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Engineering electrochemical capacitor applications

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HIGHLIGHTS

- Electrochemical capacitors are used today in a broad range of applications.
- Approaches presented for the design of capacitor storage systems.
- No single commercial product offers superior performance in all applications.

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ABSTRACT

Electrochemical capacitor (EC) applications have broadened tremendously since EC energy storage devices were introduced in 1978. Then typical applications operated below 10 V at power levels below 1 W. Today many EC applications operate at voltages approaching 1000 V at power levels above 100 kW. This paper briefly reviews EC energy storage technology, shows representative applications using EC storage, and describes engineering approaches to design EC storage systems. Comparisons are made among storage systems designed to meet the same application power requirement but using different commercial electrochemical capacitor products.

1. Energy storage background

Energy storage systems deliver energy to power an application. Examples include batteries in portable electronics like laptop computers or cell phones. Some energy storage systems act as a power source and deliver energy one moment then at a later time act as a power sink and store energy. An example is a gas-electric hybrid vehicle, where some of the vehicle's kinetic energy is captured and stored during a stopping event (regenerative braking) and later this energy is used to assist in accelerating the vehicle. Energy storage systems have been similarly implemented in many industrial applications to help conserve energy [1].

A metric popular in the literature and reported as being the "correct" one to compare energy storage systems is "energy/mass" [2]. It is often touted as being the only important parameter. In actual fact other parameters are usually more important. These other parameters may include, for instance, energy/volume, power/volume, cycle life, cycle efficiency, charge time, discharge time, energy storage cost, calendar life, self-discharge rate, principal failure mode, operating temperature range, and factors related to safety. In a given application, several of the parameters may be important with others totally unimportant. Sometimes an application has a single parameter that is critically important which, of course, will be the "correct" one to use in comparing storage systems.

Three technical characteristics often dictate which particular energy storage technology is selected for a given application: 1) energy/volume, which ultimately establishes the physical size of the storage system; 2) charge time/discharge time, which must be compatible with the intended use; and 3) cycle life, which often dictates the operational life of an energy storage system. In some applications, non-technical characteristics like cost and safety have importance equal to the technical characteristics.

Contrary to implications or statements made in many technical articles, popular-press publications, and storage product advertisements, mass-normalized characteristics (for instance energy/mass or power/mass) usually have little importance in the majority

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of energy storage applications. Volume-normalized characteristics are really much more important [2]. An energy storage system that does not fit in the available volume clearly cannot be used irrespective of its attractive mass-normalized characteristics. Nonterrestrial applications are an exception.

Practical characteristics, for instance maintenance requirements, operating-temperature range, and reliability are, in some applications, important and priority attributes used to select the energy storage technology. Environmental factors are increasingly being considered, particularly in applications involving renewable energy like wind and solar, where use of toxic or “non-green” materials in the storage system or in its manufacturing is highly undesirable.

2. Introduction to electrochemical capacitors

An electrochemical capacitor (EC), often referred to by the product names Supercapacitor or Ultracapacitor, physically stores charge in the electric double layer at a surface-electrolyte interface, primarily in high-surface-area carbon [3]. Because of the high surface area and the thinness of the electric double layer, these devices can have very high gravimetric and volumetric capacitances. This enables them to combine a previously unattainable capacitance density with an essentially unlimited charge/discharge cycle life. Operational voltage, limited by the breakdown potential of the electrolyte, is usually <1 or <3 V per cell for aqueous or organic electrolytes respectively.

