Replacement of Conventional Batteries with Supercapacitors in Energy Harvesting Systems

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***Abstract*—Conventionally, the major source of power in deployed sensors are batteries. Batteries are distinguished by their high energy densities, which are responsible for long-distance activity. Nonetheless, recharging a battery can be a time-consuming process. A supercapacitor is a new type of energy storage that can be charged quickly and can be used to replace traditional batteries. It has come up with an option to conventional sources of power. This paper discusses the varied sources of power and their evolution till now, meeting the energy requirements. The application area of supercapacitors in diverse fields is also explained.**

Keywords: Energy Harvesting (EH), Batteries, Supercapacitors, Hybrid Supercapacitors, Electric Double Layer Capacitors (EDLC) .

I. Introduction

Electronic circuitry's continual downsizing is an enabler for implantable biological sensors. Batteries are used to power most implantable sensors. Even though they have high energy densities, charging for longer duration in sensing devices might not be feasible. The functional boundary between capacitors and batteries has blurred due to recent advances in supercapacitor technology, with capacitors having progressively enormous capacity. Although supercapacitors' energy density is still modest, the prospect of using them as a battery replacement now exists.This idea is especially appealing in applications that require quick charging and minimum charge circuitry. Supercapacitors have traditionally been used as a source of peak output power for battery-operated devices [1]. Furthermore, supercapacitors are frequently employed as energy harvesting storage units. For instance, energy harvesters such as solar cells provide sufficient operating power to charge the supercapacitor which in turn delivers it to the load.[2]

The goal of this study is to look into the possibility of using a supercapacitor as a battery replacement in low powered devices.Implantable sensors have traditionally been powered by batteries. Batteries allow the circuitry toget seal and encapuled with the suitable power management for long periods of time.

Batteries, on the other hand, come with a variety of drawbacks:

1. Secondary batteries take a lengthy time to charge. Telemetry Research Ltd's implantable sensor charges in 4 hours and discharges in 9 hours.[3]
2. Various types of batteries are prone to memory effects, which means that if they are not properly maintained, they will degrade with time.
3. Many dangerous heavy metals can be found in batteries.

In today's world, supercapacitors are employed in numerous secondary power source applications. Typically, the supercapacitor is used to complement a traditional battery supply during high load situations. The difference can be much understood from their energy and power density values and in the number of charge and discharge cycles.

Because of the fact that supercapacitors can be charged and discharged quickly depending on their power densities, these are preferred in the applications requiring erratic current pulses. Supercapacitors, on the other hand, have a low energy density, thus batteries are still preferable in applications that require consistent power for longer periods of time. [1] Supercapacitors, in addition to having quick charging capabilities, have the following advantages over batteries:

1. Capacitors can withstand extremely high charge and discharge currents and can simply ascertain their state of charge by monitoring their terminal voltage.
2. Capacitors have low chances of harm as compared to the batteries because of the RoHS (Restriction of Hazardous Substances Directive) compliant. [2]

II. Batteries

A chemical reaction is used to generate electrical power in batteries. They are made up of one or more electrochemical cells that are coupled in series or parallel to provide adequate output. A negative electrode called as anode, a positive electrode called as cathode, and an ionic conductor called as electrolyte are present in each cell of the battery. Both the positive and negative electrodes are separated, and the electrolyte serves as a medium for ionic mobility between the two electrodes. The majority of batteries fall into one of two categories: primary or secondary. Because primary batteries are difficult to recharge electrically, they are typically used once and then discarded.Secondary batteries, on the other hand, may be quickly recharged using electricity. The widespread usage of portable gadgets has accelerated the work in research &development of secondary batteries, which now come in a variety of chemistries. The capacity (C) is defined as the entire charge contained in the battery with discharge rate, temperature conditions and ebd volatge values.The deliverable capacity of a battery totally depends on the type and number of materials used in anode and cathode. Manufacturers often indicate C in Ah for secondary batteriesTo represent charge or discharge current, manufacturers employ multiples or submultiples of C. [3], [8].

III. Traditional Capacitors

Capacitors are the passive devices madeof conducting sheets placed between two metal plates, also, known for their high power densities and high number of cycle life, thus, find more number of applications in analog and digital circuit applications. Between the two plates, a static charge can collect and be swiftly released, resulting in a high power density. A dielectric is a thin insulating substance that can polarise in an electric field and is sandwiched between two plates.[4]Charges flow through the dielectric, creating an internal electric field that balances the fields on the two plates. In the internal field, increased permittivity dielectrics can be used to store higher levels of charge. Capacitance can also be increased by shortening the gap between the plates. The dielectric's breakdown potential might also affect a capacitor's performance. When the plates break, the energy trapped between them is released. To avoid dielectric collapse, a minimum separation distance is used to limit capacity at higher voltages. In recent years, polymer foils have dominated the static capacitor business because they are more stable at high temperatures, cost less to make, and last longer than dielectric papers.

