Lithium Ion Battery, Opportunities and Challenges for Submarines

Abstract —Rapid development of battery technology has attracted a large interest from the conventional submarine community. The possibility of increasing the on-board storage of electrical energy by replacing today's lead acid batteries with lithium ion batteries is attractive, as submarine designers seek to boost energy storage and provide both tactical and performance benefits. The unique and harsh operational environment on a submarine places stringent requirements on the battery system. The enclosed environment requires that the battery is safe, and any potential cell faults can be managed onboard. Safety cannot be guaranteed by low probability of occurrence of faults. This is obvious from the battery faults reported from different areas of battery applications.

Saab Kockums has an ongoing project developing a lithium ion battery suitable for installation on a conventional submarine. The project is funded by FMV, and a strong project team has been formed together with PMB Defence (AU) and EST-Floattech (NL). The strong commercial partnering of companies with complementary skills and experience allows leveraging of the massive commercial investment and greater technical depth within an integrated systems team. This integrated systems team approach ensures complete coverage of cell research, technology selection, battery system design, submarine integration, operational analysis and commercial longevity for low cost of ownership. The project goals are to build a battery system based on a standard format, commercially available cell and an existing battery management system, with performance significantly superior to the available lead acid batteries. The system shall be integrated on both existing as well as future submarines, and be able to utilize the ongoing improvements in cell chemistry and energy density without major re-design. A demonstrator system has been built and tested. The results show that the combination of this lithium ion battery with the well-proven Stirling AIP gives performance superior to what today's conventional submarines can offer.

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1 Introduction

Battery technologies have rapidly evolved during later years. This has been primarily driven by the demand for increased energy storage in consumer products such as mobile phones, tablets and electrical vehicles.

The battery technology where the most development currently is being done is Li-ion based batteries.

The possibilities to use Li-ion batteries in submarines, and thereby enhance the submarine's performance, have gained large interest in the submarine industry.

2 Opportunities and benefits

Increased energy storage

By increasing the on-board energy storage, the mission endurance of a conventional submarine can be extended. Air independent propulsion systems have significantly prolonged the time a submarine can be submerged and the endurance in patrol mode. By increasing the energy storage in the batteries, the submerged endurance during operation modes with higher power consumption can be enhanced.

Performance

The main advantage with a Li-ion battery compared to a lead acid battery is the significantly higher volumetric energy density, especially for high power discharges. The energy available in lead acid batteries drops fast with an increased discharge power, while a Li-ion battery's available energy is less dependent on the discharge power. High rate discharge is also possible for a low state of charge for a Li-ion battery. This is not true for a lead acid battery.

For the low power discharge operation modes of a submarine, the energy density of the Stirling AIP is still superior compared to a Li-ion battery on a system level. The combination of a Li-ion battery for high power discharges and the Stirling AIP for low power discharges therefor offers a very attractive solution for submarines.

Li-ion batteries have higher energy efficiency than lead acid batteries. This means that a Li-ion battery can be charged in a shorter time than the lead acid battery, and the submarine is exposed for a shorter time. The higher efficiency also means that more efficient use is made of the stored diesel.

Installing a battery with higher energy density in an available submarine, two options are available;

If the whole available volume is used for battery, a significantly higher amount of energy can be stored onboard. This will of course lead to an extended operating range.

The other option could be to only use the volume required to store the same amount of energy as the replaced battery. This will free up volume onboard, which could be used for other necessities, for example increase the volume of diesel and/or LOX.

Looking at a new submarine design, the option could be to build a smaller submarine with the same performance.

Battery life-time

The life-time of a lead-acid battery in a submarine ranges from 4-8 years, and is depending on parameters such as usage cycles and temperature. The life-time of Li-ion batteries varies between different types of Li-ion chemistries, used cycle depth, charge and discharge rates, temperature, etc. But it is reasonable to expect that a Li-ion based submarine battery should provide significantly longer life-times. Claims of long life-time must be taken with some consideration though as not many applications have hade cells in operation for more than 10 years. Accelerated ageing tests are used but do not replicate the exact conditions which the batteries face during their life.

