UNIVERSITY **POLITEHNICA** OF BUCHAREST

Doctoral Thesis

Normalități și anormalități în exploatarea conformă și excesivă a pilelor secundare de tip Li-polimer

Normalities and abnormalities during the proper and excessive use of Li-polymer rechargeable batteries

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TABLE OF CONTENT

ABSTRACT

The doctoral thesis has as its main objective the development of methods for correcting some deficiencies resulting from the abnormal exploitation of lithium-based accumulators, especially those of the lithium-polymer type, in order to revitalize or recondition them. The direct result of these methods aims to extend the life of these batteries in accordance with the current trends of integration into the circular economy concept, as an alternative to the recycling process.

The thesis was designed as a summation of 13 independent chapters/sections, chapters slightly different from the classical meaning of a chapter, each of them dealing with a problem of practical interest, with the corresponding particularities, and possible solutions or remedies being proposed theirs.

The doctoral thesis is structured in two parts:

1. part I, which includes 4 chapters of documentary study on the general aspects and properties of lithium-polymer batteries;
2. part II includes experimental study, optimization and modeling sections summed up over 9 chapters. In the experimental study, a series of lithium-polymer batteries were refurbished, a spot welding device was built and tested to reintegrate batteries into original devices or other repurposed devices, a device was designed and built for determining the detachment force of nickel plates welded to batteries. At the same time, a model based on regression equations was developed that allows determining the optimal parameters for the spot welding stage based on the maximization of the detachment force of the nickel plates connecting the accumulators.

The thesis is completed with a chapter of conclusions, the list of works published and presented at national or international conferences and bibliography.

GENERAL ASPECTS REGARDING LITHIUM-POLYMER BATTERIES

CHAPTER 1

INTRODUCTION

Technological progress brought about by the use of batteries in the most diverse applications in a wide range of fields has led to increased funding for research into the development of new sources of energy storage, necessary to meet the growing demand for energy. The amount of disposable batteries has increased greatly in the last decade, but it has also brought with it an increase in the amount of waste generated. Despite all the efforts made for their selective collection and recycling, used batteries are still disposed of improperly, causing serious environmental problems, therefore more emphasis has been placed on the development and use of other types of more environmentally friendly batteries. Following this trend, the development and use of secondary (rechargeable) electrochemical cells has seen significant growth in recent decades. Of these, special interest is given to lithium-based batteries (lithium-ion/lithium-polymer), due to their high energy density (Melin, 2019, Kang et al., 2013).

Lithium-polymer batteries are essentially lithium-ion batteries, in which the liquid electrolyte is most often replaced by a conductive polymer membrane, which acts as an electrolyte and separator. Although they are considered to be among the safest lithium-ion batteries, the stringent requirements to increase the generated current have also led to compromises, with some lithium-polymer batteries also containing additive components such as volatile and flammable organic solvents, transferring older safety issues to this battery class as well. Although manufacturers also explicitly specify the number of charge/discharge cycles, these data are only valid under the strict conditions of laboratory testing, the actual number of charge/discharge cycles being dictated by how the battery is used during its lifetime. Recycling used batteries, seen as a solution that worked in the case of lead-acid batteries, proved ineffective on an industrial scale due to two major impediments: the recycling technology of these batteries is not fully developed and the classes of lithium-based batteries do not present the uniqueness of those on lead-based, the former having a wide diversity in terms of construction, composition, chemical behavior, the present recycling methods focusing on the recovery of useful component elements through different mechano-chemical treatments (Ciobotaru et al., 2020).

EXPERIMENTAL STUDY

The purpose of this doctoral thesis was to develop a series of methods for correcting defects resulting from abnormal exploitation, for revitalization/reconditioning and for extending the lifetime of lithium-polymer batteries as an alternative to the early recycling process of them, in accordance with current integration trends in the circular economy concept.

In order to achieve the aim of the thesis, a series of specific objectives were established:

- Notions of compliant and non-compliant exploitation of lithium-polymer batteries;
- Identification and preliminary evaluation of lithium-polymer accumulators in order to determine their condition;
- Defining a procedure to revitalize lithium-polymer accumulators with characteristics considered below the limit of practical exploitation for which they were originally intended;
- Testing the procedure on a series of lithium-polymer accumulators with different characteristics in order to have the widest possible field of applicability and determining the influence of the reconditioning procedure on the tested accumulators by evaluating the performance of the investigated accumulators;
- Testing a procedure for reintegrating refurbished batteries into electronic devices and developing a model to determine the optimal parameters for the spot welding step.

CHAPTER 5

METHODS AND MATERIALS

The lithium-polymer accumulators used as raw material in the case of the experimental study are accumulators recovered from electronic devices that no longer functioned in the parameters desired by the user due to non-compliant exploitation, long-term storage and non-use or their overloading. The internal resistance of the batteries was measured using an ohmmeter dedicated to this purpose, which uses the 4-electrode method (RIM 1000, Voltcraft, Germany) (figure 5.1.).

