Supercapacitors as Power Buffers between Energy Harvesters and Wireless Sensors

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The Problem

- Energy: The amount of work that can be done
- Power: The rate at which work is done
  (or at which energy is delivered)
- You can store energy, not power
- Energy harvesting sources have infinite energy but limited power
- Periodic wireless transmission requires bursts of energy at higher power than the energy harvester can deliver
- Supercapacitors buffer that power gap:
  - They are charged at low power from the harvester
  - And deliver bursts of energy at high power to the load

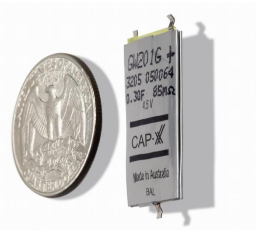
Agenda

- Why use a supercapacitor?
- Supercapacitor properties

  (What you need to know when designing your system)
  - What's inside
  - Power buffer
  - Temperature performance
  - Leakage current
  - Charge current
  - Cell Balancing
  - Ageing
- Supercpacitor circuits
- Interfacing the supercapacitor to your energy source

Why use a Supercapacitor?

- Physical charge storage
  → "Infinite" cycle life
- Low impedance (ESR)
  → High power delivery
  → Transmission over a cellular network
- High power delivery at low temps (-40°C)
- Easy to charge
  → Just need a charge current & over-voltage protection
- Low leakage current
- Available in thin, small form-factors



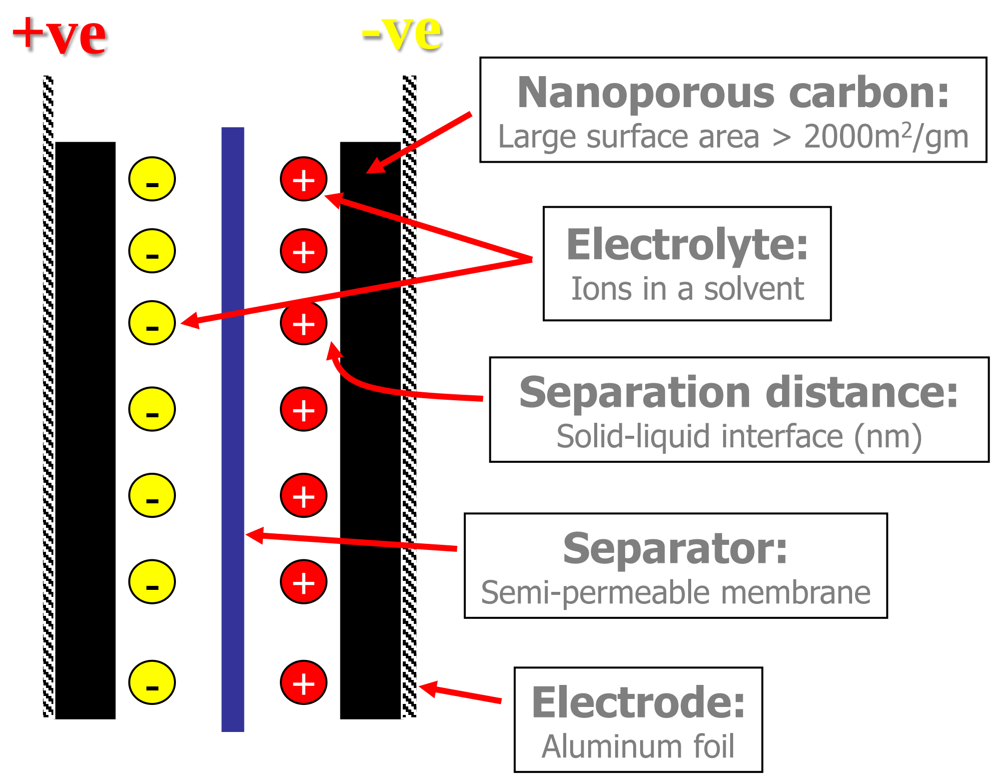
What’s Inside?

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

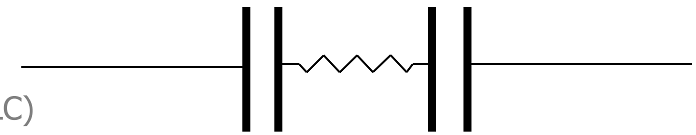
Basic Theory:
Capacitance is proportional to the charge storage area, divided by the charge separation distance (C α A / d)

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

No dielectric, working voltage determined by electrolyte

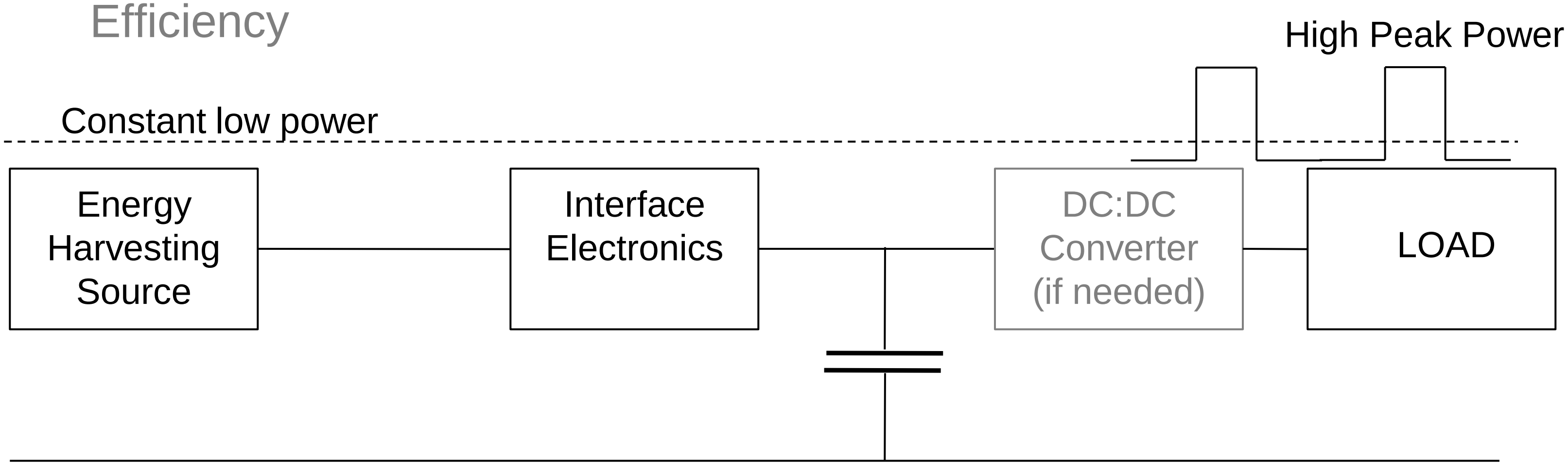


Basic Electrical Model:
Electric Double Layer Capacitor (EDLC)



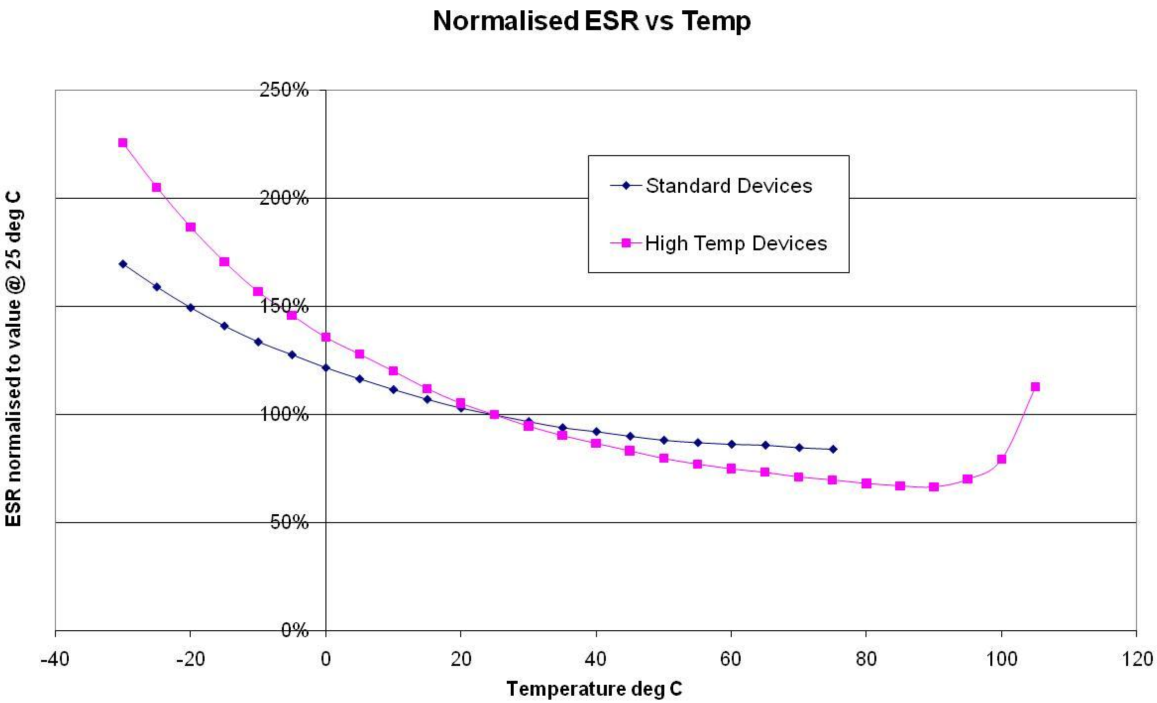
Supercapacitor as a Power Buffer

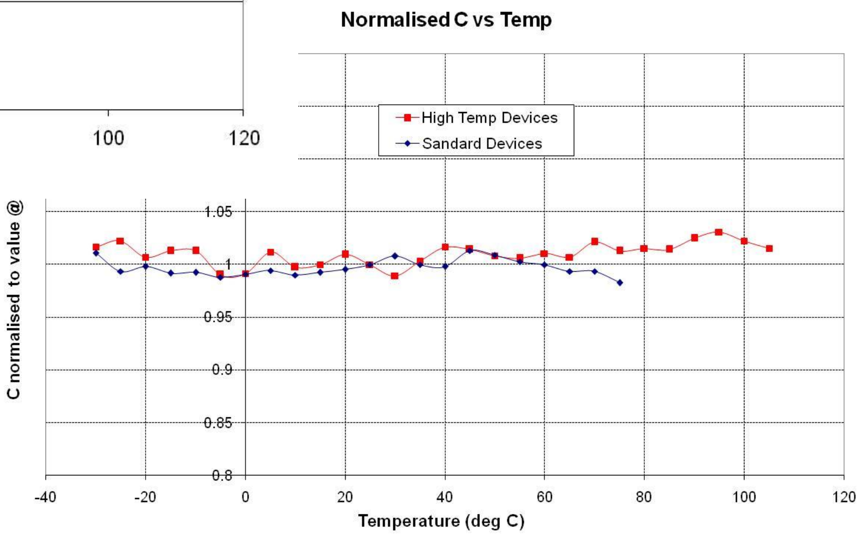
- Average load power < Average source power
- System design with:
  - Interval between peaks, Peak power, Energy source, Harvester size, Efficiency



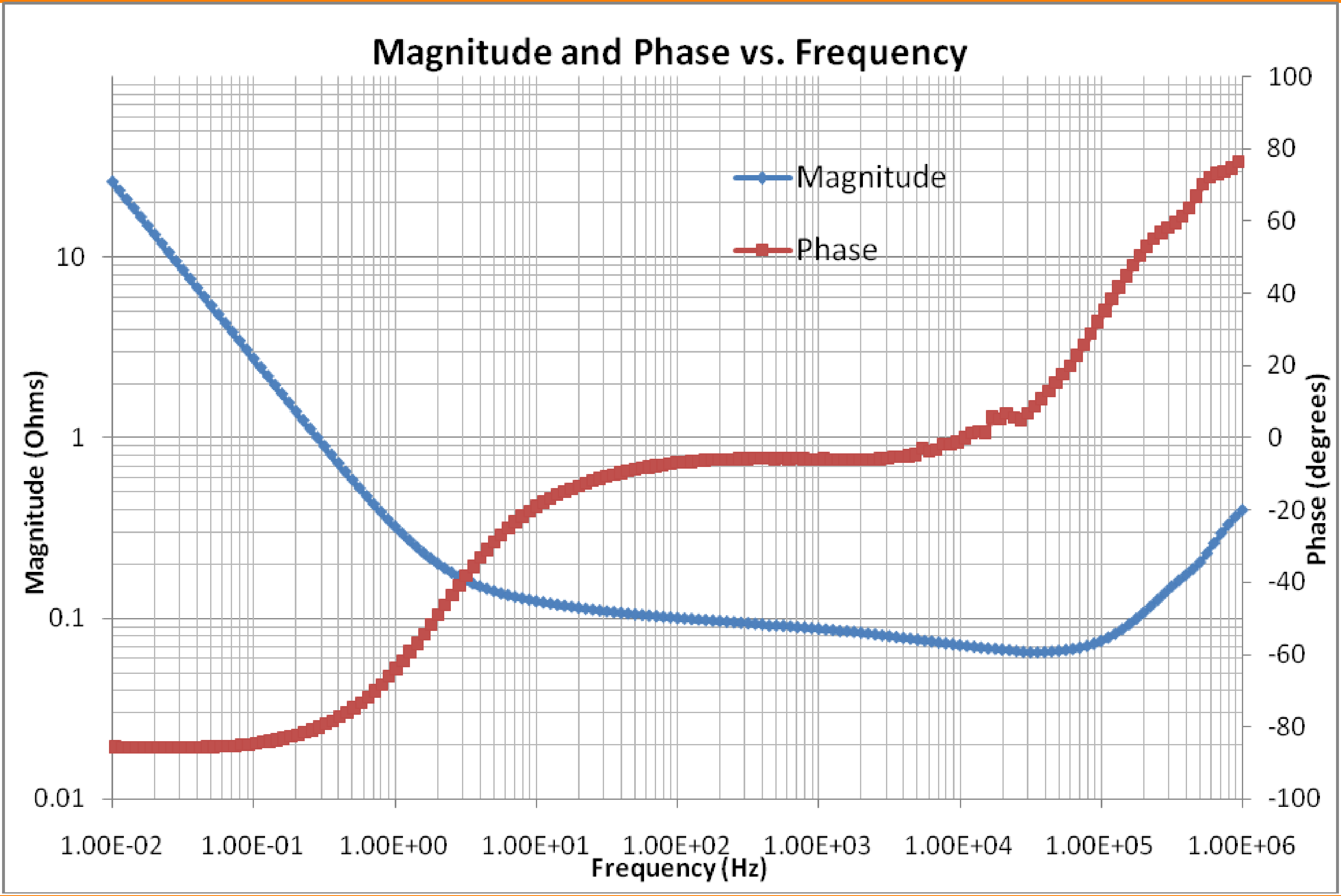
- Source sees constant power load (set at maximum power point?)
- Load sees low impedance source that delivers high peak power for the required duration
  - Low ESR = high power; High C = delivered for required duration

