Efficient Charging of Supercapacitors with Energy Harvesters

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Darnell Power Forum, September 19-21, 2012

Scope

- Wireless sensors coupled with low power energy harvesters are becoming ubiquitous
- An high power energy store is required to provide peak power for data collection and transmission
- Supercapacitors are an ideal energy storage device for this function
- What supercapacitor properties are important for this function?
- What is the optimum solution to charge the supercapacitor?

Agenda

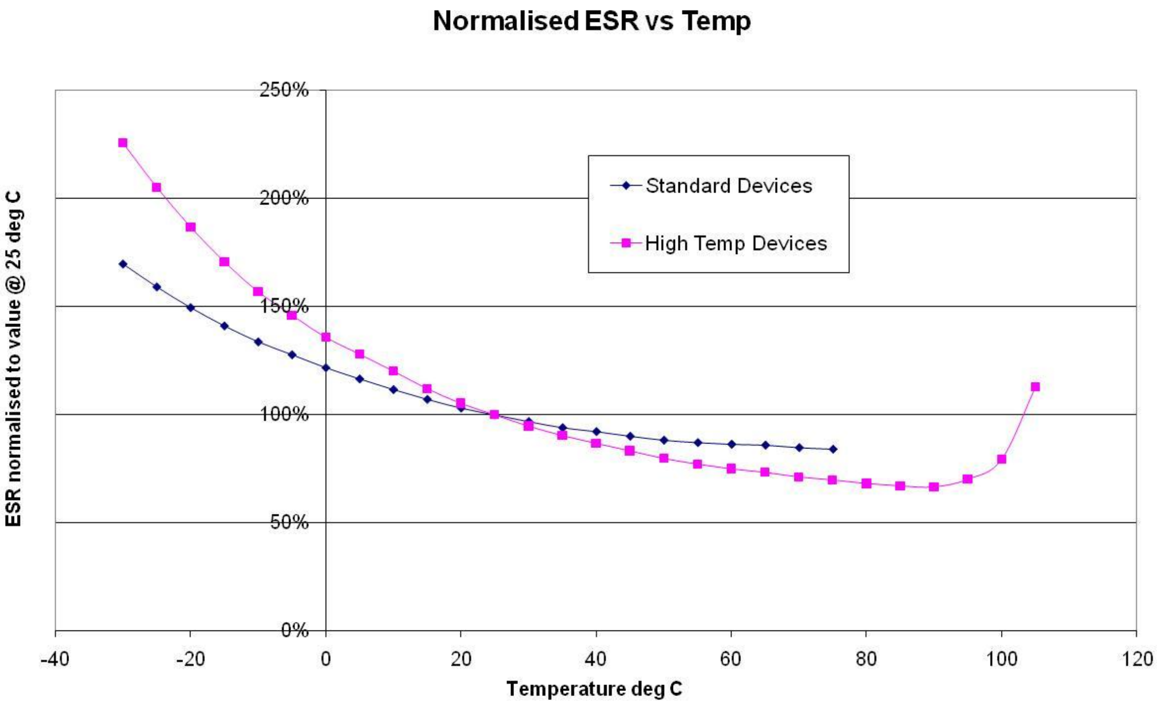
- Why use a supercapacitor?
- Supercapacitor properties

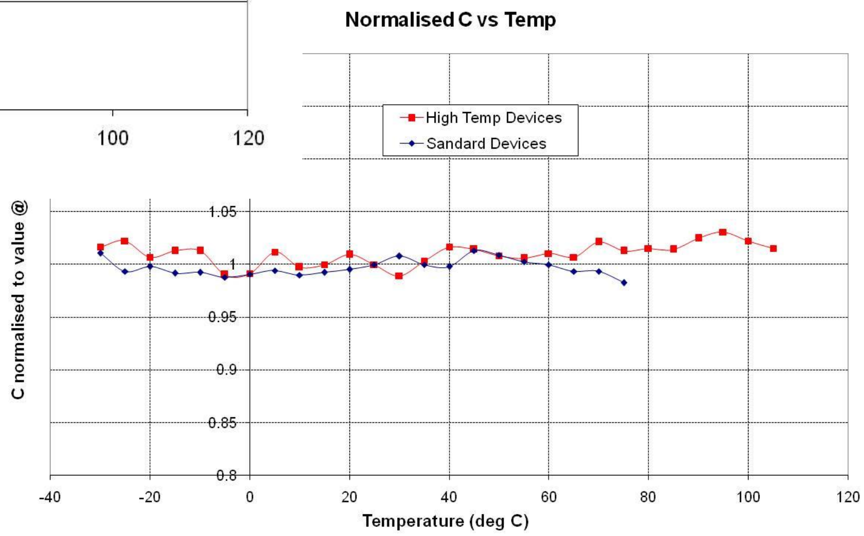
  (What you need to know when designing your system)
  - Temperature performance
  - Leakage current
  - Charge current
  - Cell balancing
- Interfacing the supercapacitor to your energy source
  - Supercapacitors just want current, not constant voltage
  - If the energy harvester delivers short cct current, is it better to charge directly, or use a Peak Power Tracking charger IC?

Why use a Supercapacitor?

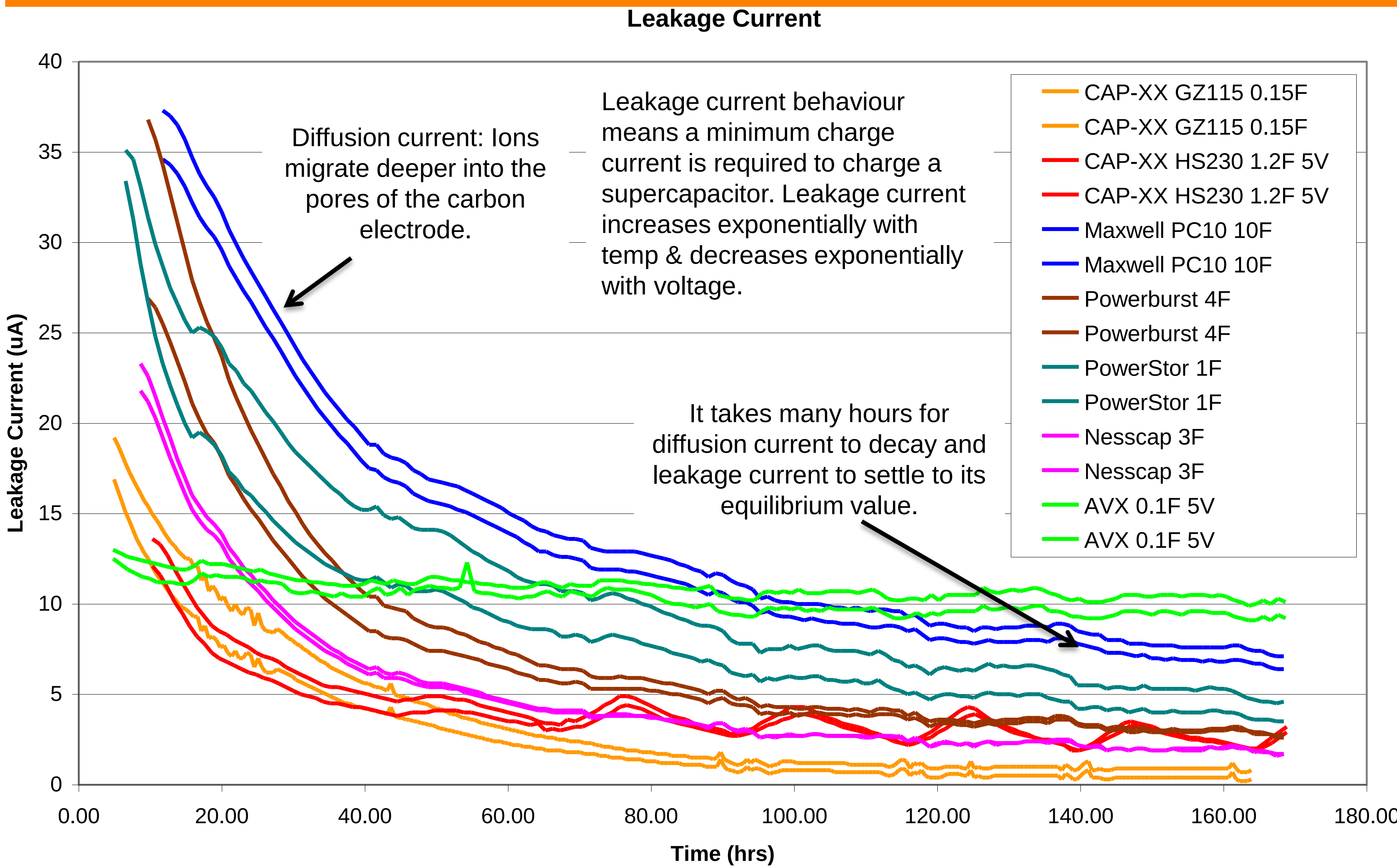
- Physical charge storage
  - “Infinite” cycle life
- Low impedance (ESR)
  - High power delivery
  - Transmission over a cellular network
- Super High C
  - Energy to deliver the power for the duration needed
- High power delivery at low temps (-40°C)
- Easy to charge
  - Just need a charge current and over-voltage protection
- Low leakage current
- Available in thin, small form-factors

