

Recent Advancements in Supercapacitor Technologies

G. Rajakumar

Professor, Department of Electronics and Communication Engineering, Francis Xavier Engineering College, Tirunelveli, India

E-mail: rajakumar@francisxavier.ac.in

Abstract

Supercapacitors (SCs) are a form of energy storage that fills the vacuum left by traditional capacitors and batteries. They have greater energy storage capacity than capacitors and can deliver electricity at higher rates than batteries. Both the capacitor and supercapacitor have two electrodes (plates) separated by a dielectric, however super capacitors have electrodes with a larger surface area and thinner dielectrics, allowing for higher energy densities. Super capacitors are extensively employed in portable electronic devices due to its high storage capacity. The design, properties, and uses of supercapacitors are briefly discussed in this article.

Keywords: Supercapacitor, storage capacitor, batteries, electrodes, dielectrics

1. Introduction

Supercapacitors (SCs) are energy-storage electrochemical systems that work by storing and discharging energy through the cyclic desorption and adsorption of ions at the interfaces of electrode materials and electrolyte. Super capacitors, also known as electric double-layer capacitors or ultra-capacitors are energy storage devices with extremely high capacities and low internal resistance. Compared to batteries, supercapacitors can store and deliver energy at rates that are relatively higher. This is because the mechanism of energy storage only requires a simple charge transfer at the interface present between electrode and electrolyte [1]. Energy storage systems are important in our civilization. The most crucial factors to consider while choosing an energy storage device are lifetime, dependability, protection, specific power, specific energy and several other factors [2]. Supercapacitors also have the advantage of being environmentally sustainable because unlike batteries, they don't require chemical combustion. Supercapacitors come in different varieties, including

Electrochemical Double-Layer Capacitors (EDLCs), pseudocapacitors, and hybrid capacitors [3]. A supercapacitor is made up of two electrodes, electrolyte as well as a separator that electrically isolates two electrodes. The most crucial element of a supercapacitor is its electrode material [4].

A bank of super-capacitors can bridge the small period of time between a power outage and the start-up of standby power generators due to their high power capability. Although the supercapacitor's energy density is higher than that of normal capacitors, it is still far lower than that of batteries or fuel cells. Total area, conductivity, wetting of the electrode, and penetration of electrolyte solutions have a significant impact on how well an electrode material conducts electrochemistry [5][6]

The overview of the supercapacitor and its working are discussed in section 2, followed by the types of supercapacitors in section 3, related works in section 4, application of SCs on recent technologies in section 5, challenges in section 6 and conclusion in section 7.

2. Supercapacitor - Overview

A supercapacitor is a device that can rapidly store electrical energy and release it gradually. Supercapacitor is also known as Electrical Double Layer Capacitor and Ultracapacitor (EDLC). The conventional capacitors, such as ceramic and electrolytic ones can store and release the electric power quickly but supercapacitors don't work in the same way [7].

2.1 Principle

Supercapacitor stores electrical energy within two electrostatic double layers, which are created when small layers of charge are deposited on the interface present between the electrolyte and the internal sides of the capacitor electrode plates [8].

2.2 Construction

The supercapacitor consists of the following components [9]:

- A pair of electrodes
- Two active collectors
- A separator
- Electrolyte solution

- **Electrodes:** Activated carbon is used to make the supercapacitor's electrodes. The porous structure of the electrodes makes it easier to store multiple charge carriers. The capacitance will increase if the electrodes can store more charge carriers. There are two electrodes, one is positive electrode and the other is negative electrode.
- **Carbon:** It is of many forms, including activated carbon (AC), carbide-derived carbon (CDC), carbon fiber-cloth (AFC), graphite (graphene), carbon aerogel, within which carbon nanotubes (CNTs) are the most often used electrode materials in supercapacitors.
- **Collectors:** The electrodes and capacitor terminals are connected by using current collector. Foil Metals are typically used in the construction of current collectors. The supercapacitor has two current collectors; positive electrode and negative electrode.
- **Separator:** In order to prevent short-circuits, the separator is employed to separate the electrodes or to provide insulation. The majority of separator is made of Kapton material. The separator is usually a thin material. The separator acts as a shield between the electrodes by permitting the charge carriers to pass through.
- **Electrolyte Solutions:** Acetonitrile as well as propylene carbonate are the two main electrolytic solvents used in supercapacitors. Positive cations as well as negative anions are two charge carriers present in the electrolyte solution.