Figure 5.1. Ohmmeter for measuring the internal resistance of batteries

The voltage values measured for the preliminary determination of battery viability were measured using a DT9205A digital multimeter (figure 5.2.)

Figure 5.2. DT9205A digital multimeter

The voltage of the lithium-polymer batteries and their charge and discharge capacity during charge/discharge cycles were determined using a professional LiPro Balance Charger Imax B6 charger (figure 5.3.). It allows the battery to be charged/discharged under reproducible conditions, at the chosen parameters.

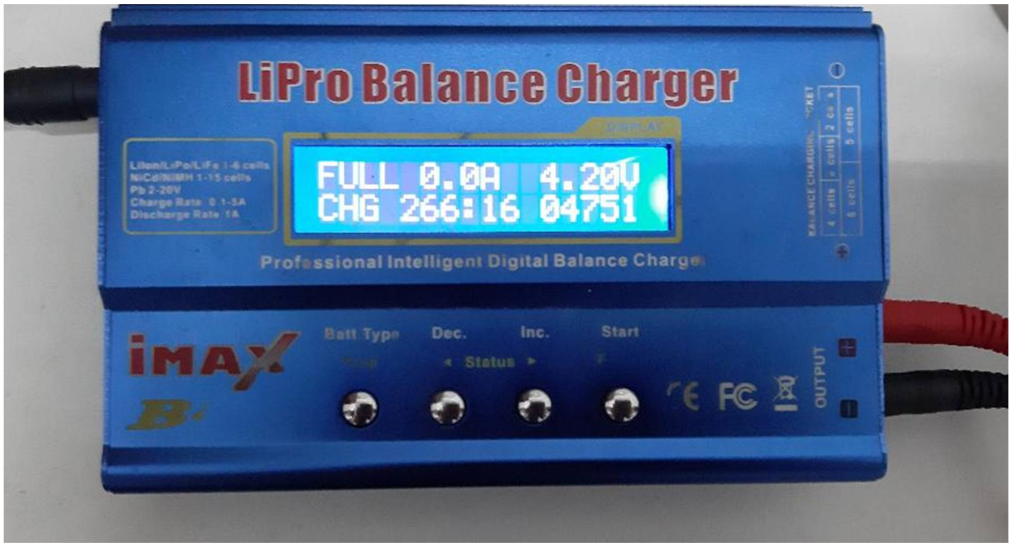


Figure 5.3. A professional LiPro Balance Charger Imax B6 charger

The LiPro Balance Charger Imax B6 provides information on:

- charge (Q_i)/discharge (Q_d) capacity,
- battery terminal voltage during charging/discharging (U),
- loading time (t_i) / unloading (t_d),
- the intensity of the charge (I_i)/discharge (I_d) current.

The professional charger is powered by a DC power supply (LABORNETZGERAT LN-103pro, MCI-Power, Germany) set to a constant 12V operating mode.

The application of the reconditioning procedure for depleted lithium-polymer batteries is only carried out on batteries that have met a series of geometric and electrical integrity criteria (Ciobotaru et al., 2021):

- not to have deformations: the outer casing of the accumulators should not be perforated or swollen;
- have well-defined contact terminals so that they can be connected to the equipment used;
- not to present traces of electrolyte on the outer case;
- not undergo a heating process during the charging/discharging stages.

After the sorting stage corresponding to the geometric integrity, the accumulators are preliminarily evaluated to establish their current state (figure 5.4.). Thus in this stage it is measured:

- the electromotive voltage (in fact, in reality it is the voltage in the absence of current in the circuit, because these accumulators can no longer be viewed through the prism of classical concepts) of the accumulators to establish the path that the accumulator will follow (if the terminal voltage, in the absence of current, at the battery terminals it has a value higher than 3V, the lithium-polymer battery can be directly subjected to the reconditioning procedure, otherwise, for electromotive voltage values lower than 3V, it will have to undergo a preliminary charging stage using to an external battery mounted in parallel, so that the professional charging/discharging device allows the recognition of the battery and therefore its charging)
- internal resistance/initial internal impedance of the battery;
- current charging capacity of the battery;
- the discharge capacity of the accumulator in the state in which it is found.

The actual reconditioning procedure of used accumulators consists of a series of 5 charging/discharging stages in a controlled regime.

A number of situations may occur during the performance of these reconditioning procedures:

- if after 3 charge/discharge cycles, no significant increase in the charge/discharge capacity values is observed, then the battery can be directed to recycling;
- if during the charging/discharging processes, the battery shows an improvement in the capacity values, but heats up excessively, then the battery can be directed to recycling;
- if there is a large difference between the charging and discharging capacity values during the 5 stages, such as the charge capacity value being much higher than the discharge capacity value, it means that the battery loses part of its charge through unwanted processes, such as secondary reactions , and thus it is recommended that the battery be sent for recycling.

