THE SHAPE OF BATTERIES TO COME

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ABSTRACT

Traditional battery technologies have been in use for decades, with only occasional incremental improvements. Now, battery users are increasingly accepting new technologies and the number of qualification tests underway is accelerating, as are actual deployments. The adoption of these new technologies is being fueled by business factors, such as shrinking maintenance budgets and reduced pools of skilled technicians, and also by application factors. These application factors may be changes in established load patterns as new equipment is introduced or they may be new types of applications, such as wireless micro-base stations for 3G data services or support for small distributed generators.

As is frequently the case there is a strong push for battery development from the automotive sector. This paper will discuss hybrid electric vehicles (HEVs) and some of the commonality between HEV and stationary applications. Not surprisingly, lithium ion technology features prominently on both tracks.

There is a natural tendency for users to deploy their new batteries in the same ‘package’ (ampere-hour capacity and number of strings) as their traditional units, and to require that they ‘plug-and-play’ with existing charging equipment. This is an operational necessity in the short term but may not be the best approach for the long term. As these batteries become more commonplace the design of dc systems will be optimized around them.

This paper will discuss ways in which battery system design is likely to change, both in response to the characteristics of new battery technologies and also to reflect application trends.

THE FORCES OF CHANGE

This paper is all about change. To understand why things are starting to change rapidly in the battery industry first requires an understanding of some of the underlying trends that are driving these changes.

Technology Changes

Lead-acid batteries were invented 147 years ago; nickel-cadmium 107 years ago. Large format valve-regulated lead-acid (VRLA) batteries first hit the market around 23 years ago. It’s not unusual for a manufacturer to sell the same range of cells (albeit with incremental improvements) for 30 years or more. We exist in a community that has been advancing at a glacial pace, at least as perceived by the outside world. This is even reflected in the battery lexicon: glass battery containers ceased to be used decades ago, yet we still persist in calling plastic containers ‘jars.’

This slow-paced world is starting to change. A quick look at the portable battery industry helps to indicate why. The first commercial shipments of lithium ion batteries did not start until around 1993. By 1998, lithium ion constituted more than 50% of the value of the portable battery market and it was virtually impossible to buy a laptop computer powered by anything other than lithium ion. Since then this technology has taken over the cell phone market, is well entrenched in digital cameras and is now appearing in professional-grade power tools.

It’s worth noting that lithium ion batteries didn’t enjoy this success because they were cheaper—in fact they became successful *despite* their high cost. What they offered was increased value—the ability to power a laptop through an entire transcontinental flight, or to talk on a mobile phone for a few hours longer. The acceptance of higher initial cost in return for higher value is now a growing trend in stationary applications also.

Larger lithium-based batteries are starting to appear in stationary battery markets and are joined by technologies as diverse as nickel-metal hydride and high-temperature sodium-sulfur. And these are just the products that are ready to go commercial; others waiting in the wings include lithium-sulfur, nickel-zinc, metal-air, and vanadium redox and zinc-bromine flow batteries, not to mention non-battery storage devices such as flywheels and supercapacitors.

Business Changes

Major changes are occurring in businesses everywhere, and battery users are certainly not exempt. Personnel costs such as medical insurance are rapidly increasing. Competitive pressures are on the rise in most industries, even those that were once protected monopolies. Through early retirements, natural wastage or forced layoffs, companies everywhere are doing more work with fewer employees. The consequence among large battery users is that many technicians with specialized battery knowledge have retired, and maintenance crews are spread more thinly across a broader spectrum of high-tech equipment.

At the same time both businesses and the general public are becoming less tolerant of service outages, whether in the form of a lost wireless call or a momentary power disruption that causes digital process controllers to malfunction. In this environment batteries are undoubtedly becoming more important, yet there is a paradox in that battery maintenance is both increasingly critical yet increasingly unaffordable. These competing trends are making users more open to value propositions for higher-priced but longer-lived batteries, especially if they can offer significant savings in labor costs.

