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PROPOSAL OF BATTERY MANAGEMENT STRATEGY FOR SMALL GEOSTATIONARY SATELLITE POWER SYSTEM DEVELOPMENT

EL HABIB BENSIKADDOUR[1], AISSA BOUTTE[1]

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During a space mission, the supply of the satellite with required electrical power depends on each phase of the orbit/season until its end of life. To maintain the mission, different strategies to manage the electrical power (production, storage, and distribution) could be adapted to the mission function (*e.g.*, low earth orbit, LEO, Geosynchronous). The management strategy for the battery modules must be carried out at the head of the satellite project phases, closely with the mission definition. In our case, we propose a strategy that covers the need for a Small Geostationary Satellite (SGEO) by dimensioning its battery modules and their management system (BMS). The small GEO-SAT presents a new attractive performance for several commercial telecommunication missions, and different space agencies are interested in developing this kind of Small-TELECOM platform. This paper summarizes the power-budget analysis of a small GEO-SAT, gives results of sizing the battery module (Li-ion cells assembled), and proposes different manufacturers that could cover this kind of mission. Moreover, different battery management modes are discussed and simulated by STK and Simulink software.

1. INTRODUCTION

The small geostationary satellites can represent attractive performances through different satellite literature, especially in terms of cost and modularity, for several telecommunication space missions [1–3]. A communication satellite is classified as small if it is less than 1000 kg [2]. Taking advantage of the technological advancement and the miniaturization of some systems, and the COTS (commercial off-the-shelf) and low-cost approach already engaged in LEO satellites for earth observation and that proves their efficiency, we can envisage missions with a narrow covering and limited communication services that previously were not competitive for the geostationary missions [4].

The electrical power on board the satellites is provided by the electrical power subsystem (EPS). This subsystem includes all the equipment needed to generate, store, condition, and distribute the electrical energy necessary for the satellite operation [5, 6]. The battery is an essential component of EPS which ensures the storage of electrical energy. Therefore, this paper aims to propose a battery management strategy for a small geostationary satellite capable of carrying a payload of 2.5 kW.

The battery comprises many electrochemical cells assembled in series and parallel to store electrical energy. NiCd and NiMH were the only rechargeable cells suitable for satellites for many years. However, during the last two decades, Li-ion cells have become mature for all types of space missions [7]. As a result, Li-ion is the most favorable for satellite applications; more than 98 % of newly manufactured satellites are powered by Li-ion [7]. Table 1 shows the comparison between different cell types.

Table 1

Comparison between types of cells technologies [7]

Parameter	Li-ion	Ni-Cd	Ni-MH
Energy density (W/kg)	110 – 160	45 – 80	60 – 120
Nominal Cell Voltage (V)	3.7	1.2	1.25
Relative capacity	3	1	1.4
Memory effect	No	Noticeable	Little
Operating temperature (°C)	-20 to 60	-40 to 60	-20 to 60
Temperature sensitivity	High	Low	Low
Self-Discharge	5 – 10%	20%	30%

Li-ion batteries provide several attractive advantages and improvements over other battery forms, such as high energy density, high cell voltage, No memory effect, and Reduced self-discharge.

However, Li-ion batteries represent some disadvantages in particular [7]: High sensitivity to temperature, the need for protection required against overcharge and over-discharge, and the need to elaborate Cell Balancing operation [8].

Two aspects must be treated precisely for the lithium battery onboard satellites; the design and management [9]. The goal of the design is to find the type, number, and arrangement of cells that can meet the mission requirements efficiently. Moreover, associated electronics should ensure a battery management system (BMS). The BMS in modern EPS is achieved by dedicated hardware and software to manage the following tasks [10,11]:

- Voltage, current, and temperature monitoring.
- Measures acquisition and communication with Onboard Computer OBC.
- Cell Balancing [8].
- Battery charge control.

Several works have been proposed relating to the design and management of electrical power subsystems onboard satellites. In [12], the design and management of EPS onboard satellites are presented based on power characteristics and demand analysis. Besides, a finite-state management strategy was developed in [13] for EPS onboard LEO small satellite. Furthermore, recent work [14,15] proposed a fully open BMS addressing several applications, including space.

