

A Backup Power System Using Ultracapacitors

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Transforming a series of ultracapacitor cells into a power source requires attention to cell balancing, packaging, power electronics and system integration.

Backup power systems are an integral part of most, if not all, mission-critical installations. Services as varied as data centers, communications networks and plant operations rely on continuous availability of quality power. Small backup systems traditionally rely on batteries for energy storage, while larger systems may use a generator set (genset) or more exotic systems such as flywheels, superconducting magnetic energy storage, or more recently, fuel cells.

However, each of these technologies has limitations. Batteries are notoriously unreliable, flywheels have needed more maintenance than originally thought, and generator sets and fuel cells have poor turn-on response. A relatively new technology is now available that is ideally suited to the backup power market: ultracapacitors. Used alone or in concert with longer-term energy sources, such as gensets or fuel cells, ultracapacitor systems are proving to be the next wave in high-reliability backup power.

Why Ultracapacitors?

Ultracapacitors are best suited to mission-critical environments that require relatively short power support. Installations that need on the order of 60 sec of support, whether to simply buffer poor power transients, perform an orderly shut down or to transfer to a secondary source (e.g., a genset or fuel cell), can make excellent use of ultracapacitors, particularly because short outages can be totally served by the ultracapacitor system, relieving the genset from having to come on at all.

Ultracapacitors are reliable devices because of their composition and construction. The energy-storage mechanism of an ultracapacitor is a highly reversible process, relying on the movement of ions within an electrolyte. Unlike a battery, an ultracapacitor doesn't make or break chemical bonds. Therefore, it's capable of fast response and

can deliver hundreds of thousands of complete cycles with minimal change to performance. A cycle life of more than 500,000 cycles has been demonstrated with minimal degradation.

Furthermore, cycle depth isn't an issue, so ultracapacitors can be micro-cycled (cycled less than 5% of their total energy) or full-cycled (cycled greater than 80% of their total energy) with the same long life. The highest performance ultracapacitors use advanced organic electrolytes that provide excellent conductivity to temperatures as low as -40°C and stable operation to 65°C. The best ultracapacitors are constructed of hermetically sealed packages, preventing the electrolyte from drying out.

There are no mechanical moving parts as in a flywheel, eliminating all maintenance. These electrical, chemical and mechanical features give the ultracapacitor long operational life and long shelf life with no degradation.

Energy-storage-system design, whether using ultracapacitors, batteries or other devices, requires a consideration of numerous requirements. The application defines the external considerations of system voltage range, packaging, and input and output power ratings. The designer defines the internal considerations of cell balancing, power electronics control for charging and discharging and thermal management.

Ultracapacitor Cell Balancing

Ultracapacitors, like batteries, operate on a "cell" basis—each ultracapacitor "cell" operates at a low voltage (ranging from 1 V to 2.5 V, depending on the chemistry) and must be placed in series to reach an appropriate voltage for the application. For example, a system using 2.5-V cells operating at a maximum of 50 V would require 20 cells in series. In a perfect world, each cell would behave the same as all the others and the voltage would divide equally across the 20 cells.

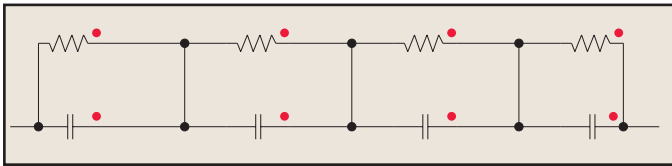


Fig. 1. Passive cell balancing with resistors.

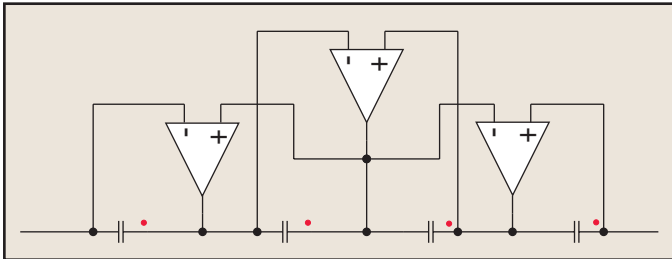


Fig. 2. Active cell balancing model.