Excellent Performance across a Wide Temperature Range

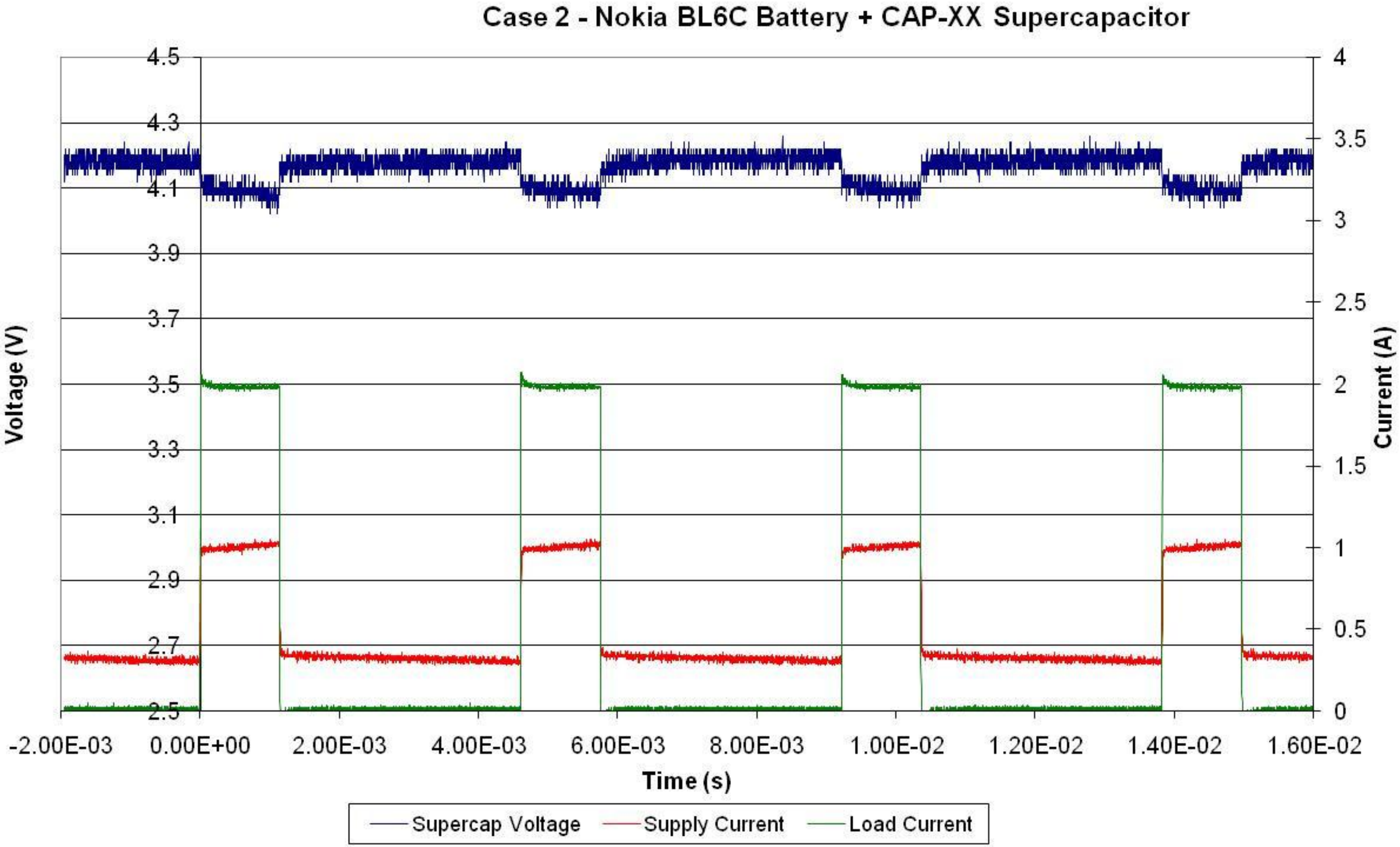




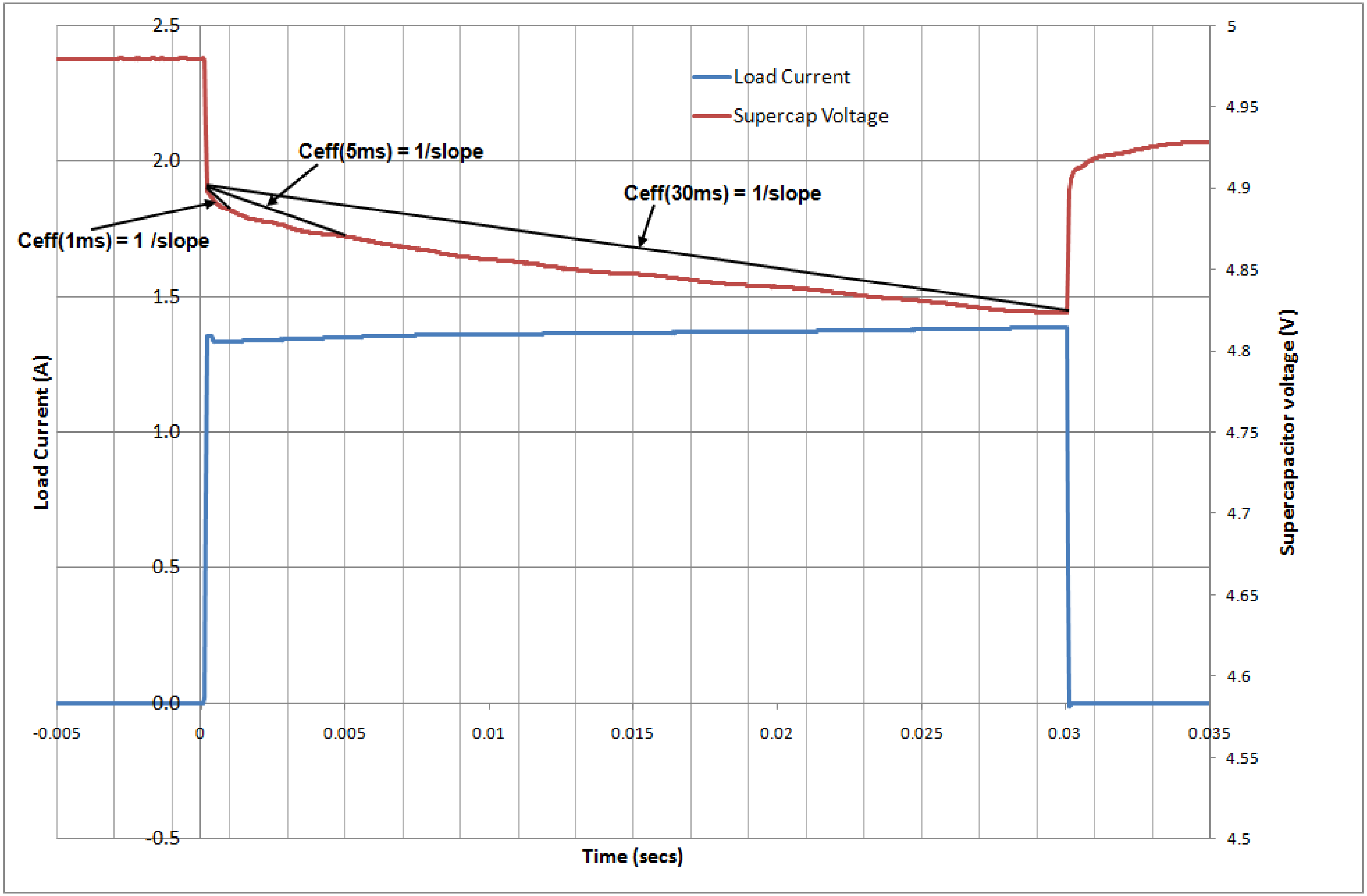
Poor Frequency Response …



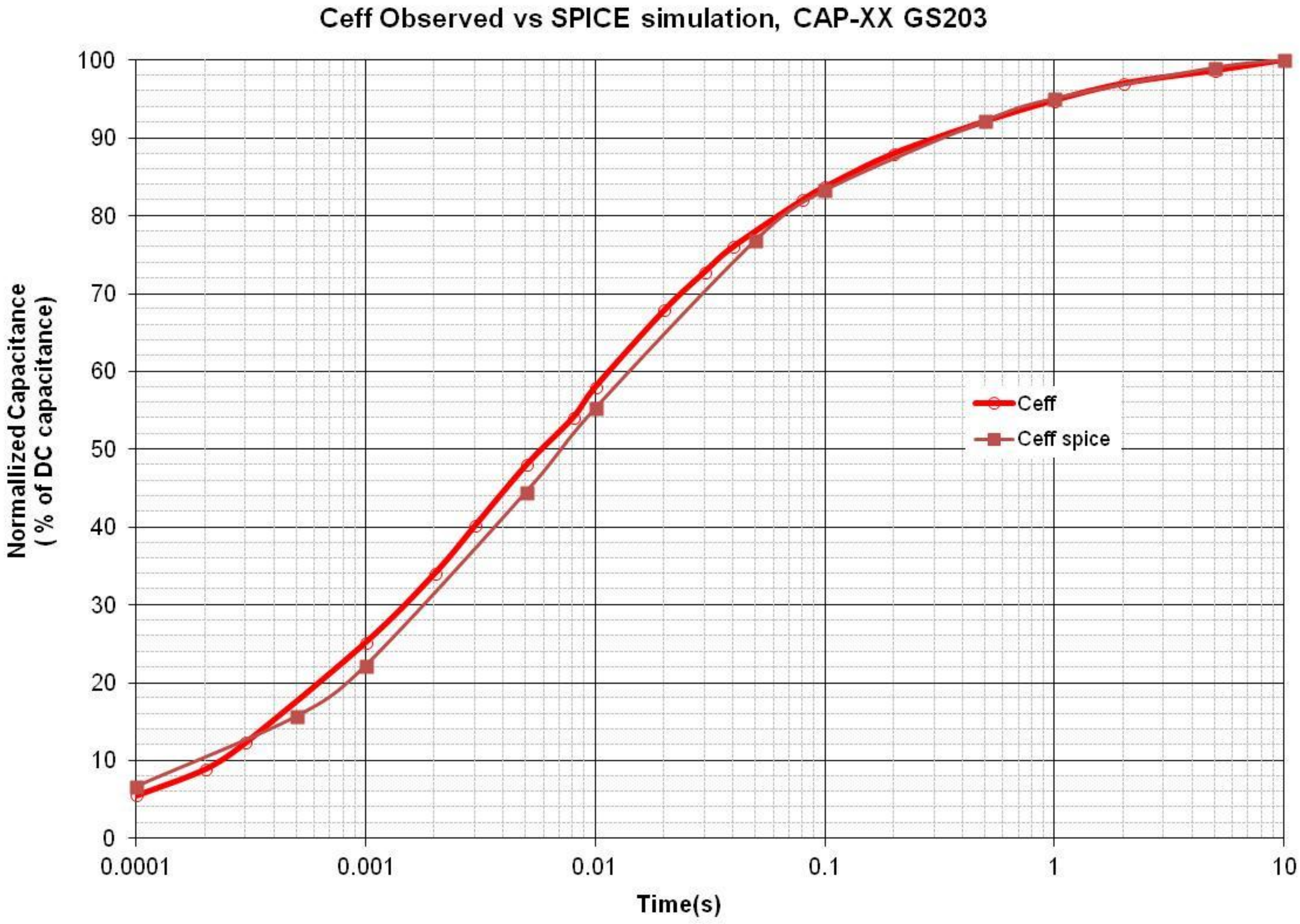
…but Excellent Pulse Response



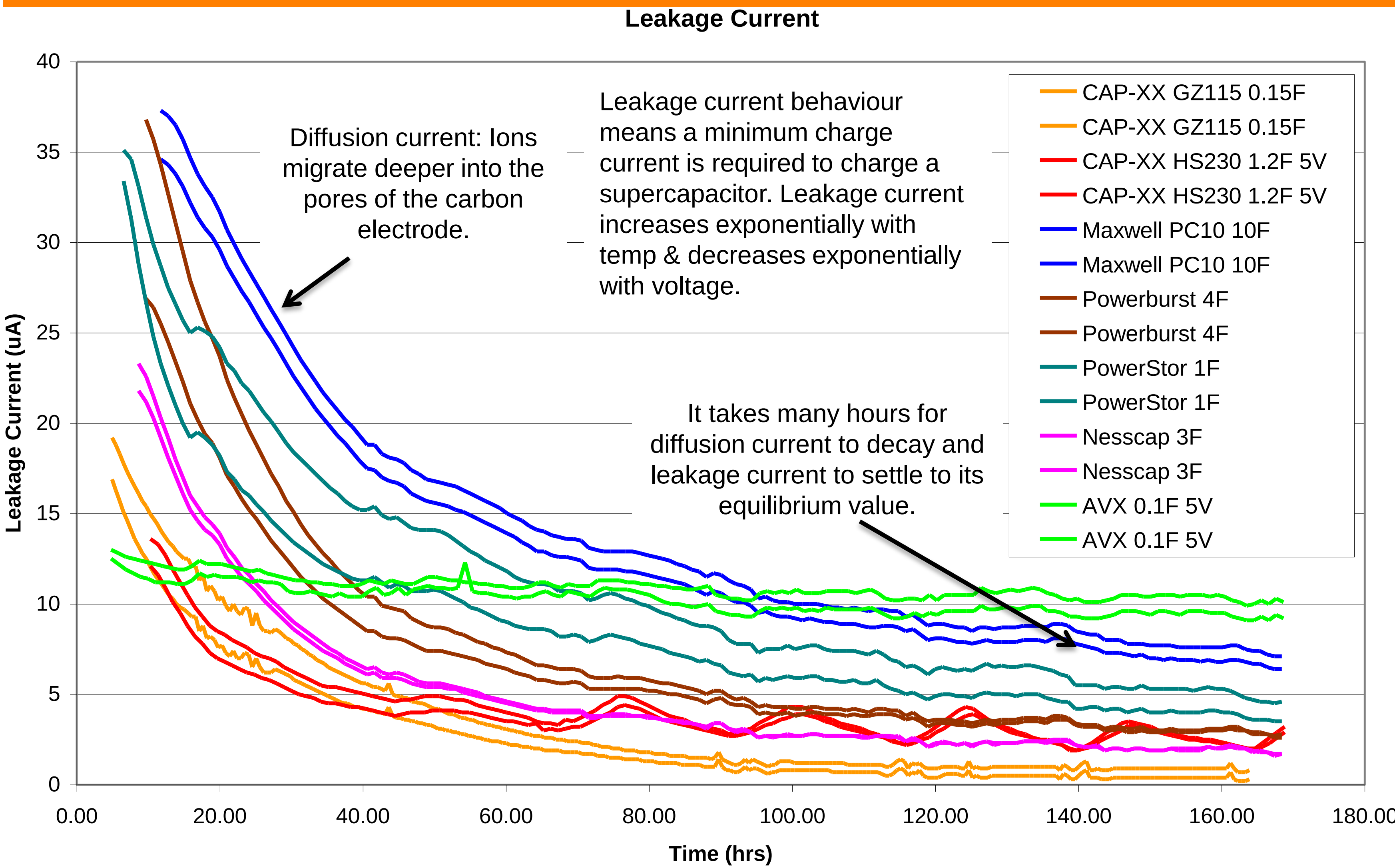