In addition, we may conclude that the supercapacitor is a combination of battery and capacitor as its principle is quite similar to that of a lead-acid battery. The supercapacitor combines both the battery's discharging ability and the charging ability of a typical capacitor.

2.3 Working

The operation of supercapacitors is carried out in two phases: charging and discharging. The process of charging and discharging is described below.

2.3.1 Charging process

Electrolyte solution contains both positive and negative ions. The supercapacitor begins to charge once a voltage is applied across its electrodes. Ions with opposing polarity begin to be drawn to the electrodes. By definition, this means that the positive electrode attracts negative ions or charges, while negative electrodes attract the positively charged ions. Thus, a layer of positively charged ions forms close to the negative electrode, while a layer of negative ions forms close to the positive electrode. Since the electrical charge carriers

constitute into two layers, they are often known as Electrical Double Layer Capacitor (EDLC).

2.3.2 Discharging

The supercapacitor's electrodes lose their ability to draw ions when a load is applied across them; as a result, the ions begin to disperse through electrolyte solutions and enter the mixed state. Figure 1 illustrates the working of supercapacitor.

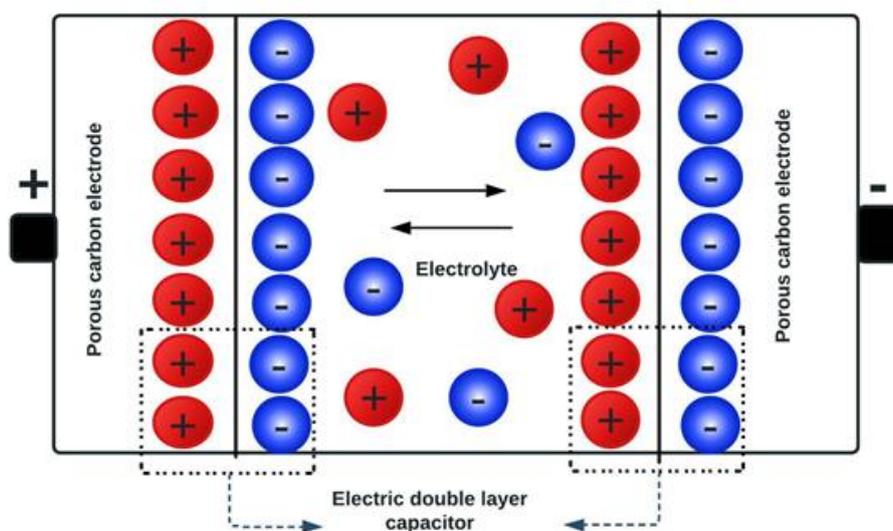


Figure 1. Working of supercapacitor

2.4 Relationship between voltage and capacitance

Variable capacitance is one among the important properties of a supercapacitor. Therefore, SC becomes a part of energy system, due to its capacity variation, which cannot be avoided in the majority of energy system designs, ranging approximately 15% to 20% of both the rated capacity over the full voltage range. This can be used to calculate the supercapacitor's capacitance. The formula links the charge with the voltage carried between both electric double layers, indicating that the voltage is inversely proportional to the charge stored. As the voltage increases, the intensity of the charge distribution near the electric double layer increases [10].

$$\text{supercapacitor's capacitance} = \frac{\text{Charge distribution}}{\text{Voltage stored}}$$

The below table 1 lists the parameter comparison analysis on Supercapacitor, Capacitor and Battery.

