Gateway to a New Thinking in Energy Management - Ultracapacitors

What is an Ultracapacitor?

Electrochemical Double Layer Capacitor?

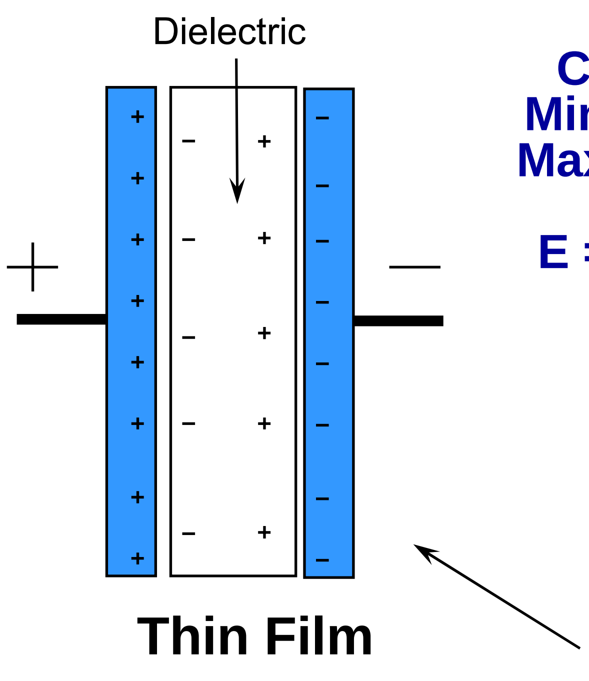
Energy Storage Capacitor?

Supercapacitor?

Science of the Technology

- A 100-year-old technology, enhanced by modern materials

- Based on polarization of an electrolyte, high surface area electrodes and extremely small charge separation

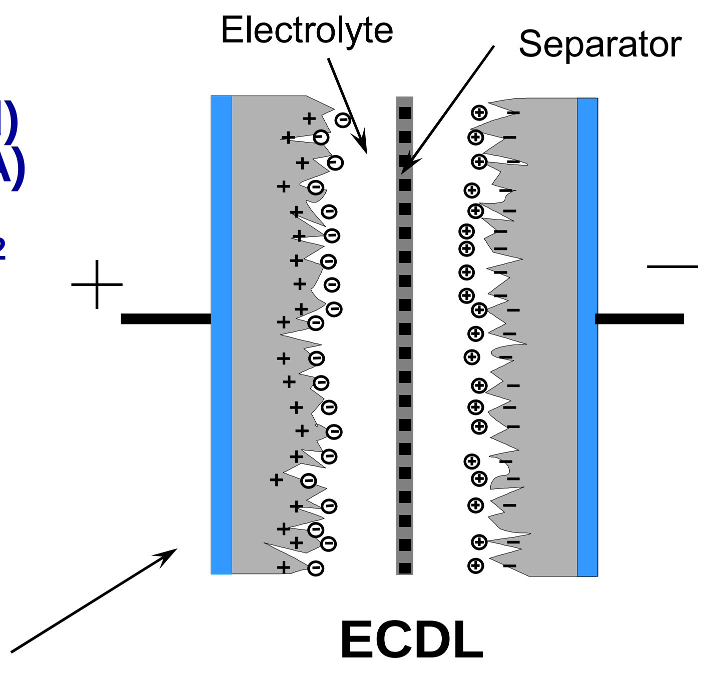


$C = \varepsilon_r A/d$

Minimize (d)

Maximize (A)

$E = 1/2\ CV^2$



Basic Equations

Definition of Capacitance: $C = Q/V$ (1)

Charge = current * time: $Q = I*t$ — $C = I*t/V$ (1a)

Solving for voltage: $V = I*t/C$ (2)

Dynamic Voltage: $dV/dt = I/C$ (3)

Stored Energy $E = ½ C*V^2$ (4)

At initial voltage V_o, $E_o = ½ C*V_o^2$

At final voltage V_f, $E_f = ½ C*V_f^2$

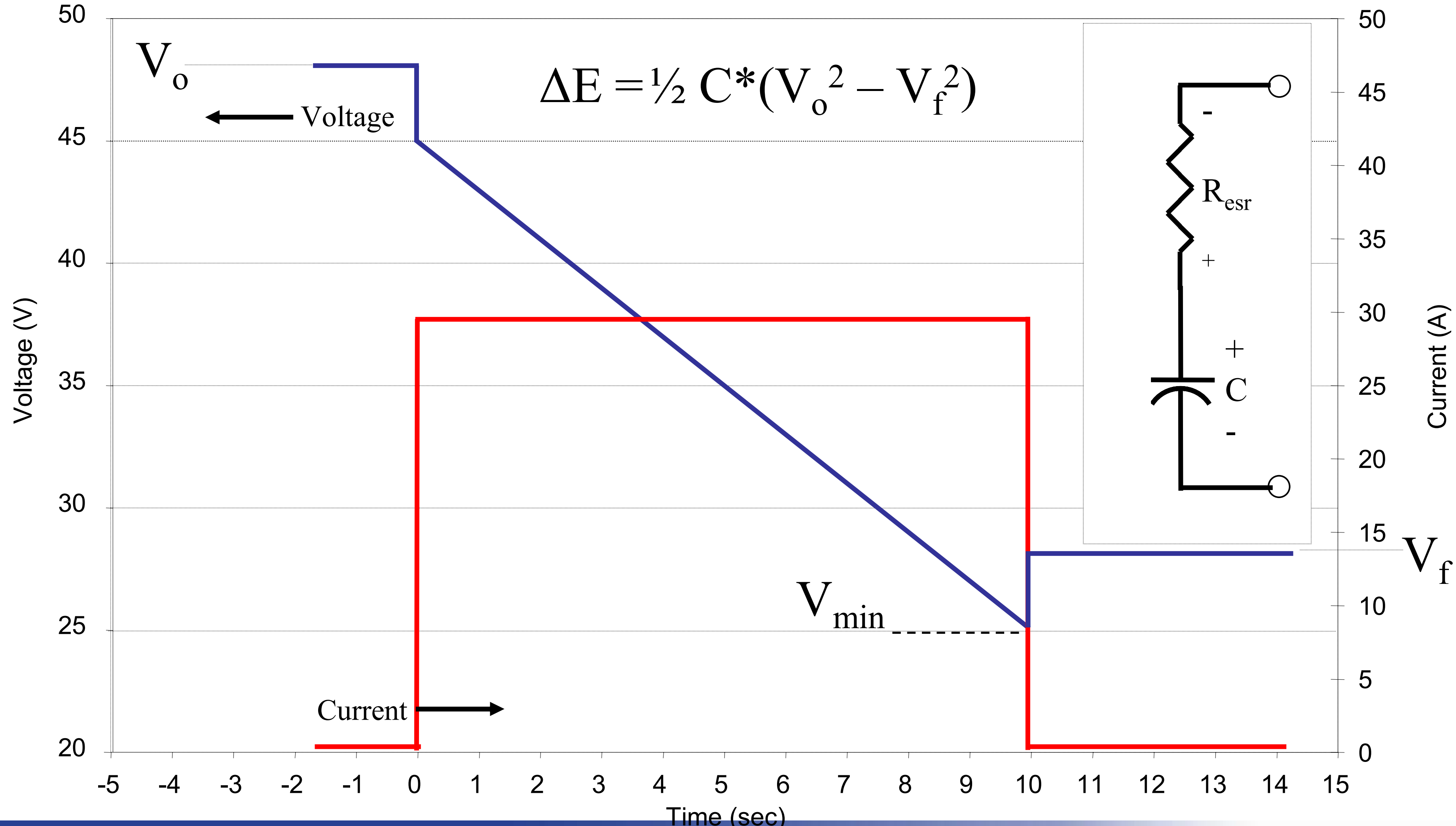
Delivered energy = $E_o – E_f$

$$\Delta E = ½ C*(V_o^2 – V_f^2) \quad (5)$$

Voltage & Current vs. Time

C = 15 farad; R_{esr} = 100 milliohm

V_o = 48V; I = 30A

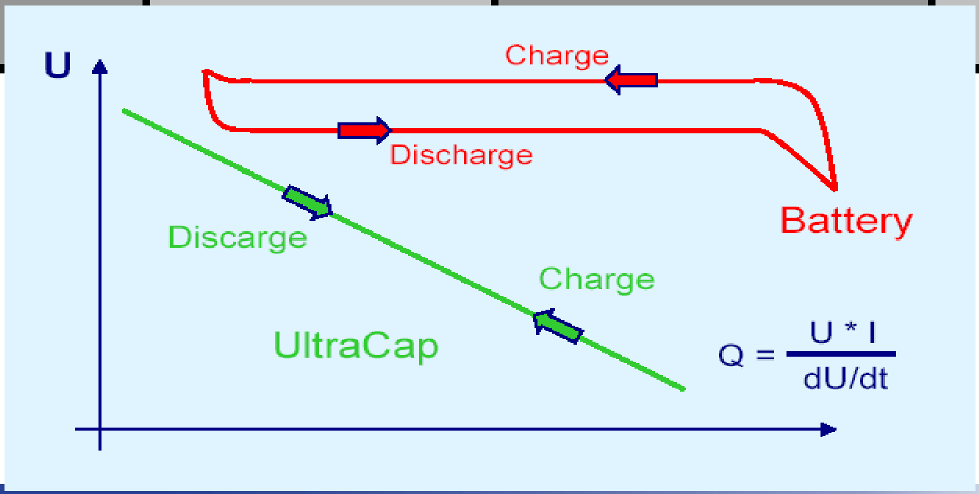


Ultracapacitor Performance Characteristics

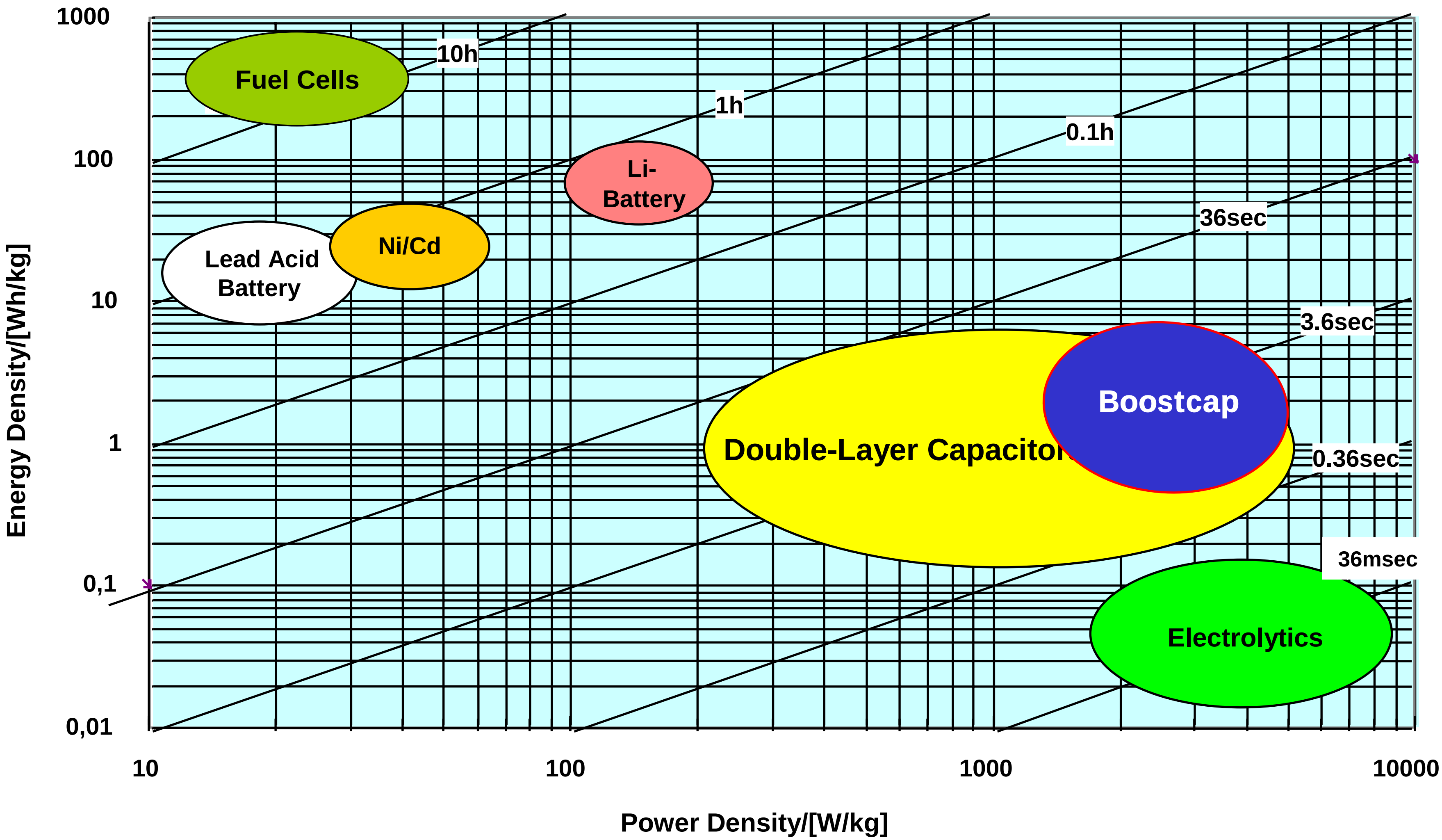
- Ultracapacitors perform mid-way between conventional capacitors and electrochemical cells (batteries).
- Fast charge/discharge capability
- Highly reversible process: 100,000’s of cycles
- Excellent low temperature performance
- Low voltage, DC devices
- Extremely long life