$C_{EFFECTIVE}$ as a Function of PW



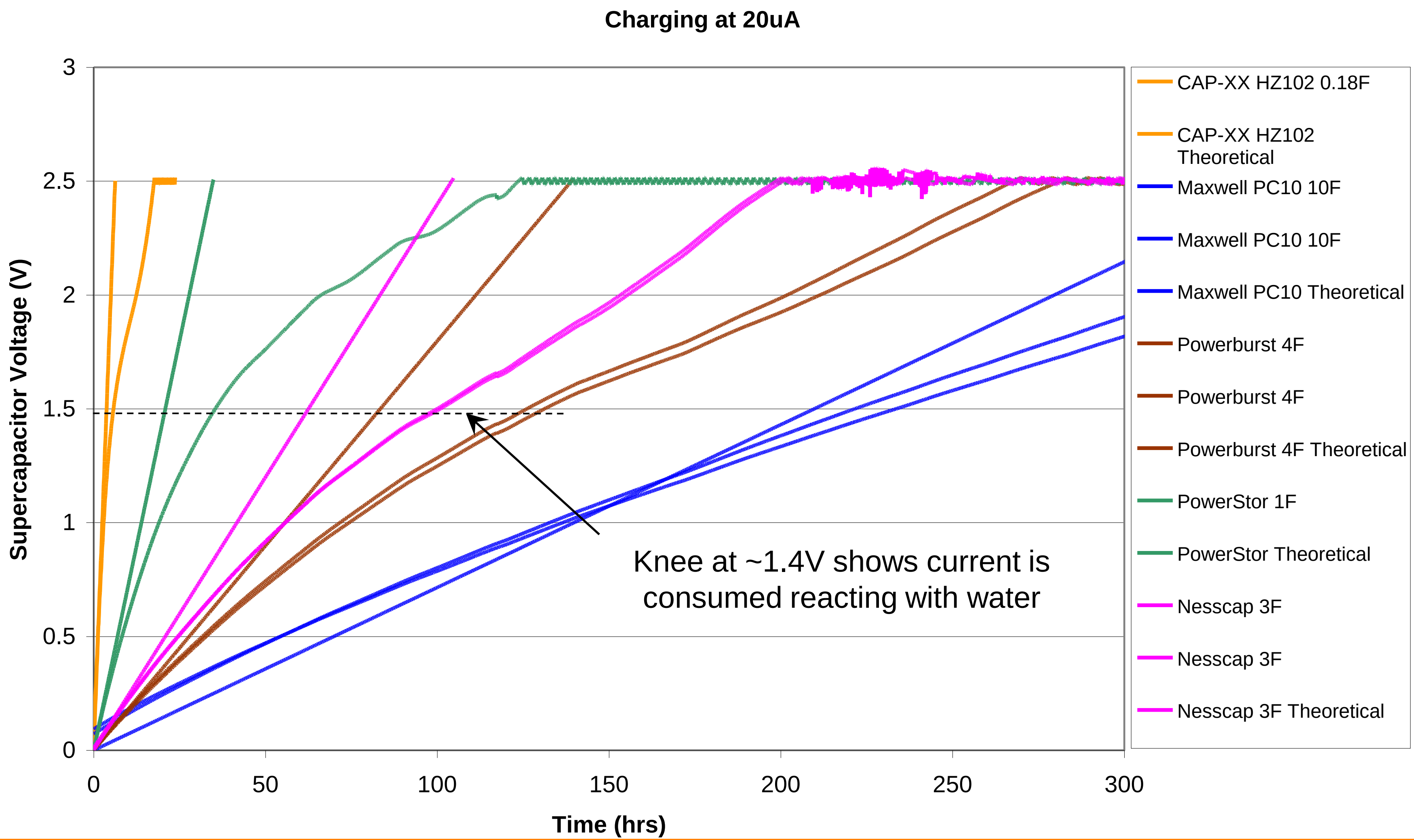
$C_{EFFECTIVE}$ Data



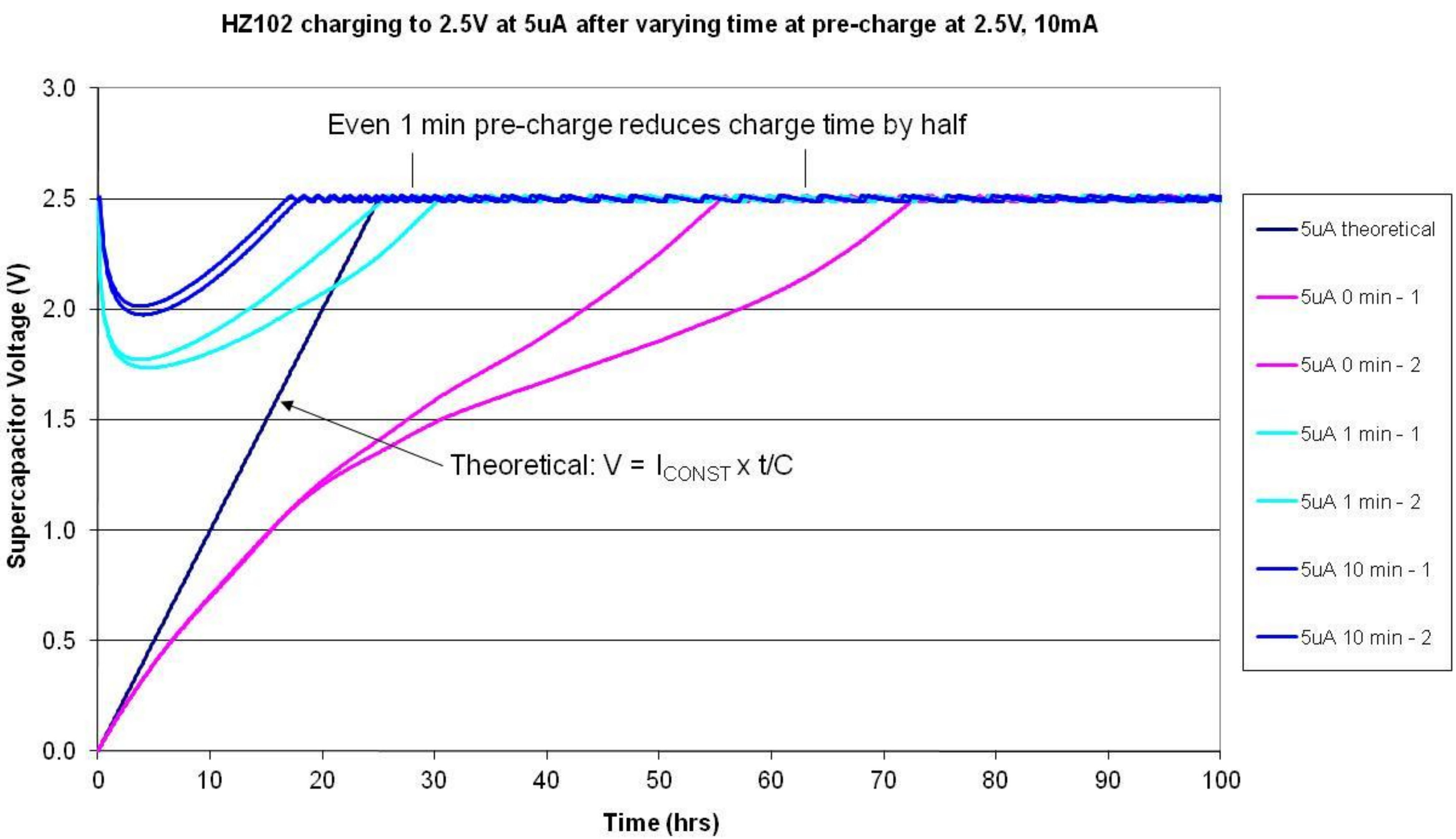
Supercapacitor Leakage Current



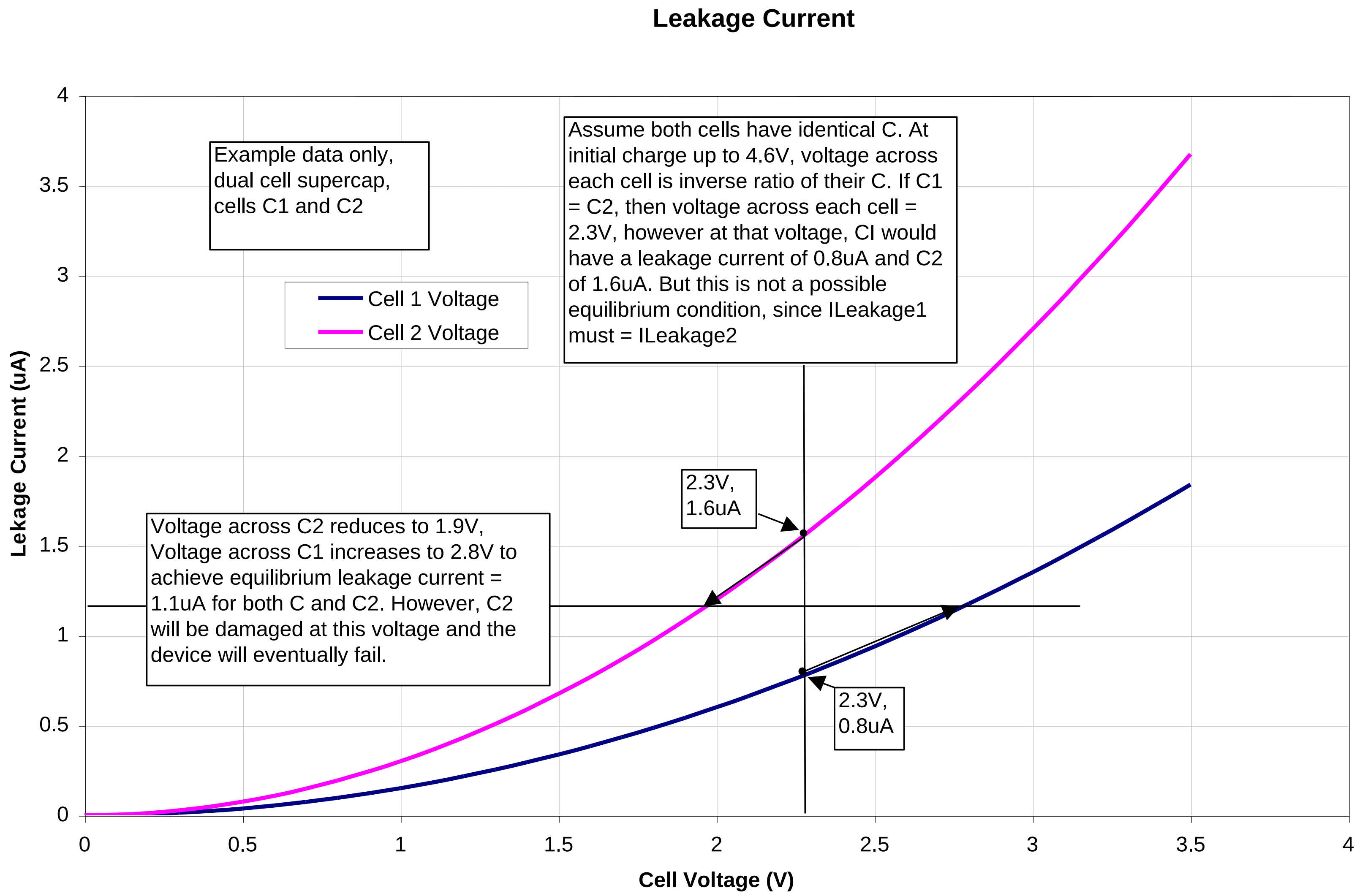
Supercapacitors Need a Minimum Initial Charging Current …