CHAPTER 8

RECONDITIONING OF SOME BATTERIES USED IN ELECTRONIC DEVICES

8.1.Recontioning of a laptop battery that contains a lithium-based battery

The next case discussed in this doctoral thesis refers to the revitalization of the accumulators from the battery of a Dell Lattitude 13 notebook. Initially, this battery was charged using the laptop charger, and when the laptop was turned on, it showed a remaining run time of 14 minutes. The battery was detached from the laptop and then to get to the constituent battery packs the outer case was removed.

Figura 8.1. Imagine a notebook-ului Dell Lattitude 13

Problem: One of the battery banks is unbalanced in terms of electrical charge storage capacity, and the laptop software triggers the laptop to shut down when the battery voltage drops below a critical value.

Proposed solution: independent charging of each group of 2 batteries mounted in parallel. Procedure The laptop battery is equipped with six lithium-polymer batteries mounted in three groups of two batteries as follows: each group contains two batteries mounted in parallel, and the groups are mounted in series.

A schematic diagram of the laptop battery is shown in figure 8.2. (Ciobotaru et al., 2020):

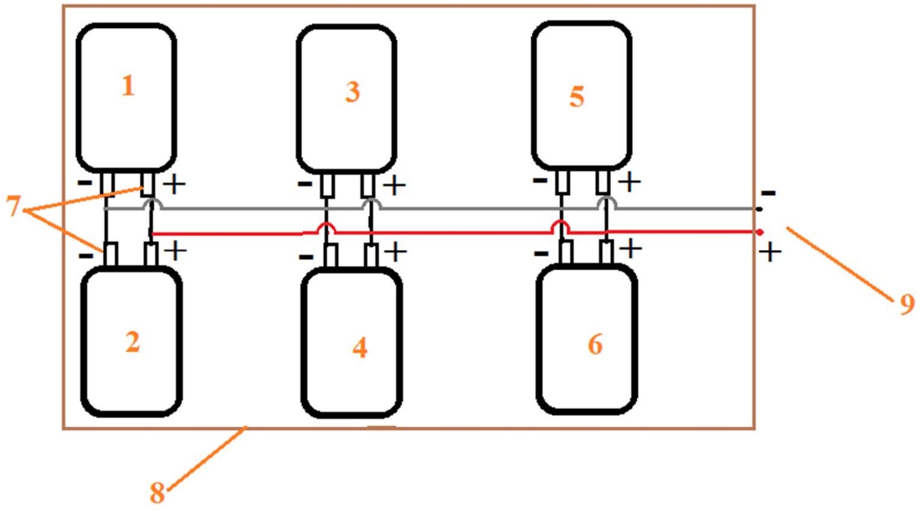


Figure 8.2. Principle diagram of the investigated notebook battery: 1-6 lithium-polymer batteries, 7 battery terminals, 8 battery case, 9 – case (Ciobotaru et al., 2020)

The arrangement of the accumulators and the practical way of making the connections for the revitalization procedure are represented in figure 8.3 (Ciobotaru et al., 2020).

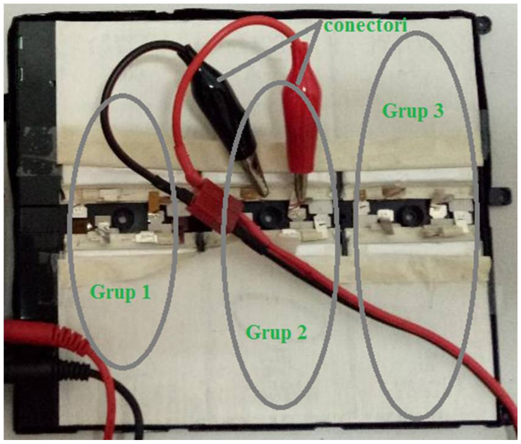


Figure 8.3. Arrangement of accumulators in the studied battery The revitalization and battery performance evaluation procedure was carried out with the help of a LiPro Balance Charger Imax B6 professional charger.

The charging procedure of each group was carried out independently at an initial charging current of 1.5 A until a voltage value of 4.2 V was reached, which was the first charging stage. In the second charging stage, the applied voltage value was kept constant at 4.2V and the charging current decreased with increasing charging time until reaching a value of 10 mA. The entire procedure was pre-programmed in the Professional Imax B6 charger (Ciobotaru et al., 2020).

The discharge procedure for each group was performed at a constant discharge current of 1A. This step ended when the voltage value per group reached 3V. Internal resistance measurement was performed in sets of five replicate measurements, and the mean resistance value of each group was calculated using these values (Ciobotaru et al., 2020).

In table 8.1., you can find the measured values of the charge and discharge capacities for each group of lithium-polymer batteries existing in the battery of the investigated laptop.