Maintenance

Li-ion batteries are less sensitive to handling (as long as they are handled within the safe limits). A lead acid battery must be recharged as soon as possible after a discharge in order to not suffer remaining defects. A flooded lead acid battery used for submarines requires regular gas charging. For longer storage periods, trickle charging and electrolyte agitation is required. Li-ion batteries have longer storage life at lower state of charges.

However, lead acid batteries have the advantage that they can be stored in dry charged state for years, where after commissioning can be done.

Flooded lead acid batteries require manual maintenance, such as water filling and density checks, which is time consuming, expensive and reduces the availability of the submarine.

Li-ion batteries do not require much maintenance. Balancing of the system is often used to keep all cells at the same state of charge, but this can be done automatically by the battery management system.

3 Challenges

The introduction of a Li-ion based battery into a submarine requires a thorough analysis and presents many challenges, of which some are summarized below.

Safety

Lead acid batteries have been used in submarines for over a century and the risks associated with them are well understood. The hazards are managed by auxiliary systems and proper operating methods. Examples of hazards are related to Hydrogen production, electrical hazards and chemical hazards related to the corrosive electrolyte.

Submarines are a new application for Li-ion batteries, and there is little relevant historical data available to quantify the safety characteristics of Li-ion submarine batteries. Additionally, the high initial cost of a Li-ion battery and desire for as low as possible operating cost means considering lifetimes that are well beyond most commercial experience. Only very special applications, such as space vehicles and satellites, have more than 10 years of experience under high reliability operation.

Various chemistry combinations exhibit different performance characteristics and different hazards. In general, Li-ion battery hazards result from:

- Thermal abuse (for example external heating of a cell);
- Electrical abuse (such as overcharge, over-discharge, external short circuit);
- Mechanical abuse (denting or puncturing); and
- Internal cell faults (caused by cell manufacturing defects or foreign metallic particles)

With long life expectations, demonstrating safety through-life is not practical and would come at a high cost. Further, technology advancements or design changes make any such demonstration obsolete. The approach to safety must allow demonstration of hazards and their control.

Even if the safest possible cell is used, it must be assumed that faults can occur and these faults must be possible to handle onboard the submarine. The handling of the faults includes prevention of cascading thermal runways, clearing of smoke and venting products from cell faults, as well as extinguishing of a possible battery fire.

The Li-ion battery has significantly higher short circuit currents than the lead acid battery system. These currents are not possible to break using the standard battery breakers installed on the submarine. New breaker technology must therefore be included in the battery system to manage the increased short circuit currents.

Weight

The weight of a Li-ion based battery will be lower than for a lead acid battery. This weight loss will require compensation to maintain the stability of the submarine if a lead acid battery is replaced. This can be done for example by adding ballast inside the submarine, adding a keel plate on the bottom of the submarine, or a combination of these two methods.

System complexity

A lead acid submarine battery system contains in the range of hundreds of cells connected in series. The cells are equipped with auxiliary equipment and measurement sensors. The functionality of the system is well-known and the design has evolved through decades of use.

The number of cells in a Li-ion based system is magnitudes higher. Likewise, the component count for sensors and connection points increases rapidly. In addition to this, safety critical functionality might be implemented in hardware and software to ensure that the cells are kept within their safe operating region.

Life cycle cost

To be an attractive future battery technology for submarines, it must be possible to motivate the inevitable higher initial procurement cost a Li-ion battery system will have. The value of increased operational capabilities, longer life time and lower cost for maintenance shall match this increased cost.

Future proof system

Continuous investment in the mass markets for consumer products and electrical vehicles must be possible to leverage of, and future enhancements and improvements shall be possible to include in the submarines battery system.

4 Ongoing project

Saab Kockums has an ongoing project developing a lithium ion battery suitable for installation on a conventional submarine. The project is funded by FMV, and a strong project team has been formed together with PMB Defence (AU) and EST-Floattech (NL). The strong commercial partnering of companies with complementary skills and experience allows leveraging of the massive commercial investment and greater technical depth within an integrated systems team.

