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Supercapacitors: Review of materials and fabrication methods

Dharmesh J. Pandya [a], P. Muthu Pandian [b], Indradeep Kumar [c], Ashish Parmar [d], Sravanthi [e], Navdeep Singh [f], Alaa Jasim Abd Al-saheb [g], Vanya Arun [h]

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Abstract

It is hoped that supercapacitors will power devices in the future. Future hybrid electric automobiles and other electrical infrastructure will benefit from these parts. Improving supercapacitors' energy and power densities is essential to tap into their potential fully. Improvements in electrode materials and fabrication methods could solve this problem. The development of better supercapacitor electrodes has necessitated the production of several different materials during the past few years. It is prudent to investigate all facets of supercapacitor units due to the rapid development of technology. This paper reviews a brief overview of the broad spectrum of current supercapacitors. Modern fabrication methods, materials for supercapacitors, and their future potential are analysed. Also discussed the main technical obstacles that could hinder future growth efforts in various industries.

Introduction

Global energy production has increased over the past few decades due to industrialization and the rapid expansion of numerous other businesses. Because there are more people on Earth than ever before, we require more energy [1]. These factors contribute to the hazardous strain on the global electrical grid. The majority of power plants in the world used to run on petroleum. However, we now lack sufficient oil, so we need to develop alternative sources of energy. Lately, there has been a lot of focus on creating innovative solutions to address the global energy issues. A significant amount of money has been invested in developing energy storage systems and technologies in the last few years. The supercapacitor [2], sometimes known as an ultracapacitor or an electrochemical device, exemplifies this type of device. Supercapacitor technology has received a lot of funding in the last few years because it has the potential to drastically alter the energy storage business.

A supercapacitor differs from other types of capacitors due to its large surface area and thin dielectric layer between the electrodes. As a result, their capacitances are much higher than those of regular capacitors [3]. Supercapacitors have a much higher energy storage capacity when used in conjunction with other energy storage technologies like fuel cells or batteries. Supercapacitors are better than conventional energy storage techniques because they have a high power density, are frequently charged and discharged, and function well in high temperatures. Supercapacitors have a higher power rating and can store a lot more electrical energy than rechargeable batteries. In terms of power density, supercapacitors are less compact than batteries and fuel cells. This is why it is so important that supercapacitors have the same energy density as batteries. The main drivers [4] behind scientists' efforts to create new materials and synthesis techniques are to use them in supercapacitor technology. Comprehensive explanations are given on the manufacture of electrodes and new materials for supercapacitors. The advantages and disadvantages of supercapacitor technology are discussed, as well as its uses and effects on various industries.

The survival of our species depends on energy. When it comes to generating electricity, the use of fossil fuels affects the environment and the economy. When talking about renewable energy sources, electrochemical energy must be covered. Batteries, supercapacitors, and fuel cells are just a few of the alternative energy sources that rely on the electrochemical energy conversion principle [5]. SCs are better than capacitors (high Pd) and fuel cells/batteries (low Cs) because they have a high specific capacitance (Cs), a long lifespan, a high power density (Pd), almost no maintenance needs, no memory effect, are safe, and have a big energy storage capacity. They make it possible to transmit power to areas where the cost of doing so would be unaffordable because of a lack of infrastructure or remote location [6]. The SCs are widely used in electric and hybrid vehicles for short-term acceleration and energy recovery during braking, as seen in Fig. 1. They use less power (dynamic operation) and shield the batteries from high-frequency rapid charging and discharge. SCs and fuel cells are both very potent energy generators. That differentiation, however, becomes clear from the subsequent illustration. For their size, they have a respectable battery life. Certain Ed and Pd properties are shared by batteries, SCs, and fuel cells. This hard data shows that combustion engines are more efficient than electrochemical ones. Electrochemical devices need to improve in Ed and Pd to catch up to internal combustion engines, which now have a significant edge [7]. The Leyden Jar, a glass vase packed with metal foil, was the world's first practical capacitor and was built between 1745 and 1746. The jar acted as the dielectric in this experiment, and the metal foils as the electrodes. Prior to the other set of electrodes receiving a negative discharge, one set of electrodes was positively charged. The charges could be neutralized by a metal wire [8]. A commercially viable electrolytic capacitor was created in the 1920s. In 1957, General Electric created the first supercapacitor. It also went by the name “asymmetric double-layer capacitor” and featured activated charcoal plates. In the EDLC. EDLCs have great cycle stability and high reversibility since the charge is maintained electrostatically (as opposed to faradaically) because there is no electrical connection between the electrode and the electrolyte. Because of their high electrical conductivity, light weight, and large surface area (SSA), carbon aerogels, activated carbons, carbon nanotubes, graphene, and carbide-derived carbon (CDC) are some of the most promising structural materials for EDLCs. Researchers have suggested using pseudo capacitors made of unique electrochemically active materials (Faradaic charge transfer) to increase the Cs of SCs. From 1975 through 1980, B. E. Conway conducted a variety of research projects. One of them dealt with RuO2 pseudocapacitors [9].