Application Changes

The days of POTS (plain old telephone service) are on the wane. As demonstrated by other papers at this year’s Battcon conference, data and video services are becoming an increasingly important part of telephone companies’ product offerings. These broadband services are too power-hungry to be backed up for hours, like lifeline voice service. Many telephone companies are now considering backing up broadband services for a few minutes or even just for seconds; just enough to prevent nuisance rebooting of their equipment. Similar forces are at work with 3G data services in wireless communications. The result is that telecom battery duty cycles are becoming far more diverse, with high-power, short-duration battery options starting to become more common.

Fuel cells are now starting to be deployed for telecom outside plant applications, particularly in areas prone to prolonged power outages. This also gives rise to a need for short-duration battery backup, to bridge the fuel cell startup time and to avoid unnecessary cycling of the fuel cell.

This growth in high-power, short-duration battery applications is seen in other areas, such as short-duration UPS, power quality systems and new areas like support for microgrids and distributed generation. Indeed, this pairing of high-power batteries with generators is analogous to what is happening in electric vehicles (EVs) and hybrids.

BATTERIES IN MOTION

EVs with battery-only energy sources have long been restricted to specialized applications such as delivery vehicles and small buses, where speed is relatively unimportant and routes are predictable and limited. Despite extensive efforts by battery and car manufacturers and millions in industry and government funding, EVs have failed to make any headway in the passenger car market.

Enter the HEV. The Toyota Prius first went on sale in Japan in 1997 and shortly afterwards in the US. Sales were initially limited by availability but by 2004 new models and increased production—not to mention increasing gas prices—caused sales to soar. Figure 1 shows US sales of HEVs based on figures from the Electric Drive Transportation Association[1].

All of today’s hybrids are powered by nickel-metal hydride (Ni-MH) batteries. That, too, is likely to change. Industry analysts are firmly predicting that the next generation of hybrids will sport lithium ion batteries[2]. Respected battery industry watcher Hideo Takashita of Japan’s Institute of Information Technology predicts that the first volume shipments of lithium-ion-powered HEVs will be in 2008-09 and that HEV volume for Japanese and US manufacturers will reach one million vehicles by 2010[3].

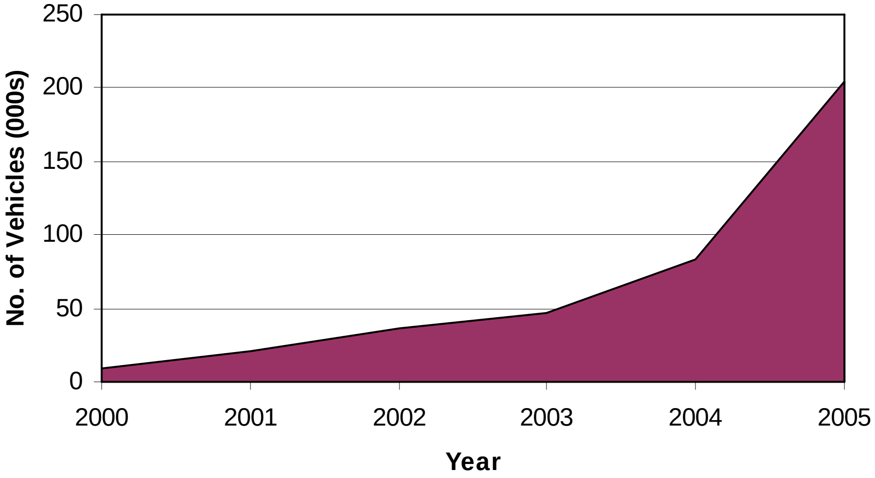

Figure 1 – US Sales of HEVs

The big question now is not whether hybrids will be successful, but in what ways will they evolve? The vocabulary of hybrid cars is wide and there is some dispute about certain terms, but it is generally agreed that today's HEVs are all "full hybrids," meaning that they have smaller engines than comparable vehicles, and couple these with high-voltage batteries (~300V) and electric motors. One area that could see rapid growth in the future is in "plug-in" hybrids.

Plug-In Hybrids

There has been much talk about the so-called "hydrogen economy," a point in the future when our now-ubiquitous HEVs will shed their internal combustion engines in favor of clean-running fuel cells powered by hydrogen. In the early hype surrounding this concept one of the facts that was overlooked is that hydrogen is not a fuel but a storage medium—and not a particularly efficient one, at that. The problem is that hydrogen is not available to us in its molecular form but is bound to other elements, such as oxygen (in water) and carbon (in methane and other hydrocarbon gases). Since the whole point is to get away from using hydrocarbons the most obvious source of hydrogen is from water. However, a considerable amount of energy must be supplied to break the chemical bonds with oxygen.