Excellent Performance across a Wide Temperature Range

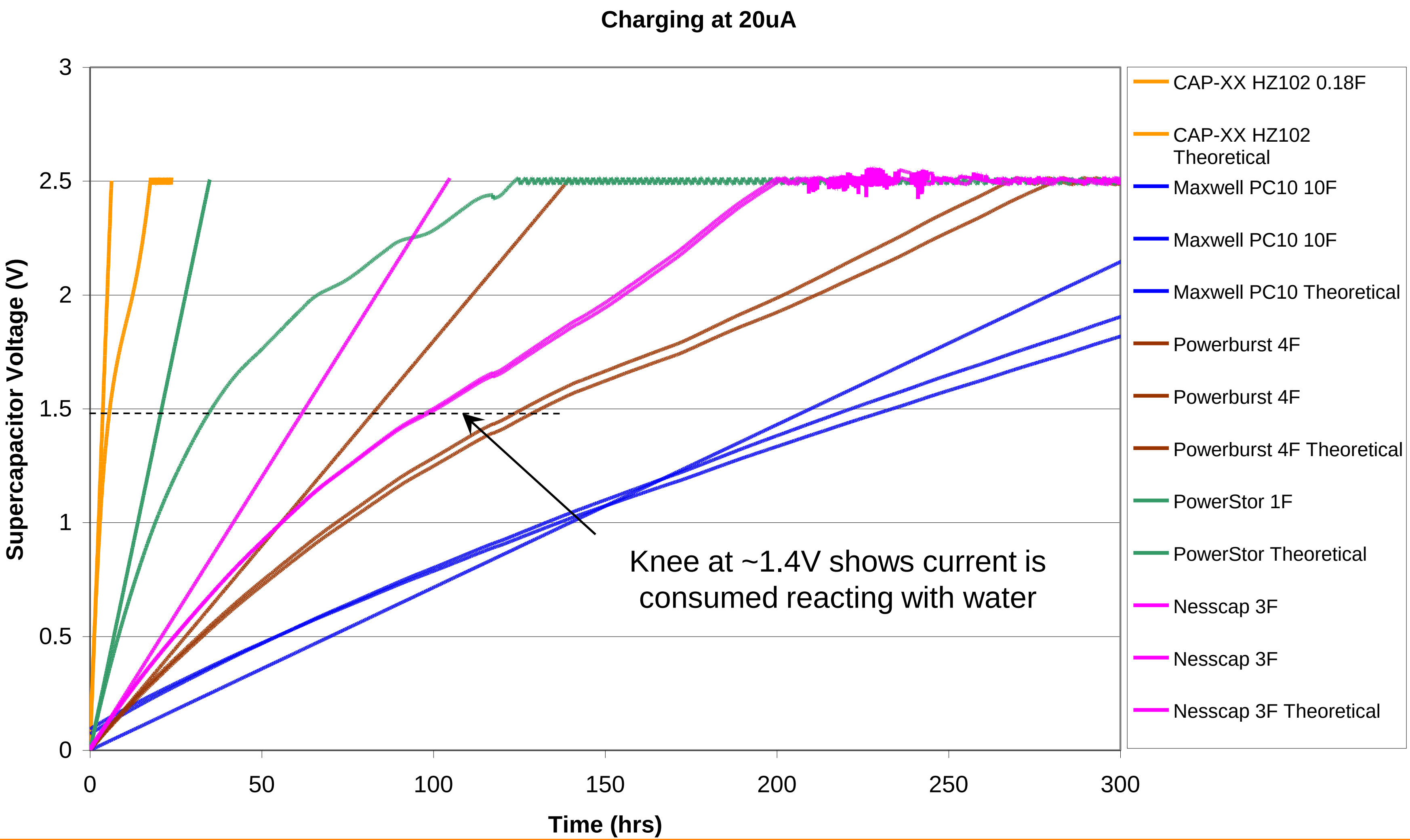




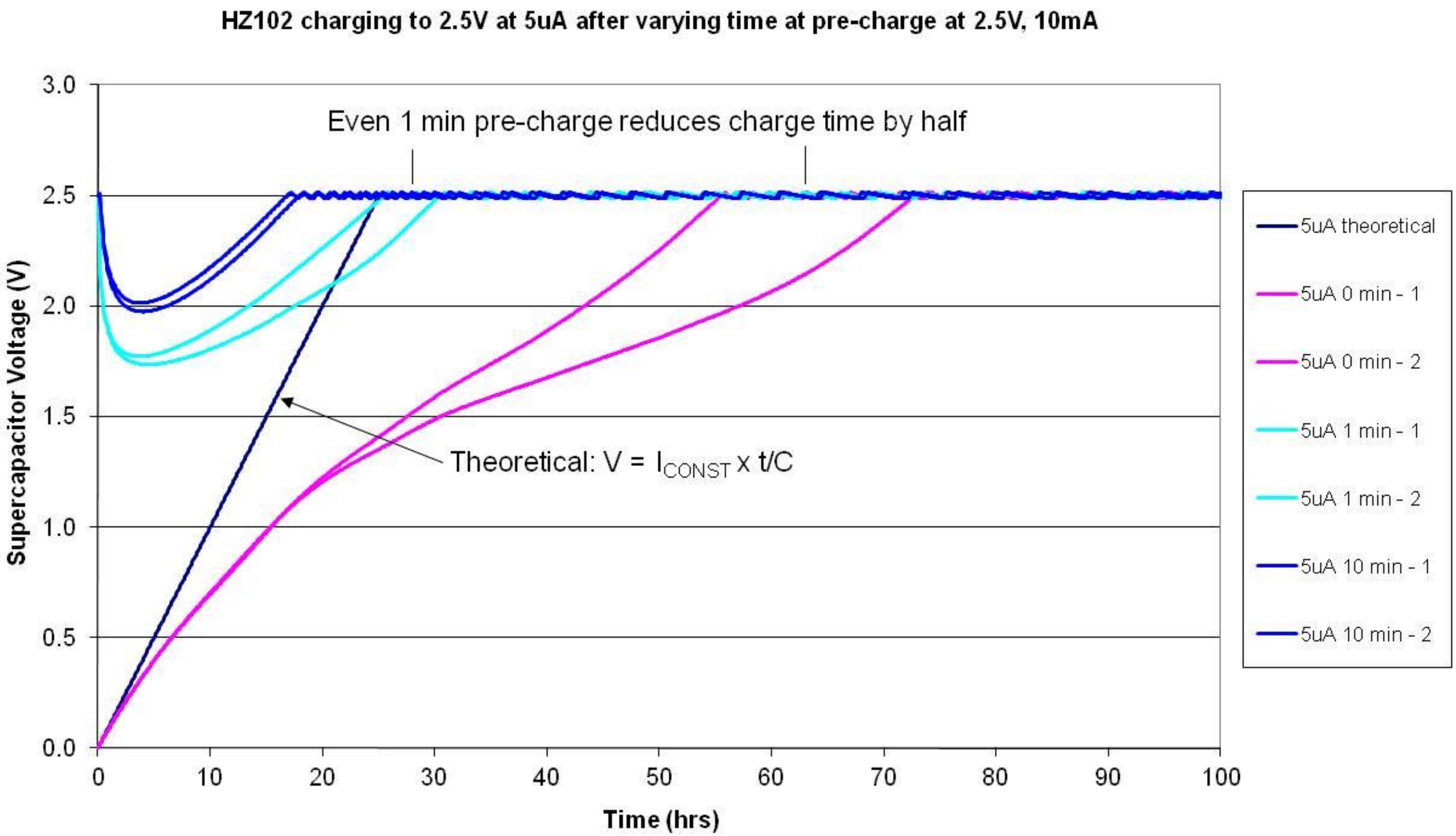
Supercapacitor Leakage Current



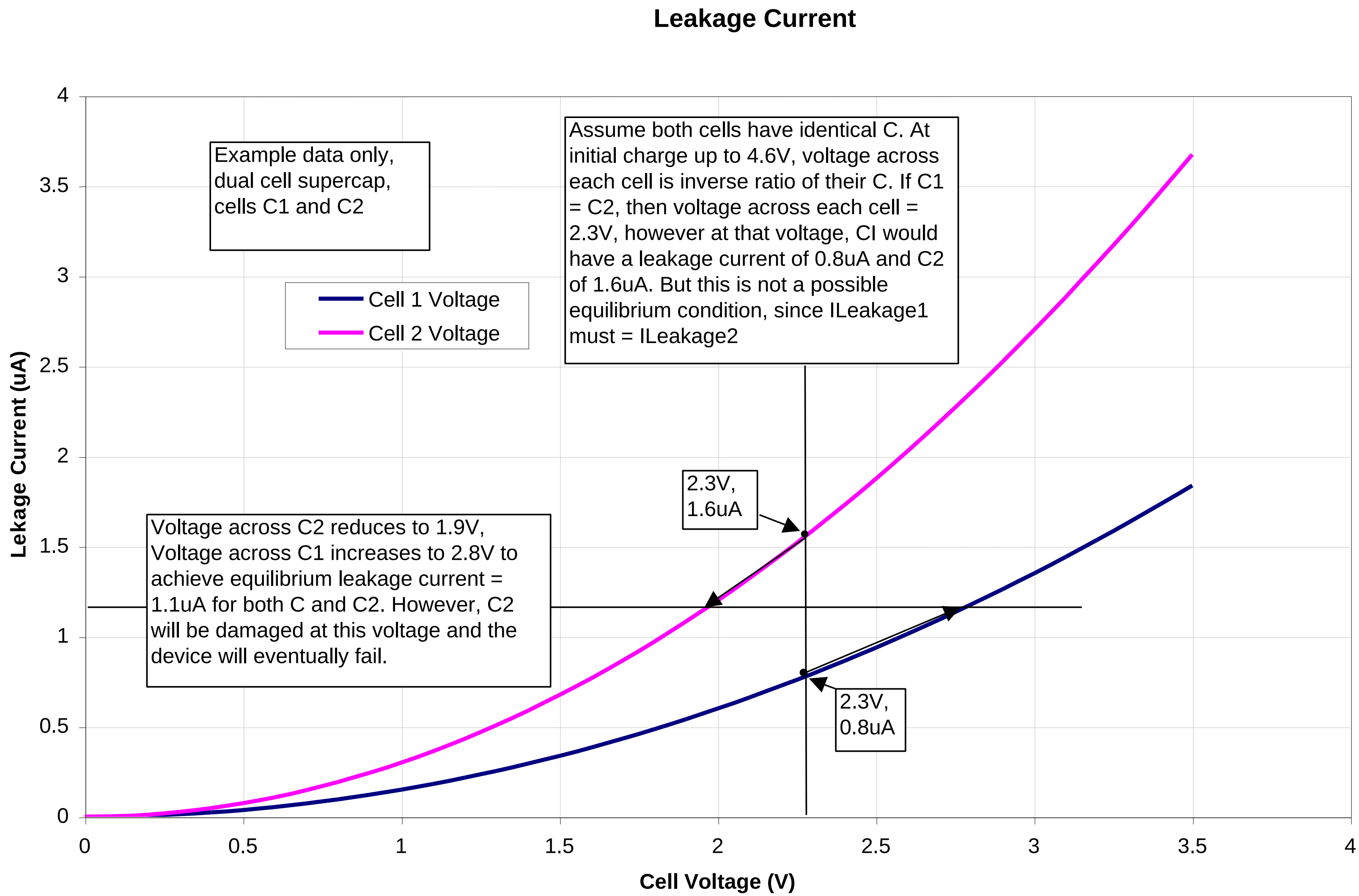
Supercapacitors need a Minimum Initial Charging Current …



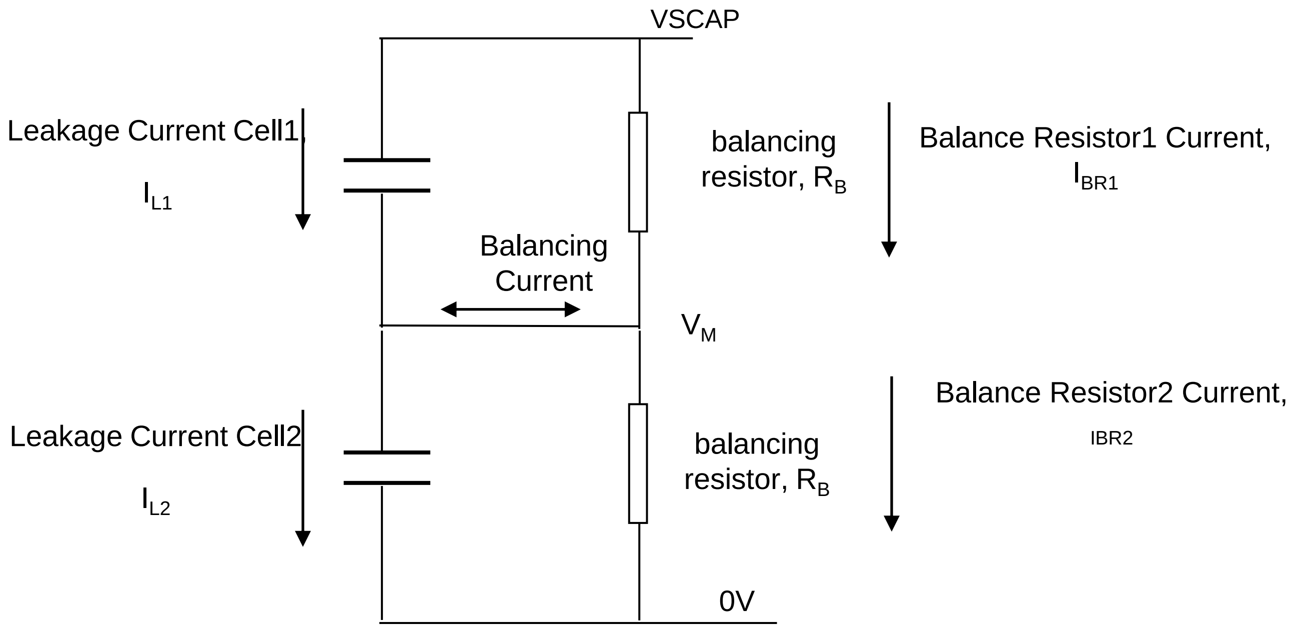
…but a Short Initial Charge at "High" Current can overcome this



