sensors expo
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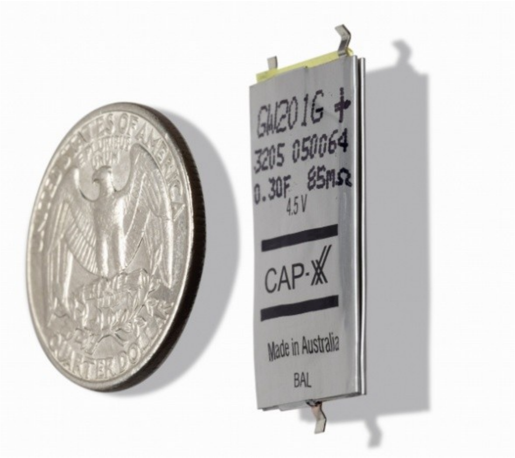
June 7-9, 2010 • Donald E. Stephens Convention Center • Rosemont, IL

CAP-XX



Using a Small Solar Cell for Harvesting and a Supercapacitor for Power Management in a Wireless Sensor

9th June 2010

Agenda

- Supercapacitor Properties
  - What’s inside
  - Power buffer
  - Leakage current
  - Charge current
  - Ageing
- Solar cell characteristics
- Circuits to charge supercpacitors from solar cells
- Sizing your supercapacitor

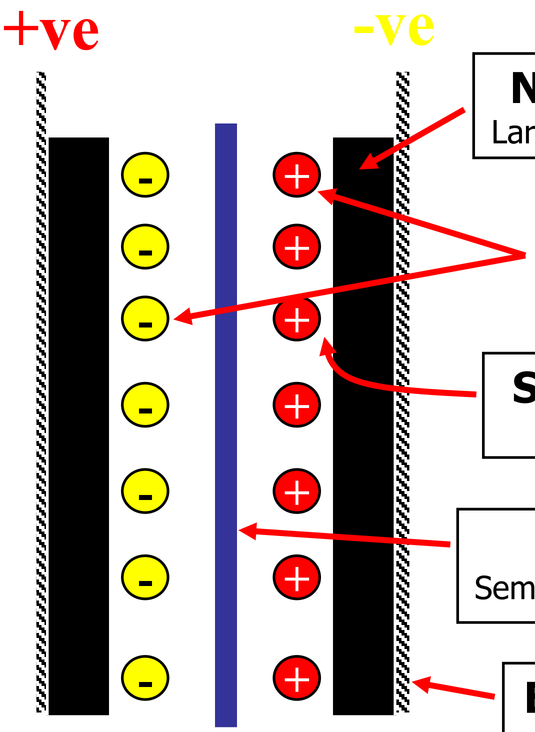
What is a Supercapacitor?

A supercapacitor is an energy storage device which utilizes high surface area carbon to deliver much higher energy density than conventional capacitors

Basic Theory:
Capacitance is proportional to the charge storage area, divided by the charge separation distance (C α A / d)

As area (A) ↑, and
charge distance (d) ↓
capacitance (C) ↑↑↑↑

No dielectric, working voltage determined by electrolyte



Nanoporous carbon:
Large surface area > 2000m^2/gm

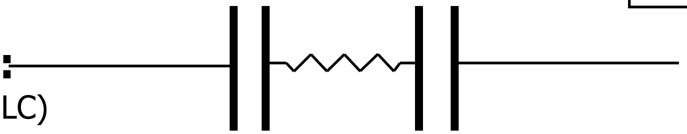
Electrolyte:
Ions in a solvent

Separation distance:
Solid-liquid interface (nm)

Separator:
Semi-permeable membrane

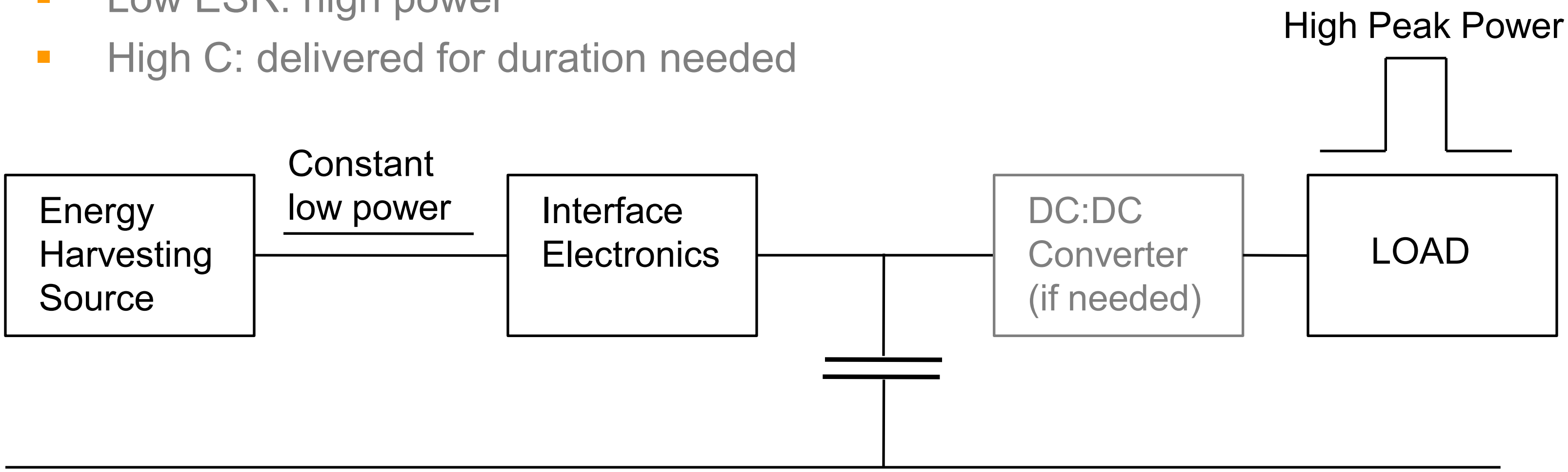
Electrode:
Aluminum foil

Basic Electrical Model:
Electric Double Layer Capacitor (EDLC)



Supercapacitor as a power buffer

- A supercapacitor buffers the load from the source. Source provides low average power, supercapacitor provides peak power to the load.
- Average load power < Average source power
- Source sees low power load
- Load sees low impedance source that delivers high peak power for duration needed
  - Low ESR: high power
  - High C: delivered for duration needed



High Peak Power

Energy Harvesting Source

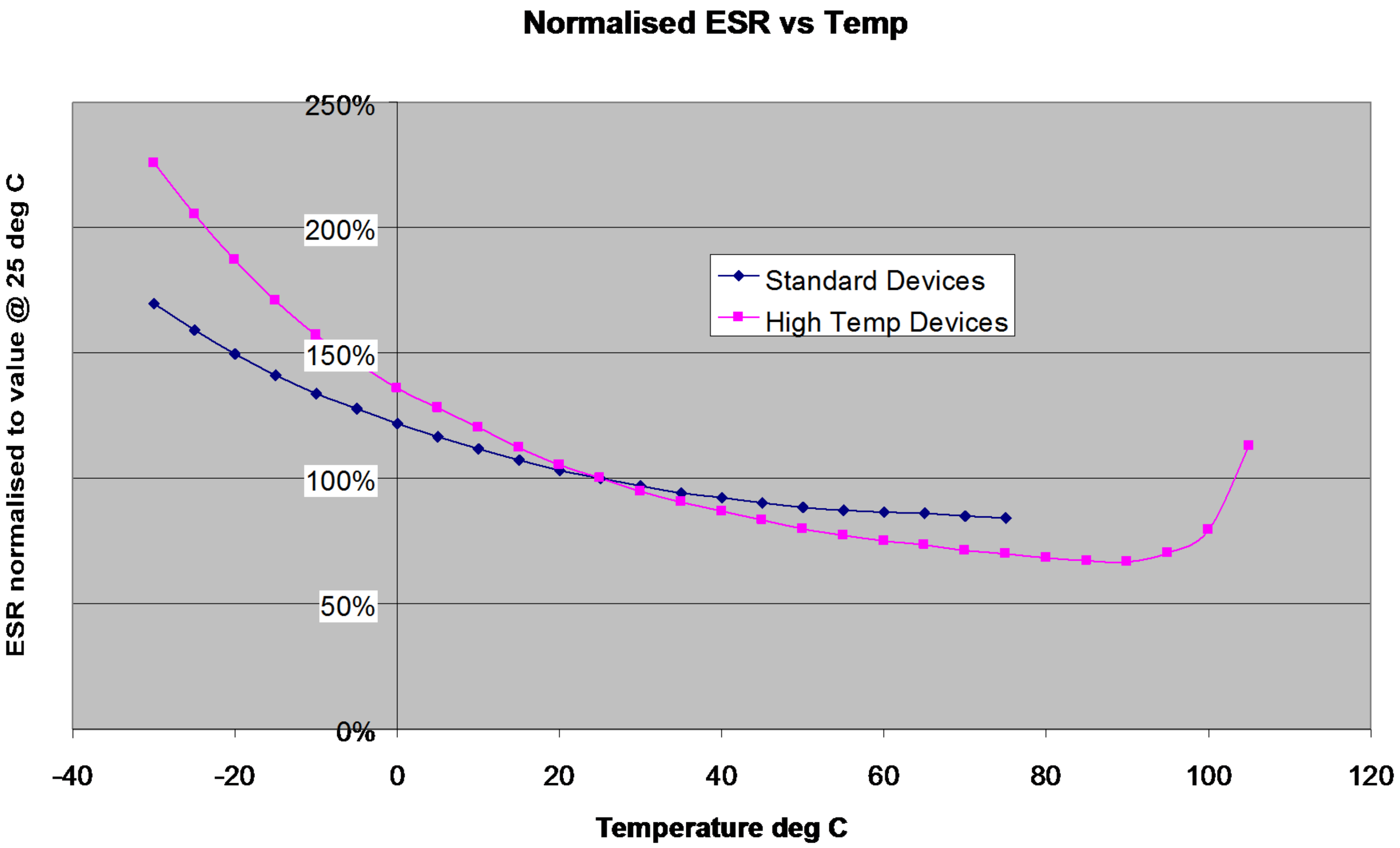
Constant low power

Interface Electronics

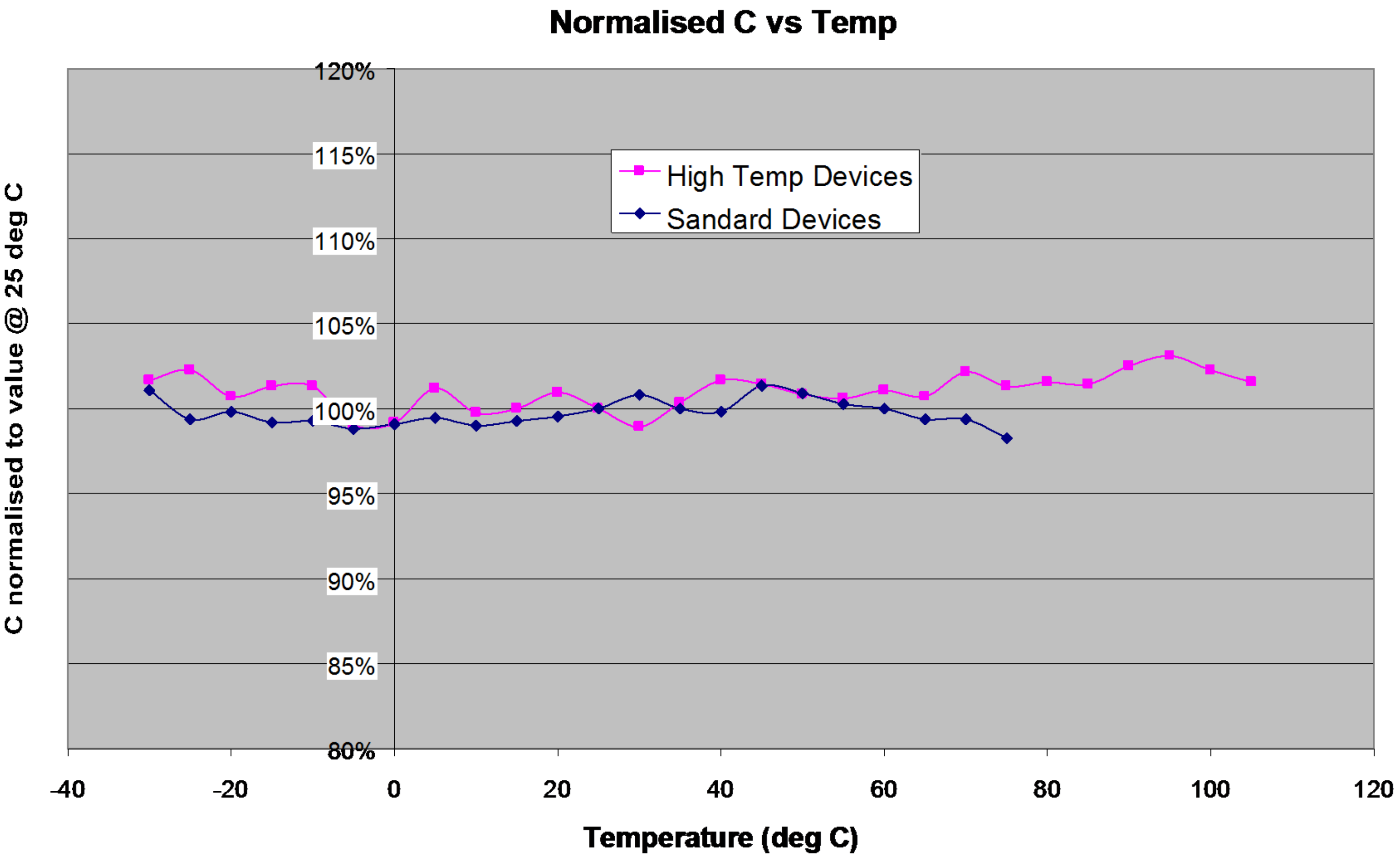
DC:DC Converter (if needed)