IV. Electrochemical Capacitors

Supercapacitors work on the same basic principles as electrostatic capacitors, with bigger area plates and closer spacing between plates resulting in a higher effective capacitance. Supercapacitors are formally called as electric double-layer capacitors since an electrical double layer is generated next to a wide area electrode and an electrolyte in these devices (EDLCs). Electrochemical supercapacitors (ESs) differ from regular capacitors in that they have lower power densities, higher charge storage densities, and different material requirements.The electrolyte in electrical double-layer capacitors allows charged ions to accumulate on porous electrode surfaces with significantly more area than ordinary capacitors. The charge is separated by a solvent cage layer of value from 5 to 10 angstroms at the interface. In comparison to standard static capacitors, a combination of large surface area and small charge separation enables the generation of high energy density..

The selection of proper electrodes, separators, electrolytes and sealants is necessary for optimising ES design. To maximise charge storage capacity, electrode materials must be conducive and porous.Collectors must have good contact with the electrode layer, be stable during charge and discharge, and be highly conductive to promote electron transmission.

Electrolyte materials must have high ion mobility in order to deliver ions to the double layer quickly. To improve electrolyte performance, operating voltages, toxicity, corrosion, and safety must all be optimised. Separators must be electronically insulating and allow for strong ionic mobility from the electrolyte to the electrode surface to prevent short connections between the two electrode layers.

The electrolyte determines which polymer to use and how to make it. Sealants must be non-conductive, withstand corrosion and deterioration, and prevent ion leakage between stacked cells. Sealants are generally formed of low melting temperature PE material or viscous rapid setting polymers such as epoxies, depending on the cell type. Sealants have little direct effect on performance; instead, they aid in the regulation of safety and moisture. Short circuits can occur within constructed cells if a seal fails.EDLC and pseudocapacitive materials are the two types of electrode materials used in ESs, depending on the storing mechanism. While this technology advances into the next generation of ES devices, each of these materials will have its own set of benefits and drawbacks. Carbons used in EDLC materials allow physical charge storage at the electrode-electrolyte contact. [4]

TABLE 1. Comparison of Batteries and Supercapacitors.[5]

Performance	Lead – Acid Batteries	Lithium Batteries	Supercapacitors
Power density (W/kg)	30	100	3000
Energy density (Wh/kg)	30-45	100-210	3
Typical life-time (years)	< 2	5	30
Time of charge (s)	> 1000	> 1000	0.3-30
Time of dis-charge (s)	1000-10000	1000-10000	0.3-30
ESR	From 50 mΩ to a few Ω	From 50 mΩ to a few Ω	Fractional mΩ to several mΩ

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V. Hybrid Supercapacitors

In hybrid (asymmetric) supercapacitors, many types of electrodes are used (HSCs). One electrode may be highly distributed carbon, such as a double-layer electrode, and the other electrode may be a battery one or one electrode may be carbon and the other electrode is a pseudocapacitor, such as one based on electron-conducting polymer (ECP). The fundamental advantage of HSCs over EDLCs is that they have a higher energy density due to their larger potential window. In comparison to electric double-layer capacitors (EDLCs), the fundamental flaw of HSCs is a decrease in cyclability due to the nondouble-layer electrode's restrictions.The system of +(NiOOHNiO2)/KOH/C, in which the positive alkaline battery electrode is employed, is an example of such HSCs. The Elit and Esma firms (Russia) created this HSC (Beliakov and Brintsev, 1997 and Burke A, 2000).

When compared to EDLC, that is, a system with two AC-based electrodes, using ACs as the basis for the negative electrode in hybrid systems allows for a four- to five-fold increase in potential variation range and a four- to five-fold increase in energy density. All of the processes that occur in the positive electrode's bulk and on its surface are comparable to those that occur in alkaline batteries.Overcharging leads in the destruction of non-stoichiometric nickel oxides due to the evolution of free oxygen at the NiOx electrode's 70–80 percent discharge degree. The rate of this process is accelerated as the temperature rises. As a result, a capacitor's NiOx electrodes should not be fully charged. The positive electrode's crystalline lattice is protonated as a result of its discharge. The capacitance of a hybrid C/NiOx capacitor is governed by the capacitance of the NiOx electrode, which is dependent on the electrode process rate on this electrode, in the range of high discharge currents. The capacitor's working potential range is 0.8–1.7V. [6]

VI. Applications of Supercapacitors

A. Power Electronics

Electrochemical Supercapacitors (ESs) look to be excellent candidates for applications that require high power densities, fast transient responses, and a small footprint.