Cell Balancing is Essential



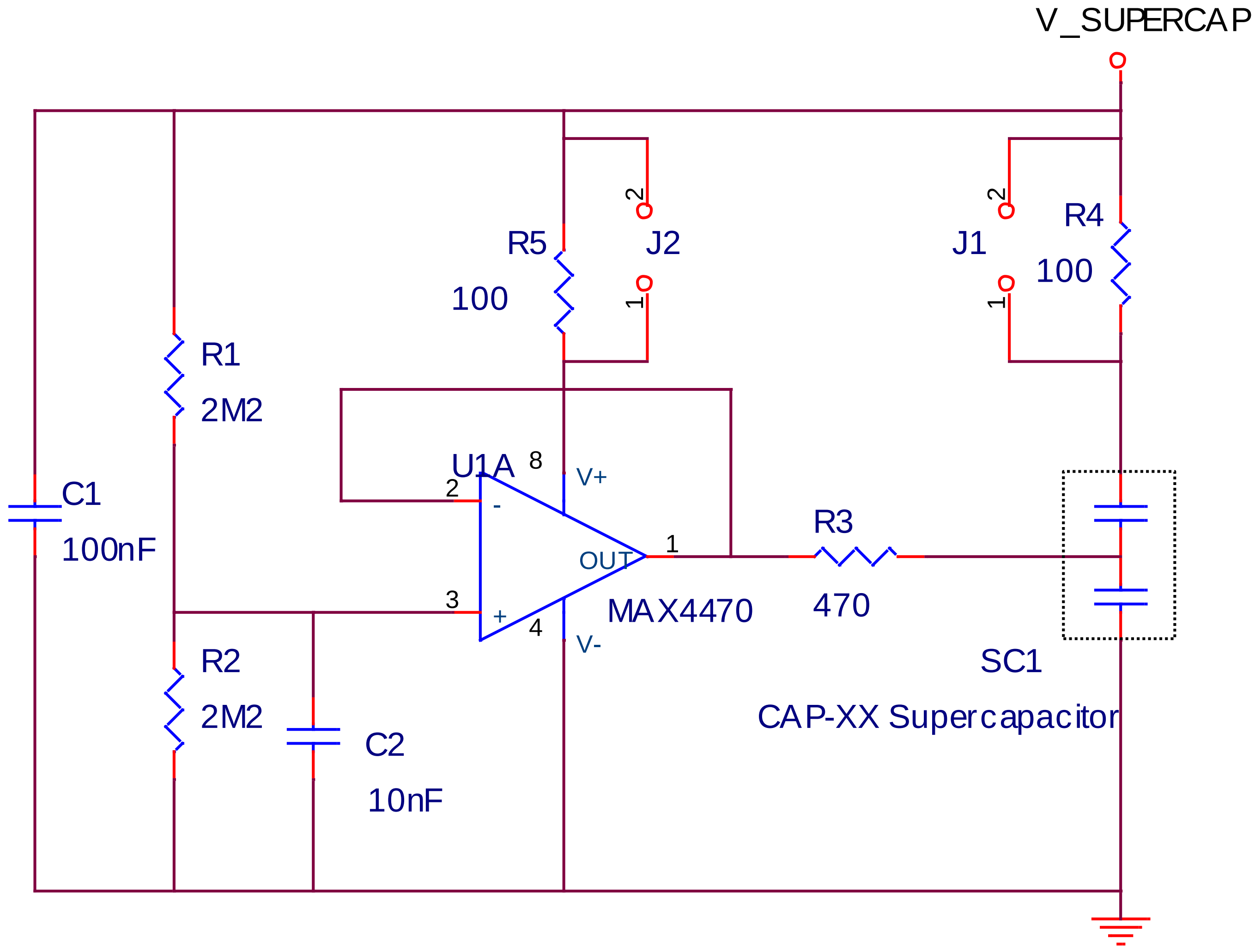
Simple Passive Balancing



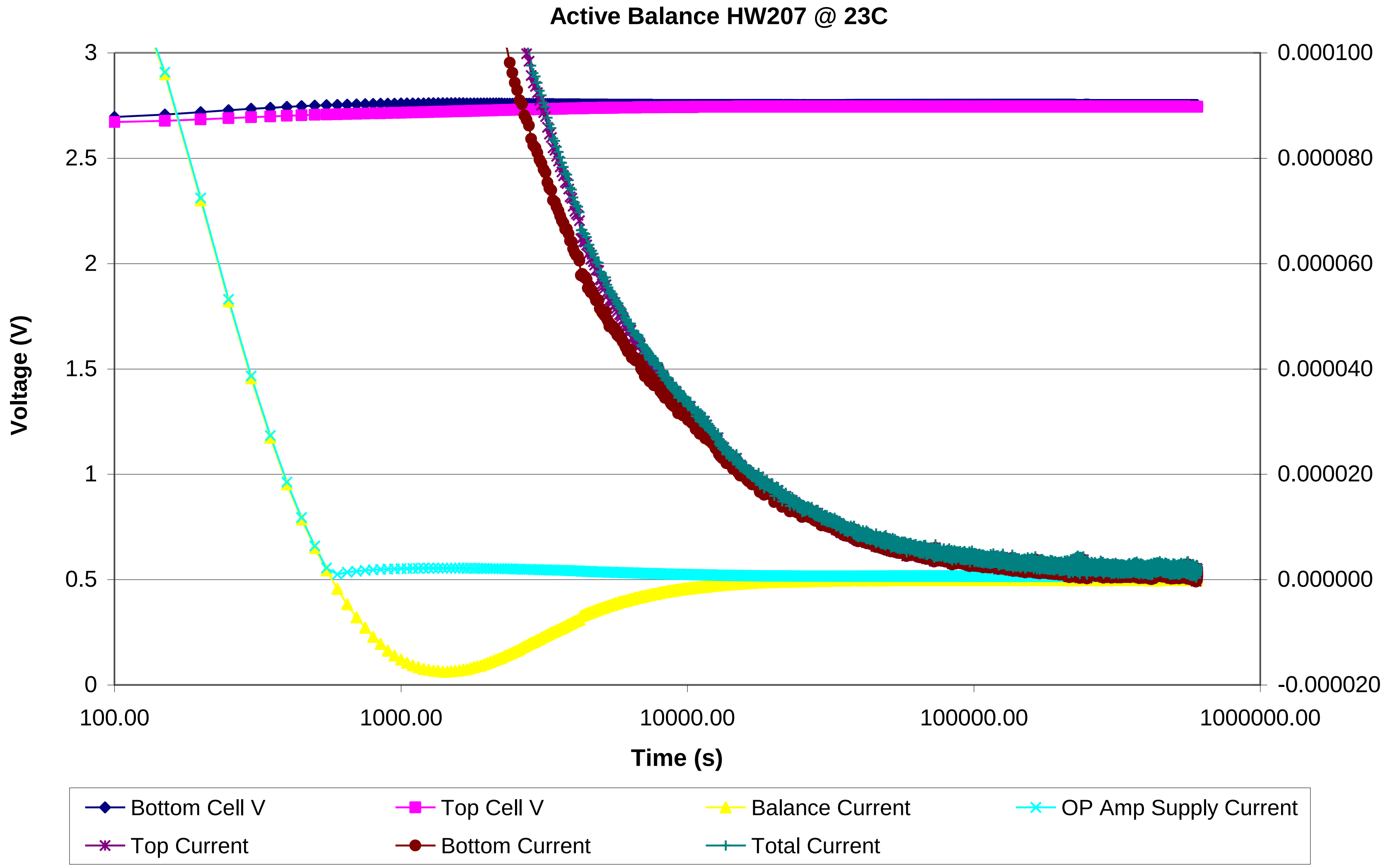
- The purpose of this circuit is to maintain V_M close to V_{SCAP} / 2
- $V_M = R_B \times I_{BR2} = R_B \times (I_{BR1}$ - Balancing Current)
- For this circuit to work, Balancing Current must be << I_{BR1}, I_{BR2}
- VM must be prevented from going >> V_{SCAP} / 2 or << V_{SCAP} / 2 for any significant 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



Supercapacitor Interface Circuits

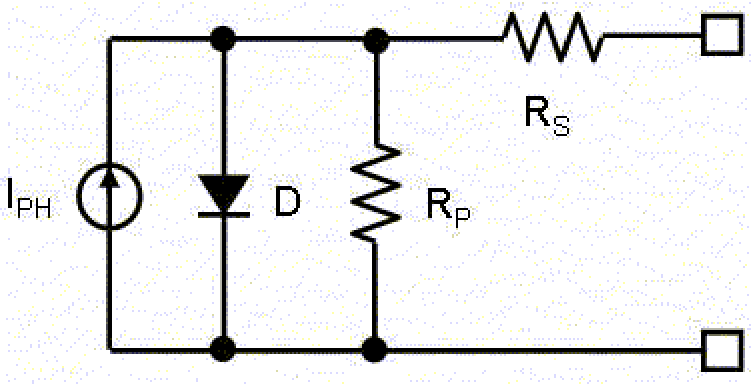
Design principles:

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

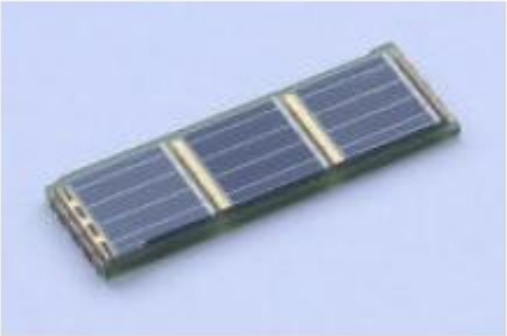
- A discharged supercapacitor will look like a short circuit to your energy source
- Most energy harvesters don't care – will deliver current into a short circuit
- Definitely a problem for batteries, and some other power supplies
  - Interface electronics must manage this either in the design:
    - 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

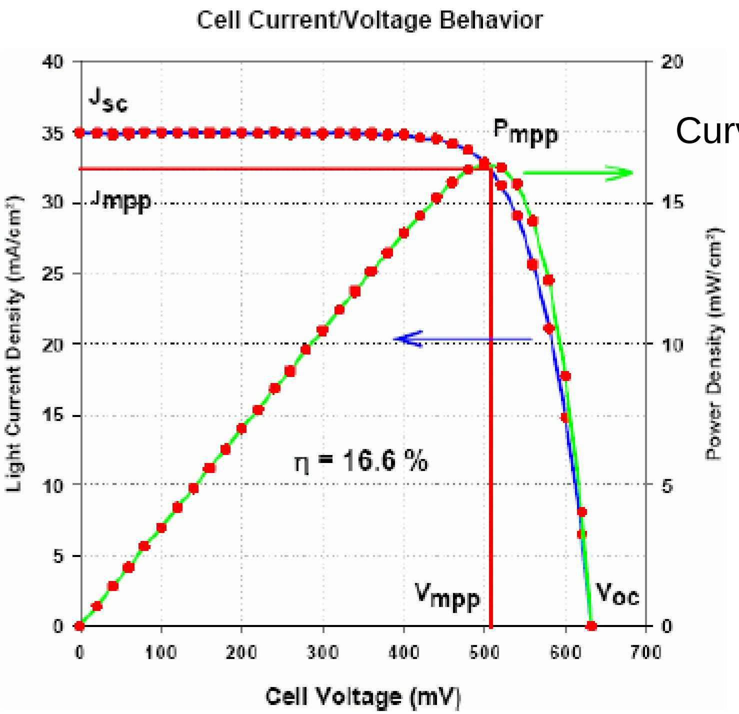
XOB17, 22mm x 7mm x 1.6mm used for measurements in following slides



