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Supercapacitors: the near Future of Batteries

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ABSTRACT: *Supercapacitors or EDLCs (i.e. electric double-layer capacitors) or ultra-capacitors are becoming increasingly popular as alternatives for the conventional and traditional battery sources. This brief overview focuses on the different types of supercapacitors, the relevant quantitative modeling areas and the future of supercapacitor research and development. Supercapacitors may emerge as the solution for many application-specific power systems. Especially, there has been great interest in developing supercapacitors for electric vehicle hybrid power systems, pulse power applications, as well as back-up and emergency power supplies. Because of their flexibility, however, supercapacitors can be adapted to serve in roles for which electrochemical batteries are not as well suited. Also, supercapacitors have some intrinsic characteristics that make them ideally suited to specialized roles and applications that complement the strengths of batteries. In particular, supercapacitors have great potential for applications that require a combination of high power, short charging time, high cycling stability and long shelf life. So, let's just begin the innovative journey of these near future of life-long batteries that can charge up almost anything and everything within a few seconds!*

I. Introduction

A capacitor (originally known as a condenser) is defined as a passive terminal electrical used to store energy electrostatically in an electric field separated by a dielectric (i.e. insulator). So what is it that adds the 'super' to an ordinary 'capacitor'? In response to the changing global landscape, energy has become a primary focus of the major world powers and scientific community. Witnessing today's era of global energy crisis, one such device, the supercapacitor, has matured significantly over the last decade and emerged with the potential to facilitate major advances in energy storage. This paper presents a brief overview of supercapacitors based on a broad survey of supercapacitor research and development (R&D). Following this introduction, methodology (section 2) is provided with respect to the fundamentals of conventional capacitors and of supercapacitors including taxonomy of supercapacitors, discusses the different classes of such devices, and illustrates how the different classes form a hierarchy of supercapacitor energy storage approaches. Section 3 presents the results and findings of this technical research work which sums up the entire analysis of the major quantitative modeling research areas concerning the optimization of supercapacitors. Finally, Section 4 which is the conclusion/discussions summarizes the prospectus on the future of supercapacitor R&D. An additional key element of the paper is the appendix and references section that precisely jots down all the links that have culminated together into this research paper. Let us just quickly skim through the history of batteries that led to the creation of supercapacitors.

When was the Battery Invented? One of the most remarkable and novel discoveries in the last 400 years was electricity. We might ask, "Has electricity been around that long?" The answer is yes, and perhaps much longer, but its practical use has only been at our disposal since the mid to late 1800s, and in a limited way at first. One of the earliest public works gaining attention was enlightening the 1893 Chicago's World Columbia Exposition with 250,000 light bulbs, and illuminating a bridge over the river Seine during the 1900 World Fair in Paris.

Early Batteries: Volta discovered in 1800 that certain fluids would generate a continuous flow of electrical power when used as a conductor. This discovery led to the invention of the first voltaic cell, more commonly known as the *battery*.

Invention of the Rechargeable Battery: In 1836, John F. Daniel, an English chemist, developed an improved battery that produced a steadier current than earlier devices. Until this time, all batteries were primary, meaning they could not be recharged. In 1859, the French physicist Gaston Planté invented the first rechargeable battery. It was based on lead acid, a system that is still used today. In 1899, Waldmar Jungner from Sweden invented the nickel-cadmium battery (NiCd), which used nickel for the positive electrode (cathode) and cadmium for the negative (anode). High material costs compared to lead acid limited its use and two years later, Thomas Edison produced an alternative design by replacing cadmium with iron. Low specific energy, poor performance at low temperature and high self-discharge limited the success of the nickel-iron battery. It was not until 1932 that Shlecht and Ackermann achieved higher load currents and improved the longevity of NiCd by inventing the sintered pole plate. In 1947, Georg Neumann succeeded in sealing the cell. For many years, NiCd was the only rechargeable battery for portable applications.

Battery Developments: Benjamin Franklin invented the Franklin stove, bifocal eyeglasses and the lightning rod. He was unequaled in American history as an inventor until Thomas Edison emerged. Edison was a good businessman who may have taken credit for inventions others had made. Contrary to popular belief, Edison did not invent the light bulb; he improved upon a 50-year-old idea by using a small, carbonized filament lit up in a better vacuum. Although a number of people had worked on this idea before, Edison gained the financial reward by making the concept commercially viable to the public.

Table1: Performance comparison between supercapacitor and Li-ion (Courtesy of Maxwell Technologies, Inc.)

