On the technical reliability of Lithium-ion batteries in a zero emission polar expedition

Adrian Soto, Alberto Berrueta, Pablo Sanchis, Alfredo Ursúa
Department of Electrical, Electronic and Communication Engineering
Institute of Smart Cities, Public University of Navarre
Pamplona, Spain
adrian.soto@unavarra.es

Ignacio Oficialdegui
WINDSLED PROJECT
Pamplona, Spain
ofiignacio@gmail.com

Abstract— **This contribution presents a technical analysis of the Lithium-ion batteries (LIBs) used in the WindSled project. In this project, an expedition has been carried out by means of a 0-emission vehicle that have covered more than 2500 kilometers in Antarctica Eastern Plateau pulled by kites. This adventure allowed the performance of 10 scientific experiments with a minimal disturbance of the polar environment. The required electricity for the survival and the scientific experimentation was delivered by flexible PV panels installed on the sled and commercial LIBs. The study performed in this contribution aims at the quantification of the LIBs degradation after the expedition. The results show a capacity fade of 5 % and an internal resistance increase of 30 %. Based on these results, it can be claimed that the LIBs used in the WindSled Project can successfully operate under −40 ºC. Moreover, these batteries can be used in upcoming expeditions, entailing an improvement from an economical and environmental point of view compared to primary batteries.**

Keywords— Antarctica, battery, energy storage, lithium-ion, polar expedition, renewable energy, sub-zero temperature

I. INTRODUCTION

Since the industrial revolution in 1769, the levels of CO_2 concentration in the atmosphere have kept a relentless growth rate. Although the industrial development has made it possible to the human being to fulfil with cultural, scientific and social well-being levels totally unattainable few centuries ago, there is an increasing necessity of a change in the energy model into a new one in which the energy generation and storage are not tied to the fossil fuels. Therefore, it is usual to see new research proposals aimed at this critical issue.

Renewable energies, especially photovoltaic (PV) and wind generation, are gaining popularity in this realm, since they allow us to devise a new energy model, based on sustainability. Those technologies have already reached high maturity levels, becoming plausible alternatives to the conventional systems both from an economical and technical point of view [1]. However, due to the intermittent nature of the renewable resource, it is imperaive to tie them up with energy storage systems. During the last decade, lithium-ion batteries (LIBs) have been put forward as the best alternative to energy storage for transport sector as well as for grid support, allowing an increasing share of renewable sources in the electric mix [2], [3]. Despite their high effieciency, energy density and power density, there are sundry challenges that this technology, based on electrochemical reaction with ion intercalation, still need to overcome.

From an economical point of view, between 30 to 50 % of the total cost of an electric vehicle (EV) is directly related to the battery. For that matter, the automotive sector has been forced to optimize the manufacturing processes of LIB as much as possible. This fact, in tandem with the large financial investment conducted in the last years with a view to build new giga factories, have procured to slash the manufacturing costs of LIBs. According to Bloomberg NEF in 2010 the cost per kWh was $1200, while in 2018 an approximate figure of $200/kWh was reported [4].

From a technical point of view, the dependence of LIBs performance with the temperature is a limiting factor. On the one hand, LIBs can entail a risky situation when the ambient temperature exceeds 45 ºC [5]. On the other hand, as the temperature decreases, the performance of LIBs, in terms of power and energy capability is also depleted [6].

Most of LIBs available in the market have a crystalline structure based on graphite in the anode, which presents a bad behavior with temperatures below 5 ºC. Low temperatures hinder the diffusion of lithium ions within the electrodes, in addition, they evoke a conductivity reduction in the electrolyte and the solid electrolyte interface (SEI). During the charge of the cell, low temperatures have a much more critical impact since an effect denoted as lithium plating takes place. This process consists on the deposition of metallic lithium on the surface of the anode, which leads to an irreversible capacity fade (once the lithium is deposited, it cannot be recovered) and an internal resistance increase (since the remaining ions cannot go through the deposited lithium). Additionally, it can result in an internal short circuit due to the tendency of the lithium to be deposited forming dendrites. Thus, several warm-up methodologies can be found in the scientific literature, particularly focused on EV [7].