In this paper, we try to propose a strategy for the management of the charge/discharge of the battery module "Lithium-ion technology", for the different modes of operation throughout the life of the satellite. It should be emphasized that this battery module is proposed to be installed in a small geostationary telecommunication satellite. During the analysis phase, we will also focus on the design of the power distribution and control unit (PCDU) by determining its bus voltage, propose an architecture for the battery management system (BMS) and perform an

1 Satellite Development Center, POS 50 Ilot T12, Bir-El Djir, Oran, Algeria. Email: hbensikadour@cds.asal.dz and aboutte@cds.asal.dz

STK/Simulink simulation to cover and validate the proposed operating modes by propagation in gyro orbit of the small GEO-SAT over the four seasons of the year.

The paper is organized as follows. Section 2 presents the electrical power subsystem (EPS) onboard a satellite. section 3 describes the procedure followed to find the best design of a satellite's battery(s); the results obtained for a geostationary mini satellite were also presented. In section 4, the battery management system (BMS) and its functions are discussed. Finally, section 5 represents a simulation performed, by Simulink and AGI-STK, to study the state of charge variation during one year of operation. The simulation results have clearly shown that the sizing can perfectly meet the mission requirements.

2. EPS IN GEOSTATIONARY SATELLITE

EPS is the subsystem responsible for providing the electrical energy required for the operation of a satellite in all conditions encountered during the mission. In addition, the EPS must generate, store, condition, control, and distribute the electrical energy for Payload and Platform equipment [16].

Solar panels (photovoltaic panels) are the most common source of electrical energy in satellites. The photovoltaic-battery system can be used in direct energy transfer (DET) architecture or with maximum power peak transfer (MPPT) [16,17]. To the best authors' knowledge, MPPT is more efficient, but DET is much more reliable. The MPPT is used for small earth observation missions (less than 5 years), but it is not often used in GEO satellites [2,3]. Consequently, the DET is the adequate architecture for a small GEO communication satellite [6].

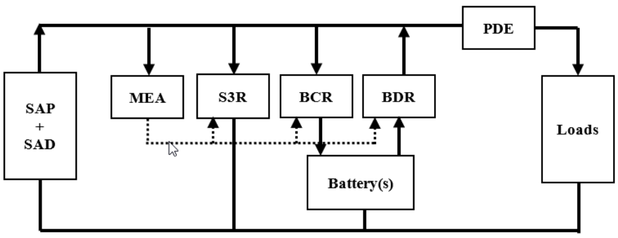


Fig. 1 – Regulated BUS Architecture.

On the other hand, three architectures of DET can be used: unregulated bus, semi-regulated or regulated bus. conventionally, for geostationary satellites, the most optimized architecture for the EPS is the regulated bus [18]. However, another approach is used by certain satellite manufacturers based on the use of Semi regulated architecture in the geostationary (*e.g.*, Surrey Satellite Technology Ltd –SSTL and their Mini Platform (GMP) underdevelopment) [19,20]. The success of this approach is not yet proven for the GEO Satellite. Consequently, the classic approach, which consists in using a regulated bus, is adopted for our proposal for GEO satellite design (see Fig.1) [10]. The description of this architecture is given in the next paragraphs.

The solar panel (SP) comprises several photovoltaic cells connected in series and in parallel to obtain the voltage and current required. For more efficiency, communication satellites use GaInP/GaInAs/Ge triple-junction solar cells [21].

The SP must be continuously facing the sun. Indeed, the Solar array drive assembly (SADA) mechanism drives the solar panel towards the sun.

Power control plays a vital role in the satellite as an interface between the solar panels, battery, and power bus. The modules that provide this function are:

- Shunt regulator (SR): The SR is a set of shunts that can be controlled to dissipate the excess current delivered by the SP [22]. The configuration used SR could be a sequential switching shunt switch regulator (S4R) or sequential switching shunt regulator (S3R) [22].
- Battery charge regulator (BCR): BCR is a set of buck circuits used to charge the battery(s).
- Battery discharge regulator (BDR): BDR is a set of boost circuits used to discharge the battery(s).
- Main error amplifier (MEA): MEA is used to switch between S3R mode, BCR mode, and BDR mode.

The EPS shall regulate the SAP power via SR in sunlight periods and recharge the battery via BCR. However, during eclipse periods or whenever the power delivered by the SP is not sufficient, the EPS shall regulate the power discharged from the battery via the battery discharge regulator (BDR) [6,16].