Table 8.1. Discharge and discharge capacity values of lithium-polymer battery groups (Ciobotaru et al., 2020)

Group	Discharge capacity, mA h	Charge Capacity, mA h
1	1839	1922
2	1637	1714
3	1656	1703

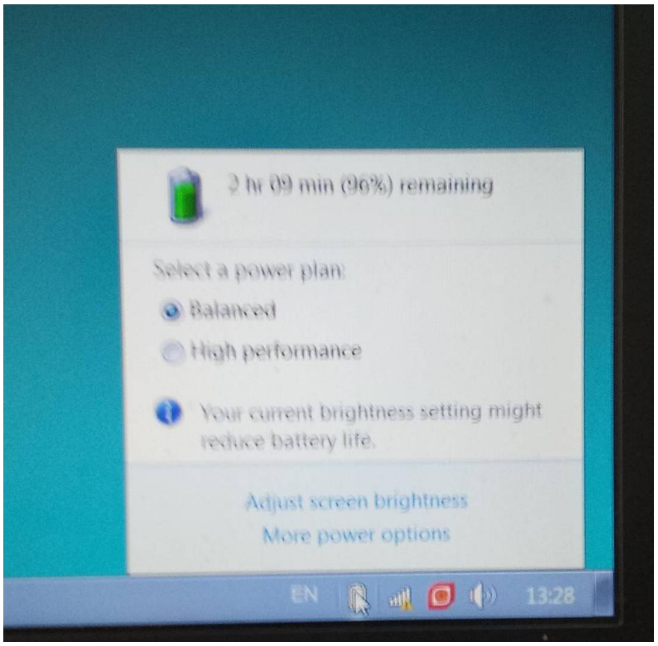
The technical specifications of the investigated battery allow the calculation of the initial capacity of the battery groups, using the energy (E) and voltage (U) provided (equation 1). The laptop battery formed by the three groups of accumulators provides a voltage of 11.1 V and an energy of 30 W h (Ciobotaru et al., 2020).

$$Q_i = \frac{E}{U}, A\ h \tag{8.1}$$

Thus, the initial capacity of the lithium-polymer battery groups is 2702.7 mA h. After the revitalization stage, the capacity of Li-polymer battery groups mounted in series is approximately equal to the arithmetic mean of the discharge capacity values of the three groups (equation 2) (Ciobotaru et al., 2020):

$$Q_r = \frac{\sum_{i=1}^{3} Q_i}{3} = 1710{,}7\ mA\ h \tag{8.2}$$

Upon completion of the revitalization procedure, the battery was charged and mounted inside the laptop. When starting the laptop, an operating time of two hours and nine minutes is obtained (figure 8.4.) (Ciobotaru et al., 2020).



2 hr 09 min (96%) remaining

Select a power plan:

● Balanced

○ High performance

Your current brightness setting might reduce battery life.

Figure 8.4. Capture with the indication signaled by the notebook regarding the operating time of its battery (Ciobotaru et al., 2020)

The improvement in battery life can be calculated from the values of the battery operating times, more precisely as the ratio between the operating time after the reconditioning procedure and the operating time before applying the reconditioning procedure (equation3) (Ciobotaru et al., 2020) :

$$P = \frac{t_r}{t_i} \tag{8.3}$$

Thus, a 9.2 times improvement in operating time is obtained for the tested battery. It is further proposed, with a view to a quantitative characterization for the revitalization operations, the introduction/definition of a parameter kr, called the revitalization coefficient defined as the ratio between the capacity of the accumulators after the application of the reconditioning procedure and the initial capacity of the accumulators (equation 4) (Ciobotaru et al., 2020).

Thus, for the three groups of batteries, the reconditioning coefficient has a value of 0.633..

$$k_r = \frac{Q_r}{Q_i} = \frac{1710{,}7}{2702{,}7} = 0{,}633 \quad (8.4)$$

The most common expressions used to show improvements are in percentage forms. The proposed coefficient can also be interpreted as a percentage form, namely, a value of the reconditioning coefficient of 0.633 is equivalent to 63.3%, a value that shows the degree of recovery compared to the initial performances (Ciobotaru et al., 2020).

8.3. Reconditioning of lithium-polymer batteries that have been used in professional racing cars

A number of electronic devices require current sources capable of providing a very high value of current intensity for a short period of time (e.g. professional racing cars require a current of approx. 50 A for approx. 120-180 seconds). When the performance of the batteries falls below what is needed, they are replaced and sent for recycling, although they can still be used for other purposes. Problem: re-introduction of other batteries into use; finding new applications for such batteries. The batteries received and tested (3 identical batteries S1, S2, S3) are of the T1G6P type lithium-polymer class (Turnigy 5.0 ωmatched power systems, figure 8.14.) (Benga et al., 2018).

Figure 8.14. Battery S1 lithium-polymer T1G6P

The specifications provided by the manufacturer are as follows:

- supplied voltage of 14.8 V (4 batteries mounted in series);
- nominal capacity 5000 mA h;
- stored energy 74 W h;
- the ability to provide a high value current (up to 100-150 A) for a duration of 30 seconds.