Technology Comparison

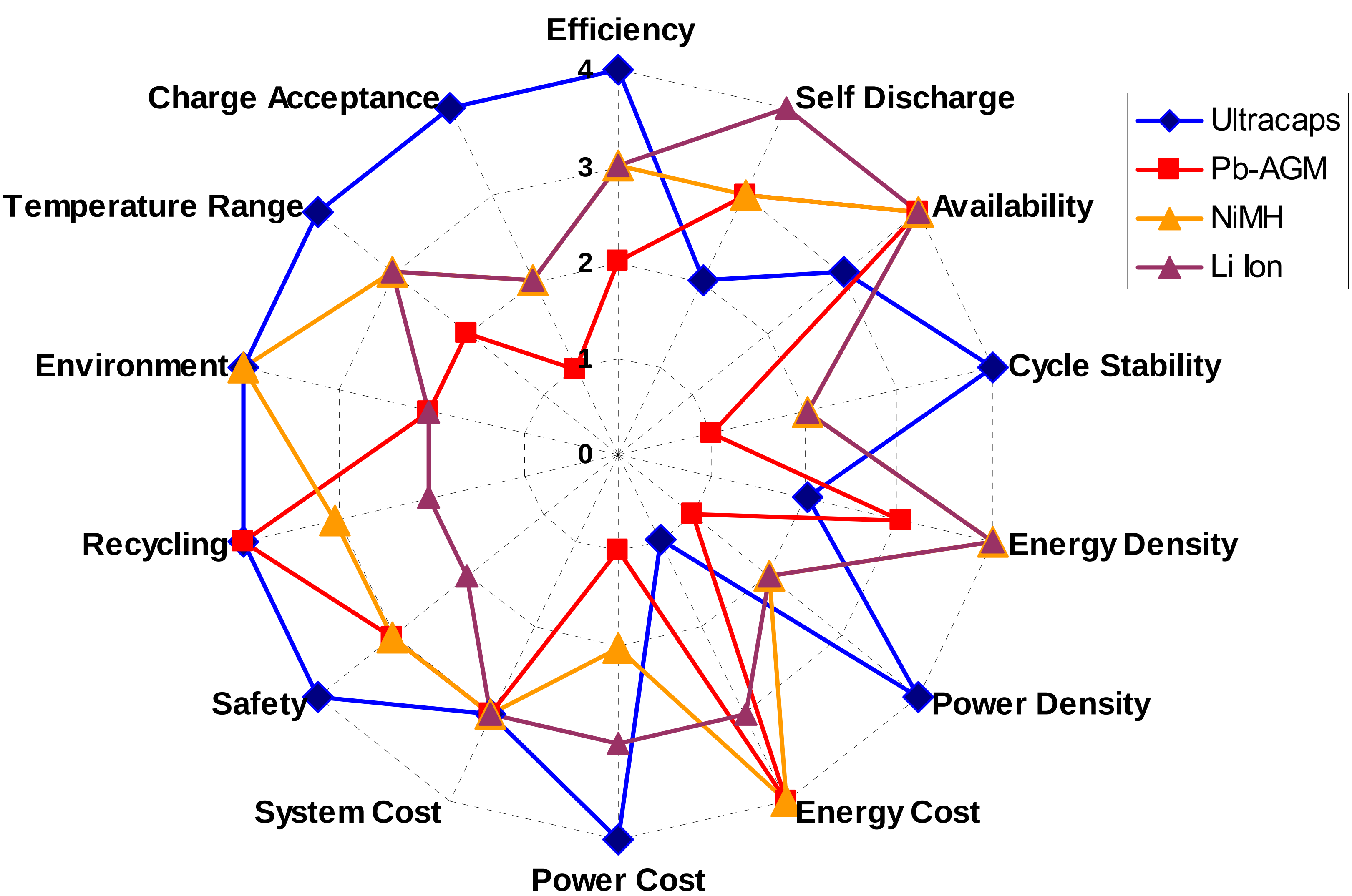
Available Performance	Lead Acid Battery	Ultracapacitor	Electrolytic Capacitor
Charge Time	1 to 5 hrs	0.3 to 30 s	10^{-3} to 10^{-6} s
Discharge Time	0.3 to 3 hrs	0.3 to 30 s	10^{-3} to 10^{-6} s
Energy (Wh/kg)	10 to 100	1 to 10	< 0.1
Cycle Life	1,000	>500,000	>500,000
Specific Power (W/kg)	<1000	<10,000	<100,000
Charge/discharge efficiency	0.7 to 0.85	0.85 to 0.98	>0.95



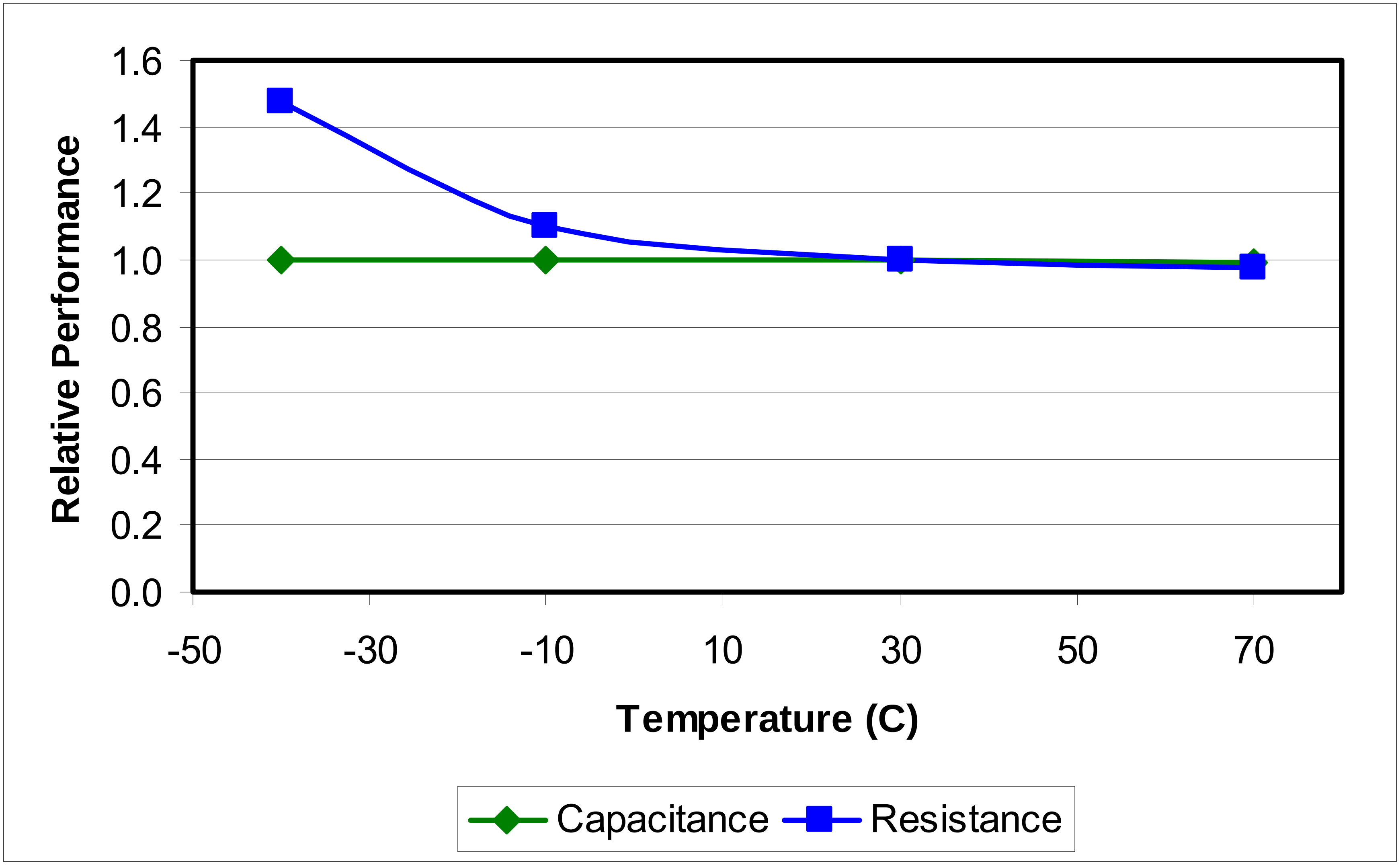
Technology Comparison *(page 2)*



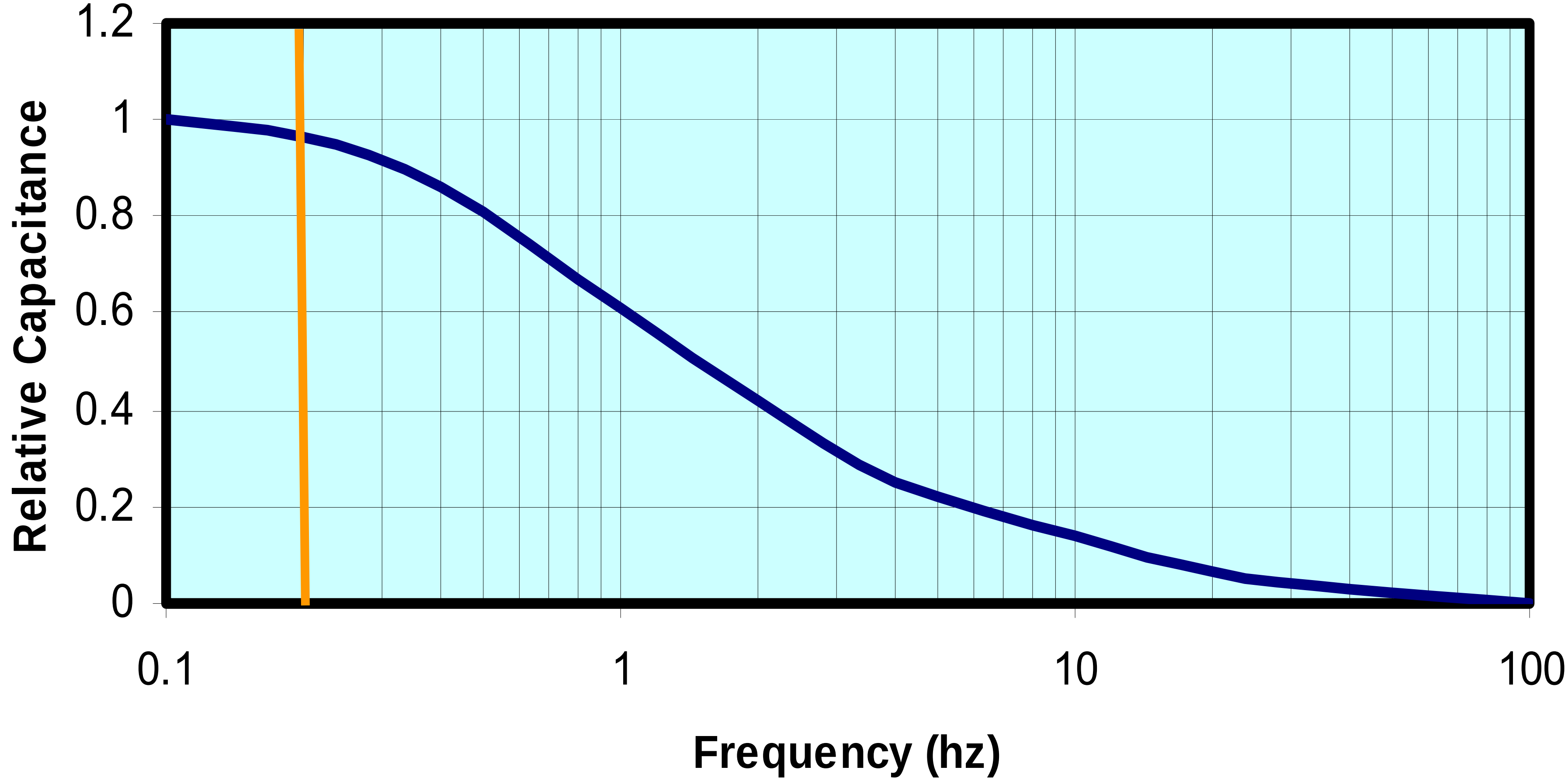
Ultracapacitors vs Batteries



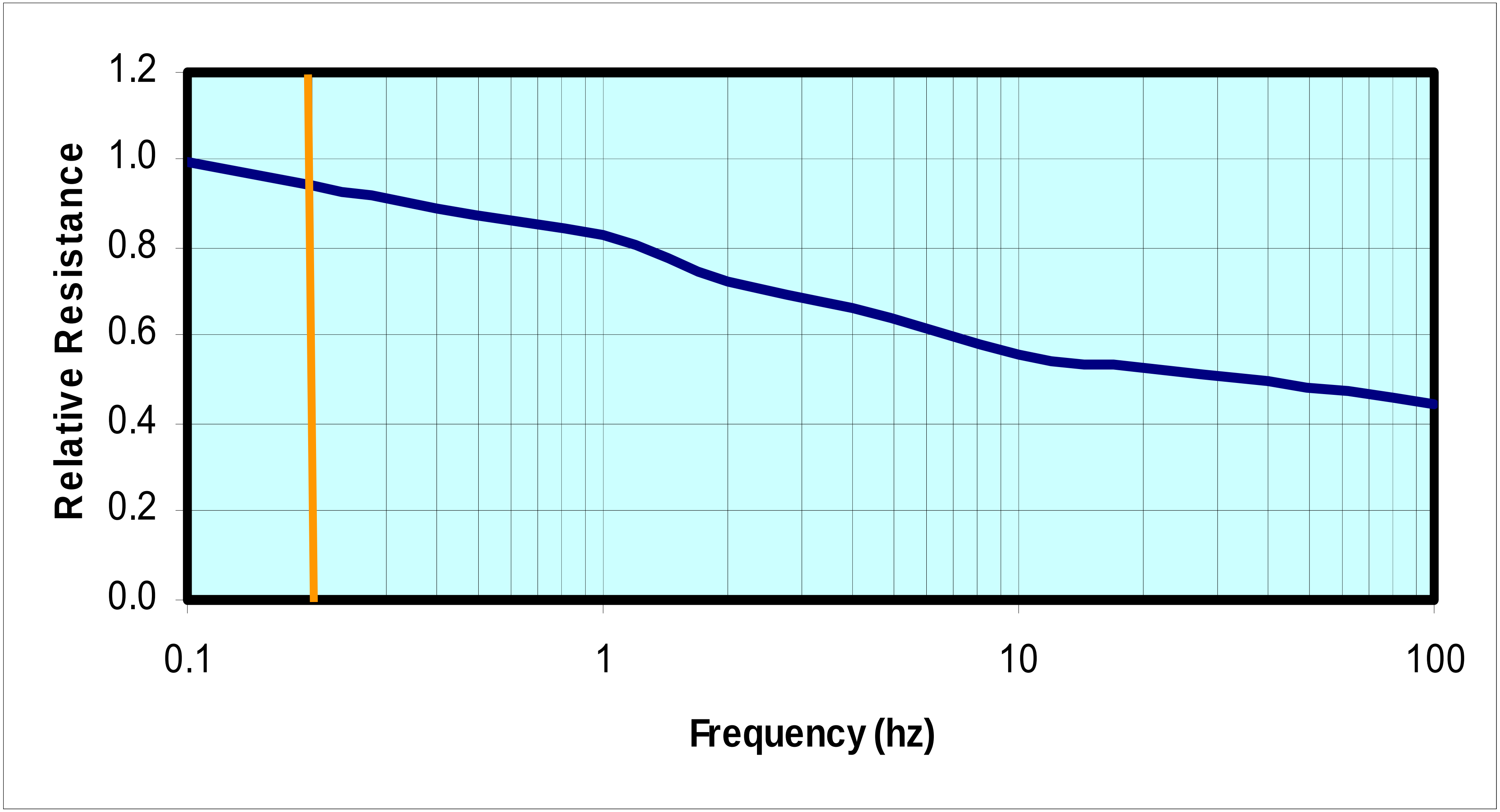
Ultracapacitor Performance vs. Temperature



Capacitance, Frequency Response



Resistance, Frequency Response



Ultracapacitor Aging

- Unlike batteries, Ultracapacitors do not have a hard end of life criteria.
- Ultracapacitors degradation is apparent by a gradual loss of capacitance and a gradual increase in resistance.
- End of life is when the capacitance and resistance is out of the application range and will differ depending on the application.
- Therefore life prediction is easily done.