Table 1. Performance Comparison of Supercapacitor, Capacitor and Battery [11][12]

Parameters	Supercapacitor	Capacitor	Battery
Specific power (W/kg)	4000-9000	>5000	300-1500
Specific energy (Wh/kg)	4-9	0.01-0.05	100-265
Charge temperature	-40 to 65°C (-40 to 149°F)	-30°C to +125°C	0 to 45°C (32°to 113°F)
Discharge temperature	-40 to 65°C (-40 to 149°F)	>70°C	-20 to 60°C (-4 to 140°F)
Life of service (industrial)	10-15 years	10-15 years	5-10 years
Charging voltage	2.3 to 2.75V	~3.8 V	~3.6 V
Charging time	1-10 sec	5-10 sec	10-15 sec
Life cycle	1 million or 30,000h	>50000	500 – 2000
Efficiency	High	>95%	Medium
Discharging	Fast	Fast	Slow
Charge method	Voltage across terminals	Voltage across terminals	Current and voltage
Charging circuit	Simple	Simple	Complex

3. Types of supercapacitor

Based on the way that energy is stored, three groups of supercapacitors (SC) were developed as shown in figure 2 [13].

3.1 Electrochemical Double-Layer Capacitors (EDLCs)

EDLCs are composed of an electrolyte, two electrodes made of carbon-based materials, and a separator. EDLCs can either electrostatically store charges or operate via a non-Faradic method that avoids the necessity for charge transfer between the electrode and electrolyte.

The energy storage concept used by EDLCs is the electrochemical double layer. When the voltage was supplied, there was no build-up of ions on the electrode's surface since the opposing charge exists at the potential difference. Electrolyte ions diffuse across the separator and onto the oppositely - charged electrode pores as a result of attraction. This is made possible by the storing mechanism of EDLCs, which allows for quick energy absorption, distribution, and power production.

3.2 Pseudocapacitors

This type of supercapacitor is considered as a high electrochemical pseudocapacitance material and oxide-based conducting polymer electrodes. Similar to oxidation-reduction reactions, the Faradaic mechanism used for storing charge involves the transfer of charge between the electrode and electrolyte. When a potential is applied to a pseudo-capacitor, reduction and oxidation occur on the electrode material as a result of the charge passing through two layers, causing the Faradic current to flow through a SC cell. In addition, compared to EDLCs, the Faradic mechanism used in pseudocapacitors enables them to achieve high specific capacitance and energy densities.

3.3 Hybrid Capacitors

Supercapacitor of a certain type having asymmetrical electrodes, one of which mostly exhibits electro-static capacitance and the other exhibit electro-chemical capacitance. The hybrid capacitors have also combined the performance characteristics that were previously impossible. Although hybrid capacitors were less studied than pseudo-capacitors or EDLCs, efforts have been made to improve hybrid capacitors and produce more accurate quantitative models. In addition to the greater emphasis on developing higher energy and long life SCs, the enormous simplicity with which hybrid capacitors' performance and design can be tuned has enabled them to overtake EDLCs as the dominant SCs class.

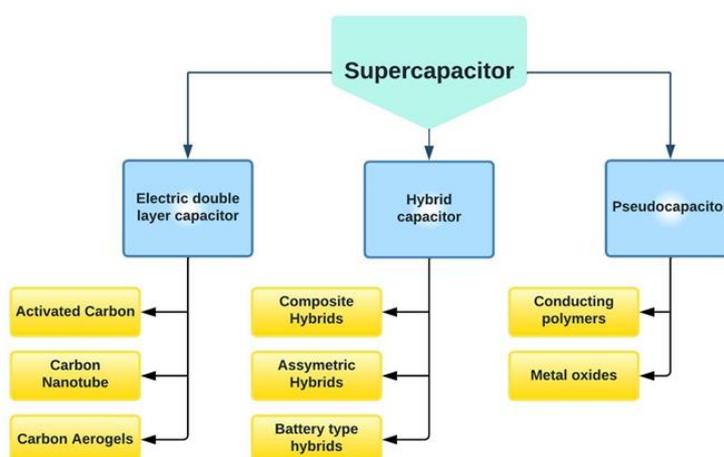


Figure 2. Types of supercapacitor

4. Related Work

Z. Tehrani., [14] designs a, large volume screen printing technology can be used to create a flexible, ultra-thin supercapacitor. In order to create flexible electrodes for