- 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

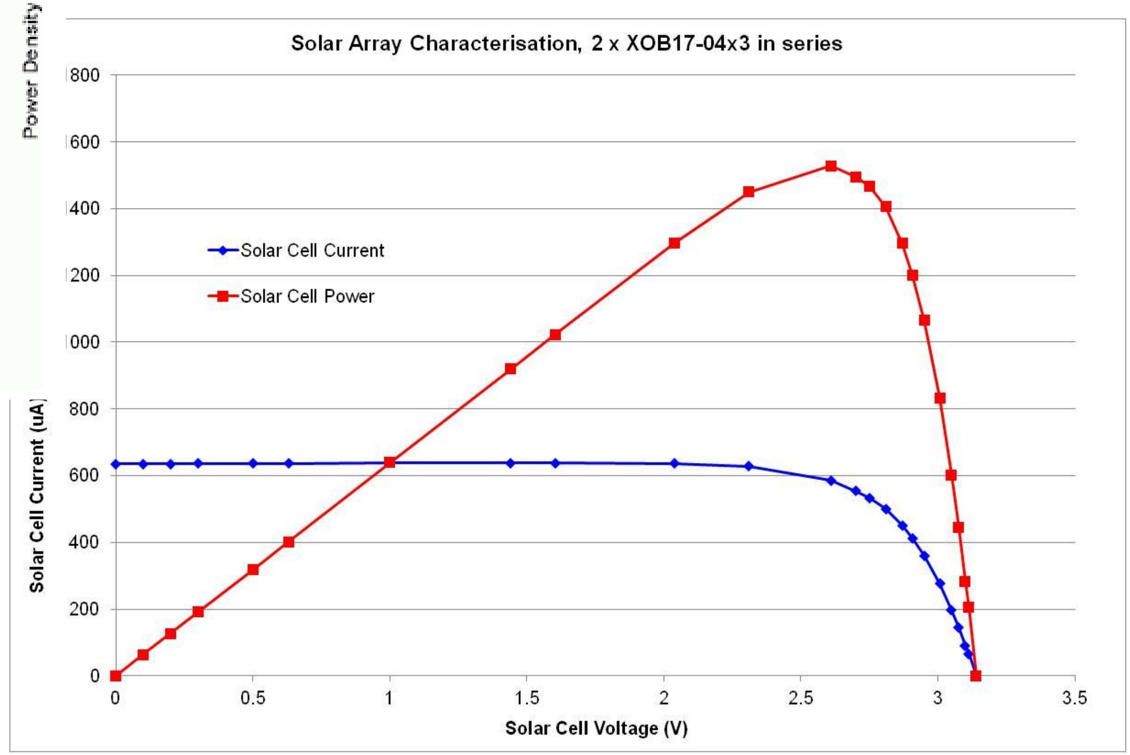
- Will deliver current into a short circuit (discharged supercapacitor)
- Will discharge the load if light level drops

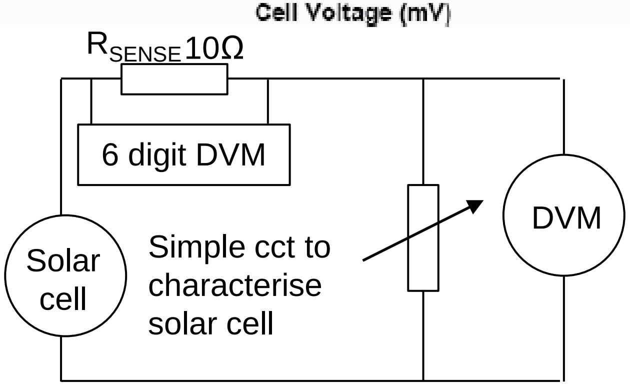
Solar Cell V-I: Power Curve



Curves provided in data sheet

Curves developed in lab in our light conditions





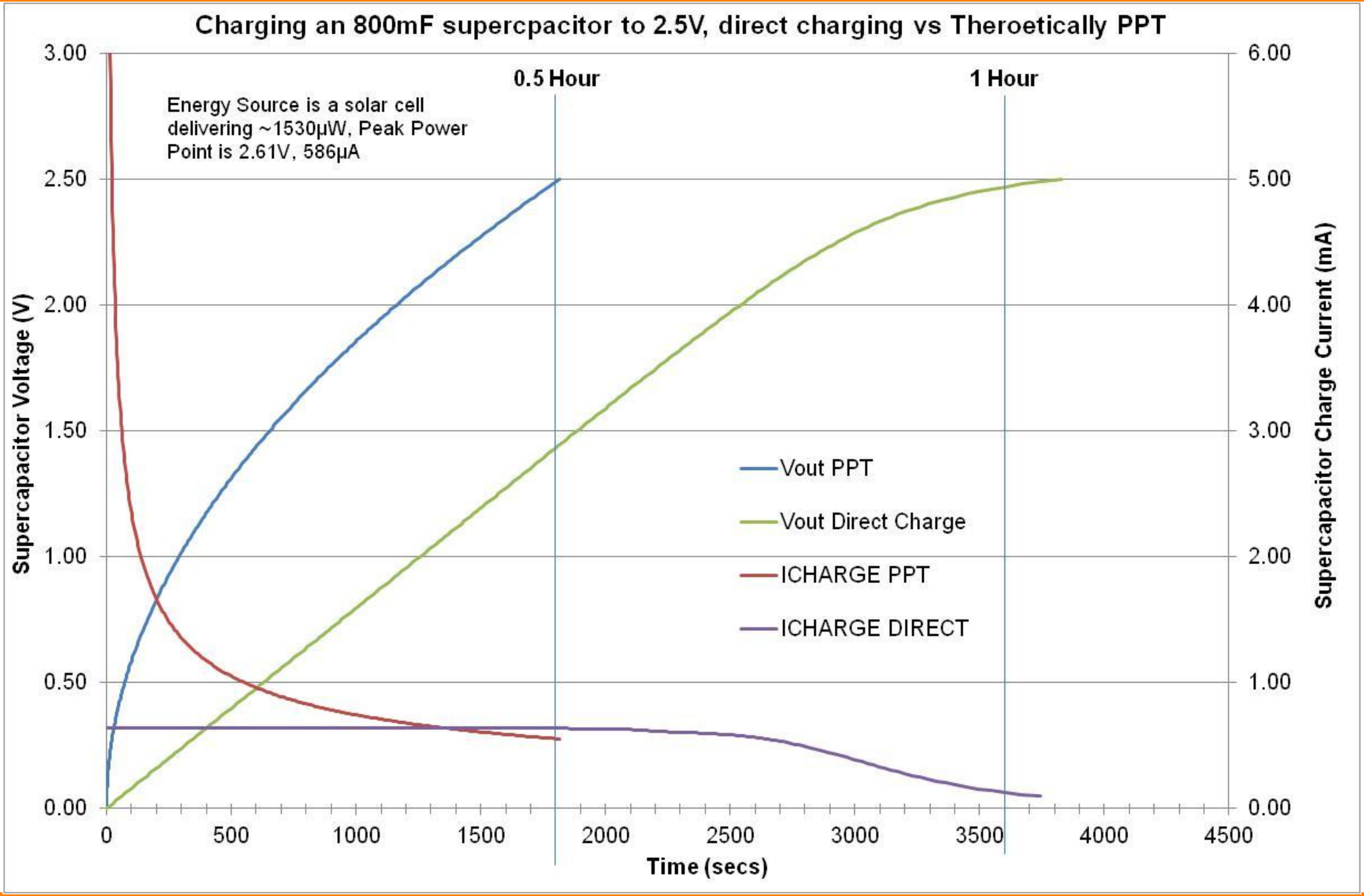
Charging a Supercapacitor with PPT: Theory...

- $V_{IN}.I_{IN} = V_{OUT}.I_{OUT} \times \eta$
- If η = 90%, $I_{OUT} = P_{IN} \times 90\% / V_{OUT}$
- PPT maximises P_{IN}, hence I_{OUT}
- Gives very high charge current when V_{OUT} is low (start of supercap charging), > I_{SCAP} of energy harvester

Other considerations for PPT IC:

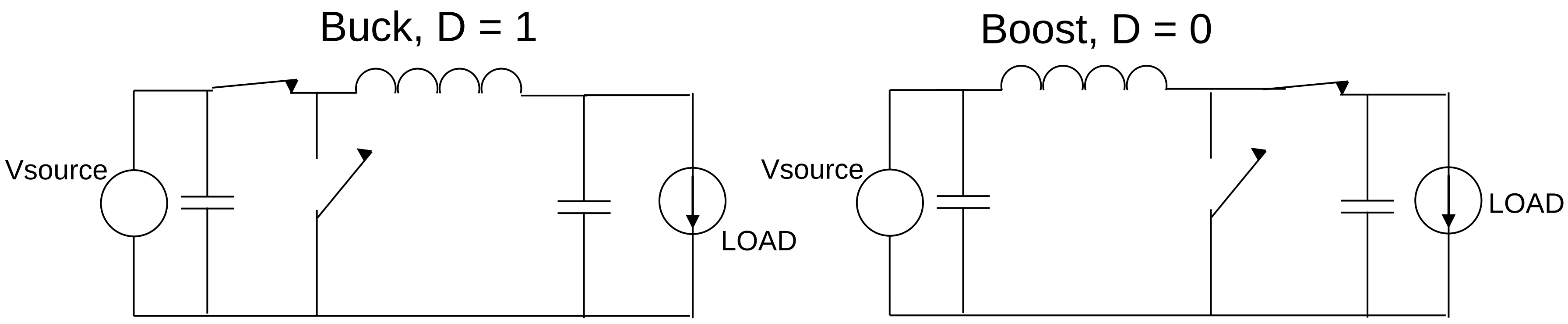
- Need $P_{SUPPLY} << P_{IN}$
- Must behave well into a short cct (some ICs are designed to charge a battery, and do not understand 0V on their o/p, or cannot have user-programmable o/p voltage)