The analyzed systems were used as a power source for "mini professional racing cars" for approximately 12-14 months, even though the manufacturer's warranty was limited to 12 months. These batteries were used to start the mini-cars at maximum acceleration, which consume a starting current between 30-50 A, which is within the parameters prescribed by the manufacturer, namely in the range of 100-150 A. The problem is that the time for such a regime recommended by the manufacturer is 30 seconds, while these sources are exploited to the maximum for more than 2 minutes. As their performance declined over time, they were considered unfit for their original intended purpose, where starting speed and acceleration were of paramount importance, and thus were directed to recycling due to their inability to perform at the expected parameters (Benga et al., 2018).

Preliminary testing of these units showed low values for both discharge capacity and stored energy of around 496 mA h and 7.93 W h, respectively, well below 5000 mA h and 74 W h. Furthermore, as these batteries are actually a series of 4 Li-Po cells, a dedicated charger with balancing function is required (the battery was supplied with such a connector by the manufacturer) to balance the individual charge of each cell and preventing an unevenly distributed load in individual cells. This type of charger was used for all charging stages for the analyzed systems, namely the LiPro Balance Charger Imax B6 (Benga et al., 2018).

Before the actual evaluation, the systems were subjected to several charge/discharge steps to restore their spinel complex structure at the cathode. The revitalization of the systems began with a loading stage, carried out in two sequences; first, a constant current (2.5 A) charge sequence for 2 hours, followed by another constant voltage (17V) charge sequence, until the point where the charge current value dropped below 50 mA, which is 1% of the battery capacity divided by the time unit, 1 h (Benga et al., 2018).

The discharge step was performed with a discharge module at a constant current of 1 A until the voltage reached a value of 12 V. After each step, the loader provides the following information:

- load capacity,
- discharge capacity,
- full charge voltage,
- breaking voltage,
- loading time,
- download time,
- charging current,
- discharge current.

The charge/discharge current was held constant at 1 A for both charge and discharge stages. These values were recorded by the loading / unloading device.

The internal resistance of the batteries was measured with a professional battery internal resistance tester (RIM 100, Voltcraft, Germany), 5 measurements were recorded and then the average of these measurements was calculated (Benga et al., 2018).

The results obtained in the evaluation stages of the refurbished accumulators are presented in tables 8.5.-8.7.

Table 8.5. Discharge and charge capacity values of lithium-polymer batteries after the 5th cycle (Benga et al., 2018)

Acumulator	Discharge capacity, mA h	Charge capacity, mA h
S1	4839	4563
S2	4742	4464
S3	5376	4770

Table 8.6. Internal charging resistance values of the lithium-polymer battery

Group	**Internal resistence after charging, mΩ**					**Average, mΩ**	**SD**	**RSD, %**
S1	13,09	13,37	13,19	13,04	13,31	13,20	0,14	1,06
S2	14,61	14,78	14,67	14,7	14,74	14,70	0,07	0,44
S3	14,17	14,24	13,94	13,75	14,1	14,04	0,20	1,40

Table 8.7 Values of the internal discharge resistance of the polymer lithium battery

Group	**Internal resistence after discharging, mΩ**					**Average, mΩ**	**SD**	**RSD, %**
S1	13,84	14,01	13,78	14,08	13,79	13,90	0,14	0,98
S2	15,43	15,28	15,12	15,49	15,38	15,34	0,15	0,95
S3	16,04	15,86	15,93	16,1	15,97	15,98	0,09	0,59

Conclusions

The three lithium-polymer batteries tested were successfully reconditioned and continued to be used for purposes other than what they were originally used for.

CHAPTER 9

APPLICATIONS OF REVITALIZED LITHIUM-POLYMER BATTERIES

One of the batteries (S1) was tested to evaluate the possibility of being used as a cold crankshaft amperage system (cca system) of an automobile, which means that it was discharged to a current of 100 A for 10 seconds with a professional digital battery tester (Voltcraft BT- 3, Germany), capable of testing cold cranking current (approx) up to 600 A (Benga et al., 2018).

Problem: In the case of connecting to the terminals of a discharged lead-acid battery, if it is desired to start the vehicle immediately and not to recharge the lead-acid battery from the li-polymer one over time, once started (the system is also able to start cars with diesel engines that requires approx. 100 A for 30 seconds), the vehicle's battery charging system comes into operation once the engine starts, feeding the lithium-polymer battery with 14.4-14.8 V directly on the output terminals, a totally contraindicated procedure, which has has been discussed previously.

Solution: To ensure a unidirectional current circuit only from the li-polymer battery to the lead battery a group of diodes was placed on the connector wires, mounted in parallel to handle the high value current generated by the car's alternator/rectifier.