Mazza and Hammerschlag[4] analyzed the losses, starting from electrical energy in the grid, in using hydrogen to drive a fuel cell vehicle and in powering an electric vehicle with a lithium ion battery. As shown in Figure 2, nearly twice the energy is available to perform the work of propelling the battery-powered vehicle, compared to the fuel cell vehicle. The authors concluded that plug-in hybrids—essentially the same as today's full hybrids, but with a larger battery to allow battery-only driving for, say, 40 miles—would be a much better option than fuel cell vehicles.

Indeed, the obstacles for the hydrogen economy seem to be considerable. Not only is hydrogen a rather inefficient storage medium, but it will also be a long, long time before the energy required for electrolysis could all be supplied from renewable sources such as wind energy. Even if there were abundant wind energy available, the transmission network to bring it to a conveniently located electrolyzer would have to cut through an awful lot of people's backyards.

Plug-in hybrids, in contrast, can operate from the existing petroleum infrastructure and can also recharge at night, making more efficient use of baseload generation. On a typical commute the engine may never be used, removing pollutants from city centers. On longer trips, the vehicle would function exactly as today's HEVs.

This is not the end of the story, of course. If plug-in hybrids are charged from legacy coal-fired generation then pollution would be merely shifted rather than reduced, compared with today's full hybrid. The larger battery will also cost significantly more, so much will depend on the balance of costs between electricity and petroleum. Plug-in hybrids will also have to compete with full hybrids using carbon-neutral fuels such as bioethanol and biodiesel.

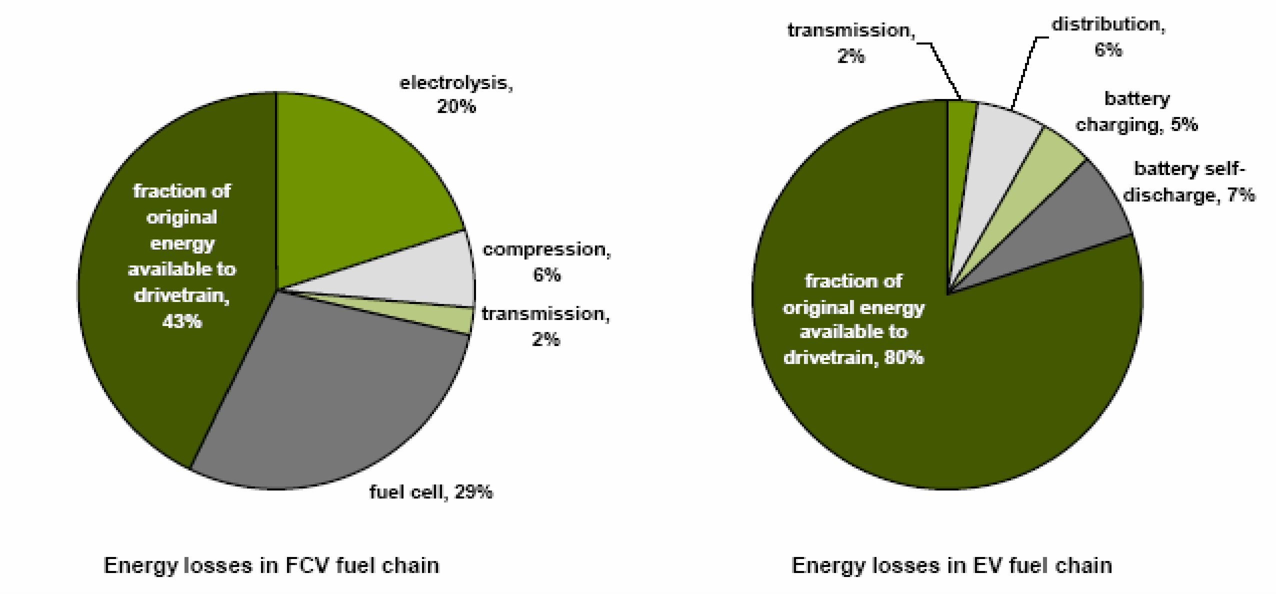

Figure 2 – Relative losses along the fuel chain for fuel cell vehicles (FCV, left) and battery-powered electric vehicles (EV, right), from Mazza and Hammerschlag[4]

