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Supercapacitors Enable Energy Harvesters to Power IoT

The environment has abundant energy, so energy harvesters are an ideal power source for IoT applications, eliminating the need to replace and dispose of batteries. However, small energy harvesters often cannot provide the peak power required to collect and transmit data. This article will show how to use a supercapacitor charged from an energy harvester to provide the peak power required using a small solar cell as a case study.

The typical power architecture has an energy harvester supplying a supercapacitor charging circuit with the supercapacitor directly supplying the load. The high C and low ESR of the supercapacitor maintains a sufficiently stable voltage for the load to function during its peak power bursts.

Characterize the energy harvester

Experimentally verify the power available from your energy harvester in your expected conditions. For example, a well-lit office is ~500lux but solar cell power is typically quoted at 50,000 lux (summer day) or 100,000 lux (1KW/m^2). Connect a potentiometer and current sense resistor across the solar cell array in the light level you require and vary the resistance from open circuit through to short circuit, measuring current and voltage at each step deriving a V-I curve and the peak power available. Consider the open circuit voltage and voltage at the peak power point when selecting your solar cell array – determined by the number of cells in series, ~0.65V/cell, which determines the possible charging ICs (constrained by input voltage range), and whether to use a single-cell supercapacitor (2.75V max) or dual-cell supercapacitor (5.5V max), and how the supercapacitor is coupled to the IoT application. Fig 1 shows the V-I curve for the solar cells used for this case study at ~500 lux, peak power = 1.4mW at 2.6V.

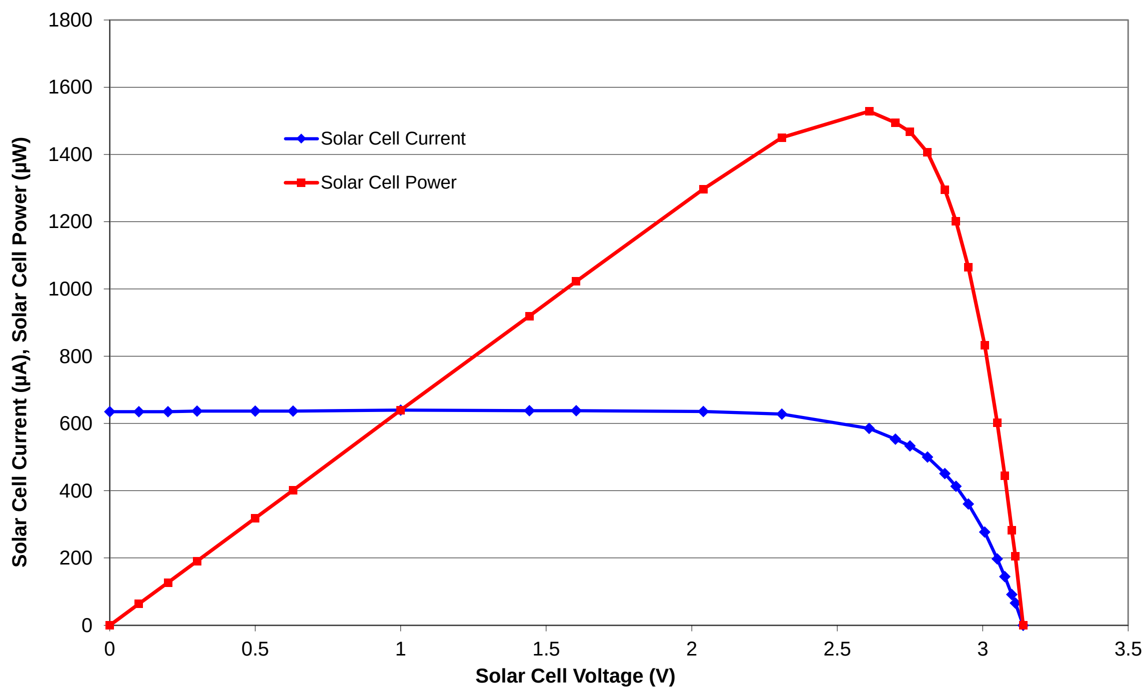

Fig 1: V-I curve for solar cell array in typical light conditions

The energy harvester supplies low average power to charge the supercapacitor, which then supplies periodic or sporadic peak power to collect and transmit data. The power available from the energy harvester sets the power budget:

IoT power x duty cycle = EH average power.

