The Practical Application of Lithium Ion Batteries in Energy Storage and Other Stationary Applications

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Abstract

Extensive development work has been, and is being, carried out to scale up lithium ion battery technology. Moving from small-scale portable units to the higher capacities required for electric vehicles and other applications is no simple task. The balance of material and assembly costs are entirely different for the larger cells, necessitating new materials for virtually all components. Now that realistic designs are emerging from the research efforts, it is necessary to consider their integration into real dc systems, from both a physical and an electrical viewpoint.

This paper presents a case study on the integration of a 67kWh lithium ion battery into an energy storage system. This is based on a feasibility study carried out by Saft for Sandia National Laboratories (SNL). Such systems are expected to exhibit a high degree of modularity, and the reasons for, and benefits of, such an arrangement are discussed. Also covered are the electrical aspects of the operation of multiple parallel battery strings.

One of the safety requirements of lithium ion batteries is the use of electronic charge controls, implemented at the individual cell level. Design issues for these electronics are considered, and the preferred system is described. The possibility of extending the functions of the electronics into the area of battery monitoring is also explored.

Lastly, even an ideal battery would be useless if it is not properly integrated into a working system. Some of the issues of system integration are discussed, and their potential impact on battery design is considered.

Funded in part by the DOE Energy Storage Systems Program.

Development Update

The development of the latest generation of lithium ion batteries in large capacity format was discussed in a recent paper [1]. Many of the characteristics of these batteries make them particularly well suited for energy storage applications. These characteristics include

- Very high energy density and power density
- Excellent cycling capability
- >95% energy efficiency on charge/discharge
- Good high and low temperature capabilities
- Hermetically sealed – no gassing or electrolyte loss
- Zero routine maintenance

Since performing that work, additional experiments to extrapolate battery life under float charging conditions at high temperature have begun to bear fruit. Using models established and validated with earlier generations of lithium ion, the life expectancy of these batteries is conservatively estimated at 15 years, based on the conditions found in typical outdoor cabinets in the USA [2].

Energy vs. Power

As with many other battery types, it is possible to produce higher power designs by using thinner plates, resulting in a larger surface area for the same amount of stored energy. This allows a higher proportion of that energy to be discharged in a short time. In addition to the high-energy cell design used in electric vehicles, Saft has produced high-performance and mid-range types. Although these designs involve a sacrifice in energy density, the higher power capability can be significant, as shown in Table 1. There is a similar tradeoff between energy and power with

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The authors would like to acknowledge Nancy Clark and her colleagues at the Sandia Energy Storage Systems Program, with thanks for their cooperation and advice.

other technologies, but in the case of lead-acid batteries, high power also comes at the expense of battery life. This is because the support structure of the positive plates (the lead-alloy plate grid) is gradually corroded during normal operation. The thin plates used in high power designs corrode more rapidly than thicker ones, so the life is shorter. There is no such tradeoff with lithium ion, since there are no side reactions during charging.

Table 1 – Energy density vs. power density

Cell Design	Energy Density (Wh/liter)	Power Density (W/liter)	P/E Ratio
High-energy (HE44)	321	920	2.9
Mid-range (MR35)	300	1930	6.4
High-power (HP30)	234	2620	11.2

The choice between high energy and high power types is largely an economic one. While high power designs are more expensive per watt-hour, they are less expensive per watt for short discharges. The most cost-effective type for a particular application will depend on the nature of the load, or the balance between multiple loads.

Energy Storage Applications – Power Requirements

Broadly speaking, the high-energy designs produced by Saft are suitable for discharge times of greater than about 1 hour. The mid-range designs are best for discharge times of 15-60 minutes, with high-power types being optimized for shorter times. Of course, these numbers are not absolute. Issues such as the normal state of charge and operating temperature will also influence the most cost-effective type.

Table 2 summarizes the optimum design (high-energy [HE], mid-range [MR], or high-power [HP]) for each of the energy storage applications identified by SNL in their Opportunities Analysis – Phase II, as summarized in the FY99 annual report [3].