There are a number of isolated locations nowadays in which the connection to an electrical grid is unfeasible. Therefore, the use of a power generation and energy storage systems in situ is mandatory. Some clear examples are stand-alone telecommunication systems or environmental monitoring stations located in remote areas, of great importance inasmuch as they record the weather, detect seismic disturbances and monitor the volcanic activity [8]. In this contribution, the performance of LIBs used in the WindSled project, a scientific expedition carried out in East Antarctica, the coldest area in the Earth, are dully analyzed. Due to the incipient environmental interest of the Antarctica, the laboratory and personnel of the expedition traveled in the

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Fig. 1 A picture of the WindSled taken during the expedition.

sled shown in Fig. 1, pulled merely by means of kites. The required electricity for the survival and the scientific experimentation was delivered by flexible PV panels installed on the sled. This electrical energy was stored in LIBs specially designed to withstand the extreme temperatures, near to −50 ºC, during the 52 days of journey. The expedition succeeded in performing ten scientific experiments with high international impact.

This contribution attempts to prove the technical viability of LIBs as electrical energy storage system for frigid weather. Furthermore, the results shown in this contribution allow researchers to quantify the aging suffered by the LIBs during this expedition. In such a way, the degradation results can be useful as a baseline in the design phases of upcoming projects in which energy storage is required in similar environments.

The remaining of this contribution is organized as follows. Section II offers a brief description of the polar expedition, including the energy consumption of the scientific equipment. Section III presents the experimental procedure and tests carried out on the LIBs for the comparison of their characteristics before and after the expedition. In Section IV, the results, that show the effect of freezing weather on LIBs, are presented. Finally, in Section V, the principal results obtained are summarized, as well as the study conclusions

II. EXPEDITION

Up to a few decades ago, Antarctica was an entirely disclosed place for humans, and that brought us some of the most famous expeditions conducted by renowned characters such as Roald Amundsen (the first man to reach the geographical south pole in 1911), captain Robert Falcon Scott or Sir Ernest Shackleton. Even though it has elapsed more than a century, the Antarctic continent is still an unexplored place and a totally inhabitable location due to the severity of the climatology. The extreme wintry conditions make of this breathtaking and merciless place, the best mute guardian of the changes suffered by the atmosphere in the last millenniums, since the ice cap that covers the continent, hides the data that reveals the CO_2 concentration in the atmosphere. Nevertheless, not only does Antarctica behave like a timeless library, it also allows us to keep moving forward with the conquest of space. NASA and ESA use Antarctica as a test bench for the equipment designed to be sent to the space, as described in the following lines.

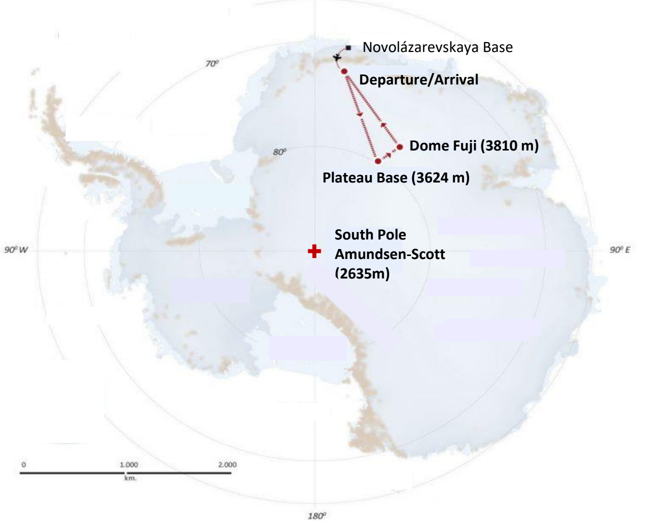

Fig. 2 Itinerary followed by the expedition.

A. *Details of the expedition*

The expedition described in this contribution has shown the feasibility to perform an exploration in such a bleak location, solely by dint of the sun and wind as power sources. 2538 km were covered during the journey in 52 days, reaching a maximum altitude of 3768 m above sea level (Dome Fuji). Fig. 2 shows a summary of the itinerary followed by the so called "WindSled Project". This non-motorized vehicle departed from the Russian base Novalazárevskaya in December 12th, 2018 and did not come back to this enclave until February 1st, 2019, outpacing places such as the North American research base Plateau Station (abandoned in 1969) and climbing to the top of the emblematic Dome Fuji.