LOAD

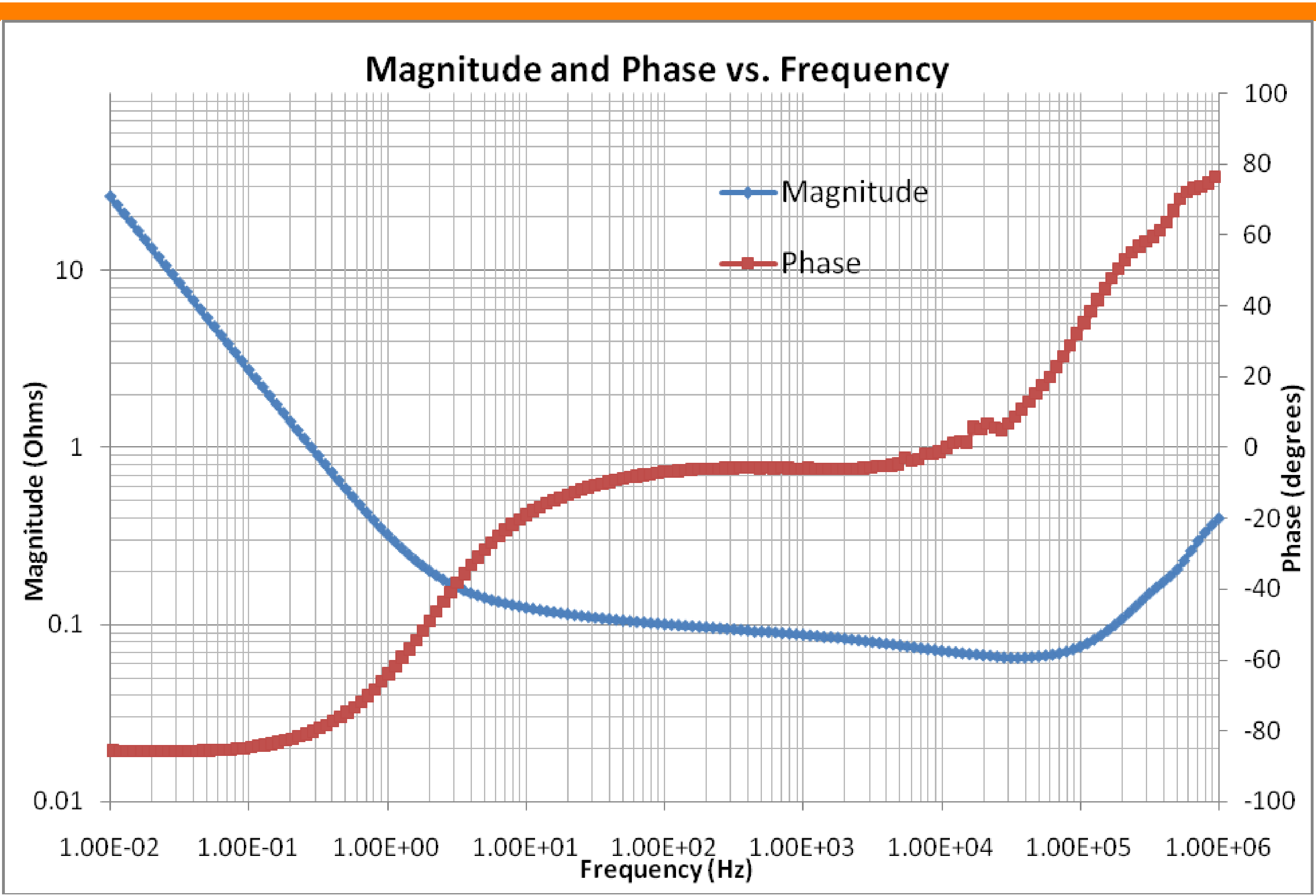
Excellent performance over a wide temperature range: Power Delivery



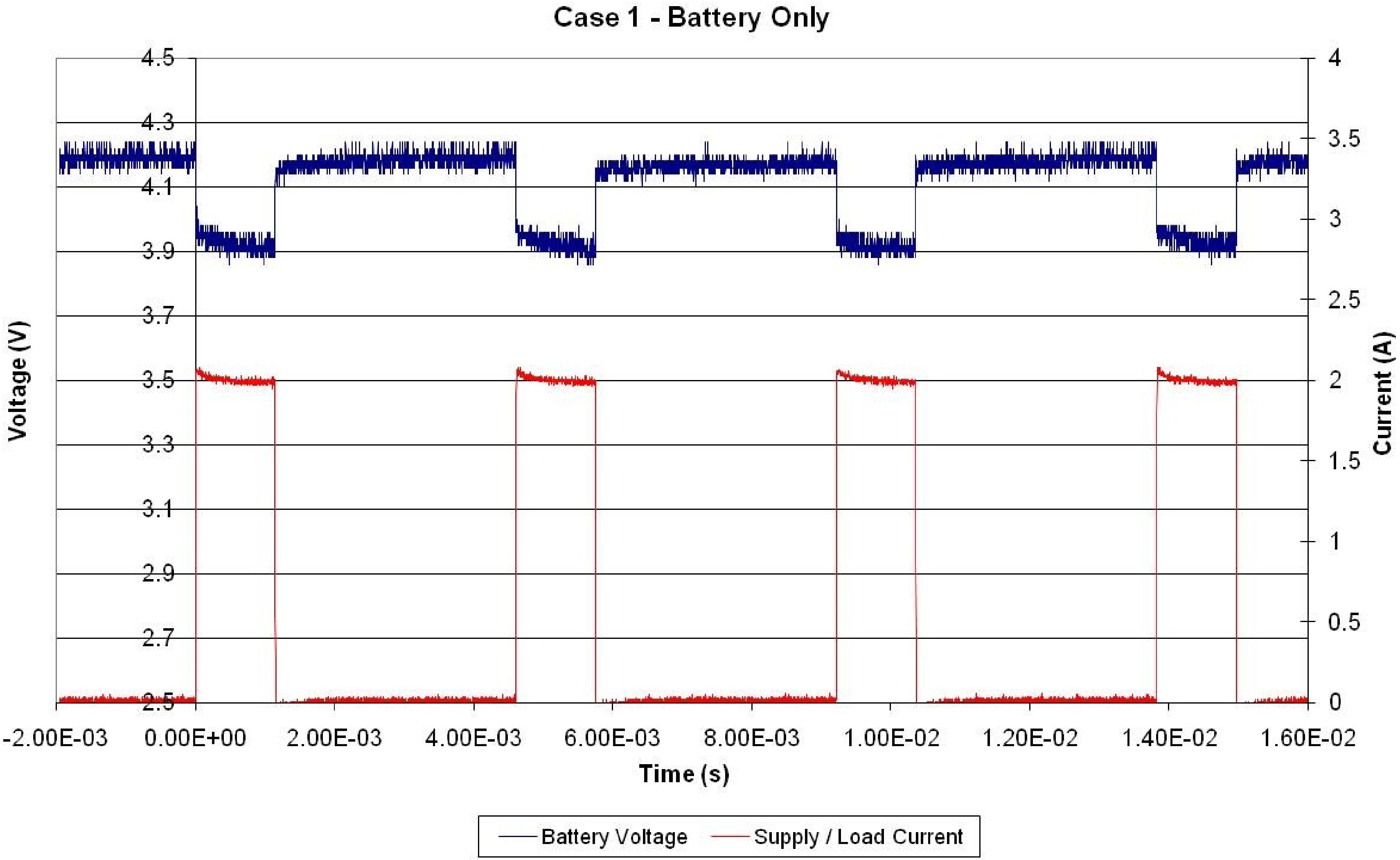
Excellent performance over a wide temperature range: Energy Storage



