LONG-TERM FIELD EXPERIENCE WITH A STATIONARY LITHIUM-ION BATTERY IN A SUB-STATION APPLICATION

Mats Leksell
KTH Royal Institute of Technology
Stockholm

Peter Krohn
Vattenfall Research and Development AB
Älvkarleby

Bertil Nygren
ABB AB / Corporate Research
Västerås

Trond Beyer
SAFT
Oslo

ABSTRACT

In January 2006 the by then world's largest stationary Lithium-ion battery was commissioned at Älvkarleby Power station, Sweden. It is developed in cooperation between Vattenfall Vattenkraft AB, ABB AB / Corporate Research and SAFT.It is designed to provide a nominal system voltage of 220 V and a capacity of 210 Ah. The battery consists of in total 50 battery modules, each containing six cylindrical cells. There is a Battery Management System that controls and manages the discharging and recharging of the battery.

The battery has now been in service for 6 years and several tests have been performed on the battery during the years. The tests have investigated the status of the battery with the overall aim to monitor the ageing process and expected life-time of the installation. By nature, test of a stationary battery system of this size is a challenge and extra care has been taken to ensure the quality of the results. Extensive logging of all results was done both in the battery management system itself and on a separate analogue recording system.

There are two major tests that have been performed: internal resistance and capacity tests. The results from the tests are subsequently compared to battery models provided by the manufacturer SAFT.

The aim of the paper is to elaborate on primarily the life-time of the battery taking into account the ageing effects of the 6 years in service. Initial analysis of the results shows that a resistance increase in the range of 20 % was found for the 2011 test as compared to the measurements made in the end of 2005. Extrapolating 20 % during 5 years linearly to the resistance doubling at end of life ends up in a life time of 25 years, which is acceptable for this technology and application. This would mean that a corresponding capacity, if measured, would approximately be 96 % at the end of life.

Also the capacity tests indicate a rather slow ageing of the battery but what is more interesting is that the analysis shows that ageing actually seems measurable.

INTRODUCTION

In January 2006 the Li-ion battery was commissioned at Vattenfall hydropower station in Älvkarleby Sweden. The battery serves as emergency power back up in case of outage in the general power supply for the service power grid in the station. Power is supplied for emergency light, water pumps and station monitoring and control system.

The hydropower station has two power backup batteries working in parallel. The batteries are connected not to feed each other and can be separated during both operation and maintenance.

A Li-ion based battery was chosen to replace one of the old lead acid batteries when an upgrading programme for the hydropower station was launched. Main expectations from the new system were:

- Improved plant security
- No special requirements for internal environment
- Lower costs for operation and maintenance
- Possibility for monitoring
- Durability equivalent to other components in the power plant
- Less demand for space and explicit safety requirements of the building and inside it
- Less environmental influence

A main problem to solve at that time was the lack of space to fulfill a new requirement for dual battery strings. With the Li-ion battery the need for floor area was substantially reduced.

A compact DC supply and distribution central was ordered to fit the limited area in the backup power room, see Figure1. In fact, the system delivered by ABB AB, turned out to be a little bit too compact with respect to maintenance reasons. Luckily there has not been so much demand for that type of work space.

Air conditioning was estimated not to be necessary for the Li-ion battery, but for the lead-acid battery room it is necessary to have ventilation according to Vattenfall internal regulations. The room is built with fan ventilation from outdoor air.

Figure 1.The 5 battery strings are placed on individual sliding shelves (left), Battery chargers are placed on the back of the second cabinet door and the BMCs on the left hand side wall (right).

If a Li-ion cell would vent in an emergency, emitted gases will be lead outdoors through an exhaust vent channel in the cabinet.

The Li-ion battery cells are fully sealed which means that there is no need for any maintenance at all. The only regular work required is monthly inspections to observe general conditions like heat and moisture in the battery room.

An internal battery control module, called BMC, is monitoring all parameters and selected alarms are forwarded to the hydropower plant main control system.

