# FIELD EXPERIENCE FROM THE WORLD'S LARGEST STATIONARY LITHIUM-ION BATTERY

**Peter Krohn**
**Vattenfall Research and Development AB**
**Älvkarleby**

**Bertil Nygren**
**ABB AB/Corporate Research**
**Västerås**

**Trond Beyer**
**SAFT**
**Oslo**

## ABSTRACT

Vattenfall Research and Development AB (formerly Vattenfall Utveckling AB), in close cooperation with Vattenfall Vattenkraft, ABB AB / Corporate Research and SAFT, has completed an evaluation project for determining the suitability of Lithium-ion batteries as a stationary back up power supply in hydropower plants.

The Li-ion battery has six cylindrical cells connected in series to form a module. A string of ten modules is then connected in series to provide a nominal system voltage of 220 V. Finally, five strings are connected in parallel in order to obtain a total battery capacity of 210 Ah.

SAFT, the company responsible for producing the batteries, has, in cooperation with ABB, developed a solution for large-scale stationary batteries with good float charging characteristics. Each battery module has an electronic circuit for controlling and managing discharging and recharging the battery. A BMC, Battery Management Calculator, controls the battery string and continuously calculates the state of charge and manages the communication with peripheral equipment. During the evaluation project, the battery has been bench marked to procurement specifications, where a specially designed load profile has been given an important role. The battery has showed excellent capacity throughout testing with the relatively low current according to battery design.

The battery system has a lot of relays for self protection, and the control process and is totally dependent on the BMC's. With many components, the risk for equipment failure increases. A few smaller accidents have also happened during the first year. In spite of such incidents, the back up function of the battery has never fallen below the required level, thanks to a high degree of redundancy.

A major advantage for Li-ion battery technology compared to the lead acid battery system is the reduced amount of floor space required. The lead acid battery room has an area of 13 m², while the Li-ion battery is contained in an 800 mm industrial cabinet.

The batteries are fully sealed and maintenance free. That gives a number of advantages for the service crew. Problems associated with the build up of hydrogen gas and handling of acid are reduced or eliminated. On site maintenance is also reduced due to the possibility of viewing charge status and other parameters remotely. These properties, together with the reduced size, were the main reasons why Vattenfall has chosen this solution.

The duration time of the evaluation, one year, has been too short to examine aging characteristics of the system.
The highest obstacle against Li-ion batteries today is the cost. Developments in the electric vehicle industry are expected to decrease the cost level. Other battery types, such as lithium polymer batteries, will probably have a wider deployment because of the possibility of production at lower costs.

## INTRODUCTION

In 2004, ABB AB/Corporate Research Center presented a new type of battery configuration, which could be interesting as back up power in bridge signal cabins and substations.

Vattenfall Vattenkraft has been investigating alternatives to replace lead acid batteries in back up power installations for quite some time. In Spring 2005, the decision to build a pilot Li-ion battery system from ABB at the hydropower plant in Älvkarleby was made. The new battery system became operational on the 11th of January 2006.

The main reasons why a Li-ion battery solution was chosen were the benefits of a small footprint and the potential feature of being maintenance free. The two, nine year old, lead acid batteries were about to be replaced and, at the same time, a larger capacity was needed. Moreover, the two old batteries were also placed in the same room which from a fire hazard point of view had to be corrected.

Instead of building a completely new battery room with separate fire cells and extensive wiring, the solution was to put in a fire wall in the old battery room and create two fire cells. In the larger one of those cells, a new lead acid battery was installed and, in the smaller cell, a Li-ion battery was installed, together with some other power distribution equipment. In spite of the larger cost of the Li-ion battery, this solution was marginally more expensive than the original idea of building a completely new battery room.

## THE DC POWER SYSTEM

### Electrical System Configuration

In Figure 1, the new DC power system at Älvkarleby hydro power station is shown. It consists of two batteries working in parallel; one free ventilated lead acid battery string of 300Ah and one Li-ion battery with 5 strings in parallel of 210Ah.