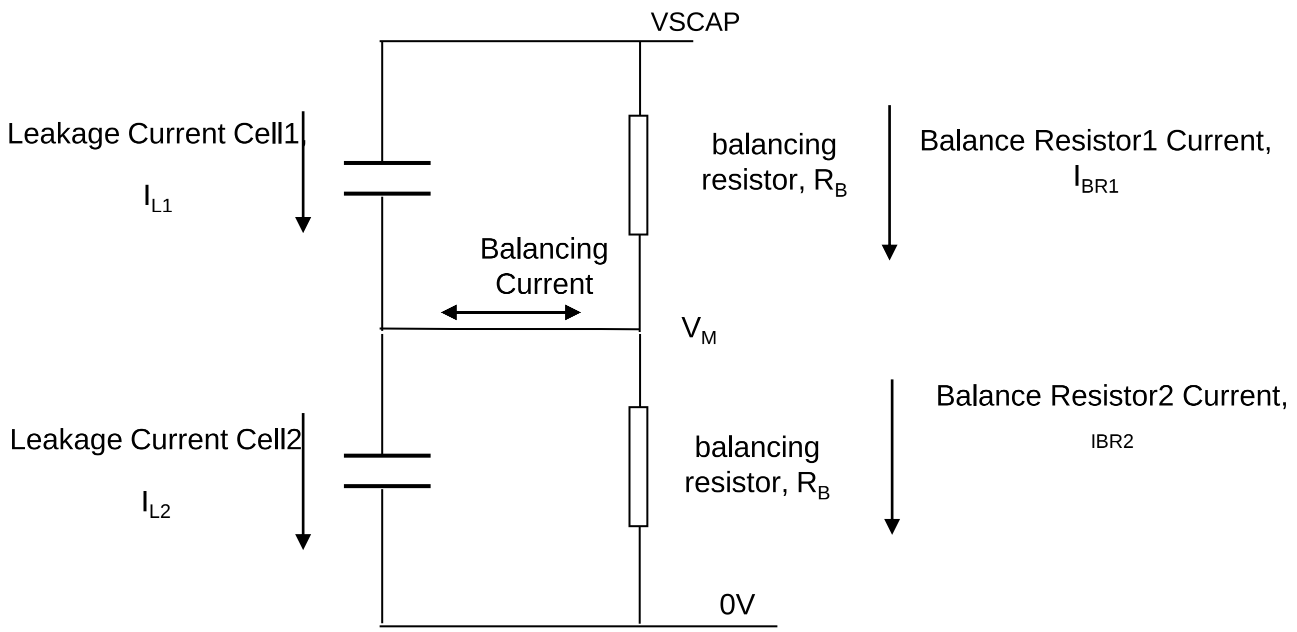
…but a Short Initial Charge at "High" Current can Overcome this



Cell Balancing is Required



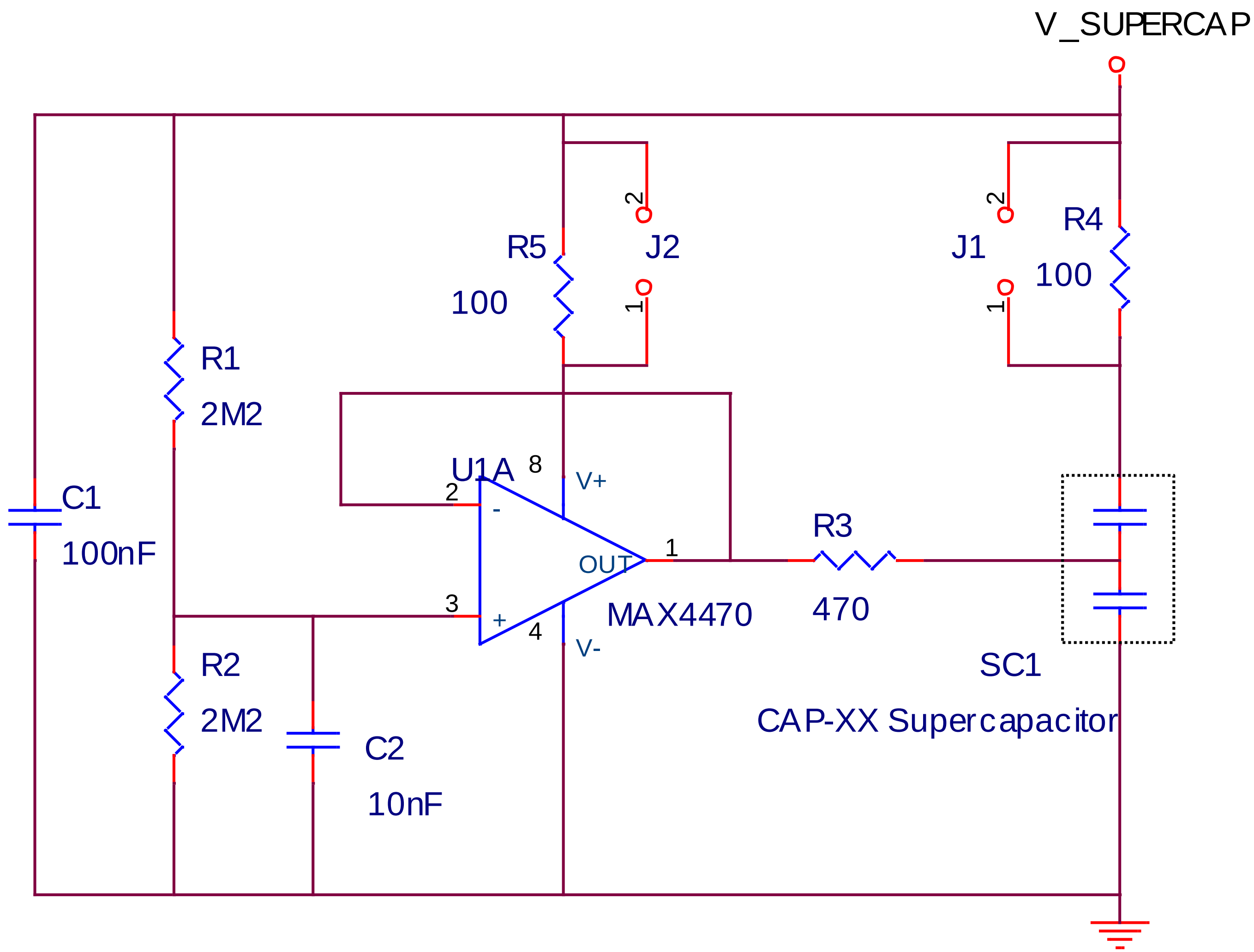
Simple Passive Balancing



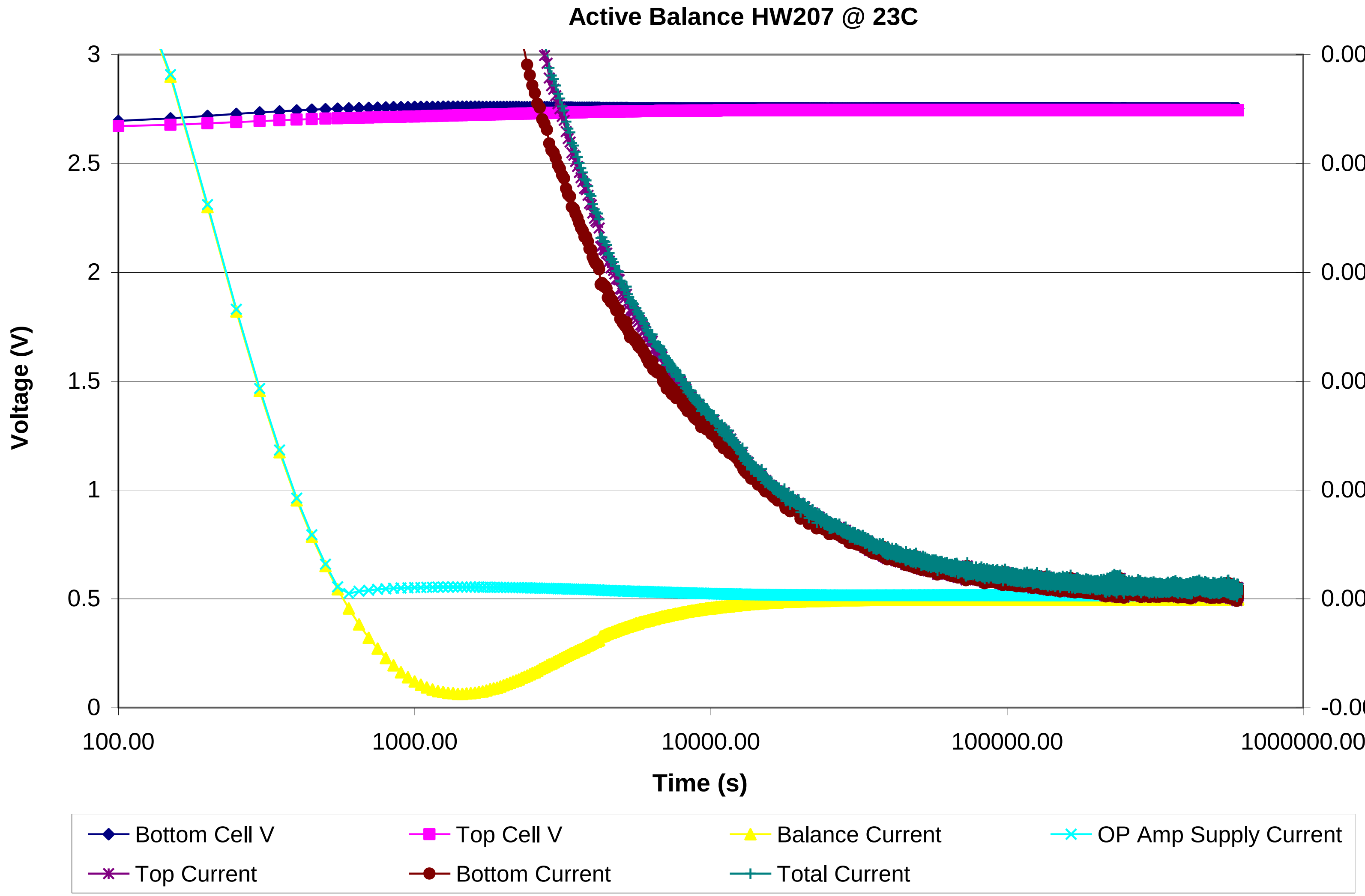
- The purpose of this circuit is to maintain V_M close to V_{SCAP} / 2
- $V_M = R_B \times I_{BR2} = R_B \times (I_{BR1}$ - Balancing Current)
- For this circuit to work, Balancing Current must be << I_{BR1}, I_{BR2}
- VM must be prevented from going >> V_{SCAP} / 2 or << V_{SCAP} / 2 for any significant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

Active Balance Circuit for Very Low Leakage Current

- 2 capacitor cells in series need voltage balancing, or slight differences in leakage current may result in 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