Saab Kockums responsibility is the overall project lead and responsible for the system requirements and submarine integration.

FMV, the Swedish Defence Materiel Administration, is the project owner and the design authority. FMV is also responsible for the analysis of how the enhanced energy storage can be used to improve the operational capabilities of Swedish submarines.

PMB Defence has a 30-year history of manufacturing lead acid batteries for Australia’s Collins class submarines. PMB’s development, production and support expertise has placed it in a unique position of understanding the operational, technical and safety aspects of submarine batteries. PMB has conducted research and development activities on new technology batteries, such as Li-ion, for many years. PMB’s multi-disciplined engineering team has experience ranging from cell development, technology improvements and characterisation; through to module design, assembly and testing; to complete system integration and platform out fitting, maintenance and support.

EST-Floattech was founded in 2004, with a cleaner shipping industry as its mission. EST-Floattech has a long experience in providing Li-ion based energy storage solutions to the marine industry and for land based applications.

This integrated systems team approach ensures complete coverage of cell research, technology selection, battery system design, submarine integration, operational analysis and commercial longevity for low cost of ownership.

The project goals are to build a battery system based on a standard format, commercially available cell and an existing battery management system. The system's performance shall be significantly superior to the available lead acid submarine batteries. The system shall be possible to integrate on both existing as well as future submarines, and be able to utilize the ongoing improvements in cell chemistry and energy density without major re-design.

Some fundamental design decisions have been taken for the system:

- The cell shall be of a well-used standard format. This ensures that cells are available from different suppliers. If, for some reason, the selected cell at a later stage shows not to be the best choice, other options are available. The cell can then be changed without requiring a total re-design of the system. As the development is fast, future cell chemistry enhancements can be utilized in the system. The long service life of a submarine also requires that a cell format selected today must be available when the battery shall be replaced in the future.

- The system must be tolerant to a worst case single cell fault. It is not possible to guarantee that an internal short-circuit in a cell will not happen during the life-time of the battery, even though the probability of a fault might be low.

- The emissions from such a fault shall be contained, and not released into the submarine's atmosphere.

- A single cell fault shall not cause a cascading fault.

A number of cells of different sizes, geometries and chemistries have been tested and evaluated for use in the system. The tests have included abuse as well as performance testing to characterize the cells.

To ensure that an internal fault in a cell cannot initiate a cascading thermal runaway, the cells are packaged in a way so thermal insulation is provided. Through careful and innovative use of design and materials, the released energy can be absorbed and fault propagation to adjacent cells avoided. Cells must be protected against both the thermal conduction between cells, as well as heat from ejected material. The material ejected from the cell reaches very high temperatures (see Figure 1 and Figure 2) and must be captured in a way not risking overheating any of the other cells within the module. This design ensures that thermal management during the fault is handled within the module and not dependent on external systems

This puts hard requirements on the thermal insulation and packaging, as it cannot consume too much volume in order to maintain the system level energy density.

Extensive testing of faults in different locations within the modules has been performed with expected results, as shown in Figure 3.

Figure 1. Thermal runaway of single cell.

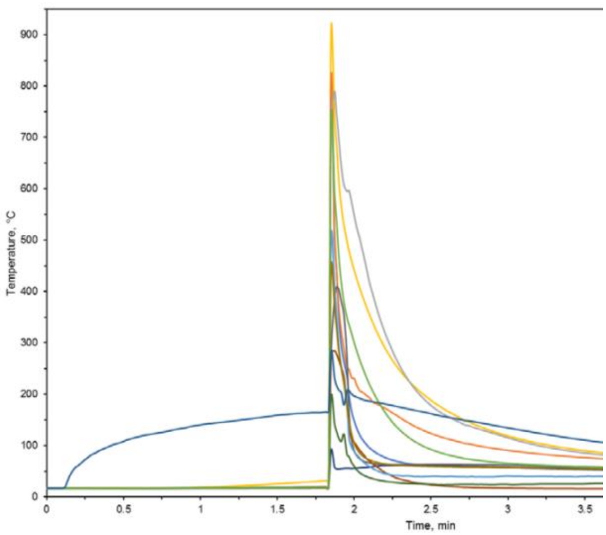


Figure 2. Temperatures measured for different locations around cell during thermal runaway.