The WindSled is built by the three modules shown in Fig. 3, that do not surpass a length of 9 meter and a width of 4 meters, carrying a total weight of up to 2 tons. It is capable to harbor a total of 6 crewmembers and 10 scientific experiments like the ones described below. The first module is the so-called locomotive module, from where the kites can be controlled, and it is also the workshop where all the scientific work and fixing of the material are performed. The second one is the load module, where the scientific equipment, food and expedition materials are carried. Additionally, the load module is covered by 10 to 12 m^2 of flexible PV panels and the 4 LIBs studied in this contribution. Finally, the last module is the habitability module.

B. *Scientific exploration*

The 10 scientific projects performed during the polar exploration are presented below.

- The Galileo Experimentation & Scientific Test in Antarctica (GESTA) led by ESA evaluates by the first time the data recorded by the receptors in the Antarctic continent during this expedition.

- The Ice Coring project of the institute of Climate Change of the University of Maine (EEUU) analyzes sundry

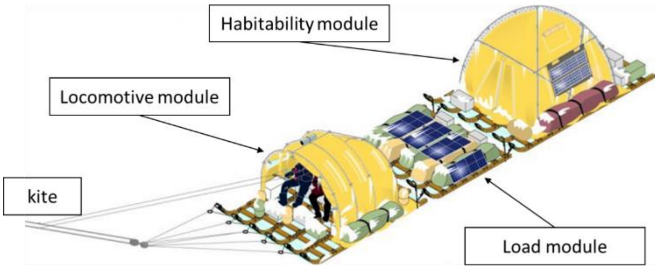

Fig. 3 A schematic picture of the WindSled.

ice cores in order to collect information about climate change in the last 200 years.

- MICROAIRPOLAR is a project of the Autonomous University of Madrid in collaboration with Spanish Meteorological Agency (AEMET). The main objective of this project is to establish the dispersal and colonization capabilities of airborne microorganisms in polar regions [9].

- The Thermal Infrared Sensors (TIRS) of Mars Environmental Dynamic Analyzer (MEDA), the WindSled freighted a sensor developed by the University of Alcalá (Spain) and the Center of Astrobiology (CSIC-INTA) which will travel to Mars in the mission Mars 2020. In Antarctica it was tested under extreme climates [10].

- The objective of the project SENTINEL led by the Institute of Environmental Assessment and Water Research (IDAEA) is to get an on deep knowledge about the accumulation and amplification processes involving the persistent organic pollutant and determine how Antarctica acts as a watchman of global contamination.

- Signs of Life Detector (SOLID) is a device developed by CSIC-INTA able to detect extraterrestrial life in the planetary exploration. During this polar expedition, the ice cap is sampled in order to search parallelism with what it can be found in other planets [11].

- Antarctic Air Temperature Transect (ANTAIR) is a project of the University of Alcalá analyzing the evolution of the air temperature among a transect that passes through Antarctica.

- Experiment focused on the deliquescence of the ice cap in Antarctica. This experiment tries to find if it is possible to form liquid water in the salt draw from deliquescence under the extreme frigid and dry conditions of Antarctica.

- Stress resistance and new bio-chassis based on microbial communities from high-insolation habitats (HELIOS) led by University of Valencia. The main objective of this project is to get a deep knowledge of the bacterial communities living in artificial surfaces (solar panels) in extreme conditions [12].

- Spanish Meteorological Agency (AEMET), the Antarctic research group of AEMET delivers weather forecast to the WindSled during the journey.

Likewise, the electric consumption of each scientific equipment is briefly summarized in the Table I. Moreover, the consumption of the required electronic devices during the expedition, 2 laptops, GPS, satellite phone, smartphones and cameras to record the expedition is also included.

TABLE I. PEAK POWER AND DAILY ENERGY CONSUMPTION OF THE MAIN ELECTRONIC EQUIPMENT CARRIED BY THE EXPEDITION

Equipment	Peak power (W)	Daily consumption (Wh)
TIRS of MEDA	0.045	0.36
Ionosfera + GMV Galileo	30	29
Electronic devices	90	40
Micro air Polar + weather station	1.4	4.7

C. *Energy storage system*

Lithium-ion batteries it's a family of different electrochemistries, each of one with different performance features (energy density, temperature, safety, calendar age, etc.). Depending of each application, it is important to choose which electrochemistry will perform better according to technical requirements. Windlsled project LIBs requirements were mainly high energy density and reliability at low temperatures (below -40 ºC). The batteries chosen for Windlsled project used MP176065 xtd cells from Saft. MP176065 xtd cells use Lithium Nickel Cobalt Aluminum Oxide (NCA), a high thermally stable cathode. Electronic components and cells integration are a key factor in LIBs. Battery packs were designed and assembled by Amopack, official distributor of Saft in Spain.

