Pressure-tolerant Li-ion batteries, implementation and certification on MUV ICTINEU 3

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Abstract

During the design of the ICTINEU 3 submersible a particular lack was detected if a really highly operational vehicle was to be achieved: the need for a more efficient and powerful battery system than those existing models based on lead-acid batteries.

After reviewing the state of the art, in 2007, few alternatives were foreseen on battery systems suitable for manned submersibles. Lithium-ion-polymer cells showed as the most probable substitute for lead-acid cells. With a few experiences on the table and only a handful of providers in the market, yet Ictineu Submarins decided to develop its own pressure-tolerant battery system based on li-ion-polymer cells.

After 5 years of research and development, a prototype system is going under final testing and certification process. It will be implemented in the manned submersible ICTINEU 3 and certified by GL.

The system is based on modules that contain all elements needed for functioning and safety (cells, electronics, control, safety and protection devices and power switches for charge and discharge). Main facts of the battery system are: compactness, robustness, pressure tolerant up to 1200m, safe and certifiable modules; a total of 42 kWh, 150V, in only 480kg of weigh. A satisfactory weigh/power ratio of 11.4 kg for each kWh has been achieved for the complete system (i.e. battery plus necessary systems and container), while typical lead-acid systems provide a mean of 30kg/kWh.

OVERVIEW

The ICTINEU 3 is, a work class vehicle with high capabilities for research, ocean observation and underwater intervention, but also suitable for filming and leisure. It has been designed for 1.200 meters depth, and a crew of three: one pilot and two observers (passengers). It will be certified and classified by Germanischer Lloyd according to the highest standards of quality and safety. Approximate dimensions are L x W x H = 4,8m x 2m x 3m. Approximate weight is 5300 Kg (in air). Although it's small and lightweight, at the same time it will be versatile and a highly operational vehicle.
Propulsion and manoeuvring are based on a configuration of 8 electric thrusters, 2,5kW each, and internal buoyancy tanks for a variable ballast. This provides a complete 6 controllable degrees of freedom system and so a high maneouvrability of the vehicle

ICTINEU 3 is battery supplied with ample, above-the-standard energy capacity. This provides large amounts of available energy that improves operability and revert in safer and more comfortable dives of up to 8h long.

One of the critical goals for ICTINEU 3 has been to reduce dry weight as much as possible so that transportation (air, sea and road) and deployment is simplified, and costs are reduced. For this and other multiple reasons, the battery modules, which constitute an important payload, need to be built as light and compact as possible. We exploit for this purpose the following two concepts:

The battery cells are of the Lithium-polimer type (LiPO), providing 2x to 5x energy densities with respect to classical (Lead-acid, Ni-Ca or Ni-MH) types.

The battery modules are housed in oil filled, pressure compensated containers. This provides extra savings in weight and volume as compared to batteries at atmospheric conditions housed in pressure-tight containers.

Lithium-ion-polymer cells exist for a few years now and they have arrived at a quite mature stage, its advantages, and the state of the art of this technology has already been exposed in many articles and presentations in previous UI editions so it has been considered not necessary to repeat this part in this article and will concentrate in our particular development case.

DESIGN

Energy requirement and stored capacity

In order to determinate the characteristics of the battery system needed for ICTINEU 3 submersible two main factors were analysed: the kind of desired mission the submersible was to perform, and the equipment carried on it. Following is the main criteria applied:

1. Energy consumption of the ICTINEU 3 submersible is predicted by an energy balance based on a 8h mission profile. The considered mission consists on an average of 1h descent, 6h bottom, and 1h ascent time.

2. According to our estimation, there is an average power consumption of approximately 1,5 kWh in ascent/descent and 3,0 kWh on bottom, this gives us a total energy consumption of 1,5*2 + 3,0*6 = 21 kWh.

3. For longevity and safety reasons, one mission is to be assured with 80% of battery capacity. This must be guaranteed until the end of life of the battery.

4. The end-of-life of a battery is defined as the time when the battery capacity has lowered to 80% of the capacity of the new battery.

5. The two previous conditions lead to a minimum energy capacity of the new battery of C = 21 kWh / 0,8 / 0,8 = 32,8 kWh.

6. On the other hand during an emergency situation one can imagine the need to use 6 thrusters at full speed plus all lights and variable ballast pump at maximum. This gives a maximum power consumption of approximately 20kW.

7. Because of resistive losses, the maximum power of 20kW is too high for a 48VDC system, even for a 96VDC one. We have selected a 148VDC configuration which meets different criteria of safety and low power losses.

With this information and the architecture we wanted on our electrical system for safety reasons, it was decided to use four modules in parallel resulting in a 3+1 redundant layout. It consists of four battery modules rated 148VDC, 70Ah each, so 10,36 Kwh each. The main reasons are:

1. The said (emergency) 20kW correspond to a discharge rate of 20kW / 41kWh = 0,49C, which is easily achievable with available lithium polymer cells.

2. Using a 3+1 redundant battery, in case of failure of one module the system can continue to operate: one bank of batteries will continue discharging at 0,49C (10kW/20,5kW) while on the other side, with just one battery working it will operate at a current rate of 10kW /10,36kWh = 0,97C, also easily achievable with this technology.

System description

With the previous considerations and adding some more design conditions regarding handling, safety, fire resistance, maintenance and certification requirements we have developed the battery system as follows.

The ICTINEU's battery system is composed by four battery modules of 10,36 kWh each connected in parallel, giving the total energy capacity of 41,44 kWh.