Product Portfolio Range

PC Series
- 4 and 10 F
- Modules rated at 5 and 15 V

BC Series (Power & Energy)
- 120, 140, 310, 350 F
- Modules and packs rated at 15 V

MC Series (Power & Energy)
- 650, 1200, 1500, 2000, 2600, 3000 F
- Modules rated at 16 V and 48 V

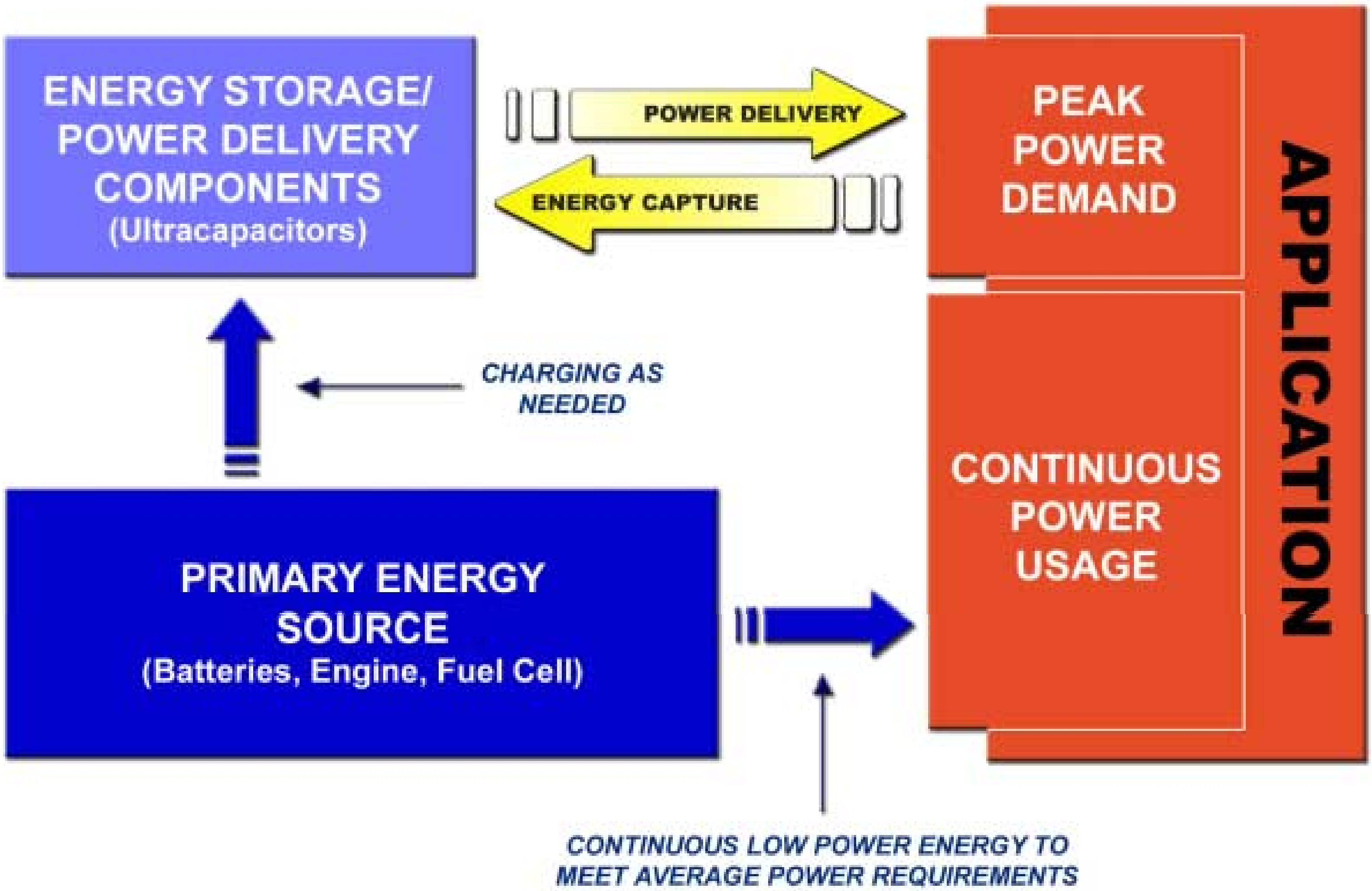
PowerCache Modules
- 50 V, 1.6 and 2.3 kWm

When should Ultracapacitors be considered?

Is there a need for?

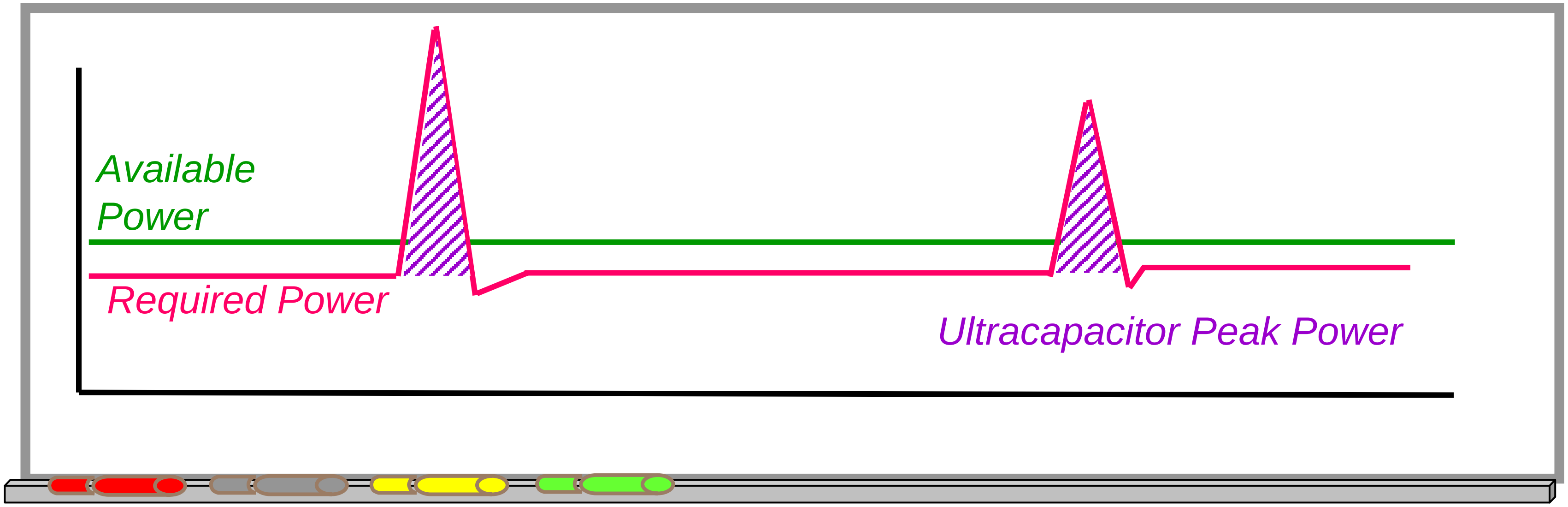
- High reliability back-up power
- Momentary bridge power (1 - 60 seconds)
- Voltage sag compensation
- Buffering large momentary in-rush or power surges

Application Model



Peak Power Shaving

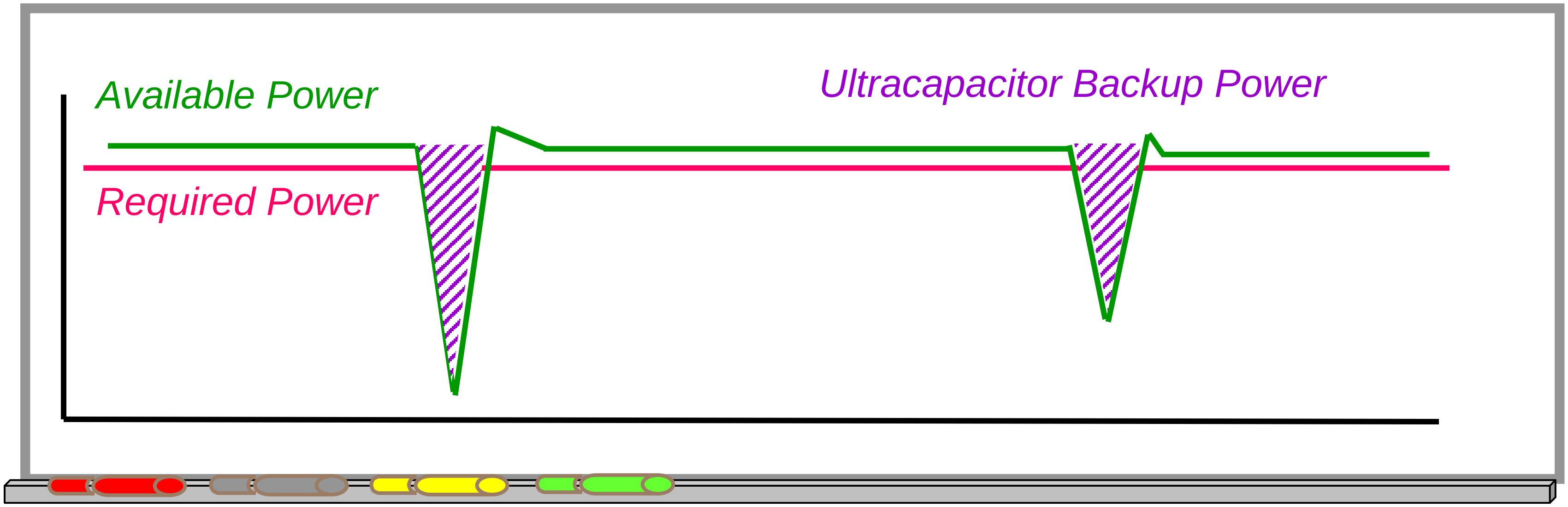
- Ultracapacitors provide peak power ...



Back-up Power

- Ultracapacitors provide peak power…

  ...and back-up power.



Ultracapacitor Market

Ultracapacitor Market

Ultracapacitor World Market

- **Consumer Products**
  - Digital Camera
  - PDA
  - Toys
  - Memory back-up
- **Industrial**
  - UPS
  - Windmill
  - Stationary Fuel Cell
  - Automation/Robotics
- **Transportation**
  - Hybrid Bus/Truck
  - Engine starting
  - Light Hybrid
  - Local Power
  - Rail

Ultracapacitors ● Microelectronics ● High-Voltage Capacitors

Maxwell TECHNOLOGIES

Today's Leading Industrial Markets

Energy saving and voltage stabilization

Pitch control and back up power

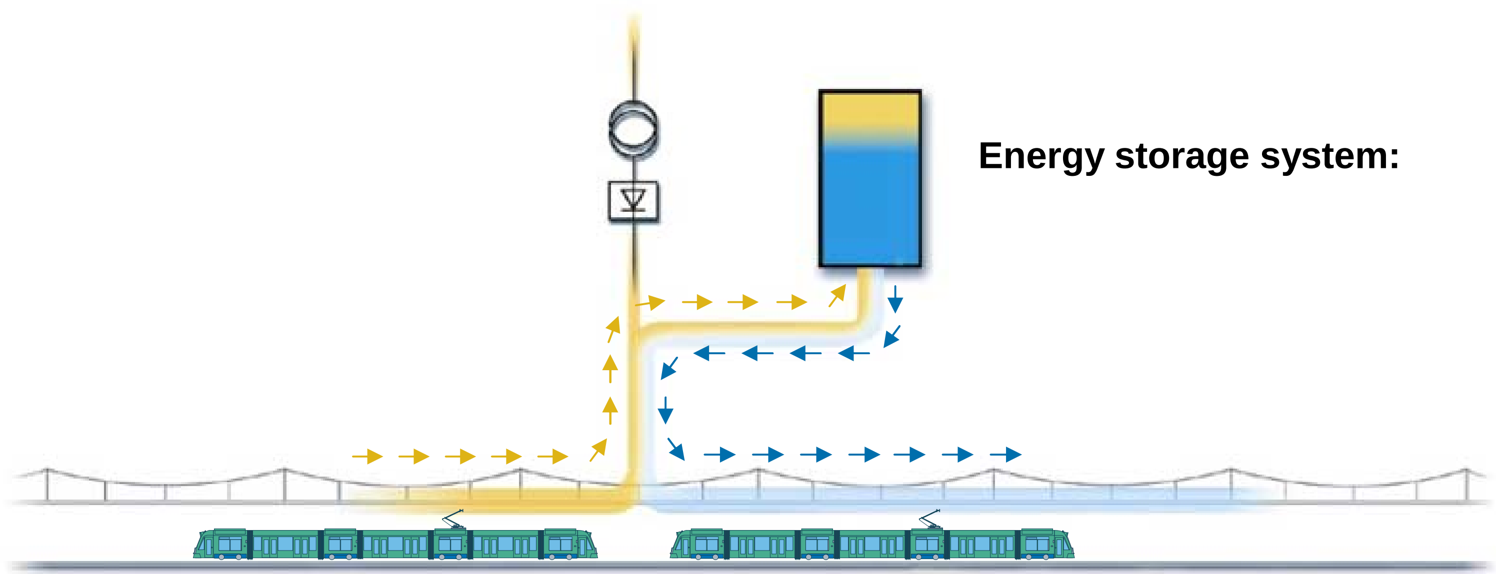
High power transmission or last gasp messaging

