specific frequency and temperature as it can vary widely due to these factors. Therefore, high-current designs must consider ESR variations in expected environmental conditions. It is important to note that there are multiple definitions and methods to measure ESR, depending on the standard used. Most datasheets specify the IEC 62391-1 standard, which measures the immediate voltage drop when a fully charged capacitor is discharged through a predefined constant current load. And then use the equation:

$$ESR_{DC}(Ohm) = \frac{\Delta V}{I_C}$$

Peak Current (A):

Typically, current ratings are not specified for capacitors since there is no current passing across them. However, sometimes it is specified in supercapacitor datasheets as the current needed to discharge the supercapacitor from its rated voltage (UR) to (UR / 2) in a predefined period (usually 1 or 5 seconds).

$$I_{Peak}(A) = \frac{0.5\,C * Ur}{C * ESR + \Delta t}$$

Max Energy Storage (Wh):

Defined as the maximum energy a supercapacitor can store. This can easily be calculated using the below equation:

$$E_{Max}(Wh) = \frac{C\ Ur^2}{2 * 3600}$$

This figure is used to calculate how many supercapacitors are needed based on the power and discharge time requirements of the application.

Power Density (W/Kg):

Used to estimate how much power the supercapacitor can deliver per unit mass.

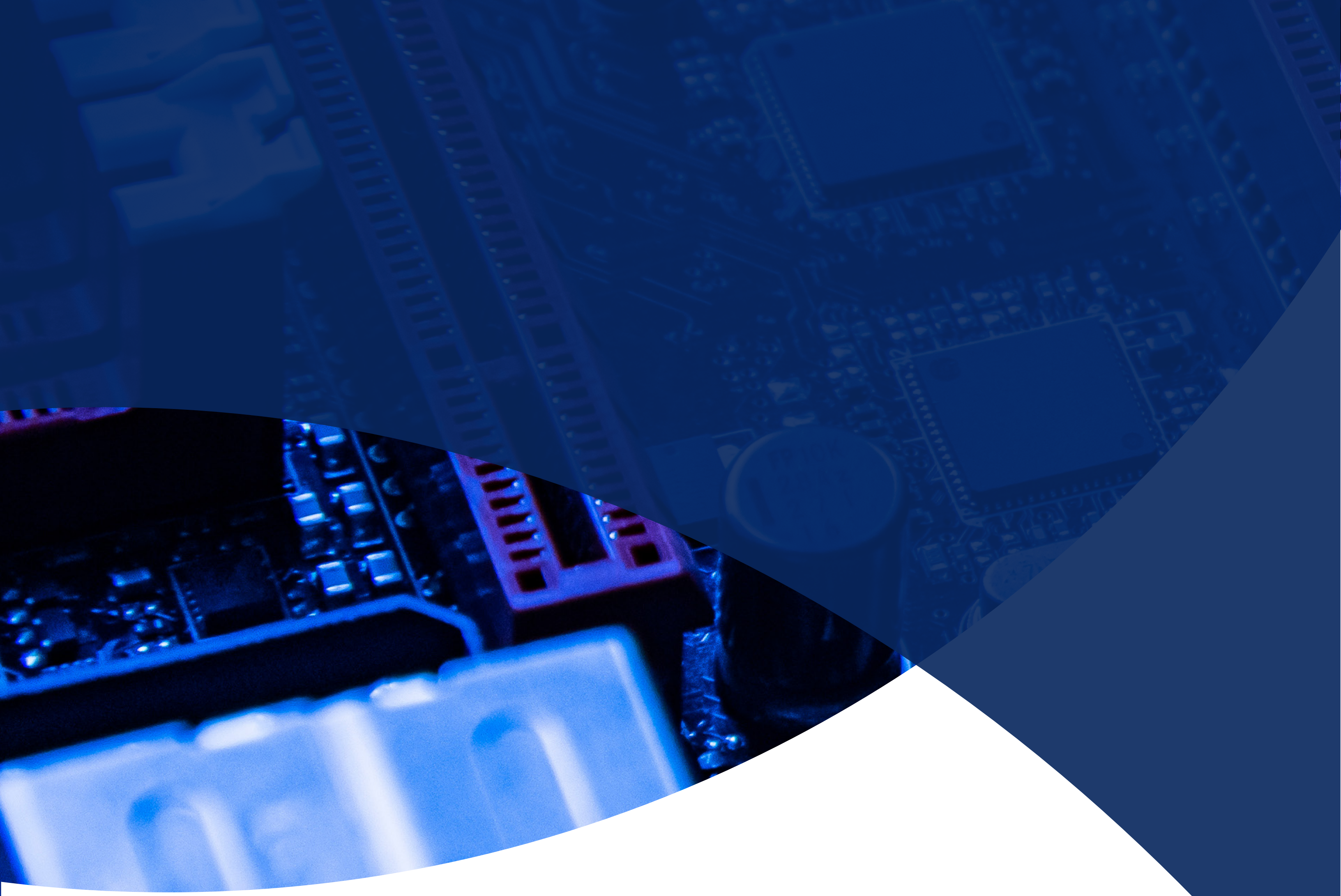
$$P_a\left(\frac{W}{Kg}\right) = \frac{0.12\,Ur^2}{ESR * mass}$$