In figure 9.1. the test montage of the starting current generated by the li-polymer battery is shown. For the 100A rating, the nominal terminal voltage must be above 11.5V and remain stable for 10 seconds (measured value was 15.6V – when each cell is fully charged, the per cell is 4.2 V, the value on the battery consisting of 4 accumulators mounted in series is 16.8 V) (Benga et al., 2018).

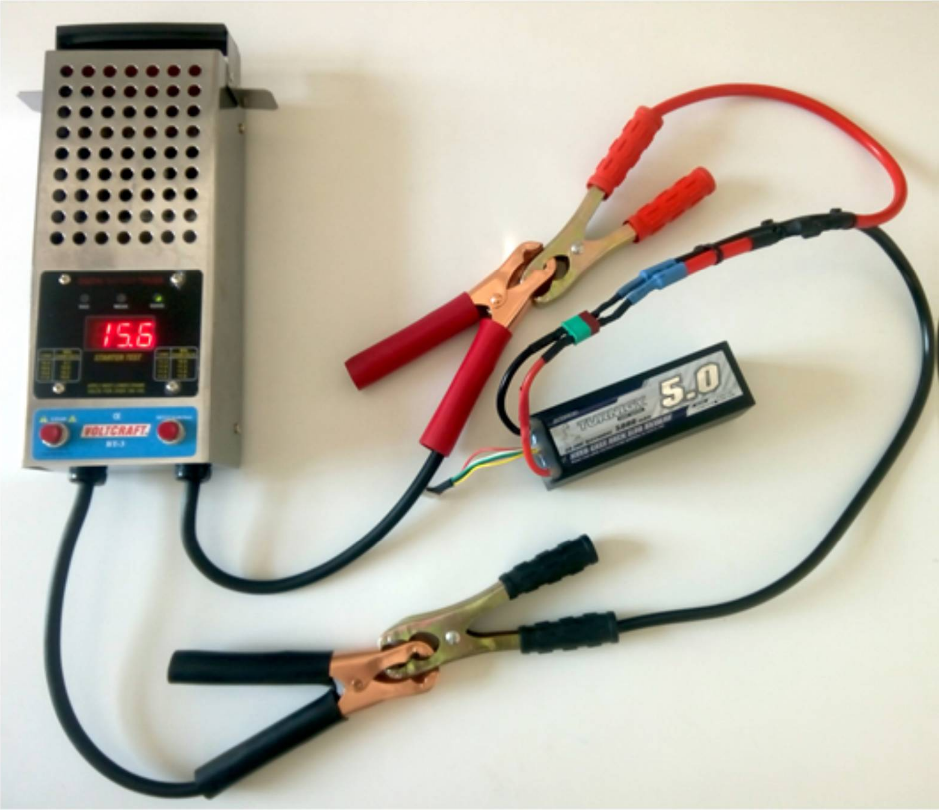


Figure 9.1. Experimental setup of battery start-up testing at a current of 100 A for 10 seconds (Benga et al., 2018)

The installation of the diode group that allows the current to pass unidirectionally from the external battery to the car battery is to prevent the car's lead-acid battery charging system from sending charging current to the external battery when the car is started. The explanation of why this extra protection is needed lies in the comparison of the different charging regime of the lead-acid battery compared to the li-polymer one. If a 12V lead-acid battery consisting of 6 lead-acid batteries in series can be charged without any problem in a series system, at the terminals of the 6-battery series, for the battery consisting of 4 lithium-polymer batteries, charging is done with the professional charger dedicated through the balancing socket that ensures the individual charging and balancing of each unit from the 4 units placed in series. During the storage period, it is desirable that the battery is detached from the power cables.

Problem: A reconnection of the cables through a normal connector has a 50% chance of reverse connection, with polarity reversed, with disastrous consequences of melting the protective fuses in the battery box.

Solution: Using standard colored cables (red/black) and a safety connector with a geometric key that does not allow wrong connection that would lead to polarity reversal (figure 9.2.).

Problem: The alligator clips can accidentally touch shorting the li-polymer battery

Solution: The high current cables to which the connecting clamps are attached were designed from the start of different lengths to avoid touching metal parts and short-circuiting the system in case of careless handling (figure 9.3.).

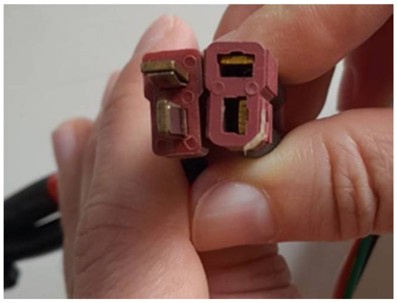


Figure 9.2. Geometric key connector that prevents polarity reversal when reconnecting

Figure 9.3. Connecting pliers connected to cables of different length

The tested systems behaved normally by maintaining the required current for 10 seconds. The discharge current of 100 A provided is enough to start a normal car, even a diesel one, up to a displacement of 3000 cm3. After this test, battery S1 was again charged to full capacity, and then the internal resistance was measured. After this evaluation, the S1 system was subjected to a power-up test and again evaluated.