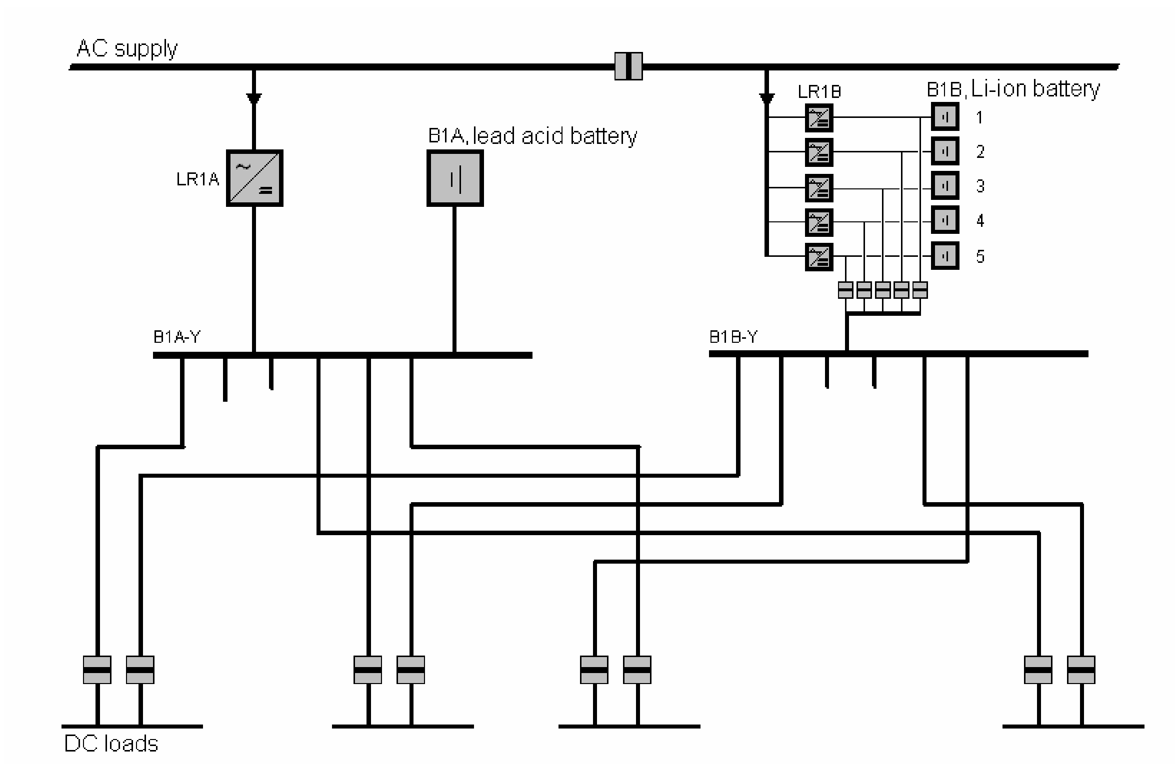


**Figure 1. One-line diagram for the DC power system at Älvkarleby hydro power station.**

The system is in use every day and gives, for example, power to the control system of the whole station, power to oil pumps, and power to regulate water gates opening and shutting. Normally, most of the power is taken from the battery chargers, and only momentary power peaks are supplied by the battery modules.

As there is a reverse charge protection diode in the Li-ion section, not shown in Figure 1, the voltage between the Li-ion battery poles is slightly higher than nominal 220 VDC. During float charging, it was also found difficult to adjust the voltage of the different chargers in such a way that a perfect balance between the two different batteries was achieved.

**Battery Design**

The Li-ion battery was built up from 42 Ah cells originally developed for the car industry. Six of those cells are normally packaged into modules and connected in series, which gives a nominal voltage of 24VDC. Ten such modules were connected in series to give the desired system voltage.

