Finding the optimal combination for a hybrid mixture of ultracapacitors and batteries can be approximated, as Jeff Myron at JSR Micro and Steve Bastien at Electro Standards Laboratories explain, by theoretical modelling that can provide a measure of the performance improvements possible with the hybrid approach.

Mix and match to model ultracap performance

The idea of combining ultracapacitors and batteries in hybrid energy storage modules (HESM) has been around for some time and the technical benefits are largely acknowledged and recognized. Batteries are generally good at storing energy but less proficient at delivering and accepting energy at high rates. Ultracapacitors are the exact opposite. They do not store as much for a given weight and space but are very comfortable running at high rates.

If we partition the energy storage and power flow into devices that specialize, and integrate these two strengths in a coordinated module or system, we are able to realize many benefits.

A common and practical approach to batteries power limitations, or better said, power density limitations, has been to oversize the battery. The maximum charge rate of batteries is many times slower than its max discharge rate; therefore how much the battery is oversized is frequently dictated by the charging power needed.

A benefit of oversizing the battery, whether it is for charge rate or discharge rate, is extended cycle life. As you reduce the portion of state-of-charge (SOC) used, cycle life is extended. In conjunction with compromises in the battery cell (power or energy version), the approach of "oversizing" has worked and been more economical than the HESM approach.

However, times are a-changing.

So what is changing? In short:

- the rate of cost reduction in ultracapacitors is faster than that of batteries
- improving power electronics.

The effect of ultracapacitors' faster cost reduction rate is straightforward — as costs come down the economics and cost-of-ownership benefits of an HESM become more and more attractive for "pulsey" applications compared to oversizing the battery.

The effect of improved power electronics is related to getting the most out of the partitioning/integration concept. An analogy is the two-cycle internal combustion engine (ICE) compared to the four-cycle. The two-cycle ICE has a battery and ultra cap directly in parallel to each other, while the four-cycle ICE has a battery and ultra cap coordinated via power electronics, such as a bi-directional DC/DC convertor with controllers. The two-cycle ICE is cheaper to make and less complex, however the four-cycle is more efficient and less polluting.

Awareness of the HESM approach and its improving economic viability is increasing, but how do you know if it is worth looking into for your application? Electro Standards Laboratories working with JM Energy/JSR Micro, which has commercialized advanced lithium ion capacitors have devised five figures of merit to assess if it is worth pursuing for a given load profile.

These figures of merit are built on two concepts — battery stress or inefficiency and the ratio of stored energy relative to what is deliverable to the load.

As the discharge current, measured in amperes, increases, the ratio of stored energy versus deliverable to the load, decreases by a square function. The loss is commonly referred to as I^2R losses. I^2R equals the power in watts dissipated as heat in the battery. If this value is ratio'd to the power delivered to the load we have a Battery Stress Factor.

As the battery temperature increases, its cycle and calendar life degrades and therefore high I^2R losses stress a battery. If the battery is generating 200W with 100W going to the load and 100W being dissipated as heat within the battery, we have a BSF of 1, which is not good. If 1% of the total energy is I^2R losses and 99% being delivered to the load then we have a BSF of 0.01. The BSF concept also works when charging as energy being stored replaces energy being delivered to the load.

Application load profiles can be quite complex so we need a method to convert it to a simplified pulse model to which the figures of merit can be applied easily.

Converting complex load profiles into an equivalent simplified pulse model with constant power pulses, with a certain