Function	Supercapacitor	Lithium-ion (general)
Charge time	1–10 seconds	10–60 minutes
Cycle life	1 million or 30,000h	500 and higher
Cell voltage	2.3 to 2.75V	3.6 to 3.7V
Specific energy (Wh/kg)	5 (typical)	100–200
Specific power (W/kg)	Up to 10,000	1,000 to 3,000
Cost per Wh	$20 (typical)	$0.50-$1.00 (large system)
Service life (in vehicle)	10 to 15 years	5 to 10 years
Charge temperature	–40 to 65°C (–40 to 149°F)	0 to 45°C (32°to 113°F)
Discharge temperature	–40 to 65°C (–40 to 149°F)	–20 to 60°C (–4 to 140°F)

II. Methodology

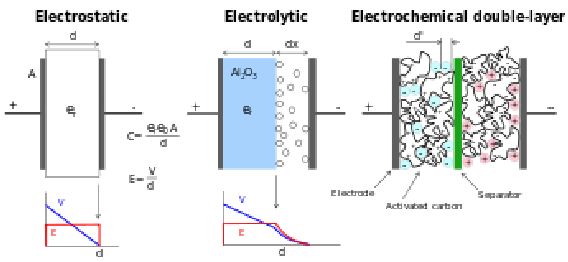

Fig 1: Supercapacitor diagram

The supercapacitor differs from a regular capacitor in that it has a very high capacitance. A capacitor stores energy by means of a static charge as opposed to an electrochemical reaction. Applying a voltage differential on the positive and negative plates charges the capacitor. This is similar to the buildup of electrical charge when walking on a carpet. Touching an object releases the energy through the finger.

The *supercapacitor*, rated in farads, which is again thousands of times higher than the electrolytic capacitor. The supercapacitor is ideal for energy storage that undergoes frequent charge and discharge cycles at high current and short duration. Rather than operating as a stand-alone energy storage device, supercapacitors work well as low-maintenance memory backup to bridge short power interruptions. Supercapacitors have also made critical inroads into electric power trains. The charge time of a supercapacitor is about 10 seconds. The self-discharge of a supercapacitor is substantially higher than that of an electrostatic capacitor and somewhat higher than the electrochemical battery. The organic electrolyte contributes to this. The stored energy of a supercapacitor decreases to 50% in 30-40 days. A nickel based battery self discharges 10 to 15 percent per month but Li-ion discharges only 5% per month.

***Principle*:** In a conventional capacitor, energy is stored by moving charge carriers, typically electrons, from one metal plate to another. This charge separation creates a potential between the two plates, which can be harnessed in an external circuit. The total energy stored in this fashion increases with both the amount of charge stored and the potential between the plates. The amount of charge stored per unit voltage is essentially a function of the size, the distance and the material properties of the plates and the material in between the plates (the dielectric), while the potential between the plates is limited by the breakdown field strength of the dielectric. The dielectric controls the capacitor's voltage. Optimizing the material leads to higher energy density for a given size.

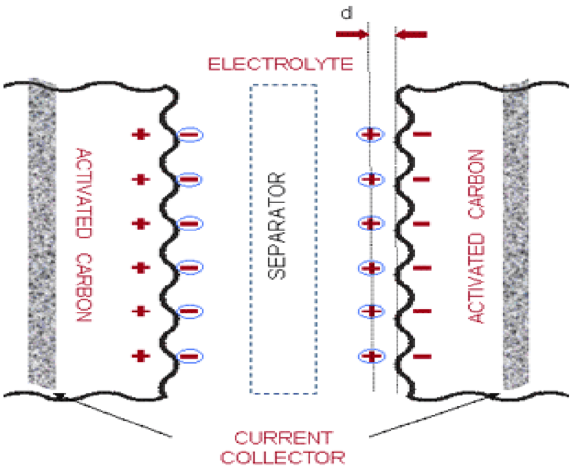

Fig.2: Schematic of EDLC

The two key storage principles behind the supercapacitor theory are:

- Double-layer capacitance – Electrostatic storage achieved by separation of charge in a Helmholtz double layer at the interface between the surface of a conductive electrode and an electrolyte. The separation of charge is of the order of a few angstroms (0.3–0.8 nm), much smaller than in a conventional capacitor.
- Pseudo capacitance – Faradic electrochemical storage with electron charge-transfer, achieved by redox reactions, intercalation or electrosorption.

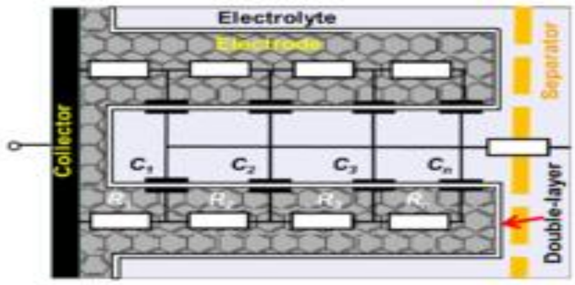

Fig 3: Simplified View of EDLC

EDLCs do not have a conventional dielectric. Instead of two plates separated by an intervening insulator, these capacitors use virtual plates made of two layers of the same substrate. Their electrochemical properties, the so-called "electrical double layer", result in the effective separation of charge despite the vanishingly thin (on the order of nanometers) physical separation of the layers. The lack of need for a bulky layer of dielectric and the porosity of the material used permits the packing of plates with much larger surface area into a given volume, resulting in high capacitances in small packages. In an electrical double layer, each layer is quite conductive, but the physics at the interface between them means that no significant current can flow between the layers. The double layer can withstand only a low voltage, which means that higher voltages are achieved by matched series-connected individual