Table 2 - Energy storage applications

Application	Discharge time (min)	Cell design (HE / MR / HP)
Rapid reserve	$10^1 – 10^2$	HE / MR
Area & frequency control	Cycles of $<10^1$	HE*
Commodity storage	$10^2 – 10^3$	HE
Transmission system stability	$10^{-3} – 10^{-1}$	HP
Transmission voltage regulation	$10^1 – 10^2$	HE / MR
Facility deferral	10^2	HE
Customer energy management	$10^1 – 10^2$	HE / MR
Renewable energy management	$10^{-3} – 10^3$	HE / MR / HP
Power quality & reliability	$10^{-3} – 10^0$	HP

* Cycles clustered in 2-hour blocks, favoring high-energy design

System Size Limitations

It must be recognized that large format lithium ion batteries are still undergoing development, and there is very little field experience with these products outside the electric vehicle application. With this in mind, it would be prudent to limit the stored energy of the first prototype systems. However, there are several aspects to system size, some being more of an issue than others.

The following is a listing of factors influencing battery size, and the extent to which each is expected to limit the first energy storage systems.

Cell capacity

The high-energy cell types produced by Saft at the pilot plant level are currently limited to a capacity of 44 Ah. This cell has a cylindrical format, which provides even support for the plate elements. As cell capacity is increased, greater care must be taken in design and assembly to achieve the same level of support. It is also possible that cell designs will migrate towards prismatic formats, since these offer greater energy density in multi-cell assemblies. If this is the case, the desirable level of support for the plate stack will be more difficult (but certainly not impossible) to achieve. Another issue that will feature strongly in designing larger cells is that of thermal management. Having said this, there is no theoretical limit to cell capacity, and cell capacities of around 100 Ah have already been shown to be achievable in cylindrical formats.

String voltage

There are no particular constraints on lithium ion cells regarding string voltage. The function of the cell electronics is to balance all the cell voltages, so uniformity is achieved regardless of the number of cells in series. EV systems routinely operate at voltages over 300V, and there is no reason why string voltages of several kilovolts could not be designed for safe operation. Indeed, the trial application discussed later in this paper involves a nominal battery voltage of 840V. Working at high string voltages does require some care in electronics design, to avoid high common mode voltages, and there is always the personnel safety issue to consider.

Parallel cells/strings

Because of the relationship between cell voltage and state of charge, lithium ion cells connected in parallel are inherently self-balancing. A further benefit is that an electronic control circuit can work on a single cell or a grouping of parallel cells. Therefore, the overall cost for electronics is reduced when parallel cell connections are used. Against this, the string current is multiplied by the number of cells in parallel, so the connecting hardware and protective devices must be sized accordingly.

There is a benefit to being able to standardize on a particular multi-cell module for a broad range of applications. To limit the number of module designs, it is likely that the number of parallel cell connections will be limited to two or three, and that higher capacities will be achieved by using parallel strings. For many years, the ‘conventional wisdom’ in the industrial stationary market was that the number of parallel strings should be limited to between four and six. However, it has been common practice in telephone company central offices to deploy over 20 battery strings on a common dc bus, and recent technical papers [4, 5] have debunked many of the myths associated with multiple-string systems.

Basing the battery design on a modular approach tends to favor the use of multiple strings. This is reinforced by the use of electronic controls at the cell and string level, combined with the ease of operating multiple strings. As with most of the other system size considerations, there is no theoretical limit to the number of parallel strings, but prudence dictates that the first prototype systems be limited in this regard.

Trial Application

The initial feasibility study carried out by Saft for SNL considered the listing of energy storage applications, and the suitability of lithium ion batteries for each. Large-scale applications, such as multi-MWh commodity storage systems, were immediately ruled out by the low volume/high cost nature of the current production. As mentioned above, it was also desirable to prove out the technology with relatively modest systems before proceeding to larger installations. The focus was therefore on a system that would be based at a customer facility where power demand was not especially high, but power quality was of much greater importance.

