International Journal of Advance and Applied Research
Peer Reviewed | International Open Access Journal
ISSN: 2347-7075 | Impact Factor – 8.141 | *Website:* https://ijaar.co.in/
Volume-13, Issue-3 | January – February 2026

Original Article

Super Capacitor Technology and its Application

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Manuscript ID: IJAAR-130371
ISSN: 2347-7075
Impact Factor – 8.141

Volume - 13
Issue - 3
January – February 2026
Pp. 388 - 393

Submitted: 15 Jan.2026
Revised: 26 Jan. 2026
Accepted: 30 Jan. 2026
Published: 10 Feb. 2026

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Quick Response Code:

Website: https://ijaar.co.in/

DOI: 10.5281/zenodo.22056809

DOI Link:
https://doi.org/10.5281/zenodo.22056809

Introduction:

The main sources of energy are fossil fuels and recurring natural occurrences. One of these sources' immediate problems is energy storage and regulation. For the energy to be continuously provided, it must maintain its enormous potential. For energy peak shaving, energy sources are transformed into various forms and partially stored in the grid system (Novas *et al.*, 2020). Additionally, these sources can be stored during intermittent and temporal intervals between the production of energy and its use by end users. The main storage techniques in use today are electrochemical storage devices, hydrogen energy storage, and water energy storage in dams (Sahin, 2020). However, the lifespan of these conventional storage devices is less than half that of the supercapacitor (SC), most of them contain some contaminants that are harmful to nature, and they have some technical drawbacks (Omar *et al.*, 2012). Scientists have proposed SCs as an alternate solution for individual and hybrid applications with other storage devices. In addition, as the power source for electric and hybrid vehicles, SCs are increasingly used as interim energy storage for regenerative braking. High power density, rapid charge-discharge time, low input resistance, long lifespan, and environmental friendliness are only a few benefits of the SCs. Over the past ten years, a number of hybridization topologies have been put out and used to improve energy storage systems' power density and cycle life. The most recent technological advancements encourage direct competition between SCs and rechargeable batteries. In order to find potential ways to use these materials in Li-ion batteries in the future, the electrochemical activities of several materials and their composites have been studied. The SC can address many of the drawbacks of batteries by storing electrical energy as a solid-state device. SCs have a new history and were created in the middle of the 19th century. First, in the early 1950s and 1957, engineers at General Electric (GE) Corporation created capacitors. Becker created the first SC without a recognized double layer. In 1966, the SOHIO firm developed a second iteration of the SC, which was patented as an electrolytic capacitor. The Pinnacle Research Institute (PRI) created the first SCs for military use in 1982; they were known as PRI ultra-capacitors. By the end of 1980, the equivalent series resistance (ESR) values had dropped but the charge and discharge currents had increased in response to rising capacitance values. Maxwell Laboratories took over this work in 1992 and gave them the name "Boost Caps" to highlight their power

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uses. Evans developed a high voltage tantalum electrolytic capacitor in 1994, which combined the properties of electrolytic and electrochemical capacitors; however, it was limited to specific military applications (Evans, 2007).

How to cite this article:

Chawale Kartik. (2026). Super Capacitor Technology and its Application. International Journal of Advance and Applied Research, 13(3), 388 - 393. https://doi.org/ 10.5281/zenodo.22056809

Construction and Working of Supercapacitor:

The basic structure of an SC consists of aluminium current collectors and electrodes instead of dielectric materials. The operation principle of the SC is based on the storage of energy by the distribution of the ions near the surface of the two electrodes. The two interfaces create a space charge zone called the electrical double layer (EDL). By transferring electrons from one electrode to another, conventional capacitors store energy. SC made of carbon materials has a larger surface area, where charges are stored by a phenomenon called the electric double layer. Pseudo-capacitance is the primary charge storage mechanism for SC employing metal oxide or polymeric materials. Supercapacitors can reach higher capacitance due to their thinner dielectric and larger electrode surface area, even though they are regulated by the same capacitance formulae as electrolytic capacitors (Li and Jie, 2008). Two carbon-based electrodes are separated by a dielectric material, which has electrical characteristics that impact SC performance in addition to acting as an insulator. In SC, charges are electrostatically held rather than transferred. When a voltage is applied across the terminals, an electric field is created in the electrolyte and because of this electrolyte is polarized. This causes ions to diffuse through the dielectric to the porous electrodes of opposite charges. Thus electric double layer is formed at each electrode, as a result, distance between electrodes decreases and surface area of electrode increases. The energy storage capacity depends on the active material used in the electrolyte, the surface area of electrode and utilization rate of micro-holes in the porous electrode.