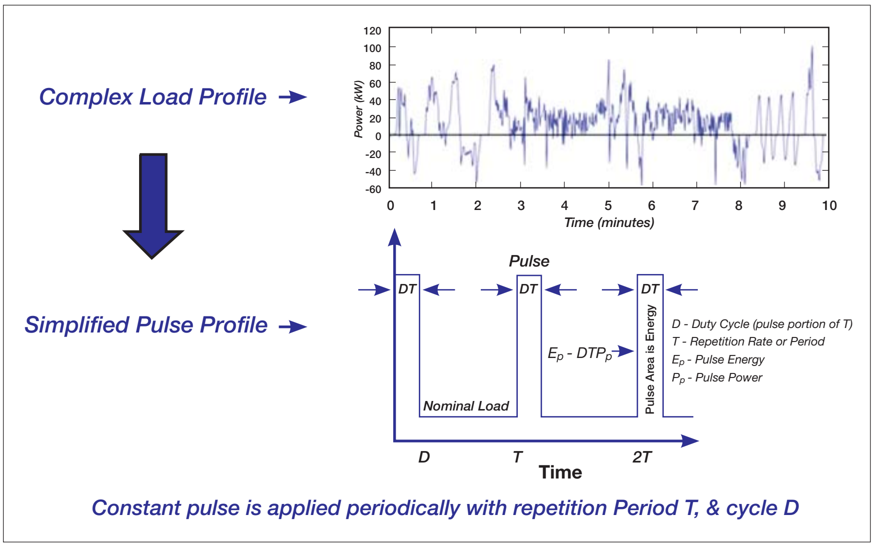

Figure 1 – Complex load profile and simplified pulse profile

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duty cycle and a given period, allows us to simplify the analysis and obtain useful estimates. To calculate the figures of merit we need:

- Pulse energy E_p
- Repetition rate or period T
- Duty cycle or pulse portion of T   D
- Battery resistance R_{batt}
- Battery open circuit voltage range OCV_r

The E_p estimate is obtained by averaging the peak values greater than the third of the highest peak value in the power profile. This tends to remove very small pulses that do not impact performance too much, while retaining the more important larger pulses. Averaging helps to prevent any high peaks in the data from skewing the results. The pulse period T is equal to the dominant time period determined by Fourier analysis.

A potential HESM design topology is to place the ultracapacitors behind a bi-directional DC/DC convertor and the use of a low power micro controller in order to manage the energy balance between the battery and ultracapacitors. Engineers worry that DC/DC converter efficiency (K_{dc}) limitations will reduce the deliverable capacity of the batteries. This concern is because any current support coming from the lithium ion capacitors has to pass through the converter twice — first to charge, and then to discharge, the capacitors.

An inefficient convertor that loses 10% on each pass through the converter may seem to represent too large a loss. However the K_{dc} loss must be compared to the battery heating loss (I^2R) when the hybrid approach is not used and often the losses in the battery are higher than the converter losses.

In cases when the K_{dc} loss is higher than the I^2R losses, a controller can easily disable the hybrid function temporarily until the power profile is such that the hybrid operation is beneficial. Aside from charge capacity, the usable energy capacity must be considered and when high power pulses are present, the usable energy capacity is generally higher with a hybrid system

BSF is a core principle, however it is mathematically more efficient to define an instantaneous unit-less measure of the state of pulse loading on the battery and distribute that term across each figure of merit. We defined the Battery Loading Factor (BLF or ρ) for this purpose for a given pulse cycle [n]. This term can be used to define the other figures of merit including the BSF.

$$\rho[n] = \frac{4 \, . \, R_{batt}[n] \, . \, P_P}{\left(v_o[n] \right)^2}$$

Now that we know how stressed a battery is for a given load profile we can add some ultracaps to handle the peaks and calculate the how the stress on that same battery is managed with ultracaps added to handle the pulses or transients.

This leads us to the Hybrid Improvement Factor (HIF).

The hybrid battery/capacitor system (symbolically indicated as β) is defined by evaluating the ratio of the BSF for the battery (alone) compared to the BSF for the battery when used in a hybrid battery/ultracap system.

To be clear, the BSF for the hybrid system indicates the state of stress/loading on the battery only and not on the ultracaps in the hybrid system. However, the use of ultracaps in the hybrid approach is specifically for the purpose of reducing the pulse power loading on the battery and requiring it to only need to provide the overall energy and average power requirements demanded by the pulse power loading.

