



The construction and applications of supercapacitors

Eaton supercapacitors



Overview

The need for a fast charging and reliable source of energy storage has grown dramatically through the proliferation of IoT and mobile devices. The number of IoT end devices is anticipated to jump from the current 13.8 billion to nearly 31 billion — a more than twofold increase by the mid-2020s. These massive machine-type communications (mMTC) are defined by their low throughput and small payload wireless connectivity to accomplish high power-, size-, and cost-constrained sensor nodes. All of these devices inevitably come with the need for small form factor energy storage to meet the operational lifetime requirements of an IoT node (i.e., 2 to 10 years) with little to no maintenance or replacement of a battery. Conventional storage technologies for these platforms often revolve around coin cells utilizing Lithium or alkaline battery technologies and/or small form factor storage with high energy density, high voltage with less discharge, and rapid recharge.

Larger applications such as data centers, industrial plants, healthcare facilities, and other public areas increasingly require environmentally-friendly and quality power with little risk of downtime. For these applications, reliable sources for back-up power with only short back-up times in the event of power quality interruptions eliminate the potentially catastrophic results of power outage and downtime. While battery technology meets many of these requirements, they tend to wear out quickly in rapid cycle applications, come with a complex battery management system (BMS), and have the potential for thermal runaway, which leads to safety concerns. Electric double-layer capacitors (EDLC) (aka supercapacitors), however, offer clean energy storage without the safety concerns, do not use heavy metals, and are much simpler in terms of power management.

This whitepaper discusses the construction of supercapacitors, their principles of operation, and various applications that they are ideal for.

Supercapacitor construction

The concept of a supercapacitor stems from conventional capacitors. A basic capacitor stores energy between two conducting plates or electrodes, separated by a non-conducting region or a dielectric (e.g., glass, air, ceramic, polymer films, etc.). The ideal capacitor holds equal and opposite charges on the opposing faces of the conductors, while the dielectric composition develops an electric field. In other words, the electrolytic capacitor's energy storage is formed within an electrostatic field based on electric-charge storage.

A supercapacitor, on the other hand, stores charges at the interface between an electrode and an electrolytic solution; this interface would represent a capacitor. Electrical energy is stored as a consequence of the generation of a double layer of electrolyte ions on the electrode's surface. This double layer is composed of the inner Helmholtz plane (IHP) and the outer Helmholtz plane (OHP). The IHP is defined by the accumulation of ions close to the electrode's surface (specifically adsorbed ions), while the OHP matches the amount of charge in the electrode with dissolved and solvated ions distributed in the electrolyte that have shifted closer to the polarized electrode (non-specifically adsorbed ions). This double layer is then separated by a thin monolayer of solvent molecules acting as the equivalent of a dielectric in a standard electrolytic capacitor. The thickness of the double layer depends upon the concentration of the electrolyte, the size of the ion and the size of the solvent molecule.

Principles of operation

When a voltage is applied to the capacitor terminals, a diffuse layer forms between the OHP and the bulk of the EDLC. This, in turn, forms another double-layer, where the OHP at the opposite electrode is of equal and opposite polarity to the OHP on the other side of the diffuse layer. A two terminal supercapacitor would then be the equivalent of two capacitors in series. Due to the high electrode surface area and thin IHP and OHP, the supercapacitor essentially bridges the energy and power gap between a battery and traditional capacitors as it leverages the basic theory behind capacitors. On the other hand, it leverages a form of electrochemical storage as it stores energy between the ions of the electrolyte and the electrode in a "double layer of charge".

As shown in the equation below — the double-layer capacitance — the high surface area (S) of the electrodes and small distance (D), allows for a higher capacitance:

$$C = \epsilon_0 \epsilon_r \frac{S}{D}$$

In this equation, ϵ_0 is the permittivity of vacuum, ϵ_r is the relative permittivity of the dielectric, S is the specific surface area of the electrodes, and D is the distance between the electrodes. The electrodes are often activated carbon with a high specific surface area to increase the surface area. The solvent replaces the dielectric found in typical capacitors, and by doing so, it accomplishes an extremely small distance on the order of Angstroms between the negative and positive charges. This small charge separation distance in the double layer causes voltage ratings to be relatively low. However, stringing multiple EDLCs in series allows designers to meet the desired voltage levels for higher powered applications. Furthermore, the supercapacitor exhibits much faster charging and discharging than battery while storing much more charge than the electrolytic capacitor. Supercapacitors tend to have higher energy density but lower power density, while capacitors have higher power density but lower energy density. For the aforementioned reasons, capacitors are used as basic building blocks in the average electronic circuit. For example, in power management circuitry for power factor correction (PFC), ripple reduction, and decoupling capacitors, and in filters for RF circuits. Supercapacitors, however, are customized for one very specific purpose — energy storage.