The concept of storing energy in the electric double layer that is formed at the interface between an electrolyte and a solid has been known since the late 1800s. The first electrical device using double-layer charge storage was reported in 1957 by H. I. Becker of General Electric [4]. Unfortunately, this device was impractical in that, similarly to a flooded battery, its electrodes needed to be immersed in a container of electrolyte. It was never commercialized. Becker did, however, appreciate that large capacitance values were possible that subsequently were reported by R.A. Rightmire, a chemist at Standard Oil of Ohio (SOHIO), to whom can be attributed the invention of the device in a format now commonly used. His patent [5], filed in 1962 and awarded in late 1966, and a follow-on patent by fellow researcher D.L. Boos in 1970 [6], form the basis for the many thousands of subsequent patents and journal articles covering all aspects of electrochemical capacitor technology. This technology has grown into an international industry with annual sales of several hundred million US dollars that is poised for continued rapid growth near term primarily in the many emerging transportation applications and explosive growth long term after expansion into electric power grid applications.

Following the commercial introduction of NEC's Supercapacitor in 1978 under license from SOHIO, ECs have evolved through several generations of designs [7]. Initially they were used as dc power devices for volatile clock chips and complementary metal-oxide-semiconductor (CMOS) computer memories. But many other applications have emerged over the past 38 years. Early electrochemical capacitors were generally rated at a few volts and had capacitance values measured from fractions of farads up to several farads. The trend today is for cells ranging in size from mF-size devices with exceptional pulse power performance when compared with batteries up to devices rated at thousands of farads, with systems in some applications storing several million Joules of energy and operating at voltages as high as 1000 V. Today kF is a common and very practical unit for capacitance.

In the past electrochemical capacitors tended to live “in a world of their own”, as their properties and performance differ so greatly from other capacitor types. They have a capacitance per unit volume or weight that is unmatched by any other technology. Most ECs are totally unsuitable for ac line-filtering applications since they cannot charge or discharge sufficiently fast to operate at 120 Hz [8]. However, most can charge and discharge much more rapidly than any battery technology, including today's high-power lithium-ion battery products. As a result, ECs are often used in applications having rapidly varying load power profiles, as encountered in hybrid electric vehicles. ECs have even been used as battery replacements in some limited applications [9]. ECs have their own spectrum of optimal applications that component engineers have only recently begun to exploit [10]. This paper shows representative example EC storage applications and describes engineering approaches for the design of electrochemical capacitor energy storage systems.

3. Electrochemical capacitor application examples

It is convenient to sort energy storage systems into three types, which are dc, pulse, and bidirectional. A dc energy storage system only delivers power, i.e. it is discharged by the application. The depletion rate can vary with time but stored energy continually decreases. One example of a dc energy storage system is the battery in a cellular phone. It is periodically charged but while in use, only delivers power.

The flashlight in Fig. 1 has a dc energy storage system that uses several 100-F-size electrochemical capacitor cells to power light-emitting diodes. There is a two-position light intensity switch (providing approximately two or 4 h of operation), a standard USB port for charging the capacitors, and solar cells to trickle-charge the capacitors to maintain them at full charge. Advantages of using electrochemical capacitors over, for instance, secondary batteries includes providing the ability to rapidly recharge the energy storage system (in about a minute) and greatly extending the flashlight's operating life with no maintenance [11].

A pulse energy storage system delivers power intermittently, sometimes at very high rates. Power is delivered as a single pulse in some applications while in others power is delivered as a train of repetitive pulses. Again stored energy monotonically decreases with time. An example is the SLI (Starting-Lighting-Ignition) battery used in a conventional internal-combustion-engine automobile. When this battery cranks an engine, power is delivered to the starter motor in a high-power pulse, typically lasting less than 1 s. Usually only a single pulse is required to start the engine. The SLI battery also serves a second function, which is to provide dc electrical power for lighting and ignition.

The Rockster R1100DE rock crusher shown in Fig. 2 has a hybrid power system [12]. Part of the power is provided by a diesel generator. The remaining power is provided by an electrochemical capacitor energy storage system, including the very high power peaks encountered in this application. Stored energy “load levels” the power, that is, the capacitors supply power to meet high-frequency features in the power profile while the internal combustion engine supplies power to meet low-frequency and dc features. The storage system in this equipment is exposed to an

Fig. 1. Flashlight with electrochemical capacitor energy storage. A switch selects the LED light output level.