Battery stores chemically the electrical energy, during sunlight, to supply the loads during eclipse phases or whenever the power delivered by the SP is not sufficient. The main roles of a battery in a satellite are [5,16]:

- Support energy needs during the launch phase.
- Provide energy during eclipses.
- Provide energy when demand exceeds the electricity production of SAP.

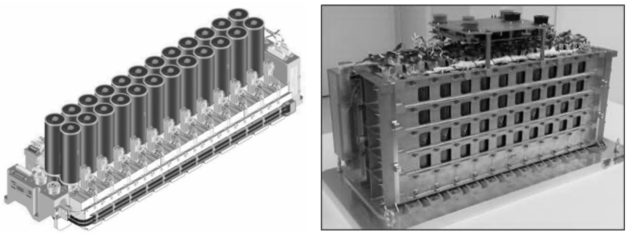
Power distribution electronics (PDE) are the electronics responsible to distribute the power to other Subsystems.

3. BATTERY IN GEOSTATIONARY SATELLITES

The modular approach to manufacturing space batteries is essential to meet the requirements of the GEO satellite [20]. The main advantage of modularity is reducing the costs and development time [3]. As a result, the Li-ion batteries manufacturers for space applications have developed qualified modules for geostationary satellites.

Two technologies are used to assemble the satellite batteries. The first one consists of using commercial off the shelf (COTS) Li-Ion cells [23]. This type of battery is often used for low earth orbit (LEO) satellites [7]. On the other hand, the second is based on the space-grade Li-ion cells, such as the batteries supplied by SAFT, which is considered the world leader in designing and producing li-ion batteries for GEO satellites [6].

Figure 2 shows two examples of battery modules. The first module is manufactured by SAFT based on VES 180 lithium cells. The number of cells in this module can be modified (parallel: from 2 to 6; series: from 10 to 12) [7]. GS-YUASA does the second module based on LSE190 lithium cells. The arrangement of cells in this module can be changed (parallel: from 1 to 3; series: from 6 to 12) [24]. Moreover, the two modules illustrated are supplied with dedicated measurement and control electronic circuits to monitor the cells. The main functions of this electronic are cell balancing [8], cell bypass activation, and cell package voltage acquisition [7,24].



SAFT 2P12SVES180SA GS-YUASA MA190

Fig. 2 – Two examples of battery modules [7, 24].

3.1. BATTERY CELLS ARRANGEMENT

The battery cells must be arranged (series and parallel) to reach the capacity required for the space mission. Some requirements must be defined before selecting the appropriate cell arrangement, including eclipse time, the total power required, working voltage, and a maximum depth of discharge (DOD) [25]. The GEO orbit has a period of 24 hours with two Earth's equinox seasons per year (44 days for each) [3]. Figure 5 represents a typical eclipse duration of over one year for a GEO satellite orbit. The worst-case eclipse duration is 1.125 hours.

From literature [5,6], the power sizing bus of the satellite is done through a collection of data from different satellite mission and their designed power budget giving an empiric/linear formula improved and used frequently. The total power required for the satellite (payload & platform) depends on the size of the satellite; in our case, the total power is given by equation (1) [6]:

$$\begin{aligned} P_{Total} &= 1.16 \times P_{Payload} + 56, \\ P_{Total} &= 2956\ \text{W} \approx 3\ \text{KW}. \end{aligned} \tag{1}$$

The working bus voltage (Vbus) depends on the energy required; in our case, it is determined by the "D" factor calculated by [25]:

$$D = \sqrt{0.5 \times Power}\ , \tag{2}$$

$$\begin{cases} \text{if} \quad D < 28 & \Rightarrow \quad V = 28\,\text{V}, \\ \text{if} \ \ 28 < D < 50 & \Rightarrow \quad V = 50\,\text{V}, \\ \text{if} \ \ 50 < D < 100 & \Rightarrow \quad V = 100\,\text{V}. \end{cases}$$

The obtained value of D is 38.44. Hence, to cover the mission we should take an appropriate bus voltage (equal to or greater than 38.44) from the indicated intervals in (2) the Vbus is 50 V.

The depth of discharge (DOD) denotes the capacity consumed by the battery. Therefore, the DOD is a key parameter to define the number of battery life cycles. Typically, the maximum DOD for LEO satellites is about 40 %, and for GEO satellites, it could reach 80 % [6,10].