The battery has five parallel strings and the total capacity is 210Ah at 220V. Each string has ten modules series connected, with six cells series connected in each module. There is a dedicated battery charger for each string. In contrast to the lead-acid battery the Li-ion is dependent of several relays and electronics for full operation. Despite that dependency, the modularity increases reliability in the battery system. A drawback from the parallel buildup of the system is the difficulty to have an even distribution of current supply through all the rectifiers.

Experience from the pilot project has showed a weakness in the cell-balancing shunt resistors which therefore have been exchanged. Except for those, only a couple of standard components have failed during these first six years.

The battery was designed to meet a specified load profile for a nominal total of 132Ah. To have an expansion load possibility and a large operative safety margin the battery ended up with quite an oversized capacity. The nominal profile was originally intended to be used for battery test also. That test method appeared to be too complicated for ordinary use, and with the strong characteristics from the battery it was decided to use a constant current discharge for yearly tests. Yearly test is not a recommendation but a simple way to achieve statistics to verify the expected 20 years lifetime.

DESCRIPTION OF FIELD TESTS

Tests of the battery have been carried out at regular intervals with the main aim to evaluate the state-of-health (SOH) and thereby keep track of the ageing of the battery. The early tests were reported in a paper presented at Battcon 2007 [1] and concerned field capacity tests and a factory acceptance test.

During the last year, 2 tests have been performed to continue to monitor the ageing of the battery. In May 2011 a test of the internal resistance of the battery was done and in November 2011 a field capacity test was done. The tests are described below together with the results and in the next section, the results are compared to models that the battery manufacturer provides.

Internal resistance test May 2011

In May 2011 the internal resistance of the battery was evaluated at distinct current levels during a discharge of the battery that started from a state with full charge and went down to a level of approximately 20 % State of charge (SOC). The rate of the discharge was approximately C/4 and at regular intervals the load was disconnected and the test of the internal resistance was performed.

The internal resistance was found by making a step-response test of the load current. The terminal voltage was recorded during the test on a transient recorder via a test circuit that eliminated the DC level of the battery. A typical test result is shown in Figure 2, where *ibatt* is the total load current and $\Delta vbatt$ is the change in battery voltage due to the step change of current. Due to noise in the measurements the current and voltage levels were evaluated from averaging obtained during the period T_{before} just before the step and a period T_{after}, 4 seconds after the step. It can be noted that the increase of the current is actually not a pure step as the internal design of the current sink only allows the current level to be changed in discrete levels. This means that the load current was increased in a row of smaller steps instead of just one big.

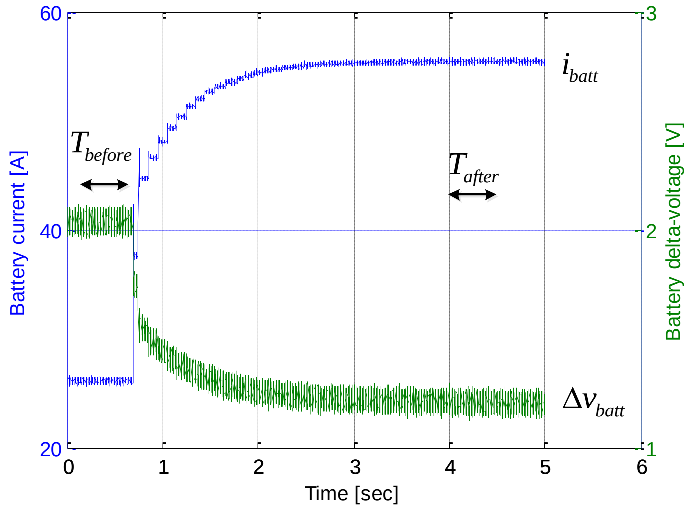

Figure 2. Typical result from a recorded step test for evaluation of the internal resistance

To obtain a consistent estimation of the internal resistance, tests were done at several SOC levels and with different magnitudes and direction of the step. The measured results are given in Table 1. As can be seen the value of the internal resistance varies a bit with both the type of step and with SOC level. However, apart from the tests at low current level (10 to 1 A) the result is consistent having an average value equal to 29.3 mΩ. The value can be compared to a measurement that was done in 2005 when the internal resistance was found to be 24.6 mΩ at SOC-value round 70%. This increase of 19% would extrapolate approximately to a doubling of internal resistance over 20 to 25 years. This is acceptable for this technology, in which the only consequence of resistance increase is added heat generation; at the load level for this application this additional heating is of no consequence.

