What is an Ultracapacitor?

An ultracapacitor, also known as supercapacitor or double layer capacitor, is an energy storage device which utilizes high surface area carbon to deliver much higher energy density than conventional capacitors.

Ultracapacitors are also known as supercapacitors or double layer capacitors.

They store energy similar to traditional capacitors. The main difference being the high surface area achieved by using a carbon based electrode.

Since capacitance is directly proportional to surface area, this increase in surface area allows capacitance ranges up to several thousand farads.

Basic Theory:
- Capacitance is proportional to the surface area of the carbon, divided by the charge separation distance (\( C \propto \frac{A}{d} \))
- As area (A) ↑, and charge distance (d) ↓, capacitance (C) ↑↑↑
- \( C = \frac{dI}{dV} \)
- ESR = \( \frac{dV}{dI} \)
- Charge stored: \( Q = CV \)

Basic Electrical Model:
- Electric Double Layer Capacitor (EDLC)
What is an Ultracapacitor

- The aluminum foil is used to get charge into and out of the carbon charge storage.
- The carbon is highly porous giving a massive charge storage area (1000s of m²/gram).
- Charge transport is by movement of ions in the electrolyte which can pass through the separator.
- There is no dielectric, ions in the electrolyte are next to ions at the carbon surface, so charge separation distance is in the order of Å.
- Massive charge storage area/minute charge separation distance = supercapacitance.
- Multiple layers are stacked and connected in parallel for low ESR.
- The more layers the lower the ESR and higher the C.
- Thicker carbon can be used for more capacitance.
- No chemical reactions take place during charge/discharge unlike a battery.

Typical surface area for carbon is in 1000-2000 m²/gram.
Since no dielectric is used, charge separation is in the order of angstroms.
Since no chemical reaction is taking place the life expectancy of these cells are stated in 10 years or hundreds of thousands of cycles.
Carbon electrodes are tailor made for achieving higher capacitance or lower ESR.

Main advantage of these devices are:
- Long life
- High Power Density
- Wide Temperature Range

Current Challenge:
- Low cell voltage
- Low Energy Density
- Cost

Ultracapacitors fill in a gap between traditional capacitors and batteries.
They provide a higher energy density than traditional capacitors, and higher power density compared to batteries.
With the long life capability, it provides a good solution for short-term high power applications.
One main difference between batteries and ultracapacitors is in their discharge curve.

Batteries tend to have a flat discharge curve, whereas ultracapacitors have a linear drop in voltage as power is delivered.

Because of this difference, designers need to allow for maximum voltage swing on the ultracapacitors in order to extract the energy stored. Typically dropping the voltage by 50% will allow removing of 75% of the energy.

Even though ultracapacitors are not a direct replacement for batteries in most applications, they do fill a power gap that exists between traditional capacitors and batteries.

In some applications, they replace batteries, while in some they are used to complement batteries and allow for the use on smaller or less powerful batteries.

The combination of batteries with ultracapacitors has shown drastic increase in battery life in some high power application.

As can be seen in this spider chart, ultracapacitors are strong in power density, power cost, safety, environmental, charge acceptance, efficiency and cycle stability.

These are some typical attributes where traditionally batteries are challenged.
No energy storage solution in the market can achieve the high energy and power density combined.

Fuel cells are one of the most energy dense solutions available. Their challenge is in quick burst power and startup time. This is why the combination of Fuel cells with ultracapacitors is very natural and provides for a perfect energy storage solution (if cost was not a factor!)

A more economical solution is the combination of lead acid batteries with ultracapacitors.