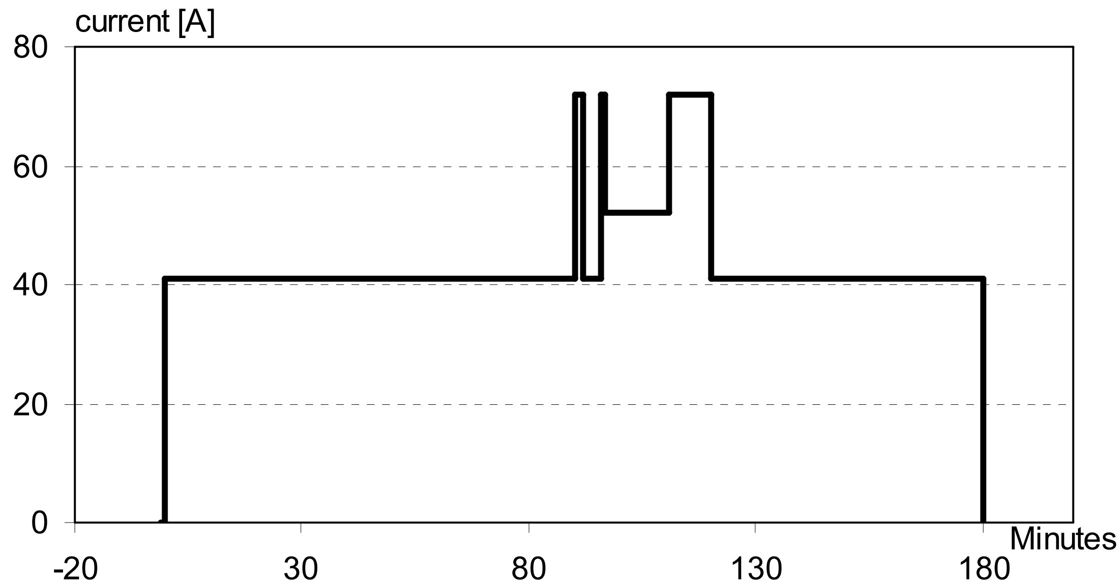


**Figure 2. Specified load profile, nominal 132 Ah**

The capacity was designed to meet the specified load profile given in Figure 2. The choice of capacity was based on experience from similar design work on nickel cadmium battery back-up power units and taking into consideration the superior properties of Li-ion cells. The long term behavior of Li-ion cells tested on float-charge was also evaluated in order to get a battery with a 20 year lifetime. Those two facts gave a final design of five strings in parallel given a total capacity of 210 Ah.

No extra cooling had to be provided for the batteries. The cells are designed to work without aging in temperatures up to 60 °C. The chargers, on the other hand, had to be placed in a fan ventilated cabinet. See Figure 3. In the battery room of the lead acid battery, an air conditioner was installed to meet the demand for specified ambient temperature.

Each string was equipped with its own charger and BMC, which gave a high degree of redundancy. If one cell in a string malfunctions, the BMC will automatically open up that string. Still, there will be 80 % of the rated capacity left.
The new lead acid battery was made with 108 cells in series with a total capacity of 300 Ah.

**Battery Room**

After the rebuild of the original battery room, the new lead acid battery occupied an area of $13m^2$, while the Li-ion battery was placed in an industrial cabinet with a foot print less than $0.5\ m^2$. Chargers, diodes and relays were placed in an adjacent, ventilated cabinet. See Figure 3.

**Figure 3. Left: each battery string is sitting on a sliding shelf, right: backside of chargers sitting on cabinet door plus five BMCs on left hand side wall.**

If a Li-ion cell would vent in an emergency, it will emit hot gasses such as hydrogen, carbon monoxide, carbon dioxide and trace amounts of hydrocarbons such as methane. The shelves in the cabinet are designed to lead these gases towards the back of the cabinet for safe ventilation.

**Remote Monitoring**

The possibility to remotely control the battery system has been used in three ways. First, to send alarms from the BMCs automatically to the power station control centre. It is also possible to remotely monitor all status figures and indications from the control room. And last, the built in information is used as an acquisition system for evaluation of the project.

## EVALUATIONS

### Factory Acceptance Test

Before delivery, the Li-ion battery was tested at ABB Corporate Research laboratory. Beside a capacity test according to Figure 2, the dimensioning of diodes and fuses were verified. In order to get a “fingerprint” of a fresh battery, the internal resistance was measured with a transient recorder. The idea is to measure the internal resistance in the same way regularly in order to trend the aging.

### Field Capacity Tests

During the first year, two capacity tests have been conducted. At the first test, two months after delivery, the capacity according to Figure 2 plus an additional load of 40 A during 72 minutes was discharged. The state of charge was changed from 100 % down to 20 % with a total delivery of 179 Ah.

The second capacity test was made similar to a lead acid capacity test, a so called “5-hour test” and, in this case, with a current of 40A. Theoretically, that would correspond to a discharge down to 5% state of charge of the Li-ion battery. During the test, one string was disconnected after about one hour due to a bad physical contact of a signal cable in one of the BMCs. The current was automatically redistributed to the other four strings. See Figure 4. The test was ended after 4 hours and 23 minutes when the state of charge reached 6 % in the remaining four strings. In total, the battery had delivered 175 Ah.