LIBs are assembled by the connection of individual cells in series and/or parallel. Series connection increases the battery voltage, whereas parallel connection rises its capacity. A battery manufactured by n serial and m parallel cells is named as an nSmP battery [7]. Due to the challenging work conditions that the batteries would have to overcome in order to fulfil with the objectives of the expedition, one of the cells with highest performance on the market was chosen. MP176065 xtd cells have a nominal voltage of 3.65 V and a nominal capacity of 5.6 Ah. The batteries were assembled trough a 4S4P configuration, reaching a nominal voltage of 14.6 V and an energy capacity of 327 Wh. Unfortunately, due to a human error, scarcely had the expedition begun when one of the batteries suffered an external short circuit. The fuse of the battery acted as expected, letting the battery unusable and reducing the number of usable batteries to three.

The energy storage system, with an energy capacity of 1308 Wh, could seem oversized at a first glance. Nevertheless, the lack of previous works with LIBs exposed to such extreme conditions and in a real application, led into oversizing the system to guarantee the safety of the adventurers and the completion of the scientific experiments.

The operation of each battery analyzed in this contribution is described below.

Battery 1 (E1): connected to the weather station of AEMET, fed by a PV panel of 90 W (by means of a charge controller), it was fully discharged several times.

Battery 2 (E2): connected to the ESA equipment, and to a PV panel of 75 W (by means of a charge controller). Always at high of state of charge (*SOC*)

Battery 3 (E3): connected to the MICROAIRPOLAR equipment, and to a PV panel of 75 W (by means of a charge controller), it was fully discharged several times but in minor extent than E1.

Battery 4 (E4): it was short circuited during the first day of expedition

III. EXPERIMENTAL SET UP

The tests presented below are designed to quantify the degradation suffered by each of the four batteries. During the polar journey of 52 days, each battery operated under different working profiles. To this end, a number of tests reproducible in almost every laboratory have been settled. In this way, the analysis performed in this contribution can be extrapolated to several applications.

There are slight variations of the characterization tests to quantify the degradation of a Li-ion battery in the literature [2], [13]–[15]. In this contribution, four of the main parameters of LIBs have been analyzed, capacity, internal resistance in terms of the DC and AC components and the relationship between the state of charge (*SOC*) and open circuit voltage (*VOC*) [4], [16], [17], [20]. The experimenal procedure which allows to measure each parameter is dully described in the following subsections. Altogether, in this contibution we have studied the four batteries mentioned above (E1, E2, E3 and E4) and two cells, henceforth defined as L1 and L2. The cells L1 and L2 have the same characterisitcs to the batteries used in the expedition, but were stored in the energy storage an microgrids laboratory of the Public University of Navarre safeguarding them from the extreme weather contiditions. In this way, the degradation of E1 – E4 due to the extreme weather is quantified.

A. Capacity

Capacity is defined as the amount of charge that can be stored in a battery, usually expressed in Ah. Capacity measurement is split up in two phases, charge and discharge, always under controlled temperature conditions and with standardized current profiles. For a better comparison of cells with different capacities, the battery current is usually referred to the battery C-rate. This term is defined as the battery current divided by the nominal capacity, as defined in (1).

$$C\text{-}rate = \frac{I}{C_N} \qquad (1)$$

Due to the influence that temperature has on the battery performance, capacity tests are usually carried out in the scientific literature at a temperature of 25 ºC [13], [14]. The current should not exceed a C/3 rate in order to avoid an undesirable self-heating that would lead into an inaccurate capacity measurement [17]. The discharge process is carried out between a maximum and a minimum voltage threshold [13], [14]. In this contribution the cell voltage limits are set to 4.2 V and 3 V, which mean a battery operation range of 16.8 V to 12 V. Charge process comprises two phases, firstly an upper voltage limit is reached by means of constant current (CC), followed by a constant voltage (CV) phase meanwhile the current decreases until a cut-off limit set by the manufacturer.

In this contribution, three capacity measurements have been performed consecutively at an ambient temperature of 25 ºC. The battery charge was a CC – CV charge with a current of C/3 in the CC phase and a cut-off current in the CV phase of C/70, while the battery discharge was performed at a C/3 rate.