Techno-Economic Analyses of Supercapacitors:

The cycle life, performance reliability, and cost of SCs have become critical factors as their use in the energy and transportation industries has grown. Short-term power for global system for mobile (GSM) communication bursts and high brightness flashes in cell phones, hybrid battery–SC systems for UPSs and power-quality enhancers, automotive systems for integrated starter generator applications, power tools, and additional high-power short autonomy-time UPS systems without batteries are some of the traditional uses of SCs. The SC market has now begun an ongoing phase of rapid expansion following a period of stability (Kularatna, 2016). This is the result of the recent acts of three major corporations. According to a report; "Supercapacitor: Applications, Players, Markets 2020–2040", it is foreseen that a yearly additional SC market of over 0.5 billion USD will emerge in 2030 if only a few per cent of 48 V mild hybrids adopt SC peak shaving in ten years. Although the specific energy density is greater for lithium-ion batteries, specific power density is greater for SCs, at a value more than ten times the others. The cycle life is also very high for SCs; however, the charge

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and discharge efficiency is better for lithium-ion batteries. The SC charge and discharge time is under one minute.

Table1.Comparison of SCs with different types of batteries

Analysed Parameters	Lead-Acid Battery	Lithium-Ion Battery	Redox-Flow Battery	Supercapacitor
Specific energy density	10-100	150-200	10-50	1-10
Cycle life	1000	5000	10000	>50000
Fast charge duration	1-5 h	0.5-3 h	1-10 h	0.3-30 s
Fast discharge duration	0.3-3 h	0.3-3 h	1-10h	0.3-30 s
Shelf life (years)	5-15	10-20	5-15	20
Cost	Loww	High	Medium	Medium
Operation Temperature (°C)	-5 to 40	-30 to 60	0 to 40	-40 to 75

Supercapacitor Technology Application:

Consumer Electronics: One of the most established application areas of supercapacitors is consumer and portable electronics. Supercapacitors can provide short-duration backup power, voltage stabilization, power buffering, and peak-power assistance in electronic devices. They are useful in memory protection systems, real-time clocks, emergency lighting, cameras, wireless sensors, and portable electronic equipment. Their rapid charging capability allows energy to be stored during short intervals and released when required. Because supercapacitors can tolerate repeated cycling better than many conventional batteries, they are particularly suitable for electronic systems that experience frequent charge and discharge events. Miniaturized supercapacitors are also being investigated for flexible electronics, wearable devices, and Internet-of-Things sensors. Simon *et al.* (2020) noted that emerging micro-supercapacitor technologies are particularly relevant to small-scale electronics and IoT applications.

Electric Vehicles and Hybrid Vehicles: Electric and hybrid vehicles represent one of the most important application areas for supercapacitor technology. During vehicle acceleration, a large amount of power is required for a short period, whereas during braking, considerable kinetic energy must be recovered. Supercapacitors are well suited to these rapid power fluctuations. During regenerative braking, they can absorb energy quickly and subsequently release it during acceleration. This reduces the high-power stress imposed on the main battery and can potentially improve battery life and overall energy efficiency. Battery–supercapacitor hybrid energy-storage systems combine the high energy density of batteries with the high power density of supercapacitors. Recent reviews identify this hybrid configuration as an important approach for improving the performance of electric-vehicle energy-storage systems. Rahman *et al.* (2024) emphasized that battery supercapacitor hybrid systems can exploit the complementary characteristics of batteries and supercapacitors in electric vehicles.

Renewable Energy Integration: The increasing use of solar and wind energy has created a need for

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energy-storage technologies capable of responding rapidly to fluctuations in power generation. Supercapacitors can help smooth short-term variations in renewable-energy output because they can absorb and release electrical energy rapidly. In solar photovoltaic systems, they can provide transient power support during sudden changes in solar irradiation. In wind-energy systems, they can compensate for short-duration variations in generated power and support voltage regulation. Supercapacitors can also operate as part of hybrid energy-storage systems in which batteries provide longer-duration energy storage while supercapacitors handle short-term power fluctuations. Such integration can reduce battery cycling and improve the operational stability of renewable-energy systems. Recent research has identified renewable-energy smoothing, power management, and grid stabilization as promising applications for supercapacitors.

