BACK TO THE FUTURE?

RETURN OF THE HYBRID

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In the last few years, the term "hybrid" has appeared in many different contexts associated with the concepts of improved portable power and better power quality. The term has many meanings ranging from its original use, some 400 years ago, to describe the offspring from the mating of a tame sow and wild boar to modern comments concerning new corn seeds or types of improved automobiles. Because electrochemical products require the interface of several scientific and engineering disciplines, it seems appropriate to consider them all as some form of "hybrids."

As applied to electrochemically-based products, the term has its own families of broad definitions. An Internet search on hybrids quickly reveals numerous references to products called by such names as nickel-metal hybrid batteries and maintenance free hybrids. The term has been applied to batteries or supercapacitors with mixed electrode components. For example, the word "hybrid" frequently serves to describe a lead-acid cell design using a lead-antimony alloy for the positive current collector and a lead-calcium alloy for the negative current collector. The term also sees service in describing multiphase electrode systems where one electrode uses a solid reactant like NiOOH or Zn and the other electrode operates via a gaseous reactant (*e.g.*, air electrode in a zinc-air cell, or the metal hydride hydrogen storage electrode in a Ni-MH cell).

In this particular discussion the term "hybrid" refers to combinations of energy and power devices where at least one device is an electrochemical system such as a supercapacitor or a battery. Although applicable to systems where the energy device could be a photovoltaic panel, an internal combustion engine, or even a stationary power plant, most of this review concerns cases where both devices are electrochemical systems.

BACK TO THE FUTURE—WE'VE BEEN HERE BEFORE!

Anyone who has had the opportunity to work in battery or portable power application development comes to realize the frequently conflicting needs for a power pack to be both a high energy and high power device. Almost 40 years ago several groups proposed hybrid battery systems to optimize and maximize the overall electrical power and stored energy available to specific applications. In one sense, hybrid electrochemical energy storage systems have served society for over 100 years with the original hybrid system being the basic primary and secondary battery.

> *"For many of his experiments, Planté needed a more powerful source of current and voltage than was available in the mid nineteenth century. ...Primary batteries could yield current, but because of their internal resistance they were inadequate for producing the analog of lightning. Consequently, Planté developed a piece of apparatus, which was a variant on the invention that he and Alfred Niaudet planned for lighthouses. A bank of 800 individual, test-tube sized lead-acid batteries was prepared. Rotating commutators atop these banks of cells shifted them from parallel (for charging by two Grove nitric acid batteries) to series (for discharging). These 1600 volts were then further increased by being used to charge up a glass and metal foil capacitor bank of 80 plates."*
>
> *Bottled Energy*[1]
> *R. H. Schallenberg*

Since World War II, news of portable applications with some compelling need for both large amounts of stored energy and correspondingly high power have been proposed as the next generation of portable energy storage systems. In the 1960s and 1970s a Japanese automobile company published research on a power plant design that they believed constituted a practical electric vehicle (EV). They incorporated a zinc-air energy storage system with a lead-acid pulse power battery bank. The system concept proved to be too far ahead of its time, with numerous materials and electrical control issues.

In the 1970s, ECOM (now CECOM) funded and published the results of work conducted at Gould Inc. to develop an advanced communication power source that combined a very high energy zinc-air battery (BA-591) with an advanced, very thin plate, spiral wound Ni-Cd pulse power source. This power pack operated a portable transponder, transmitter, and receiver system so that a tracking aircraft could follow the deployment of every individual parachuting into a target area.[2] At least four papers at the 2001 fall ECS meeting in San Francisco discussed various aspects of supercapacitors, batteries, and fuel cells as hybrid systems. Further, the Power 2001 conference also provided ample opportunity to hear presentations on advanced combinations of electrochemical devices to solve energy and power requirements in portable applications.[3] Based on many presentations and discussions at several battery-related conferences over the last five years it seems that we have come full circle! From wristwatches with tiny PV-battery/capacitor systems to utility scale systems of turbines and batteries, many energy storage systems fulfill some of the promise of hybrids today.