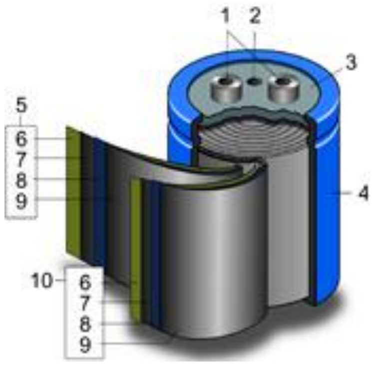

Fig 3: Schematic construction of a wound supercapacitor
1.Terminals, 2.Safety vent, 3.Sealing disc, 4.Aluminum can, 5.Positive pole, 6.Separator, 7.Carbon electrode, 8.Collector, 9.Carbon electrode, 10.Negative pole

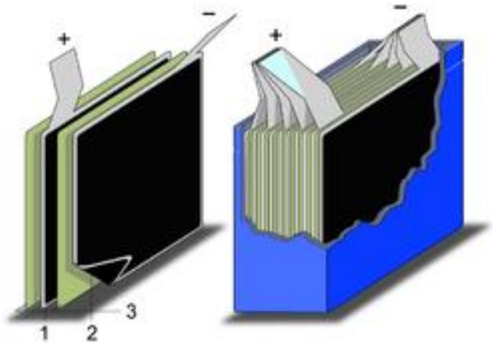

Fig.4: Schematic construction of a super capacitor with stacked electrodes
1.Positive electrode, 2.Negative electrode, 3.Separator

Each EDLC cell consists of two electrodes, a separator and an electrolyte. The two electrodes are often electrically connected to their terminals via a metallic collector foil. The electrodes are usually made from activated carbon since this material is electrically conductive and has a very large surface area to increase the capacitance. The electrodes are separated by an ion permeable membrane (separator) used as an insulator to prevent short circuits between the electrodes. This composite is rolled or folded into a cylindrical or rectangular shape and can be stacked in an aluminium can or a rectangular housing. The cell is typically impregnated with a liquid or viscous electrolyte, either organic or aqueous, although some are solid state. The electrolyte depends on the application, the power requirement or peak current demand, the operating voltage and the allowable temperature range. The outer housing is hermetically sealed. Most EDLC's are constructed from two carbon based electrodes (mostly activated carbon with a very high surface area), an electrolyte (aqueous or organic) and a separator (that allows the transfer of ions, but provides electronic insulation between the electrodes). As voltage is applied, ions in the electrolyte solution diffuse across the separator into the pores of the electrode of opposite charge. Charge accumulates at the interface between the electrodes and the electrolyte (the double layer phenomenon that occurs between a conductive solid and a liquid solution interface), and forms two charged layers with a separation of several angstroms – the distance from the electrode surface to the center of the ion layer (d in Fig. 1). The double layer capacitance is the result of charge separation in the interface. Since capacitance is proportional to the surface area and the reciprocal of the distance between the two layers, high capacitance values are achieved.

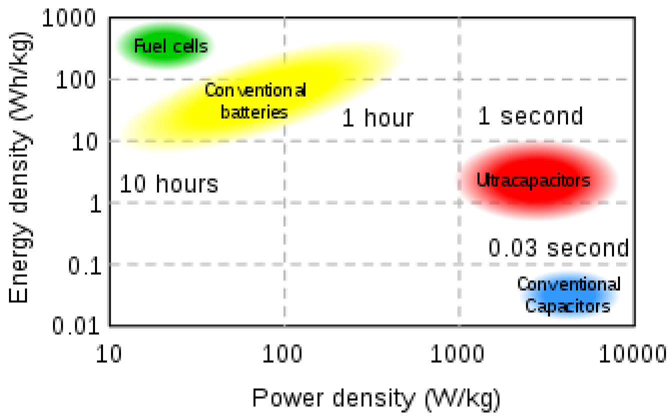

Fig. 5: Ragone chart showing energy density vs. power for various energy-storage devices

In general, EDLCs improve storage density through the use of ananoporous material, typically activated charcoal, in place of the conventional insulating dielectric barrier. Activated charcoal is an extremely porous, "spongy" form of carbon with an extraordinarily high specific surface area—a common approximation is that 1 gram (a pencil-eraser-sized amount) has a surface area of roughly 250 square metres (2,700 sq ft)—about the size of a tennis court. As the surface area of such a material is many times greater than a traditional material like aluminum, many more charge carriers (ions or radicals from the electrolyte) can be stored in a given volume. As carbon is not a good insulator (vs. the excellent insulators used in conventional devices), in general EDLCs are limited to low potentials on the order of 2 to 3 V.