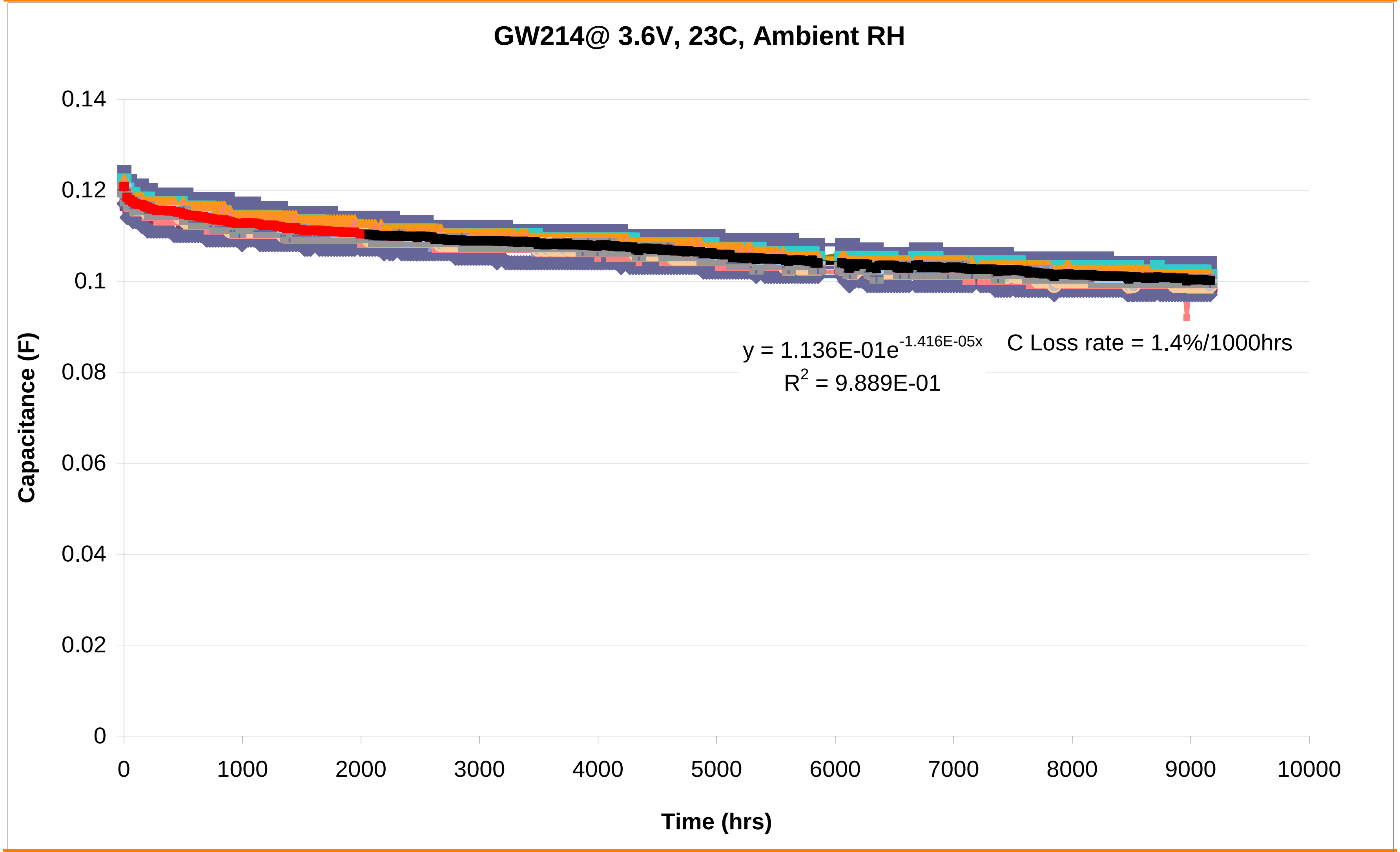
Active Balance: Very Low Currents



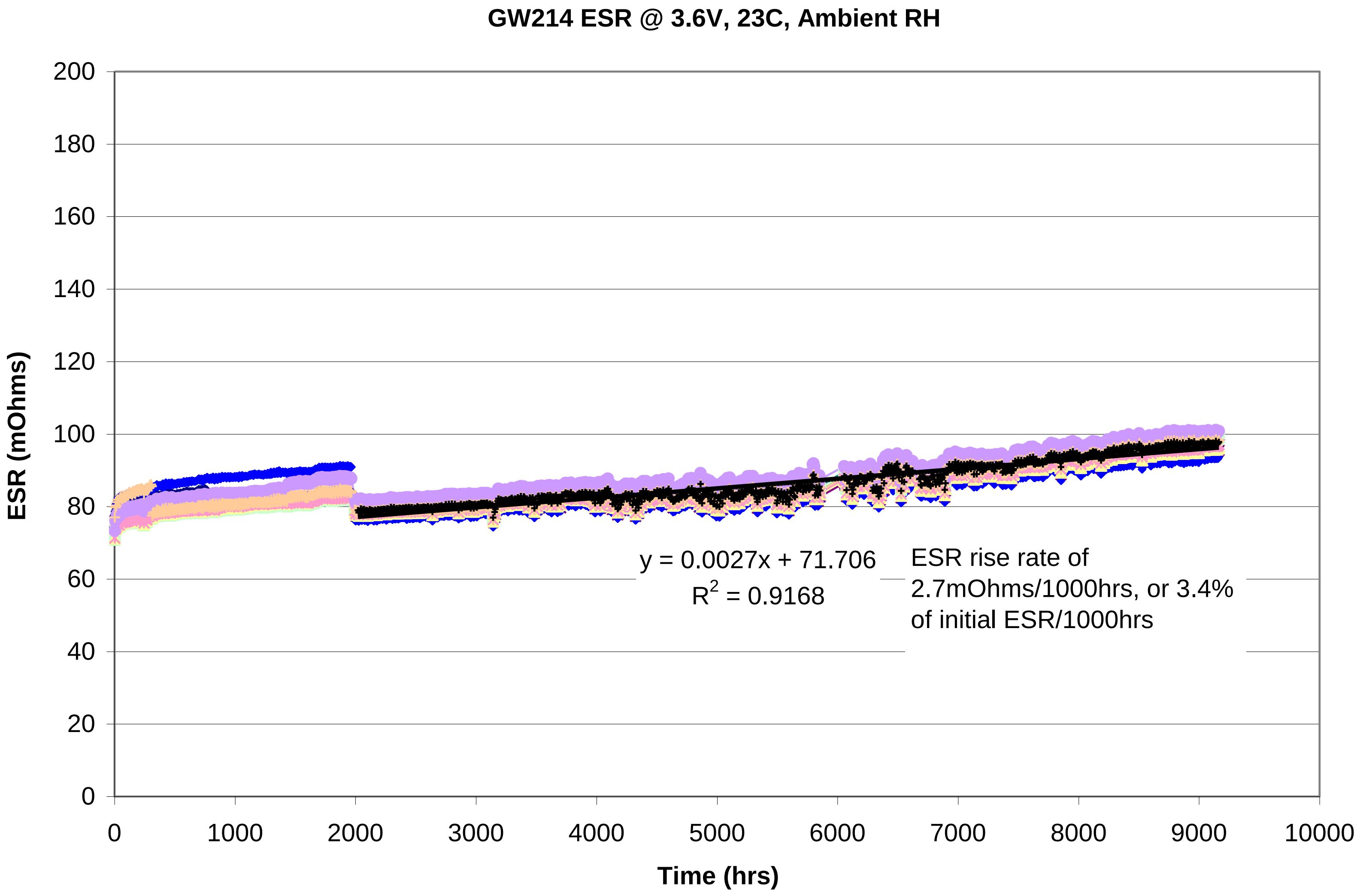
Take Ageing into Account when Sizing your Supercapacitor

- Supercapacitors use physical not electrochemical charge storage
- Ageing is a function of time at temperature and voltage, not number of cycles
- Determine expected ageing from operating profiles (voltage and temp combinations) and their duty cycle
- Size the supercapacitor so you have the required C & ESR at end of life after allowing for ageing

Supercapacitor Ageing: C Loss



Supercapacitor Ageing: ESR Rise



Supercapacitor Interface Circuits

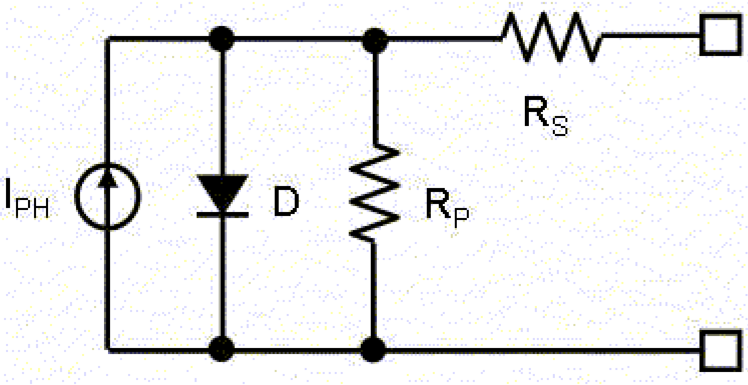
Design principles:

1. Must behave gracefully into a short circuit
2. Must start charging from 0V
3. Must provide over-voltage protection
4. Must prevent the supercapacitor from discharging into the source
5. Should be designed for maximum efficiency

In-rush Current

- A discharged supercapacitor will look like a short circuit to your energy source
- Most energy harvesters don't care – will deliver current into a short circuit
- Definitely a problem for batteries, and some other power supplies
  - Interface electronics must manage this either in the design:
    - Keep the source near its maximum power point
    - Graceful behaviour into a short circuit
  - Or with a separate current limit
    - AAT4610 (www.cap-xx.com/resources/app_notes/an1002.pdf
  - Or with a supercapacitor charging IC
    - LTC3225

Example 1: Solar cells



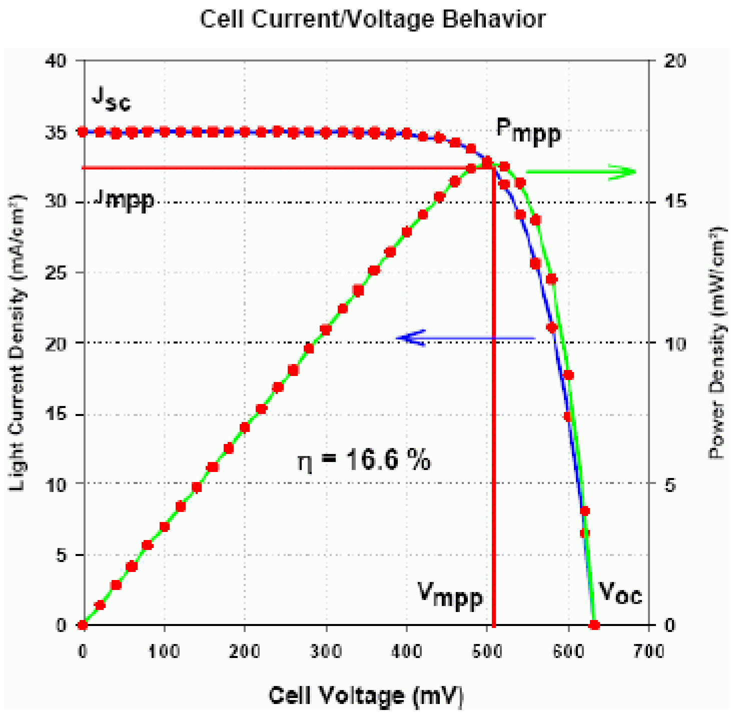
Simplified Circuit Model of a Solar Cell

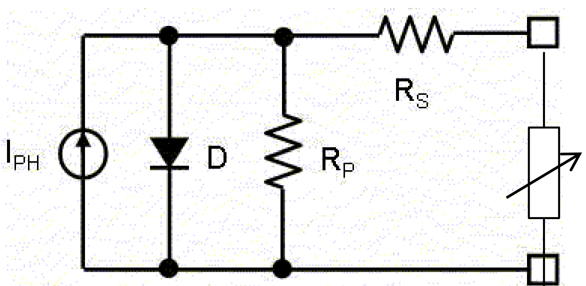
XOB17, 22mm x 7mm x 1.6mm used for measurements in following slides

