Advanced EV and HEV Batteries

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Abstract - Nickel metal hydride is the dominant battery chemistry for hybrid electric vehicles thanks to the success of Toyota's Prius. However, that same success has stimulated interest in both other types of vehicles ranging from micro-hybrids to plug-in hybrids to full electric vehicles, and other types of energy storage devices such as ultracapacitors, Pb-acid, and Li-ion batteries. Li-ion batteries in particular promise advantages over nickel metal hydride batteries in terms of energy and power density, but face challenges in terms of life, cost, abuse tolerance, and low-temperature performance. To address these challenges, a variety of lithium-ion chemistries and cell designs are under development. These developments are being accelerated by the application of computer-aided design tools for batteries that simulate performance, especially thermal behavior, and abuse.

I. INTRODUCTION

Three types of battery chemistries are major contenders for automotive applications: Pb-acid, nickel metal hydride, and lithium ion (see Table I). Because of their low cost, Pb-acid batteries completely dominate the market for starting/lighting/ignition (SLI) batteries and are widely used in electric vehicles such as golf carts and wheel chairs. Nickel metal hydride (Ni/MH) batteries dominate the market for hybrid electric vehicles (HEV) and were used in electric vehicles (EV) such as GM's EV1. Li-ion batteries have not yet found a significant market in automotive applications due to problems with cost, life, abuse tolerance, and low-temperature performance, yet there is enormous optimism that these batteries will displace Ni/MH in HEVs and perhaps, ultimately make EVs practical.

The optimism about Li-ion batteries stems from the advances in the technology. Lithium-ion cells for consumer applications have more than doubled in energy density over the last ten years. New cathode materials have been developed that promise long life and good abuse tolerance, materials costs have been significantly lowered, and many other improvements seem possible. The rapid improvements in Li-ion technology can be attributed to the relative simplicity of the system compared to other battery chemistries. The relative simplicity of Li-ion systems enables the benefits that modeling brings to the design cycle.

TABLE I
KEY PROPERTIES OF HIGH-POWER ENERGY-STORAGE DEVICES

Chemistry	Cell Volts	W/kg	$/kWh	$/kW
Pb Acid	2.2	600	200	8
Ni/MH	1.2	1200	750	30
Li-Ion	3.6	2000	1000	40
Ultracap	2.5	2000	4000	100

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II. AUTOMOTIVE OPPORTUNITIES FOR ADVANCED BATTERIES

The United States Advanced Battery Consortium (USABC) has published goals for advanced energy systems in 42 V, HEV, and EV vehicle applications [1]; see Table II. The start-stop vehicle has the minimum energy requirement and highest value, and so is the most attractive opportunity for ultracapacitors.

TABLE II
SELECTED USABC GOALS

Vehicle Type	Cost ($/kW)	Energy Reqmt (kWh)	Disch. Pulse Power (kW)
42V Start-stop	25	0.25	6
42V M- HEV	20	0.3	13
42 V P-HEV	20	0.7	18
HEV-min	20	0.3	25
HEV-max	20	0.5	40
EV	75	40	80

The conventional lead-acid, SLI battery fails to meet many of the USABC goals. Of particular concern is cycle life (energy throughput over life) [2]. The use of valve-regulated lead acid (VRLA) technology improves energy throughput. GM's hybrid Silverado truck uses VRLA batteries, but further improvements in lifetime energy throughput are desirable. A major cause of failure is positive electrode corrosion and several companies working to make improvements in this area. If some of these efforts are successful, they may enable bipolar lead-acid battery designs. Such a breakthrough would not only promise to increase lifetime energy throughput but also significantly reduce battery weight, and make lead-acid attractive for the full range of automotive applications.

Lead-acid batteries are often considered in combination with ultracapacitors. Ultracapacitors provide power and lead-acid batteries provide energy. However, the high-cost of ultracapacitors currently makes such systems unattractive [3]. Cost reduction is the highest priority for ultracapacitor developers.

Nickel-metal hydride dominates the HEV battery market because it offers the lowest cost in terms of $/Wh over the life of the battery. Since Toyota introduced the Prius with Ni/MH batteries, steady improvements in the power capability of the batteries have been made. In California, where over half on all Prius cars reside, Toyota provides a 10-year warranty on battery life, so does not see battery life as an issue. The cost of nickel is currently a major concern. Panasonic EV Energy has recently described how a metal prismatic cell case is used in their new design; this is the 4th battery design since the Prius was introduced. The latest design provides higher volumetric energy density over plastic packages. Further, then new design can be used to build battery packs of arbitrary size as opposed to the monolithic plastic battery cases. This should allow larger volume production and so reduced costs.

In full EVs, NiMH found use in GM's EV1 and Honda's EV Plus, but the batteries were too expensive to enable EVs on a wide scale. Use of NiMH in HEVs is feasible because the battery is small enough to make the cost manageable.