Set how often the IoT application reports to meet the power budget available from your energy harvester.

Supercapacitor Properties

Supercapacitors are ideal power buffers between an energy harvester and a load demanding more power than the energy harvester can deliver, due to:

- Low ESR to enable high power delivery
- High C to support the peak power demand for the duration required
- Low leakage current, important not to waste the low charge current available
- Simple charging
- Single cells up to 2.8V, suitable for many applications that can run in the 1.8V – 2.5V range. Dual cells can be used in series for voltages up to 5.5V
- Small thin form-factors for IoT applications, particularly wearables

An example is the CAP-XX HA130 which is 20mm x 18mm x 1.7mm, 800mF, 60mΩ ESR, 2.75V, typical leakage current 1µA. Organic electrolyte supercapacitors have an order of magnitude lower leakage current than aqueous electrolyte supercapacitors, but require over 48hrs on voltage to decay to final levels of leakage current.

Supercapacitor Charging

Supercapacitors are much simpler to charge than batteries, only requiring charge current and over-voltage protection rather than a constant-current constant-voltage charge regime. Supercapacitors charge from 0V and due to their low ESR and high C will look like a short circuit to the charging circuit. Supercapacitor charging circuits must:

- Start charging from 0V
- Behave gracefully into a short circuit
- Provide over-voltage protection
- Prevent the supercapacitor from discharging back into the source
- Be designed for maximum efficiency

Most energy harvesters have high input impedance, so will charge directly into a supercapacitor at 0V, supplying short circuit current.

If a solar cell array is configured so that:

Target Supercapacitor charge voltage < Solar cell open circuit voltage in your application's light level < max supercapacitor voltage

then the simplest charging circuit is that of Fig 2, since the supercapacitor cannot go over voltage. D1 prevents the supercapacitor discharging back into the solar cell when light fades. The BAT54 is chosen for its low forward voltage at low currents and low reverse leakage current.

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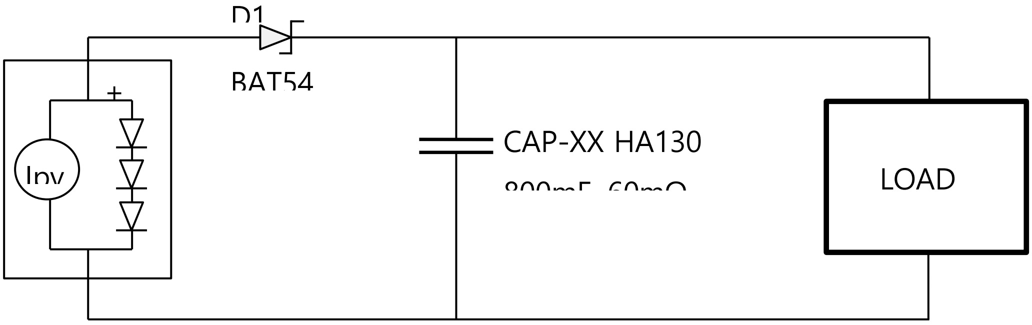

Fig 2: Simplest Supercapacitor Solar Cell Direct Charging Circuit

An alternative approach, which maximises efficiency, is to use a boost converter with maximum power point tracking (MPPT). The IC varies the input current drawn to maintain the solar cell near its peak power point and still charges the supercapacitor when light level falls so that solar cell voltage < supercapacitor charge voltage. We chose the BQ25504 from TI since it only requires 15µW and 330mV at the input to run, and is 80% efficient with only 10µA input current. Fig 3 shows our circuit.