B. Internal resistance

Moreover, the internal resistance has been measured in two different ways. The DC resistance (R_{DC}) has been measured by means of a current step, while the measurement of the AC resistance (R_{AC}) has been done by means of a sinusoidal signal. R_{DC} in LIBs is a compendium of the phenomena that take place when an electric current goes through the battery. This parameter encompasses the electronic conductivity of the cathode, anode, collector, each electrical contact, ionic conductivity of the membrane and electrolyte, and the polarization and mass diffusion phenomena.

The most commonly technique performed for the measurement of R_{DC} consists on the application of a current step (ΔI) to a relaxed battery. With the measurement of the voltage response (ΔV), R_{DC} can be calculated by means of Ohm's law, as shown in (2). The duration of this current step is set to 10 s, as suggested in the literature [13], [14], [16]. This parameter does not distinguish between all the phenomena that take place internally in a LIB. However, due to the simplicity of this methodology LIBs can be modelled with a low computational cost making it suitable for engineering applications [3], [17].

$$R_{DC} = \frac{\Delta V}{\Delta I} \qquad (2)$$

In this contribution, C/3 current steps have been performed at 5 levels of *SOC*, with a room temperature of 25 ºC. Additionally, the AC internal resistance has been measured imposing a 1 kHz sinusoidal signal to the batteries and recording the real component of the impedance.

C. VOC – SOC relationhsip

The relationship between *SOC* and *VOC* has been also characterized, given its interest for the measurement of the battery state of charge. There are two main methodologies to measure this relationship, the galvanostatic intermittent titration technique (GITT) and the pseudo-*VOC* test. The first of them is based on the application of a current step until the desired state of charge is reached. Afterwards, a resting period is done until the voltage stabilization is ensured, which is typically after 1 h [16]. By contrast, the battery is continuously charged by means of a low, constant current when the pseudo *VOC* methodology is applied. With this low current, the electrochemical equilibrium can be assumed during all the charge/discharge process. Its main drawback is the long duration of the tests.

The relationship between *SOC* and *VOC* is considered invariable during the useful life of LIBs [3], [13]. Nevertheless, to the best of our knowledge, these tests have not been conducted before in such extreme weather conditions as the ones described above. Therefore, a GITT followed by hourly rests was performed and the results are shown below.

IV. RESULTS AND DISCUSSION

In this section the parameters of the batteries employed during the Antarctic expedition and the cells stored in the laboratory, unused and safeguarded from extreme weather conditions, are compared. Specifically, the significant items are capacity, R_{DC}, R_{AC} and the *VOC* – *SOC* relationship, since they are the main indicators of LIBs aging.

A. Capacity

The capacity results are shown in Fig. 4. The data shown in the figure represent the cell capacity. Additionally, for better comparability of the results, the cell capacity is normalized to the average capacity of L1 and L2.

Fig. 4 shows a capacity fade in the batteries used in the polar expedition of around 5 % compared to the cells kept in the laboratory. If the results are studied in a thoroughly manner, it is especially remarkable that the battery with a higher degradation is E2. It is noteworthy that the total amount of full charge/discharge cycles of this battery was considerably lower than that of E1 and E3. Moreover, E4, which could not be used during the expedition due to a short

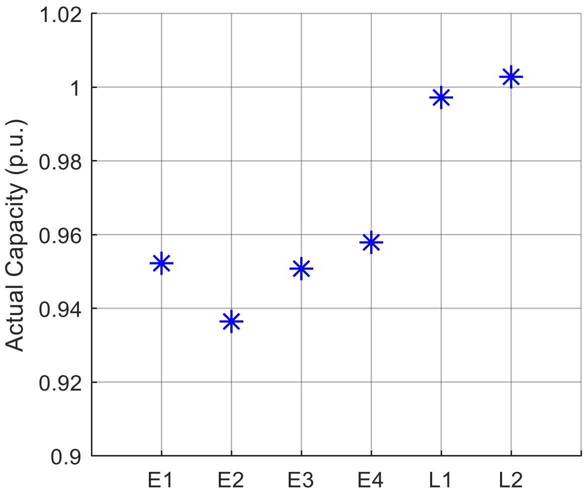

Fig. 4 Actual capacity of each battery.

circuit during the first day, does not show a significant difference compared to E1 and E3.

