Advanced Electrochemical Capacitors for ASD Ride-Through and UPS Power Conditioning Applications

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Abstract

This paper discusses the characteristics and advantages of advanced-design electrochemical capacitors that make them well suited for ASD ride-through and UPS power-conditioning applications. It discusses the results of bench-testing a 11,000-F, 1-MJ capacitor and presents the preliminary test results from the integration of an advanced-design, 400-V electrochemical capacitor with an existing boost converter-based, embedded ride-through solution for AC motor drives. Application within a UPS and test results are also briefly discussed.

Overview

Energy storage is not new. In fact, the flywheel, in the form of the potter's wheel, is the oldest known energy storage device dating back to antiquity. Storing energy for use at a later time makes sense from several viewpoints—economics, resource utilization, pollution control, and efficiency. The necessity of energy storage arises because the demand for energy is not constant over time. Sometimes we demand more energy than is available; at other times, available energy is not needed. The central-station power plant typifies this situation as most electric utilities experience daily, weekly, and seasonal demand.

Without a doubt, the king of energy storage is the lead-acid battery. Used in applications as diverse as the starting of automobiles, powering of electric trucks (forklifts), and backup energy during power outages, the market demand for lead-acid batteries has created an industry expected to reach $5.8 billion dollars by the year 2003 [1]. It has been the clear choice for medium- and high-power applications because of characteristics such as high current capability, operation over a wide operating range, good charge retention, and low cost of materials and manufacture. However, the technology is not perfect. Limited cycle-life, slow time to recharge, and reduced life with elevated temperature have stunted the growth of new applications for central station and transportation, which have stringent cost and life requirements for energy storage. Something better is needed.

A possible alternative is the electrochemical capacitor. Owing to recent advances in design, electrochemical capacitors now have more energy storage and power capability than ever before. So much, in fact, that they are being compared with lead-acid batteries. Applications that were once thought solely within the domain of batteries are now being reexamined. Engineers are now asking, "Does it make sense to use an electrochemical capacitor instead of a battery? What new applications, which, prior to this technology advancement, were not possible, are now possible?"

What Is an Electrochemical Capacitor?

While traditional capacitors are rated in fractions of a Farad, electrochemical capacitors are rated in Farads or even thousand of Farads. And, the energy density is not fractions of a Joule[1], but thousands of Joules.

[1] One Joule equals one watt-second [1 W-sec.]

Often referred to as “Supercapacitors” or “Ultracapacitors,” both of which are trademarked[2], electrochemical capacitors are devices that store electrical energy as charge separation in porous electrodes with very high surface areas [2]. They are true capacitors in that energy is stored via charge separation at the electrode-electrolyte interface, and they can withstand millions of charge/discharge cycles without degradation. They are also similar to batteries in many respects, including the use of liquid electrolytes and the practice of configuring various-sized cells into arrays to meet the power, energy, and voltage requirements of a wide range of applications.

Within electrochemical capacitors, charge is stored electrostatically, not chemically as in a battery (see Figure 1). They have an electrolyte solvent, typically potassium hydroxide (drain cleaner) or sulfuric acid (both aqueous electrolytes), and consist of two capacitors connected in series via the electrolyte. They are often called double-layer capacitors because of the dual layers within the structure, one at each electrode.

In an electrochemical capacitor, the physics of capacitance has not changed. As in any capacitor, the amount of capacitance is directly related to the surface area of the electrode. What has changed is the surface area of the electrodes. Specifically, the surface area of a carbon electrode is an amazing 1,000 to 2,000 m^2 per gram. To give a better idea of this size, it is approximately the figurative equivalent to stuffing a baseball field into a baseball glove!

Carbon is the element almost uniquely suitable for fabrication of electrodes within electrochemical capacitors. When fabricated into felt or woven into a fabric, it makes an excellent electrode structure with good mechanical integrity and electrical conductivity.

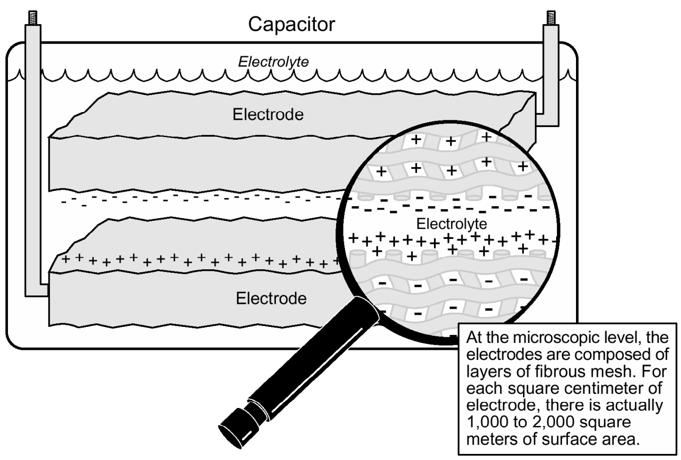


FIGURE 1~~1~~. REPRESENTATIVE CONSTRUCTION OF AN ELECTROCHEMICAL CAPACITOR WITH A DOUBLE LAYER.