The realities of manufacturing result in minor variations from cell to cell. This is true with batteries as well as ultracapacitors. Variations in capacitance and leakage current, both on initial manufacture and over the life of the product, affect the voltage distribution. Capacitance variations affect the voltage distribution during cycling, and voltage distribution during sustained operation at a fixed voltage (such as in backup applications) are influenced by leakage current variations. A cell management circuit maximizes the performance and life of ultracapacitor cells installed in series.

Cell balancing is the most effective method of managing series ultracapacitor cells. (Another method of cell management simply discharges overvoltaged cells, which protects the cells but leaves other performance issues unresolved.) A robust cell balancing circuit provides fast response to out-of-balance cells, while adding minimal parasitic leakage current when the cells are in balance. Two methods balance cells: passive and active.

Passive balancing is most appropriate in low duty-cycle applications that can tolerate higher leakage, such as in backup power systems. A passive balancing system is designed to overwhelm the inherent variations in leakage current by installing a resistor in parallel with each cell. The resistor is typically sized at 10 times the average leakage current of the cell. The benefits to this balancing method are simplicity and low cost. The drawback of this technique is slow response due to the linearity of leakage current with voltage and high parasitic losses due to the 10-times additional leakage current.

Fig. 1 shows a simple passive balancing network. Because of the higher leakage current and slow response, passive balancing solutions are not appropriate for high duty-cycle applications, such as dynamic load leveling, nor in standby applications where the higher leakage current could jeopardize the backup energy source.

An active balancing circuit is required in high duty-cycle applications and where low parasitic losses are necessary. They may be used anywhere a passive system is used, cost

notwithstanding. In contrast to passive solutions, an active balancing circuit behaves nonlinearly and works to force the cells to have equal voltage, resulting in the most effective use of the ultracapacitor string. A number of schemes are used to achieve active balancing, and many are patented or patent pending.

Active balancing circuits can be fairly simple and elegant, or complex. The benefit to active balancing is fast, accurate equalization of the voltage distribution and minimal parasitic losses. The drawback is higher cost. Fig. 2 shows a simplified diagram of an active balancing circuit incorporating a comparator. Note that in this configuration, each circuit stretches across two cells, comparing their voltage and moving charge to equalize the two cells, while other active circuits may be configured differently.

Ultracapacitor System Packaging

Packaging ultracapacitor cells requires the same design considerations as packaging series strings of batteries and other electrical components. The major difference is the larger number of interconnects; whereas many batteries are available in 6-V and 12-V increments, for example, ultracapacitors are more often available in single-cell increments of 1 V to 2.5 V. Some manufacturers are making ultracapacitor modules available at higher voltages. However, the most flexibility to the power electronics designer is found by using individual cells and tailoring the system design more precisely.

When integrating ultracapacitor cells into a system, you must consider an assembly that ensures proper mechanical support, minimizing intercell stress. Interconnects, or bus bars, should be of compatible materials to avoid galvanic corrosion, with the possible addition of an appropriate joint compound. Bus bars should be large enough in contact area with the ultracapacitor terminal, and in cross-sectional area, to minimize added resistance. Cells and interconnects should be properly isolated, whether by using insulating materials or appropriate stand-off distances.

In high duty-cycle applications, some mechanism to cool the cells, whether by air cooling the cells directly or conducting the heat to some type of heat exchanger, is necessary to maintain the ultracapacitors within rated operating temperatures. As with any component, proper installation requires following the manufacturer's instructions. For example, threaded terminals should be tightened to no more than the manufacturer's torque recommendation.

Fig. 3 shows a typical assembly of cells. Note the bus bars, the intercell insulation, the integrated cell balancing circuits, and the proper torque and hardware.

Ultracapacitor Charging

Charging ultracapacitors is one of the simpler aspects of power management. Assuming you have integrated a decent cell balancing circuit, an ultracapacitor bank can be charged with almost any source, so long as the applied

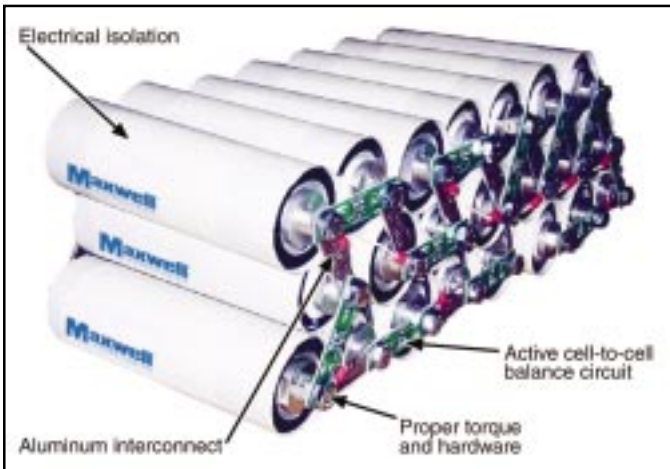


Fig. 3. Packaging.

voltage is less than or equal to the maximum rated bank voltage. Constant current and constant power sources work well, and the ultracapacitor can tolerate high charge currents, as long as thermal management considerations based on duty cycle are included.