THE IMPACT OF HEVs ON THE STATIONARY BATTERY MARKET

All this information about hybrid vehicles is very interesting, but what does it have to do with the stationary battery market? The answer is – plenty! The sheer size of the automotive market will bring about significant economies of scale for the batteries used in HEVs, so lithium ion is likely to be a big winner.

The other aspect is that the combination of a high-power battery with a generator is likely to be a common model for stationary power systems. This is already the case for UPS, in which the battery rides through momentary power fluctuations and bridges to standby generation for longer outages. In the case of UPS there is a limited amount of cycling involved, but the HEV model will be more closely followed in the implementation of distributed generation (DG) in the utility grid.

Just as computers have evolved from central intelligence (mainframes) to distributed intelligence (networked PCs) and wireline telephone networks have evolved from central switching (central offices) to distributed switching (outside plant), the utility grid is expected to evolve from central generation to DG. Just as mainframes and central offices haven't disappeared, nobody is predicting the demise of large generating stations, but their outputs will be augmented by DG located in the distribution infrastructure. There are several potential benefits for this arrangement:

- Reduced transmission and distribution (T&D) congestion, with fewer upgrades and less new construction required
- Reduced T&D losses
- Increased efficiency with use of combined heat and power (CHP) systems
- Higher security (reduced impact of natural disasters or terrorist attack)

As with HEVs, batteries allow the generator to be sized for the average load, with the battery providing load peaks and improving response to load step changes. More importantly, the combination of storage and generation allows the creation of microgrids—small load centers with the ability to disconnect from the grid in the event of system disruption. Storage, typically in the form of a battery, is essential for microgrid control and frequency regulation.

Lastly, what about all those fuel cells that are being developed? If the hydrogen economy and fuel cell vehicles are still way out in the future, will the fuel cell manufacturers be content to sit back until the laws of physics are repealed? In fact, large fuel cell generators in the 200-250 kW range are already in use as DG units. Rather than burning natural gas in central generating stations, it makes much more sense to consume it in smaller fuel-cell-based CHP systems where the heat can do useful work such as water heating. Fuel cells powered by natural gas may well appear as DG units in a microgrid near you.

The other area in which fuel cells are appearing is in standby power for telecom outside plant, as mentioned previously. Operating in standby mode for most of the time removes any issues about life of the membrane in proton-exchange membrane (PEM) fuel cells. By using replaceable hydrogen cylinders from industrial gas suppliers, fuel cells can be freed from complex infrastructure issues, essentially becoming mechanically recharged hydrogen batteries that can provide power for prolonged periods. This can make them attractive for hurricane-prone areas that can see prolonged outages.

The extent to which fuel cells pose a threat to traditional 8-hour telecom battery systems will depend very much on their eventual production costs. Whatever happens in that area, however, will not remove the need for small high-powered storage systems, whether in the form of batteries or supercapacitors, to cover short power disruptions and bridge to the fuel cells for longer outages, just as in UPS systems today. The longer run times for batteries, in minutes rather than seconds, will help to minimize on-off cycling of the fuel cells and the necessity for swapping out partially used hydrogen tanks.

SYSTEM DESIGNS FOR THE FUTURE

Although lithium-based batteries have started to be deployed in telecom applications, they are being installed as direct replacements for VRLA batteries, in the same capacity increments, numbers of strings, and so on. Beyond the obvious differences of non-aqueous batteries with electronic interfaces, the way in which dc system design might change in other stationary applications is not yet apparent.

Electronic design will be a critical and evolving area for lithium batteries. The electronics must balance the individual cell voltages on float and monitor for overcharging or overdischarging conditions. It is rather tempting to take the opportunity to pack in features and to make a sophisticated electronics package. Care must be taken, however, not to neglect reliability. If the failure of a balancing circuit or communications link on an individual cell would cause the cell balancing function to be lost for the entire battery then this constitutes a statistical series system, as discussed by the author in his Battcon 2005 paper[5]. This has an impact on overall reliability, especially in high-voltage batteries. There is a significant argument to be made in favor of simple electronic systems, provided that they are fail-safe and the functional necessities of lithium batteries are met.

