HIGH-PERFORMANCE SUPERCAPACITOR: A COMPREHENSIVE REVIEW

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Abstract— Rapid technological development demands more energy that inspires mankind to explore high-performance energy devices. Among two major energy storage devices i.e., batteries and capacitors, electrochemical capacitors i.e., supercapacitors play a crucial role in energy storage due to their distinctive properties. Supercapacitors can store large amounts of electrical energy and release it quickly, making them ideal for use in a wide array of applications. They combine the properties of both batteries and capacitors into a single device. In comparison with batteries, supercapacitors possess high specific capacity, high power density, long cycle life, economic efficiency, environmental friendliness, high safety, and fast charge/discharge rates. Due to its magnificent characteristics, the supercapacitor has attracted considerable attention among various energy storage devices. The current article cast light on the brief discussion of supercapacitors; types of supercapacitors: electrochemical double-layer capacitors (EDLCs), pseudo capacitors, and hybrid supercapacitors; the structure of supercapacitor; parameters for the estimation of performance: specific capacitance, energy density, and power density; and applications of supercapacitors.

Index Terms— Super-capacitors; Metal oxides; Electrolyte; Pseudo-capacitors; Hybrid super-capacitors

I. INTRODUCTION

In the current scenario, the increased human population all over the globe requires clean and renewable sources of energy including advanced energy storage technologies for low-carbon and sustainable economic development [1-4]. Common energy storage systems include batteries, capacitors, and supercapacitors [5]. These three systems have different energy storage and conversion mechanisms, these are all based on similar electrochemical thermodynamics and kinetics, i.e., the process of supplying energy occurs at the phase boundary of the electrode/electrolyte interface with independent electron and ion transport. The current advances in smart electronic devices have encouraged a significant increase in the use of supercapacitors [6]. Supercapacitors are excellent energy storage devices, considered as replacements for Li-ion batteries. Supercapacitors are high-capacity capacitors with a capacitance value much higher than other regular capacitors. These components are the choice over the regular type of capacitor since they feature high power density. They combine the properties of batteries and capacitors into a single device. These components consume less power and are safe and easy to operate [7]. Supercapacitors are considered as one of the potential candidates in the domain of energy storage devices for the forthcoming generation. Due to its excellent performance, easy handling, and stability have gained remarkable attention. In comparison with batteries, it delivers high power density and cyclic stability. The battery has a larger weight and volume, large internal resistance, poor power density, and poor transient response, while this supercapacitor has low weight and volume, low internal resistance, great power density, and great transient response. Supercapacitors are used to hold an enormous number of electric charges.

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Supercapacitors add the properties of both capacitors and batteries together into one device.

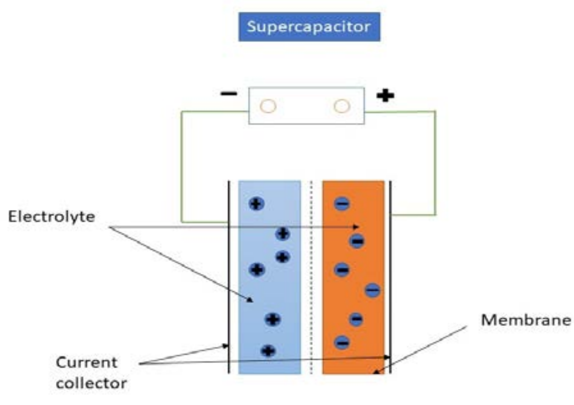
In 1950, from the design of fuel cells and rechargeable batteries, General Electric engineers experimented with porous carbon electrodes in the design of capacitors. In 1957 H. Becker developed a "Low voltage electrolytic capacitor with porous carbon electrodes". As per Becker, the energy was stored in the form of charge in carbon pores as in the pores of the etched foils of electrolytic capacitors. At that time, he was unaware of the double-layer mechanism [8]. In 1966 another version of the component "electrical energy storage apparatus" was developed at Standard Oil of Ohio (SOHIO) [9]. Donald L. Boos patented the electrochemical capacitor in 1970 and was registered as an electrolytic capacitor with activated carbon electrodes. Early capacitors used two aluminium foils covered with activated carbon, the electrodes that were soaked in an electrolyte and separated by a thin porous insulator. In comparison with electrolytic capacitors of similar dimensions, this design gave a capacitor of the order of one farad. This basic mechanical design is the foundation of almost every electrochemical capacitor. SOHIO did not commercialize their invention, in 1978, licensing the technology to NEC, who marketed the result as a "supercapacitor". In 1991 Brian Evans Conway described the difference between "supercapacitor" and "battery" behavior in electrochemical energy storage. In 1999 he defined the term "supercapacitor" so that to refer to the increase in observed capacitance by a surface redox reaction with faradaic charge transfers between electrodes and ions. His supercapacitor stored electrical charge partially as a result of faradaic reactions and partially in the Helmholtz double-layer with "pseudocapacitance" charge transfer of electrons and protons between electrode and electrolyte.