Discussions were held with an eastern utility on the likely applications for such a system. It was agreed that power quality was the application in which it was easiest to justify the system cost. This involves the use of an energy storage system to ride through voltage sags of less than one second. Although this discharge time would favor a high-power cell design, it was decided to try to address at least one other application – customer energy management – by including a capability for peak demand reduction. The longer discharge time and larger block of discharged energy associated with this second application pushes the optimum cell design towards the high-energy end of the spectrum.

The targeted applications influence the configuration of the overall system, including such questions as whether to operate in standby mode, or with primary facility power routed through the power conversion system. Following discussions with the utility and with a power electronics manufacturer/systems integrator, a trial system was proposed with an output capability of 400-500 kW at 480 Vac. The lithium ion battery would comprise 245 high-energy cells operating in the range of 700-956 V (2.86-3.90 V/cell). A single string of this type would have a capacity of 33.5 kWh, and two strings were proposed to produce a total capacity of 67 kWh.

Figure 1 shows the instantaneous power capability of this battery at various temperatures, compared to the depth of discharge. This information is important, since it defines how much of the battery's capacity can be discharged before the system will be incapable of riding through a voltage sag. Based on the system rating of 400-500 kW, the graph shows that for new batteries at 25ºC, about 40% of the capacity can be used for peak demand reduction without affecting the power quality capability.

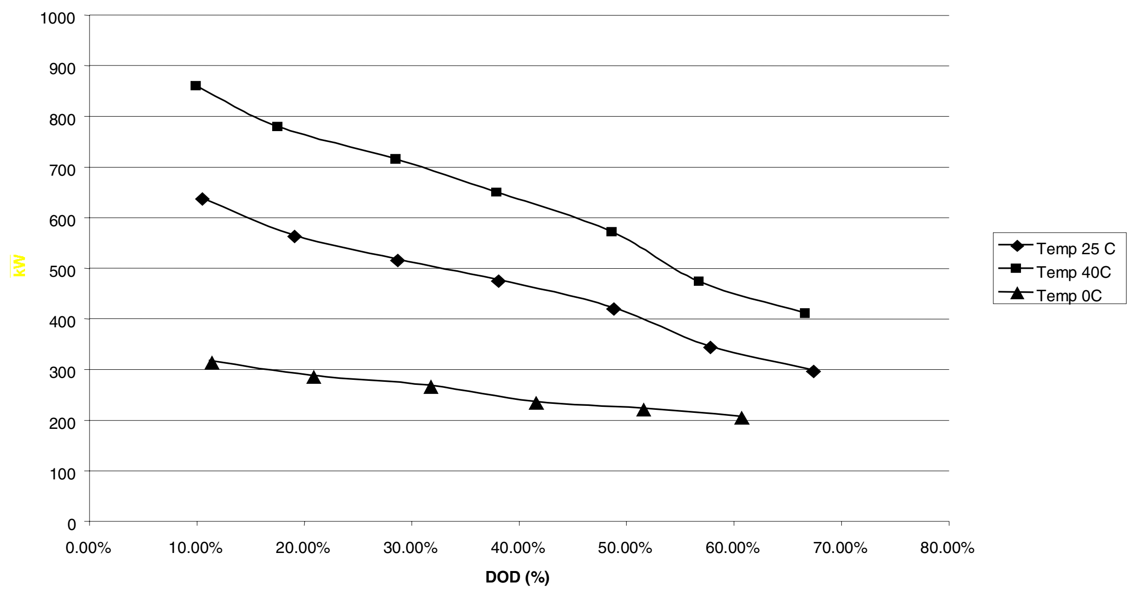

Figure 1 - Instantaneous power discharge (kW) of the 67 kWh battery compared to the depth of discharge (%)

Based on the feasibility study, SNL issued a contract to Saft for the next phase of the implementation of this trial system. The contract covers the construction of a 9.6 kWh lithium ion battery assembly. Future phases will involve testing to a customer load profile, scaling up to the full 67 kWh, integration into an energy storage system, and the siting of this system at a user facility.