Because of their high capacitance values ranging from 1 to 2700 F, equivalent series resistance typically 10 times lower than resistances of conventional capacitors, and long cycle lives, ESs are new energy storage devices with excellent potential for portable applications such as power electronics systems. Because of its enormous capacitances, ESs are ideal for backup energy storage in power electronics systems with limited space.Several battery systems, including lithium kinds, have been employed in memory protection and backup power applications for many decades. Batteries, on the other hand, are not always the best option. Some batteries require complicated recharging circuits; otherwise, temperature runaways and explosions can occur. They must be replaced frequently because to their short cycle life, and they must go through a series of conditioning steps before entering service. Finally, they may not live long enough to keep data during a long-term power loss when you really need them.Long cycle lifetimes and safety are still highly desired attributes in data centres around the world that rely on batteries to secure important data on their servers and storage controllers.

B. Memory Protection

ESs are used on electrical circuit boards to manage voltages that can vary due to component power consumption, distances between devices, and conductance. They function by holding a fluctuating electric current while putting out a consistent level. The ES's size determines how much power it can store. An ES, like a battery, can provide enough energy for a circuit to operate for a limited duration. ESs have been used in this application for decades, for example, to provide enough power to keep a mobile computer alive while the batteries are changed.

C. Battery Enhancement

Emerging technologies are ESs with low equivalent series resistances (ESRs). Although these capacitors lack the energy density of a traditional battery, their power densities are more than ten times higher. These characteristics make ESs useful additions to battery-based systems in which the battery provides energy and the ES provides short-term power. Enhanced peak power performance, extended run-time, and lower internal losses are all advantages of this combination. ESs with capacitance values ranging from 1 to 5000F, power densities of 4300 W/kg, and maximum energy storage of 8125 J are already available.Their ESR values range from 0.3 to 130 m, which is five times less than a standard battery's ESR. For delivering fluctuating loads, combining batteries with ESs is advantageous. [4]

D. Portable Energy Sources

ESs can be used as rechargeable stand-alone power sources for some portable electronic devices with moderate energy consumption. Batteries are currently the most convenient power sources. They do, however, take a long time to recharge and must be charged overnight. This is seen as a current technological constraint. ESs allow for the creation of devices that can be recharged quickly, maybe in a matter of seconds, and that can be charged and discharged again without significant efficiency loss.

The powering of light-emitting diodes (LEDs) that provide highly efficient and instantly rechargeable safety lighting is a common use of ESs.The ES-based design presented new challenges in terms of voltage regulator selection, capacity, and output voltages. This novel architecture gives the target application power for the specified amount of time.

ESs can overcome the power supply constraints of batteries and the energy delivery limits of traditional capacitors when compared to conversional capacitors for portable electronics. They manage peak power events such as wireless transmission, GPS, audio, LED flash, video, and battery hot swaps before being recharged at an average power rate from a battery.

E. Power Quality Improvement

A voltage variation or fluctuation that causes damage or malfunction of electronic equipment or other electrical devices is referred to as an electrical power quality problem. Power fluctuation is a major issue that can harm sensitive electronics. ESs can be utilised as energy storage devices in systems that aim to improve power distribution reliability and quality. It's worth mentioning that power quality applications necessitate reliable ride-through power in real time. It is detrimental to traditional lead–acid batteries to use them for such quick, deep-cycle electric power needs.Traditional batteries' higher ESRs also result in larger voltage drops on their terminal voltages and additional losses due to the pulsing behaviour of the load current when used in this application. In this aspect, using ESs has a number of advantages versus using batteries.

F. Renewable and Peak-off Power Supplies

Renewable and off-peak power sources that rely on intermittent energy sources like wind or solar radiation must store energy to ensure that it is available at all times. In these situations, ESs have a lot of advantages over traditional batteries. If a photovoltaic (PV) equipment generates power and stores it in a battery, for example, the battery's limited cycle life necessitates replacement every 3 to 7 years. ESs, on the other hand, can withstand a huge number of charge and discharge cycles without significant performance loss, and hence must be changed every 20 years, which is also the lifetime of a PV panel. As a result, the absence of frequent maintenance lowers life-cycle expenses. ESs also have the advantage of being able to work efficiently across a large temperature range. Remote stations may be located in cold areas, and if batteries are used for energy storage, auxiliary systems must keep the temperature near room temperature, adding to the cost and energy consumption.

VII. Conclusion

One of the most serious and exciting issues confronting science and technology in the twenty-first century is the search for alternative energy sources. Many people throughout the world are interested in environmentally friendly, efficient, and sustainable energy generation and use. Electrochemical energy storage and conversion devices such as batteries, fuel cells, and electro-chemical supercapacitors (ESs) are crucial for delivering alternative energy in portable, stationary, and transportation applications, for example.ESs are the most viable complimentary devices among the electrochemical energy storage and conversion breakthroughs. Among the various energy storage devices, they constitute a new breed of technology. They have a higher energy storage capacity than traditional capacitors and deliver more power than batteries. Supercapacitor capacity restrictions now hinder their widespread adoption as a battery replacement. This disparity will narrow as supercapacitor capacities rise, and supercapacitors are expected to become increasingly popular alternatives for regular batteries.

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