The higher the HIF, the better the stress reduction and capacity improvements that will be seen with the hybrid battery/

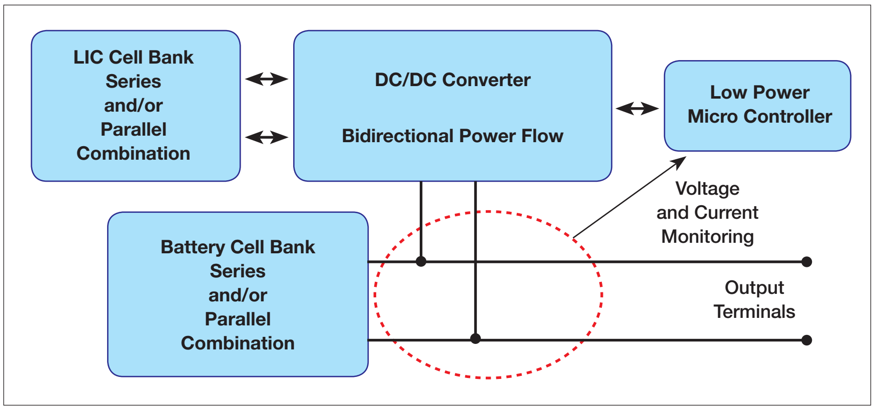

Figure 2 - Potential HESM design topology with ultracapacitors and batteries

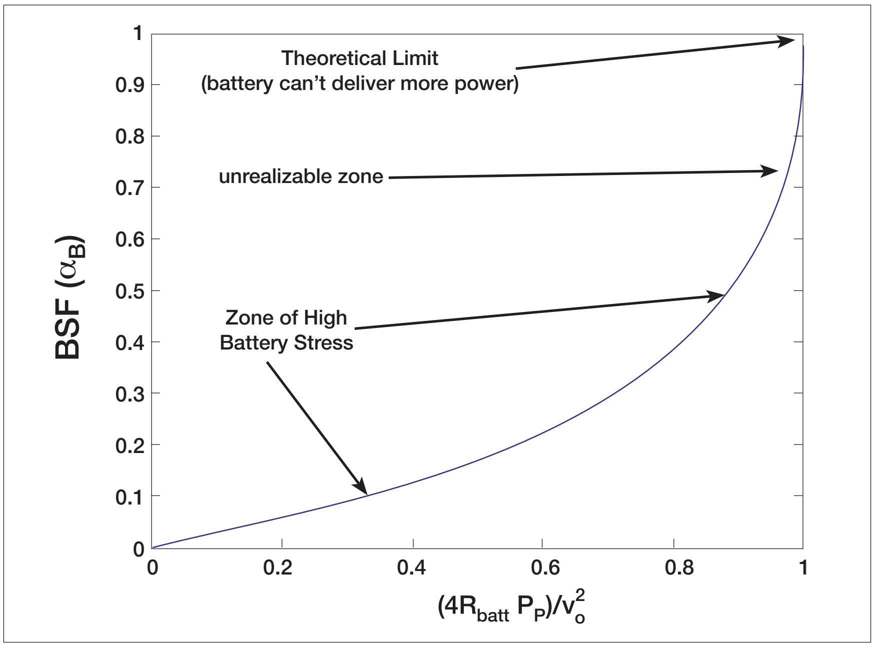

Figure 3 - Plot of Battery Stress Factor or α for a battery operating alone, as a function of Battery Loading Factor (BLF or ρ)

capacitor approach. Note that the HIF also provides a measure of temperature performance. Specifically, the temperature rise would roughly be reduced by the factor β for the hybrid system compared to the batteries operating alone.

Evaluation of the BSF for the hybrid system proceeds on the same lines as that for the battery system, only now the load current is not equal to the battery current. It is assumed that the capacitor has been sized sufficiently to store the pulse energy, with the understanding that the conversion efficiency of the DC-DC converter needed for charging and discharging the capacitor, and the capacitor internal resistance, will both affect the size of the capacitor needed to supply the pulse energy to the load and cover the energy needed in any such loss mechanisms.

The load current will still need to be about the same, but will be reduced somewhat since the battery will provide a little more voltage when not loaded as much. The battery current profile will change drastically, since instead of a peak pulse current, a much lower average current will be seen over the entire pulsed period. This load levelling is the primary effect sought to relieve stress on the battery.