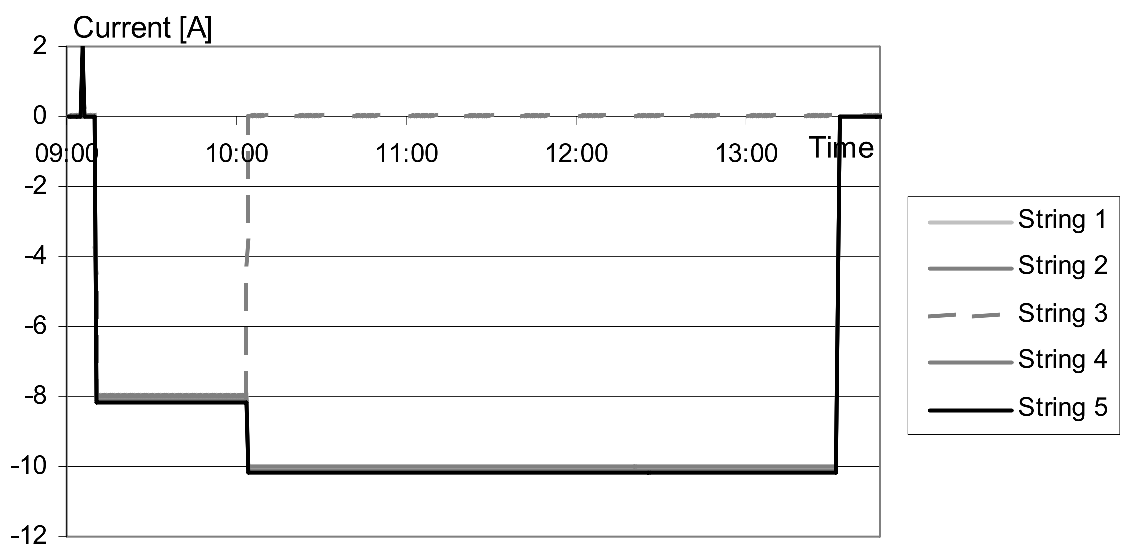


**Figure 4. “5-hour test”, current registered in each string.**
**All strings have the same behavior except for nr 3 because of a malfunctioning contact.**

The third capacity test was conducted in a similar way to the first one. The discharged capacity this time was 187 Ah, with the state of charge reaching 20%.

### Teething Troubles

Besides the earlier mentioned bad electrical contact of a signal cable, there have been minor problems with a malfunction of a relay in the control circuit and battery balancing after deep discharge tests. Those experiences will be valuable during the ongoing development of a stationary battery system for both telecom and power utility applications.

## DISCUSSION

### Maintenance and Surveillance

Thanks to the information collected by the BMCs, it is possible to have a remote surveillance of the Li-ion battery. The hydro power business unit in Vattenfall is working on a centralized maintenance organization of its power stations throughout Sweden and, from that point of view, the new possibilities demonstrated in Älvkarleby to control the battery system fit very well. Most of the maintenance work of substations is related to the battery.

In the pilot installation, a lot of warnings and alarms are forwarded from the BMCs to the control center. That will not be appropriate in a future company-wide power station monitoring system, a fact that has to be considered by the plant manager. One unexpected feature was the relatively large need of power to the relays and other support equipment. In a next generation, those power losses would be largely reduced by adopting another design philosophy.

### Fuses and Relays

The conventional thinking for back up power is to have the most reliable supply system. That means, for example, no fuses or contactors are used in the cabling between the battery and the distribution panel. In the Li-ion battery, on the other hand, several safety devices to protect the battery itself are included.

Even though the fears about individual component failure have come true, the maintenance personal have improved confidence because of the built in redundancy from the five parallel strings in the system. That means the reliability is lower but the availability can be higher in such a system.

### Battery Aging

During the one year evaluation period, there has not been any aging observed in the battery system. Because this is a new technology, it is suggested to the power plant maintenance personnel to regularly, once a year, perform a 5 hour discharge test. That will be the easiest way to detect aging of the battery. A more scientific way to observe the internal resistance of the battery will also be discussed with the owner of the plant.

### Environment

Prior to the installation, theoretical life cycle assessment (LCA) and life cycle costing (LCC) studies were made. The results were all consistent; the Li-ion has environmental advantages compared to conventional lead acid and NiCd batteries as well.

### Future Systems

From several points of view, such as environmental advantages, space savings and maintenance-free operation, the Li-ion battery solution is interesting as a replacement for lead acid batteries. On the other hand, the price level is currently too high. Only under special conditions can we expect Li-ion to be the choice. The Älvkarleby case is one such example, where space was limited and using Li-ion was a way to avoid building a new battery house.

## ACKNOWLEDGEMENT

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