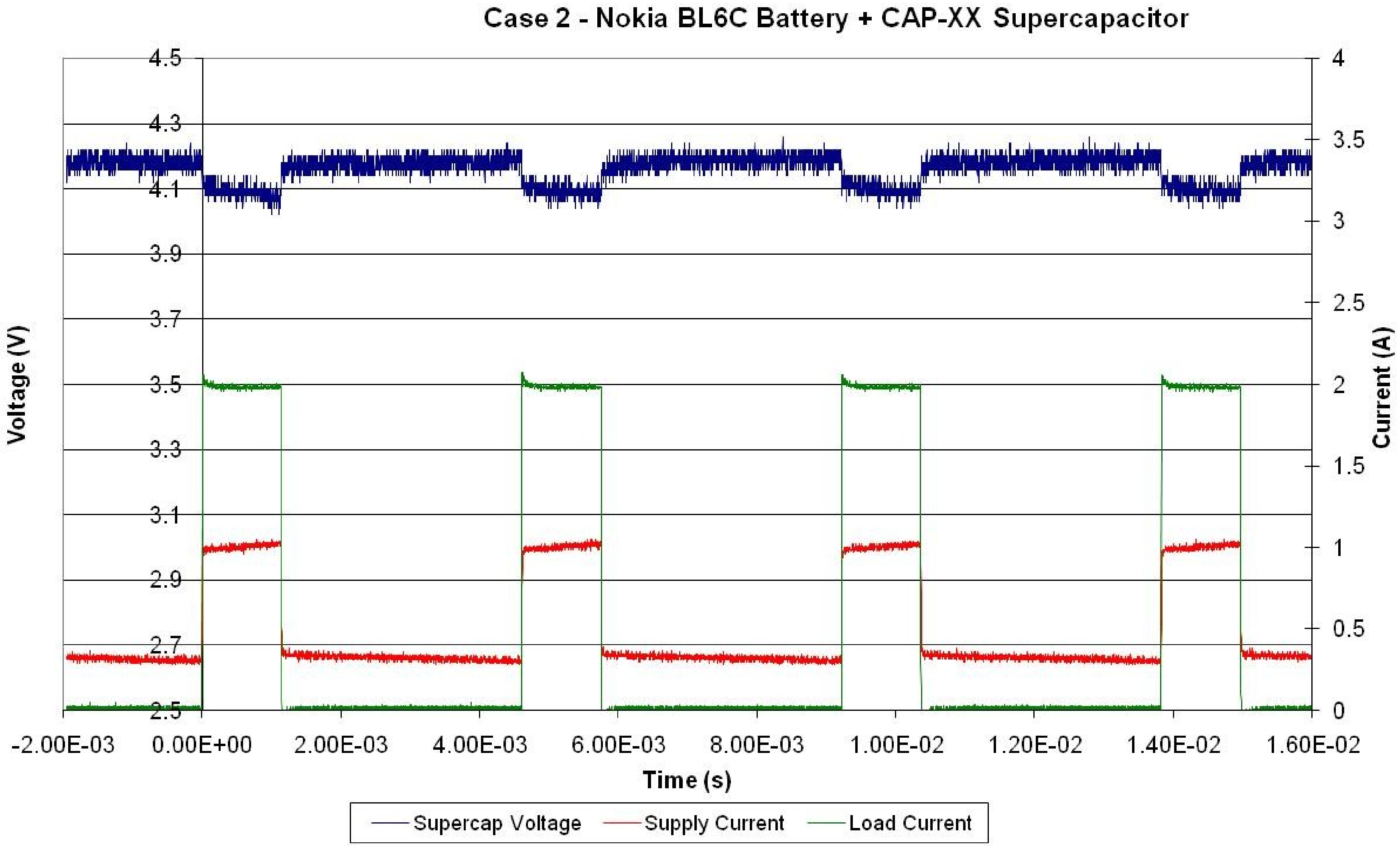
Poor frequency response …



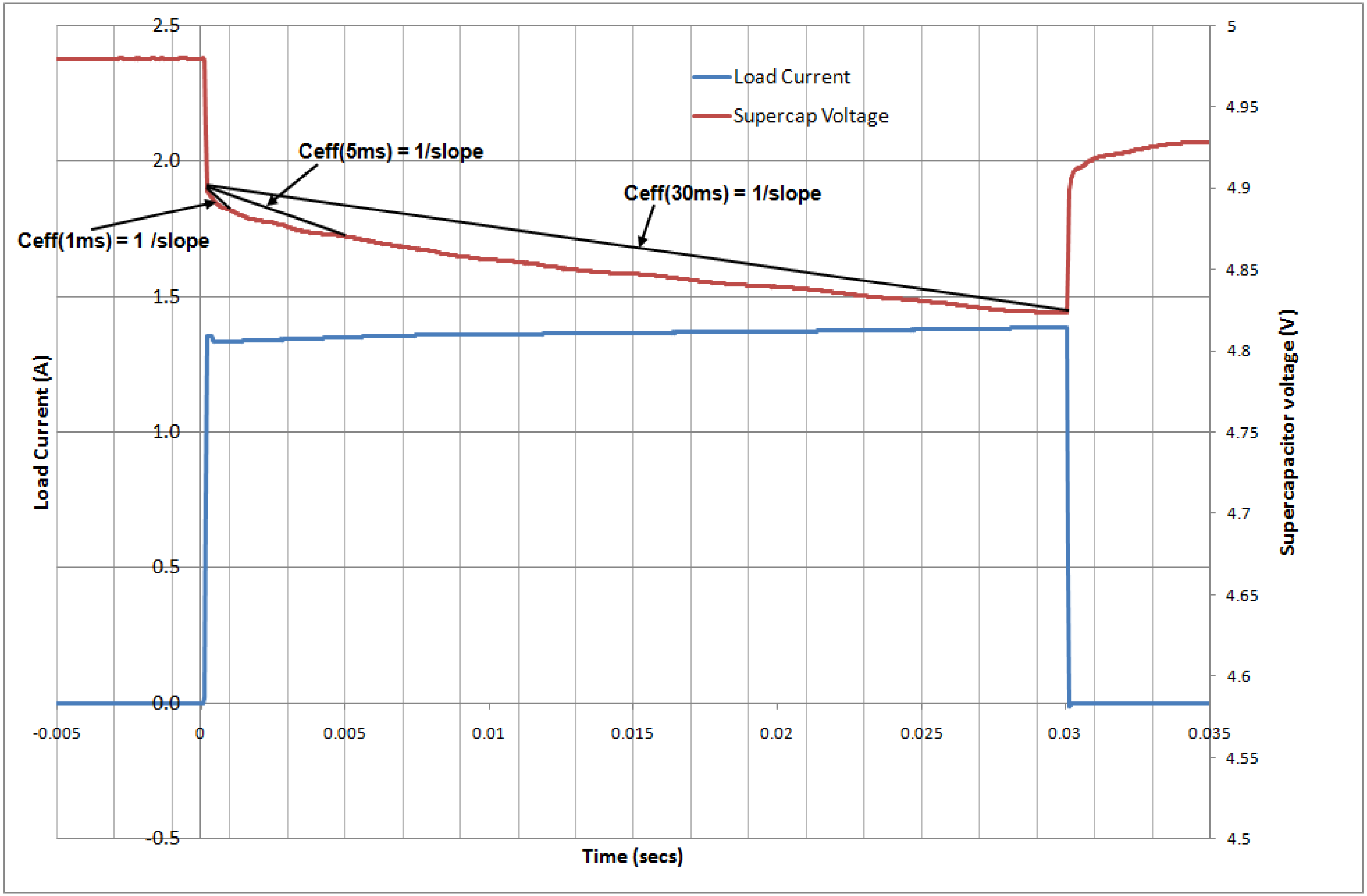
…But excellent pulse response



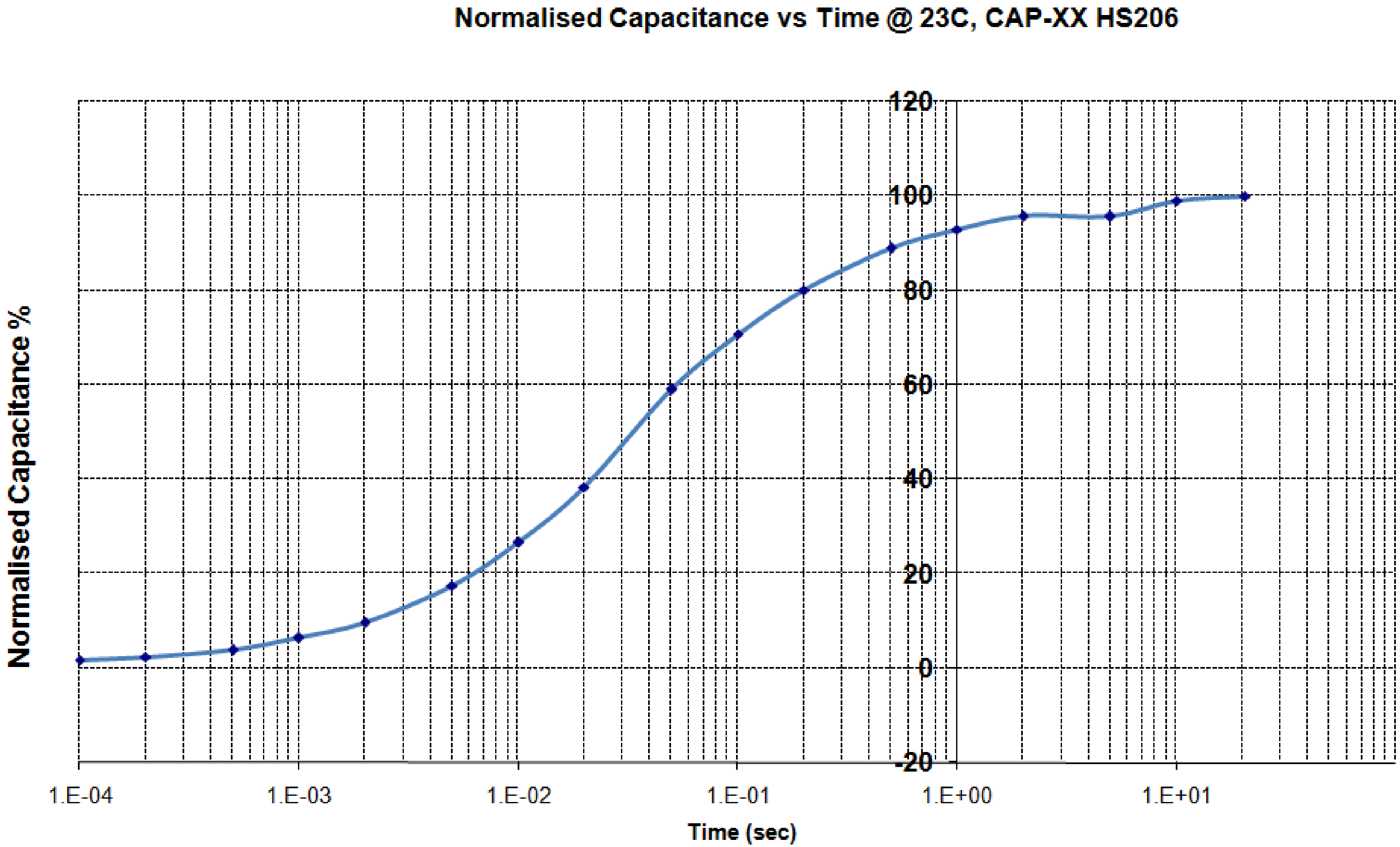
Excellent pulse reponse



Ceffective as a function of PW



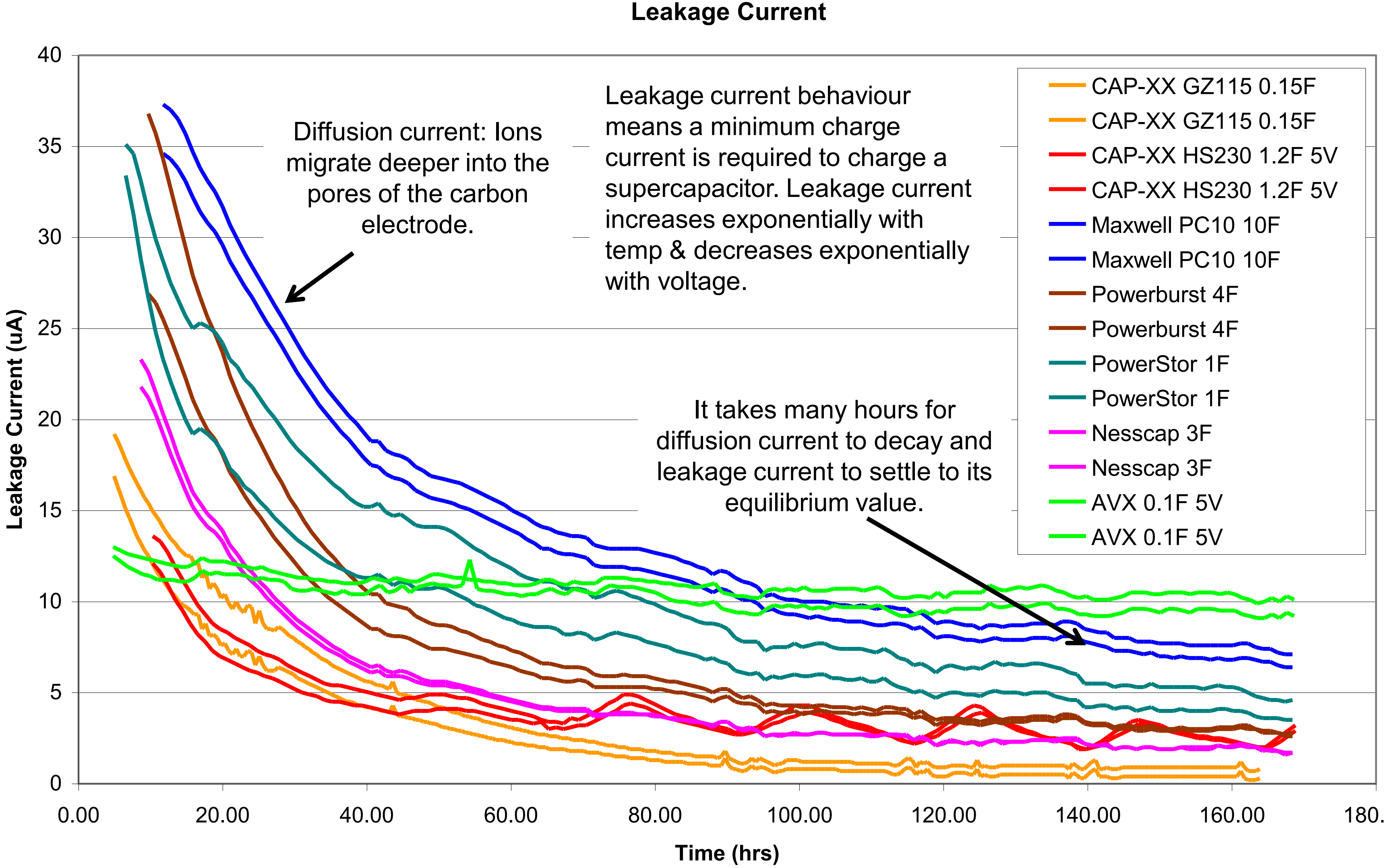
Ceffective data



CAP-XX Required C reduces faster than Ceff

- HS206, DC Capacitance = 600mF
- ΔV = I. Δt/Ceff
- 2A for 1ms
  - Ceff = 6.5% of 600mF = 39mF
  - ΔV = 2A x 1ms/39mF = 51mV
- 2A for 10ms
  - Ceff = 26% of 600mF = 156mF
  - ΔV = 2A x 10ms/156mF = 128mV
- 2A for 100ms
  - Ceff = 70% of 600mF = 420mF
  - ΔV = 2A x 1ms/39mF = 476mV

Supercapacitor Leakage Current

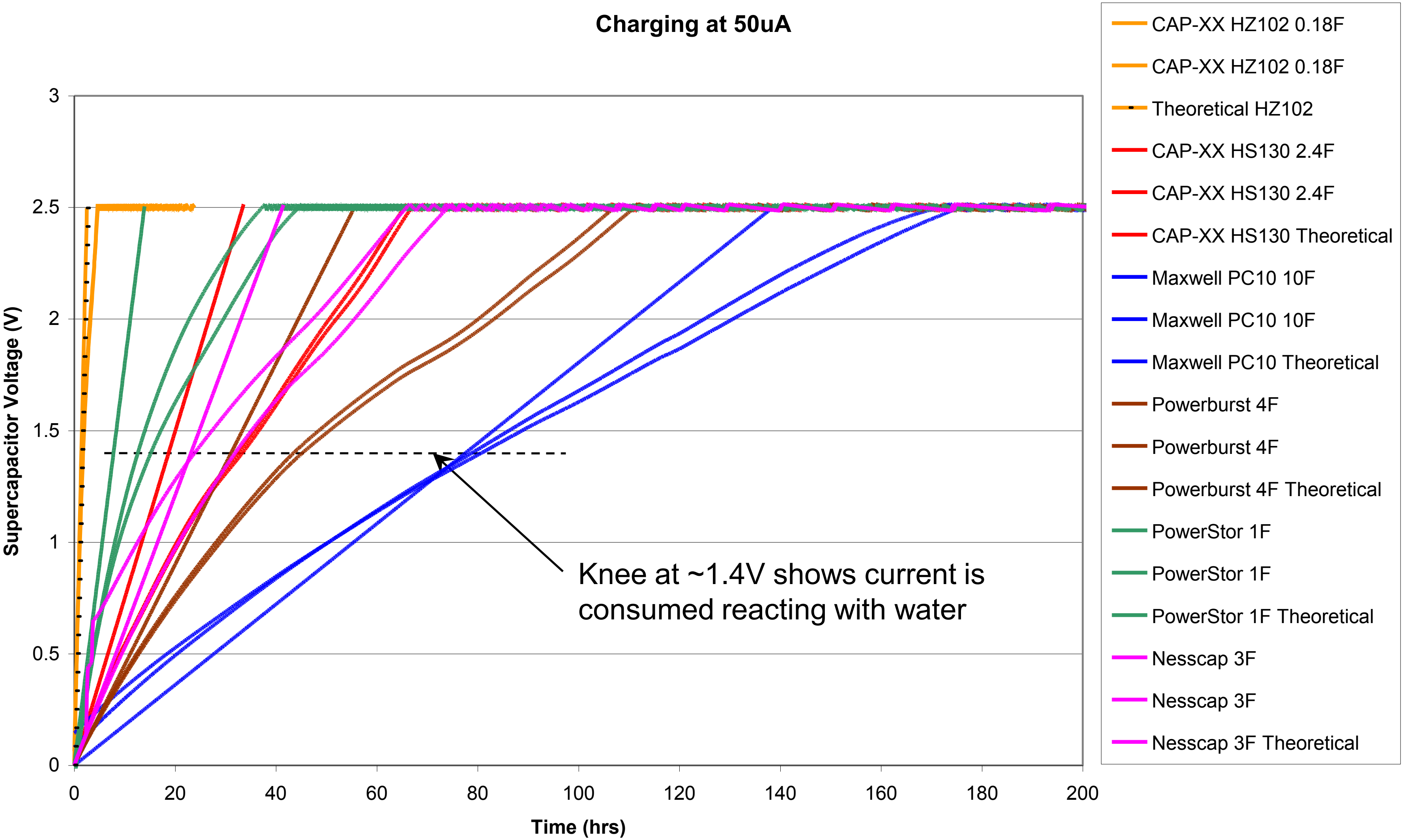


Diffusion current: Ions migrate deeper into the pores of the carbon electrode.