The internal resistance value recorded after the start-up test was 13.4 mΩ. After this measurement, the S1 system was charged to full capacity, and at the end of the charging stage, the charger indicated 404 mA h, which means that the start-up test consumed only 404 mA h of the total capacity of the battery (Benga et al., 2018).

Comparing the value of the internal resistance of the battery after the first cold jump start with the previous one, only a very small increase in its value can be observed from 13.2 to 13.4, which is about 1.5%. This gives us the right to say that this device can be successfully used for more than one cold start. This is a real advantage, as it is not necessary to reload the system after each start. On the other hand, a virtual short-circuit current (Ish) can be calculated for this system, its physical meaning being that of a maximum current value when the terminals are short-circuited, an action totally prohibited and considered dangerous from the point of view practically. This is why this is a virtual representation of the maximum current that the system can produce (when the external resistance tends to be 0) (Benga et al., 2018).

The short-circuit current can be calculated using equation 9.1:

$$I_{sh} = \frac{14{,}8}{R_{i,i}} \qquad (9.1)$$

In the case of the S1 system, the ISh value is 112 A, which means that this system could be safely used at 110% of the tested value, which is a value of 110 A for 10 seconds. Calculating the total load consumed during the cold start taken at full current for 10 seconds results in a total consumed capacity of 0.305 A h, which is less than 6.1% of the battery capacity. This means that the system can be used for at least 8 startup connections, each connection providing a current of at least 110 A until the system is 50% discharged (Benga et al., 2018).

The system was successfully field tested on two vehicles, one of which had a fully discharged lead battery (Suzuki Vitara/petrol, Opel/diesel).

Conclusions

This chapter presents a series of practical solutions that facilitate the use of the proposed system and that solve a series of problems that may appear in current systems and that generate non-compliant use:

- problem encountered in practice: the possibility that when the car's lead-acid battery charging system starts, it sends charging current to the external battery.
    - a solution proposed and applied: the incorporation of a group of diodes for the unidirectional passage of current from the external battery to the car battery
- problem encountered in practice: reverse connection of system polarity
    - a solution proposed and applied: the incorporation of a safety connector with a geometric key

- problem encountered in practice: the appearance of a short circuit caused by touching the metal parts of the connecting pliers
    - a solution proposed and applied: connecting pliers of different length.

CHAPTER 11

REINTEGRATION OF RECONDITIONED BATTERIES IN ELECTRONIC DEVICES

After applying the revitalization or reconditioning procedure, batteries can be reintegrated into electronic devices that have shown deficiencies, if a number of factors are taken into account:

- the disassembly and removal of the accumulators from the devices must be carried out in such a way that the replacement of the accumulators after reconditioning is carried out without great difficulties;

- hot welding/gluing of batteries in devices must not cause other damage to the devices (short circuit, overheating or detachment of other components); - the materials used to build the assemblies must be similar in terms of properties to those used in the initial assemblies;

- the operating parameters of the reintegration stages in the devices should not influence the integrity of the accumulators.

In order to test a procedure for reintegrating the batteries into the original devices or other devices that can use such battery packs, a series of spent lithium-ion batteries that were recovered from electronic devices such as laptop batteries were used.

CHAPTER 13

REINTEGRATION OF RECONDITIONED BATTERIES IN ELECTRONIC DEVICES

The procedure for reintegrating refurbished batteries into devices has been tested on a range of lithium-ion batteries. Thus, a first example presented is that of a group of four MH12210 lithium-ion batteries (figure 13.1.) were connected in parallel to form a group that provides a median voltage of 3.7 V and a capacity 4 times more greater than that of an individual battery.

Problems: Possible accidental short circuits at the top of the component units and the absence of a rigid structure.

Solution: Using modular coupling systems that increase the rigidity of the battery and insulating rings to prevent accidental short circuits (figure 13.1.)

Figure 13.1. MH12210 lithium-ion batteries equipped with modular coupling systems and insulating rings to prevent accidental short circuits

The connection of the accumulators was made by welding the nickel plates on the terminals of the accumulators with the system presented in chapter 12. The accumulator system was placed in modular coupling systems and protective insulating rings were glued (figure 13.2.).

Figure 13.2. Battery consisting of 4 lithium-ion batteries mounted in parallel

The lithium-ion battery pack was attached with pliers-shaped electrical connectors of different lengths (see Chapter 9) to avoid short-circuiting due to accidental contact with the pliers, after which the pack was sealed with heat-shrink tubing (figure 13.3.).

Figure 13.3. Lithium-ion battery pack with attached connectors

A second example, in which eight revitalized lithium-ion batteries were reintegrated into a group providing a voltage of 14.4 V. These batteries were grouped into four groups of two batteries mounted in parallel, groups which then had were connected in series, thus providing a nominal voltage of 14.4 V and a capacity twice that of the individual elements used (13.4.).