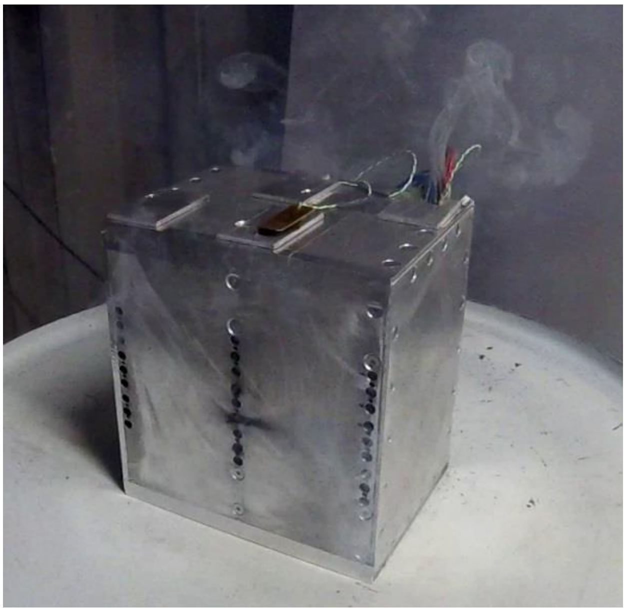


Figure 3. Thermal runaway inside sub-module.

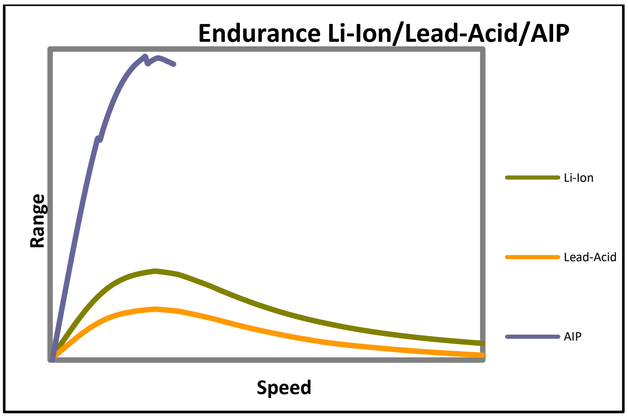
The system is managed by EST-Floattech's battery monitoring system from their well-proven Green Orca battery system. The BMS provides redundant safety (software and hardware) as well as active balancing of cells.

Demonstrator system

A demonstrator system has been built and tested at PMB's premises in South Australia. This demonstrator system integrates the cell, packaging and BMS and is supervised by Saab Kockums Ship Control and Monitoring System. Two strings have been built up and tested in a climate controlled room. Charge and discharge rates representative of a submarine have been run at different temperatures.

The results show that the designed system can be integrated, meets its initial functional and performance requirements, and provides the predicted energy density.

Applying the verified energy density on a submarine shows that for high power discharge rates, the endurance can be three times the endurance provided by a lead acid battery of the same volume. For lower rates the endurance is doubled. However, for the low rates the Stirling AIP system provides far better endurance.



The next project phase is progressing and includes design optimizations, further integration studies and module integration and testing. A large scale land based test site is being designed for system qualification, before the system is installed on a submarine to undergo sea trials.

Author/Speaker Biography

Anders Wikström is working at Saab Kockums Electrical systems department, where his area of responsibility is battery systems on submarines. Mr Wikström is the project manager for the future battery technology project. Mr Wikström has a Licentiate of Engineering and a Master of Science degree in Electrical Power Engineering from the Royal Institute of Technology (KTH), Stockholm, Sweden.

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