Train Stations

Windmills

AMR

Siemens SITRAS® SES - Solution



Time t_1
Vehicle 1 is braking
→ Energy storage system stores the braking energy

Time t_2
Vehicle 2 is accelerating
→ Energy storage system delivers the energy

Advantage: Cost savings through reduced primary energy consumption and prevents critical voltage sag levels within immediate grid network

SITRAS® Energy Storage System

Nominal voltage	750 V DC
# of Ultracapacitors	1,344
Energy stored	2.3 kWh (8.2 MJ)
Energy saving per h	65 kWh/h
Max. power	1 MW
Capacitor efficiency	0.95
Operational temperature	–20 to 40 °C

ESS rack composed of 42 2600F cells

SITRAS® Installation Examples

Dresden
Hellerau
Full-time service since September 2002

Cologne
Schlebusch
Full-time service since July 2003

Madrid
Sainz de Baranda
Full-time service since July 2003

Maxwell Technologies

Wind Turbine Pitch Systems

- Modern wind turbines consist of three-bladed variable speed turbines
- Independent electro-mechanical propulsion units control and adjust the rotor-blades
- Latest technology uses the wind not only to produce wind energy but also for its own safety

Pitch System Storage Systems

- Each pitch systems is equipped with an ultracapacitor emergency power supply
- Ultracapacitors represent an optimum emergency power supply system due to their
  - Enhanced level of safety
  - High reliability
  - Efficiency
  - Scalability

Switch box including 2600F ultracapacitors

75 V, 81 F ultracapacitor module

4 modules are put in series to power 300 V pitch systems of 3-5 MW wind power plants

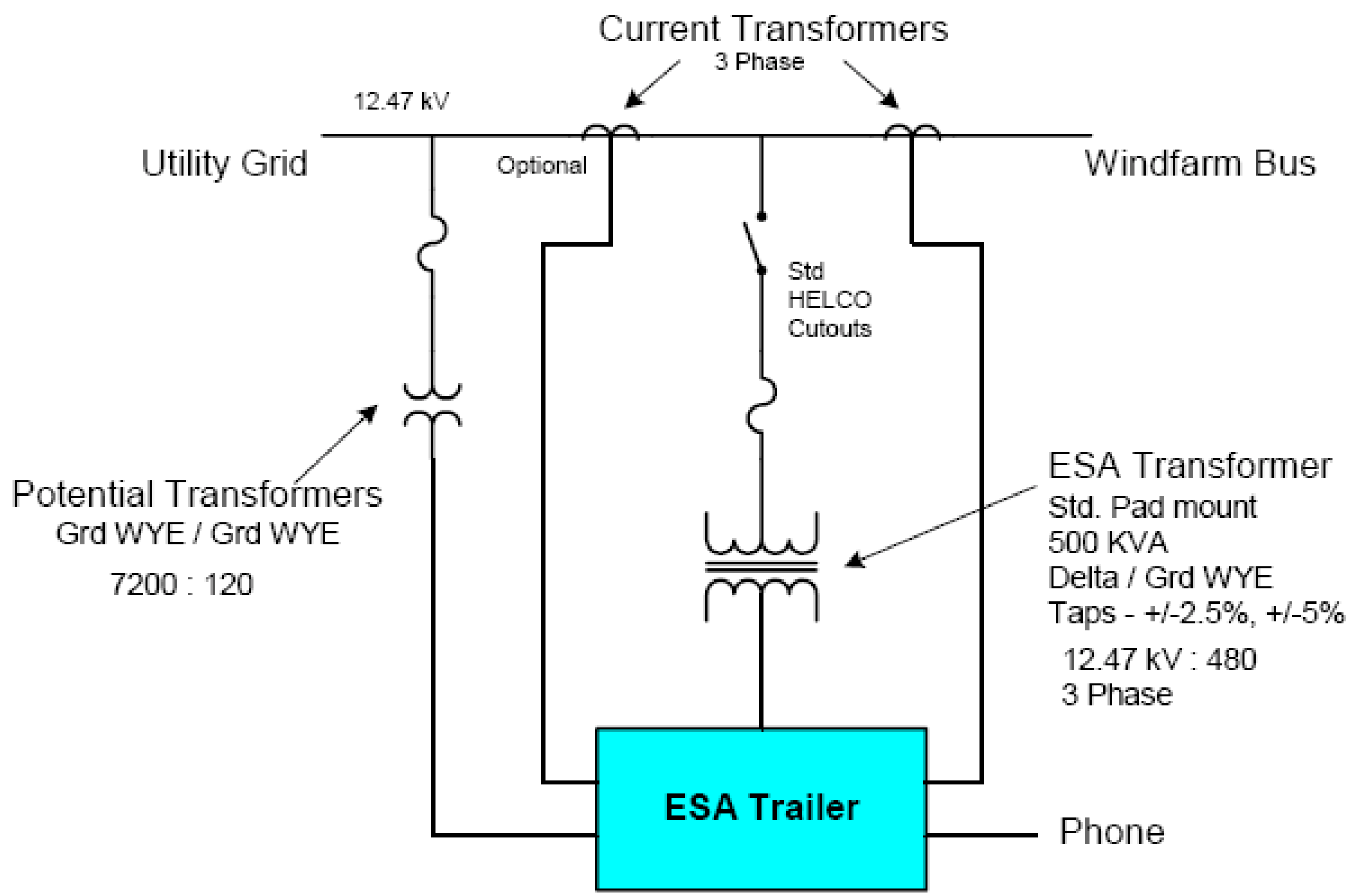
S&C Electric, ESA Announcement

Newly Invented Electronic Shock Absorber Will Give Big Boost to Hawaii Wind Farm.

Hawaiian Electric Company, Inc. (HECO) and S&C Electric Company held on Jan. 17 a dedication at Lalamilo Wind Farm near Waikoloa on the Big Island of Hawaii to mark the installation of the first PureWave® Electronic Shock Absorber (ESA), an innovative grid stabilizing device for wind farms.

S&C, a leader in power electronic system design and delivery, received exclusive rights from HECO to design, build and commercialize the ESA. The device employs S&C's trademarked DSTATCOM Distributed Static Shunt Compensator with the addition of ***ultracapacitor energy storage***. Production of the first PureWave® ESA began in early 2005. Attendees at today's dedication toured the inside of the 30-foot trailer that houses the ESA system.

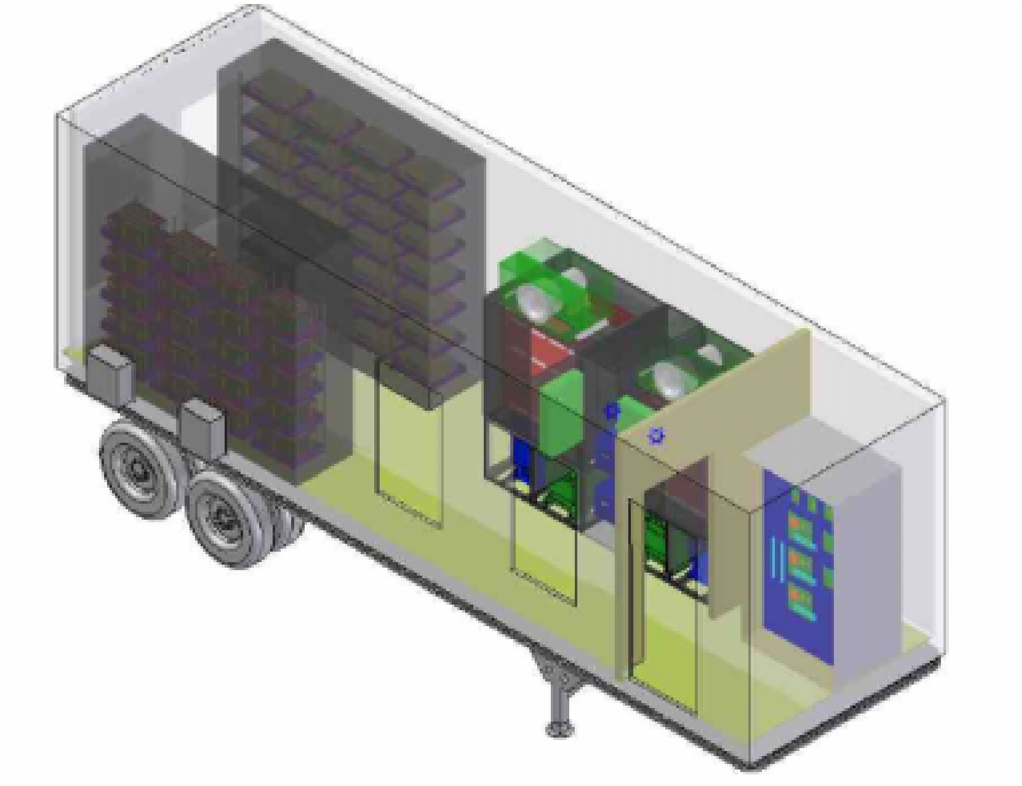
ESA Single Line Diagram



S&C Electric, ESA System

Initial System

Nominal voltage	800 V DC
# of Ultracapacitors	640
Energy stored	3 MJ
Max. power	263 kW
Operational temperature	–25 to 50 °C



On Site Installation

S&C Electric, ESA system will be on display at:

IEEE T&D, Dallas, TX – May, 2006
Windpower, Pittsburgh, PA – June, 2006

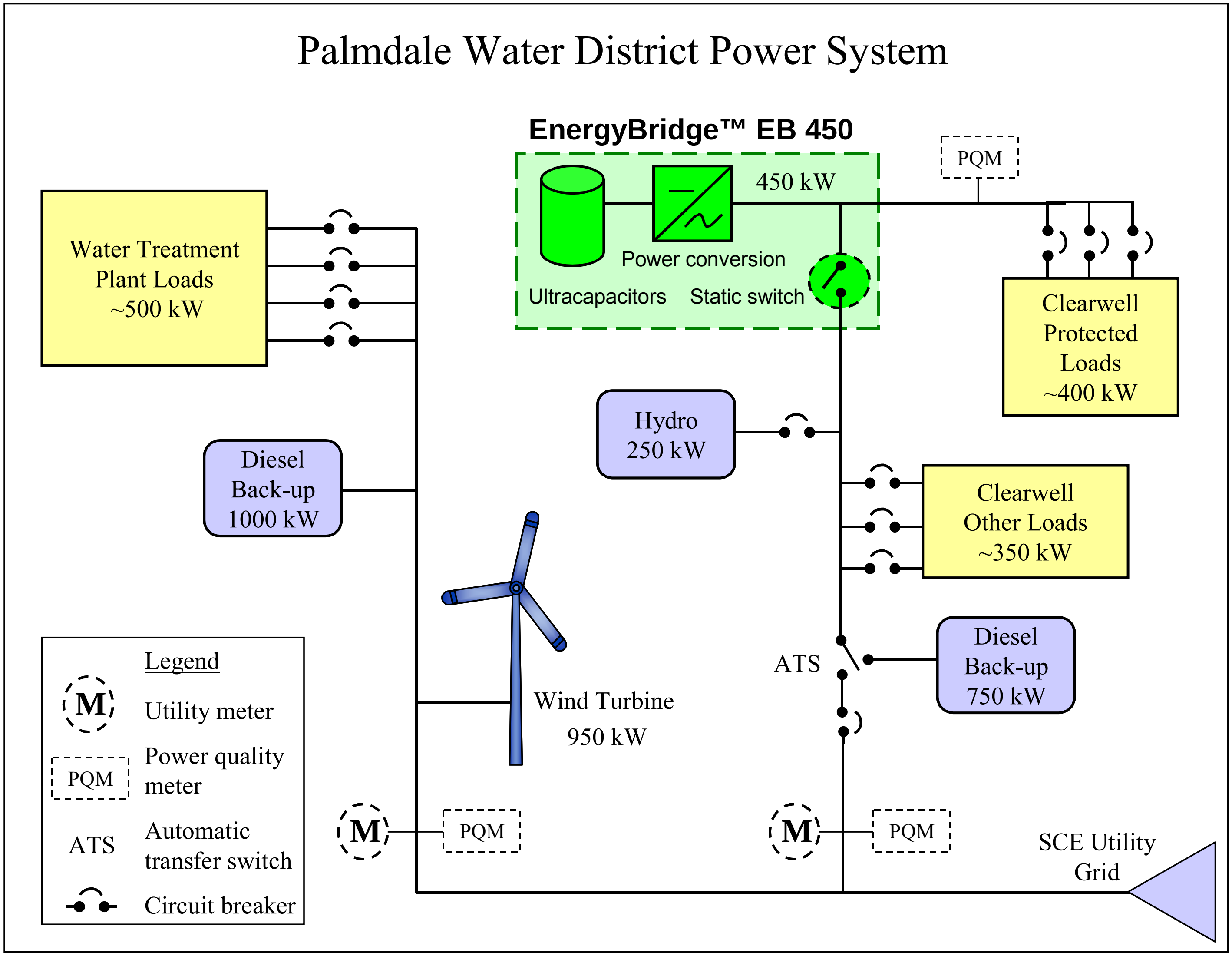
Northern Power, Energy Bridge

CEC Awards Grant to Northern Power to Integrate Advanced Power Electronics Technology

WAITSFIELD, Vt. -- Northern Power Systems, a subsidiary of Distributed Energy Systems Corp. (NASDAQ: DESC), has been contracted to design, engineer and install an advanced energy storage system for the Palmdale Water District's Southern California water treatment plant and adjacent pumping facility.

Northern's Power Technology Group (PTG) will integrate its advanced power conversion, switching and controls solutions with ***Maxwell Technologies ultracapacitor modules*** to create a system that will provide critical load support for the protected loads. In the event of a grid outage, the high- reliability system will be capable of creating short-term power as the transition is made to on-site or backup generation power. The system will be able to support 450 kW for 20 - 60 seconds depending on the loads, enough time to bring a generator on line and avoid any interruption in power at the Palmdale facility.