Leakage current behaviour means a minimum charge current is required to charge a supercapacitor. Leakage current increases exponentially with temp & decreases exponentially with voltage.

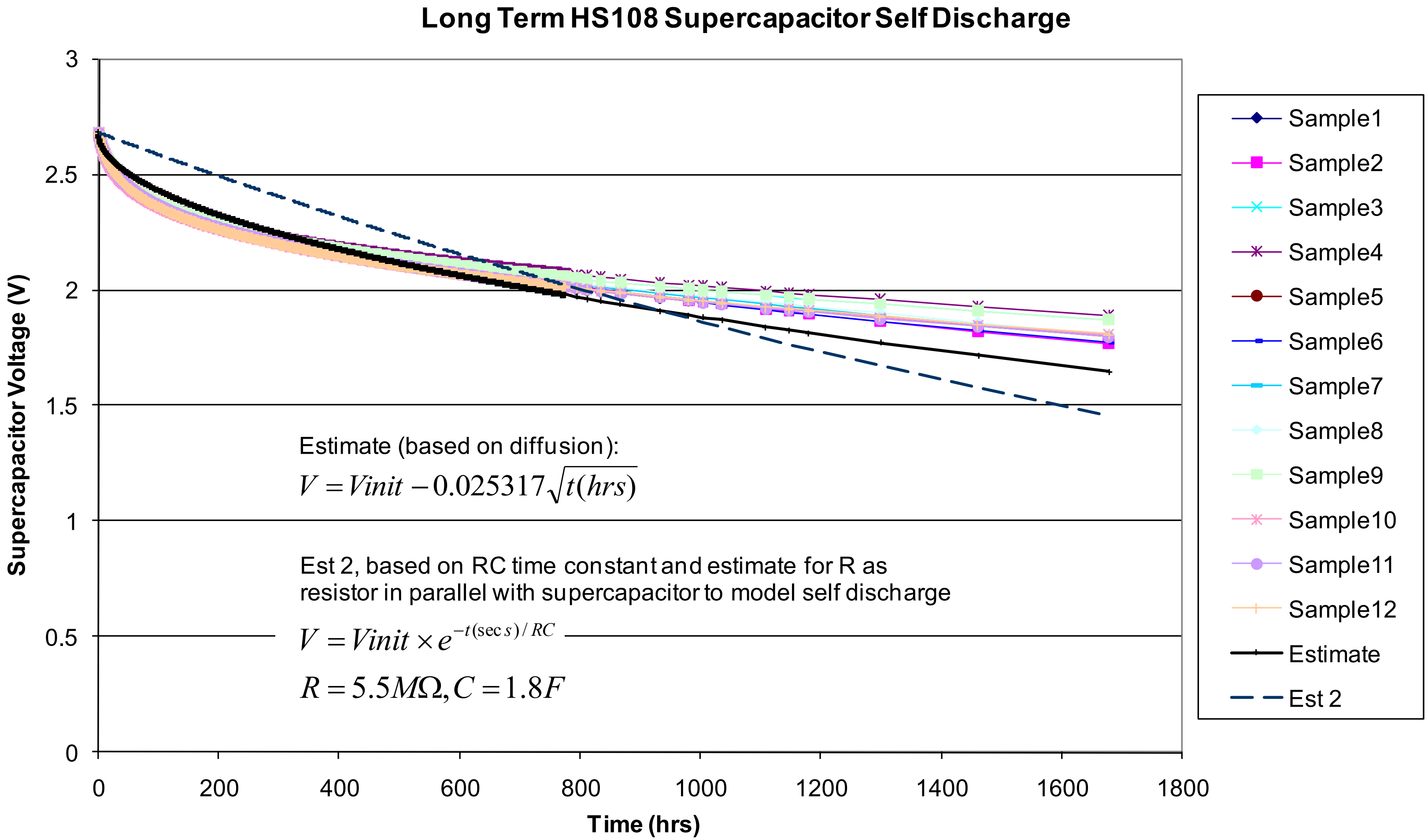
It takes many hours for diffusion current to decay and leakage current to settle to its equilibrium value.

Supercapacitors need a minimum initial charging current …



Knee at ~1.4V shows current is consumed reacting with water

Self discharge characteristic empirically determined



Estimate (based on diffusion):

$$V = Vinit - 0.025317\sqrt{t(hrs)}$$

Est 2, based on RC time constant and estimate for R as resistor in parallel with supercapacitor to model self discharge

$$V = Vinit \times e^{-t(\sec s)/RC}$$

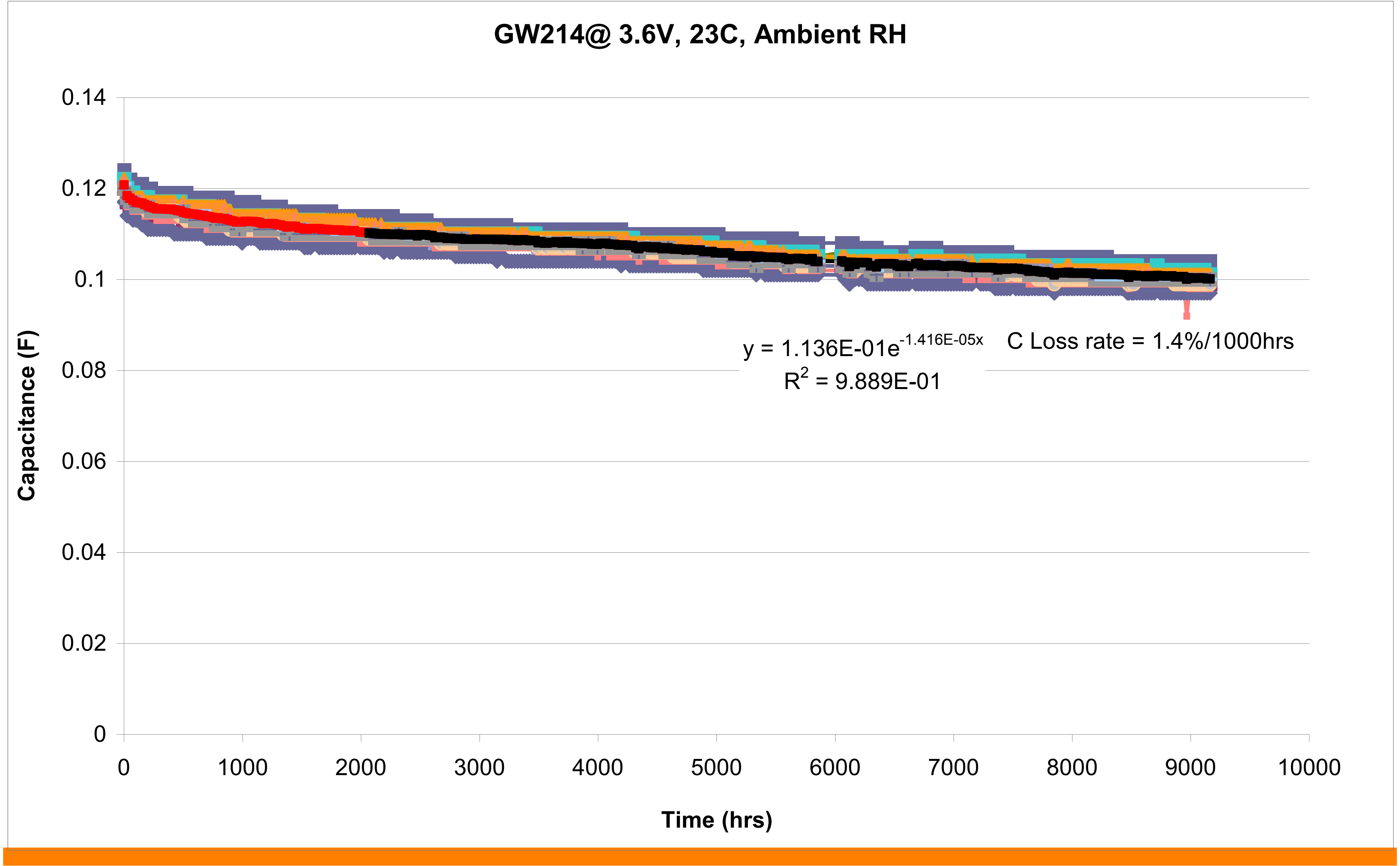
$$R = 5.5M\Omega, C = 1.8F$$

Figure 12: Supercapacitor self discharge characteristic

Take ageing into account when sizing your supercapacitor

- Supercapacitors use physical not electrochemical charge storage
- Ageing is a function of time at temperature and voltage, not no. of cycles
- Determine expected ageing from operating profiles (voltage and temp combination) and their duty cycle
- Size supercapacitor so you have required C & ESR at end of life after allowing for ageing