dependable energy storage applications, this has made it possible to sequentially place current collector, electrodes, electrolyte materials, and adhesives onto one Polyethylene terephthalate (PET) substrate. The electrodes were built using gel electrolyte and activated carbon ink, both of which were developed specifically for this use. There have been demonstrations of supercapacitors with surface areas ranging between 100 to 1600 mm diameter as well as a complete device thick of 375 μm . The capacitance was in the 50–400 mF range. The gel resistance was decreased as a result of this innovation from 90 to 0.5. Future homes may use this large-area printed gadget for sustainable green energy storage.

Chen, J., [15] suggested using SCs to benefit from the electric engines of such a high-speed railway driven by 27 kV AC catenary. The back-to-back converter's intermediate DC stage, where output and input are coupled to two distinct points on the trains' main power line, which is then connected to the storage system through a reversible DC/DC converter. The proposed state machine logic has four modes (charge, discharge, transfer, and standby mode), and it switches between them based on the degree of power line charge as well as the maximal charging time of the ESS. The first back-to-back converters serves as the master converter, while the other converter as well as the DC/DC of the SCs serve as slaves.

Orti, G., [16] Suggests a novel Energy Management System (EMS) using a HESS, which combines the economic analysis with a cutting-edge power flow control method. A cell as well as SCs module make up this device. The main objective of this study is to extend the lifetime of the batteries by adding a SCs module to the EMS in order to absorb higher frequency currents and leave the batteries to handle gradual current variations. Additionally, the system's economics are examined in relation to the long-term impact.

V.V.Joshi., [17] propose that , at the DC link of a motor drive system, the fuel cell stacking is integrated with the battery and supercapacitor to drive the induction motor. The reversible new boost converter is used to connect the battery and supercapacitor, while the fuel cell is directly connected to the DC link. On the drive side, the induction motor's field-oriented vector control is used to meet multiple speed of the vehicle and load torque requirements.

H. Gualous., [18] proposes a supercapacitor ageing prediction model for telecommunication applications based on voltage and temperature. Whenever the supercapacitors are polarised at the maximum voltage, experimental tests are conducted at constant temperatures. Both Equivalent Series Resistance (ESR) as well as Equivalent

Capacitance (C) are evaluated by using the DC and AC characterisation and are used to calculate the supercapacitor's ageing rate. The Arrhenius law that defines how temperature affects the speed of a chemical reaction is taken into consideration to calculate the lifetime of supercapacitor.

M. K. Choudhary.,[19] claims that the batteries are currently utilised to maintain the DC bus voltage, however the batteries also have a high energy density and low power density. The supercapacitor has a low energy density but a high-power density. Therefore, the integration of the supercapacitor and the battery is more effective to achieve high density of energy and power. It is more difficult to combine different sources. Thus, a control method is required to combine the batteries and supercapacitor to supply constant power to the load. This paper proposes an innovative method for power and the DC bus voltage control.

5. Applications of Supercapacitor

5.1 Transportation

Supercapacitors are often employed in applications involving transportation. Whenever a high peak power is needed, usually for starting a vehicle, they are often discharged into the powertrain after being charged with waste energy. The supercapacitors have a high power density discharge capability when needed and may recharge quickly from even brief periods of braking. The overall result is a stabilisation of the primary power source's output power. This can significantly increase fuel efficiency [24].

Hybrid electric vehicles (HEVs) are a good fit for supercapacitors because they can make up for the shortcomings of battery technology.

The powertrain is modelled on Toyota's previous-generation vehicle, the TS030, which had a 530 horsepower V8 gasoline engine and an ultracapacitor that, when needed, provided a 300 horsepower bump to the back wheels.