Typical applications are:

- Secure power—where immediate backup power is needed for critical applications
- Energy Storage—where energy is stored from low power medium and supported for high power loads.
- Pulse Power—used as a buffer with low power energy sources to provide peak power demands

Industries served:

- Transportation—HEV, rail, buses, truck, crane, etc. To augment main the engine to reduce high power demand and increase efficiency.
- Industrial—AMR, wind turbines, emergency lighting, etc. To act as main energy source for applications needing high reliability sources, or to augment existing low power energy sources in case of AMR.
- Consumer Electronics—digital cameras, mobile phones, tovs, wireless remote control and PDAs.
### Applications- AMR

**Function**
- Back up power in case of power failure
- Current for burst transmissions (1-2 Amps)

**Advantages**
- Excellent performance over wide temp. range
- High cycle count
- Long life – 10yrs
- Maintenance free
- Green vs. Batteries

**Product**
- PB, PBL, PBF and customs

**Related**
- Burst transmission, Sensors, alarms, gps...
- Dying Gasp, SSD, USB, Battery replacement

### Applications: Access and Security

**Function**
- Supply power to motors and actuators during power disruption
- Supply power to alarm

**Advantages**
- Redundant local power
- Reduction in cabling
- Weight reduction
- Built in active or passive balancing

**Product**
- TPL, custom PB/PBLL Modules

### Applications: UPS

**Function**
- Short term bridge power in case of power drop-out / glitches
- Buffering against voltage sag – high value mfg
- Graceful power down – robotics, medical, actuators
- Power for material delivery. Track with recharge.

**Advantages**
- Ultimate in reliability – no maintenance
- Integrated solution, replaces external UPS
- Wide temperature range
- Fast energy in case of emergency

**Product**
- TPLS

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In this application, the cells are used as a backup source to power an actuator or alarm in case of power outage or emergency. Advantage is in long life, reliability, and small foot print.

The cells are used as short-term backup solution and also a buffer against any voltage sags. Advantage is in their ability to provide fast response to outages, extended operating temperature, and reliability.
End of Life & Failure Modes

- In general ultracapacitors do not have a hard end of life failure similar to batteries.
- Their end of life is defined as when the capacitance and/or ESR has degraded beyond the application needs.

Failure under typical use condition:
- Over voltage
- Loss of capacitance
- Increase of ESR
- Bulging
- Possible venting

Failure under Abuse Conditions:
- Over voltage
- Loss of capacitance
- Increase of ESR
- Bulging
- Possible venting
- Mechanical Stress
  - Deformation
  - Broken lead
  - Increase in ESR

Self Discharge & Leakage Current

Self Discharge: Is the voltage drop on a charged cell after a set period of time.
Leakage Current: Is the stable parasitic current expected when capacitor is held indefinitely on charge at the rated voltage. This value is voltage and temperature dependent.

Series/Parallel Combination

Why in Series: Since ultracapacitor cells are limited to 2.7V per cell, for higher voltage application multiple cells have to placed in series.

Design considerations: When placing capacitors in series their effective capacitance is reduced by the number of cells placed in series:

\[
\frac{1}{C_{T}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots + \frac{1}{C_n}
\]

Also when placing cells in series appropriate cell balancing needs to be added to ensure all cells are charged uniformly.

Unlike batteries, UC do not have a hard end of life failure mode.
They show a gradual decrease in performance over its useful life.
Each application will have a different end of life criteria.
The state of health can be easily monitored within each discharge cycle.

UC cells will typically have a higher leakage current during the first 72 hours of use.
The leakage current will drop drastically and hold over the lifetime of the part.
The leakage current is voltage and temperature dependent.

Similar to traditional capacitors UC cells can be placed in series to achieve higher voltage.
Placing cells in series will increase the voltage and reduce the effective capacitance.
Series/Parallel Combination

**Why in Parallel:** Since not all capacitance values are covered by cell offered, customers can place multiple cells in parallel to achieve higher capacitance/storage.

**Design considerations:** When placing capacitors in parallel their effective capacitance is increased by the number of cells placed in series:

\[ C_{sys} = C_1 + C_2 + C_3 + \ldots + C_n \]

Also when placing cells in series/parallel combination appropriate cell balancing needs to be added to ensure all cells are charged uniformly.

When cells are placed in series, they will not always share the voltage uniformly. Thus, a balancing scheme will need to be used.

Two common methods of balancing is Active and Passive balancing.

With passive balancing same value resistor is placed in parallel to each cell. Resistor size will depend on the cell leakage.