- 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

- 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

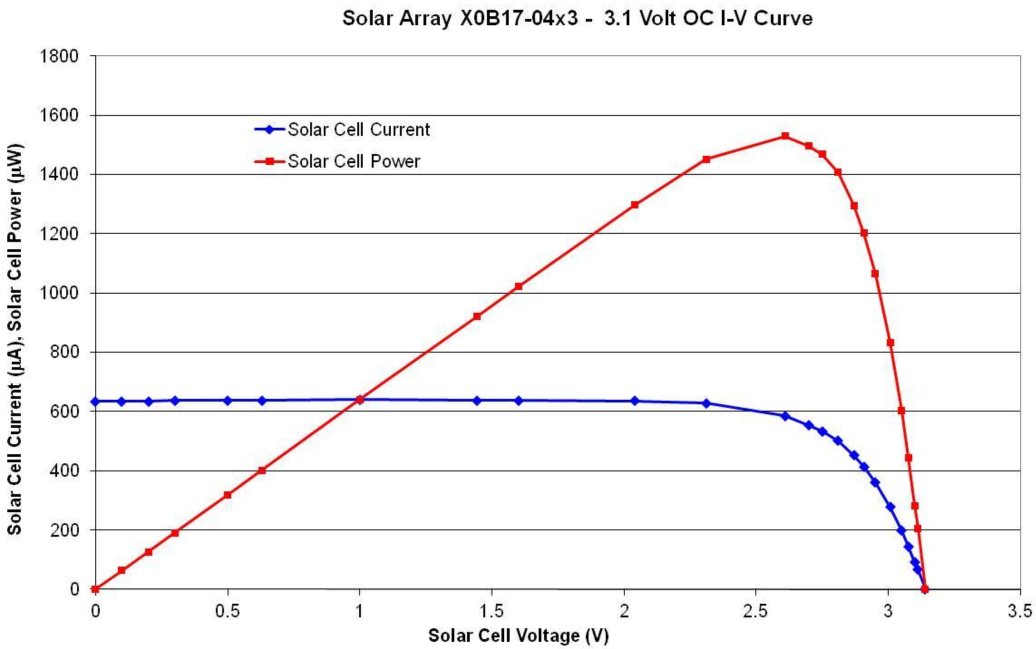




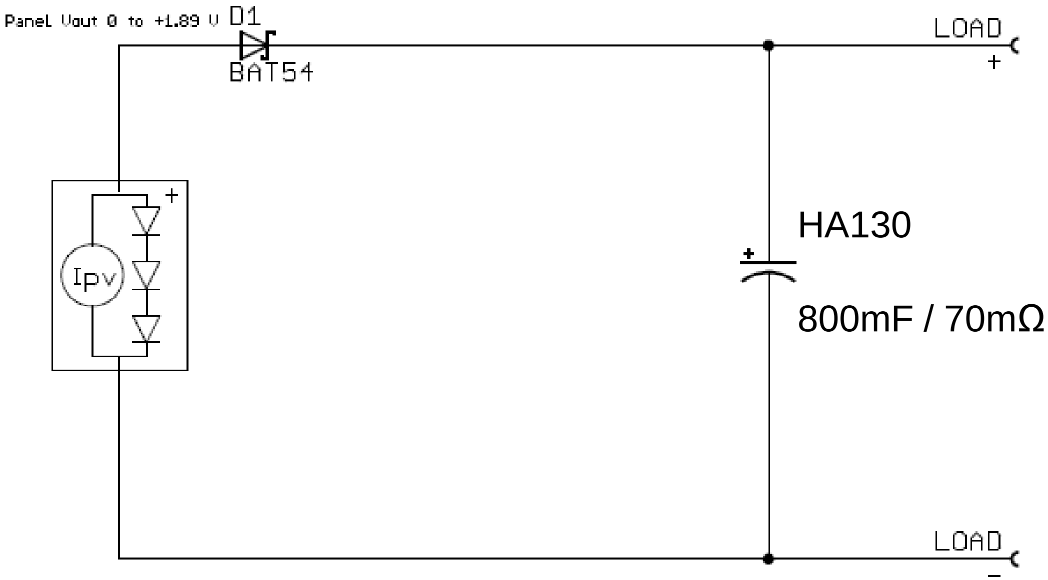
How to characterise your solar cell

Curves provided in data sheet

Curves developed in lab in our light conditions

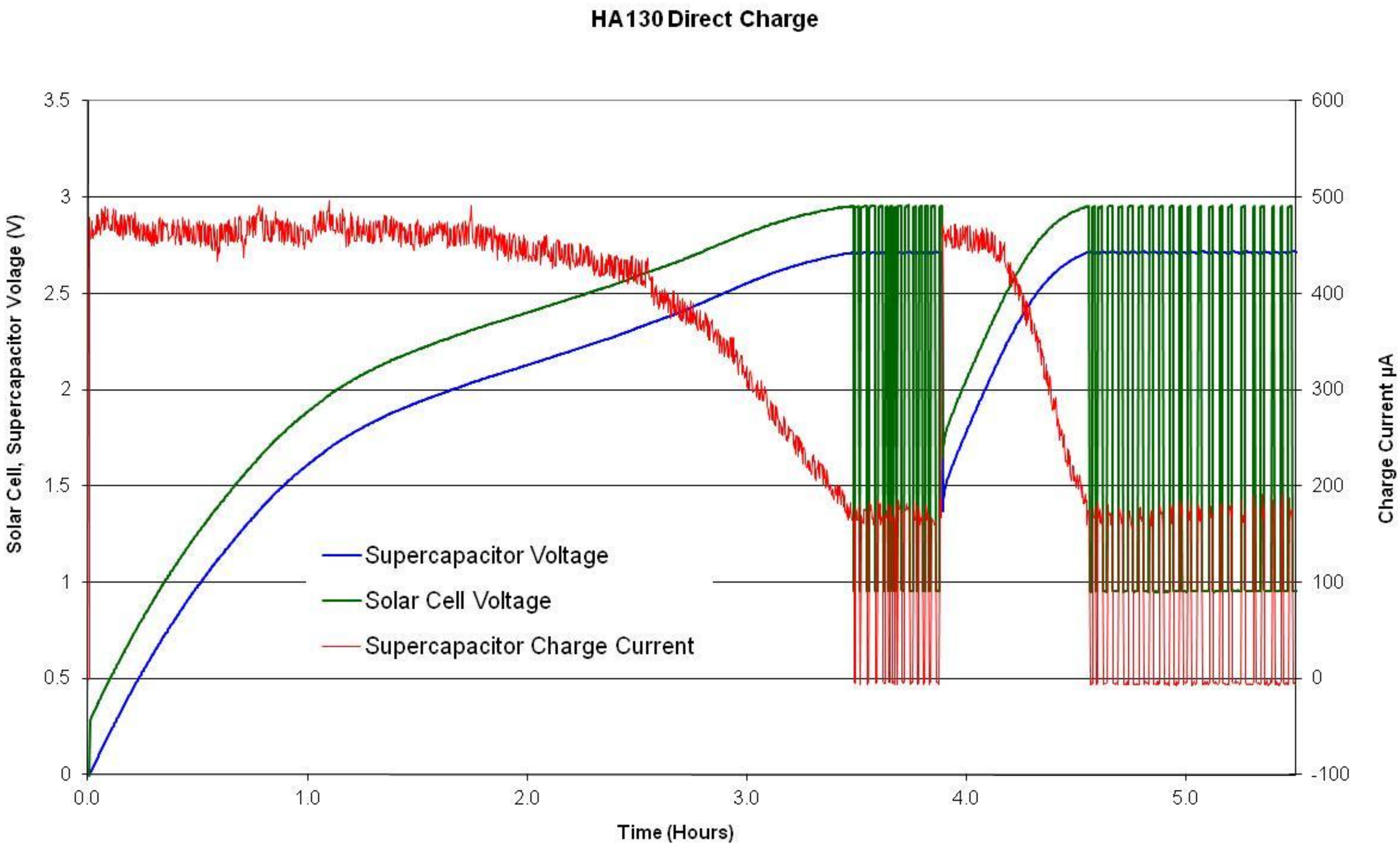


Direct Charging Circuit

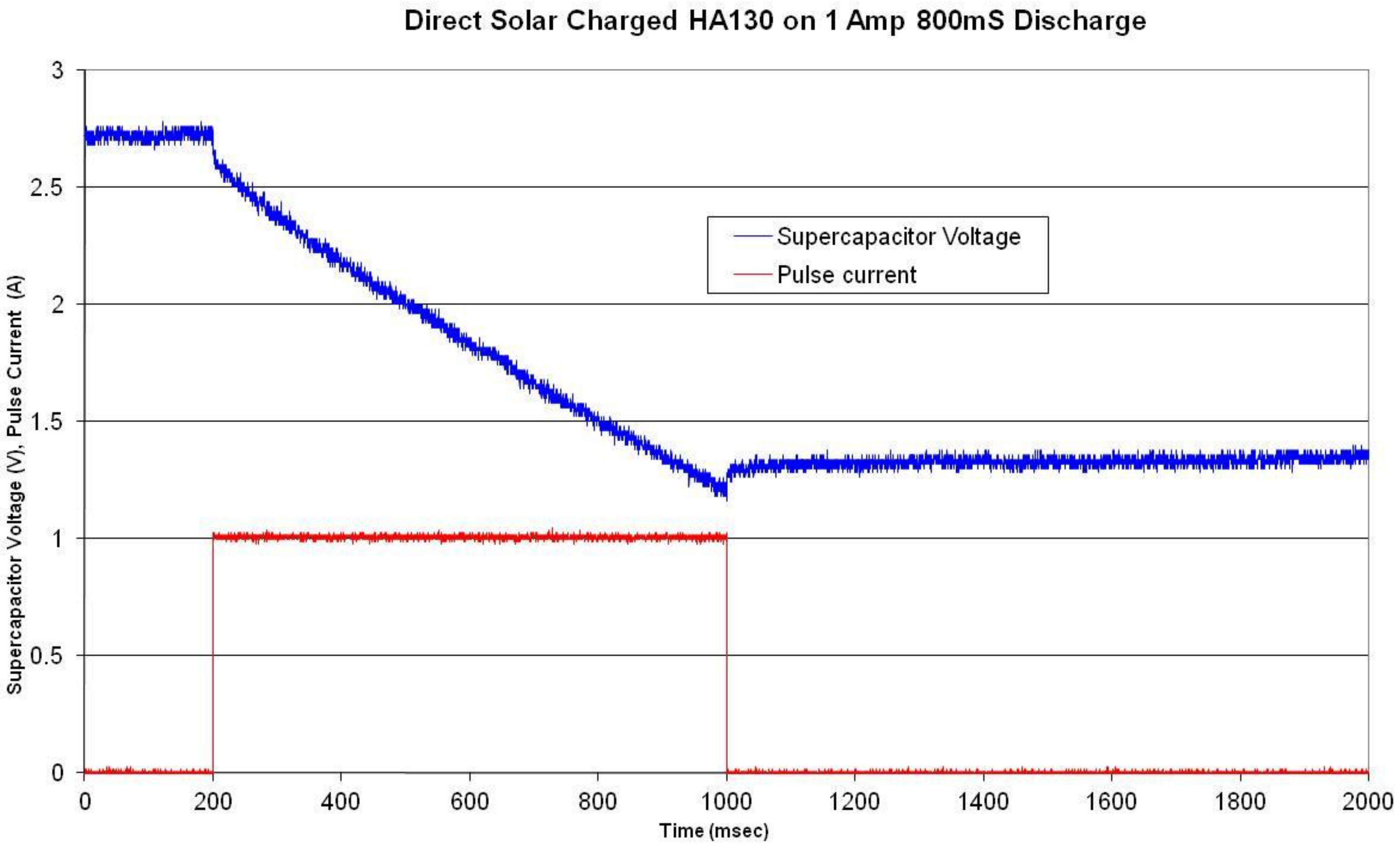


- Simplest circuit, starts charging from 0V
- V_{OC} < 2.7V at maxìmum light level
- D1 prevents the supercapacitor from discharging back into the solar cell when light levels fall
- BAT54 chosen for D1 due to low V_F. V_F is <0.1V at currents < 10μA
- HA130 provides excellent energy storage & power delivery
- **Fastest charge. But will NOT charge if V_{SOLAR} < V_{SCAP}** (e.g. if light level falls)