Field capacity test Nov 2011

The aim of the Field capacity test in November 2011 was to again measure the capacity of the battery. The set-up was similar to previous tests with a constant current-sink capable of drawing up to 55 A. During the test the battery was loaded with 40 A which corresponds to approximately C/5. During the test, all string load currents were recorded with a transient recorder and the BMC system logged all internal data from the five strings. The battery was discharged from an initial SOC of 100% and the end of the test was set to be done when the battery voltage level became lower than 200 V, i.e. approximately a voltage drop of 10 % from nominal voltage level. Table 3 shows the actual voltage levels of the cells at the end of the test.

Table 1. Internal resistance [mΩ], vs. SOC and size of current step

	Current step size						
SOC	55→26A	26→55A	55→1A	55→15A	55→30A	55→45A	10→1A
93%	31.9						
91%		31.4					
89%	32.1						
73%		30.5					
72%	30.1						
36%			30.1	27.7			
31%					27.0		
29%						27.0	
28%							38.6
20%	28.0	28.4	30.8	28.5			
17%					28.1	27.9	
16%							40.3

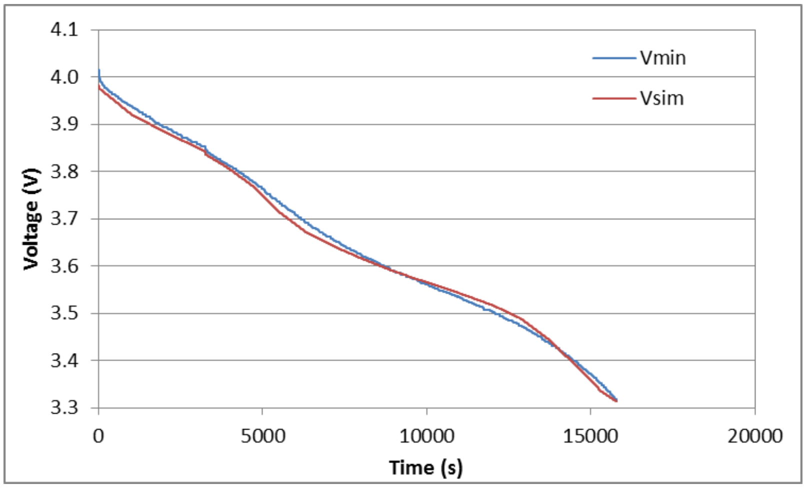

Figure 3. String #2 test data from August 2006

SIMULATED BATTERY PERFORMANCE

Saft has developed detailed models for Li-ion battery systems, including those based on the VL45E cell type used in Älvkarleby. These models, produced with Matlab-Simulink, can be used to assess the change in battery performance over time by comparing the discharge test data with model predictions.

The first task was to establish a baseline for the data comparison. It was found that the actual battery performance was better than predicted by the model due to two factors: first, the model is conservative, representing the low end of the manufacturer's capacity range under the allowable quality standard; second, the battery strings were charged to slightly higher voltage than that specified by Saft for 100% SOC (4.02 V/cell versus 4.00 V/cell), thus each string was operating at greater than 100% SOC. (This may be a difficult concept for those used to conventional lead-acid technologies, but it is a consequence of the characteristic of 'slope' described in a previous Battcon paper[2].)

Because the Matlab model did not allow for operation above 100% it was necessary to establish an offset factor in order to match the model output to the test data. Taking String #2 as an example, it was found by trial and error that an offset factor of 0.964, applied to the test current as a model input, brought the model voltage output into close alignment with the minimum cell voltage for that string during the 2006 test. This is shown in Figure 3, where *Vmin* is the minimum cell voltage (of the 60 cells) and *Vsim* is the simulated voltage.