The basic approach is to look at the BSF value to determine if the battery is stressed too much and whether a hybrid should be considered. Then HIF is investigated to see how much improvement the hybrid system would offer. This is usually a simple a question of whether the duty cycle is low enough in the given application. Figure 4 shows a plot of β versus D, for K_{dc}= 0.9 and for various loading conditions (α_B =0.10, 0.20, 0.30, 0.35 and 0.40). The curve is somewhat insensitive to loading, primarily dependent on D and generally nearly follows a 1/D type of relationship.

A duty cycle of 1 means there is no pulse and that the load requires constant power all the time. A duty cycle of 0.3 means it is pulsing 30% of the time. If we have an HIF of 5, then the discharge time is five times longer than the battery alone.

In the end, most people want to answer the question — how much more energy can I deliver to the load?

This is captured in the Energy Capacity Factor (ECF or x). The ECF for the hybrid system shows the ratio of usable energy capacity for the hybrid system EH relative to the capacity used for the battery alone EB. The idea behind the usable energy capacity is that under high power peak loading, the full capacity can't be used because the battery becomes overloaded and unable to provide power, sometimes even to the point of being damaged.

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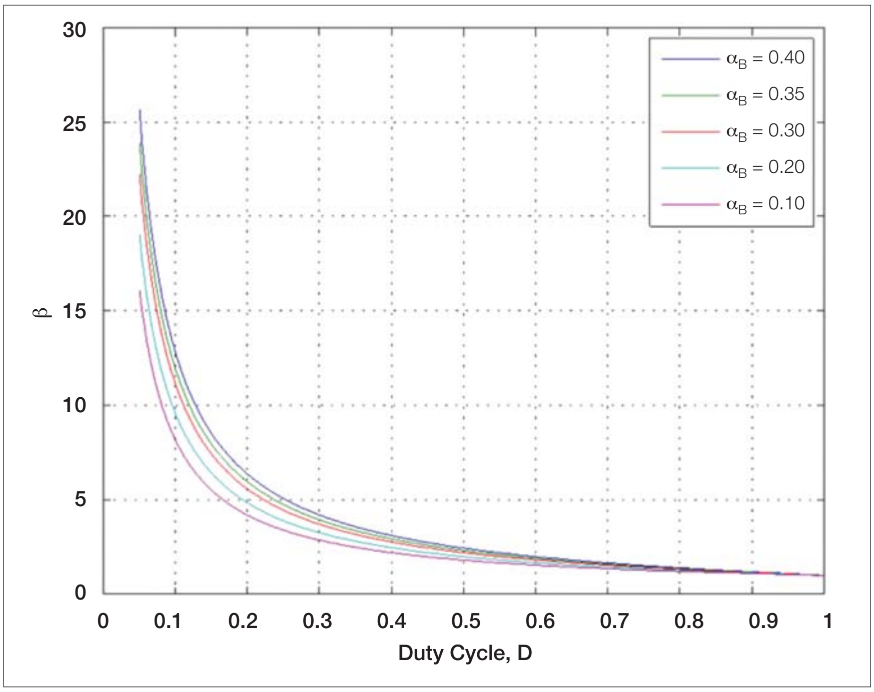

Figure 4 — Hybrid Improvement Factor (β) versus Duty Cycle (D)