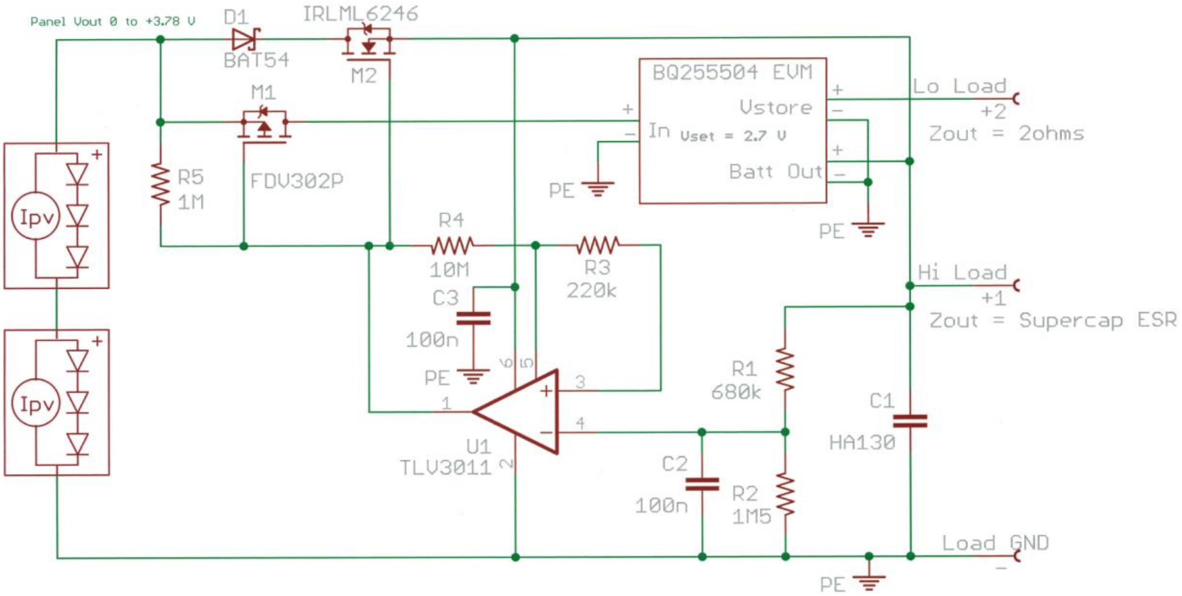

Fig 3: Supercapacitor charged by solar cell with MPPT Boost Converter

However, we have found this IC would not start charging a supercapacitor from 0V and did not behave gracefully into a short circuit. It recognised a discharged supercapacitor as a damaged battery. To overcome this, we bypassed the BQ25504 with M2 to charge the supercapacitor directly until 1.8V. Initially the gates of M1 and M2 are high with the source of M2 = 0V (discharged supercapacitor) and the source of M1 high (open circuit voltage of solar cell, turning M2 ON and M1 OFF. When the supercapacitor reaches 1.8V the output of U1 turns low, turning M2 OFF and M1 ON and the supercapacitor is charged by the BQ25504.

Fig 4 compares the two charging circuits. The BQ25504 circuit charged in 2.4hrs compared to 3.5hrs for the direct charge circuit. The direct charge circuit has the advantages of simplicity and low cost but the disadvantages of a 1.1 hour (45%) longer charge time, and the supercapacitor won't charge if light levels fall so that the solar cell voltage < supercapacitor voltage + V_F of D1. The boost convertor circuit has the advantages of maximising solar cell output power and still charging the supercapacitor even if light levels fall so that the solar cell voltage falls to ~130mV, but only if light levels during initial charge are sufficient to charge the supercapacitor to 1.8V through M2.