In 1978 Panasonic marketed its Goldcaps brand, and it became a successful energy source for memory backup. After that in 1987 ELNA "Dynacap" s entered the market. The internal resistance is higher in the first-generation EDLC which limits the discharge current and was used for low-current applications including powering SRAM chips or for data backup. In the 1980's end, improved electrode materials increased capacitance values. Equivalently there was a development of electrolytes with better conductivity that lowered the equivalent series resistance increasing charge or discharge currents. The first supercapacitor having minimal internal resistance was developed in 1982 and utilized for military applications through the Pinnacle Research Institute and was given the name "PRI ultracapacitor" [10]. In 1992, Maxwell adopted the term ultracapacitor from PRI and called them "Boost Caps". In 1994 David A. Evans, by using the anode of a 200V high voltage tantalum electrolytic capacitor developed an "Electrolytic-Hybrid Electrochemical capacitor". Lithium-ion capacitors belong to recent developments and these were pioneered by Fujitsu's FDK in 2007. The electrostatic carbon electrode was combined with a pre-doped lithium-ion electrochemical electrode which increases the capacitance. The electrochemical energy storage systems have evolved with huge development by introducing novel concepts of pseudocapacitance [11], battery-type behavior [12], and asymmetric and hybrid device [13, 14] architectures towards high-performance and next-generation energy storage devices in several decades.

II. Structural feature of supercapacitor

Two types of electrodes are separated by an ion-permeable membrane known as a separator and an electrolyte ionically connecting both electrodes in supercapacitors. The electrodes are polarized, and ions in the electrolyte form electric double layers of opposite polarity to the electrode's polarity after applying the voltage. That is positively polarized electrode will have a layer of negative ions at the electrode and a layer of positive ions on the negatively polarized electrode.

Figure 1. The figure illustrates the structure of the supercapacitor.



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III. FARADAIC AND NON-FARADAIC PROCESS:

Faradaic process:

It is a chemical process that transfers charges across the metal-solution interface. Oxidation or reduction occurs due to electron transfer. According to Faraday's law, the amount of chemical reaction caused by the flow of current is proportional to the amount of electricity passed. These reactions are governed by Faraday's law that's why they are called a faradaic process.

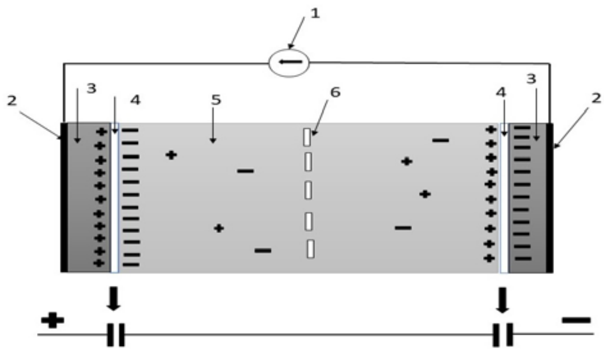
Non-Faradaic process:

In this process, for a specific range of potential, charge-transfer reactions are thermodynamically or kinetically unfavorable if no charge-transfer reaction occurs in them. While methods such as adsorption and desorption can occur on the surface of electrodes. When the potential or solution composition changes charge does not cross the interface that is external currents can flow. The current depends on the surface area of electrodes and the concentration of electrolytes. When electrode reaction takes place both Faradaic and Non-Faradaic processes occur.

IV. TYPES OF SUPERCAPACITORS:

There are three types of supercapacitors, the electrostatic double-layer capacitor, pseudo capacitor, and hybrid capacitor.

Figure 3. The typical construction of supercapacitor. 1. Power source, 2. Collector, 3. Polarized electrode, 4. Helmholtz double layer, 5. Electrolytes having positive and negative ions, 6. Separator.



1. Electric double-layer capacitor (EDLC):

EDLC includes two electrodes, a separator, and an electrolyte. The electrolyte consists of positive and negative ions dissolved in water. The separator is used to separate two electrodes. The carbon electrodes or derivatives with much higher electrostatic double-layer capacitance are used in EDLC. EDLC works on a charge storage mechanism as the charge is stored on the surface of the electrode without causing any irreversible chemical reaction via the formation of an electrical double layer. Charges are stored electrostatically in a supercapacitor. When a voltage is applied across the terminals an electric field is generated at each electrolyte which leads to the polarization of the electrolyte. These ions diffuse through the dielectric to the porous electrode of opposite charges. This is how the formation of an electric double layer takes place at each electrode. This results in an increased surface area of each electrode and a decreased distance between the electrodes. It is non-faradic no reaction occurs between the electrode and electrolyte. In this, the separation of charge is less than in conventional capacitors ranging from 0.3-0.8 nm. Electrodes used in it are carbon aerogel, activated carbon, CNTs, carbide-derived carbon (CDC), graphene etc.