The main consideration for charging will be externally driven: How much charge power is available from the application? In some installations, full utility power may be available, enabling fast recharge. In other installations, the unit may be sharing power with the critical load that it is protecting and, therefore, must limit its recharge power so as not to overload the very system it's supporting. The system designers can account for these specific installation requirements in their choice of power levels for the charger.

The specifics of the power-supply architecture are left to the designers' discretion, as long as the supply can provide current into a low resistance load. The ultracapacitor's impedance is so low that a power supply that contains short-circuit fault detection may trip, going into a current limit mode and limiting the recharge time of the system. As long as the supply can feed a near-short and has an output voltage that is limited to the ultracapacitor bank's maximum voltage, almost any supply architecture should work.

Ultracapacitor Power Delivery

Ultracapacitors deliver energy by reducing the electrostatic field across the electrolyte. When this occurs, the voltage on the ultracapacitor drops. Ultracapacitors obey the standard capacitor law for energy storage:

$$E = \frac{1}{2} C * V^2$$

When an ultracapacitor must deliver 75% of its energy, it must be discharged to 50% of its initial voltage. Most electronics are designed to operate in a narrower range than 1:2. A narrower range can be accomplished by using more ultracapacitors or by incorporating power electronics. More ultracapacitors provide more stored energy so the energy actually needed can be extracted without deeply discharging the ultracapacitors. However, this comes at the cost of additional unused capacity.


For installations that require a narrower voltage range or that wish to discharge greater than 75% of the ultracapacitor's energy, power electronics can be used in between the ultracapacitor and the load, providing a more manageable voltage range to the load.

A dc-dc converter can narrow the voltage range experienced by the rest of the power system. The input to the dc-dc converter will be the wide operating voltage range of the ultracapacitor. The output will be the narrower (perhaps even constant) dc voltage required by the load. This allows the ultracapacitor to be deeply discharged, while providing a relatively constant voltage to the load.

Fig. 4 shows two discharge curves, one with and one without power electronics. In this particular design, 22 cells were used in series for a system voltage of 56 V (2.54 V/cell). In this installation, the minimum voltage the load could tolerate was 40 V. This meant only 45% of the energy could be delivered to the load if only ultracapacitors were used (discharging from 56 V to 40 V). This is graphically depicted by the solid blue line.

Integrating a dc-dc converter, the output voltage can be isolated from the ultracapacitor voltage, enabling a much deeper discharge without exposing the load to excessively low voltage. This is depicted by the green line in Fig. 4. While the ultracapacitors discharge to 20 V (dotted blue


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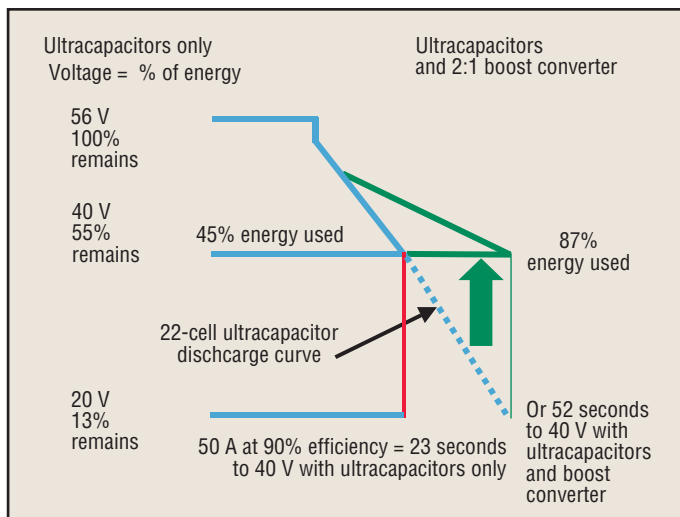


Fig. 4. Discharge curves for ultracapacitors with and without power electronics.

line), the actual output is limited to no less than 40 V (solid green line). The system can now deliver 87% of its energy while delivering acceptable voltage to the load.