The long-term negative effects of burning fossil fuels to produce energy will be felt by the environment and the world economy. Any sustainable energy portfolio must include electrochemical energy [10]. Among other alternative energy sources, batteries, supercapacitors, and fuel cells all involve electrochemical energy conversion. Because they can bridge the power-to-energy gap between fuel cells and batteries, SCs are attractive. They are safe (ample energy storage), have a high specific capacitance (Cs), a long lifespan, a high power density (Pd), essentially no maintenance requirements, and no memory effect. In remote locations without electricity lines or where installing them would be too costly, they provide a less expensive option. Because SCs are compact, light, and efficient, employing them as portable power sources can greatly benefit laptops, digital cameras, cell phones, and other mobile devices [11]. The high specific power (Pd) required by electric and hybrid cars to accelerate swiftly and regain kinetic energy during braking is provided by SCs. In addition to the striking SCs, the image displays additional energy-dense devices including fuel cells. Generally speaking, batteries release average levels of energy and power. The employment of ed and pd can enhance batteries, supercapacitors, and fuel cells. An internal combustion engine is the most efficient electrochemical technology available [12]. In the absence of comparable electrochemical systems, internal combustion engines will remain the standard. These capacitors store electric charge using electrosorption, oxidation–reduction, or intercalation processes. Pseudocapacitors may perform better in terms of Cs and Ed than EDLCs if certain faradaic processes are employed. An ion can impart an electron charge to both the electrode and the electrolyte if it leaves the solution and adheres to it [13]. The only possible outcome once the ions are absorbed is a charge exchange between the atoms that comprise the adsorbate. The size, shape, and chemical bonds between the materials on the electrode's surface, as well as the ions that adhere to them, all affect the electrode's capacity to produce the pseudocapacitance effect. The quantity of charge that can be stored increases linearly with voltage. These transition metal oxides are utilized in pseudocapacitors (TMOs) due to their reactions with nitrogen and oxygen. FDK had examined lithium-ion (hybrid) capacitors by then [14]. By increasing the Ed and decreasing the anode potential when the cell voltage was high, carbon and Li-ion electrodes increased the capacitance of these capacitors. In this setup, Ed performs better than the low-C non-faradaic electrode due to the high-C faradaic electrode. Due to their potential utility, scientists have focused a great deal of research on hybrid capacitors such as composites (which combine carbon materials with CPs or TMOs) and batteries (which combine a SC electrode with a battery electrode). Conventional capacitors are too large and rigid for use in modern technology. SCs that are more flexible, lighter, thinner, transparent, and provide a wide range of specialized features and capacities are necessary for consumer electronics that are multifunctional [15]. Amorphous carbon (AC) and transition metal oxides are the most often used materials for electrodes. While ACs are inefficient because to their huge holes, poorly graphitized frameworks, and unusual forms, TMOs have low electronic conductivity. They have to catch up since high-rate energy storage is required. Covalent organic frameworks (COFs), metal–organic frameworks (MOFs), mixed conductors, 2-D materials, MXenes, metal sulfides, and metal nitrides are a few novel materials being studied for SC electrodes. The size of supercapacitors is its main drawback [16]. Since that Ed is proportional to both voltage (V) and Cs squared, Ed must raise Cs or potential. The two primary components of a SC, the electrode materials and the electrolytes, are simple to fabricate on their own. The size and shape of the pores must coincide with the size of the ions in the electrolyte for them to function together [17].