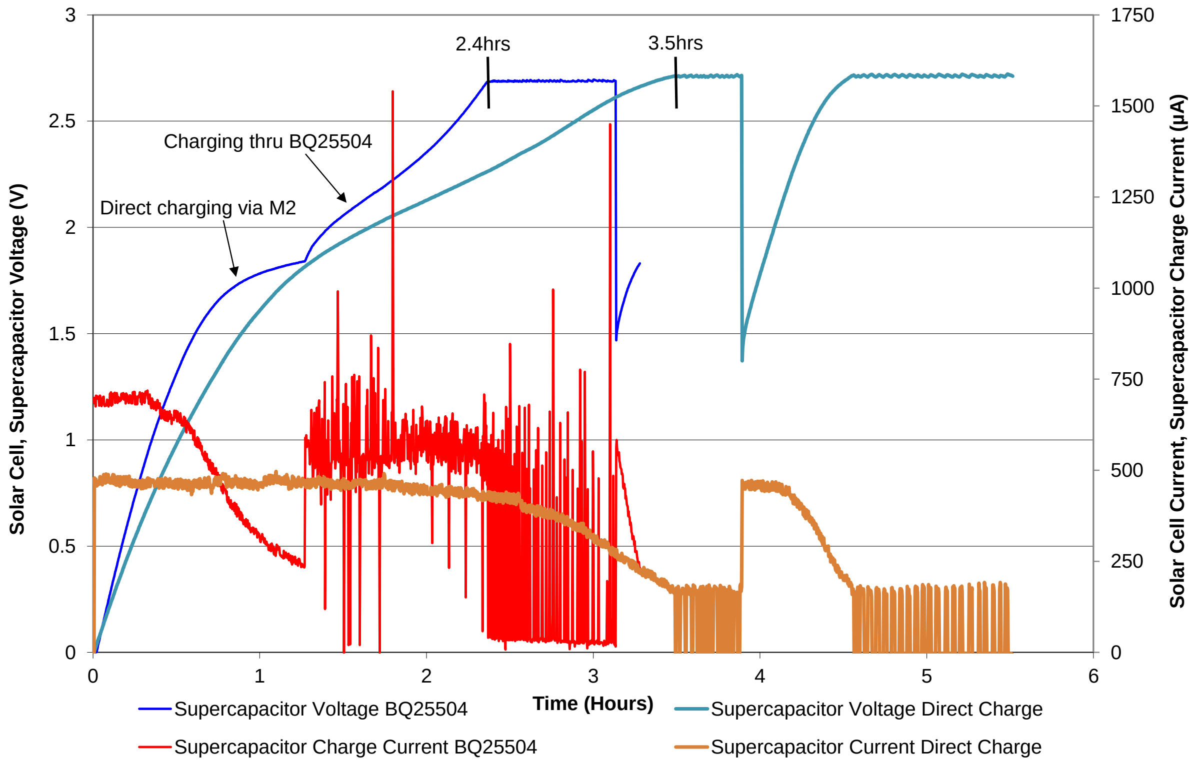

Fig 4: Comparison of direct charging and charging through a boost converter with

Sizing the supercapacitor

Consider the supercapacitor's ESR when sizing it. Vi = supercapacitor initial voltage. If the load draws a constant current I_L for duration T during peak power events then final voltage, Vf = Vi - I_L.ESR – I_L.T/C

For a constant power requirement, P, lasting duration T, then Energy = PT. As the supercapacitor voltage drops, the load current increases to keep P = V_L.I_L constant. Let Vint_f = final internal supercapacitor voltage, not including the voltage drop due to ESR, then

$$Vint\_f = \sqrt{(Vi^2 - 2PT/C)} \quad \text{..........(1)}$$

$$Vf = Vint\_f - I_L.ESR \quad \text{..........(2)}$$

$$P = Vf.I_L \quad \text{..........(3)}$$

Where Vf is the final load voltage including the voltage drop across ESR. Combining equations (2) and (3) we have:

$$P = (Vint\_f - I_L.ESR).I_L \text{ or}$$

$$I_L^2.ESR - Vint\_f + P = 0 \quad \text{..........(4)}$$

Solving (4), $I_L = \frac{Vint\_f \pm \sqrt{V_{int\_f}^2 - 4.ESR.P}}{2.ESR}$ ....(5)

Vf is given by equation (2) substituting for Vint_f in equations (2), (3) and (5) from equation (1) and for the value of I_L from equation (5). Select C and ESR such that Vf is > minimum voltage required to run the application. Allow headroom for supercapacitor ageing as there will be some C loss and ESR increase over time.

Conclusion

Supercapacitors, with high C and low ESR are an ideal power buffer to enable peak power IoT applications using low power energy harvesters. We have canvassed principles of supercapacitor charging circuits with a solar cell case study and how to size a supercapacitor.

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