Supercapacitor ageing – C loss

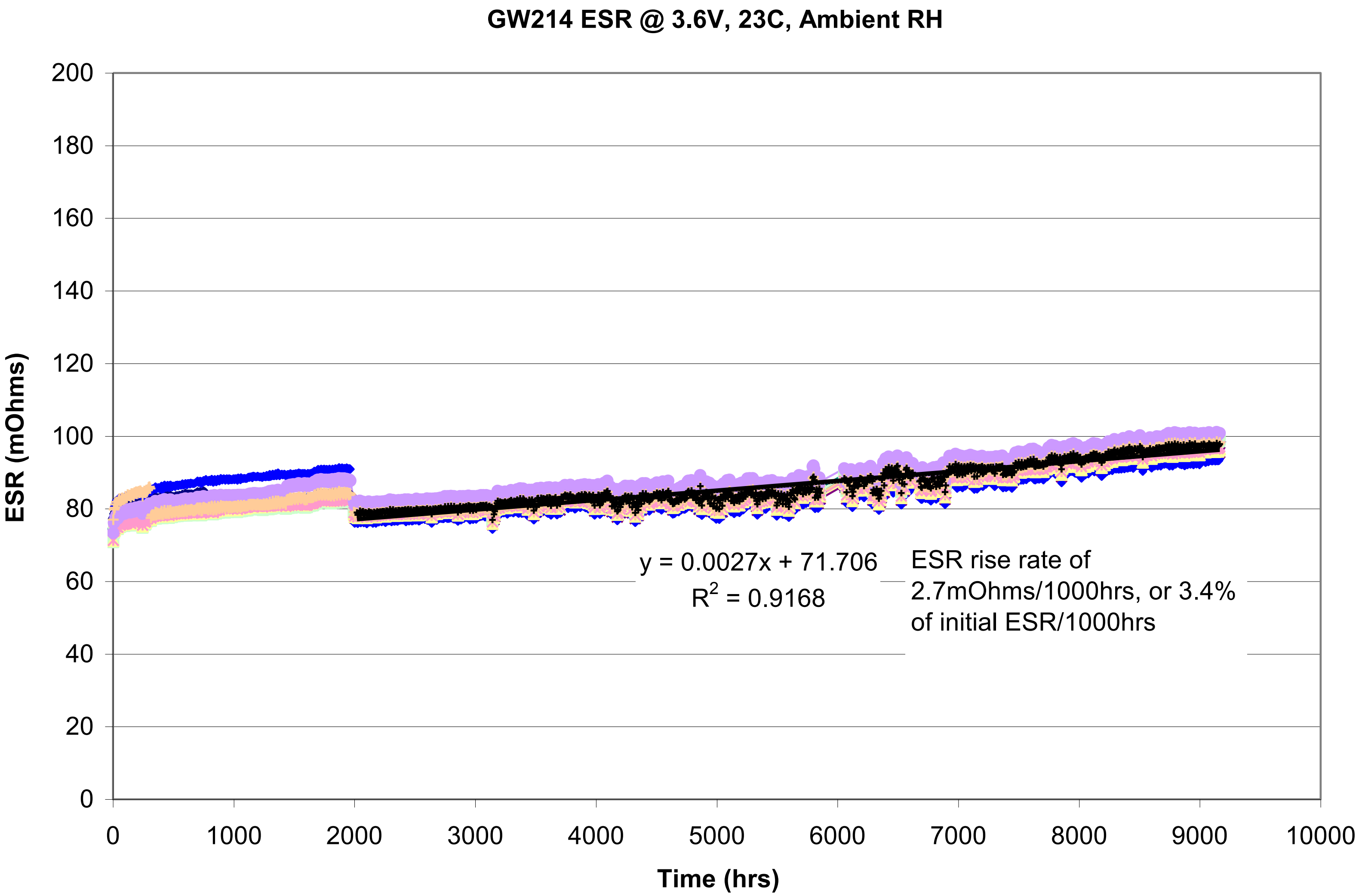


$y = 1.136E\text{-}01e^{-1.416E\text{-}05x}$

$R^2 = 9.889E\text{-}01$

C Loss rate = 1.4%/1000hrs

Supercapacitor ageing – ESR rise



y = 0.0027x + 71.706
$R^2 = 0.9168$

ESR rise rate of 2.7mOhms/1000hrs, or 3.4% of initial ESR/1000hrs

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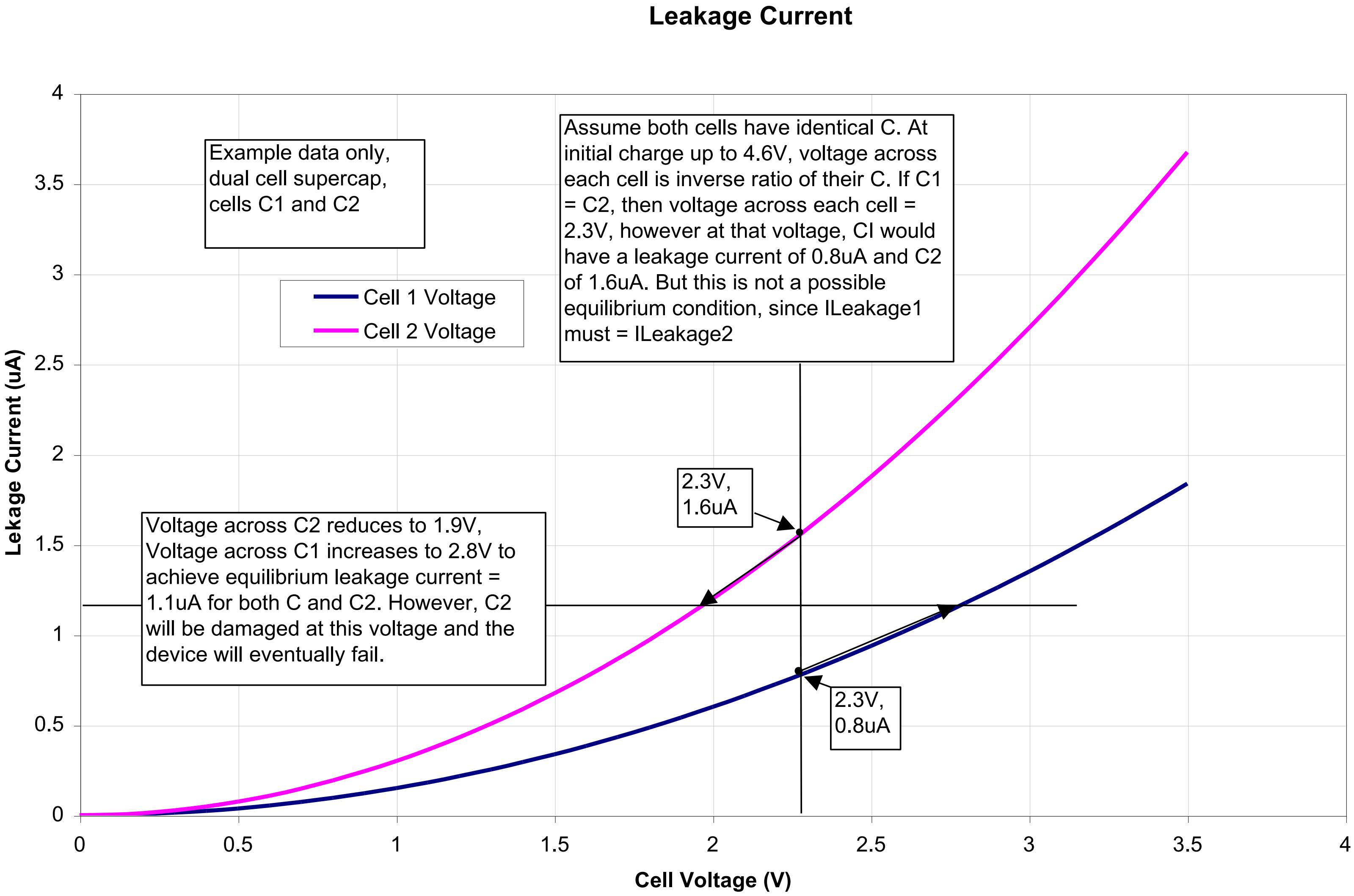
Cell balancing is needed



Leakage Current

Example data only, dual cell supercap, cells C1 and C2

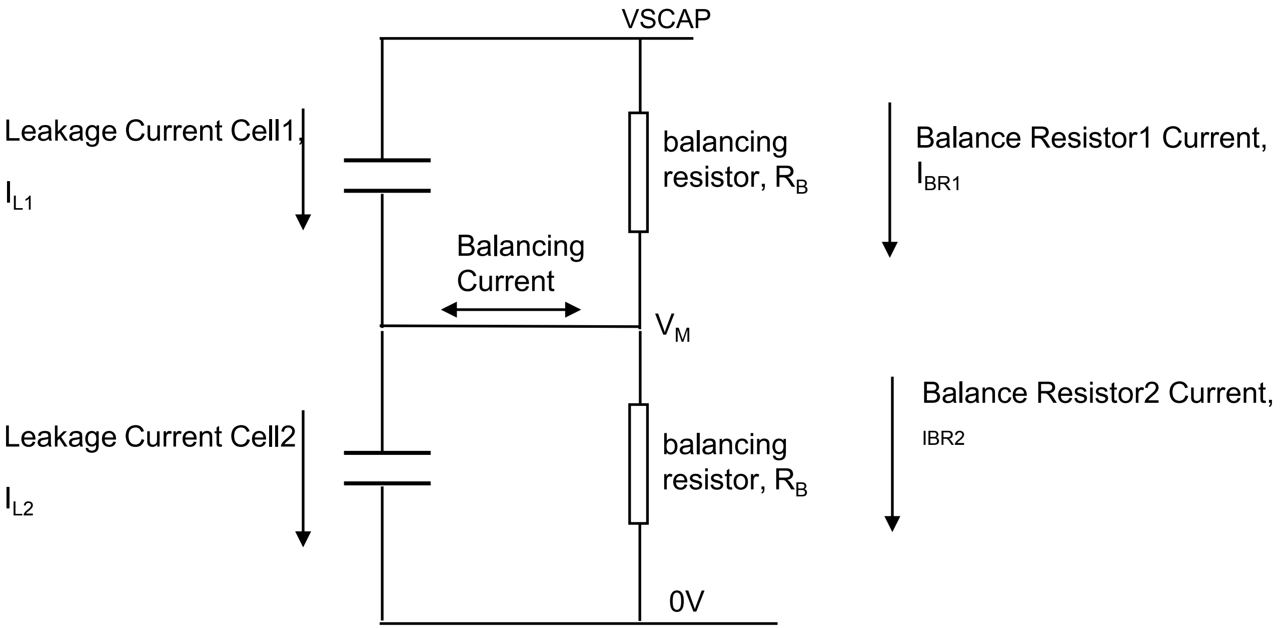
Assume both cells have identical C. At initial charge up to 4.6V, voltage across each cell is inverse ratio of their C. If C1 = C2, then voltage across each cell = 2.3V, however at that voltage, CI would have a leakage current of 0.8uA and C2 of 1.6uA. But this is not a possible equilibrium condition, since ILeakage1 must = ILeakage2

2.3V, 1.6uA

Voltage across C2 reduces to 1.9V, Voltage across C1 increases to 2.8V to achieve equilibrium leakage current = 1.1uA for both C and C2. However, C2 will be damaged at this voltage and the device will eventually fail.

2.3V, 0.8uA

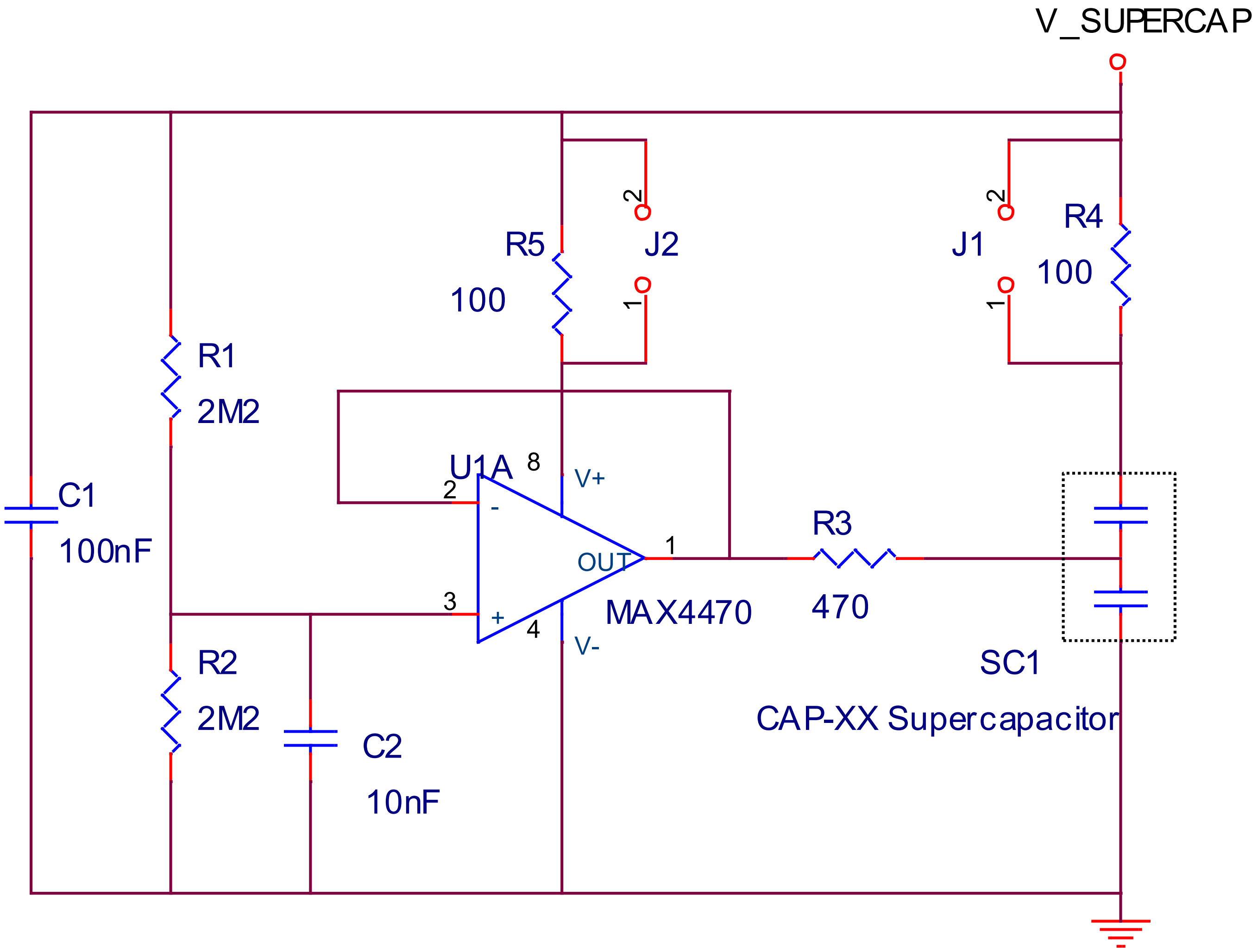
Simplest balancing is a pair of resistors



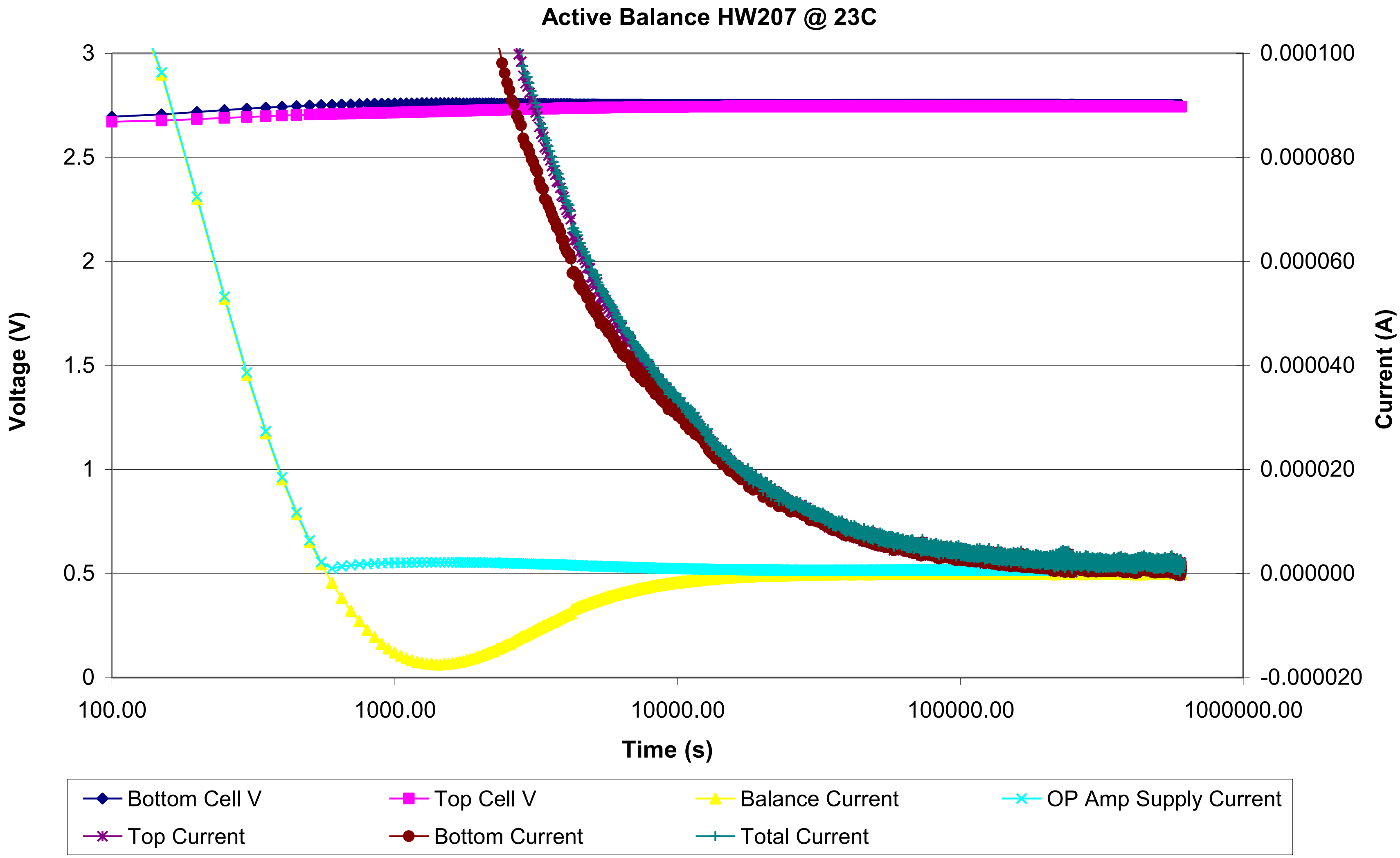
- The purpose of this circuit is to maintain V_M close to $V_{SCAP}/2$.
- $V_M = R_B x I_{BR2} = R_B x(I_{BR1}$-Balancing Current).
- For this circuit to work, Balancing Current must be << I_{BR1}, I_{BR2}.
- VM must be prevented from going >> $V_{SCAP/}2$ or <<V_{SCAP} for any significant length of time.
- SIMPLE but HIGH CURRENT SOLUTION (~100µA)