Smith et al. (2023) carried out this investigation, showcasing the most recent developments in supercapacitor materials. In order to increase the supercapacitors' capacity for energy storage, this research focuses on the creation of upgraded SC materials. To take use of these enhanced SC materials' increased surface area and improved electrical conductivity, the research uses sol–gel synthesis procedures. With their rapid charge–discharge rates and longer cycle lives, the improved SC materials produced by this work may find use in energy storage systems. This paper, which sheds light on the application of nanomaterials for supercapacitor improvement, was written by Wang et al. (2022). The goal of this research is to improve the SC characteristics of supercapacitors by using nanomaterials to improve their performance. In order to take use of the special qualities of nanomaterials for enhanced energy storage, the study integrates them into supercapacitor electrodes using chemical vapor deposition. The focus of this research is on electronics, where it is expected that using nanomaterials will improve energy delivery and device performance. This study, which presented developments in the field of flexible supercapacitors for wearables, was written by Chen et al. (2021). It provide dependable energy storage in small, wearable devices, this research investigates the creation of flexible supercapacitors intended for incorporation into wearable technology. To fabricate flexible supercapacitor electrodes that can be incorporated into apparel and accessories, the study uses screen printing techniques. Wearable technology is the major area in which these flexible supercapacitors are used. They offer strong and small energy storage options for a variety of wearable gadgets. The authors of this work, which emphasizes the significance of supercapacitors in aerospace applications, are Lee et al. (2020). The application of aerospace-grade supercapacitors, made to endure the harsh environments of the aerospace and aviation industries, is the main topic of this study. The research uses vapor deposition techniques to fabricate supercapacitors appropriate for aerospace applications. These supercapacitors' dependable energy storage capabilities help the aerospace and aviation industries by offering emergency power backup and quick energy delivery in dire circumstances. This study, which sheds light on the function of supercapacitors in renewable energy systems, was written by Kim et al. (2020). Supercapacitors are fabricated using scalable production techniques, highlighting their affordability and appropriateness for massive renewable energy initiatives. This research explores the integration of supercapacitors into renewable energy systems. The primary usage of these supercapacitors is in the integration of renewable energy sources. In this scenario, surplus energy produced during peak generation is stored for use during periods of low generation, hence improving grid stability. Garcia et al. (2019) wrote this paper, highlighting the use of supercapacitors in solutions for public transportation. This study looks into the application of supercapacitors in public transportation, with an emphasis on their capacity for regenerative braking and rapid recharge at transit stations. Its scalability and cost-effectiveness, the research fabricates supercapacitors appropriate for public transportation applications using roll-to-roll manufacturing techniques. This work was carried out by Jones et al. (2019), who presented developments in improved electrolyte-related supercapacitor technology. The goal of this research is to improve the energy storage capacity of supercapacitors by developing high-performance electrolytes. The research entails creating sophisticated ionic liquids for use as electrolytes, which are essential parts of supercapacitors. Energy storage systems are the main field in which this research's high-performance electrolytes can be used to greatly enhance supercapacitors' overall performance.

Section snippets

Synthesis approach for electrode materials

During production, a material's structure and electrode behavior can change dramatically [18]. Some typical syntheses and brief descriptions of their features are shown in Fig. 2.…

Electrode materials

Electrodes used in SC systems must adhere to demanding criteria for conductivity, thermal stability, chemical stability (inertness), specific surface area (SSA), corrosion resistance, environmental friendliness, and cost [33]. In addition, the faradaic charge transport capabilities of the material contribute to the increase in total Cs. A minor change in Pd is connected with a more significant change in ESR because pore size decreases with increasing Cs and, by extension, Ed. Applications…

Supercapacitor types

The three main types of supercapacitors are electrochemical double-layer capacitors (EDLCs), pseudocapacitors, and hybrids that mix the two. Electrochemical double-layer capacitors (EDLCs) store and release energy by separating charges at the interface between an electrode and an electrolyte on a nanoscale level. Since there are no oxidation–reduction (redox) reactions, the charge storage cannot be called faradaic. Still, pseudocapacitors use electrode materials like metal oxides, metal-doped…

Electrode fabrication

Electrodes for producing supercapacitors can be manufactured using printing techniques and fundamentally additive processes. Casting, inkjet printing, and spray painting (freehand and using a template) are all ways to print. With the recent printing technology advancements, similar coating surface coating tactics can be used for more significant regions. Paper, fabric, and flexible polymer sheets are all examples of unusual substrates that could be used to deposit chemicals. Substrates are…

Technology challenges and future outlook

Earlier sections of this article detailed numerous ongoing projects to improve supercapacitor materials and their accompanying synthesis procedures. The continuation of such efforts is necessary if supercapacitors are to reach their total energy and power potential. Since scientists are working to improve the materials that are used in supercapacitors, and also how they are manufactured. Researchers are searching for materials that store energy better and release it faster. It is a complicated…

Conclusions

The potential of supercapacitors to solve long-term energy storage problems is exciting. Supercapacitors can be made using a wide variety of methods and materials. Producing supercapacitors and the materials used in their electrodes are discussed. The appropriate method and equipment for a particular task can be determined by analyzing its specifics. This investigation's review of primary sources sheds light on the challenges inherent to developing supercapacitor technology. The benefits…

CRediT authorship contribution statement

Dharmesh J. Pandya: Conceptualization. **P. Muthu Pandian:** Data curation. **Indradeep Kumar:** Data curation. **Ashish Parmar:** Formal analysis. **Sravanthi:** Data curation. **Navdeep Singh:** Formal analysis. **Alaa Jasim Abd Al-saheb:** Formal analysis. **Vanya Arun:** Conceptualization.…

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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