Theoretical Peak Power Tracking



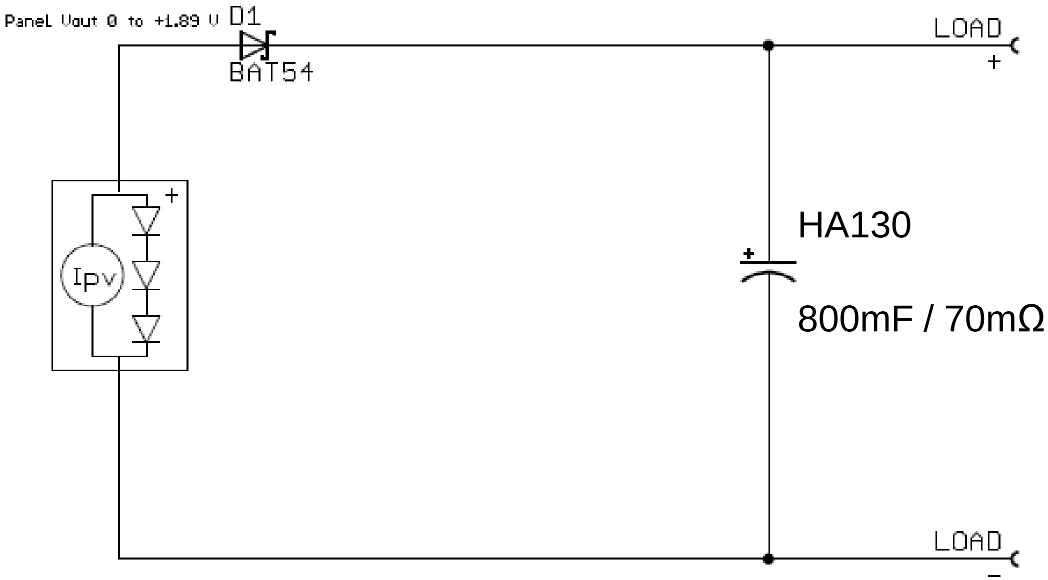
... but in Practice

- DC:DC doesn't operate that way when $V_{OUT} << V_{TARGET}$



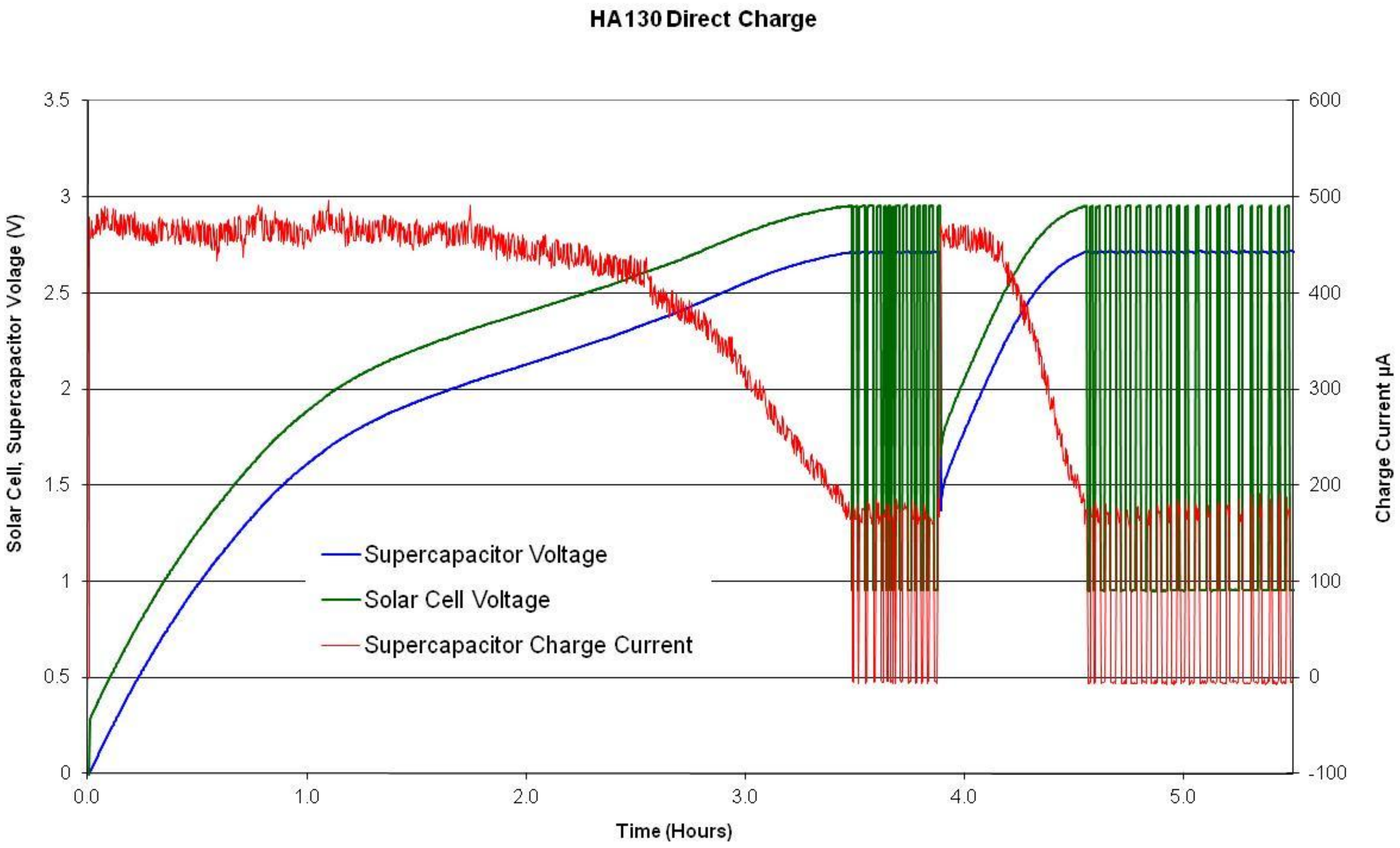
- Unlike a battery, this is the case when charging a supercapacitor from 0V
- Looks like direct charging
- Need a DC:DC where V_{TARGET} is just above V_{OUT} until V_{OUT} approaches the final value of V_{TARGET}

Direct Charging Circuit

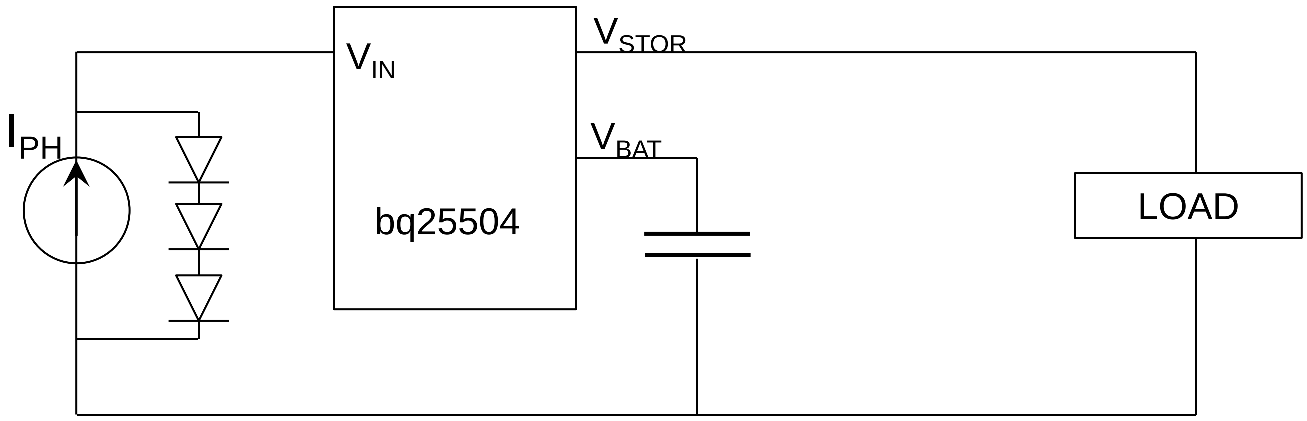


- Simplest circuit, starts charging from 0V
- V_{OC} < 2.7V at maxìmum light level
- D1 prevents the supercapacitor from discharging back into the solar cell when light levels fall
- BAT54 chosen for D1 due to low V_F. V_F is <0.1V at currents < 10µA
- HA130 provides excellent energy storage & power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