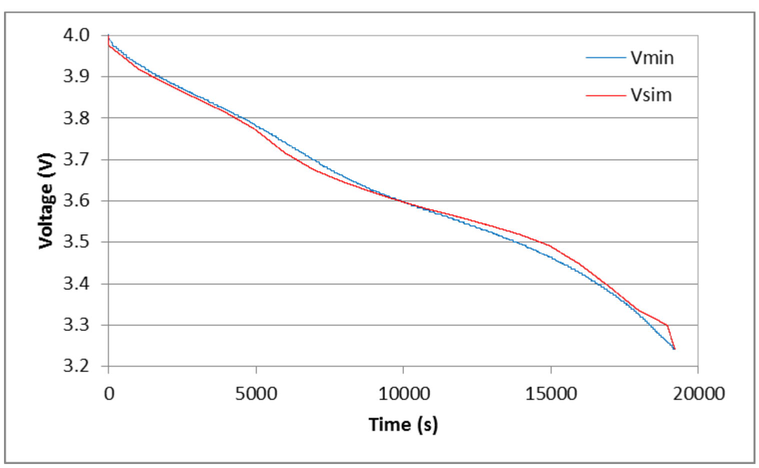

Figure 4. String #2 test data from November 2011

Table 2. 2006 test results

	String_1	String_2	String_3	String_4	String_5
Initial min. cell temp. (°C)	28	28	29	27	27
Min cell voltage at 15796s (V)	3.314	3.313	*	3.317	3.317
Simulation offset	0.962	0.964	0.967	0.953	0.953

For the November 2011 test the same exercise was performed. The recorded string current was again offset using the figures established for the baseline in 2006, but now the battery state of health (SOH, a measure of capacity) was adjusted by trial and error to match the simulation to the test data. Figure 4 shows the results for String #2 with the same 0.964 current offset factor and SOH at 0.993. (It should be noted that the charge voltage for the 2011 test was at the same 4.02 V/cell level as for the 2006 test, so the offset should still have been valid.)

It can be seen that the overall voltage levels are higher for the 2011 test; as discussed in the 2007 paper this is because String #3 disconnected itself part-way through the 2006 test and so the remaining strings saw a current increase of about 25%—a small step can be seen at around 3,000 seconds in the 2006 curves. This effect, along with temperature differences between the two tests, has been fully taken into account in the simulations. The detailed comparison by string between the two tests is shown in Tables 2 and 3.

In the case of String #3, the minimum cell voltage closely matched that of String #5 in the time up to disconnection of String #3, so the same simulation offset as String #5 was used.

AGEING IMPACT ON DIFFERENT BATTERY TECHNOLOGIES

With an ageing coefficient of between 0.992 and 0.997 it is evident that the battery has lost very little capacity between 2006 and 2011. To be sure there are some variables, such as temperature, where the resolution does not allow high precision in the analysis; however, we can be sure that the battery has experienced less than 3% capacity loss. Given the linear ageing progression that is characteristic of this particular Li-ion electrochemistry the testing strongly supports a battery life of at least 20 years under the operating conditions of the Älvkarleby substation.

Table 3. 2011 test results

	String_1	String_2	String_3	String_4	String_5
Initial min. cell temp. (°C)	25	27	27	25	27
Min cell voltage at 19200s (V)	3.241	3.242	3.257	3.254	3.247
Simulation offset	0.962	0.964	0.967	0.953	0.953
Ageing coeff to match Vmin	0.993	0.993	0.992	0.997	0.993
Capacity discharged (Ah)	42.83	43.13	42.78	43.28	43.58
Min current share*	19.6%	19.2%	19.4%	19.1%	19.7%
Max current share*	20.4%	20.4%	20.1%	20.6%	21.7%

* Excluding first minute

It is worth noting that the Li-ion battery has been subject to significantly higher temperatures than the lead-acid battery, which operates in an air-conditioned environment, maintained for the most part at around 21°C to 22°C. The recorded battery temperatures over several years are shown in Figure 5 below. If the lead-acid battery had been exposed to the same temperatures as the Li-ion system its life would be shortened by several years. The ability of the Li-ion battery to provide a long operating life under such conditions therefore raises the possibility of additional savings that could be made by eliminating air-conditioning and its accompanying energy and maintenance costs.