Test Battery

The 9.6 kWh test battery consists of 5 modules of 14 cells, with a nominal cell capacity of 38 Ah (at the 3.9 V charge voltage). The cells in each module are arranged in parallel pairs, seven in series. The battery is therefore rated at 120 V nominal, 76 Ah. The modules have been designed to fit into a tray that mounts into a standard 23-inch telecom relay rack. Each module weighs approximately 18 kg (40 lb) and occupies 16 liters (980 in^3). Figures 2, 3 and 4 show the construction.

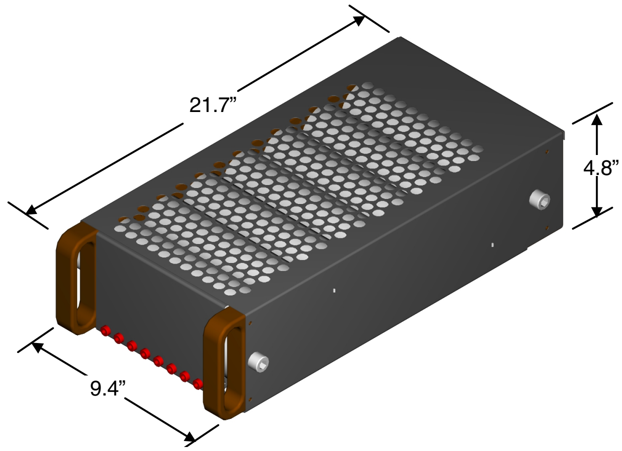

Figure 2 - 14-cell module

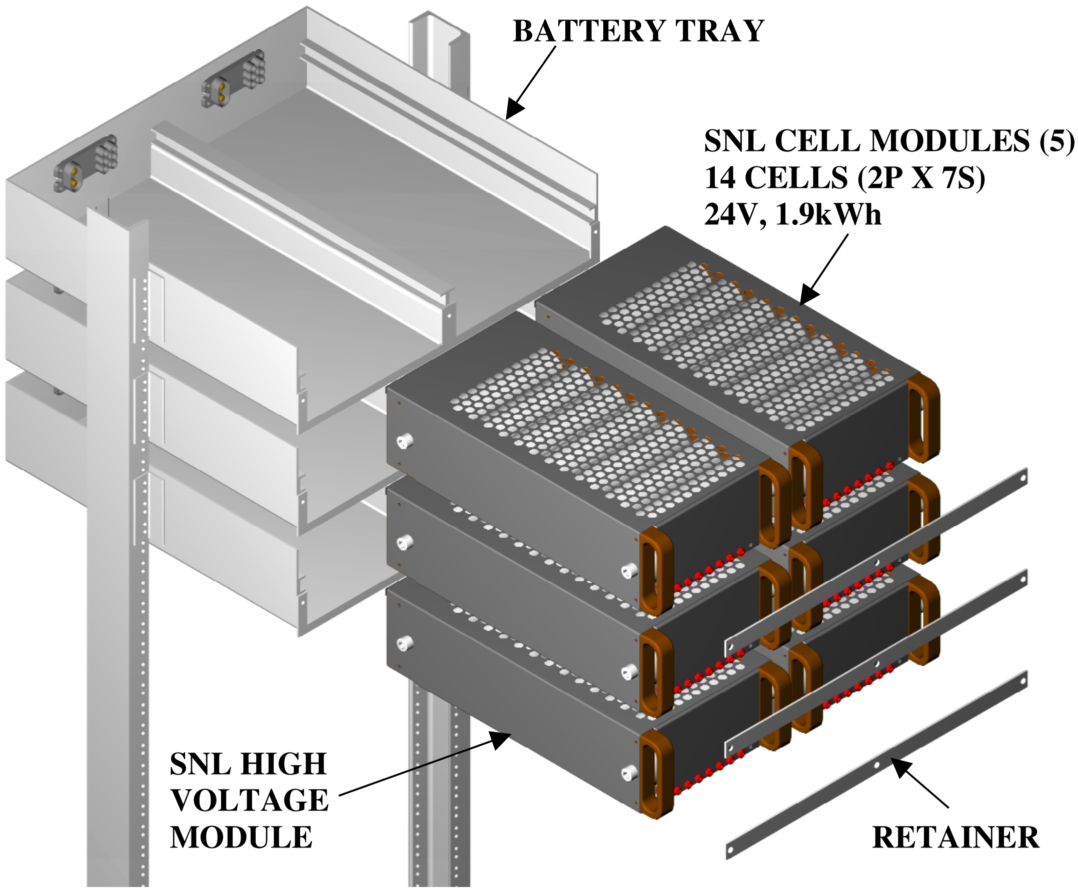

Figure 3 - Exploded view of battery assembly

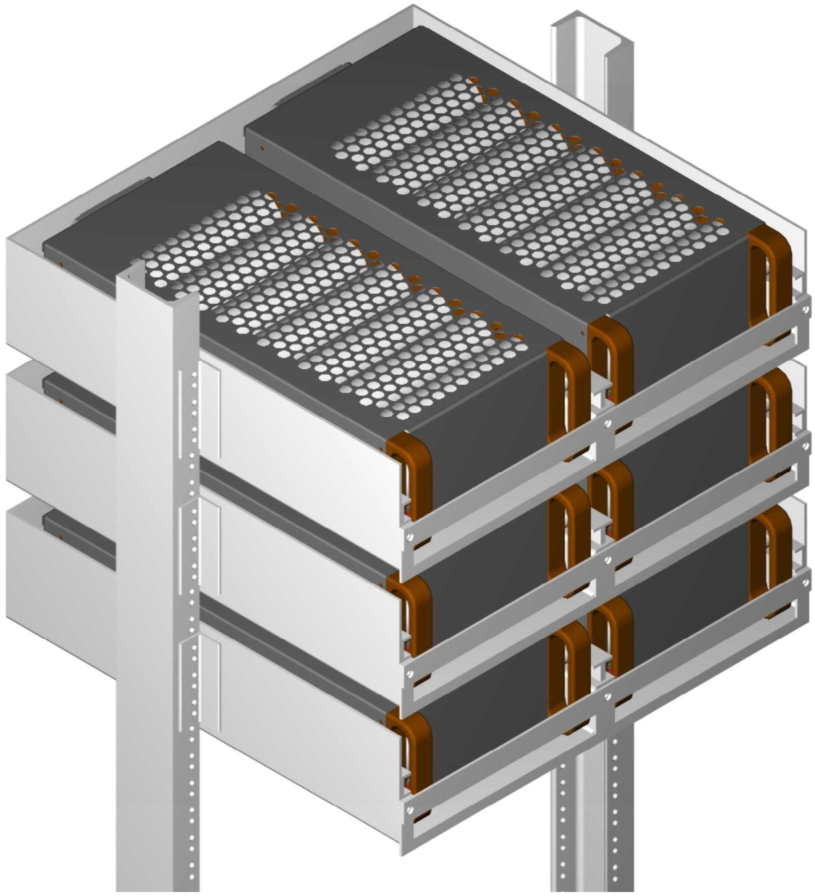

Figure 4 - Final assembly of trial battery

Battery Electronics

The general requirements for battery management electronics are the same for all applications involving lithium ion:

1. Over-charge protection and full-charge balancing
2. Over-discharge protection
3. Over-temperature protection
4. Short circuit protection

The first two of these requirements are implemented at the level of individual cells or groupings of cells, while the last two operate at module or string level. For stationary applications, the system should be able to operate independently, without a central computer or external telemetry. The system must be highly reliable and must be fail-safe. It is desirable that the electronics package be built into each module for easy replacement, with full scalability for multi-kV applications. This also means that the modules can be protected at all times, including during shipping and handling.