The procedure followed to define a specific configuration of the battery's module on board the GEO satellite is detailed in [9]. However, the following steps can summarize it:

Step 1: Define the number of packages in series (package signifies the number of cells in parallel).

Step 2: Define the Energy of batteries.

Step 3: Define Watt-hour of battery.

Step 4: Define the Capacity of the battery.

Step 5: Define the Number of cells in one package.

The designed results give that the battery power output shall be more than 4000 W at 80 % DOD, with one cell package open circuit failure. The battery is made up of one module that includes 30 Saft VES 180 cells (3P10S configuration).

4. PROPOSED BATTERY MANAGEMENT STRATEGY

The design of an excellent strategy to control batteries onboard satellites is paramount [15,16]. This strategy must ensure the efficient, safe, and reliable battery working, by considering the electrical power generated by SAP and the power needed by the satellite's equipment. In addition, it includes all the hardware and software necessary to measure and monitor the parameters of each cell and protect the cells by operating them in a safe operating area (SOA). For this reason, two concepts must be considered to perform an efficient battery management system (BMS); hardware concept and software concept, discussed in subsection 4.1 and subsection 4.2, respectively.

4.1. HARDWARE CONCEPT

The hardware concept of a battery management system must perform real-time control for the correct and safe operation of the Li-ion battery. This typically includes monitoring voltages, currents, temperature, failure recovery, and battery data communication [26].

The BMS topologies can be divided into centralized, distributed, and modular [27]. In the first category, a single central unit directly without an intermediary control all the battery cells. The cabling complexity and non-modularity are two limitations that cannot meet our proposal's requirements. For the second, an electronic is installed on each cell with a single communication link between the battery and master controller. It requires a management printed circuit board (PCB) for each cell, which is difficult, especially for many cells.

The modular topology comprises several slave units and a master unit. Each slave module handles a certain number of cells and communicates with the master via a communication protocol. This topology is ideally suited to the battery modules supplied by satellite battery manufacturers (see section 3). Hence, this topology is the most appropriate for our proposal.

In addition, data communication links are a challenge in critical applications, such as within satellites. The modular battery management system can be achieved using a series daisy-chain or parallel bus configuration. The daisy chain, such as isoSPI, is more cost-effective [14], making it the best choice for this work.

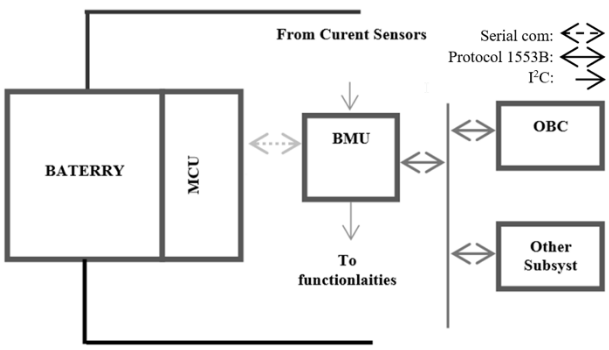


Fig.3 – BMS Hardware Architecture proposed.

Figure 3 shows the BMS hardware architecture proposed for this work. It has been inspired mainly by the available solution proposed in [14,28]. A slave module (MCU: module control unit) and a master module (BMU: battery master unit) are used.

The BMU is the system's core where the battery management software runs. The BMU must be based on two radiation-hardened microcontrollers: MC0 and MC1. The MC0 is the primary microcontroller of BMU, while MC1 is used for redundant safety. Moreover, the communication between BMU and the satellite's Onboard Computer is ensured by using two 1553 B buses (primary and redundant). A set of vital functionalities needs to be effectively achieved by the BMU, such as controlling the battery heaters and controlling the battery charging.

The control performed by the BMU is carried out based on information collected by MCU and the current sensors. The MCU measures cell voltages and temperatures. It should also perform the balancing function between different cell packages [8]. The redundancy is essential to reach the high reliability of the different MCU functionalities.

4.2. SOFTWARE CONCEPT

This section deals with the strategy used in the software part of the battery management system (BMS). Four modes are defined to perform an efficient battery management strategy for our proposal: Sunlight mode, Equinox mode, Charge mode and Discharge mode, as shown in Figure.4.