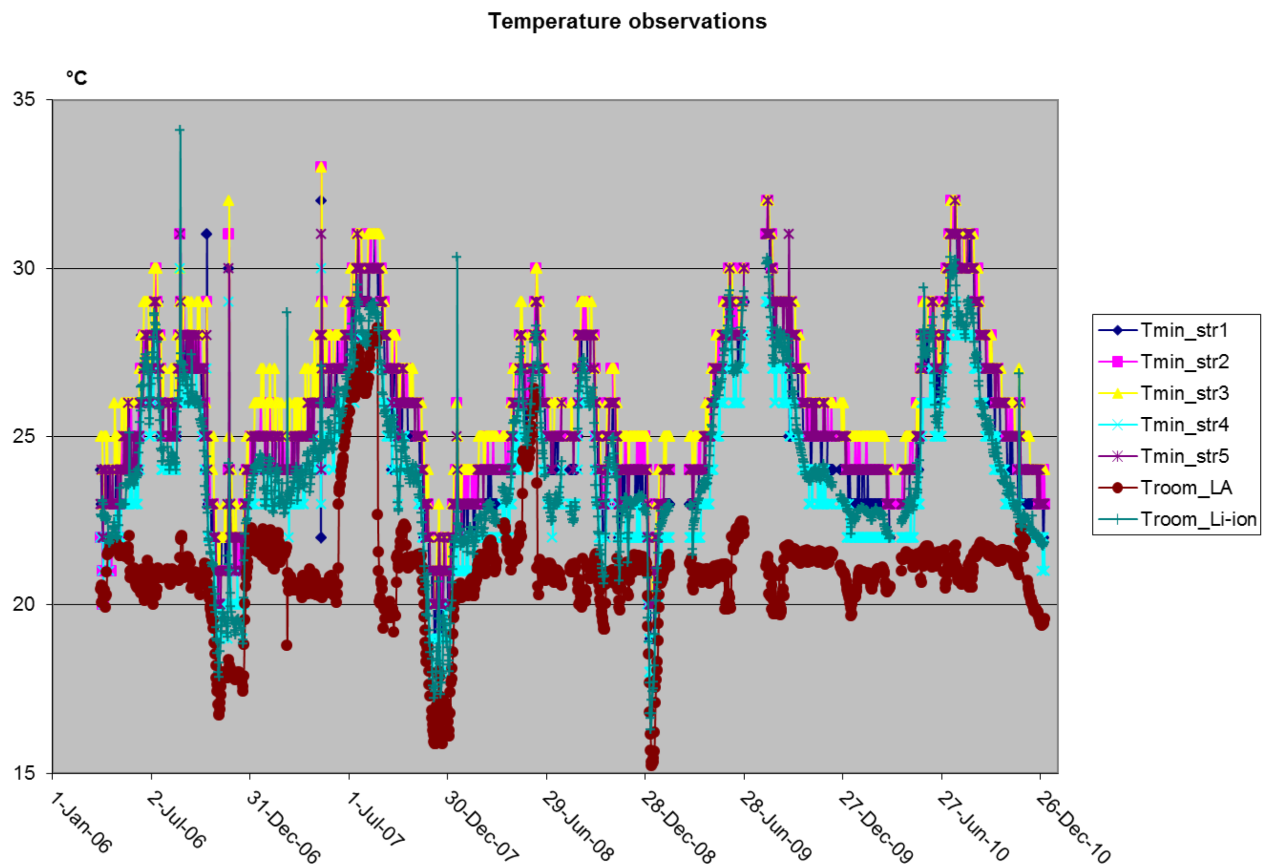

Figure 5. Battery temperatures, 2006 to 2010

SYSTEM ASPECTS

Introducing new battery technologies is not an easy task. There are several aspects that have to be taken into account[3]. For the power station application considered in this paper, it was designed with special focus on:

- Small footprint: the design should not only fit into the available space but it should also leave enough of space for a new fire cell arrangement

- High availability and redundancy: operation of a power plant is a delicate affair

- Self-diagnostics and long life: the application is also cost-sensitive

When the design of the Li-ion battery system was done it resulted in a cabinet floor area that occupied only 5% of the area that the old parallel connected lead-acid battery room did. However, one draw-back of the compact design was an increase in the temperature as the placement of the cabinets had a restriction on the cooling that could be done by convection and water cooling was not an option.

The fact that there are five independent strings working in parallel and each string has its own battery charger leads to a high availability and makes the system to become redundant.

In a substation, most of the equipment contains self-diagnostic functionality. When introducing the new battery technology it was identified as important to introduce this feature also into the new system. A secure communication line to the common Swedish Vattenfall maintenance center (900 km away from Älvkarleby) was therefore of great importance.

For compatibility with the rest of the power station, the life time of the battery should be in line with other equipment. In this case a reasonable life time is estimated to be approximately 20 years. A benefit for the NCA technology is its accurate SOC/SOH-estimator.

DISCUSSION

Albeit the cost of a DC-system is a very small part of the entire hydropower station it has to be competitive with other older proven alternatives like lead-acid and nickel cadmium. At the time the battery was built the Li-ion system was more than three times more expensive. However, the total Life-Cycle Cost (LCC) should be considered. A 100% reliable diagnostic system and no maintenance during 20 year might, with the rapid development of the Li-ion technology, change the situation. The evaluation of the battery condition after five and a half year should give an estimate of the remaining secure operation time and projected maintenance costs during its life time. To get the whole picture, also an estimation of the replacement cost should be done.

The continuous monitoring of the battery shows that it has been exposed to high temperature during longer periods in summer time but the field tests so far indicate an aging of the battery in the order of a few percent only. It has been proven that NCA technology can stand a float charge condition during longer times also at elevated temperatures.

The Swedish grid is very reliable and therefore the actual usage of the battery during the operation period January 2006 to May 2011 has been limited. In reality the main usage of the battery has been during the yearly regulated capacity tests.

From the plant operator's point of view, there are also other issues that have to be taken into account when summarizing the impact of introducing the new Li-ion technology:

- Price: the price level of a Li-ion battery is still so high that it is not the first choice on a commercial basis
- Life time: the degree of capacity ageing from the tests is promising, and if the linear ageing characteristic already demonstrated for this technology holds true, then a 20-year life seems likely.
- Modularity: it is not enough that there are individual strings in the battery but to facilitate a more common introduction of the technology, it could be beneficial if it is possible to simply unplug the old battery and then plug in the new one. Such a solution will have equal influence on the maintenance and repair strategy for the plant operator. It is also of interest if the systems could be made more independent of the actual manufacturer from an availability aspect.

Today, operators are focusing more and more on security due to recent severe accidents. The introduction of new equipment that is not verified to be more secure than present technology is difficult. Justification by saying that lead is poisonous and Sulfuric acid is dangerous is not enough. It has to be investigated e.g. what is the impact if a Li-ion battery vents, what are the problems if a pyroswitch is installed and what is the risk and effect if the electronics malfunction.

REFERENCES

[1]Krohn, P, B. Nygren, T. Beyer, *Field experience from the world's largest stationary Lithium-ion battery*, Proceedings of Battcon 2007

[2] McDowall, J, *Understanding lithium-ion technology*, Proceedings of Battcon 2008

[3] McDowall, J, M. Lippert, *Sophistication versus Simplicity – System Design Considerations for Lithium-Ion Batteries in Standby Power Applications*, Proceedings of Battcon 2010