Figure 5 shows the implementation of these principles for the trial battery. This shows individual, independent, commercially available over-charge and over-discharge ASICs, backed up by fully independent, redundant, commercially available over-charge protection ASICs. The replaceable fuse provides over-current protection. These parts are co-located with the cell connection (power path) hardware on a single printed wiring board for ease of assembly and reduction of parts.

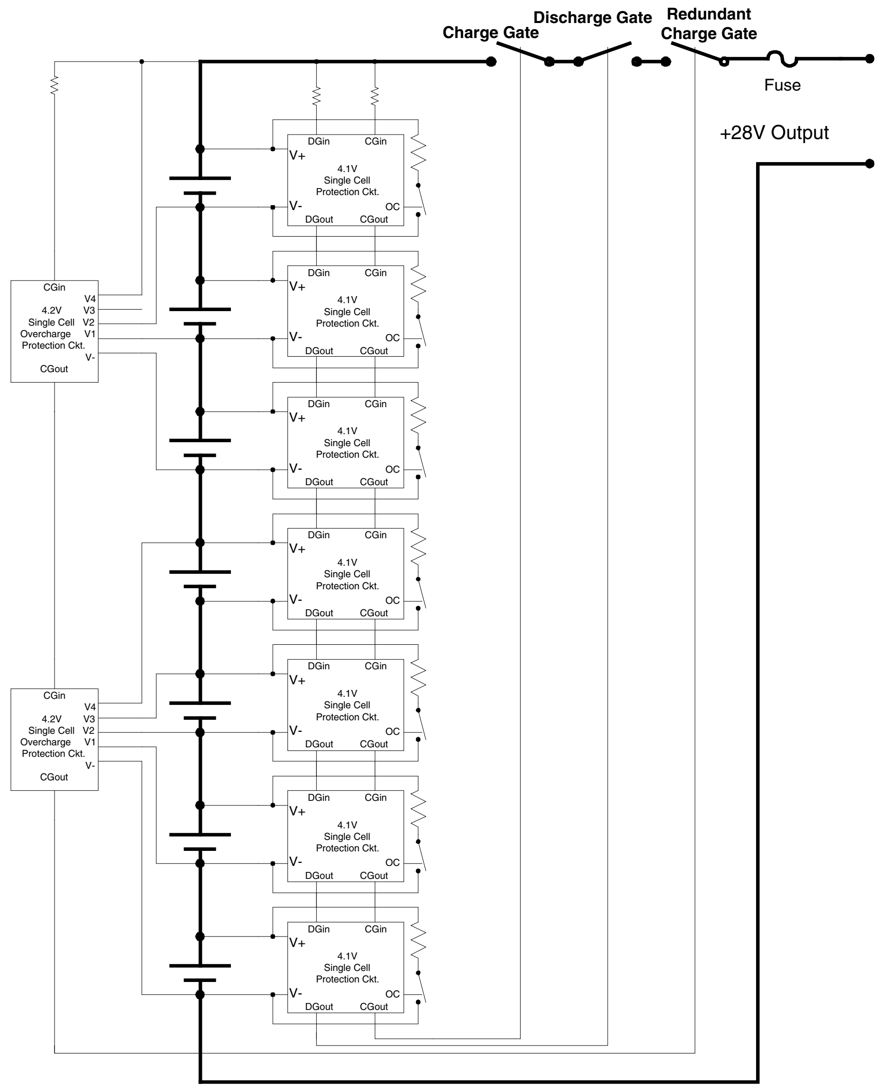

Figure 5 - 7-cell (24V) battery module electronics

The final configuration and operation of the battery management electronics is still to be determined, since this will depend on the test program to be carried out (see below).

Future Work

The next phase of this project is to consult with our utility partner to determine a suitable test cycle for the final 67 kWh system, to simulate customer loads. This will be scaled down to the trial battery level and will form the basis of a test program to be run at Saft's facility.

Conclusions

Large format lithium ion batteries can be integrated into practical systems, covering a wide range of energy storage and other stationary applications. Experience gained with smaller trial systems will allow larger batteries to be produced, starting with hundreds of kWh and building up to multi-MWh capacities.

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