Technology Breakthrough

In the past, due to limited energy storage and the inability to supply significant amounts of power, electrochemical capacitors were relegated to low-power applications such as memory backup for personal computers and real-time clocks within microwave ovens. With more energy than a traditional capacitor, but less than a battery, they fit between the two technologies. Now, electrochemical capacitors are available for a variety of high-power applications such as an energy source for fork trucks, replacement of UPS batteries, and ride-through for adjustable-speed drives [3]. Figure 2 shows an electrochemical capacitor designed for traction applications. It is rated at 11,000 Farad and 1 MJ (mega-Joule) within the voltage window of 16-8V.

[2] The term Supercapacitor is trademarked by the NEC Corporation, while the term “Ultracapacitor” is trademarked by Maxwell Technologies Incorporated.

Conventional capacitors, such as the aluminum-electrolytic type, are power-rich and energy-poor. In other words, high voltages and current are available, although for very short times. Electrochemical capacitors change this. Owing to the large surface area of the electrode, electrochemical capacitors have the ability to supply large currents, as a conventional capacitor, but they also have significant energy storage, like a battery. Specifically, conventional capacitors have an energy density (Watt-hours/kg) of < 0.1, but electrochemical capacitors have an energy density range of 1 to 12. Batteries have an energy density range of 20 to 100 [4].

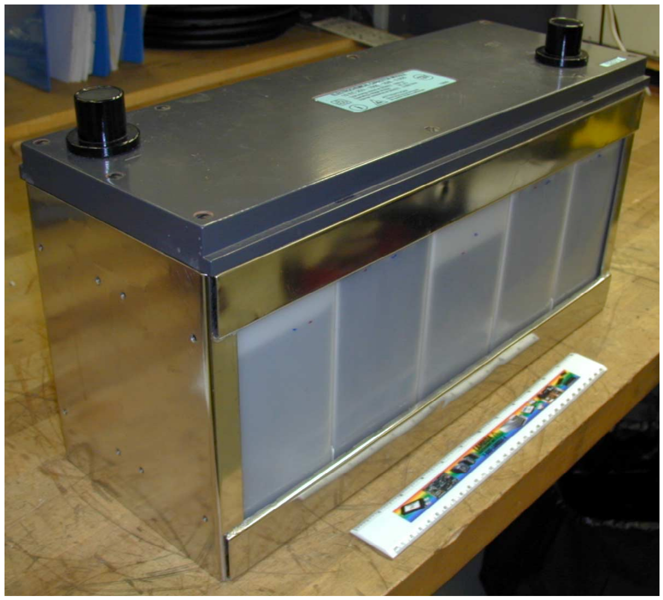


FIGURE 222. FIGURE 333. A 11,000 F, 1 MJ, 16-8 V CAPACITOR (SHOWN WITH TWELVE-INCH RULER).

Some key features of electrochemical capacitors include:

- Highest capacitance density of any capacitor technology
- Lowest cost per Farad
- Reliable, long life
- High cycle-life
- Maintenance-free operation
- Environmentally safe
- Wide operating temperature range
- High power potential

Do They Work?

EPRI PEAC has tested and verified that advanced-design electrochemical capacitors do meet manufacturer claims [5]. As shown in Figure 3, EPRI PEAC was able to verify the performance of a capacitor designed for traction applications (see Figure 2) as the load was varied from 0.1 ohm to 0.8 ohm (120 A peak and 20 A peak, respectively). EPRI PEAC confirmed the capacity as advertised by the manufacturer. Capacity with temperature and equivalent series resistance (ESR) was also measured and found to be within specification. Both a 1-MJ (11,000 F) capacitor at 16 V and a 35-kJ (0.44 F) capacitor at 400 V are a reality.