The chosen cells are high energy ones and they allow charges up to 2C rates (i.e. 140 A) and discharges up to 5C continuous rate (i.e. 350 A) and 8C peak rates (i.e. 560 A). As it has been said, even in most unfavourable conditions (an emergency max. power consumption of 20kW with only 3 modules available) a module would not operate at >0,97C. This means the battery will never go under abuse or over current, which ensures safety and long quality life for cell.

Every Battery module is independent and capable to supply by its own the energy needed by Ictinineu3 at every mission time, even in emergency. The power needs of ICTINEU 3 are much lower than the power the batteries can offer and so the battery modules and internal systems and components have been sized according to the maximum power needs, so currently the battery system has been designed to deliver 80 A rated current, but higher current rates can be achieved with minor modifications if required.

Another important requirement imposed to ICTINEU 3 development was its compactness and so the compactness of every system and subsystem, and batteries are usually one of the roomiest ones. At the end of the development a very compact and lightweight battery module has been achieved: it weights 114 kg in air and 49,64kg in water, and can be installed in a room of 44 x 60 x 27.5 cm (17.16 x 23.4 x 10.7 inch), being the real water volume displacement of 62 litres (16,38 gallon). It is important to point out that connectors fit also in the specified installation volume.

The battery module compactness and conception makes it also suitable for a high number of underwater applications, offering a very good weight and volume to power ratios, increasing the range and/or endurance of the vehicle.

Moreover, and looking to future applications, the ICTINEU 3 battery system is very simple to install into an existing vehicle or into a new development, as the battery boxes have all the power, control and safety systems already imbibed into the battery box so we could say it is a pnp (plug and play) system. Obviously the system can be controlled and monitored externally having all the desired data (cells temperature, SOC, SoH, cells voltage, current, etc.) but for simple applications, the battery module can be controlled just with two switches/signals, one for charge and one for discharge and the battery will be monitored and protected by the imbibed systems (BMS). Only signal and power connectors are needed.

In the ICTINEU 3 vehicle, all the available parameters will be constantly monitored by the managing computer, and registered in a data-base. They will be available for display in the main monitor, and alarms will be configured so they will clearly display and sound whenever any parameter gets to the defined safety limits. In parallel, a dedicated panel will display voltage and current and have a visual alarm, where values are obtained independently of the internal BMS system. This panel allows as well to switch on-off each battery module in case of emergency and to operate them manually, performing the system pre-charge and start process independently of the BMS having the possibility to force the manoeuvre.

SAFETY, CERTIFICATION AND TESTING

ICTINEU 3 manned submersible is being certified and classified by Germanisher Lloyd (GL) authority under the GL Rules for classification and construction of submersibles, 1998 and the updated 2009. As there were no specific rules for the application of li-ion-polymer batteries in manned submersibles, a particular program was discussed and agreed between Ictineu Submarins and GL for the development and testing of the battery system. GL rules and recommendations have been applied as well as different standards (IEC, UL, UN...), compelling those specific for lithium-ion batteries and those general to power systems.

Safety has always been a great concern, both for the manufacturer and for the certification authority, and for this reason an extensive risk assessment was done before the system development started. In this risk assessment some main issues were taken in account: personnel safety while making a mission underwater (discharging), safety during launch and recovery, safety during transportation and handling, charging operations by staff, on board and on land, and storage conditions.

When the company decided to go ahead with the development of a li-ion based system, knowledge and experiences from different manufacturers an integrators of such power systems were collected, including manufacturers with long time experience in implementing this systems on electric cars, bikes and even city buses.

As previous studies, Ictineu Submarins made extensive testing on other similar cells, both individual cells and packs (several cells assembled), that already hold several thousand life cycles on them. Different tests were run including pressure cycling and ageing of cells.

Cells manufacturer ensures high quality control standards during production and provides individual cell test certificates based on UN and UL standards, including some abuse tests. In addition, Ictineu Submarins scheduled an intensive and extensive test program according to rules and standards that have been applied to all elements that will be implemented in the final module. This includes cells, BMS, electronics, connectors, safety elements and housing materials. They have been run both in the company and official laboratories. Electronics and safety elements are pressure-tested at 2 times the operating depth. Cells, first individually, then assembled in packs go through functional tests, charge-discharge cycling, over-charge, pressure-cycling test with functions monitoring, and vibration test. Once the battery module is fully assembled with all components, it goes again under a functional test, inclination test, vibration tests (both for road transportation and for ship transport), pressure-cycling test, and final functional test.

A special procedure was established to ensure the maximum safety during the assembly of cells in the laboratory and cancels possibility of an accident. Safety protocols have been defined as well for the handling and maintenance of the modules. Long thinking and extensive review has been applied during the design of the architecture, cabling, connections and position of components, in order to ensure an efficient, compact and safe system.

SUMMARY

At the time of writing this article, most goals have been achieved: final vibration tests on the battery module are being performed and only final pressure-cycling is pending for the validation of the system. The result of all tests performed up to moment have been satisfactory, with no incidents and no strange behaviour found on cells during any of tests.

Ictineu Submarins believes this is a hig power, high performance battery system, easy to implement and safe in operation and maintenance. Once the system has been fully validated, it could be easily adapted and certified to other underwater vehicles, manned or unmanned, due to the modularity of the system and the compliance with international rules and standards.

This development has payed and important role to the radically reduced weight of the vehicle (5.300kg) and expects that it will definitely improve the performance and operability in manned submersibles. Thanks to the li-ion-polymer battery system and its hydrodynamic design, the vehicle is expected to be able to travel 20 miles underwater at a cruise speed of 1,5 knots.

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