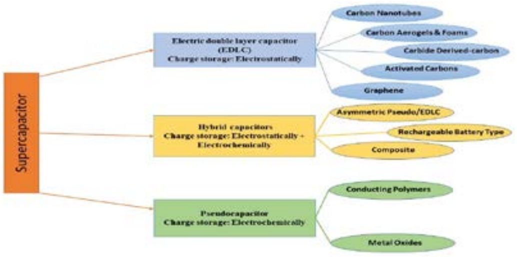
2. Pseudo Capacitor:

Pseudo capacitors are also known as electrochemical pseudo capacitors. The metal oxide or conducting polymer electrodes are used in it with a high amount of electrochemical pseudo capacitor. These supercapacitors store electrical energy by electron charge transfer between electrode and electrolyte. This can be done by a reduction-oxidation reaction known as a redox reaction. It is faradic as a reaction occurs between the electrode and electrolyte.

3. Hybrid capacitor:

The hybrid capacitor is formed by the combination of a double-layer capacitor and a pseudo-capacitor. In these electrodes with different characteristics are used. One electrode with the capacity to display electrostatic capacitance while the other electrode identifies the electrochemical capacitance. This utilizes both faradic and non-faradic processes. The electrodes used in it are composite, asymmetric, battery type, etc. [15].

Figure 2. The figure illustrates the types of supercapacitors and further what kind of electrodes are used in particular supercapacitors.



APPLICATIONS

Supercapacitors are widely utilized in buses, automobiles, cranes, trains, and elevators, where they are used for regenerative braking, short-term energy storage, or burst-mode power delivery [16-18]. These are also used in electric cars, wind turbines, photographic flash, flywheel in machines, MP3 players, static memories (SRAM), and industrial electrical motors. Supercapacitors are also used in sensors, navigators, and communication devices based on batteries. Various systems like radar systems, electromagnetic pulse weapons, torpedoes, etc. can be operated using a suitable installation of hybrid supercapacitors [19]. High specific power is used by radar systems, GPS, airbag exploitation power, avionics, and missiles. [20]. Supercapacitor applications include consumer electronics [21, 22], tool power supply [23], microgrid [24], voltage stabilization [25], renewable energy storage [26], energy harvesting [27, 28], street lights [29], medical applications [30], military and automotive applications [31-33], and energy recovery [34-37]. When compared with batteries, supercapacitors have the ability to charge much faster than batteries, their longer lifetime, stable electrical properties, and wide temperature range make them suitable for electric for electric vehicles. In addition to these, they have started to be used in UPS, electric vehicles, and various power electronics applications.

Table 1. The parameters shown in the table are used to estimate the performance of the supercapacitor. These parameters show the difference between a battery and a supercapacitor.

Sr. No	**Parameters**	**Battery**	**Supercapacitor**
1	Energy density	High, 30-250 Wh/kg	Low, 5 Wh/kg
2	Power density	Moderate, 1 Wh/kg	Very high, 10 kW/kg
3	Charge/discharge time	Take hours to charge/discharge fully	Charge/discharge within a second
4	Energy storage mechanism	In this, electrons are stored through an electrochemical redox reaction.	In this, electrons stored through ion adsorption at the electrode-electrolyte interface
5	Cycle life	500-1000 cycles	>500000 cycles
6	Self-discharge	Low, 5-20% per month	20-30% per day
7	Cost	High but prices declining	High
8	Operating temperature range	0°C to 50°C	-40°C to 65°C
9	Applications	Portable devices, electric vehicles	Brief high-power loads e.g., Laser, buses

CONCLUSION

In the current review, a detailed analysis is done on supercapacitors. It involves the evolution, progress, and advancements of the SCs. The current global market and the demand for their utilization and manufacturing firms in the world energy sector have been furnished in this review. The classification of SCs and their corresponding parameters that distinguish each one from others were mentioned. The supercapacitor shows excellent performance. This review pinpoints the significance of supercapacitors, which have recently received much interest due to their enhanced electrochemical performance, superior cycling life, excellent specific power, and fast charging-discharging rate. It also shows the difference between different energy storage devices i.e., supercapacitors, batteries, and cells. The special characteristic of supercapacitors is charging time: batteries take several hours to reach a fully charged state, while supercapacitors can be brought to the same charge state in less than two minutes. Supercapacitors have a specific power 5 to 10 times greater than that of batteries. Cycle life and safety: supercapacitor can be charged and discharged millions of times. Supercapacitors have a virtually unlimited cycle life while batteries only have a cycle life of 500 times and higher. Just because of the idiosyncratic characteristics of supercapacitors, they may be chosen as an alternative to batteries or other energy storage devices.

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