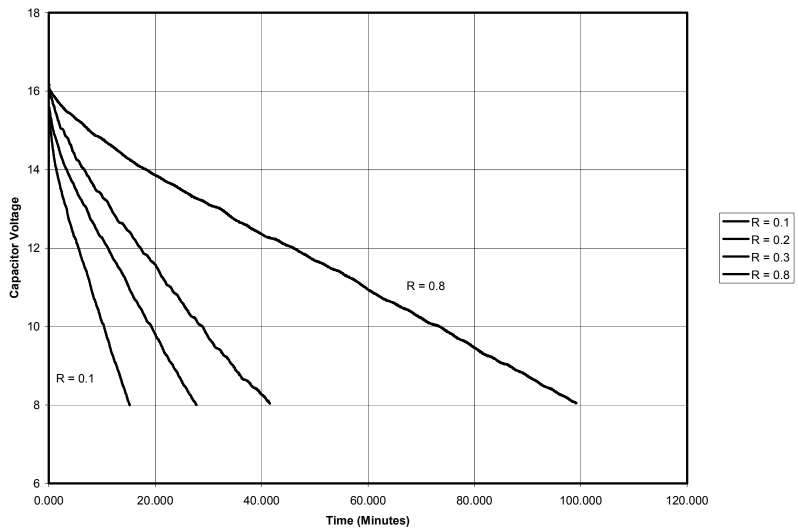


FIGURE 444. PLOT SHOWING RUNTIME VERSUS LOAD FOR A 11,000-F, 1-MJ CAPACITOR.

Electrochemical Capacitors for ASD Ride-Through

With the increasing use of ASDs in industry, concerns about the undervoltage susceptibility of these power electronic devices have also dramatically increased. When ASDs trip during voltage sags and momentary interruptions, the downtime-related costs can be extremely high. Therefore, increasing the ride-through capability of ASDs during voltage sags and momentary interruptions is vital to the industries that rely on them.

ASD programming features, such as automatic restart and undervoltage ride-through, will likely be insufficient alternatives for precision processes trying to survive or ride through a voltage sag or momentary interruption [6]. Even though the drive may not trip off line, the ride-through programming features will most likely cause unacceptable speed and torque deviations in the process, which may result in a lost product or reduced product quality. Therefore, alternative ride-through techniques must be applied to allow the drive and the process to ride through undervoltage events. The boost converter combined with the energy storage of an electrochemical capacitor is one such ride-through alternative.

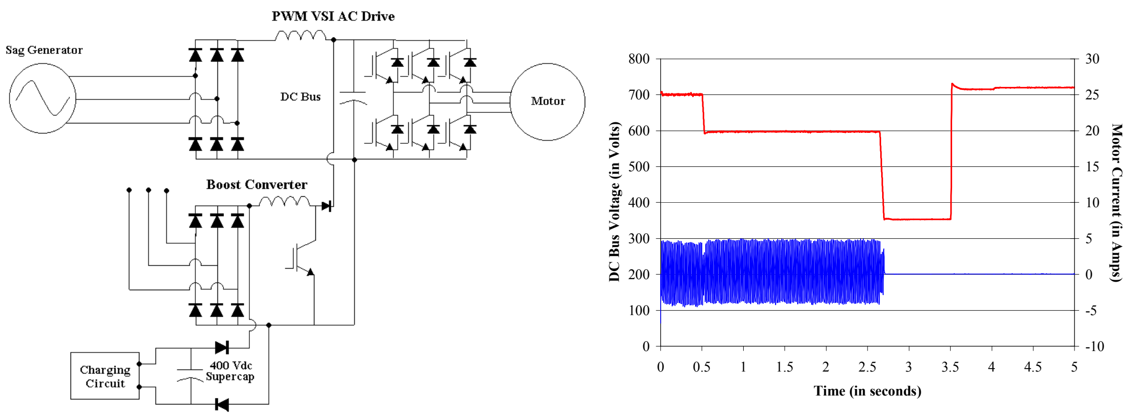
The boost converter is a DC-to-DC converter that increases, or boosts, one DC voltage level to a higher DC voltage level. For the application of increasing the ride-through of voltage-source inverter (VSI) AC drives, the boost converter attempts to hold the drive's DC bus voltage above the undervoltage trip point. The boost converter connects directly to the DC bus of the drive, as shown in Figure 4. In most applications, the control circuitry of the boost converter will sense the drive's DC bus voltage. When the DC bus voltage drops to approximately 90% of nominal (user-selected operating point), the boost converter begins operation to maintain the DC bus voltage at 90% of nominal. Otherwise, it remains in an idle state. Boost converters are usually sized to permit full-power ASD ride-through for voltage sags down to 50% of nominal. One way to increase the effective range of ride-through is by adding an energy-storage element. The boost converter uses the energy-storage element rather than the utility source to support the drive, as shown in Figure 4. Batteries, flywheels, and various capacitor technologies are examples of readily available energy-storage options.