Fast Charging Waveforms

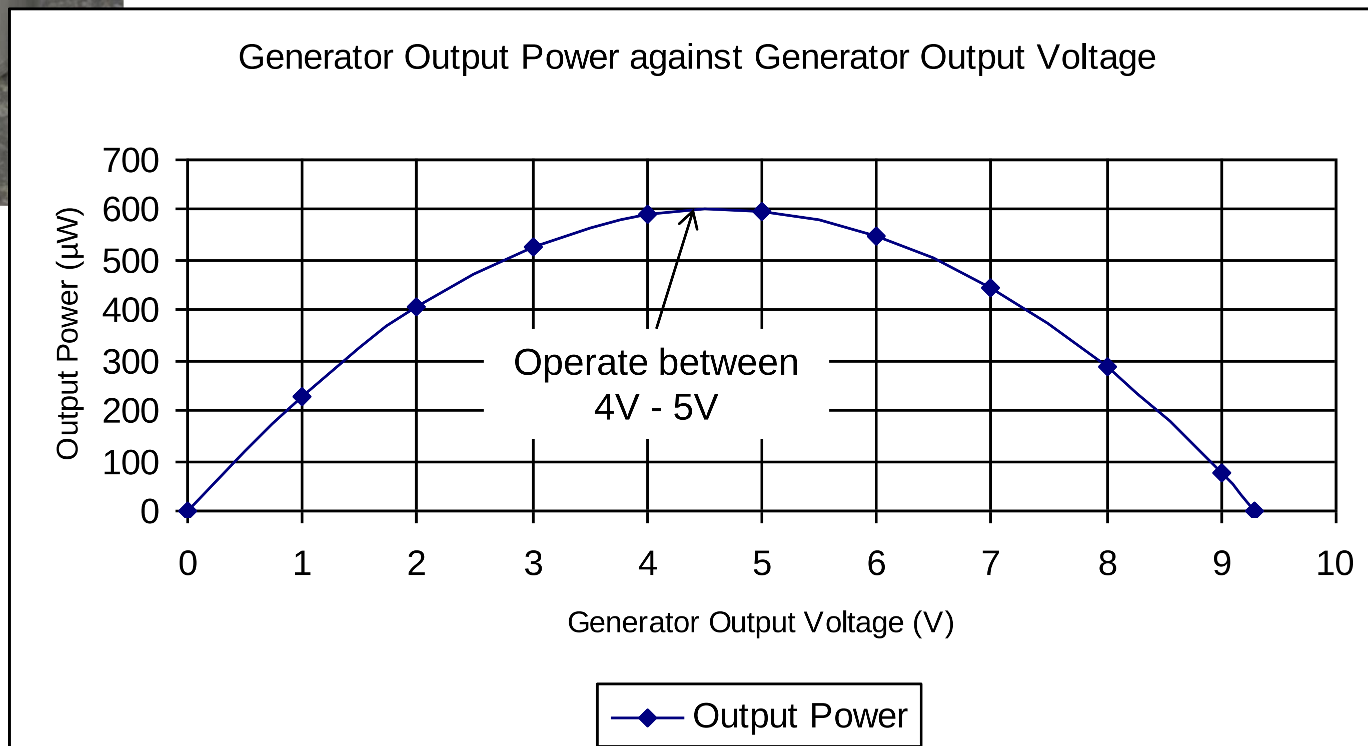


Pulse Current Discharge from the Supercapacitor

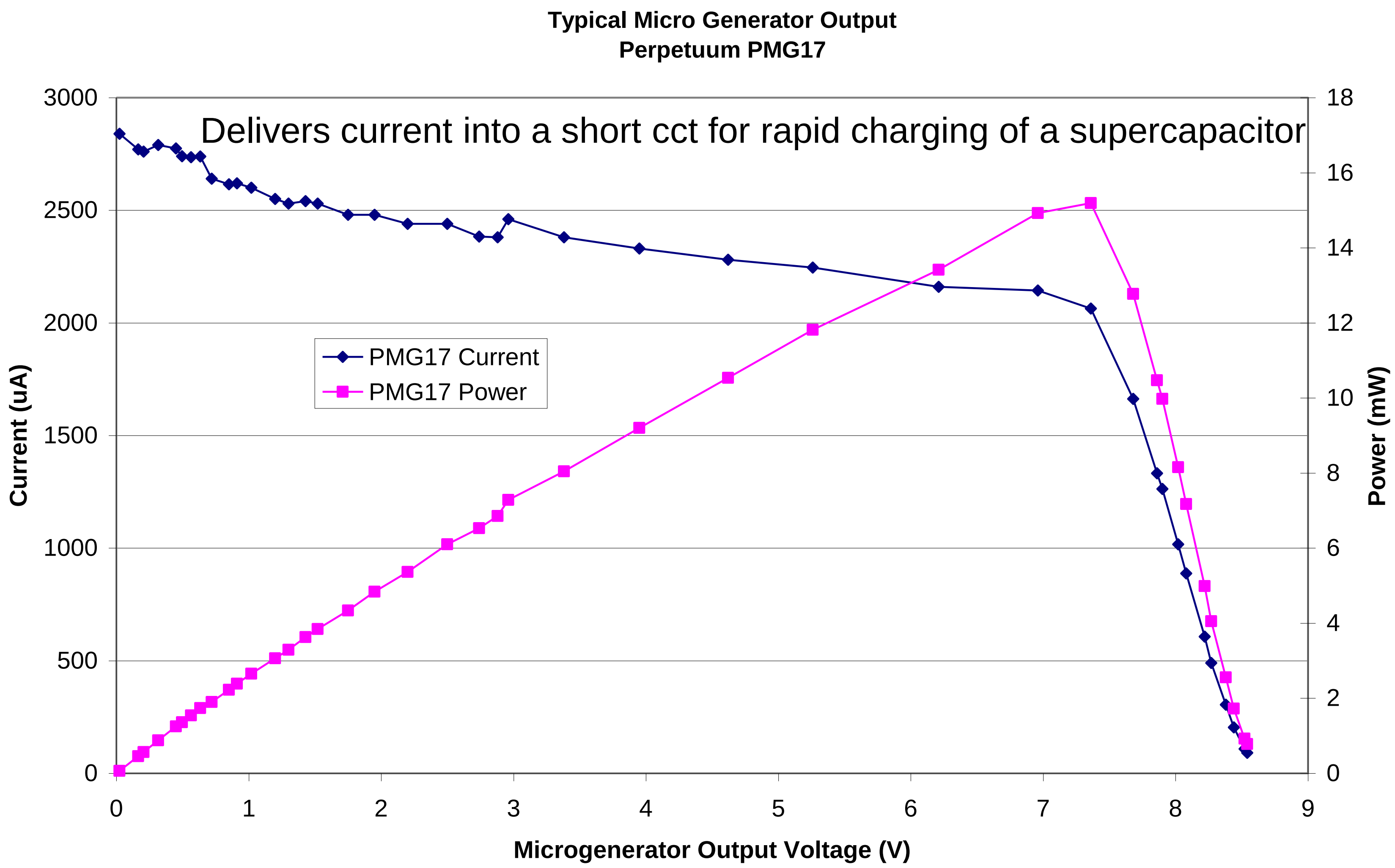


Example1: Microgenerators

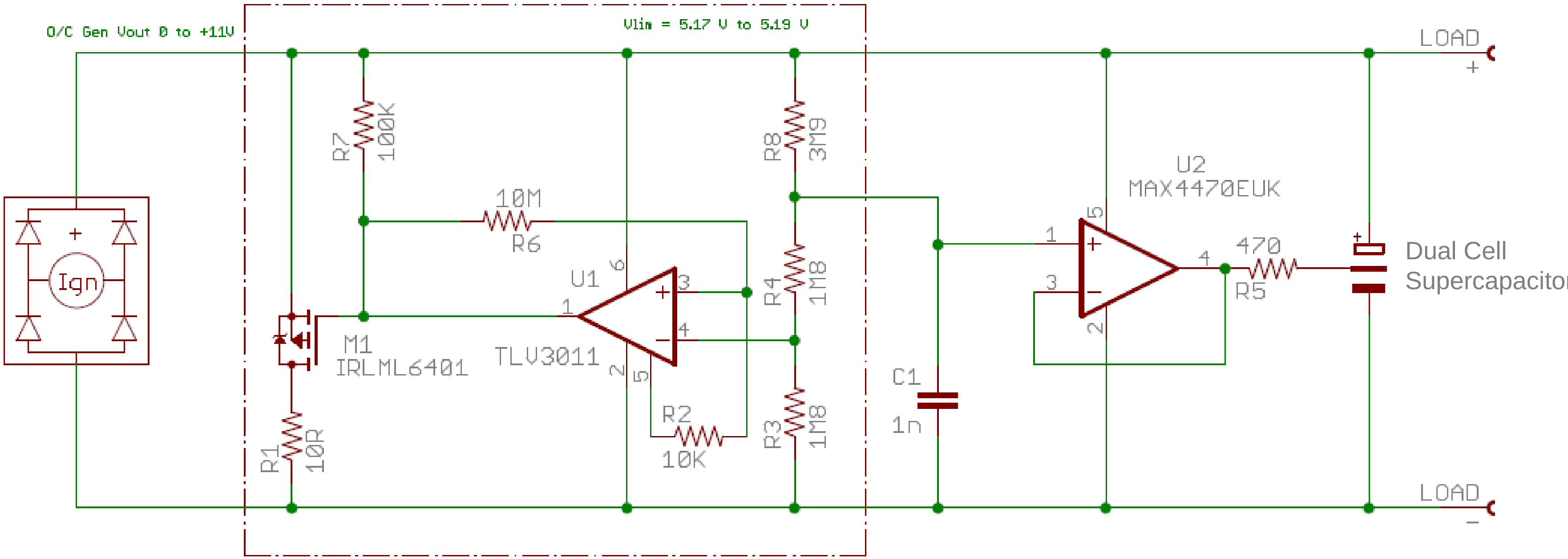
- Perpetuum microgenerator is a high impedance source
- Power match circuit to keep PMG17 @ ~5V, supercap charge current regulated so PMG17 o/p voltage ~5V
- But what this data sheet curve doesn't tell you …



Microgenerators: Characterise the Device for yourself …

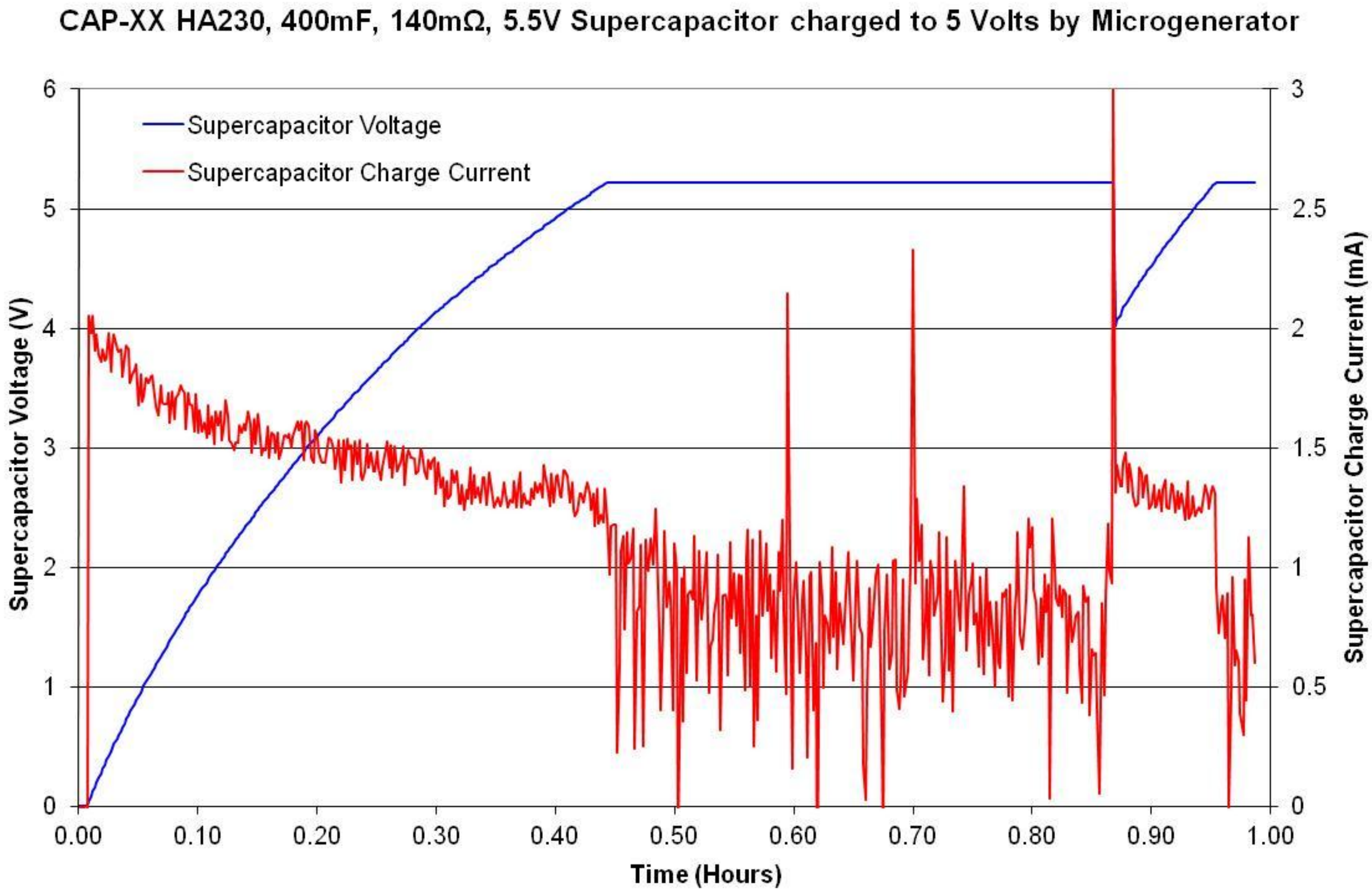


Charging cct: Microgenerator with 800mF Supercapacitor

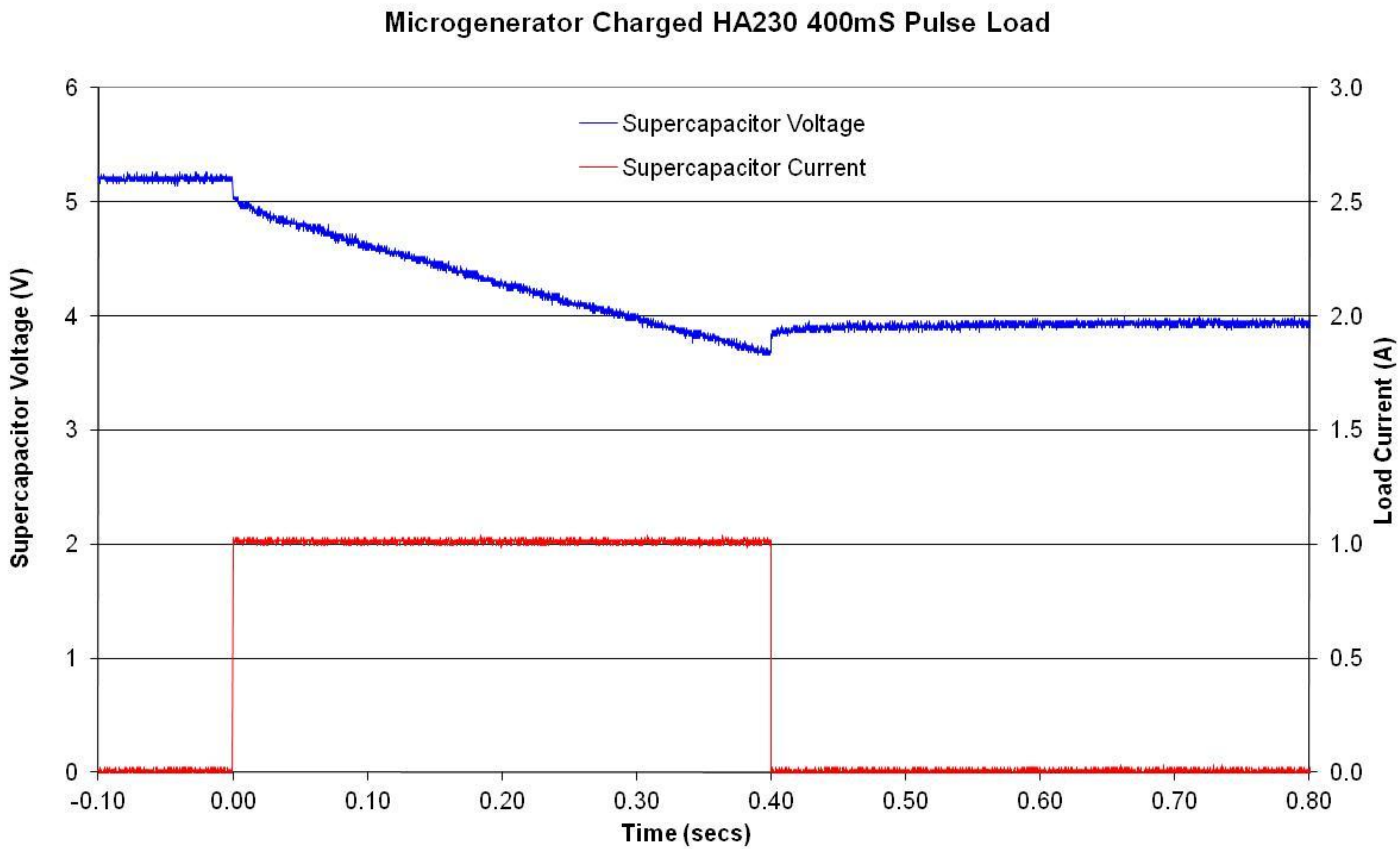


- Shunt regulator provides over voltage protection, set to 5V, with small (~20mV) hysteresis so little energy dissipated from supercapacitor.
- Active balance cct maintains cell voltages
- Diode bridge around microgenerator prevents supercapacitor from discharging back into the coil

