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Squeezing operational life out of a shrinking energy capsule

Here's what battery technologies to consider for increasing the operational life of portable devices.

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Extending the operational life of functionally dense and space-constrained portable electronics such as bio-implantable devices may propel the semiconductor industry past the lithium ion (Li Ion) barrier. While Li Ion technologies have proved adequate for a growing number of portable applications, the benefits diminish when confronted with increasing functional densities and decreasing footprint dimensions. Sustaining the power demands, in fact, of a thin-profile cellular phone loaded with still and video camera, Internet, Internet-enabled radio, or any one of many other consumer-friendly features for more than ten hours without a recharge cycle is next to impossible with Li Ion chemistries. Coupling this increase in functions with decreasing dimensions and increasing demand for extended operational life, as is the case in micro-scale ad-hoc wireless sensor nodes, aggravates the situation, forcing engineers and scientists to explore alternative technologies (for example, fuel cells, and nuclear batteries) and hybrids.

Technologies

Within the context of a portable environment, the two most important parameters of a sourcing technology are power density and energy density, with response time a close third. A battery must therefore be large enough to supply the peak-power demands of a functionally dense application and also large enough to store enough energy to sustain it for extended periods of time. Unfortunately, energy dense technologies like fuel cells and nuclear batteries have low power densities when compared against their Li Ion and ultra capacitor counterparts, as shown in Figure 1 [1]. In other words, given similar volume constraints, the fuel cell cannot source the power a Li Ion can and a Li Ion cannot sustain a low power load as long as a fuel cell can. This difference is especially troubling in space-constrained applications where over-sizing a battery just for the sake of energy or a fuel cell just for power is not an appealing option.

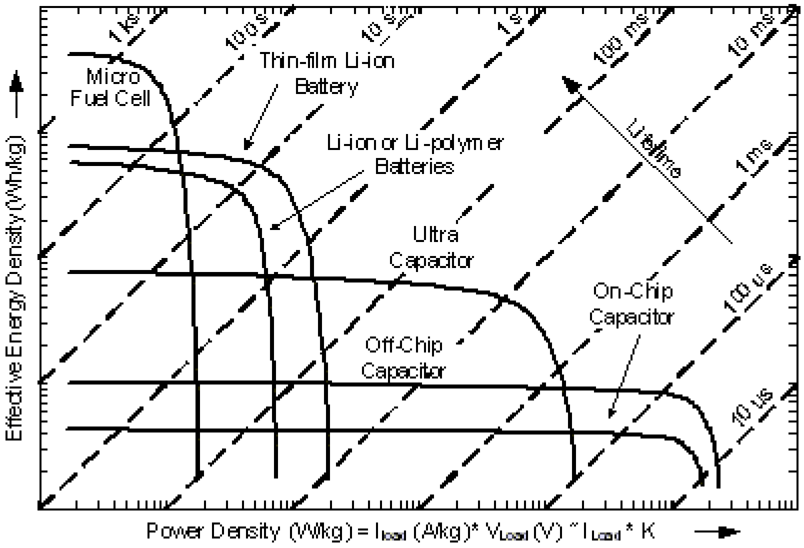

Figure 1. Ragone plot: energy and power densities of various devices

The complementary power-energy characteristics of these sourcing technologies are the driving motivational factors behind hybrid sources, and response time further justifies their increasing demand. Portable devices are notorious for hopping across an array of power modes to enable functions only when needed, extending the operational life of a system by minimizing unnecessary power sinks. Unfortunately, waking up a device from idle modes can often subject the sourcing technology to fast load dumps, requiring a quick response. Unfortunately, energy-dense fuel cells and nuclear batteries are slow to respond. Li Ion batteries are quicker to respond, but not as fast as ultra capacitors, and ultra capacitors not as fast as conventional capacitor technologies, all of which fuels the demand for hybrid devices, which are nothing more than natural extensions of the battery-capacitor hybrids normally used in most, if not all, existing electronic applications.

Selection

Not all applications, however, warrant exotic hybrid solutions. A Li Ion battery, for instance, outperforms fuel cells and hybrids in applications significantly more power-constrained than energy-constrained, assuming a similar volume-space limitation. Conversely, a fuel cell would outperform a Li Ion in an energy-intensive (that is, long lasting) application with relatively low power requirements. The middle-ground, where the demands on power density and energy density are comparable, is where hybrids find their niche, which is more often than not encountered in micro-scale applications simply because volume limitations are more severe. Ultimately, the peak power, average power, and lifetime demands of a system determine the merits of one technology over the other.