Grid and Power-Quality Applications: Supercapacitors can play an important role in modern electrical grids by providing short-duration power support and improving power quality. They can be used for voltage stabilization, frequency regulation, power fluctuation compensation, and backup power for sensitive equipment. Because their response time is extremely short, supercapacitors can respond effectively to sudden changes in electrical demand. In microgrids, they can operate together with batteries, photovoltaic systems, wind turbines, and power converters. Their high cycle life is particularly advantageous in applications involving frequent power fluctuations. Modern supercapacitor systems are therefore being considered for microgrids and distributed energy-storage applications where rapid response is essential. De Doncker *et al.* (2022) described supercapacitors as useful high-power components in mature electrical-engineering applications, including electric vehicles, microgrids, and consumer electronics.

Industrial Automation and Robotics: Industrial automation systems frequently require short bursts of high power during starting, acceleration, lifting, and braking operations. Supercapacitors can supply these peak-power requirements while reducing the load on the primary power source. They are therefore applicable to automated guided vehicles, industrial robots, elevators, cranes, actuators, and automated material-handling systems. In regenerative industrial equipment, energy generated during braking or deceleration can be captured and temporarily stored in supercapacitors and then reused during the next high-power operation. This approach can improve energy efficiency and reduce energy losses. Their long cycle life also makes them attractive for industrial systems that undergo repeated operating cycles throughout the day. The combination of rapid energy exchange and durability provides a major advantage over conventional batteries in these applications.

Aerospace, Railway and Transportation Systems: Supercapacitors are also being explored for railway and aerospace applications where high power and reliability are important. In electric and hybrid railway systems, they can capture regenerative braking energy and release it during train acceleration. This can reduce energy consumption and improve the efficiency of railway networks. In aerospace systems, supercapacitors may provide high-power pulses for actuators, emergency systems, and electrically driven equipment. Their high power density and ability to operate through a large number of cycles make them attractive for applications where maintenance and reliability are critical. Hybrid energy-storage configurations can further improve system performance by combining supercapacitors with batteries or other energy sources.

Emerging Applications and Advanced Supercapacitors:

The development of advanced electrode materials is expanding the potential applications of supercapacitors. Nanostructured carbon, graphene, carbon nanotubes, transition-metal oxides, conducting polymers, MXenes, and metal–organic frameworks are being investigated to improve capacitance, energy density, conductivity, and cycling stability. Advanced device architectures, flexible electrodes, solid-state electrolytes, and microsupercapacitors are also being developed for wearable electronics and miniaturized energy systems. Abdel Maksoud *et al.* (2021) reviewed advances in electrode materials and device technologies and emphasized the importance of materials engineering in improving the electrochemical performance of supercapacitors.

Challenges and Future Prospects:

Despite their advantages, supercapacitors have an important limitation: their energy density is generally lower than that of rechargeable batteries. Consequently, they are not always suitable as a standalone long-duration energy-storage technology. Researchers are therefore focusing on advanced electrode materials, wider-voltage-window electrolytes, asymmetric configurations, and hybrid supercapacitor–battery systems. Supercapatteries are particularly promising because they combine capacitive and battery-like charge-storage mechanisms. Yu *et al.* (2020) explained that supercapattery systems are designed to combine the high-power characteristics of supercapacitors with the higher energy-storage capability associated with battery-type electrodes.

Conclusion:

Supercapacitor technology has evolved from a specialized electrochemical-storage concept into an important component of modern energy systems. Its high power density, rapid charging and discharging, excellent cycle life, and strong regenerative-energy capability make it valuable in electric vehicles, renewable-energy systems, consumer electronics, industrial automation, transportation, microgrids, and power-quality applications. The most promising future direction is likely to involve hybridization, where supercapacitors operate together with batteries and renewable-energy sources rather than replacing them completely. Continued progress in nanostructured electrodes, electrolytes, flexible devices, and hybrid architectures could significantly improve energy density and broaden commercial applications.

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