Microgenerator Direct Charging



Pulse Current Discharge from The Supercapacitor



Peak Power Tracking

$I_{OUT} = P_{IN} . \eta / V_{OUT}$

Maximise I_{OUT} if P_{IN} = Peak Power of energy source

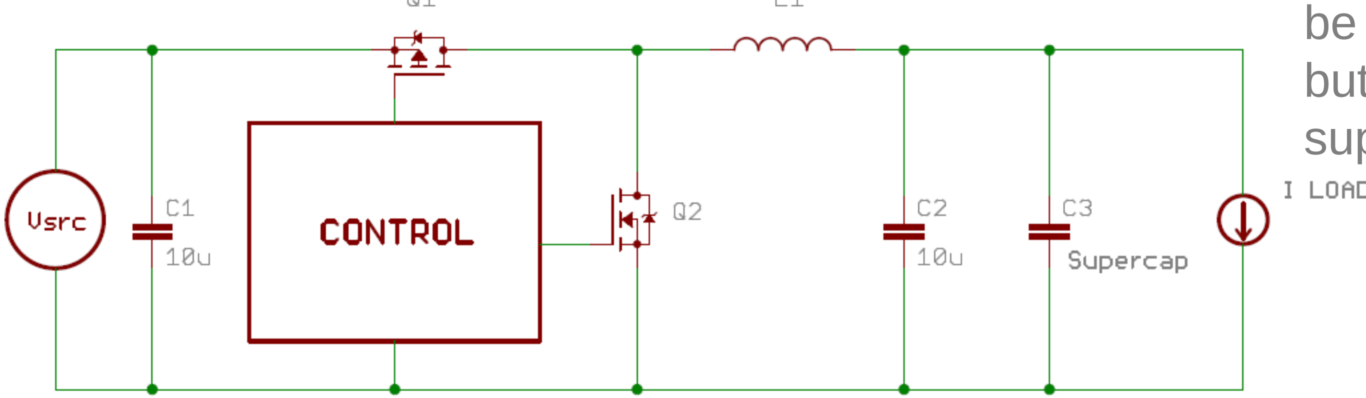
Not many low power PPT Ics

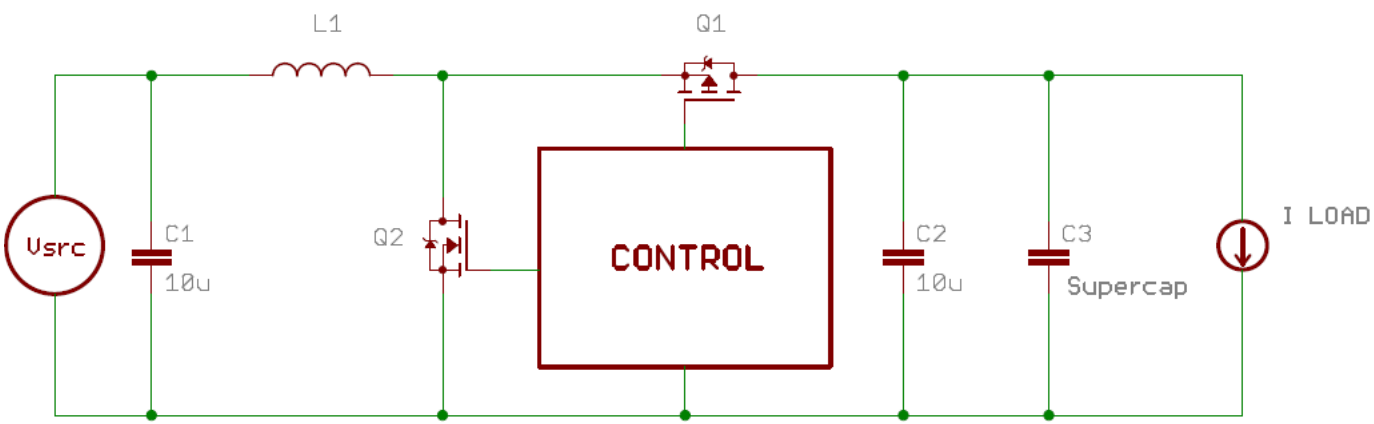
Some have fixed o/p voltage (assume Li-Ion battery), or do not behave gracefully into a supercapacitor at 0V (assume a short cct on a battery and inhibit charging)

Example: Using bq25504 charging an 800mF supercapacitor from a solar cell providing ~1.5mW

DC:DC Behaviour when $V_{OUT} << V_{IN}$

Buck



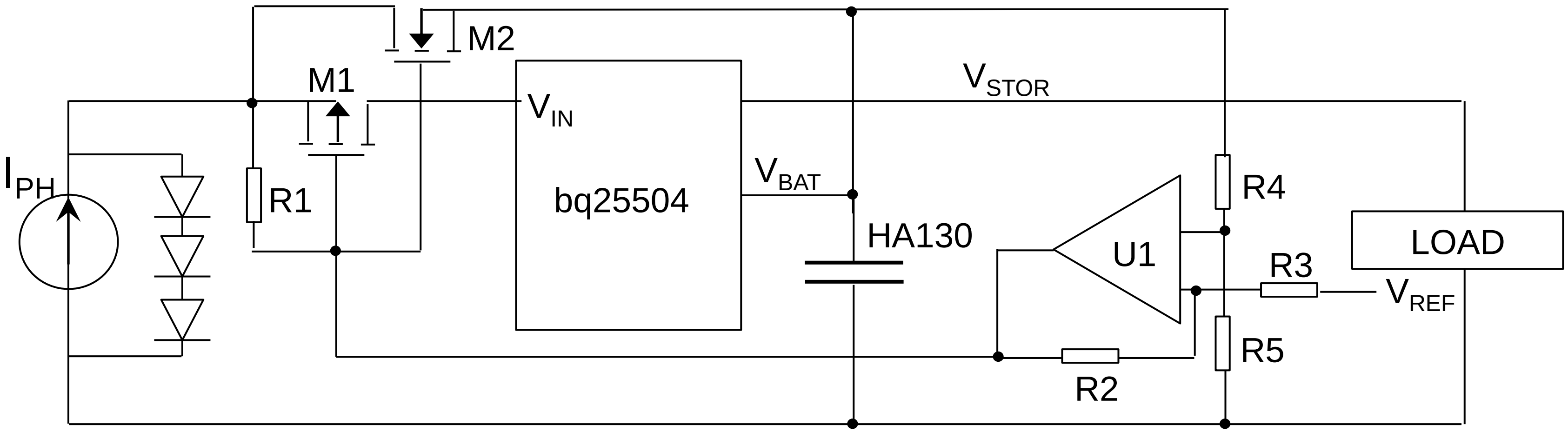


Boost

Discharged battery will be ~70% of charge V, but discharged supercapacitor is at 0V

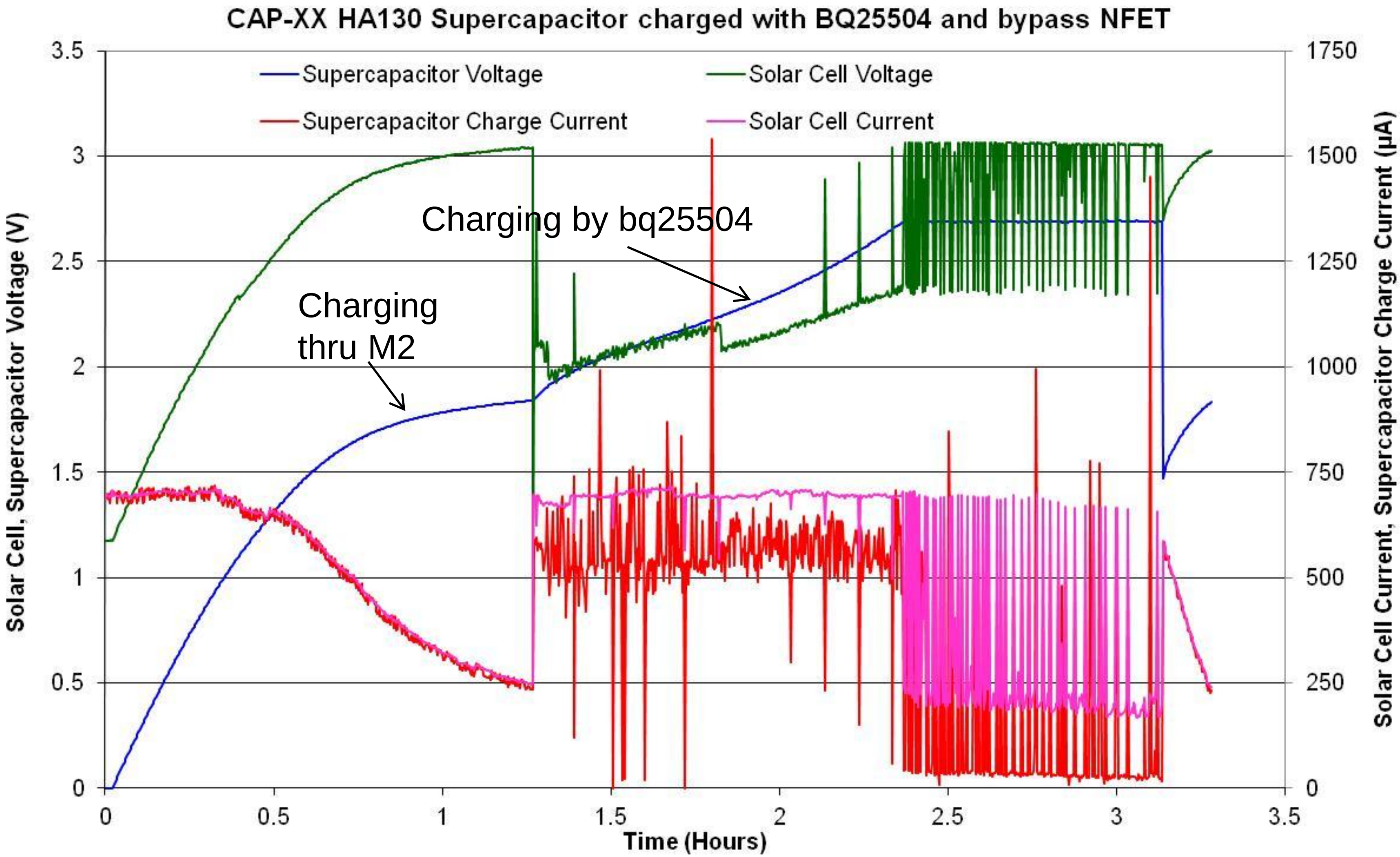
For both Buck & Boost, when $V_{OUT} << V_{IN}$, the Control turns Q1 ON (with current sense/limit), & Q2 OFF, until V_{OUT} > pre-determined threshold. Reduces to direct charging

Charge with bq25504 with NFET Bypass for Rapid Charge from 0V



- Supercap charges directly from 0V using NFET M2 to bypass bq25504. M1 is OFF, stopping the bq25504 from pulling down the solar cell voltage
- When the supercap reaches ~1.8V, the comparator turns M1 ON, connecting the bq25504 to the solar cell, and turns M2 OFF, preventing the solar cell over-charging the supercap if $V_{SOLAR\_OC} > V_{SCAP\_MAX}$
- The supercapacitor target voltage is now set by the bq25504. **There is no possibility of the supercapacitor being over-voltage**
- Achieve fast initial charge + fast charge with PPT once $V_{SCAP} > 1.8V$
- **Fast charge, and WILL charge if $V_{SOLAR} < V_{SCAP}$ and $V_{SCAP} > 1.8V$**
  (e.g. if light level falls with the supercapacitor partially or fully charged)

Waveforms for Charging with bq25504 and NFET Bypass



Peak Power Tracking

+ $I_{OUT} = P_{IN}.\eta / V_{OUT}$
  - Maximise I_{OUT} if P_{IN} = Peak Power of energy source

But supercapacitors are not charged at constant V, so some questions:

− Quiescent current?
  - Will it work?
  - I_Q of IT3652, buck with PPT (20mA) cf Power of μgen (~2mA)

− Behaviour into a supercapacitor at 0V (short cct)

− Behaviour when $V_{OUT} << V_{IN}$

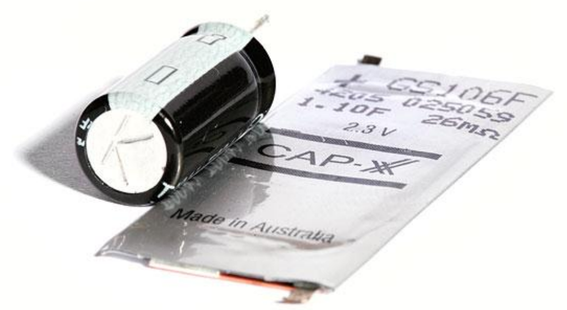
+ Boost, Buck-Boost
  - Will charge supercap if $V_{ENERGY\_SOURCE} < V_{SCAP}$

− Is it simpler/cheaper to make the open cct V of the energy harvester >= supercap max V?

? Is the energy harvester average power sufficient without PPT?

Summary: Ùsing Supercapacitors with Energy Harvesters

- Ideal power buffer
- Low voltage cells -> multiple cells -> cell balancing
- Leakage current decays over time. Charging may take longer than expected
- Allow for ageing when selecting initial C & ESR
- Solar cells and Microgenerators will deliver max current into a short circuit (ideal for charging a supercapacitor from 0V)
- Need to prevent the supercapacitor discharging back into the solar cell when light level falls
- O/C voltage of energy harvesting source. Is it cheaper to increase this and use direct charging?



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