Fast Charging Waveforms

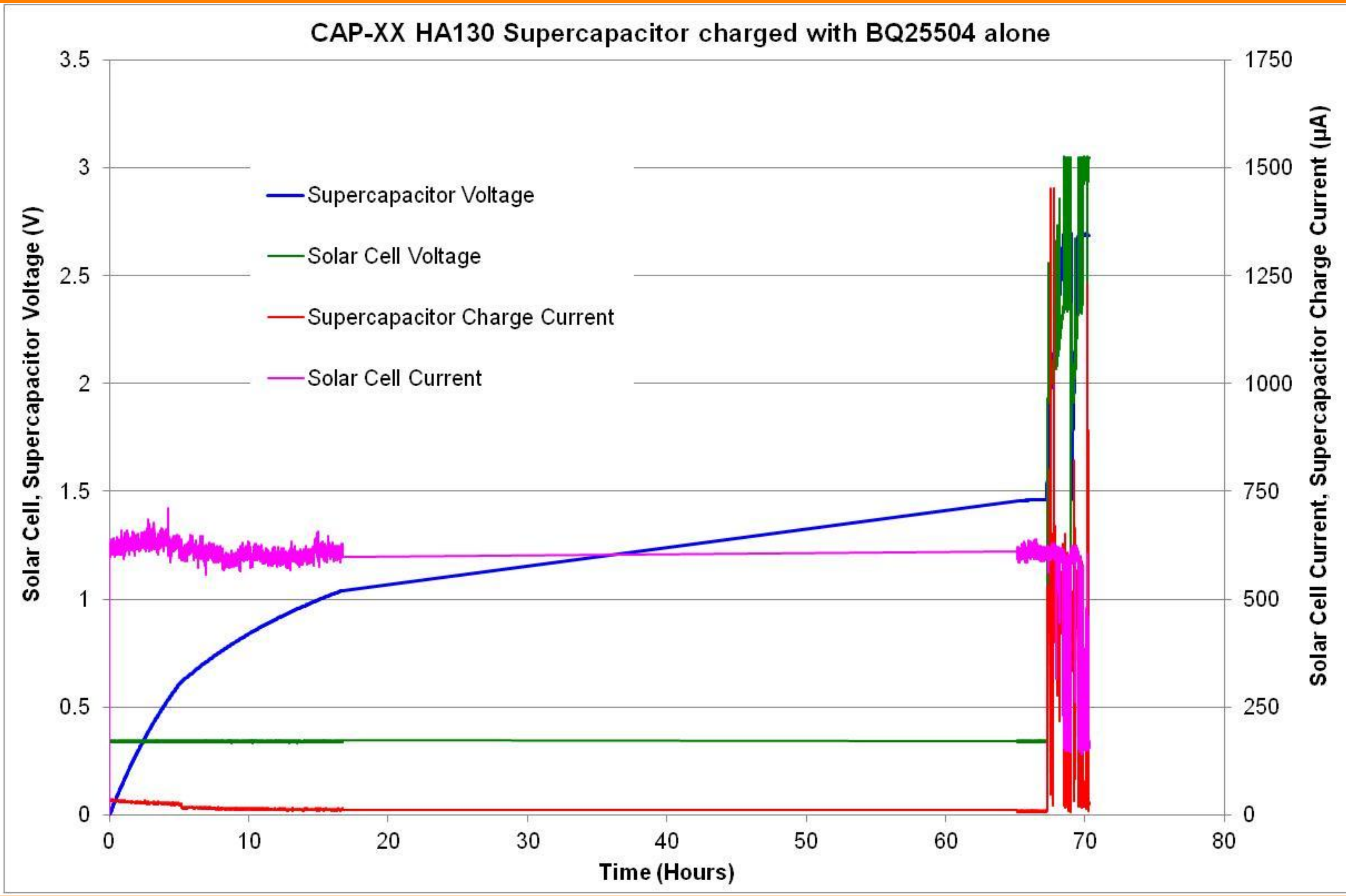


Charge with bq25504

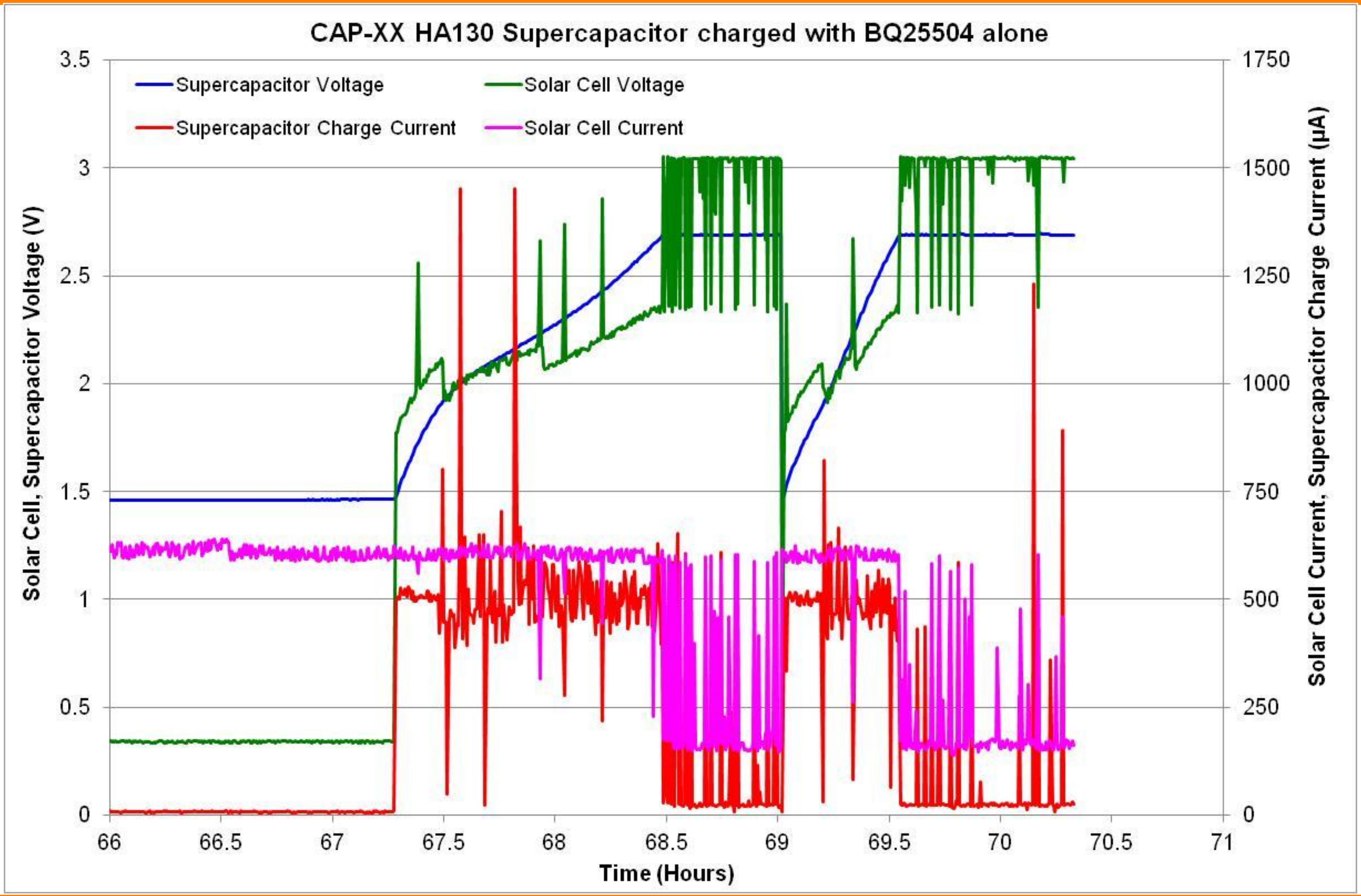


- Charge using bq25504 boost converter with Peak Power Tracking (PPT)
- The bq25504 has very inefficient "cold start" charging if V_{BAT} < ~1.5V
- It take ~67hrs for the bq25504 to charge an HA130 from 0V to 1.5V with a solar cell delivering 350µW peak power ("cold start")
- It takes another hour to reach 2.7V with the boost converter running normally with PPT
- **Slowest charge. But WILL charge if $V_{SOLAR} < V_{SCAP}$ and $V_{SCAP} > 1.5V$**
(e.g. if light level falls with the supercapacitor partially or fully charged)

Charge with bq25504 Waveforms



Charge with bq25504 (last 5h)

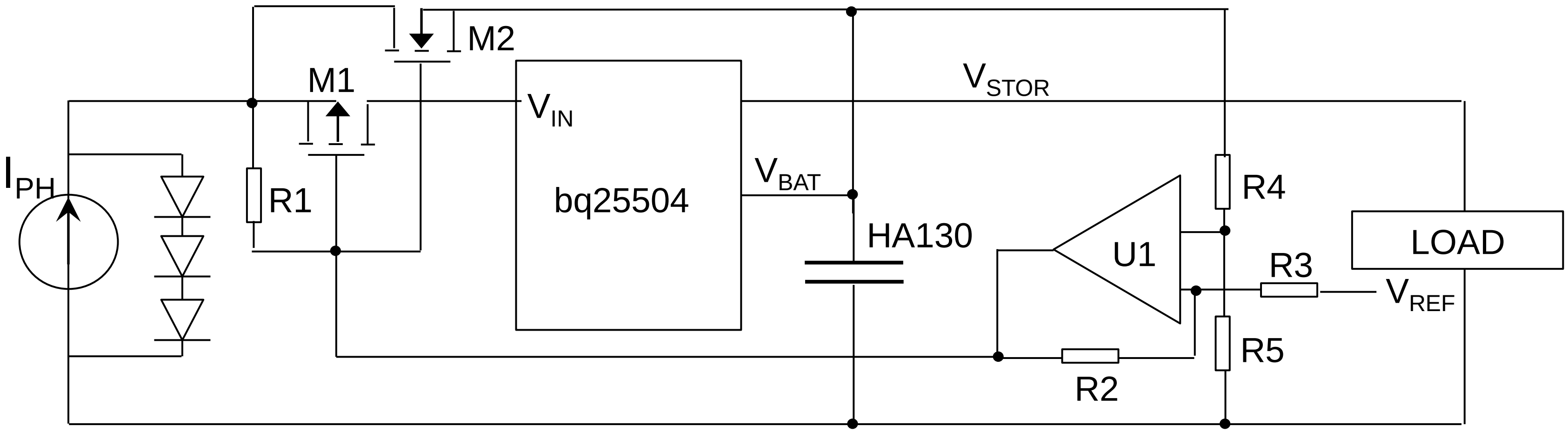


Conclusions on bq25504 Alone

- The bq25504 has very inefficient “cold start” charging if V_{BAT} < ~1.5V
- Charging an HA130 from 0V with a solar cell with 350µW peak power takes ~67hrs to reach 1.5V
- At this point, the bq25504 switches from “cold start” mode to normal operation with PPT, and takes only 1 hour to reach 2.7V

- **Conclusion:** The bq25504 does not behave well into a short cct, since it invokes battery protection features

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

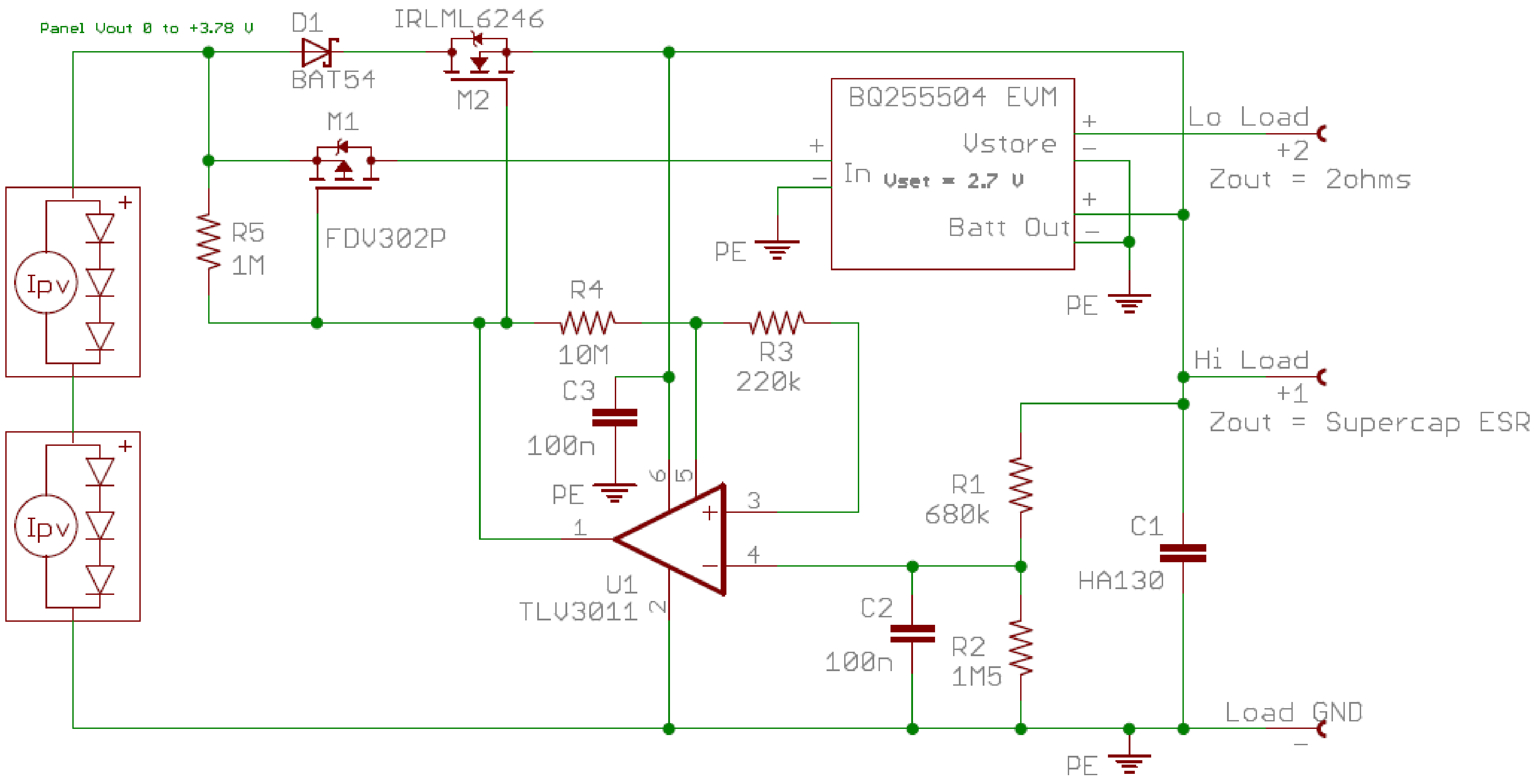


- Supercap charges directly from 0V using NFET M2 to bypass bq25504. M1 is OFF, stopping the bq25504 from pulling down the solar cell voltage
- When the supercap reaches ~1.8V, the comparator turns M1 ON, connecting the bq25504 to the solar cell, and turns M2 OFF, preventing the solar cell over-charging 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)