Energy Bridge, Palmdale



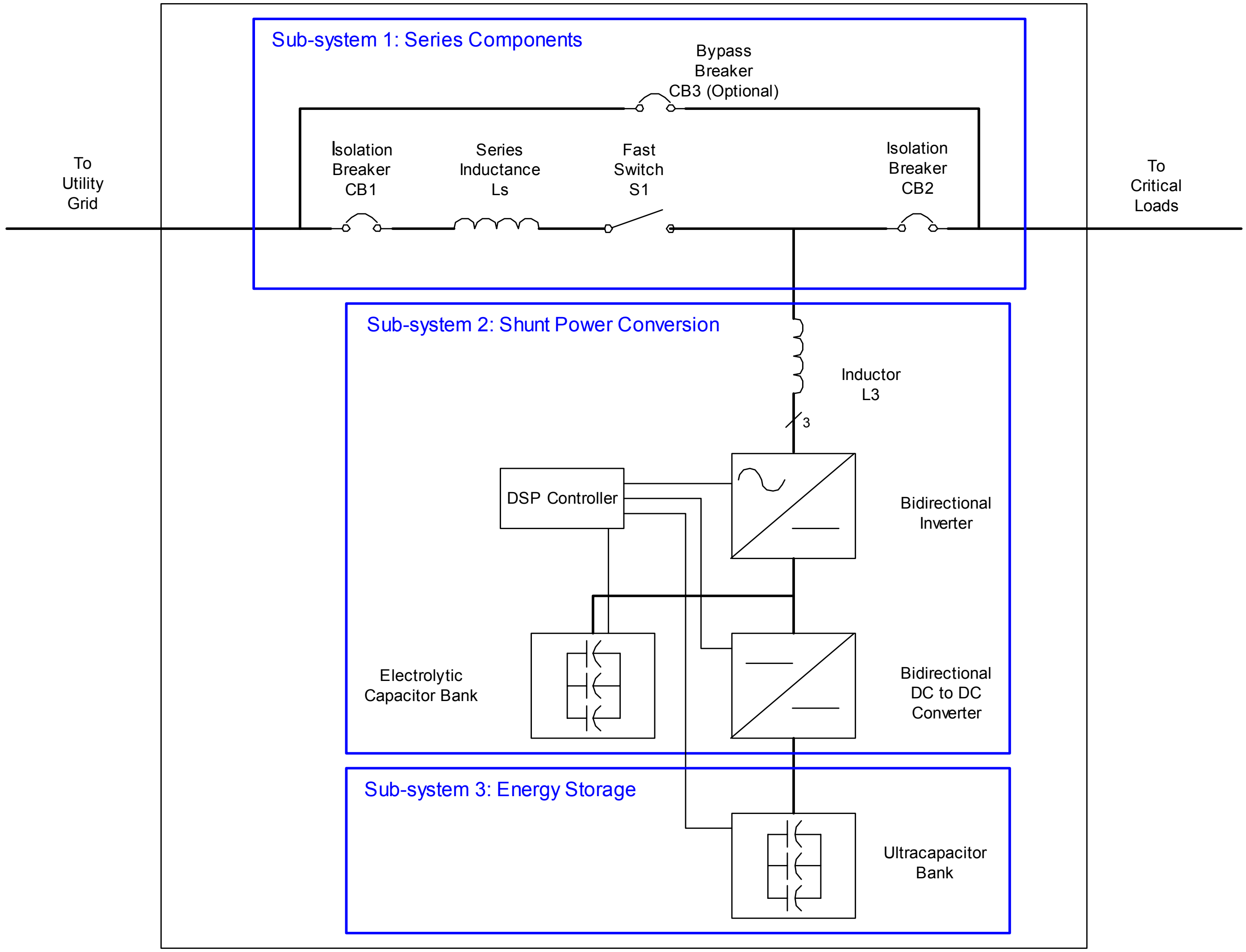
Maxwell TECHNOLOGIES

Energy Bridge Specifications

Rated power	450kW @ 0.8 pf
Back up time	30 sec.
Circuit voltage & type	480 Vac, 3 Phase wye, 3 or 4 wire
System efficiency	99% at rated load
Critical Bus Voltage	480 Vac +/- 2.5%
Critical Bus Voltage THD	<2% per harmonic, <3% total THD
Enclosure Dimensions	3'x20'x7' (DxWxH)
Operating temperature	0-40°C, de-rated above 40°C
Applicable Standards	IEEE 1547 & 519, UL1778, CBEMA

One Line Diagram

EnergyBridge™ UPS - One-line Diagram



Sizing Your System

Basic Model

- Series/Parallel configurations
  - Changes capacitor size; profiles are the same
  - Series configurations
    - Capacitance decreases, Series Resistance increases
    - $C_s=C_{cell}/(\#\text{of cells in series})$ $R_s=R_{cell}*(\#\text{ of cells in series})$
  - Parallel configurations
    - Capacitance increases, Series Resistance decreases
    - $C_P=C_{cell}*(\#\text{ of cells in parallel})$ $R_P=R_{cell}/(\#\text{ cells in parallel})$
- Current controlled
  - Use output current profile to determine dV/dt

    $dV = I * (dt/C + ESR)$
- Power controlled
  - Several ways to look at this:

    $P_{term} = I*V_{cap} - I^2*ESR$ (solve quadratic for I)

    $I = [V_{cap} - \text{sqrt}(V_{cap}^2-4*ESR*P_{term})]/(2*ESR)$
  - Solve for dV/dt as in current-controlled
  - $J=W*s=1/2CV^2$ **Solve for C.**

Applications with a single energy storage component

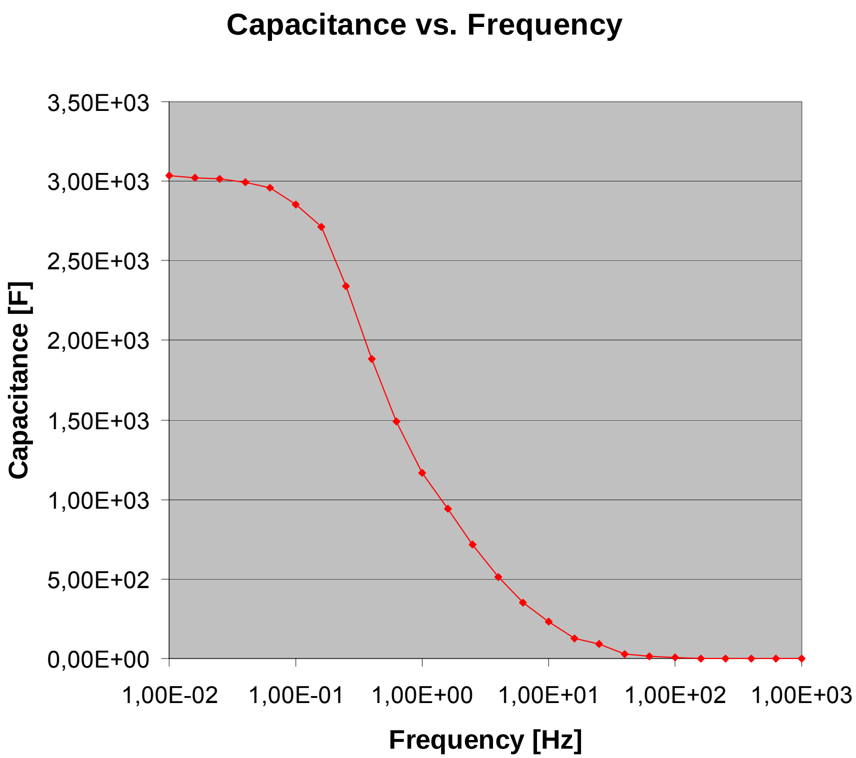
- Applications in which little total energy is required (i.e. memory backup)

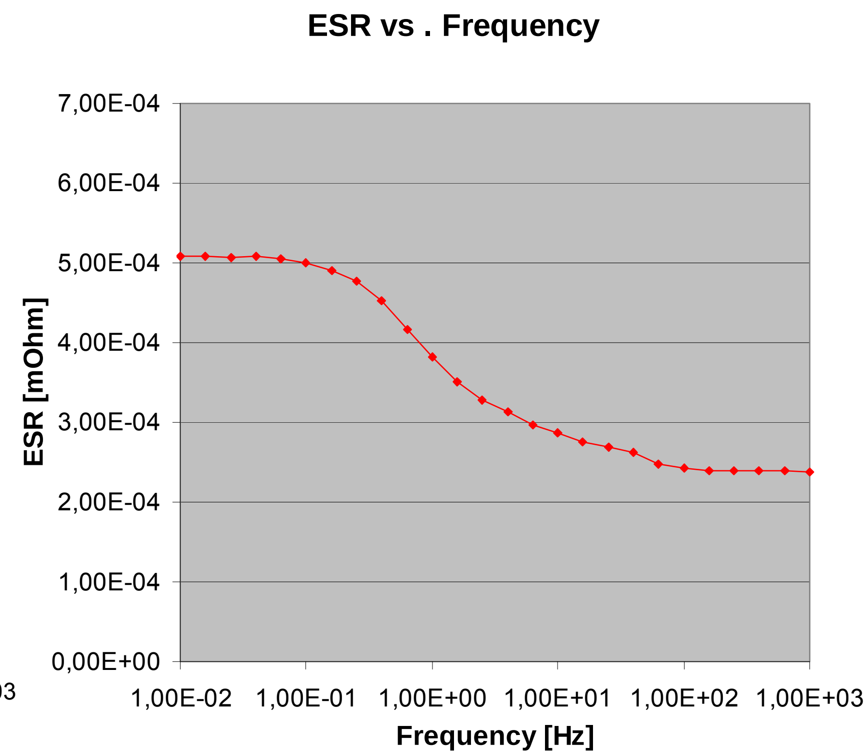
- Possibly used with other energy sources
  - Short duration, high power (i.e. pulse transmit)
  - Long duration, low power (i.e UPS backup)
  - Opportunities for high charge rates (i.e toys)

Applications with two energy storage components

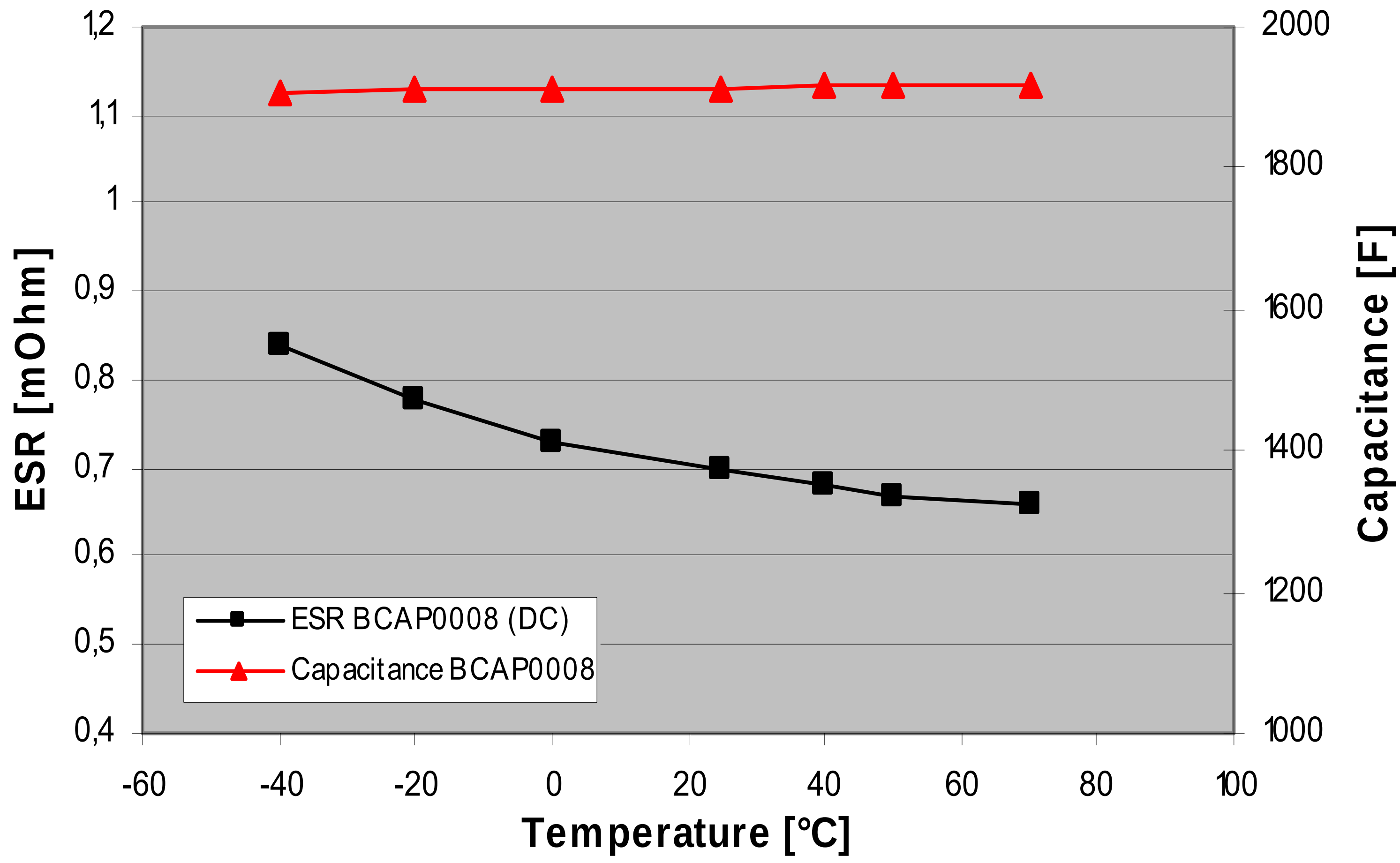
- Power vs. Energy design trade when using two components
  - Single component vs. two components
    - Engines/Fuel cells/Batteries/Solar Arrays are energy rich/power poor (or poor response)
      - Size these components for enough energy, system may be limited in power
      - Size these components for power, system may have surplus of energy
    - Ultracapacitors are power rich/energy poor
      - Size an ultracapacitor for enough energy, system may have a surplus of power
      - Size an ultracapacitor for power, system may be limited in energy
  - Two components
    - A primary source for energy; Ultracapacitor for power
    - Requires appropriate definition of peak power vs. continuous power