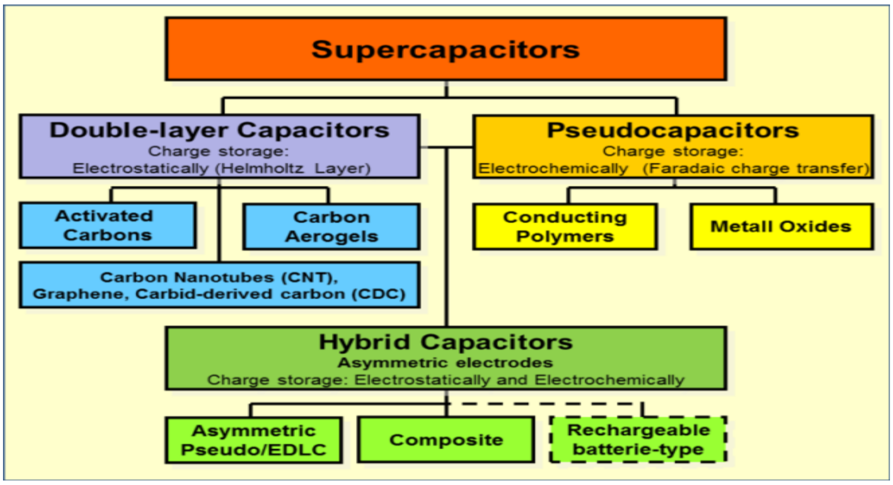

Fig.6: Classification of Supercapacitors

Double-layer capacitors – These ones with activated carbon electrodes or derivates with much higher electrostatic double-layer capacitance than electrochemical pseudocapacitance

Pseudo capacitors – These are capacitors with transition metal oxide or conducting polymer electrodes with a high amount of electrochemical pseudocapacitance

Hybrid capacitors – These are capacitors with asymmetric electrodes one of which exhibits electrostatic and the other mostly electrochemical capacitance, such as lithium-ion capacitors. They are environmentally safe. The various materials that can be used for supercapacitors are activated carbon, activated charcoal, activated carbon fibers, carbon nanotubes, carbon aerogel, carbide-derived carbon, graphene, conductive polymers, metal oxides, etc.

III. Results/Findings

This paper has presented a brief overview of supercapacitors and a short review of recent developments. The structure and characteristics of these power systems has been described, while research in the physical implementation and the quantitative modeling of supercapacitors has been surveyed. The pros and cons of supercapacitors can be summarized as:

Advantages	Virtually unlimited cycle life; can be cycled millions of time High specific power; low resistance enables high load currents Charges in seconds; no end-of-charge termination required Simple charging; draws only what it needs; not subject to overcharge Safe; forgiving if abused Excellent low-temperature charge and discharge performance
Limitations	Low specific energy; holds a fraction of a regular battery Linear discharge voltage prevents using the full energy spectrum High self-discharge; higher than most batteries Low cell voltage; requires serial connections with voltage balancing High cost per watt

Table 2: Advantages and limitations of supercapacitors

Super capacitors find many applications in consumer, public and industrial sectors and they are also vital in medical, aviation, military, transport (hybrid electric vehicles, trains, buses, light rails, trams, cranks, aerial lifts, forklifts, tractors and even motor-racing cars) services, energy recovery and renewable energy technologies. For the past two years, the Southeastern Pennsylvania Transit Authority has been capturing its braking energy and then selling it back into the power grid. SEPTA's initial project has been successful enough that it is launching into a second phase, with future expansions already being planned. Other electric modes of transportation, such as electric cars and trucks, are also participating in frequency regulation markets in PJM and ERCOT and finally with help from Supercapacitors, trains are providing new services to the grid (Courtesy: http://theenergycollective.com News posted on February 12, 2014).

IV. Conclusions/Discussions:

With every small family today having atleast two smartphones that are so overused and require more, more and still more charging, supercapacitors really seem a truly convincing option. Because of their flexibility, supercapacitors can be adapted to serve in roles for which electrochemical batteries are not as well suited. Also, supercapacitors have some intrinsic characteristics that make them ideally suited to specialized roles and applications that complement the strengths of batteries. In particular, supercapacitors have great potential for applications that require a combination of high power, short charging time, high cycling stability, and long shelf life. Thus, supercapacitors may emerge as the solution for many application-specific power systems. So, in a nutshell, it can be concluded that supercapacitors are indeed the very near future for all of us on globe!

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