Once the basics of cell balancing, charging and discharging of ultracapacitors are resolved, the system can be integrated into a product. Because the ultracapacitor is expected to last for up to 10 years, the balance of system should be designed with enough margin to match this performance because the overall system will be only as reliable as the least reliable component.

Within the unit, enclosures, cooling paths, thermal management and modularity all contribute to a robust design. Power devices must have adequate voltage and current ratings, particularly for the high current that an ultracapacitor can deliver during a fault.

A higher-level consideration is total system redundancy. In mission-critical applications, it may be desirable to service or swap out a faulty unit without disabling the entire system. In this case, an $N + 1$ architecture may be useful. The designer must then consider the costs and benefits of using smaller versus larger backup power systems. For example, where a single 4-kW system may be warranted, the designer may elect to install three 2-kW systems in an $N + 1$ configuration, allowing any one of the units to be swapped out and giving a 50% safety factor for faults.

A Design Example

Reviewing a production design will drive home the value of these design considerations. Maxwell Technologies is producing an ultracapacitor-based backup power solution, the PowerCache 48 V-1.6 kW. It is a 4-U rack-mounted unit with integrated cell management, charger, power electronics and cooling, designed to be an $N + 1$ plug-and-play system for 48-V telecommunications installations. It provides more than 30 sec of power at 50 A and is charged directly from the installation's 48-Vdc bus.

Fig. 5 illustrates the simplicity of this well-integrated

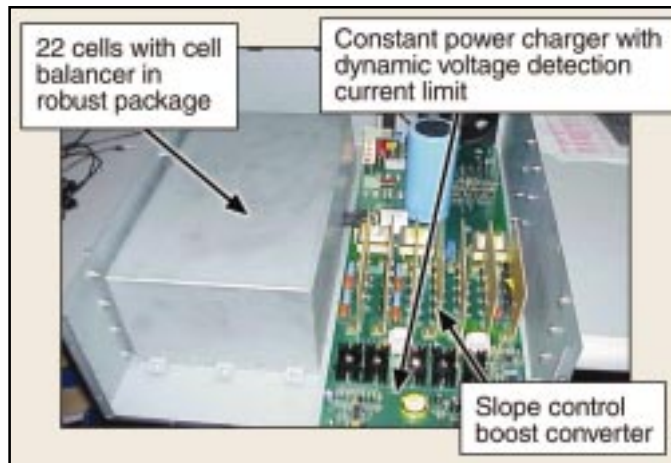


Fig. 5. System design of the PowerCache 48 V-1.6 kW.

design. On the left is a separate internal enclosure containing 22 cells with integrated cell balancing circuitry. The ultracapacitor enclosure contains the assembly previously shown in Fig. 3. It is fully enclosed because the duty cycle for this application is so low, the thermal mass of the ultracapacitors so high, and the relative power rating so low, that the ultracapacitors never need active cooling.

On the right is a single power board with both charger and dc-dc converter sections. The charger is a switch-mode buck converter that draws energy from the 54-Vdc input bus to charge the capacitors. It draws 20 A of input current and converts it to constant power output. The capacitors would receive 54 A of charge current at 20 V, tapering off to 20 A at 54 V. This provides a significantly shorter recharge time when compared to constant current charging.

The dc-dc converter provides the functionality as shown in Fig. 4. The output converter is a boost mode converter profiled to simulate a battery supply. When the bus voltage supply fails, the capacitors will direct drive the dc bus through the boost converter diodes. As the capacitor voltage discharges to 46 V, the boost converter starts operating to step up the capacitor voltage. The boost converter will allow the capacitors to discharge to 20 V while keeping the output bus at 40 V. The slope regulation automatically allows several units to operate in parallel without any current or voltage sensing. It also allows the user to know the exact run time available based on the bus voltage.

Note the fan at the rear of the unit, which draws air across the electronics. Although this is a low duty-cycle application, the size of the power electronics is small to keep the cost down. Thus, the power density is high, requiring active cooling to ensure long life.

Ultracapacitors are long-lived, reliable components. Thorough systems design, incorporating considerations of cost, application constraints and architecture options ensure that the final system is as long-lived as the ultracapacitor itself.

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