The capacity of the four batteries used in the expedition is lower than the ones stored in the laboratory. Nevertheless, there is only a slight difference among the capacity of the four batteries used in the expedition, even if they are compared to E4 that was not cycled during the journey. Therefore, the capacity fade cannot be attributed to the usage of the battery (cycle aging) and instead seems to be mostly related to calendar aging. This observation is aligned with conclusions from previous research works that identify temperature variations as accelerating factor for the aging of Lithium-ion batteries [18].

B. *Internal resistance*

The internal resistance measured in this contribution includes, besides the internal components of the cells, electrical contacts and protection circuit modules used for the battery assembly. Fig. 5 shows R_{DC} measured values as a function of *SOC*. The most highlighting issue is the increase of 30 % suffered by the batteries used in the expedition, which represents a higher degradation than the capacity fade of 5% reported above. The deposition of metallic lithium on the anode surface could be the main reason for this impedance increase.

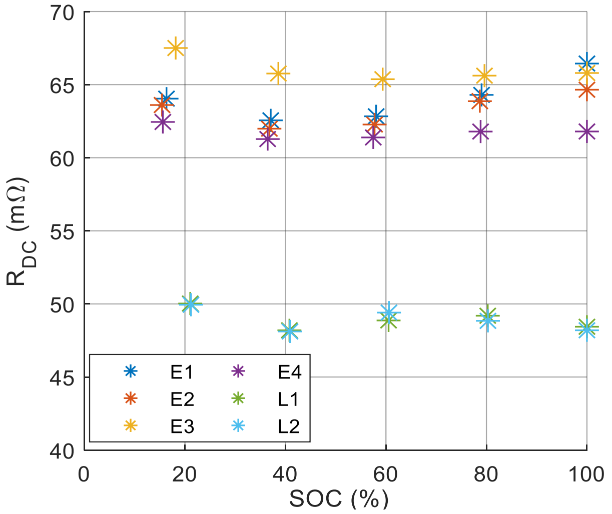

Fig. 5 R_{DC} measurements for different *SOC* values.

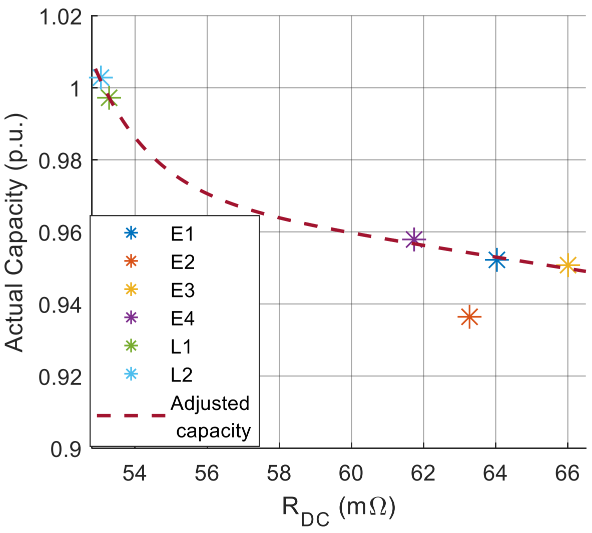

Fig. 6 R_{DC} and capacity dependence.

Fig. 6 shows the dependence between the average value of R_{DC} for the different *SOC*s; and the capacity of each battery. The red, dashed line represents an exponential fit of capacity and $R_{DC,}$ disregarding the measurement performed in E2 for being considered an outlier. Two capital issues concerning capacity measurement in mobile and isolated applications are the required equipment and the duration of the test. The experimental procedure followed in this contribution in order to obtain each data presented in Fig. 4 lasted 24 h. For that reason, an estimation method for the capacity based on the measurement of R_{DC} and a relationship such as the one presented in Fig. 6 can be highly appreciated.