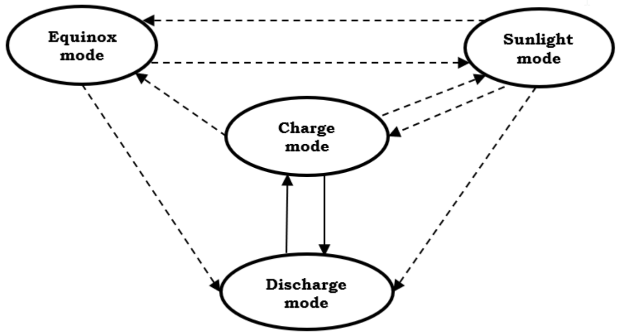


Fig.4 – Battery management strategy diagram.

4.2.1. SUNLIGHT MODE (SUN-MODE)

This mode should be active in the sunlight season. The main task of the battery management system in this mode is to control the ambient temperature to decrease the self-discharge phenomena in the battery. Although self-discharge is the amount of charge lost from the battery in rest time (battery in open circuit VOC), it can also affect the balance between the different battery cells. Indeed, full state of charge (SOC) and high temperature increase the Self-discharge rate and decrease the cycle life of Li-ion batteries [27]. Therefore, optimal ranges for SOC and temperature must be predefined to decrease the self-discharge rate and optimize the charging current implied. Hence, ranges of 60 % to 90 % of SOC, which correspond to 0 °C to 15 °C, are defined for this mode [29].

The transitions from one mode to another (Fig. 4) are defined as follows:

1- The transition from sunlight to equinox mode is done before the start of the equinox seasons.
2- This mode could switch to the discharge mode if the electrical energy provided by the solar panels is insufficient to power the satellite entirely.
3- The transition from this mode to the charge mode is done if the battery's capacity is less than or equal to 60 %.

4.2.2. EQUINOX MODE (EQUI-MODE)

The BMS operates in this mode during the two periods of the equinox (spring and autumn). The possible transitions from this mode to the others are defined as follows:

1- The transition from this mode to the sunlight mode is done after the end of the eclipse seasons.
2- The transition from this mode to the Discharge Mode is done directly if the power generated by SA is insufficient.

4.2.3. CHARGE MODE (CHAR-MODE)

The battery management (BMS) engages this mode when the battery needs to be recharged. The constant current with a constant voltage limit (CCCV) is the algorithm used to recharge the battery [27]. As described in subsection 3.2, CCCV is the algorithm recommended to charge typically Li-ion battery.

The temperature range of the chosen battery in this mode is between +10 °C and +35 °C, as specified in the VES 180 Saft datasheet [30].

Transitions from this mode to other modes are defined as follows:

1- In sunlight season, the transition from charge mode to sunlight mode is done when the battery's capacity
2- is greater than or equal to 90 %.
3- In equinox season, the transition from charge mode to the Equinox mode is done when the battery's capacity is greater than or equal to 95 %.
4- The transition from charge mode to the discharge mode is done directly if the power generated by SA is insufficient.

4.2.4. DISCHARGE MODE (DISCHAR-MODE)

The battery management enters directly into this mode if the electric power supplied by the SA is insufficient or non-existent to power the satellite. Only a transition from this mode is possible in which the transition to the charging mode is when the power generated by the solar panels becomes sufficient to power the satellite.

The expected range of battery temperature in this mode is between 0 and 40 °C, as specified in the datasheet of Saft VES 180 [30].

5. SIMULATION AND RESULTS

In this section, a simulation has been performed to study the SOC variation during one year of geostationary satellite satellite (SGO) operation. Two software are used to perform this simulation: systems tool kit (STK) and Simulink-MATLAB. The first one is used to calculate the power generated by the solar panels and estimate the eclipse durations during one year in Orbit (from 01-Jan-2019 to 31-Dec-2019). Simulink simulates the different modes of the proposed Battery management strategy. Figure 5 shows the diagram of this simulation; the StateFlow module includes the different BMS modes described in the previous section.

The simulation on STK consists in propagating on a geostationary orbit an implemented satellite model, recovering as output the solar intensity seen by its solar panels while preserving the angle of incidence (active attitude control); this for one year. This solar intensity once converted (photovoltaic effect) into electrical energy and conditioned according to the proposed BMS is implemented on MATLAB to provide the current necessary to charge our battery module. The switching between modes, explained in the previous section, is implemented in a Simulink block (figure 5). this last block interacts with the imposed seasonal course of the STK simulation introduced.