5.2 Grid Power

Current variations and harmonics are caused by a variety of non-linear loads, including Electric vehicles, Hybrid vehicles, air conditioning systems and complex power conversion systems. Abnormal voltage fluctuations and consequent power fluctuations on the grid are produced by these current discrepancies. In addition to lowering the grid's efficiency, power oscillations can result in significant frequency changes throughout entire system and

voltage reductions with in common coupling bus. Supercapacitors can be used as an interconnect between both the loads and grid to function as a gap between the grid as well as the high pulse energy consuming from charging station to solve this issue [22].

5.3 Consumer Electronics

Supercapacitors can stabilise the power supply in applications with varying loads, like laptops, Personal digital assistants, Satellites, portable media players hand-held devices, and solar systems. Supercapacitors provide energy for LED torches that can be charged in considerably less time—for example, 90 seconds—and for photography flashes in digital cameras. Supercapacitors are used to power some portable speakers [20].

Low-power devices like RAM, SRAM, micro-controllers, and PC Cards receive backup and emergency shutdown power from supercapacitors. For minimal energy applications like automated metre reading equipment or industrial electronics event notification, they serve as the only power supply [21].

5.4 Healthcare

Defibrillators use supercapacitors with an energy output of 500 joules to represent the human heart beat as a sinus rhythm.

6. Challenges

Due to their outstanding qualities, supercapacitors are widely employed in the transportation, manufacturing, armed forces, consumer electronics, and other sectors. But there are certain drawbacks to these technologies [23].

- Supercapacitors' energy densities are not particularly high. Supercapacitors' energy densities can be increased by expanding the operation voltage window, increasing the effective area for electrode materials in the double layer capacitors, or doing both. Research is being conducted to create novel materials with large surface areas and use suitable organic electrolytes that can withstand a wider voltage window. Supercapacitors' energy densities could catch up to batteries if these gaps are adequately closed.
- The supercapacitor model is similar to an ideal model, but in military applications, particularly in satellite and spacecraft power supply applications, various non-ideal characteristics may pose potential risks that must be taken into consideration.

- Because of the very low rated voltage of supercapacitors, numerous series connections are necessary for use in real-world scenarios. Due to the applications' requirement for high current charging and discharging, overcharging has a significant negative impact on the capacitor's lifespan.
- In some applications, the EDLC can provide power for a brief period of time alongside rechargeable batteries by minimising battery cycle workload and extending battery life.

7. Conclusion

Supercapacitors having significant potential in a wide range of sectors and fields emerges as a new type of sustainable and effective energy storage device. SCs are implemented in different applications, including solar cell energy storage, uninterruptible power sources, mobile phones, hybrid cars, military munitions, and communication devices. There are numerous technological benefits in SCs, they are, high power densities, rapid charging and discharging procedures. High cost and poor energy density are the two major challenges faced by supercapacitors. This must be solved without compromising performance rate and lifecycle. Future research should concentrate on electrode materials, which can be combined with conducting polymers or metal oxides to create composites by which the supercapacitors can be employed in a variety of applications.

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Author's biography

G. Rajakumar is working as a Professor in Department of Electronics and Communication Engineering in Francis Xavier Engineering College, Tirunelveli. He has 14.5 years of experience. Received his B.E (Electronics and Instrumentation Engineering) in National Engineering College, Kovilpatti under M.S University Tirunelveli, 2004, M.E (VLSI Design) in Arulmigu Kalasalingam College of Engineering – Srivilliputhur under Anna University-Chennai, 2006, M.B.A (Human Resource Management) under Annamalai University, 2009, Ph.D in Information and Communication Engineering with the specialization in VLSI Design under M.S University 2014, Post-Doctoral Fellow in VLSI Design under Delhi Technological University, Delhi, 2016 and Honorary and Doctor of Letters (D.Litt.) in Information and Communication Engineering under University of South America, USA 2017. He has published 4 patents and 5 International Engineering Books. He has published more than 30 International/National Journals. He actively participated in more than 17 international Conference, 31 National Conferences.