ASD Testing of Electrochemical Capacitors

Sponsored by EPRI, some preliminary evaluations were conducted on a 400-V electrochemical capacitor. One of the objectives of the evaluation was to assess the feasibility of using an electrochemical capacitor as the energy-storage element for a boost converter applied to a VSI AC drive to increase its ride-through. The evaluations were conducted by EPRI PEAC Corporation at its Power Quality Test Facility (PQTF). A 400-

V electrochemical capacitor and a boost converter were connected to the DC bus of a 5-HP, 460-V VSI AC drive, similar to the diagram in Figure 4. The drive and motor were loaded to 75% of full-load with an eddy-current-brake dynamometer, and a 3-second, 3-phase momentary interruption was initiated with a sag generator. The ASD DC bus voltage and the motor current were all recorded during the test and are illustrated in Figure 4.

The results show that the boost converter was able to sustain the DC bus voltage at 600 Vdc for approximately 2.1 seconds during the interruption with energy stored in the electrochemical capacitor. At the 2.6-second mark in Figure 6, the boost converter stopped operating and the DC bus voltage fell to the undervoltage trip point, prompting the drive to trip. Due to its limitations, the boost converter was only able to utilize the energy in the electrochemical capacitor until the capacitor voltage dropped to 350 Vdc. This resulted in the use of only 23.4% of the electrochemical capacitor's stored energy. Modifications to the boost converter's power-conversion components would allow the converter to operate over a wider range of capacitor voltage, thereby increasing the amount of energy drawn from the capacitor and increasing the duration of ride-through for the drive.



(a) (b)

FIGURE 555. (A) AN AC DRIVE WITH EXTERNAL BOOST CONVERTER AND ELECTROCHEMICAL CAPACITOR. (B) DC BUS VOLTAGE AND MOTOR CURRENT.

UPS Applications

For short runtimes (up to ten minutes), an electrochemical capacitor may serve as a cost-effective alternative to batteries. Figure 6 compares the power and energy density of a typical UPS battery (lead-acid) with a high-performance electrochemical capacitor. At low discharge rates, the energy density of the lead acid batteries is about 2.5 times greater than the capacitor. However, at high discharge rates, the energy density is roughly equivalent. So, for long discharges, the lead-acid battery clearly offers better performance. But, during fast discharges, due to the additional considerations such as maintenance-free operation and high cycle-life operation, the electrochemical capacitor has better performance.

It is important to note that while the voltage of a lead-acid battery is relatively flat during discharge, voltage on a capacitor decreases at an exponential rate. Because of this, power electronics are needed to take the energy out of the capacitor.

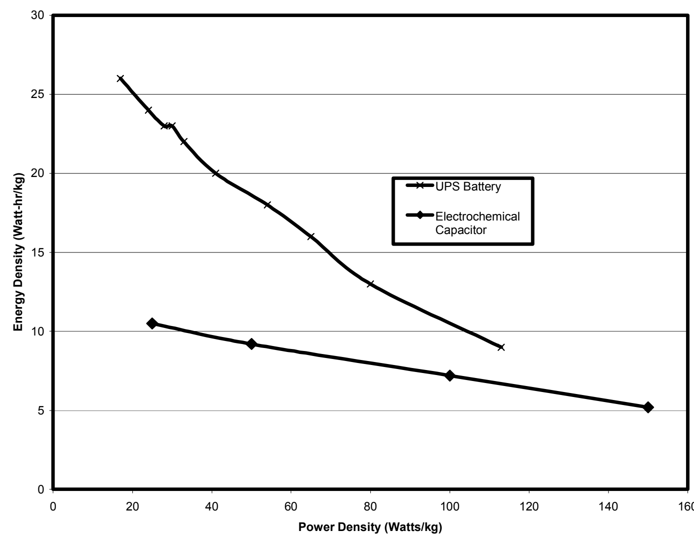


FIGURE 666. COMPARISON BETWEEN A UPS BATTERY (LEAD-ACID) AND AN ELECTROCHEMICAL CAPACITOR.

EPRI PEAC tested electrochemical capacitors within a UPS. The UPS was cycled over 3000 times without measurable decrease in capacity. This compares to an expected cycle-life of 600 for lead-acid batteries.

Conclusion

Electrochemical capacitors are ready for use in power-conditioning applications. In many applications, electrochemical capacitors may be more cost-effective and more practical for power-conditioning applications that were traditionally based on lead-acid batteries or standard electrolytic capacitors.

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