Active balance circuit

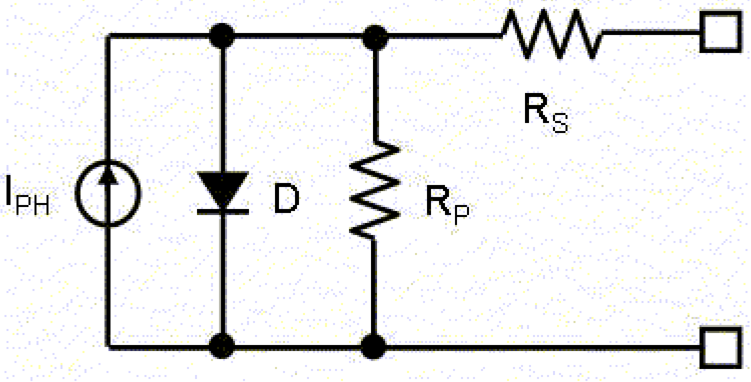
- 2 capacitor cells in series need voltage balancing, otherwise slight differences in leakage current may result in voltage imbalance and one cell going over voltage.
- Low current rail-rail op amp, < 1µA
- Can source or sink current, 11mA
- Supplies or sinks the difference in leakage current between the 2 cells to maintain balance.



Active balance – very low currents



Solar cell characteristics



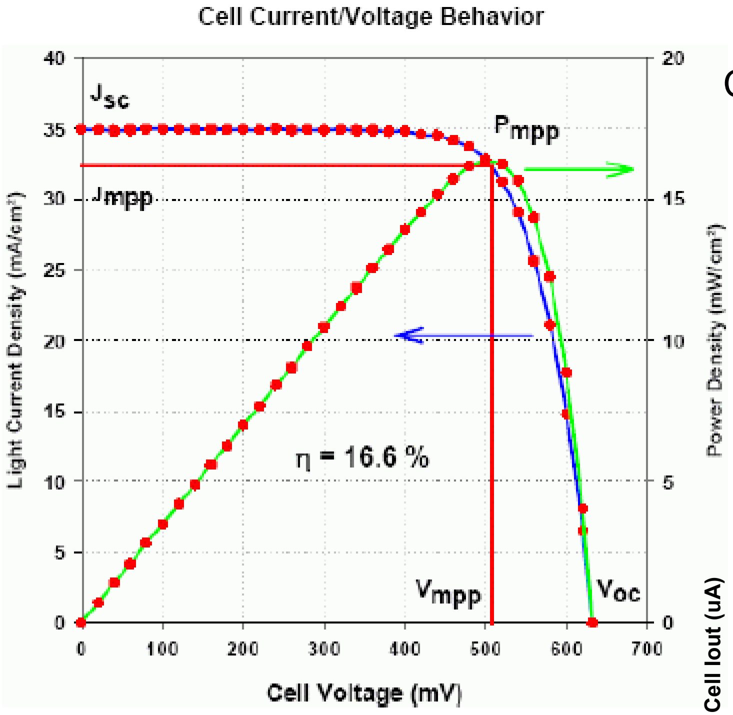
Simplified Circuit Model of a Solar Cell

- I_{PH} generates current α light falling on the cell
- If no load connected all the current flows through the diode whose forward voltage = V_{OC}.
- RP represents leakage current
- RS represents connection losses, usually not significant

XOB17, 22mm x 7mm x 1.6mm used for measurements in following slides

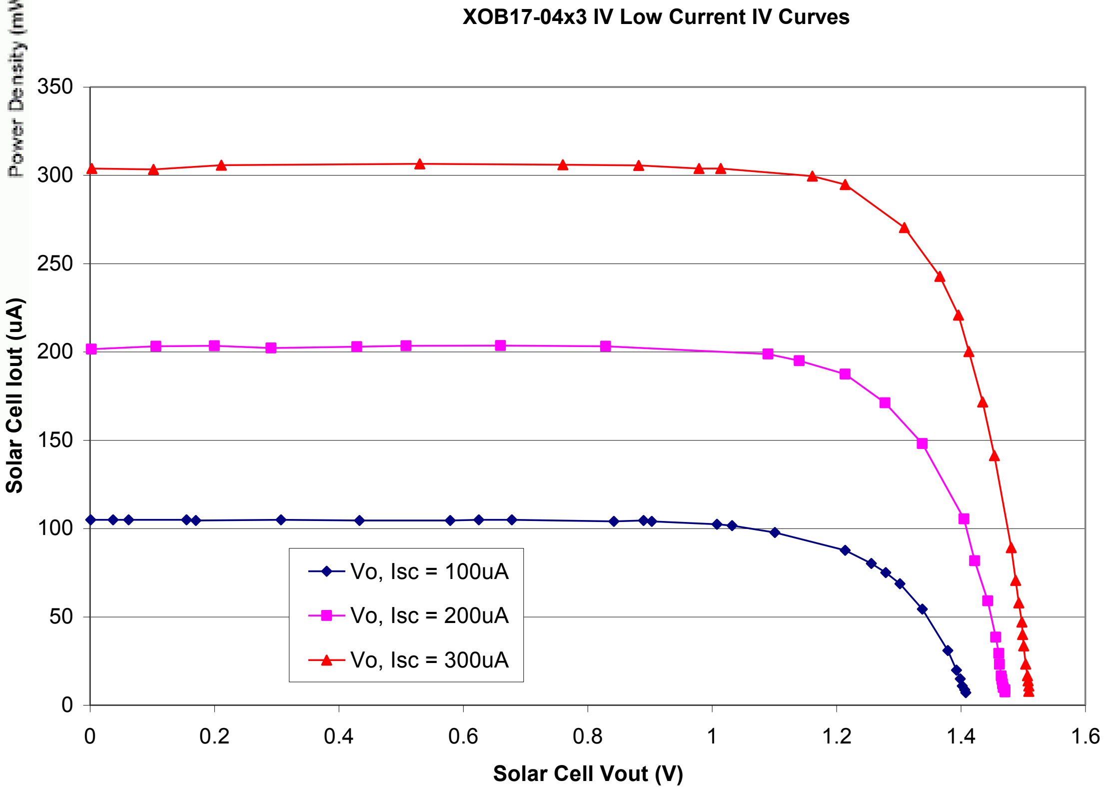
- Will deliver current into a short circuit (discharged supercapacitor)
- Will discharge the load if light level drops

Simple to characterise your solar cell in your conditions



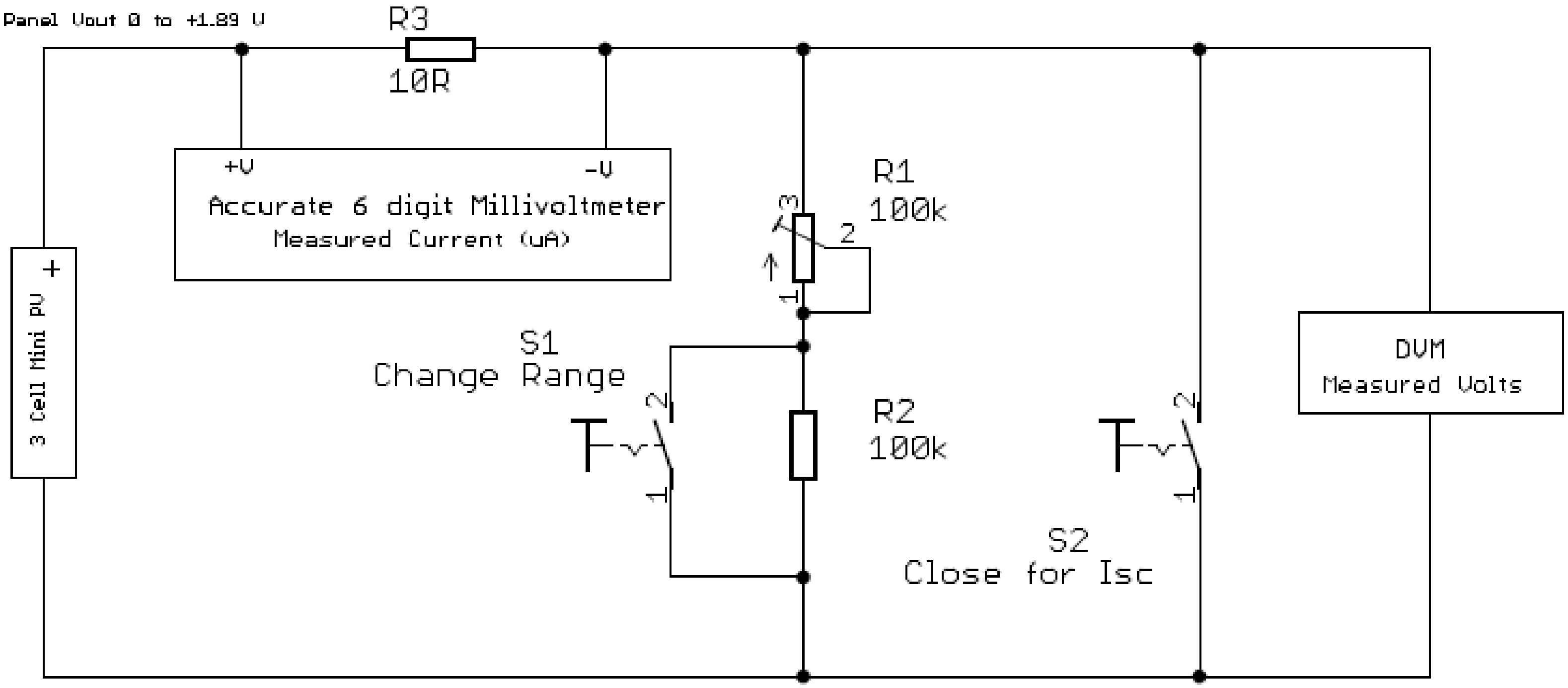
Curves provided in data sheet

Curves developed in lab in our light conditions



Simple to characterise small solar cells

Test Circuit used to record Solar Panel IV Curves

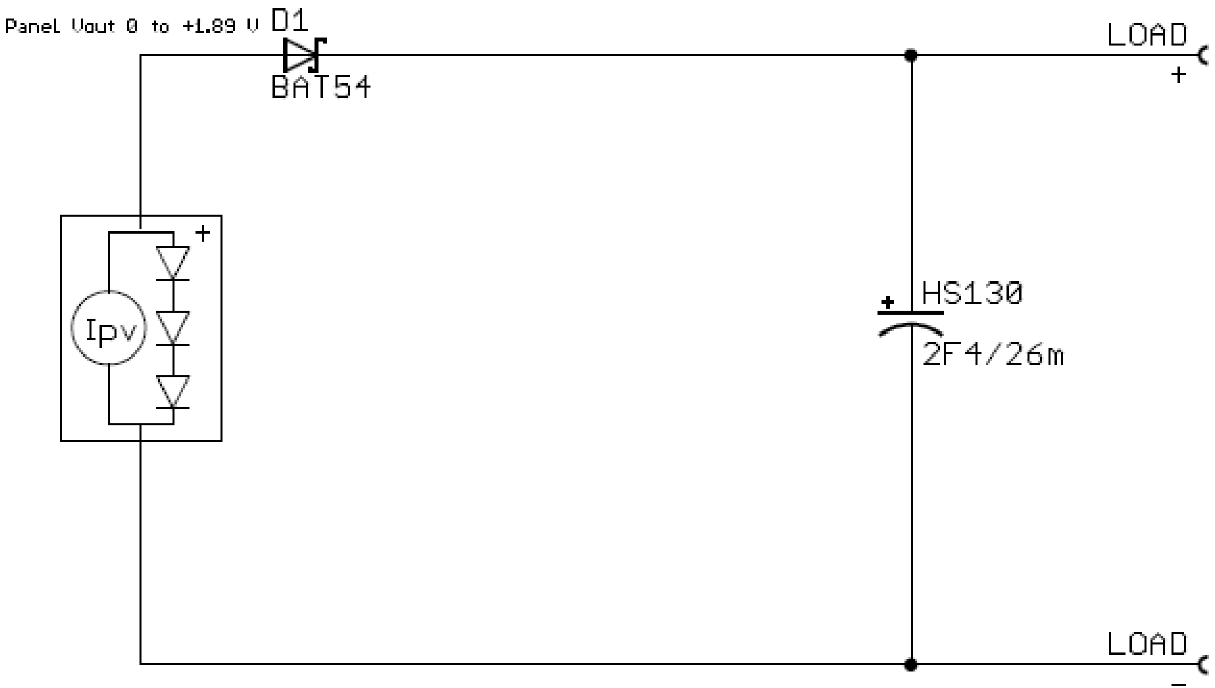


Supercapacitor Interface Circuits

Design principles:

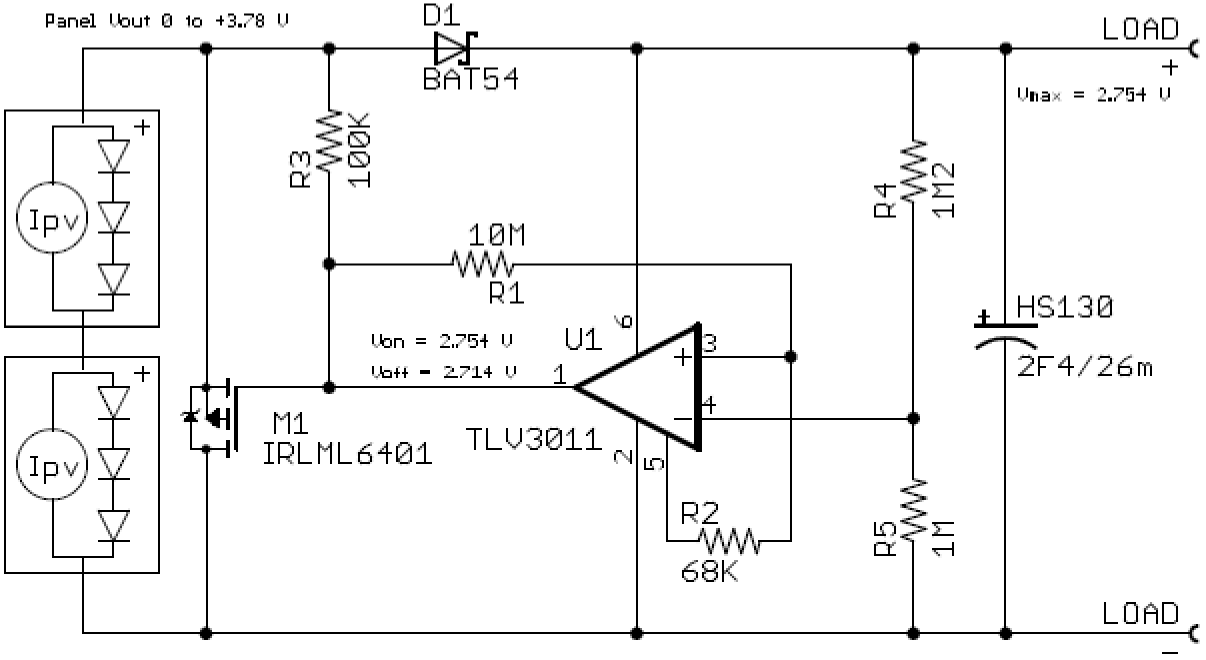
1. Must start charging from 0V
2. Must provide over voltage protection
3. Must prevent the supercapacitor from discharging into the source
4. Should be designed for maximum efficiency

Simplest charging circuit



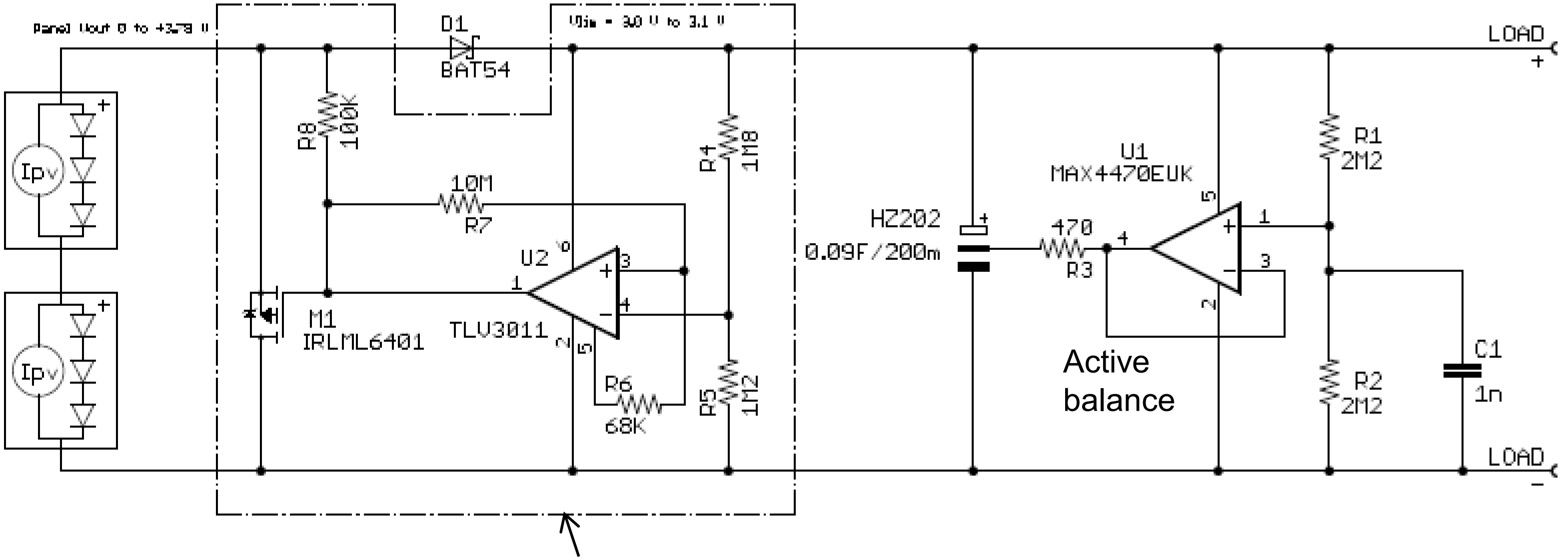
- Starts charging from 0V
- Voc < 2.7V at max light level in the application. I-V curves of slide 25 showed Voc ≈ 1.5V
- D1 prevents supercapacitor discharging back into solar cell when light levels fall
- BAT54 chosen for D1 due to low V_F. V_F at currents < 10μA, <0.1V
- HS130 provides excellent energy storage & power delivery at low voltage

Single cell supercapacitor with over voltage protection



- When VLOAD > 2.75V, turn M1 ON, VSOLAR drops & D1 does not conduct.
- When VLOAD < 2.71V turn M1 OFF, can charge solar cell
- TLV3011 is open drain, so o/p is open cct when Vscap < 1.8V (min Vss)
- TLV3011 quiescent current ~3µA

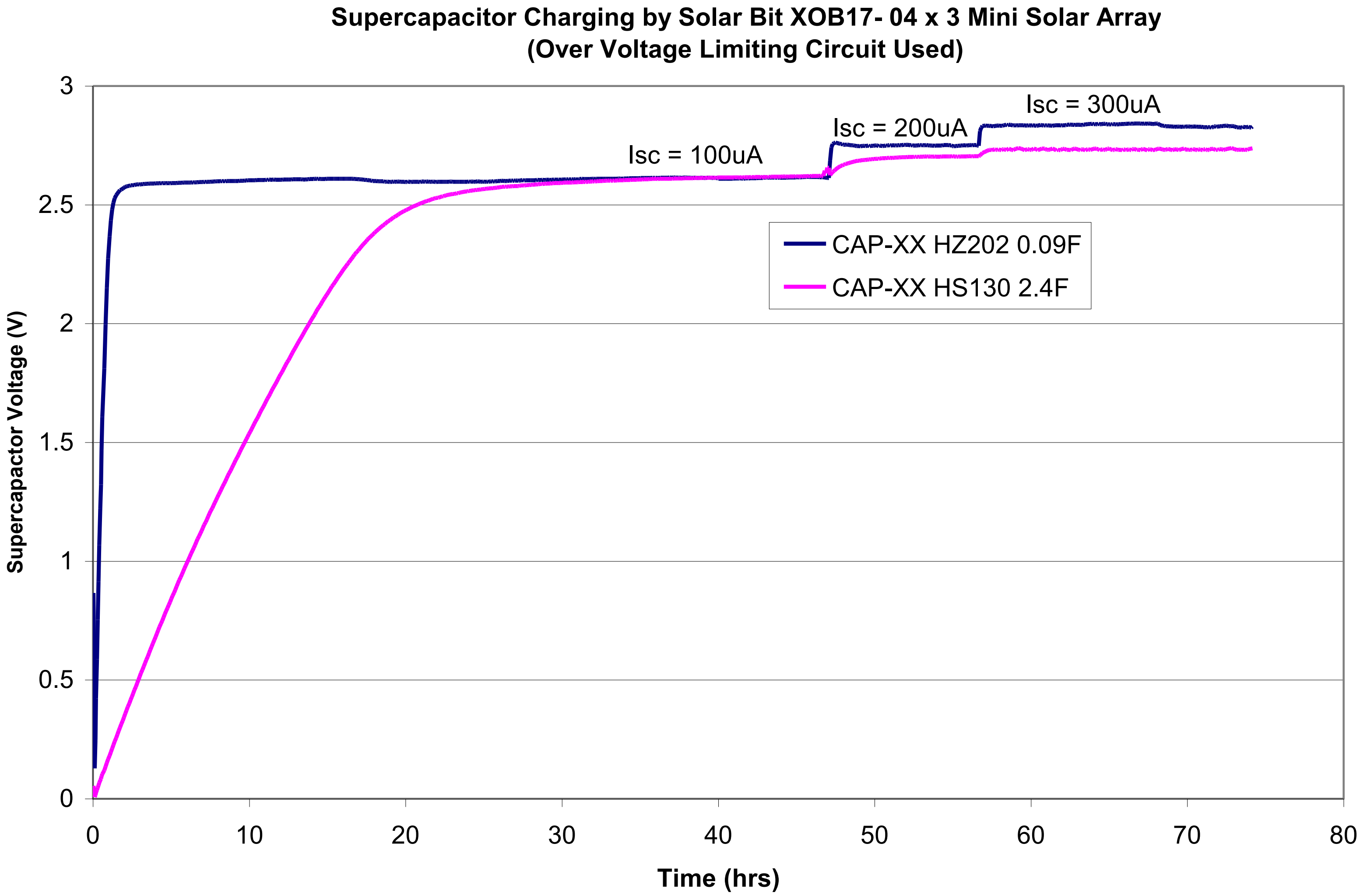
Dual cell supercapacitor with over voltage protection and active balancing



Active balance

Optional over voltage control, only needed if $V_{OC} > V_{SCAP}$ MAX (= 5.5V)

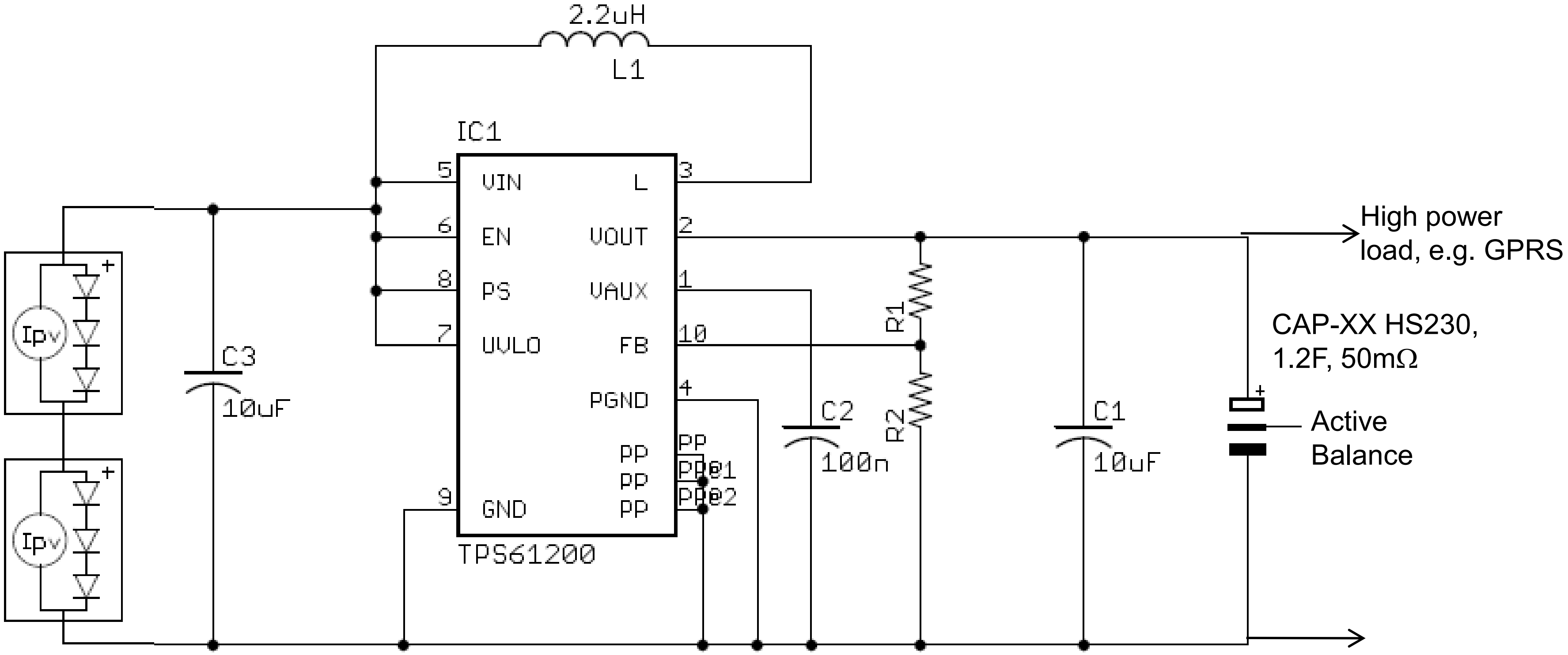
Supercapacitor charging



High Power Transmission

- Previous circuits ideal for low power transmission:
  - Supercapacitor at solar cell voltage
  - with voltage regulation on load side of the supercapacitor
  - Regulator is small
- For high power, place regulator between solar cell and supercapacitor:
  - Regulator is small, low power (solar cell o/p power)
  - Supercapacitor charged to the RF PA supply voltage, supplies the RF PA directly
  - Supercapacitor must have low ESR for power delivery as well as enough energy storage to support the transmission for its duration.