THE NEED FOR HYBRIDS

A broad cross-section of diverse electrical applications today show some surprising similarities in electrical load profiles. As our society has moved from analog to digitial systems and from connect by wire to wireless communication systems, the load patterns today

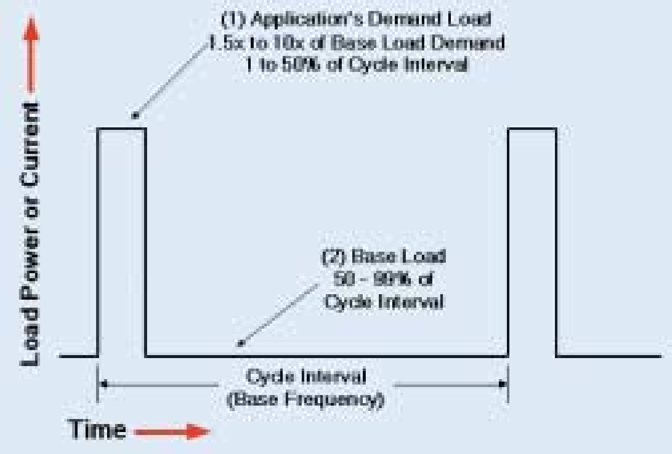

Fig. 1a. Typical testing load profile.

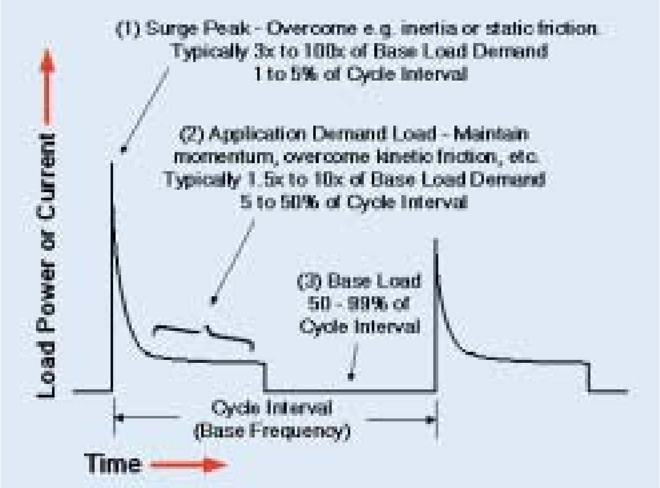

Fig. 1b. More representative application load profile.

rarely follow traditional single load resistance patterns like that seen in a flashlight bulb. To meet this diverse need many engineers approximate the load profile for testing purposes by using a simple pulse load superimposed on a low power background discharge, or even an open circuit rest period. Figure 1a provides a highly generalized example of this common test protocol. This figure shows the main elements justifying the need for a system capable of supplying high power for short periods, a base frequency of operation with a second frequency of pulse power demand. Some eclectic examples include:

- Cellular phone: transmit, receive, standby
- Forktruck: lift pallet, transport/deliver, return for next pallet
- Computer hard drive: spin-up, seek/read, idle
- Cordless drill: start/initiate bite, drill hole, stop
- EV: leave traffic light, accelerate to cruising speed, cruise
- Foundry: activate heaters, raise temperature, thermostat to off
- Air conditioning: activate compressor, cool, thermostat to off
- Pager: wake, signal, standby
- Golf cart: take off, cruise, stop

Because the actual load profile will vary depending on such factors as temperature, device age, power system age, and varying environments (*e.g.*, hills for EV, HEV; hard drive "stiction"), then the pulse power requirement may also increase. This means that designing to some nominal pulse power demand may not be sufficient. This implies the need for the power component to be sized to handle a surge load substantially larger than average and may dictate a power storage device larger, heavier, and more expensive than originally considered.

Figure 1 also begins to imply the increasing complexity of the load profile. To properly address a simple repeating profile, as shown in Fig. 1b, requires addressing the needs of up to four different frequency intervals. It gets worse: in some cases the application or a component of the hybrid power system can supply bursts of recharge power such as a regenerative braking system in an electric vehicle. This recharge energy often is supplied shortly before (or after) a major power demand burst. This may result in a greater thermal load on the overall system. As one simple example, consider an EV (or hybrid EV), which comes to a stop sign. In the process of stopping, the regenerative braking system may impose a large charging power burst on the electrochemical energy storage device (battery or supercap). This usually results in some resistance heating even if one can ignore overcharge heating or reaction heat. Following the stop, most drivers need a reasonably large discharge power burst (Fig. 1b) to initiate vehicle acceleration. In one case involving an experimental EV van some years ago the surge power to stop exceeded 500 amps at over 400 volts, and this was immediately followed by a discharge surge of about 500 amps at 350 volts. These types of large power swings help justify the research on fast response electrochemical pulse power devices such as supercapactiors and bipolar batteries.

IF HYBRID POWER SYSTEMS ARE GREAT, WHERE ARE THEY?