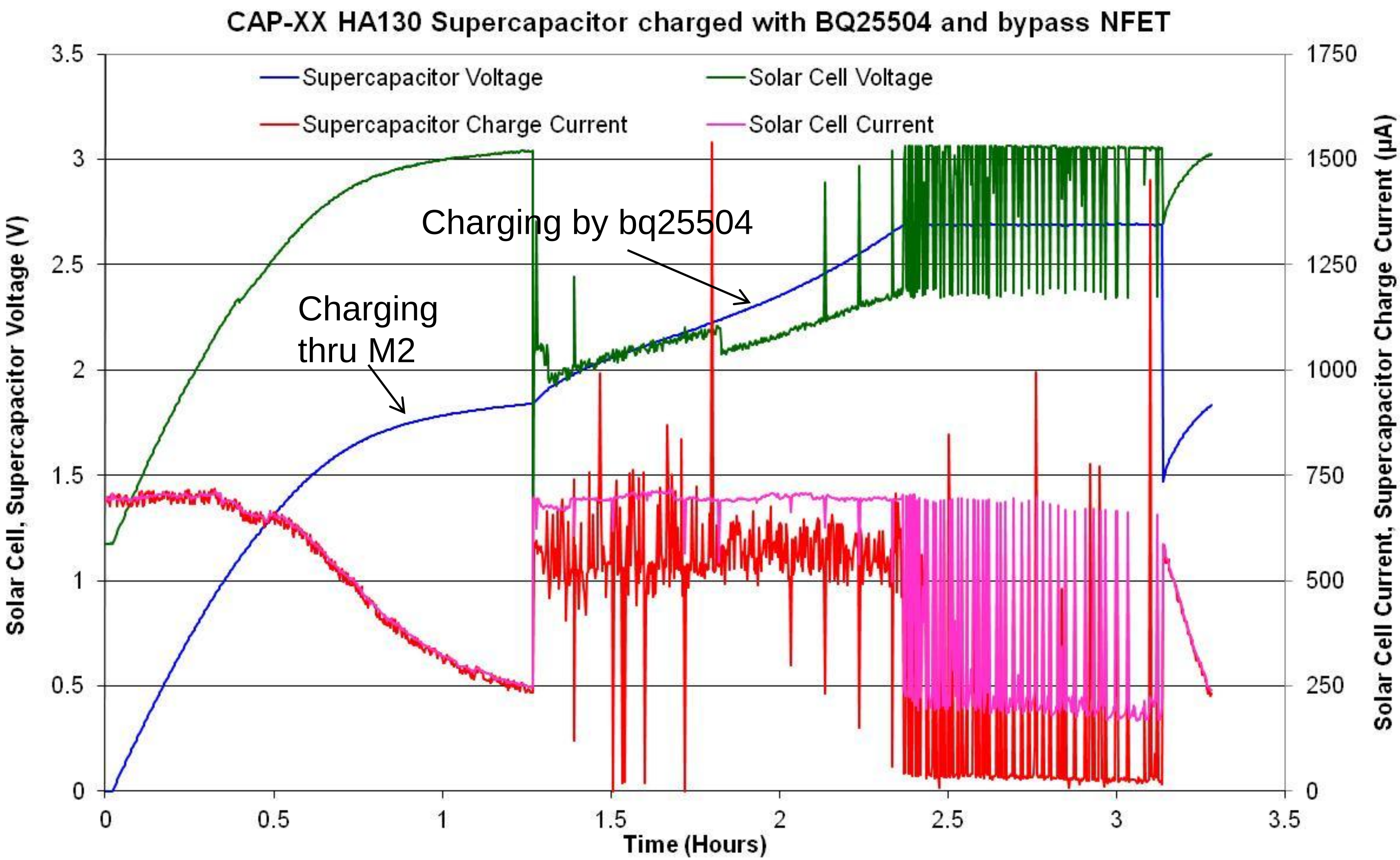
Notes on the NFET Bypass Circuit

1. When the unit first powers ON with the supercapacitor at 0V, the source of M2 is at 0V, U1 is OFF and R1 turns M1 OFF, preventing the bq25504 from operating
2. When V_{SOLAR} > V_{GSTH} of M2, M2 starts to conduct, charging the supercapacitor
3. The resistance across M2 loads the solar cell so its voltage is just above M2(V_{GSTH}) + V_{SCAP} so the solar cell provides good charge current in reasonable light
4. When V_{SCAP} =1.85V, the o/p of U1 goes low, turning M2 OFF, and turning M1 ON. This enables the bq25504 when the voltage at V_{BAT} > V_{STOR_CHGEN}, so the IC always operates in PPT mode and never in cold start mode
5. Select a low power open drain comparator with in-built reference and which operates at a supply voltage down to 1.8V or less. In our example, we used a TLV3011, which has a typical quiescent current of 2.8µA and V_{REF} = 1.242V. An alternative is MAX9016 with a typical quiescent current of 1µA and V_{REF} = 1.236V
6. Select M2 with the lowest V_{GSTH} possible, with suitable size and gate charge. The lower the V_{GSTH}, the faster the supercapacitor will reach 1.85V and enable PPT mode in the bq25504. We have used an irlm6246, which has typical V_{GSTH} of 0.8V
7. The other components used in slide 9 were: M1 = FDV302P, R1 = 1MΩ, R2 = 10MΩ, R3 = 220KΩ, R4 = 680KΩ, R5 = 1.5MΩ.
8. The hysteresis in the circuit means U1 will go low when V_{BAT} > 1.85V and U1 will go open drain when V_{BAT} < 1.77V

Circuit to Make Effective Use of the bq25504



Waveforms for Charging with bq25504 and NFET Bypass

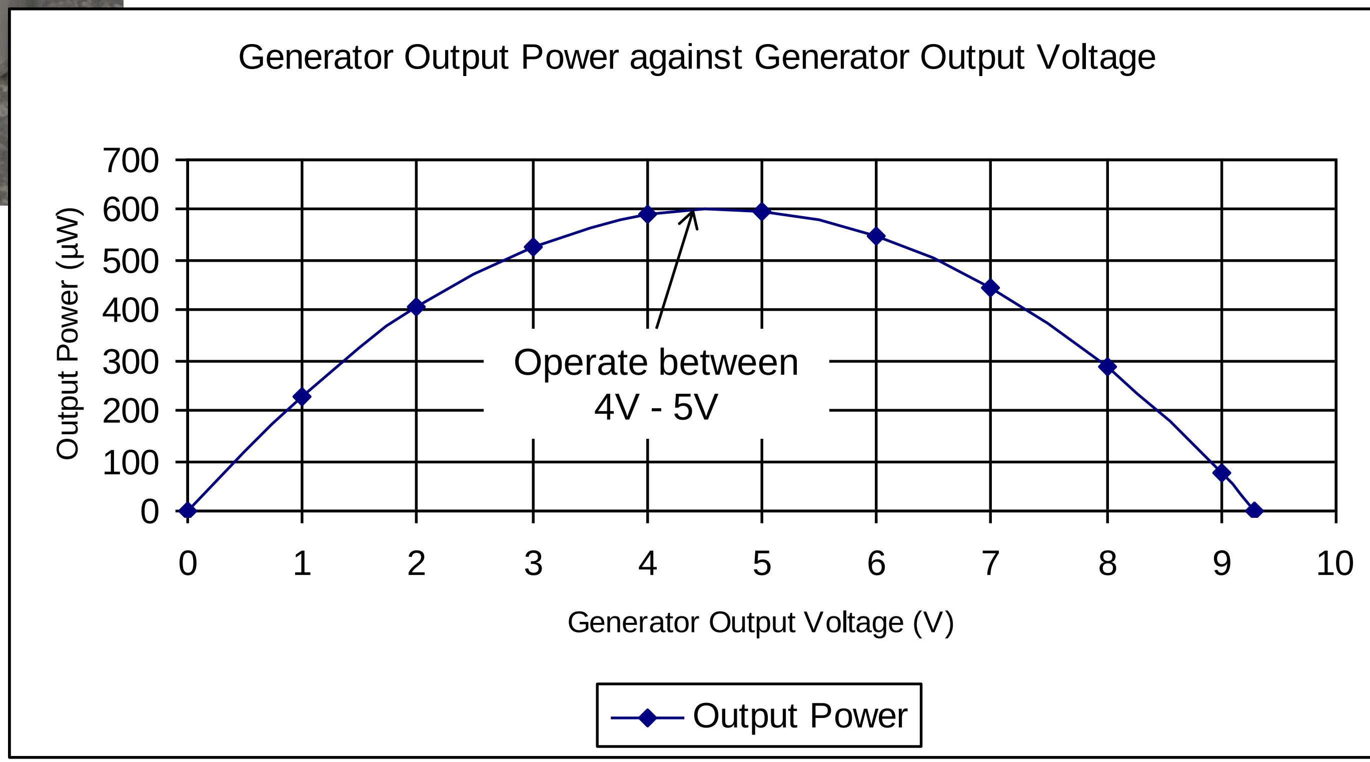


Comparison with Direct Charging

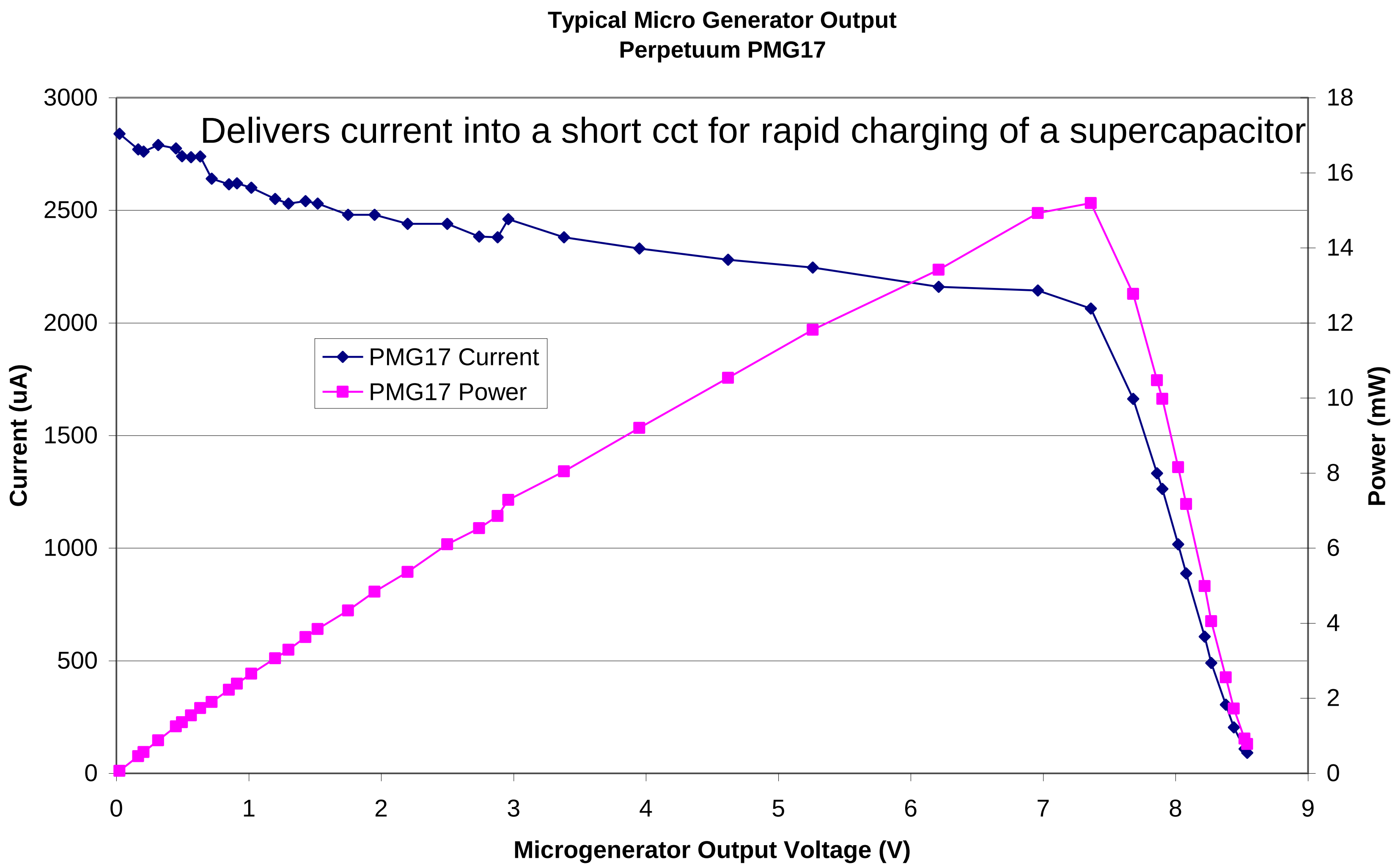
- Achieves a fast initial charge + fast charge with PPT once $V_{SCAP} > 1.8V$
- Diode prevents supercapacitor discharging into solar cell if light level falls
- Supercapacitor charged to 2.7V in 2hrs 25min, compared to 3hrs 30mins for direct charging
- HA130 provides excellent energy storage & power delivery in this architecture
- NFET bypass offers a fast charge solution AND will charge if $V_{SOLAR} < V_{SCAP}$ and $V_{SCAP} > 1.8V$ (e.g. if light level falls with the supercap partially or fully charged)
- There is a cost-performance trade-off between direct charging and PPT charging