One way to mitigate the impact of electronic failures is by use of parallel strings. To the extent that lithium-based batteries replace traditional single-string batteries, such as in substations, users will have to change their thinking and adopt some level of paralleling. This subject raises some interesting questions and also provides opportunities related to modularity.

Paralleling Cells or Strings

In low-cost, non-critical lithium ion systems it is already standard practice to parallel cells within battery strings to make up the desired capacity. This saves cost on electronics, since a single balancing circuit can take care of all the cells in a parallel grouping. However, an electronics failure can cause the failure of an entire string. It can readily be seen that more paralleling at string level and less paralleling at cell level will improve overall reliability. Sometimes compromises are made in this area, but to avoid adverse impacts on system cost it is generally better to use larger-capacity cells and to minimize cell paralleling, all other things being equal.

At the time of writing this paper, all other things are not exactly equal. Consumer-grade ‘18650’ cells (so-called because of their dimensions) are produced by the millions each month and their market prices have come down to the point where bare cells are not so much more expensive than higher quality VRLA cells. This presents system packagers with an opportunity to build very compact high-capacity systems using massive cell paralleling, in which these 2 to 2.5 Ah cells are built into arrays of hundreds of ampere-hours.

While the commercial opportunity for massive paralleling exists now, it is unlikely to last forever. Cost projections by Saft have shown that when large format cells are produced in sufficient volume, their manufacturing costs will at least be competitive with those of smaller cells. This means that system comparisons of small cells vs. large cells, massive paralleling vs. moderate paralleling, should be made on their technical merits rather than as short-term commercial opportunities.

Failing Gracefully

A big factor in this rather complicated equation is the way in which cells fail. By far the best failure mode is one of gradual wear-out. Open circuit failures should be avoided wherever possible. This raises a serious issue with the use of consumer-grade lithium ion cells in continuous float operation.

To understand the following argument requires an understanding of the portable battery market. Cell manufacturers generally restrict themselves to churning out huge numbers of cells at the lowest possible cost and with good quality. Those cells are then sold to pack assemblers, who build them into the familiar packages that we slot into our laptops, PDAs and cell phones. Unfortunately, some of those cells end up in the hands of battery ‘pirates’ who turn out a package that appears identical to the OEM battery but may be missing essential electronics for safe operation. This has led cell manufacturers, under pressure from device manufacturers, to produce so-called intrinsically safe cells.

These cells are designed specifically for simple charge-discharge operation. Even when sitting inside a mains-connected laptop, for example, a charged battery of this type does not remain connected to the charging source. If overcharged to a dangerous level, however, and in the absence of correctly functioning electronics, an electrolyte additive decomposes to produce gas, causing an increase in internal pressure to the point where an internal current breaker opens. This destroys the cell but avoids a possible fire.

When such cells are used in continuous float applications, however, particularly at elevated temperatures, unwanted side reactions involving the same electrolyte additive cannot be avoided. Under some circumstances it will polymerize, causing a massive increase in internal resistance. In others, although the cell is operated at a voltage below the normal activation threshold of the additive, the process of continuous charging causes a slow but unavoidable buildup of gas, eventually opening the current breaker and causing the cell to fail open.

The assemblers of massively paralleled systems use statistical arguments to show how this assembly method can yield a much higher level of reliability than single high-capacity strings, *where the failure mode is also open circuit*. The problem is that these 18650 cells, while unsuited for float applications, are built to very close tolerances—so when one fails open, the others in its parallel grouping and elsewhere in the array won’t be far behind. Cells that are properly designed for float service will fade in capacity, rather than opening, and are therefore much more reliable. Any potential user of lithium ion batteries in stationary applications should make sure that the cells are intended for float operation.

The Benefits of Modularity

As mentioned previously, some string paralleling is desirable, and this situation lends itself very well to one in which battery construction will become highly modular. In the telecom market we have already seen the arrival of several complete 48 V lithium-based packages, enabled by the lightness of lithium cells, and the logical extension is to build higher voltage batteries with essentially the same building blocks. An example of this can be seen in Figure 3, which shows a 48 V package and a 240 V modular system, both built from 19-inch rack-mountable 24 V modules.