In 1997, lithium-ion batteries were used in Nissan Altra EV, but the batteries were far too expensive for the mass market. Lithium-ion technology has expanded dramatically in order to address the automotive application. Developers are considering a range of different positive electrode materials and cell designs. At present, there is no clear winner in sight, though there is tremendous optimism that Li-ion technology will displace Ni/MH, as it did in the personal computer and camcorder markets. However, there are many hurdles for Li-ion technology to overcome.

Li-ion batteries have historically been more expensive than Ni/MH batteries. The high cost of nickel and cobalt favors Li-ion chemistries that are iron or manganese-based, but these chemistries are still unproven. Li-ion batteries require a more expensive manufacturing process (dry room) and much closer tolerances (thinner plates and separators). Li-ion batteries require expensive electronics for charge control and cell balancing. Besides cost, lithium-ion also facing problems with abuse tolerance (flammable solvents, exothermic electrode materials) and life.

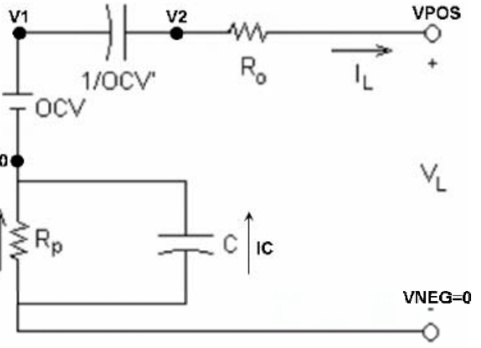
For lithium-ion to successful challenge Ni/MH in automotive applications, progress will have to be made on numerous fronts (cost, life, abuse tolerance). Unless the long development time typically associated with new batteries can be shortened, it is difficult to imagine Li-ion cells competing with Ni/MH in the next five years.

III. COMPUTER-AIDED DESIGN OF BATTERY SYSTEMS

The overwhelming complexity of battery systems inhibits the use of computer modeling in battery design. On the other hand, since small cells are easy and inexpensive to make, a “build and break” approach to battery design is extremely practical for most applications. Unfortunately, this traditional approach is problematic in new automotive applications where larger batteries are used and testing is difficult.

Automakers have pressured battery developers to use computer models to represent battery behavior; the USABC provides the “PNGV Battery Model” (see Figure 1) to battery developers. The PNGV Battery Model is used in a vehicle simulation program (ADVISOR) that allows automakers to estimate how battery performance impacts HEV performance. The model can also be used for on-line battery monitoring [4]. Since the parameters in the PNGV Battery Model are obtained from testing of actual batteries, the model is of limited use in battery design.

FIGURE 1
PNGV BATTERY MODEL



To aid the battery design process, physics-based models are used. Modeling has had some limited successes in design of Pb-acid (such as design of current collectors) and Ni/MH batteries. However, the relative simplicity of Li-ion systems has enabled modeling to address a wider range of problems. Early on, success in modeling of the charge/discharge behavior of Li-ion cells was obtained [5]. Recently, the simulation of Li-ion discharge has been revisited using a well-characterized electrolyte and remarkable agreement with experimental data [6] was reported. Even the more complex behaviors involved in capacity fade [7] and abuse testing [8] have been examined with promising results.

The successes in modeling lithium-ion systems have encouraged development of more general modeling tools for design and simulation of batteries. In particular, Battery Design Studio® [9] provides a user-friendly interface for battery design and data analysis. Such software enables battery developers to visualize and analyze data using a variety of tools ranging from simple circuit models to sophisticated physics-based models and share their results with battery users.

IV. CONCLUSIONS

The advent of HEVs has created opportunities for a range of advanced energy storage systems. The challenge is for developers to reduce costs and make technical improvements.

If battery development continues with its traditional “build and break” approach, then one can expect the status quo of battery use to continue for the next 5+ years; flooded Pb acid will dominate SLI applications and Ni/MH will dominate HEV applications. However, the ability of Li-ion technology to benefit from computer aided design allows acceleration of its design cycle and thus the possibility for an early breakthrough.

REFERENCES

[1]http://www.uscar.org/consortia&teams/consortiahomepages/con-usabc.htm
[2] D.A.J. Rand, P.T. Moseley, J. Garche, C.D. Parker, Valve-Regulated Lead-Acid Batteries, Elsevier (2004).
[3] M. Anderman, The Ultracapacitor Opportunity Report, Advanced Automotive Batteries (2005).
[4] M. Verbrugge, D. Frisch, B. Koch, 4th Annual Adv. Auto. Battery Conf., June 1-4, San Francisco, CA.
[5] T. F. Fuller, M. Doyle, J. Newman, J. Electrochem Soc. 141 1 (1994).
[6] L. Valøen and J. Reimers, *J. Electrochem. Soc.*, **142** A882-891 (2005).
[7] G. Ning and B. N. Popov, *J. Electrochem. Soc.*, 151 (10) A1584 (2004).
[8] R. Spotnitz and J. Franklin, *J. Power Src.* 113 81 (2003).
[9] See www.batdesign.com