Constant Loads: The optimum energy source for an invariant load is the one that sustains its constant load power for the duration of its life and occupies the smallest possible space. Conventionally, a sourcing technology (for example, nickel-based chemistry, Li Ion, etc.) is sized to deliver the power and energy needed, which is practical but often not optimal. For instance, referring to Figure 2(a), constant low power load P1 with short duration t1 (point A) is best supplied by a Li Ion because volume is more constrained by power than energy (that is, energy density is low and power density is high at A, and Li Ions have higher power density). The critical time boundary beyond which a fuel cell is preferred occurs when the constraints of energy and power on volume by the two technologies equal, that is, the point where their energy-to-power density ratios equal or their energy-power profiles intersect (through critical time tCrt in Figure 2(a)). Consequently, if low power load P1 were to be sustained for extended time t2 (B: t2 is longer than tCrt), a fuel cell requires less volume to sustain the load. As with point A, for higher load P2 and short duration t1 (C), a Li Ion conforms best to low volume because, even though its energy density is a bit strained, the fuel cell's power density would be more strained and require more space. For higher load P2 and extended time t2 (D), the fuel cell is again best, even though its power levels are strained, because a Li Ion would have occupied more space to store the energy required.

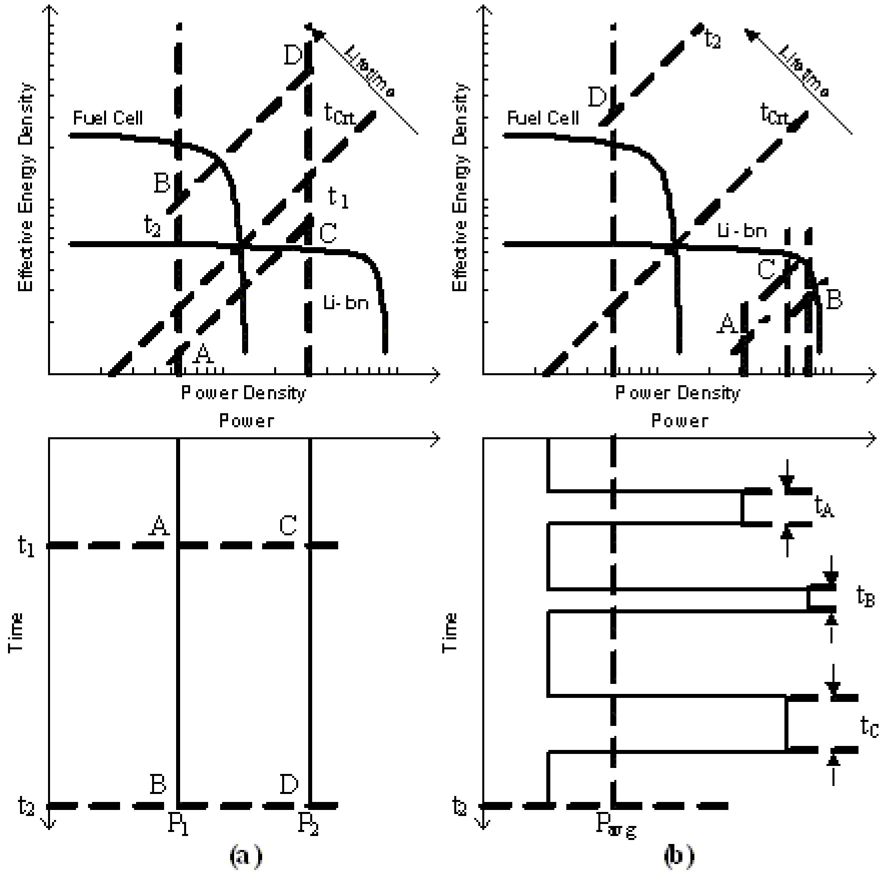

Figure 2. Energy source mappings for (a) constant and (b) time-dependent loads

Time-Dependent Loads: Selecting technologies for time-dependent loads, as in most mobile applications, is more involved. Figure 2(b) illustrates a typical load train for a mixed-signal power-moded portable application. A single source would be sized to supply both enough energy (average power Pavg for duration t2) and enough peak power (peak of pulse B), and one requirement normally overwhelms the other, the end result of which is worst-case volume demands. Decoupling these two parameters allows the designer to make more efficient use of space. For instance, the fuel cell can best supply Pavg for duration t2 because energy is relatively more constrained than power. The Li Ion can therefore be sized to supply the portion of the load that is most constrained by power (that is, pulses and points A, B, or C in Figure 2(b)). Generally, high peak-to-average power ratios (PAPR = PPeak/Pavg) applications benefit most from hybrid sources. If Pavg were higher or duration shorter than tCrt in Figure 2(b), for instance, a single Li Ion would most efficiently supply the load, not a hybrid solution.

Sample Application

A sample micro-scale and micro-power wireless sensor node whose load profile is depicted in Table I exhibits high PAPRs because it mostly idles (low average power Pavg: 7.15µA of average current) and, when fully powered, demands high peak power (PPeak: 1mA of peak current). Micro-scale proton-exchange membrane (PEM) fuel cells [2, 3] can therefore source Pavg and a thin-film Li Ion [4] PPeak. When load power PLoad is below Pavg, however, the fuel cells continue to supply Pavg but the difference (Pavg-PLoad) is used to charge the Li Ion. Conversely, when PLoad is above Pavg, PLoad is supplied by both the fuel cell stack and the Li Ion.

