Using a Supercapacitor to Power Wireless Nodes from a 3V Button Battery
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April 2009
1. The Problem

Source max power < load peak power
Source & Load power

- Wireless sensors are becoming ubiquitous:
  - Security
  - Fire
  - Condition monitoring
  - Location tracking
  - etc.

- Many of these applications require small, unobtrusive sensors, powered by small high energy batteries with long life but low rate capability: e.g. LiSOCl₂

- But the load requires burst power for data collection and transmission and that exceeds the power the battery can deliver

- Even though the average load power < average power the source can deliver, due to the intermittent nature of the load
2. The Solution

Charge a supercapacitor at average power
Provide peak power to the load from the supercapacitor
3. Organic vs Aqueous Supercapacitors
A supercapacitor is a high performance “green” electronic component.

- Physical charge storage, not electrochemical.
- No dielectric, max voltage limited by electrolyte breakdown voltage.
- ESR $\alpha$ 1/Electrode area.
- $C \propto$ Carbon volume.

Basic Electrical Model:

$C \propto \frac{A}{d}$

$A \uparrow\uparrow$, $d \downarrow\downarrow = C\uparrow\uparrow\uparrow\uparrow$

Carbon coating: 2000m$^2$ / gm surface area

Ions in Solvent

Separation distance: Solid-liquid interface (nm)

Separator

Aluminum foil

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Organic or Aqueous?

- Two possible electrolyte types:
  - Organic: Max voltage up to 2.7V/cell & higher energy density, but difficult to make
  - Aqueous: Max voltage ~1V/cell but simple to make

- Need to cascade cells in series to achieve working voltage
- An aqueous supercap will need 3 cells in series to attain the same working voltage as a single organic supercap cell

- For an equivalent carbon volume, the aqueous supercap will have 1/9 the C of an organic supercap

Figure 1. Comparison of energy density for aqueous & organic electrolyte supercapacitors rated at 2.7V
Use a supercap to buffer power

- Small form factor, single cell supercapacitors are available with high C (up to 2.4F) & low ESR (down to ~14mΩ)
- They can be charged at low currents from a low power source
- Have low enough ESR to deliver the load power required, even for GSM transmission (~8W),
- And high enough C to deliver that power for the duration needed: sufficient energy storage
- A supercapacitor looks like a low power load to the source & a low impedance source to the load
4. Solution using a single cell organic supercapacitor
• Max supercapacitor voltage = 2.7V, but max source voltage is typically 3V, e.g. CR2032
• Need over-voltage protection
• Load can operate at <2.7V (down to 0.7V for a well designed boost converter)
• Circuit below can be designed with quiescent current of <3µA

![Diagram of button battery supercap trickle charger](image)

- R is chosen to optimise supercapacitor charge time while limiting the high current stress on the battery to an acceptable level. Energy loss is independent of R
5. Losses independent of current limit R
Losses independent of $R$

- Analysis in the paper shows losses are independent of $R$:
  - For higher values of $R$, current is less, but time to charge is longer.
  - For lower values of $R$, higher current and shorter charge time.
  - So the energy lost:
    
    \[
    \int_{0}^{\text{charge time}} i_{\text{charge}}^2 \bullet R (dt)
    \]

- Depends on the supercapacitor $C$, and the voltages the supercapacitor is charged from and to.

\[
= C \left[ V_b (V_{C2} - V_{C1}) + \frac{V_{C1}^2 - V_{C2}^2}{2} \right]
\]
6. Circuit implementation of the button battery supercapacitor charger
Hysteresis: Q1 OFF when $V_{scap} > 2.696V$, Q1 ON when $V_{scap} < 2.688V$

Quiescent current when supercapacitor fully charged $\sim 3\mu A – 5\mu A$

R determined so $T_{recharge} < 5RC$, supercap charged to 99% of $V_{batt}$. In the circuit of Fig 4, this would be $5 \times 2400 = 3\text{hrs 20 mins}$
7. Design considerations
Min voltage the battery must supply

… which can be used to calculate mAh vs min battery voltage at which the system operates. The curve above shows if the system is designed to operate at \( \leq 2.6V \), then max battery energy will be extracted. Cct in 6. will run down to 1.8V.