Ultracapacitor Balancing

**Why Cell Balancing?**

- Achieve cell to cell voltage balance.
- Accounts for variations in capacitance and leakage current. Initial charge and voltage is dependent on capacitance. Sustained voltage is dependent on leakage current.
- Reduces voltage stress on an individual cell.
- Increase overall reliability of the individual cells.

**Different methods of Cell Balancing:**

- Passive
- Active

Passive Cell Balancing

Resistor placed in parallel with each cell.

Resistor size determines balance rate.

- 10x LC, slow balance,
- 100x LC, faster balance.

Good for low duty cycle or when stand by loss not an issue.
Active Cell Balancing

- Active circuit placed in parallel with each cell.
- Circuit will bypass current only when cell goes above rated voltage.
- Ideal for high cycle applications or when stand by losses needs to be at a minimum.
- There are several different topologies available. All are more complicated and more expensive than passive balancing.

Active balancing is achieved by using a circuit to bypass current when a cell goes above its rated voltage.

The benefit is having lower power consumption and allowing the cells to hold their charge for longer period of time.

Ultracapacitors Temperature Effect

One of the main advantages of ultracapacitors is its wide temperature range. The effect of temperature on ultracapacitor cells is two fold:

1. **Life**: Operating at high temperature extremes will reduce the life of the cells.
2. **Performance**: Operating at low temperature extremes will increase the internal resistance of the cell.

Temperature will affect cells in two ways:

1. **Life**: the cell life is reduced if operated at elevated temperature.
2. **Performance**: Cell resistance increases at extreme low temperature.

How to Measure an Ultracapacitor

Tecate Group uses a constant current discharge method to measure capacitance and resistance on ultracapacitor cells and modules. For this method standard capacitor formulas are used as stated below:

Most common way to measure an ultracapacitor cells is using a constant current discharge and measure voltage drop versus time.

Traditional capacitors formulas can be used to calculate capacitance and ESR.
How to Size your Ultracapacitor

There are several ways to size the proper ultracapacitor for your application. The most straightforward way is using a constant current sizing method. For this method, the following information is needed:

- **V<sub>max</sub>**: maximum voltage the application will charge to
- **V<sub>min</sub>**: minimum voltage the application will discharge to
- **I**: the discharge current
- **ΔT**: discharge time between **V<sub>max</sub>** and **V<sub>min</sub>**

Using standard capacitor formulas, we can calculate the capacitance needed:

\[
\text{Capacitance} = \frac{I \cdot \Delta T}{V_{\text{max}} - V_{\text{min}}}
\]

Note: For high current applications, the ESR effect will also need to be taken into consideration.

For constant power applications, the total energy needed can be calculated in terms of Joules (W*SEC) and the capacitance derived using the following formula:

\[
E = \frac{1}{2}CV_{\text{max}}^2 - \frac{1}{2}CV_{\text{min}}^2
\]

Traditional capacitor equations can be used to calculate estimated capacitor size needed.

### Sizing Example

1. **Define System Requirements**
   - 15 W delivered for 10 seconds
   - 10V max; 5V min

2. **Determine total energy needed:*
   - \( J = WS = 15W \times 10\text{sec} = 150\text{J} \)

3. **Determine Capacitance based on:**
   - \( J = \frac{1}{2}CV^2 \)
   - Substitute the energy from above:
   - \( 150\text{J} = \frac{1}{2}C(10^2 - 5^2) \)

4. **Solve for C:**
   - \( C = \frac{300(10^2 - 5^2)}{2} = 4\text{F} \)

5. **Add 20-40% safety margin**
   - \( C_{\text{system}} = 4.8\text{F} \)

6. **Calculate cell-level capacitance**
   - \( 10V/2.7V = 3.7 \)
   - 4 cells in series
   - \( C = C_{\text{sys}} \times \# \text{ of series cells} = 4.8F \times 4 = 19.2F \)
   - Choose closest cell available
     - 22F cell, 4 in series
     - TPL-22/12X35F

### Tecate Tools

- **Website**: [www.tecategroup.com](http://www.tecategroup.com)
- **Application notes, White Papers, etc.**
- **Sizing Tool- All UC solutions**
- **PowerBurst Product Guide**
  - **Overview with detailed design considerations**