Once the relationship between capacity and R_{DC} has been analyzed, a similar study was conducted with R_{AC}. Fig. 7 shows the lack of dependency between the capacity measurements and the resistance at 1 kHz. Therefore, the battery capacity cannot be estimated from the measurement of R_{AC}. However, this parameter is representative of distinct aging processes involved in the degradation of LIBs. R_{AC} provides relevant information about power fade, which is an aging phenomenon as important as capacity fade for many battery applications in which the battery power is a critical parameter. Moreover, R_{AC} is also indicative of degradation processes such as lithium metal plating on the anode and

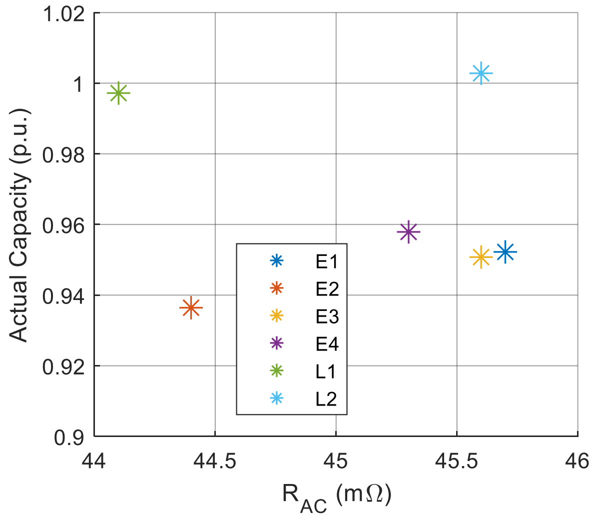

Fig. 7 Relationship between R_{AC} and capacity.

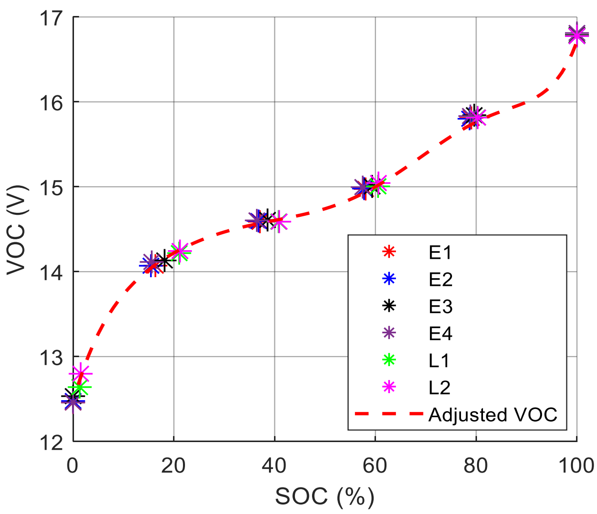

Fig. 8 Open voltage circuit (*VOC*) for different *SOC* values.

dendrites growth, which can lead to a catastrophic failure of the battery. Therefore, further research on R_{AC} can be of high interest in order to prevent premature battery degradation.

C. *VOC – SOC relationhsip*

The results of the *VOC* – *SOC* relationship presented in Fig. 8 show that this relationship does not change with battery aging. All the measured data shown in this figure, regardless of the capacity value, can be accurately fitted by means of a polynomial function. Therefore, a fit of this relationship done at the battery beginning of life allows the estimation of the state of charge of the battery by means of the measurement of *VOC*, independently of the state of health of the battery. This is the reason for the great relevance of this relationship, particularly on applications where the computational power of *SOC* estimation algorithms need to be low.

V. CONCLUSIONS

This contribution reports on the satisfactory operation of the commercial Lithium-ion batteries used in the WindSled Project during a 52-day expedition with temperatures lower than -40 ºC. The studied batteries have suffered certain degradation during the expedition. More precisely, the results show a capacity fade of 5 % and an increase in the R_{DC} of 30 %. Nevertheless, due to the fact that the actual capacity is still 95 % of its rated value, they can be used in upcoming expeditions, entailing an improvement from an economical and environmental point of view if they are compared to primary batteries.

Additionally, the relationship between some of the main parameters of a LIB is studied based on the parameters measured in this contribution. Specifically, capacity, R_{DC} and R_{AC} are the studied parameter. While the results show an exponential relationship between R_{DC} and capacity, R_{AC} have shown a lack of dependence with the capacity. Besides that, the study shows that the relationship between *VOC* and *SOC* is invariable with aging in batteries that have operated in frigid weathers. Therefore, the state of charge estimators based on the open circuit voltage are feasible in those applications.

On the other hand, this contribution shows the feasibility of carrying out scientific experiments conveyed in a 0-emission vehicle, disturbing minimally the polar environment. The WindSled project has not been a one-trip project, but will continue performing new polar expeditions, and therefore is of major importance to disclose this vehicle to the scientific community.

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