Figure 13.4. Group of eight revitalized batteries

Conclusions:

The spot welding system for welding nickel plates on refurbished lithium-based batteries has been successfully applied to the reconstruction of two batteries of medium voltage 3.7 V and 14.8 V, the obtained batteries can be used for various purposes (as external power batteries for revitalization, troubleshooting, testing, portable power sources, electrolysis, electrodeposition, etc.).

CONCLUSIONS

General conclusions

Solid polymer electrolyte lithium batteries, compared with traditional liquid electrolyte lithium batteries, have a number of advantages in terms of high safety, high energy density and long life, and will become one of the more used energy storage devices.

Considering this, the notions of compliant and non-compliant exploitation of lithium-polymer batteries were explained and exemplified in the experimental study.

The experimental study was carried out in several stages starting from:

- Preliminary assessment of lithium-polymer batteries to determine their condition;
- Defining and applying the procedures for the reconditioning and revitalization of some lithium-polymer accumulators with characteristics considered below the limit of the practical exploitation for which they were originally intended;
- Testing the procedure on a series of lithium-polymer batteries with different characteristics in order to have as wide a field of applicability as possible and then, evaluating the performance of the investigated batteries;

Testing and application of a reintegration procedure for reconditioned batteries in electronic devices. For the construction of new battery systems, a spot welding machine was built that allows the welding time to be varied. For this stage, a model was developed to determine the optimal parameters for the spot welding stage.

A device was built to test the strength of the welds made. The systems were used to perform spot welds on both real batteries and simulated systems (simulated battery case of high purity nickel plates), the data obtained indicating that the pull-off force is directly dependent on the welding time and nickel plating thickness (default nickel plating resistance, resistance value increasing with decreasing nickel plating thickness).

The spot welding system for welding nickel plates on refurbished lithium-based batteries has been successfully applied to rebuild two medium voltage batteries 3.7V and 14.8V, which can be used in different applications.

Personal contributions

Personal contributions through this doctoral thesis consisted of:

- development of an appropriate method of revitalization and reconditioning of lithium-polymer accumulators;
- the construction and use of a spot welding device for the reintegration of batteries in original electronic devices or in other devices with a new purpose;
- designing and building a device for determining the force of dependence of the nickel plates welded by the accumulators;
- the development of a model based on regression equations that allows determining the optimal parameters for the spot welding stage based on the maximization of the detachment force of the nickel plates connecting the accumulators.

LIST OF PUBLICATIONS

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1. Ioana-Alina Ciobotaru, **Florin-Mihai Benga***, Dănuț-Ionel Văireanu, *Reconditioning of Li-ion rechargeable batteries, a possible solution for batteries circular economy*, U.P.B. Scientific Bulletin, Seria B, vol. 83, nr. 1, p17-22, 2021, ISSN 1454-2331, WOS: 000627764100002.
2. **Florin-Mihai Benga**, Dănuț-Ionel Văireanu, Ioana-Alina Ciobotaru**,** Irina-Elena Ciobotaru*, A novel jump-start system based on reconditioned li-polymer batteries***,** Revista de Chimie, vol. 69, nr. 4, 2018, p. 351-353, WOS:000433223000020.
3. Ioana-Alina Ciobotaru, **Florin-Mihai Benga***, Irina-Elena Ciobotaru, Dănuț-Ionel Văireanu, *Overcoming Practical Barriers in Reconditioning Li-Polymer Batteries*, Revista de Chimie, vol. 71, nr. 4, 2020, p. 366-372, https://doi.org/10.37358/RC.20.4.8076.
4. Traian Rus, Elena Radu, Iosif Lingvay, Monika Lingvay, Oana Claudia Ciobotea-Barbu, Claudiu Campureanu, **Florin-Mihai Benga**, George-Costin Lazar, Dănuț-Ionel Văireanu, *Resistance to the action of filamentous fungi upon some coatings materials*, UPB. Scientific Bulletin, Seria B, vol. 79, no. 4, 2017, p. 167-180.
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2. Ioana-Alina Ciobotaru, Florin-Mihai Benga, Anca Cojocaru, Ioana Maior, Dănuț-Ionel Văireanu, *An Integrated System for Rechargeable Batteries Reconditioning and Recycling Management,* 22nd Romanian International Conference on Chemistry and Chemical Engineering, 7-9 septembrie 2022, Sinaia, Romania;
3. Dănuț-Ionel Văireanu, Florin - Mihai Benga, Ioana-Alina Ciobotaru, Adnana Alina Zaulet, *Myths and Reality in Using and Misusing Lithium Based Rechargeable Batteries,* 23rd International Conference “New Cryogenic and Isotope Technologies for Energy and Environment“, 26-29 octombrie, 2021, Băile Govora, România.
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