Hybrid power systems actively manage surge power control allowing optimized energy contents in numerous industrial and consumer devices today. We just do not think of them as "hybrid" devices. Pretty much any battery-operated device that employs some form of filtering capacitor can be considered a hybrid system. A portable or disposable camera's photoflash system provides an excellent example. As potential applications become larger they inevitably require more power and higher energy power sources. Only specialized, relatively expensive power sources, such as some thermal

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batteries, partially meet the needs for these larger systems. The goal looks something like J. Miller's hypothetical Ragone plot shown in Fig. 2.[4]

In the late 1990s, Sandia National Laboratories reviewed options for making a hybrid power system using a photovoltaic energy source, flywheels for stored energy, and supercapacitors as the power provider. That work showed serious economic limits and identified some redesign issues to improve the energy storage of the flywheels that would decrease their ability to handle surge loads (*i.e.* poor load-following).[5]

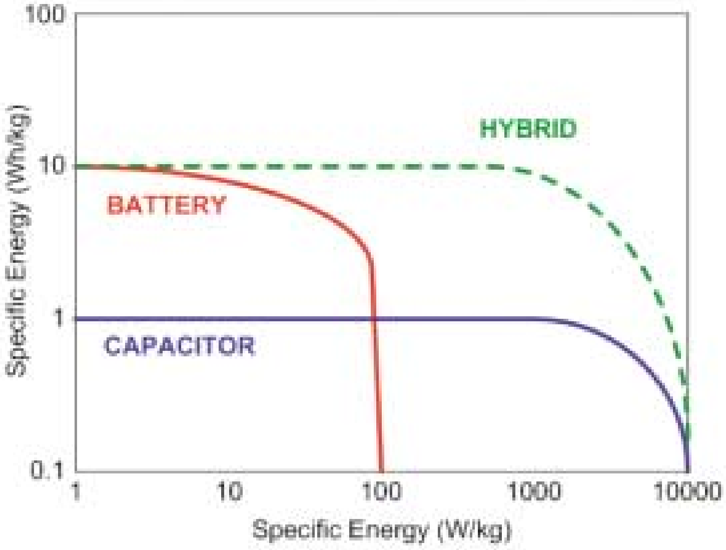

FIG. 2. *Hypothetical optimized hybrid system.*

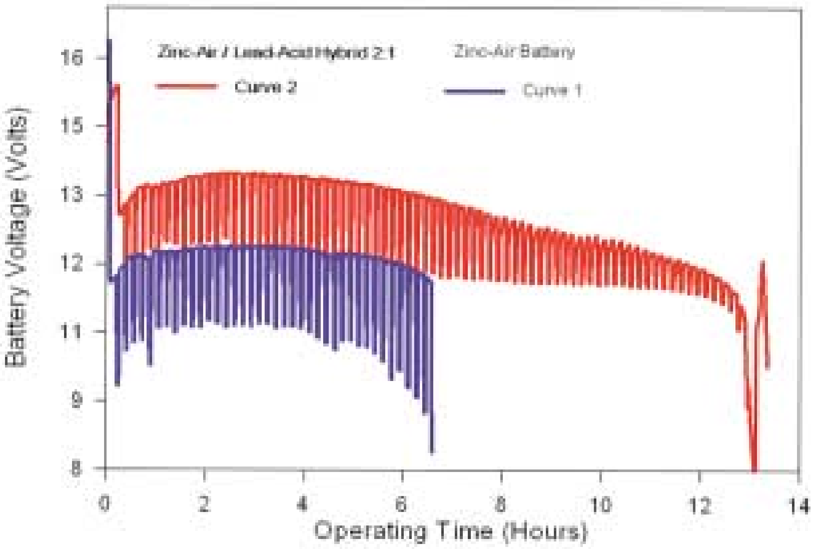

Figure 3: Operating voltage vs. run-time. (Adapted from Ref. 6.)

CHALLENGES

Many aspects of hybrid power systems must be addressed to achieve acceptable service. Some of the core issues include

- System cost (*e.g.*, $/Wh or $/watt)
- Weight and/or volume savings (*e.g.*, Wh/kg or Wh/l)
- Level of improvement in peak power expected (*e.g.*, W/kg or W/l)
- ESR (Equivalent Series Resistance)
- Load-following ability (*e.g.*, RC time constant)
- Frequency effects (alters available capacitance and ESR)
- Overvoltage or undervoltage conditions (especially for nonaqueous systems)
- Balancing of cells or capacitors in large voltage strings
- Safety considerations
- Required run-time
- Required service life
- Operating temperature range
- Relative size of pulse power loads to background loads
- Variability in pulse power demand frequency and duration

This is not intended to be a comprehensive list, but serves to show some of the factors one may need to address when considering the incorporation of a hybrid power system in an application. Although not all of these issues can be addressed here, some examples will be used as illustrative of the issues.