Capacitance and ESR vs Frequency

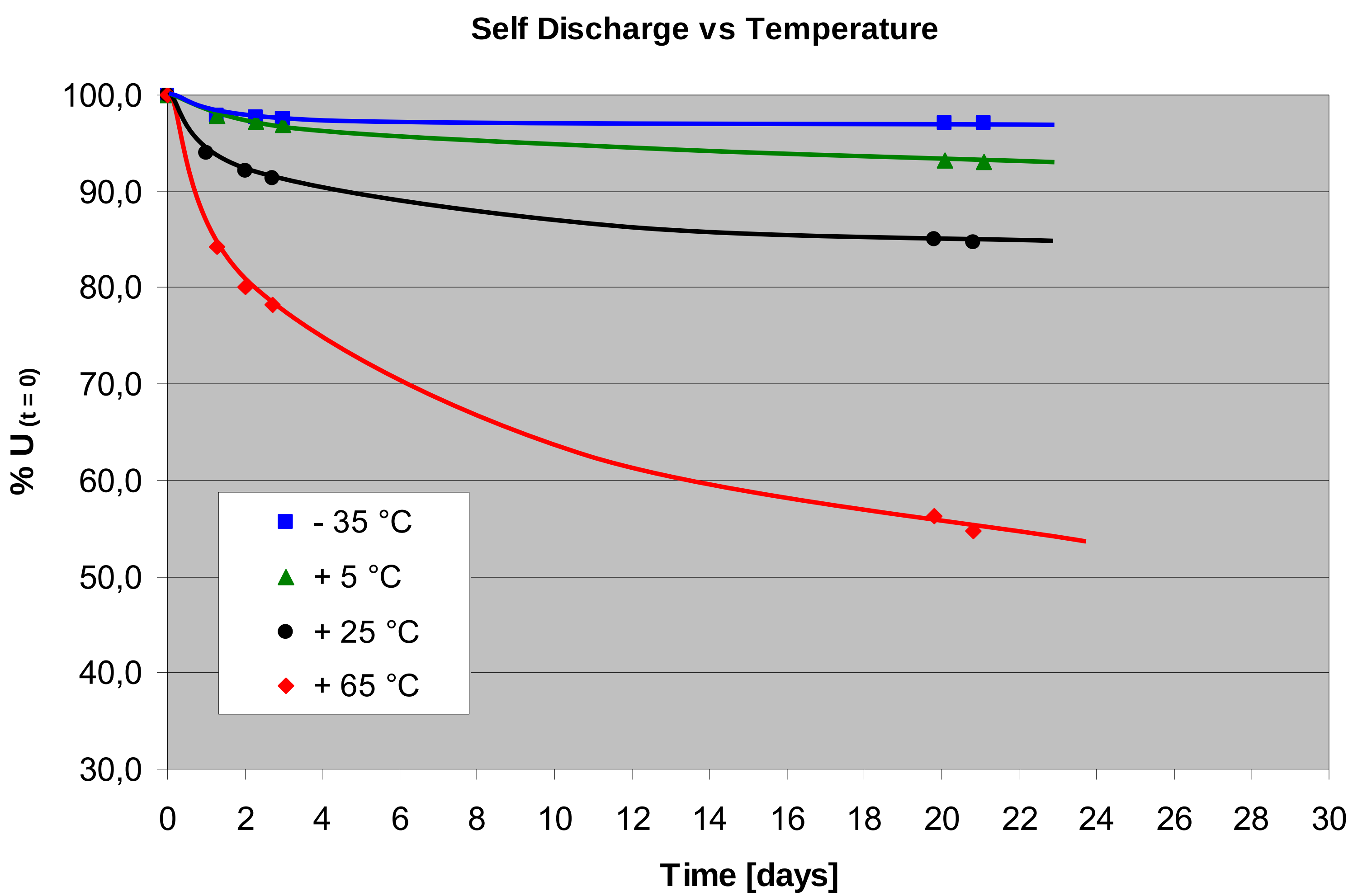




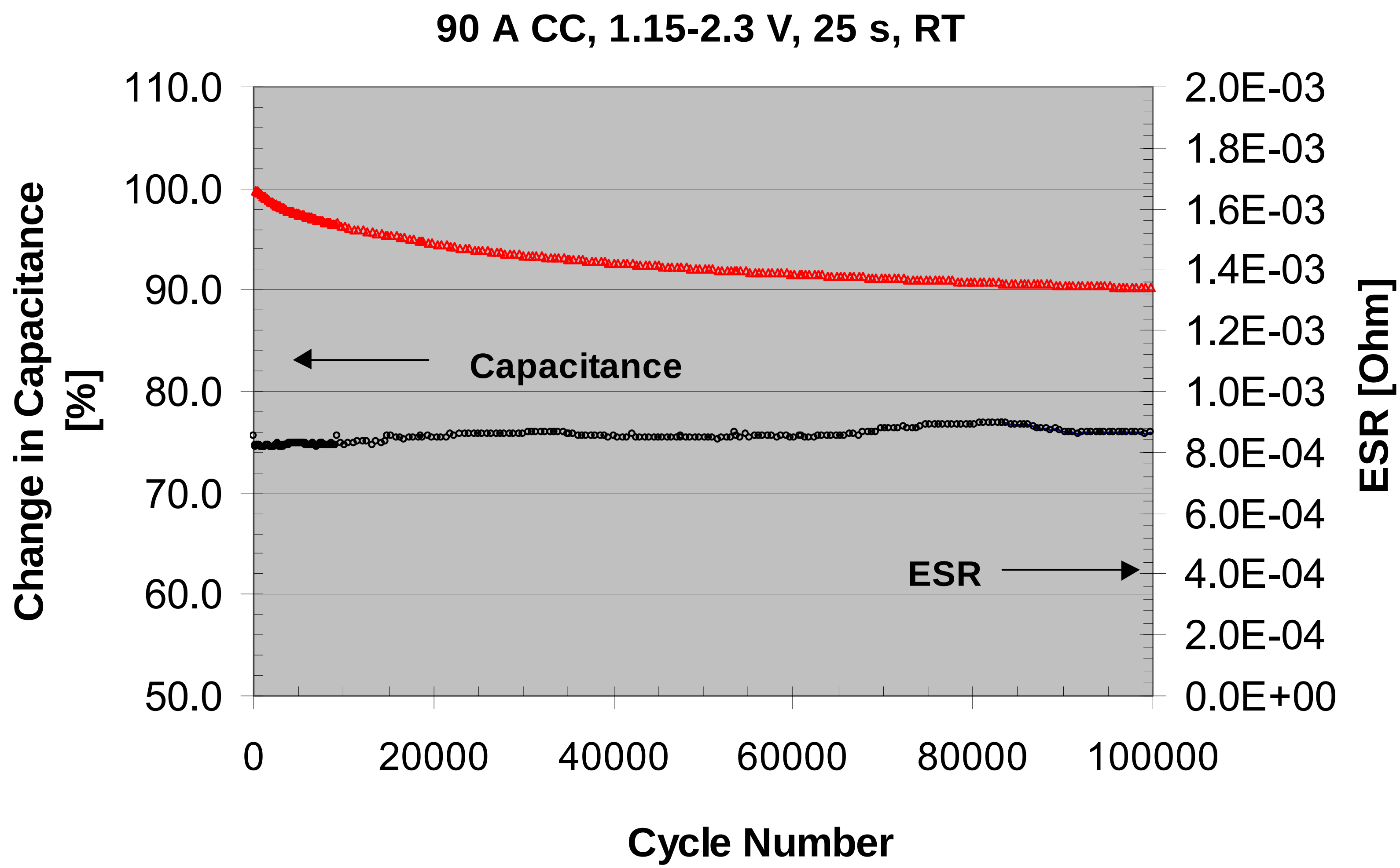
C and ESR Temperature Dependency



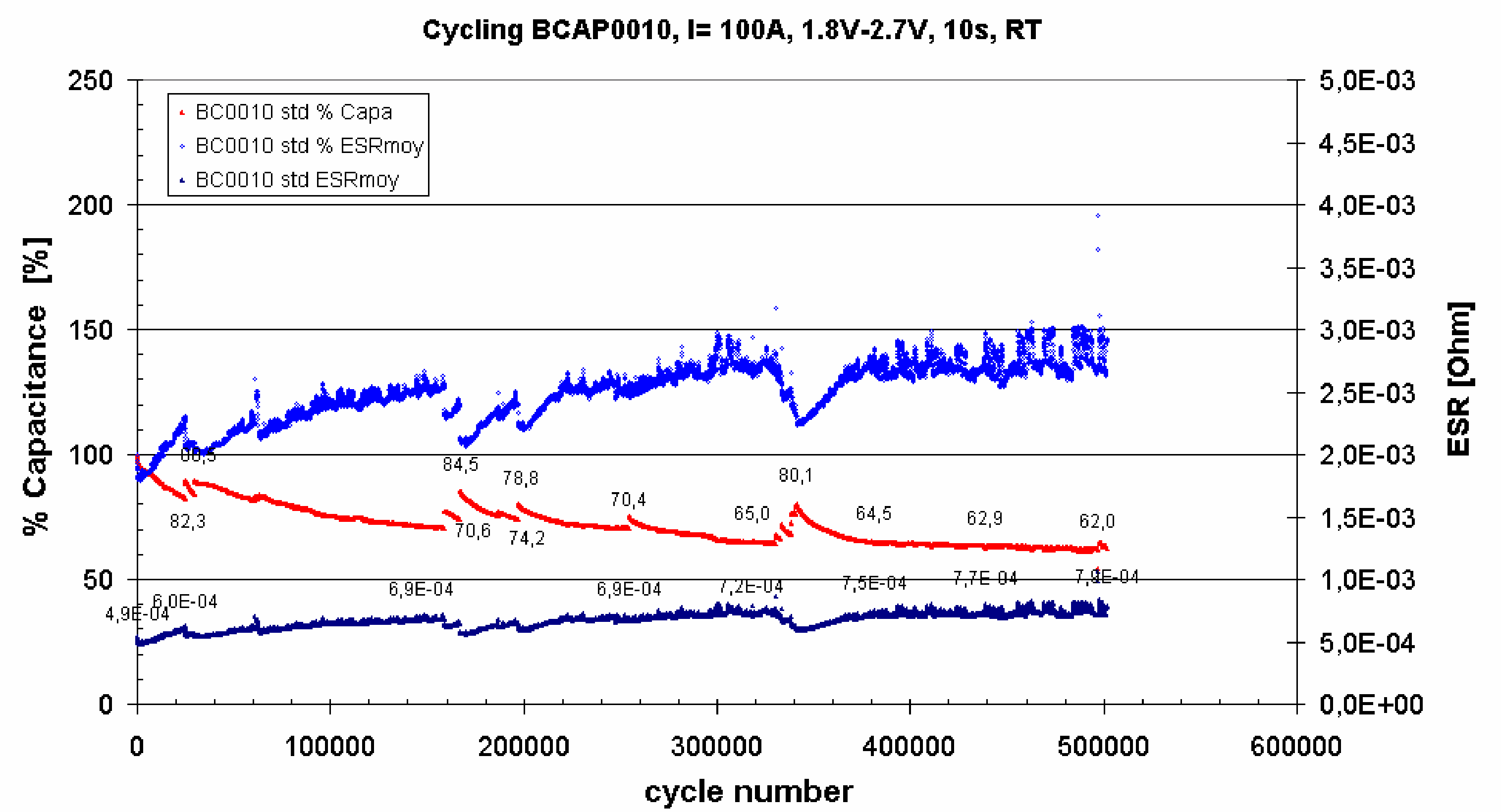
BCAP Self Discharge



BCAP Cycling Capacity



BCAP Cycling



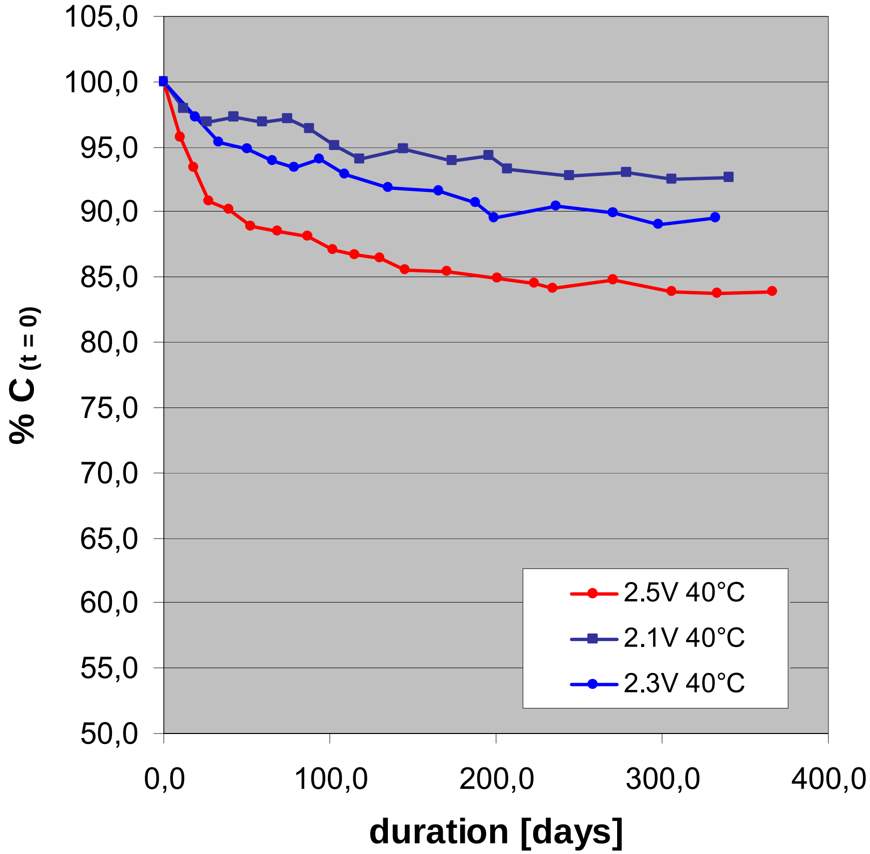
500’000 cycles between 1.8 and **2.7 V**, 100 A