It should also be stressed that a power budget study is done (see section 3) to cover the power needs of the mission. On this basis, a solar panel sizing is directly implemented on the STK satellite model; a further sizing of the battery module is implemented in the Simulink illustrated battery block. the results of this simulation are discussed in the following.

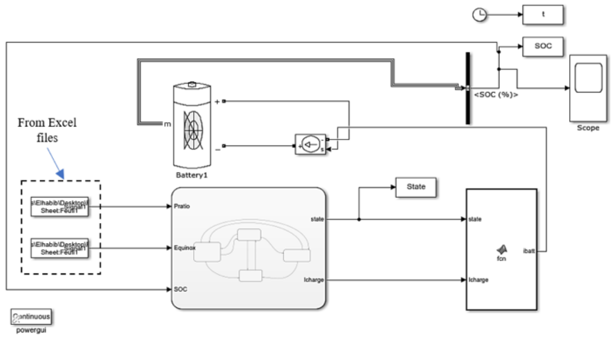


Fig.5 – Simulation of proposed battery Management Strategy.

The variations in the SOC of the battery during one year of service in orbit are illustrated in Figure 6. Although the worst case of SOC is 27.98 % (or a DOD equal to 72.02 %) as expected, this will be September 23 (autumn equinox), when the duration of the eclipse is maximum (1.121 hours).

This simulation result shows that the proposed strategy is less annoying for the design proposed which can go up to 80 % of DOD.

Therefore, we can conclude that this article's sizing and battery management strategy can meet the requirements.

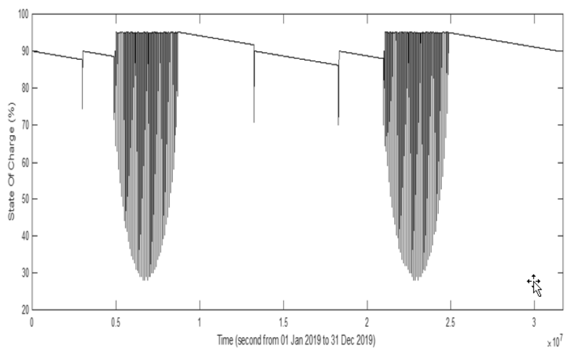


Fig.6 – Variations of SOC for one year (2019).

The pie chart, from the Fig. 7 represents the percentage in time for each mode. From this illustration, it became clear that the BMS operates most of the time under the sunlight mode (about 73 %). On the other hand, the time of discharge mode is the lowest (only 2 %).

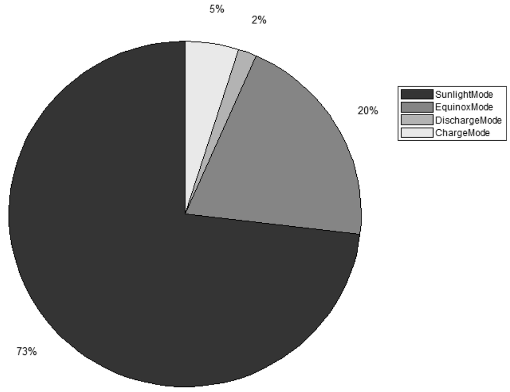


Fig.7 – Percentage in time for each mode.

6. CONCLUSION

This paper proposes, the appropriate operating environment and configuration of the electrical energy storage device for a small geostationary satellite. We also introduced a battery management system (BMS) to ensure the operation of the lithium-Ion battery under favorable conditions in terms of performance and safety; more details are given about the embedded tasks in the MBS to cover its different modes. To validate the proposed strategy, a simulation is done and discussed. The simulation results have clearly demonstrated that the sizing can perfectly meet the mission requirements. As a perspective, we are considering implementing the strategy proposed in a power control system to be proposed for our small GEO satellite.

It is necessary to emphasize that the proposed strategy is not depending on the technologies chosen to carry out this work, although it can be extended to other technologies or subsystem manufacturers than those presented as a reference in this work. In this context, the studies made, and the product simulation allow us to generalize to each type of lithium-ion battery.

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