Some of the issues with the development of commercially viable hybrid power system focus on the independent limitations associated with either the power or energy storage devices. For example, one of the largest quasi-hybrid systems uses hydroelectric generators for energy production and a large VRLA (MW class) battery bank for power management, in effect, serving as a form of capacitor. This system, located in Metlakatla, Alaska has shown the value of fast response load-following. Prior to adding the battery, the site attempted to use a large MW class diesel generator for managing burst power demand. When the local saw mill would use large log saws, the blade's motor would demand surge power as large as a few megawatts. The diesel generator could not follow this load demand fast enough to ensure the power quality of the local power grid. The battery bank, and its power control system, could respond very quickly to the motor's demands and surprisingly the load generally would not reach the megawatt levels seen earlier. The fast response prevented the saw from losing much momentum when it began to cut the wood and consequently the overall peak power demand was reduced by as much as factor of 3. This shows that with an appropriate fast-response electrochemical device, the surge demands in some cases may be substantially dampened.

ESR and Self-discharge—One excellent example showing both the limitations and advantages of a hybrid power source was presented at California State University, Long Beach by CECOM on its Land Warrior (LW) power source program.[6] Figure 3 provides an example of improvements possible when a high-energy battery was paired with a pulse

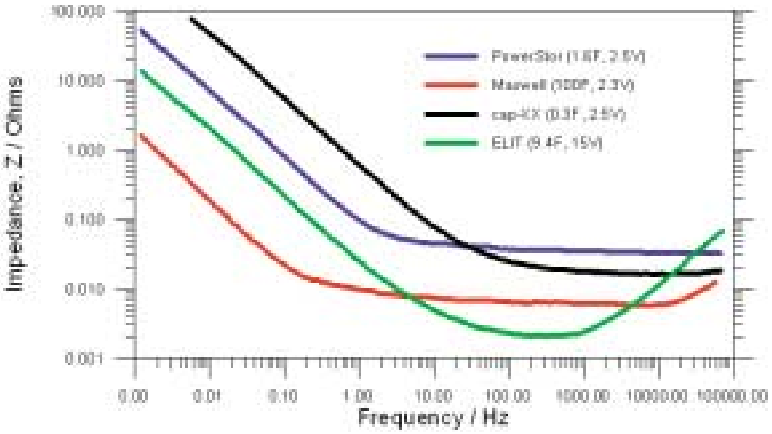

Figure 4: Frequency vs. impedance. (Adapted from Ref. 7.)

power battery. In this example the load profile was a repeating cycle of nine minutes at 25 watts and one minute at 40 watts until the system voltage decayed to 8 volts. The addition of the small lead-acid battery actually doubled the operational life of the system. Unfortunately, technical design and manufacturing issues combined to stymie the commercial viability of this lead-acid cell design.

This work also demonstrated the importance of ESR and the effect of self-discharge rate. Following expectations (based on Ohm's and Kirchoff's laws of electronics) the comparatively large ESR of the supercapacitor, when compared to an aqueous battery or PEM fuel cells, resulted in the energy storage device essentially handling all of the power demand and effectively floating the supercapacitor. To make matters worse, the leakage current or self-discharge rate of the supercapacitor put an additional discharge demand on the energy storage device. The end result: when the battery was combined with the commercial supercapacitor, the actual run times decreased!

Frequency, ESR, capacitance, RC time constants—although many modern supercapacitors commercially available or in development demonstrate dramatic increases in capacitance when compared to classical electrostatic or electrolytic capacitors, the power available and the capacitance available do have some important boundary conditions. A key aspect frequently turns out to be the operating frequency for the pulse loads. One excellent example of this condition for supercapacitors, which may dictate a particular selection depending on the load profile, is shown in Fig. 4.[7]

CONCLUSION

It seems a bit surprising when many people in the electrochemical energy storage business begin promoting hybrid systems as the "new answer" for advanced energy storage devices. But with all the materials advancements seen in the last 40 years and the needs of modern applications, maybe it finally is time for "The Return of the Hybrid." ■

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