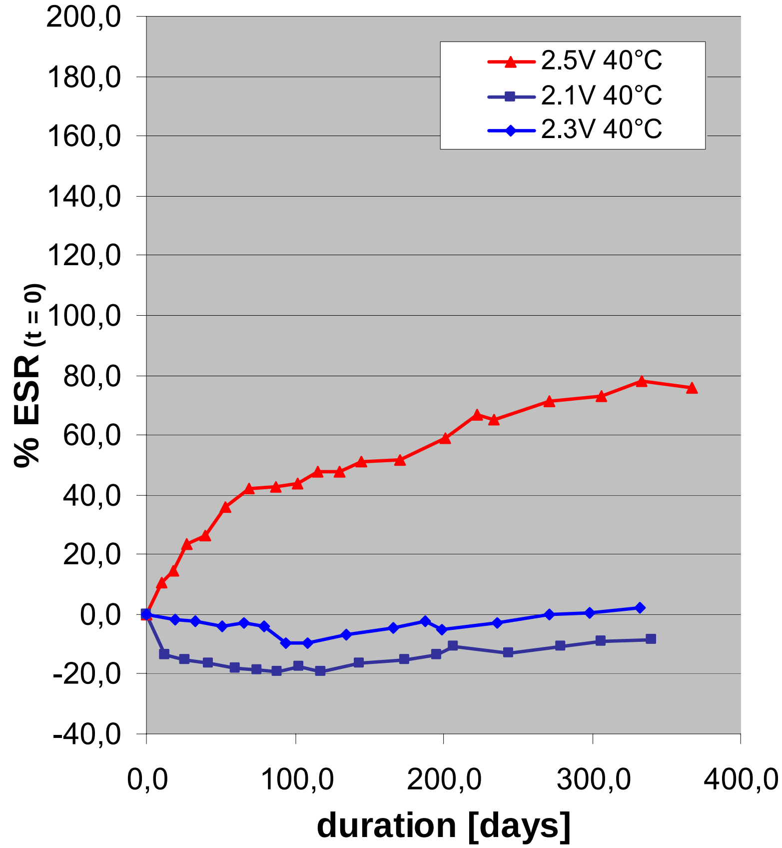
ESR (1 Hz) increase 140 % (0.49 to 0.79 mOhm

Capacitance decrease 38 % (2760 to 1780 F), 30% compared to rated capacitance

BCAP DC Life

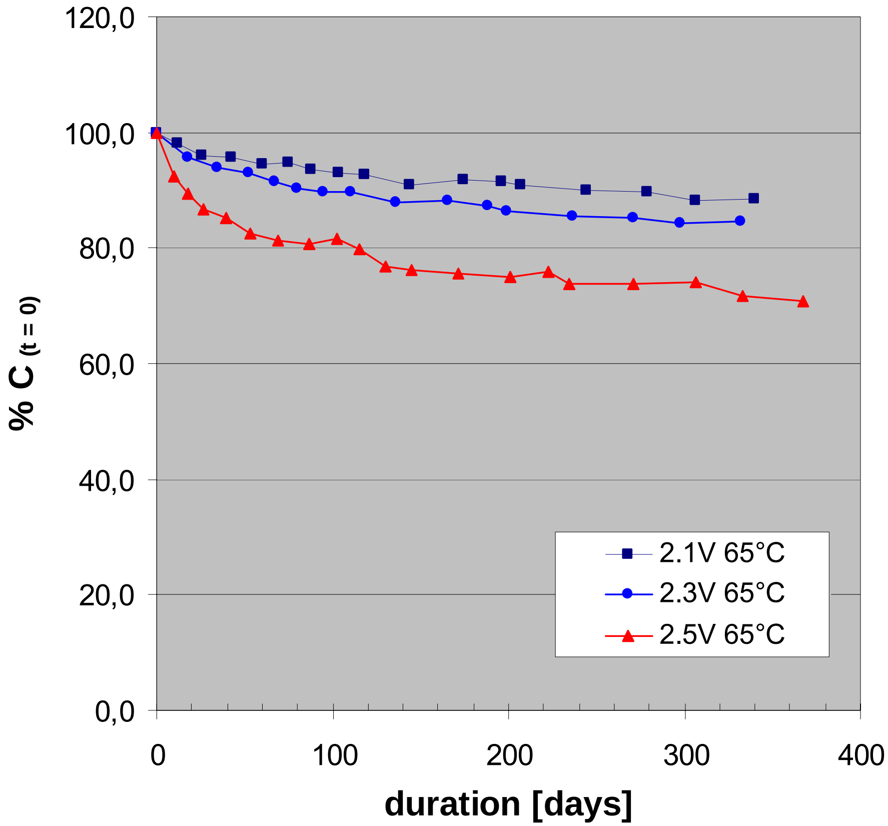
Capacitance and ESR variation at U, T = 40 °C

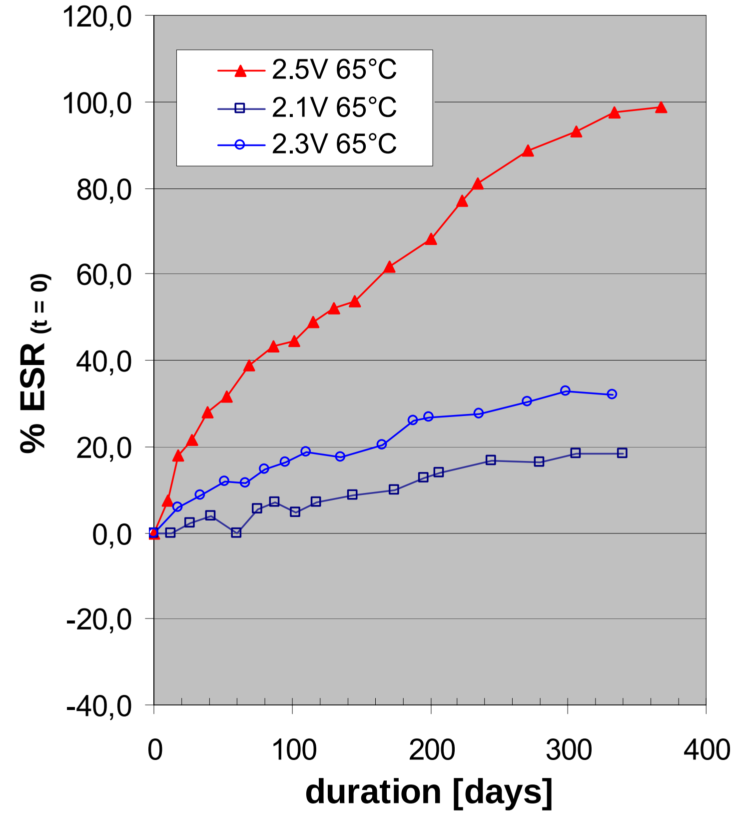




BCAP DC Life

Capacitance and ESR variation at U, T = 65 °C





Sizing Examples

Example sizing

1) Define System Requirements

15 W delivered for 10 seconds

10V max; 5V min

2) Determine total energy needed: J=WS=10W*10sec=150J

a) Determine Capacitance based on: $J=1/2CV^2$

b) Substitute the energy from above: $150J=1/2C(V_{max}^2-V_{min}^2)$

c) Solve for C: $C=300/(10^2-5^2)=4F$

3) Add 20-40% safety margin to cover I^2R losses — Csystem = 4.8F

4) Calculate number of cells in series (since maximum cell voltage = 2.5V)

10V/2.5V = 4 cells in series

5) Calculate cell-level capacitance

C = Csys * # of series cells = 4.8F* 4 = 19.2F per 2.5V "cell"

6) Calculate number of cells in parallel (we will assume a 10F cell)

in parallel = 19.2/10F = 2 x 10F cells in parallel

Guidelines to Designing an Ultracapacitor System

Why Cell Balancing?

- Achieve cell to cell voltage balance
- Accounts for variations in capacitance and leakage current, initial charge and voltage dependent on capacitance, sustained voltage dependent on leakage current
- Reduces voltage stress on an individual cell
- Increase overall reliability of the individual cells

How to Cell Balance?

- Resistor method, resistor placed in parallel, resistor value calculated at 10x leakage current for slow balance, 100x for faster balance, good for low cycle when efficiency or stand by loss not an issue

Surface Mount Resistor for low duty cycle application

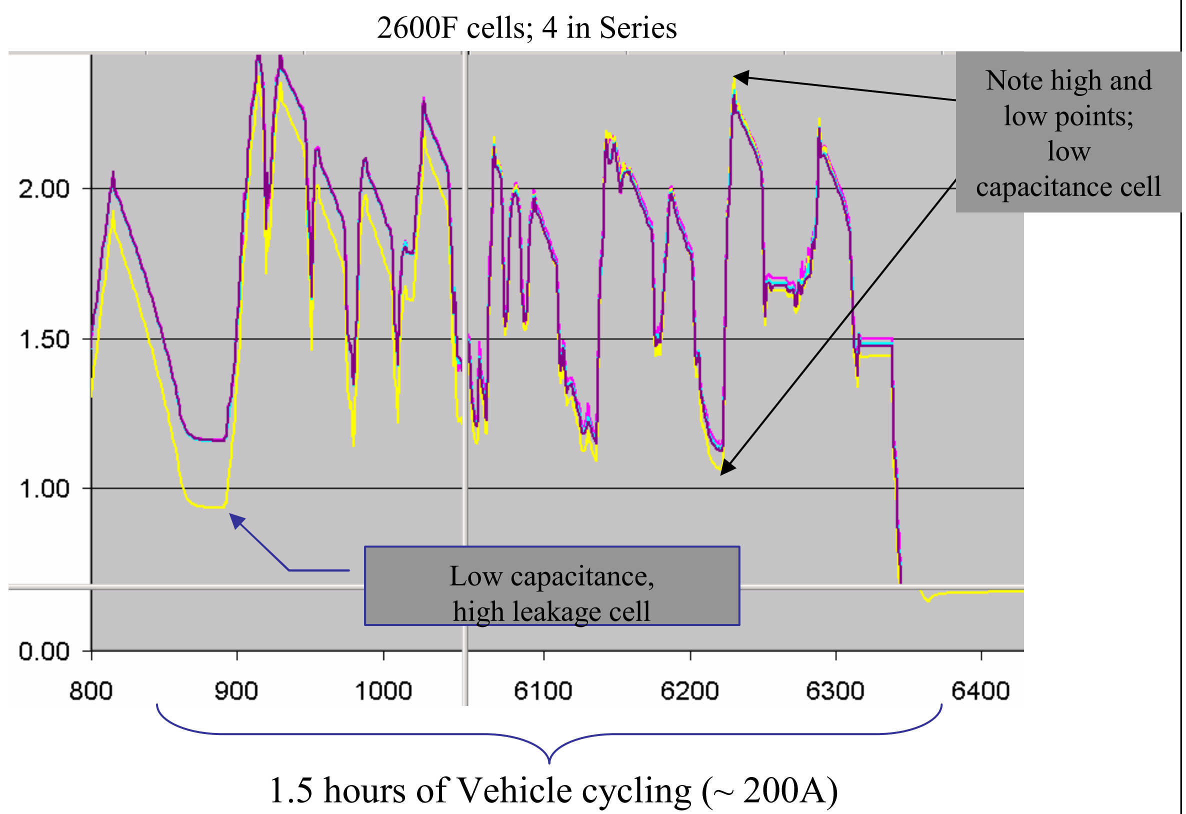
Ultracapacitor Cell Balancing

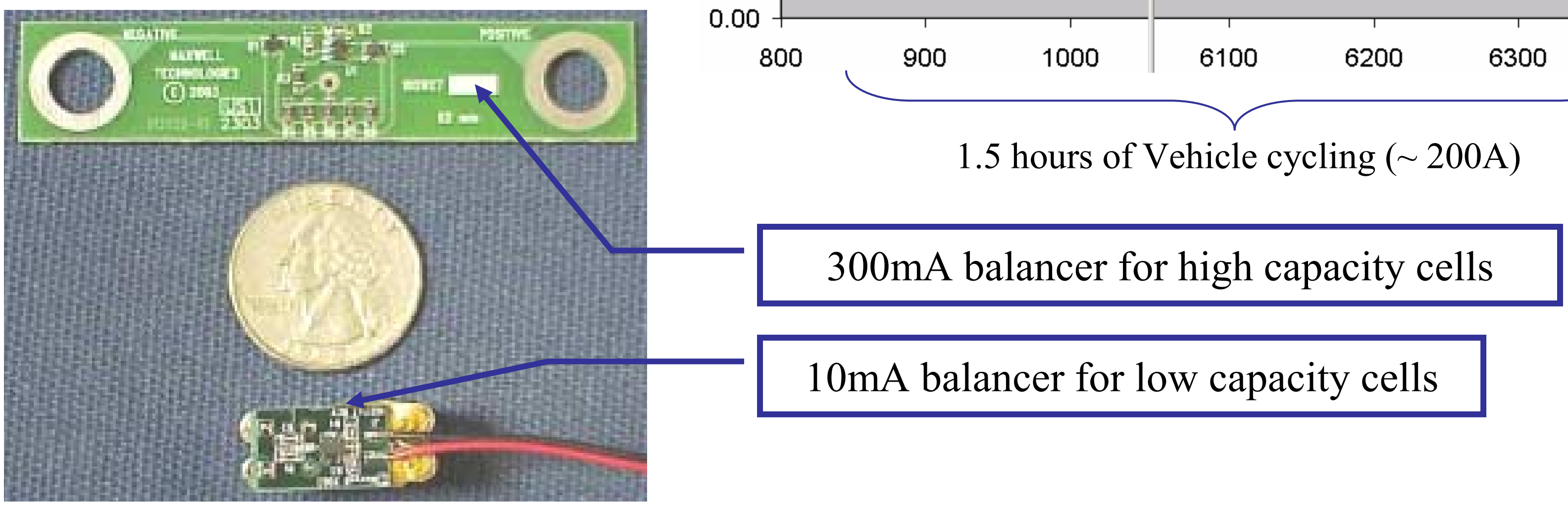
- Active method, use semiconductors to limit or balance voltage between cells, best for high duty cycle or when efficiency and stand by loss from leakage current are important, highest cell reliability option

Active cell to cell balance circuit

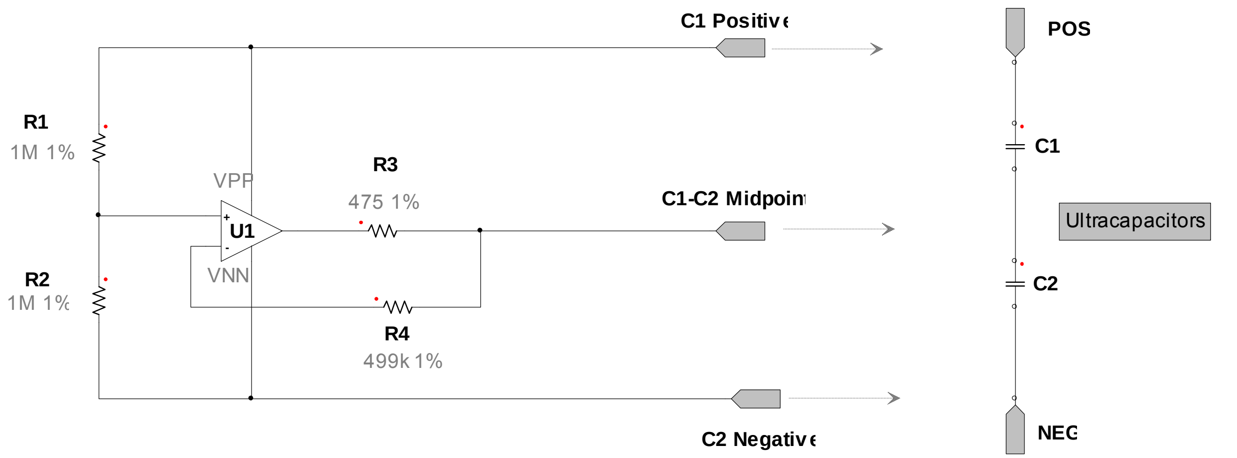
Cell Balancing

- Low Cost
- Scalable balance current
  - 10mA, 300mA circuits
- Very low quiescent current (<20µA)
  - No on/off required
- Modular installation
  - N cells requires N-1 circuits
- Voltage independent

