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
• Supercapacitor 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
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 ($C \propto A / d$)

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

No dielectric, working voltage determined by electrolyte

**Basic Electrical Model:**
Electric Double Layer Capacitor (EDLC)

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

**Electrolyte:**
Ions in a solvent

**Separation distance:**
Solid-liquid interface (nm)

**Separator:**
Semi-permeable membrane

**Electrode:**
Aluminum foil
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

**Normalised ESR vs Temp**

![Graph showing ESR vs Temp for Standard Devices and High Temp Devices](image)

**Normalised C vs Temp**

![Graph showing C vs Temp for Standard Devices and High Temp Devices](image)
Poor Frequency Response …
...but Excellent Pulse Response
$C_{EFFECTIVE}$ as a Function of PW

- $C_{eff(1ms)} = 1/slope$
- $C_{eff(5ms)} = 1/slope$
- $C_{eff(30ms)} = 1/slope$

Graph showing load current and supercap voltage over time.
C_{\text{EFFECTIVE}} Data

C_{\text{eff}} \text{ Observed vs SPICE simulation, CAP-XX GS203}

Normalized Capacitance (% of DC capacitance) vs Time (s)

- C_{\text{eff}}
- C_{\text{eff spice}}

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

HZ102 charging to 2.5V at 5uA after varying time at pre-charge at 2.5V, 10mA

Even 1 min pre-charge reduces charge time by half

Theoretical: $V = I_{\text{CONST}} \times t/C$
Cell Balancing is Required

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, C1 would have a leakage current of 0.8uA and C2 of 1.6uA. But this is not a possible equilibrium condition, since I_{Leakage1} must = I_{Leakage2}

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.
The purpose of this circuit is to maintain $V_M$ close to $V_{SCAP}/2$

$V_M = R_B \times I_{BR2} = R_B \times (I_{BR1} - \text{Balancing Current})$

For this circuit to work, Balancing Current must be $<< I_{BR1}, I_{BR2}$

$V_M$ must be prevented from going $>> V_{SCAP}/2$ or $<< V_{SCAP}/2$ for any significant length of time

SIMPLE but HIGH CURRENT SOLUTION ($\sim 100\mu A$ 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

**Active Balance HW207 @ 23C**

- **Time (s)**: 100.00 to 1000000.00
- **Voltage (V)**: 0.000000 to 0.000100
- **Current (A)**: -0.000020 to 0.000100

- **Bottom Cell V**
- **Top Cell V**
- **Balance Current**
- **OP Amp Supply Current**
- **Top Current**
- **Bottom Current**
- **Total Current**
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

GW214@ 3.6V, 23C, Ambient RH

$y = 1.136 \times 10^{-1} e^{-1.416 \times 10^{-5} x}$

$R^2 = 9.889 \times 10^{-1}$

C Loss rate = 1.4%/1000hrs

Capacitance (F) vs Time (hrs)
Supercapacitor Ageing: ESR Rise

GW214 ESR @ 3.6V, 23C, Ambient RH

ESR (mOhms) vs Time (hrs)

$y = 0.0027x + 71.706$

$R^2 = 0.9168$

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

- $I_{PH}$ generates current $\propto$ light falling on the cell
- If no load connected all the current flows through the diode whose forward voltage = $V_{OC}$.
- $R_P$ represents leakage current
- $R_S$ 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

Solar Array X0B17-04x3 - 3.1 Volt OC I-V Curve
Direct Charging Circuit

- Simplest circuit, starts charging from 0V
- $V_{OC} < 2.7V$ at maximum 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 $< 10\mu A$
- HA130 provides excellent energy storage & power delivery
- **Fastest charge. But will NOT charge if $V_{SOLAR} < V_{SCAP}$** (e.g. if light level falls)
Pulse Current Discharge from the Supercapacitor

Direct Solar Charged HA130 on 1 Amp 800mS Discharge

Supercapacitor Voltage

Pulse Current

Time (msec)
Example 1: 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 …

Operate between 4V - 5V
Delivers current into a short cct for rapid charging of a supercapacitor

Typical Micro Generator Output
Perpetuum PMG17

**Microgenerator Output Voltage (V)**

**Current (uA)**

**Power (mW)**

- PMG17 Current
- PMG17 Power
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
CAP-XX HA230, 400mF, 140mΩ, 5.5V Supercapacitor charged to 5 Volts by Microgenerator
Pulse Current Discharge from The Supercapacitor

Microgenerator Charged HA230 400mS Pulse Load

- Supercapacitor Voltage
- Supercapacitor Current

Time (secs) vs. Supercapacitor Voltage (V) and Load Current (A)
Peak Power Tracking

\[ I_{\text{OUT}} = \frac{P_{\text{IN}} \cdot \eta}{V_{\text{OUT}}} \]

Maximise \( I_{\text{OUT}} \) if \( P_{\text{IN}} \) = 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 \( \sim 1.5\text{mW} \)
DC:DC Behaviour when $V_{\text{OUT}} \ll V_{\text{IN}}$

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

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

CAP-XX HA130 Supercapacitor charged with BQ25504 and bypass NFET

- Charging by bq25504
- Charging thru M2
Peak Power Tracking

\[ I_{OUT} = \frac{P_{IN} \cdot \eta}{V_{OUT}} \]

- 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 \( \mu \)gen (~2mA)

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

- Behaviour when \( V_{OUT} \ll V_{IN} \)

- 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 \( \geq \) supercap max \( V \)?

? Is the energy harvester average power sufficient without PPT?
Summary: Using 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?
For more information, please contact

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