Example 2: Microgenerators

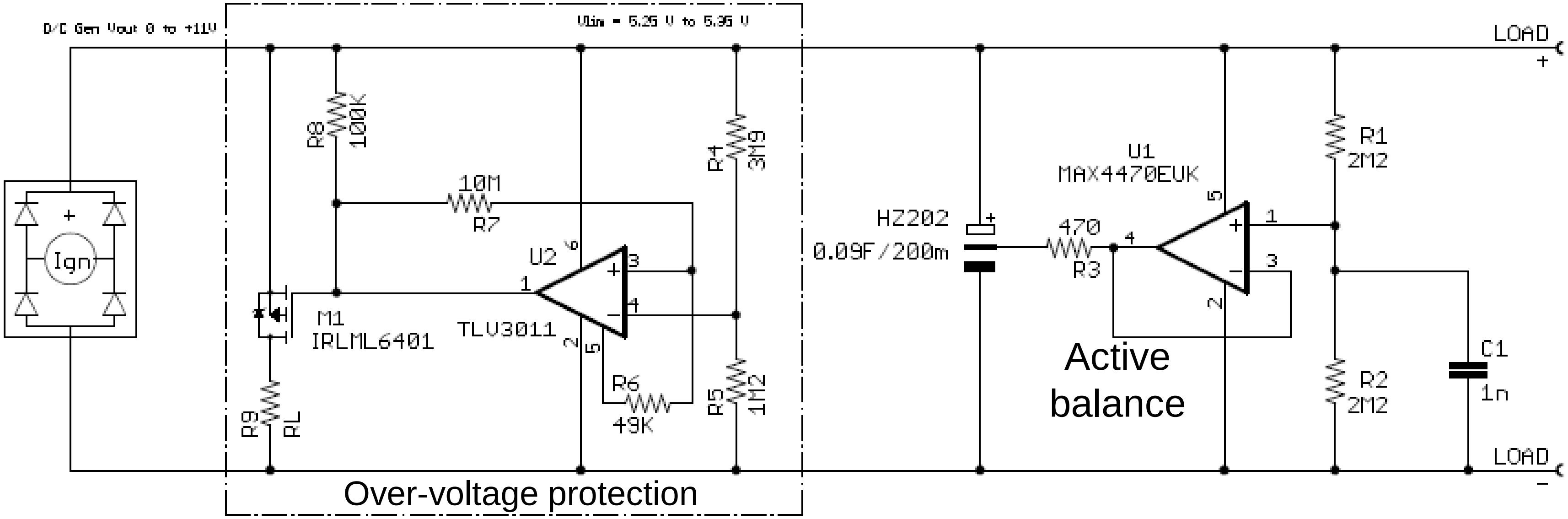
- Perpetuum microgenerator is a high impedance source
- Power match circuit to keep PMG17 @ ~5V, supercap charge current regulated so PMG17 o/p voltage ~5V
- But what this data sheet curve doesn’t tell you …



Microgenerators: Characterise the Device yourself…



…for a very simple cct



- U2 is open drain. When V_{OUT} < 1.8V (V_{SS_MIN}), U1 o/p is open cct and R8 keeps M1 OFF
- Hysteresis on U2, turn M1 ON when V_{OUT} > 5.35V, turn M1 OFF when V_{OUT} < 5.25V
- Equivalent cct of microgenerator shows it is not possible for the supercap to discharge into it when its o/p voltage < V_{SCAP}, therefore do not need any reverse current protection
- Quiescent current of MAX4470 ≈ 1µA, TLV3011 ≈ 3µA
- Choose RL to set rate of supercapacitor discharge and to ensure that RL x $I_{MICROGEN}$ < V_{MAX}, typical value ~1KΩ

No Low Power Buck with PPT

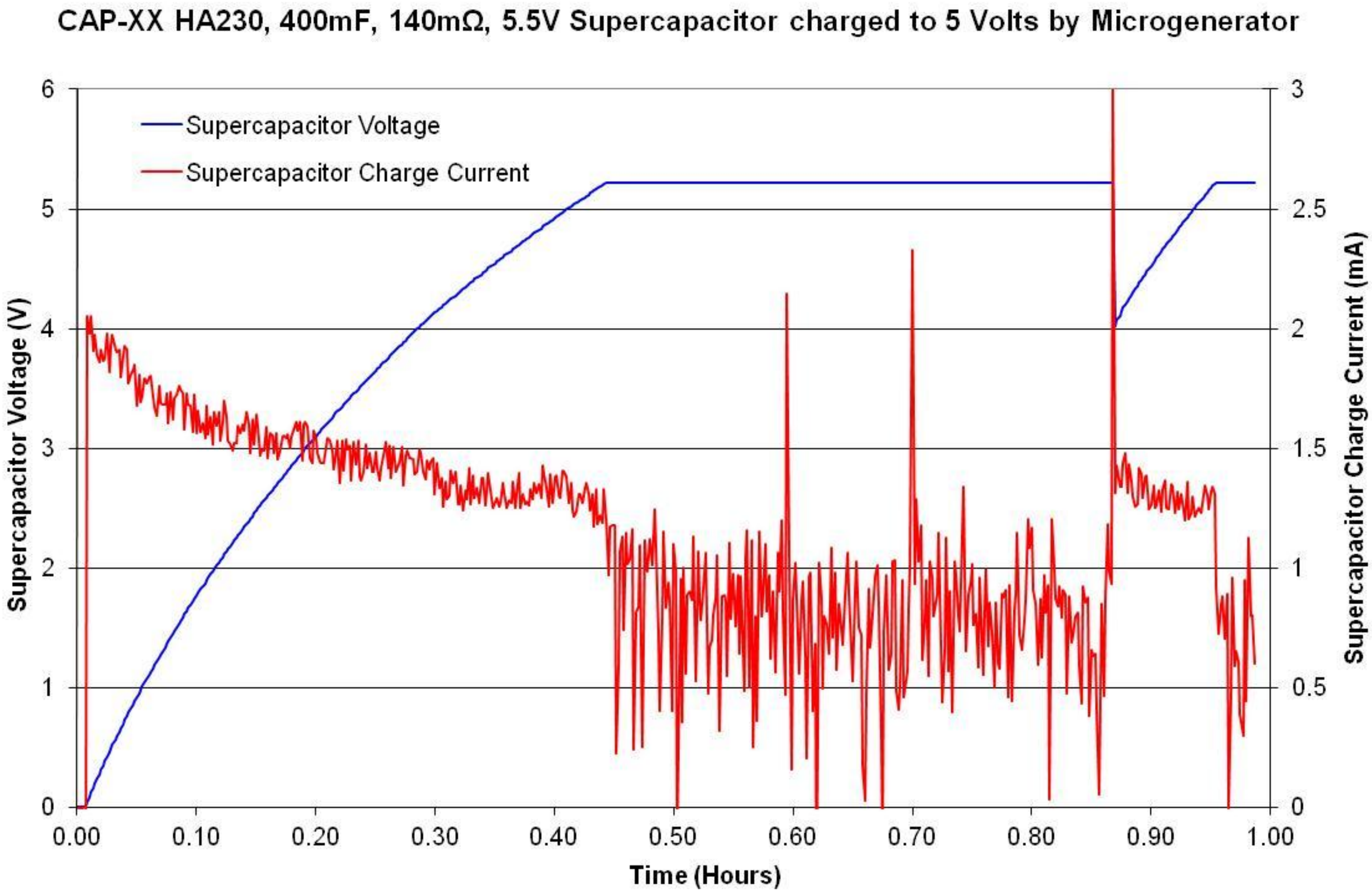
Need a Buck with:

- PPT
- Max $V_{IN} \geq 10V$
- Max P_{SUPPLY} << 15mW

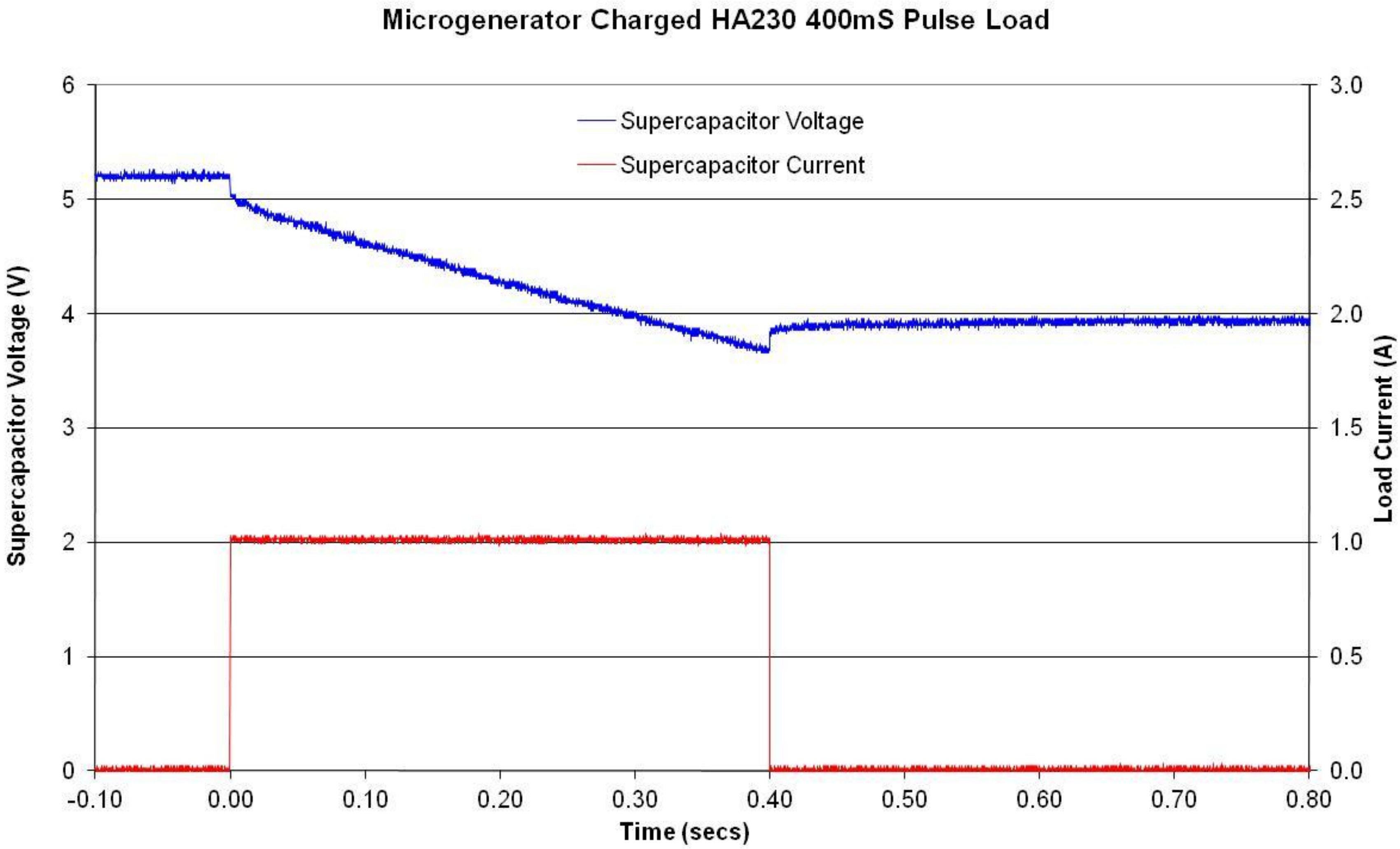
- The only IC we found with PPT was LT3652 ...
- ... but I_{BOOST} when switching = 20mA, so $P_{IN} \approx 200mW$

- May consider LTC3388-3 buck converter. No PPT, with I_{BOOST} when switching ~150µA, so $P_{IN} \approx 1.5mW$

Direct Charging with a Microgenerator

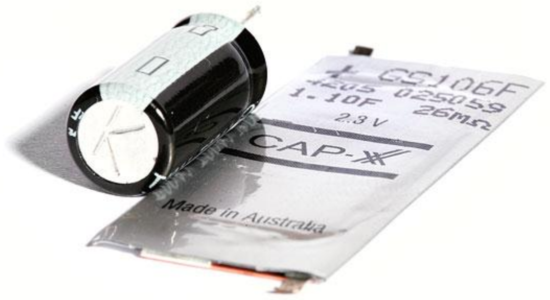


Supercapacitor Pulse Support



Summary

- PPT may reduce supercapacitor charging times, but probably by < 50% (depends on V-I characteristics of the energy harvester, V_{IN} and V_{OUT})
- Boost or buck-boost enables the supercapacitor to be charged even if the ambient energy falls so $V_{IN} < V_{OUT}$
- If V_{OUT} always > V_{IN}, direct charge may be best
- Need better PPT ICs that can charge into a supercapacitor and draw less current while switching
- A PPT IC which operated in switch mode as V_{OUT} increased from 0V to target voltage would be ideal
- There is a cost-performance trade-off between direct charging and PPT charging



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