Gravimetric Energy Density (Wh/Kg):

Also known as "specific energy," it shows how much energy the supercapacitor can store per unit mass.

Volumetric Energy Density (Wh/L):

Shows how much energy the supercapacitor can store per unit volume. Along with the gravimetric energy density, these figures of merit can help designers compare available alternatives based on the end application's size or weight constraints.



Conclusion

Supercapacitors offer a unique energy solution that combines the characteristics of traditional energy solutions. They have the potential to revolutionize energy storage and power delivery in many different fields due to their high-power density, rapid charging and discharging capability, relatively higher cycle life than batteries, and environmental safety features.

Abracon Supercapacitors

Abracon offers a wide variety of radial supercapacitors utilizing the industry's latest EDLC (Electric Double-Layer Capacitors) technology to achieve high energy and power densities. Due to their ability to provide excellent high energy and power density performance, Abracon supercapacitors can be used in applications requiring quick charge/dissipation or long-lasting power output. Abracon's supercapacitors can operate in temperature ranges down to -40°C where traditional batteries cannot. In addition, these supercapacitors have a longer usage lifecycle and mitigate the safety concerns seen in lithium batteries. These characteristics make these devices ideal for use cases such as uninterrupted power supply and backup power, micro energy storage, data transmission for LoRA/BLE/Zigbee and various energy start up designs. Abracon supercapacitors are the perfect solution for use in wireless networks, energy harvesting, cold-crack engines, micro grid and much more.

Abracon can also provide custom-made solutions for customers requiring supercapacitors that achieve more stringent electrical and/or mechanical properties, or devices that need to meet specific environmental constraints.

The table below provides a snapshot of some of the supercapacitor series Abracon currently offers. For additional information on these products or to inquire about purchasing, please contact an Abracon authorized sales representative or distributor or click here to learn more.

SERIES NAME	DESCRIPTION	NOMINAL VOLTAGE	CAPACITANCE RANGE	STOCK
ADCR-E02R7S	Low ESR Radial Supercapacitor	2.7 V	0.5 F - 10 F	Check Inventory
ADCR-T02R7S	Wide Operating Temperature Radial Supercapacitor	2.7 V	0.5 F - 25 F	Check Inventory
ADCR-S02R7S	Standard Radial Supercapacitor	2.7 V	0.5 F - 30 F	Check Inventory
ADCR-S03R0S	Standard Radial Supercapacitor	3.0 V	0.5 F - 30 F	Check Inventory
ADCC-S	Center Pin Coin Type	5.5V	0.047 F – 1.5 F	Check Inventory
ADCH-S	Horizontal Coin Type	5.5V	0.047 F – 1.5 F	Check Inventory
ADCV-S	Vertical Coin Type	5.5V	0.047 F – 1.5 F	Check Inventory
ADCM-S	Module Type Supercapacitor	5.5V, 6.0V, 7.5V	0.047 F – 12 F	Check Inventory

References

[1]: Materialscientist, “Power-energy for energy storage systems.png.” [Online]. Available: http://commons.wikimedia.org/wiki/User:Materialscientist

[2]: Elcap, “Charge-Discharge-Supercap-vs-Battery.png.” [Online]. Available: https://commons.wikimedia.org/w/index.php?curid=25527453

[3] Khawaja, Mohamad & Khanfar, M.F. & Oghlenian, Talin & Alnahar, Waed. (2019). Fabrication and Electrochemical Characterization of Carbon-Based Supercapacitor Electrodes. 1-4. 10.1109/IREC.2019.8754605.