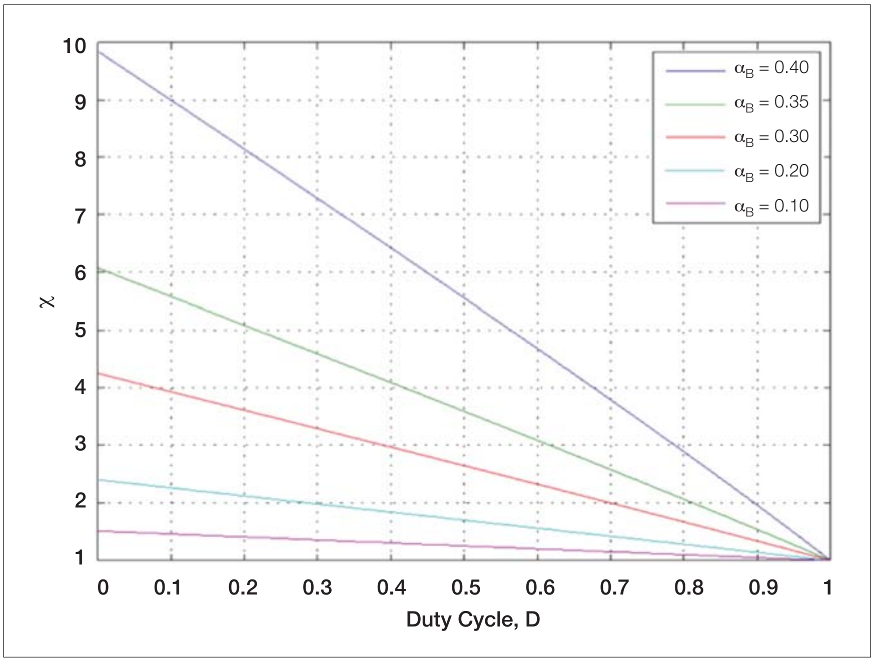

Figure 5 – Plot of Energy Capacity Factor (χ) versus Duty Cycle (D)

This is due to high internal resistance and high current draw. A hybrid system allows the peak load (which occurs over the shorter time DT) to be levelled over the longer pulse period T. This relieves the battery loading and allows much more of the available capacity to be used. (It should be noted that this parameter is not time dependent since it is a result of the entire history of the full discharge of the battery.)

If we plot ECF versus duty cycle for various BSF (α), in the high stress range of 0.1 to 0.4, with an open circuit voltage of six times the open circuit voltage range (σ=6), we observe the plot below. Here it is clear that when battery BSF is 0.2, then the ECF value can be over a factor of 2 when the duty cycle is small. This indicates a doubling of effective capacity for the battery system.

When BSF is 0.4, a doubling in capacity can occur even when the duty cycle is large, and a factor of 10 times improvement in capacity is possible when the duty cycle is small. This is approximate and real results depend on the details of the actual system, however, this estimate provides some measure of the performance improvements possible with the hybrid approach.

Computer simulations can then be used to provide more accurate predictions.

JSR/JM Energy's advanced lithium ion capacitors can enhance the hybrid energy storage approach in part because of its dramatic increases in energy density.

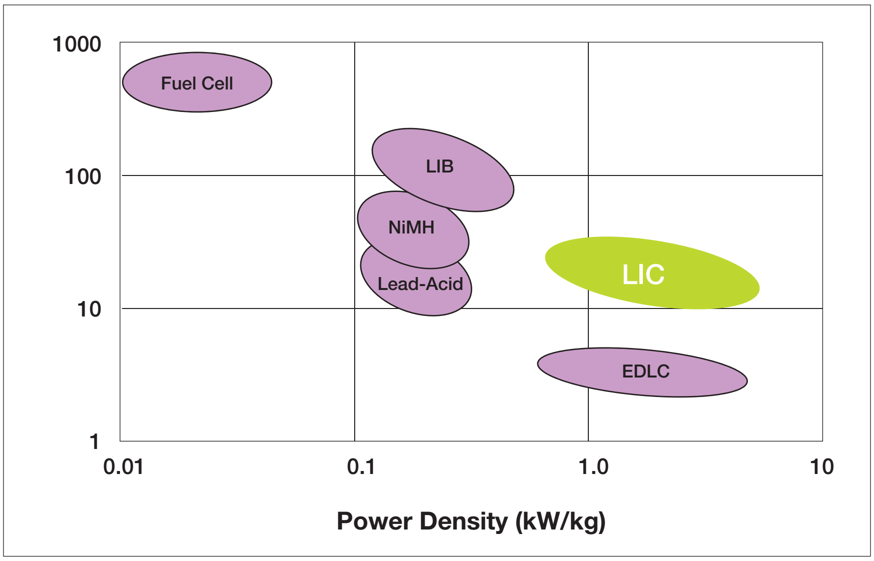

Figure 6 — Ragone plot of various energy storage technologies

Jeff Myron is energy solutions program manager for JSR Micro, with a focus on lithium ion capacitors, ultra capacitors and fuel cell membranes.

Steve Bastien is a research scientist at Electro Standards Laboratories with extensive experience in modeling, controls, and hybrid systems.