Scenario 1	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Telemetry**	**Vitals**
Peak Current	1µA	10µA	200µA	1mA	3.15µA
Duty Cycle	80%	5%	1%	0.07%	100%
Average Current	0.8µA	0.5µA	2µA	0.7µA	3.15µA
Pulse Width	2.88ks	1.8ks	600s	60s	36ks
Period	3.6ks	36ks	60ks	86.4ks	36ks

Table 1. Micro-scale and micro-power wireless sensor load profile

To regulate and fix the average power (Pavg) demanded of a stack of two fuel cells, a boosting DC-DC switching current regulator is used, as shown in Figure 3 — regulating fuel-cell current IFC to a constant value fixes fuel-cell stack-voltage VFC, thereby also fixing its power output. A bucking voltage regulator is then used to fix and regulate output voltage VOUT to, say, 1.8V, the supply voltage required to power a wireless sensor. A boosting function is needed to charge a 2.7-4.2V thin-film Li Ion because the voltage across a 2-cell stack (VFC) is approximately 0.6-1.4V. A bucking function is used at the output because regulated VOUT (1.8V), in the case shown, is always below the minimum Li-Ion voltage (2.7V). Protection circuitry should also be included to prevent the Li Ion from over- or under-charging conditions, which would otherwise be detrimental to the battery.

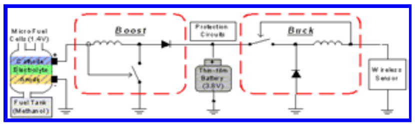

Figure 3. Hybrid fuel cell-Li Ion energy- and power-conditioning system

The simulated lifetime performance of the foregoing system under various fuel-cell currents IFC for the load profile described in Table 1 is shown in Figure 4. The fuel cells and the Li Ion battery were modeled with the macro models developed in [5-6] and behavioral Verilog-A models were used for the power conditioning blocks. When fixing IFC to 30µA, usable input power is below average load power PLOAD and lifetime TLife is only 18 days (that is, Li Ion is completely discharged in 18 days and can no longer sustain peak load power levels). When IFC is fixed to 44µA, however, average usable input power is above average PLOAD and TLife is 318 days (that is, Li Ion is kept charged 318 days). Lifetime is sensitive to IFC when usable fuel-cell power (efficiency-derated fuel-cell power PFC: PUsable = ηPFC) is near average output power. The sensitivity decreases as usable power is raised above PLOAD. However, if IFC is raised above the fuel cells' rated current, that is, beyond its power-density limit where energy density is low (Figure 1), lifetime again decreases. As a result, regulated micro-scale fuel-cell current IFC has an optimum range of operation where the usable fuel-cell power matches the average load power PLOAD.

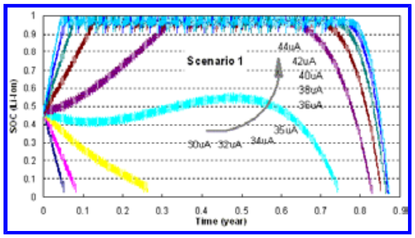

Figure 4. Lifetime Simulation: Li Ion's state-of-charge (SOC) for various fuel-cell currents

The benefits of a hybrid source are most prevalent in micro-scale applications with high peak-to-average power ratios (PAPRs) and only warranted if power- and energy-conditioning circuits are designed to exploit the complementary advantages of various energy-sourcing technologies. Although the simulation shown in Figure 4 demonstrates the viability of a hybrid source, it says little about the circuit technology used to manage it, and its overall efficiency performance. A power mixer-charger-supply prototype is therefore under development and an integrated circuit is planned, to most efficiently manage the energy- and power-conditioning functions of a hybrid-source application.

For additional details, questions, and/or comments on this article, please contact us, the Georgia Tech Analog and Power IC Laboratory, at gtap@ece.gatech.edu. More information about our research can be found at http://www.rincon-mora.com/research.

References:

[1] T. Christen and M. W. Carlen, "Theory of Ragone plots," Journal of Power Sources, vol. 91, no. 2, Dec. 2000, pp. 210-216.
[2] C.W. Moore, J. Li, and P.A. Kohl, "Microfabricated fuel cells with thin-film silicon dioxide proton exchange membranes," Journal of the Electrochemical Society, vol. 152, no. 8, Aug. 2005, pp. A1606-1612.
[3] T.J. Yen, N. Fang, X. Zhang, G.Q. Lu, C.Y. Wang, "A micro methanol fuel cell operating at near room temperature," Applied Physics Letters, vol. 83, no. 19, 10 November 2003.
[4] J.B. Bates, N.J. Dudney, B. Neudecker, A. Ueda, C.D. Evans, "Thin-film lithium and lithium-ion batteries," Solid State Ionics, vol. 135, no. 1-4, Nov, 2000, pp. 33-45.
[5] M. Chen and G.A. Rincón-Mora, "A Compact Electrical Model for Micro-Scale Fuel Cells Capable of Predicting Runtime and I-V Polarization Performance," submitted to IEEE Transactions on Energy Conversion.
[6] M. Chen and G.A. Rincón-Mora, "Accurate Electrical Battery Model Capable of Predicting Runtime and I-V Performance," IEEE Transactions on Energy Conversion, vol. 21, no. 2, June 2006, pp. 504-511.