High power circuit



High power load, e.g. GPRS

CAP-XX HS230, 1.2F, 50mΩ

Active Balance

- Texas Instruments TPS61200 has min Vin = 300mV, starts charging Vaux with load disconnected, when Vaux = 2.5V IC starts functioning.
- Has true load disconnect (back to back PFETs as o/p switch), so supercap cannot discharge back into the source
- Uses output PFETs in linear mode to limit inrush current or limit o/p voltage if Vin > Vout.
- Typically draws 50µA during operation

Single or dual cell supercapacitor?

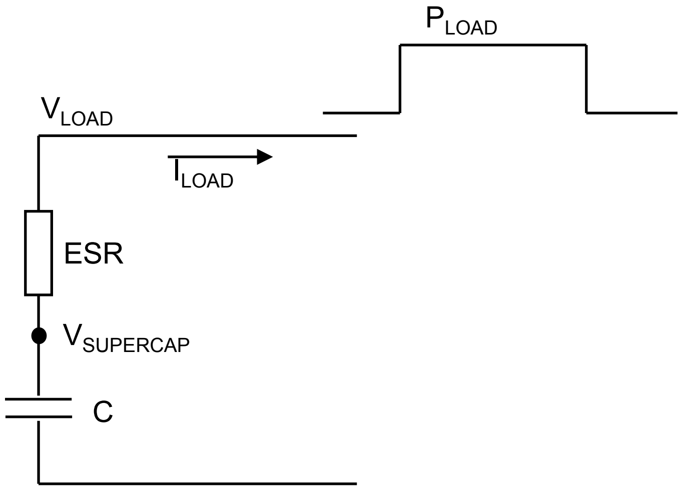
- Single cell:
  - No balancing circuit needed
  - Lower current
  - Smaller, thinner
  - Lower cost
- Dual Cell:
  - Higher energy storage ½ CV^2
  - 5V – 1.2V, 1F → 11.8J
  - 2.5V – 1.2V, 2F → 4.8J

Sizing your supercapacitor

Energy balance approach often used: Avge Load Power x time = ½ C(V_{init}^2 – V_{final}^2)

but

If the supercapacitor is supplying a constant power load, such as a DC:DC converter, where supercapacitor current increases as supercapacitor voltage decreases, to maintain V x I constant, then supercapacitor ESR may become significant, and you should solve:



$$V_{LOAD} = V_{SUPERCAP} - I_{LOAD} \bullet ESR$$

$$P_{LOAD} = V_{LOAD} \bullet I_{LOAD}$$

$$P_{LOAD} = (V_{SUPERCAP} - I_{LOAD} \bullet ESR) \bullet I_{LOAD}$$

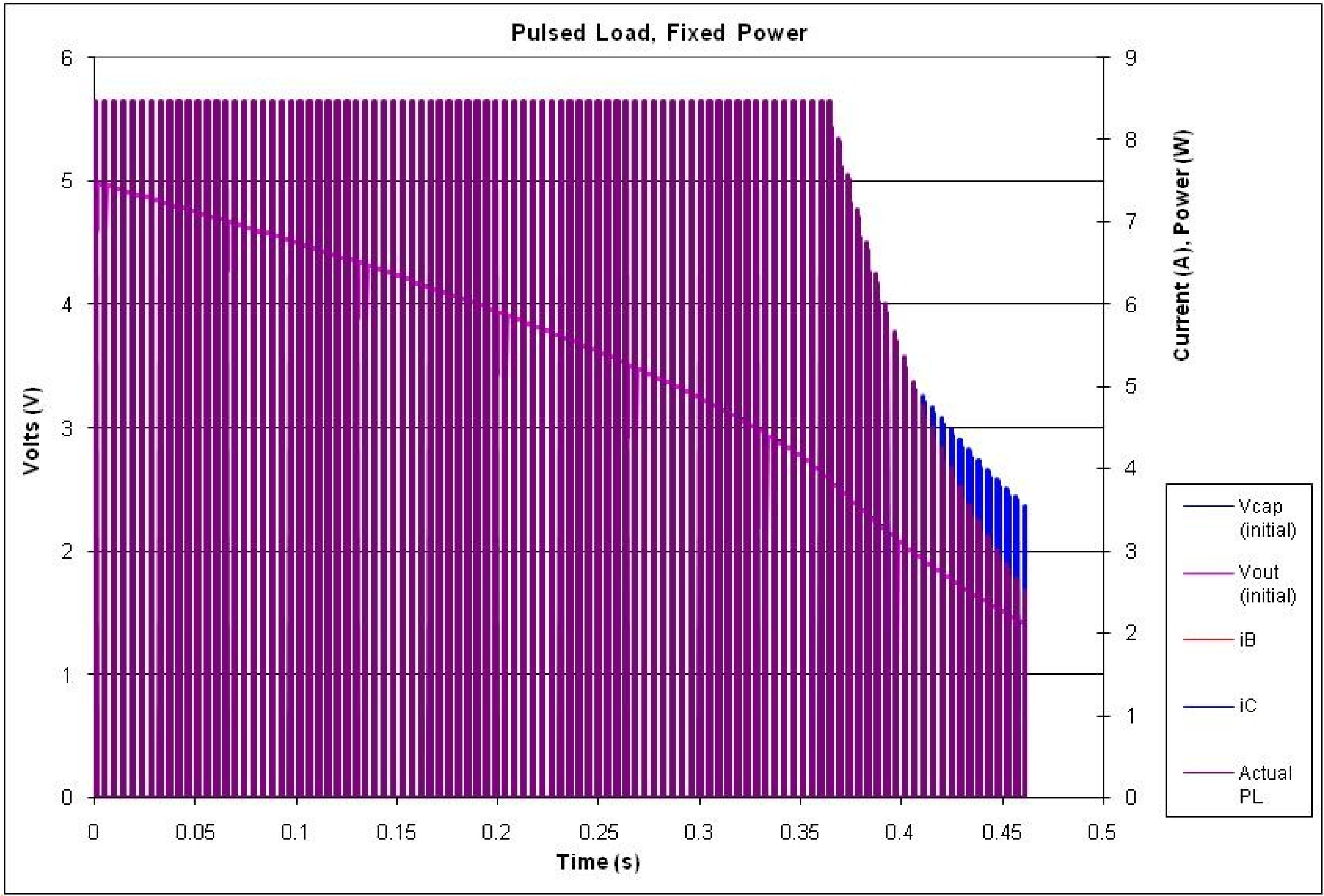
$$\therefore I_{LOAD}^2 \bullet ESR - V_{SUPERCAP} \bullet I_{LOAD} + P_{LOAD} = 0$$

$$I_{LOAD} = \frac{V_{SUPERCAP} \pm \sqrt{V_{SUPERCAP}^2 - 4 \bullet ESR \bullet P}}{2 \bullet ESR}$$

If load current is very small, then I_{LOAD}•ESR << VSUPERCAP and can use an energy balance to size the supercapacitor. Otherwise, use a spread sheet to solve the above and simulate V & I over time, or use SPICE.

Example: GPRS class 10 transmission

Average load power = 25% x 2A x 3.6V/85% = 2.11W. Load duration = 100 frames x 4.6ms = 0.46s
Load energy = 0.97J. Supercap Vinit = 5V, Vfinal = 2.5V
C = 2 x 0.97/(5^2-2.5^2) = 0.1F. Nothing about ESR



Quadratic solution:
C = 0.1F
ESR = 200mΩ

Does not work.
Vfinal ≈ 1.5V

Will only support transmission for 0.36s

Example: GPRS class 10 transmission

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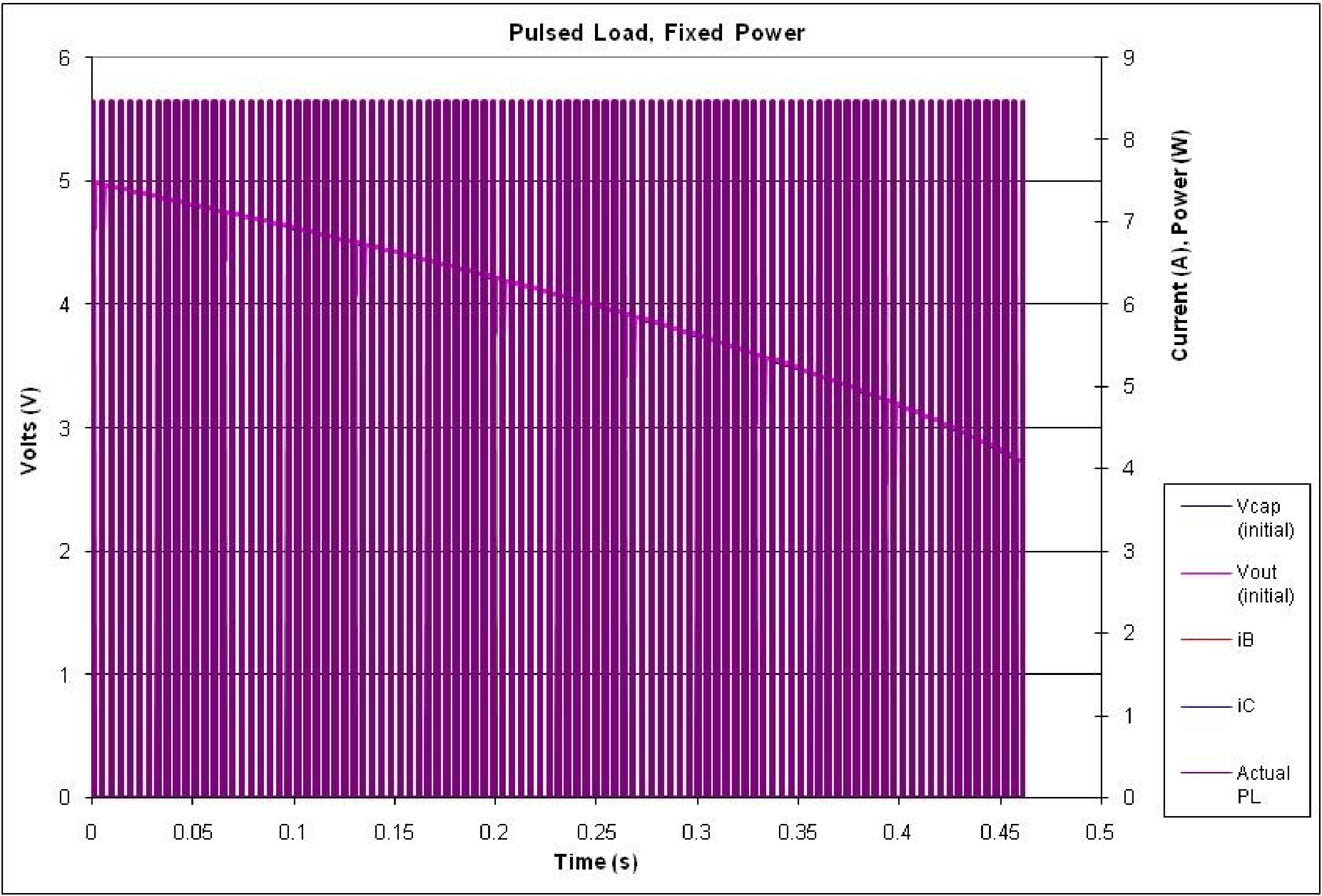

Quadratic solution:
C = 0.13F
ESR = 200mΩ

Solution works

Vfinal ≈ 2.7V

About using supercapacitors with solar cells

- Ideal power buffer
- Low voltage, multiple cells, need cell balancing
- Leakage current decays over time, charging may take longer than expected
- Allow for ageing when selecting initial C & ESR
- Solar cells deliver max current into a short circuit – ideal for charging a supercapacitor from 0V
- Need to prevent supercapacitor discharging back into the solar cell when light falls
- Single or dual cell supercapacitor?
- Low power and high power circuits
- Remember ESR when sizing the supercapacitor

About CAP-XX

- World leader in thin, flat, small supercapacitors suitable for portable electronic devices
- Research-based, market-driven electronic components manufacturer. Founded in Australia in 1997. Listed on AIM in London, April 2006
- Turn-key power design solutions
- Production in Sydney & Malaysia
- Significant sales to big brand customers in Europe, Asia and North America
- CAP-XX supercapacitor technology licensed to Murata in 2008
- Distributors throughout USA, Europe and Asia

CAP-XX

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