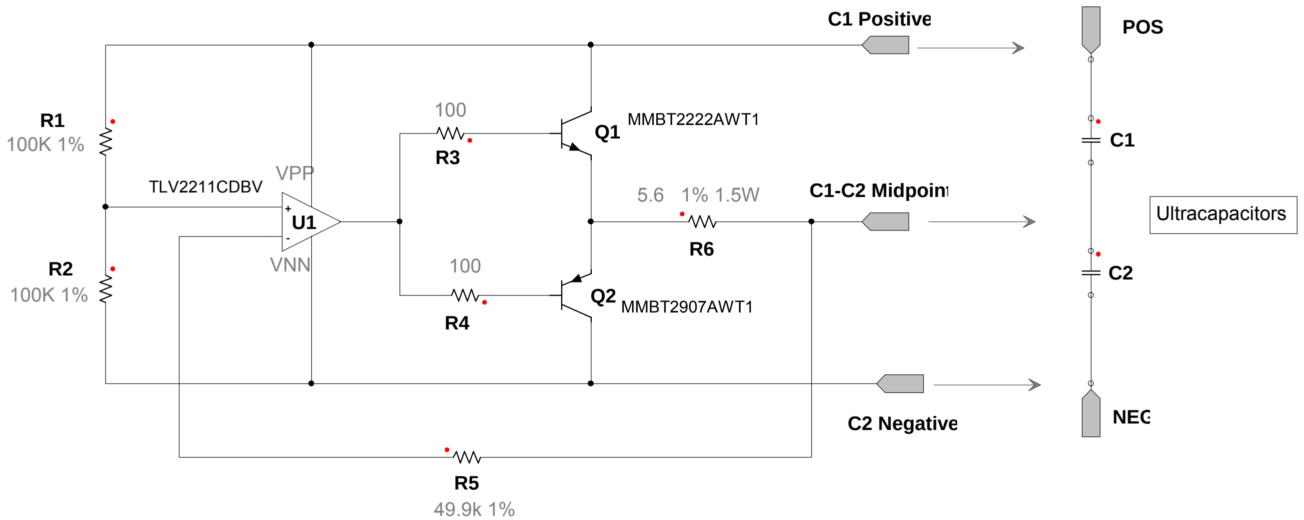




Cell Balancing



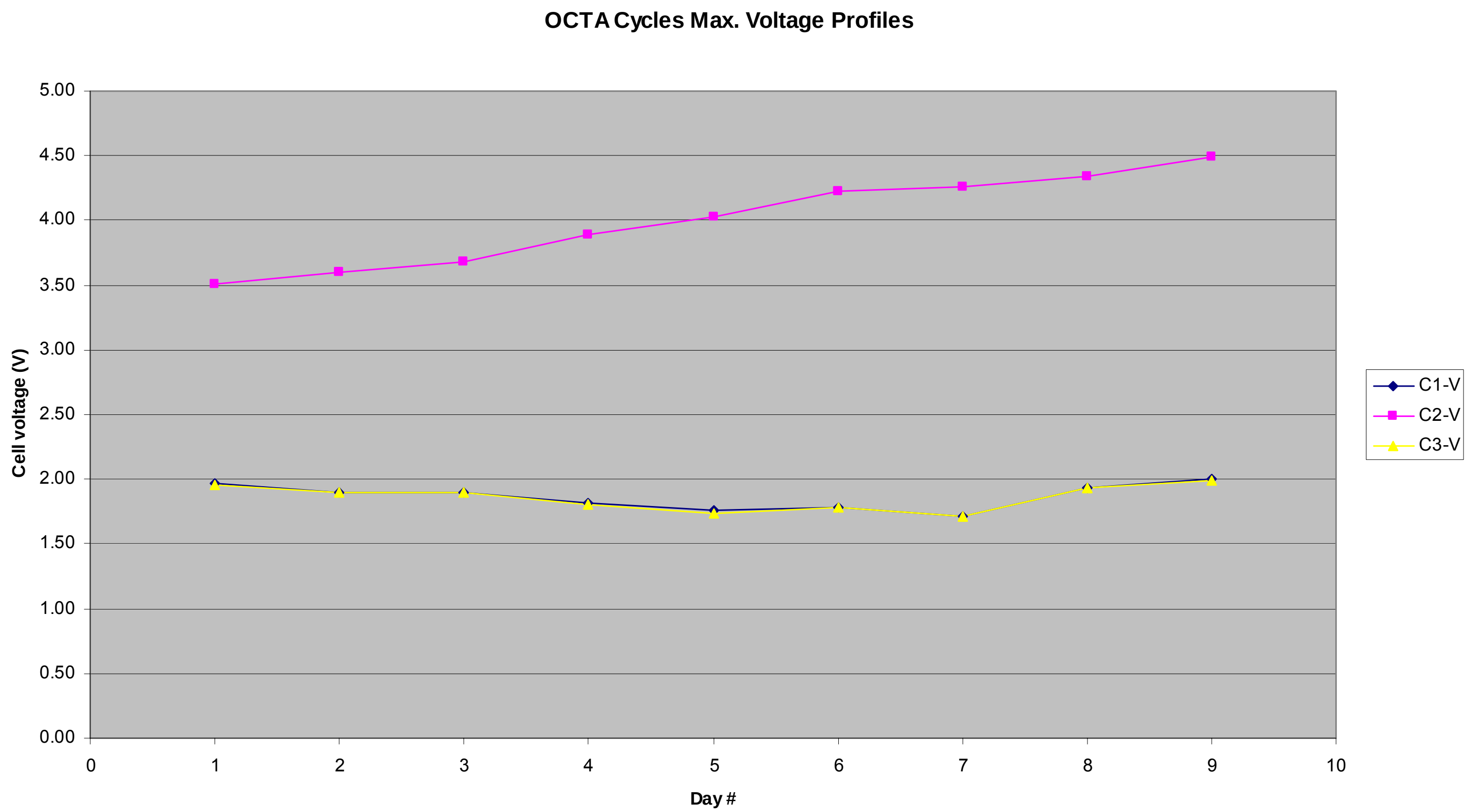
10mA Balancer



300mA Balancer

Cell Balancing

Three cells with one cell balancing resistor removed:



Ultracapacitor Packaging

Why Packaging?

- Ensure proper mechanical stress
- Ensure robust low resistance interconnect
- Ensure proper electrical isolation
- Ensure proper thermal considerations
- Ensure agency compliance
- Increase overall cell reliability
- Reduce or eliminate maintenance requirements

How to Package Cells?

- Care should be taken for the electrical interconnect, a few key guidelines to follow:
  - Do not over torque. Over torque at the terminals may cause internal failure of contact points. For example, the Maxwell BCAP specification is 100 in.-lbs
  - Use similar conductor metal interconnect bus bars to eliminate galvanic corrosion.
  - Good surface to surface contact will reduce inter-cell resistance, reducing voltage drop and temperature stress

How to Package Cells?

- Cell to cell spacing should take into consideration two key points and can be accomplished by the design of the interconnect or the cell balancer:
  - Depending on the cell some part of the outer case may be electrically the same as one of the terminals, ensure electrical isolation and watch for rubbing components that may wear through ultracapacitor insulation, do not remove the factory installed insulator sleeve
  - Some air space between the cells allows convection cooling via air flow improving reliability, depends on cycle time, short duration high cycle applications may require forced air or other cooling method

Ultracapacitor Packaging

Electrical Isolation

Aluminum Interconnect

Proper Torque and Hardware

Summary

Benefits Summary

Calendar Life

- Function of average voltage and temperature

Cycle Life

- Function of average voltage and temperature

Charge acceptance

- Charge as fast as discharge, limited only by heating

Temperature

- High temp; no thermal runaway
- Low temp; -40°C

Benefits Summary

No fixed V_{oc}

- Control Flexibility; context-dependent voltage is permitted
- Power Source voltage compatibility
  - Examples; Fuel cells, Photovoltaic devices

No V_{min}

- Cell can be discharge to 0V.
- Control Safety; No over-discharge
- Service Safety

Cell voltage management

- Only required to prevent individual cell over-voltage

State of Charge & State of Health

- State of Charge equals V_{oc}
- Dynamic measurements for C and ESR = State of Health
- No historical data required

Capacitor Manufacturer since 1965

www.maxwell.com

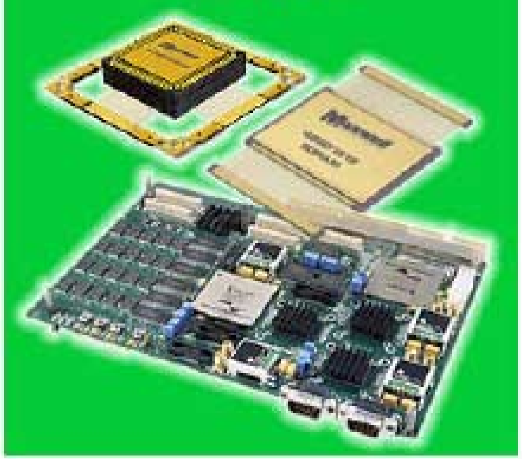
Maxwell is a leading developer and manufacturer of innovative, cost-effective energy storage and power delivery solutions.

Manufacturing facilities:
US, Europe, Asia

Certifications:

ISO 9001:2000
ISO/TS 16949
ISO 9002

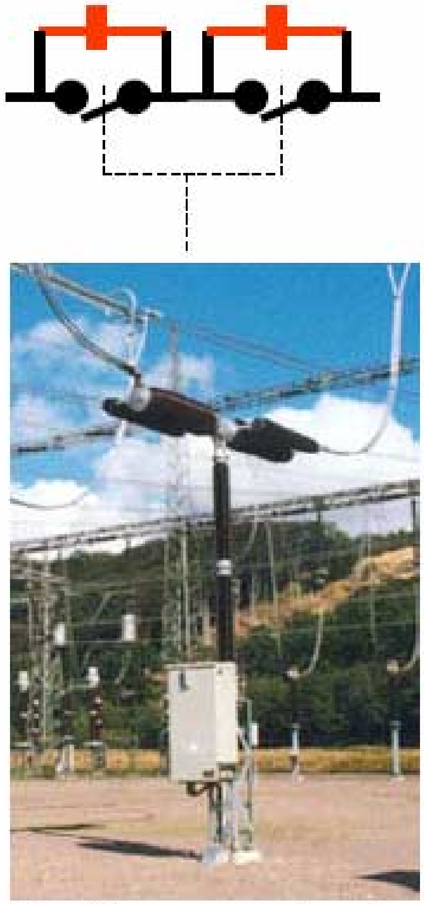
Radiation Mitigated Microelectronics for Space



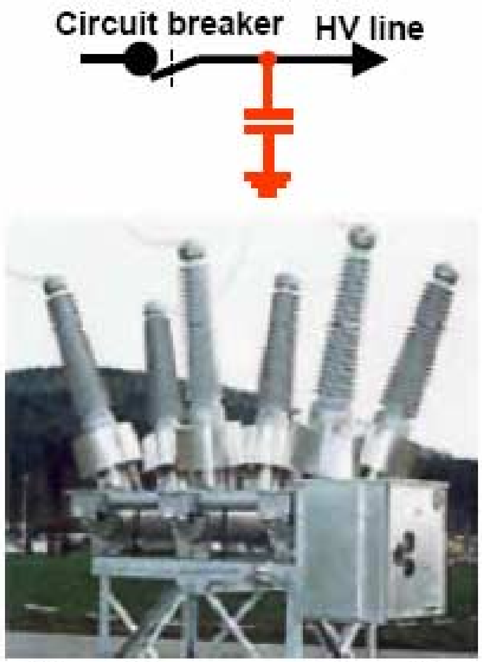
BOOSTCAP® Ultracapacitors & Modules

CONDIS® High Voltage Capacitors & CVDs

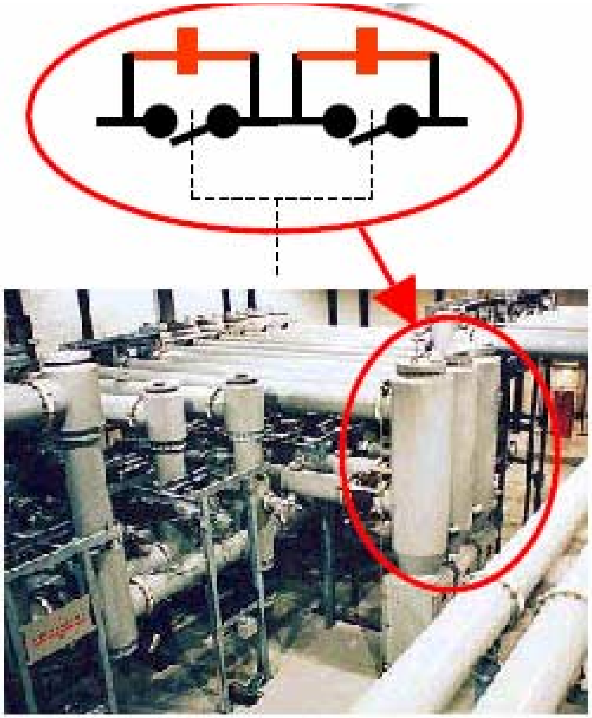
Booth at IEEE, T&D 2006



Grading capacitor for live tank circuit breaker



Coupling capacitor for dead tank circuit breaker



Coupling/Grading capacitor for GIS – circuit breaker

Useful Links

- Useful links on Maxwell Technologies Web-site:
  - White Papers
  - Technology Overview
  - Sizing worksheet
  - Application Notes
  - Data Sheets
  - Product Guide

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