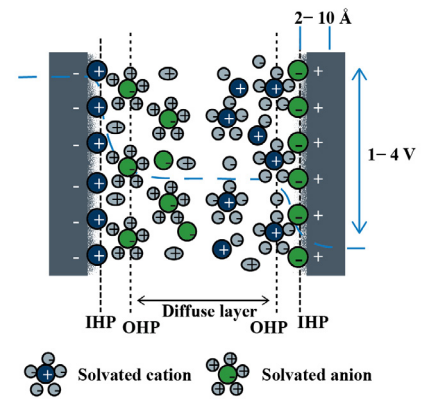


Figure 1: Diagram of EDLC illustrating the double-layer with the inner Helmholtz plane (IHP) and the outer Helmholtz plane (OHP).

Supercapacitor applications

Back-up power

Due to their high power density and long life, supercapacitors are ideal for mission-critical back-up power applications. These applications are defined by two major requirements — the ability to rapidly switch to back-up power after a power loss has occurred and the ability to maintain a power supply until longer-term back-up is engaged. Examples of longer term back-up power include traditional generators, natural gas turbines, or hydrogen fuel cells. An uninterruptible power supply (UPS) supported by supercapacitors will generally require only seconds of back-up power discharge to give time for the long term power source to start up.

Supercapacitors are also used for back-up when integrated into electronic systems. When a main power source is unstable or eliminated completely, supercapacitors can be used to ride through the power instability or provide enough time to save critical data or bring a machine to a safe position.

Outside of meeting the major parameters of rapid back-up power, supercapacitors have the additional benefit of being much more cost-effective, safer, cleaner, and lighter than their battery counterparts (e.g., valve-regulated lead acid (VRLA), absorbent gas mat (AGM) gel battery, LIB). For instance, additional cooling resources may be necessary to ensure that the batteries are operating within their safety limits.

Electronics communications

From mobile phones, wireless modems, and radio transceivers to motors, valves, and solenoids, there are numerous applications that demand short bursts of power. This can either occur with a larger battery capable of delivering a high pulse current or with a HESS composed of a smaller, energy dense battery with a small, power dense supercapacitor.

In GSM/GPRS applications, up to 2 A of current must flow from a powersource to the transceiver within a 0.6 millisecond transmit window, and higher power and longer for LTE. Supercapacitors can effectively handle the pulses while being recharged from a battery or other power source. Other parts of the design can remain low power and serviced by these other power sources without being oversized to meet the radio communications. Digital cameras require more capacitance to minimize the voltage drop during a discharge pulse. Alkaline batteries used in parallel with supercapacitors tend to extend the life of the batteries by mitigating the voltage drop that occurs at discharge.

Electric vehicles

Supercapacitors are becoming a preferred medium of energy storage in the rapidly-growing transportation market. They have a long history of providing acceleration power and recapturing braking energy in subways, trains and busses. In electric vehicles (EVs), they can be used either as sole energy storage or combined with batteries to optimize power efficiency, cost, and runtime. Due to their excellent thermal stability and wide operating temperature range, supercapacitors overcome the issues that plague lithium-ion batteries, such as battery leaks, thermal runaway, and engine cold start failures. Regenerative braking is another key EV application. With their potential to store large amounts of energy and release them very quickly, supercapacitors are ideal for capturing kinetic energy that would be dissipated as heat and converting it into electric power to recharge the EV battery.

IoT nodes

The global connection of our devices is a trend that spreads to “things,” allowing for the ability to remotely monitor (and sometimes control) devices. This has spread from industrial IoT (IIoT) with asset/process monitoring and industrial automation, to smart city, smart home, and smart grid applications. With the proliferation of IoT devices, there has also been the introduction of many IoT protocols, many of which are defined by power constraints. Low power wide area networks (LPWANs), for example, leverage proprietary narrowband modulation schemes at low payloads and data rates in order to expand the range and lifetime of a sensor node. When a company is set to deploy thousands of sensor nodes, both upfront capital expenditures (CAPEX) and OPEX from routine replacement of batteries is a serious consideration. Energy harvesting techniques are often employed in these platforms for this very reason — to minimize node maintenance.

Hybrid supercapacitors offer a good alternative to the traditional coin cell due to their high energy densities, high working voltages, as well as low leakage current and self-discharge when compared to the conventional supercapacitor, while also offering long lifetimes and cycle life when compared to the conventional battery. The conventional IoT modules with either a Bluetooth, Zigbee, or LPWAN such as LoRaWAN transceiver will operate in a power supply range from 2.1 to 3.6 Vdc and are typically powered by at most two AAA batteries or a coin cell battery. The nominal voltage at these two batteries are 1.5 V, with a capacity from 200 to 1250 milliamp hours. Eaton's HS/HSL supercapacitors offer a 3.8 V operating voltage, 500,000 charge/discharge cycles, and a typical lifetime of 10 years at the rated voltage and room temperature, all while maintaining a small form factor.

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Printed in USA
Publication No. ELX1151 BU-ELX22010
February 2022

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