Figure 3 – 240 V and 48 V Modular Battery Systems

This modularity will then be taken one step further, by treating the strings as modules also. This is a significant departure from the traditional implementation of a range of products, in which a lead-acid manufacturer, for example, might produce a 40 Ah positive plate and build it into cells of 80, 120, 160, 200 Ah, and so on. In the lithium ion world of modular strings there would be multiple strings assembled in parallel to make up the desired capacity.

With this modular format manufacturers will be able to limit the number of cell types they produce and reap the full benefits of highly automated production lines. In this way the lower manufacturing costs per cell will offset the increased cost of electronics in multi-string systems—up to a certain point, of course. A combination of actual costs and common sense will help to draw the line on the number of parallel strings.

This point can be illustrated using an analogy involving telecom rectifiers. For example, if a rectifier plant with 90 A output and n+1 redundancy is required, it makes more sense to use five 25 A rectifiers than two 100 A units. However, if the required output is, say, 900 A, very few would opt for thirty-seven 25 A units instead of ten of 100 A.

MAINTENANCE-FREE—ARE WE THERE YET?

In lithium-based batteries we are getting much closer to a maintenance-free 'black box.' The cells are hermetically sealed and assembled into a package with electronics that are capable of monitoring the state of charge and state of health of the battery, and of signaling a remote operator if something goes wrong. While these capabilities remove the need for periodic diagnostic measurements, it is difficult to pronounce that we finally have a maintenance-free battery. There is still the need for periodic visual inspections and removal of dirt and debris. Furthermore, a product cannot be truly maintenance-free unless it never fails.

Maintainability of lithium-based batteries is one area in which there is still a lot of room for improvement. Rack-mounted modules are likely to become hot-pluggable, similar to rectifiers, and electronic boards will be made easier to swap. Such changes will bring these batteries much closer to being treated as just another electronic component in the system.

CHARGING FORWARD

Today's stationary lithium-ion battery systems are typically designed to operate with 'dumb' chargers, using settings intended for lead-acid batteries. It's not that the chargers themselves are necessarily dumb, but that they are not designed for communication with a smart battery. This puts more of an onus on the battery to protect itself from, for example, too high a charge current, particularly at low temperature. It also leads to non-optimized operation. For example, a 14-cell lithium ion battery with an optimum charge voltage of 4.0 V/cell should be charged at 56.0 V to achieve the maximum state of charge (SOC). This voltage is too high for many telecom loads, so such a battery would probably be charged at the normal 54.5 V. Because the SOC of a lithium ion battery actually varies with the charge voltage, operating the battery at this level will maintain it at only about 90% SOC.

One alternative is to use 13-cell batteries and a charge voltage of 52.0 V. This is well within the voltage range of the loads, but now the problem is that a charger set to 54.5 V would impose a damaging level of overcharge on the battery. The solution in the short term is to regulate the voltage within the battery system, but it is not hard to envisage a future in which smart chargers would recognize the batteries to which they are connected, and adjust themselves accordingly. Such chargers would communicate operating parameters through CANbus or similar communication links, and would incorporate dynamic current limiting and other features to achieve optimum battery life with the minimum of operator intervention or constraints on the overall system.

SUMMARY

There is an ancient Chinese curse: ‘May you live in interesting times.’ The battery community is in such a time right now, with the confluence of business and application trends with the opportunities presented by new technologies. The HEV market is growing rapidly and seems poised to shift to high-power lithium ion batteries, a move that would significantly reduce the cost of that battery type. Many emerging applications in the stationary battery market share similarities with HEV operation and would be a natural target for this new breed of batteries.

This is not all good news, however. Users of traditional batteries will have to think long and hard about how they would configure advanced battery systems and will have to try to avoid the pitfalls of inappropriately designed systems. This paper has concentrated largely on lithium ion batteries, but this is not the only choice facing battery users. A potentially bewildering array of other emerging battery types, in addition to non-battery storage technologies, promises to keep users’ lives interesting for a long time to come.

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