Fig 5. CR2032 discharge performance

Discharge curves from the manufacturer are typically time vs constant resistive load.

Fig 6: CR2032 Capacity vs Minimum Load Voltage
Keep Supercapacitor on charge, or Charge when needed?

Key design decision to minimise energy loss:
- Always keep the supercapacitor on charge and lose the energy from circuit quiescent current and supercapacitor leakage current

Or
- Let the supercapacitor discharge after use

Factors affecting the decision:
- Time between burst load intervals
- Supercapacitor self discharge characteristic
- C value
Figure 7: Battery Life depending on whether supercapacitor is always on charge or only charged prior to each load event.
Supercapacitors do not behave like classical capacitors

They need a minimum charge current

Figure 10: Supercapacitor charging at low levels of constant current.
Supercapacitors do not behave like classical capacitors.

\[ V = V_s (1 - e^{-t/\alpha RC}) \]
\[ a = 6 \times 10^{-3} \sqrt{t} + 0.8125 \]

Figure 11. Supercapacitor charging does not follow the classical model.
Long Term HS108 Supercapacitor Self Discharge

Supercapacitor Voltage (V)

Time (hrs)

Sample 1
Sample 2
Sample 3
Sample 4
Sample 5
Sample 6
Sample 7
Sample 8
Sample 9
Sample 10
Sample 11
Sample 12
Estimate
Est 2

Estimate (based on diffusion):

\[ V = V_{init} - 0.025317 \sqrt{t(\text{hrs})} \]

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

\[ V = V_{init} \times e^{-t(\text{sec})/RC} \]

\[ R = 5.5 M\Omega, C = 1.8 F \]

Figure 12: Supercapacitor self discharge characteristic
8. Case Study
Figure 9: System Architecture: Single 3 Volt Lithium Cell Driving a 1 Watt Class 8 GPRS Load.

- GSM transmitter, 1W @ 1/8 duty cycle, RF PA is 40% efficient
- 3 sec burst. 100mA continuous current while module is on.
- Data collection & transmission 1/week
- Boost converter Vo = 3.6V, min boost converter Vin = 0.9V
- Boost converter efficiency = 80%
Sizing the supercapacitor

- Two constraints: Min C & Max ESR, they are interdependent
- Need to determine peak load current and total load energy to size C & ESR
- \[ C \geq 2 \times \frac{E_{LOAD}}{[V_{BATT \ MIN}^2 - (V_{LOAD \ MIN} + I_{PEAK} \times ESR)^2]} \]
- Load energy delivered by the supercapacitor
  \[ = \left[ \frac{(1W/40\% \times 1/8 + 3.6V \times 0.1A)/80\%}{80\%} \right] \times 3 \text{ secs} \]
  \[ = 2.52J \]
- Peak boost converter i/p power
  \[ = \frac{1W/40\% + 3.6V \times 0.1A}{80\%} \]
  \[ = 3.58W \]
- Peak current = 3.58W/min boost \( V_{in} = \frac{3.58W}{0.9V} = 4A \)
  \[ \therefore V_{LOAD \ MIN} + I_{PEAK} \times ESR) = 0.9V + 4A \times 0.1A = 1.3V \]
- Assume ESR = 100m\( \Omega \)
  \[ \therefore C \geq 2 \times \frac{2.52J}{(2.6^2 - 1.3^2)} = 0.995F \]
- Select HS108. 1.8F±20%, 28m\( \Omega \)±20%
9. Conclusions & Next Steps
Conclusions & Next Steps

1. A supercapacitor can be used to buffer a high peak power load so a low power high energy source can be used (eg, a 3V button battery)

2. A single cell organic electrolyte supercapacitor is best suited for such applications due to its:
   - Superior energy density
   - Low ESR
   - Low leakage current and no need for cell balancing

3. We have presented design considerations to optimise such a system, most notably whether to leave the supercapacitor on charge or to charge as needed

4. We have shown that supercapacitors do not behave as classical supercapacitors

5. We have presented a case study

6. Further work is required to characterise the charge & self discharge behaviour. These are crucial to choosing the best charging strategy. Currently, the best course of action is to empirically characterise the charge/discharge behaviour of the supercapacitors of interest
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