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Modeling and Simulation of Thermal Faults in Batteries for Enhanced Safety

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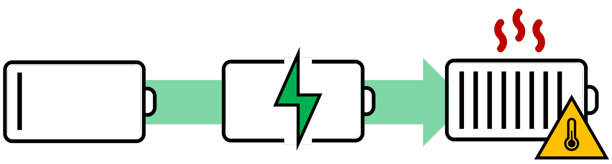
***Abstract*—Batteries are a central component of many complex systems, including mobile devices, sensors, electric vehicles, etc. Keeping the battery working in normal conditions avoids dangerous hazards for the user or the system itself and helps extend the device's life. The battery temperature is one of the most delicate aspects of these devices since some dangerous scenarios, like thermal runaway, could occur due to variable conditions. This paper uses a battery model of an electric vehicle from the automotive area as a case study to simulate the thermal response to normal usage. Then, thermal fault scenarios are modeled within equivalent circuital device descriptions and analyzed regarding state-of-charge, temperature, and voltage output. The findings presented offer a valuable starting point for improving the design phase of the batteries in multiple fields by testing fault scenarios already during simulation.**

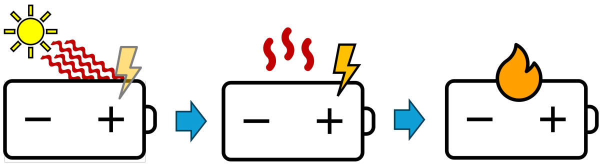
***Index Terms*—Battery design, Fault simulation, Safety**

I. INTRODUCTION

Nowadays, batteries are gaining more and more importance and appeal in modern technology, powering everything from portable electronics to electric vehicles and renewable energy systems [1]. Lithium-ion batteries dominate the battery market, and their composition constantly evolves to improve their performance and output [2]. Performance improvements usually refer to the amount of power the battery delivers, its capacity, how fast it can charge, and the temperatures it can withstand. This last characteristic is crucial, as sudden temperature changes can cause overheating, leading to serious problems, such as thermal runaway, short circuits, etc. [3]. It is well-known that once a critical state is reached in which the accumulated heat is much greater than the dissipated one, batteries can reach the point of igniting or even exploding, as pictured by Figure 1 [4]. Obviously, these kinds of incidents are dangerous in any setting in which they occur and, thus, must be avoided at all costs. The relevance of this potentially harmful phenomenon rises in areas such as automotive, where interest in producing electric vehicles is growing. The battery packs installed in electric vehicles reach significant sizes, which means bigger impact on humans and the environment. Unfortunately, recent cases of electric cars catching fire or exploding due to battery pack failures have been frequent [5]. For all these reasons, ensuring batteries' regular operation is critical to their use in various systems for safety purposes, but not limited to. Using a battery safely and maintaining a linear input and output current flow helps avoid additional performance problems, such as the total capacity [2]. High temperatures can degrade the internal components, such as the electrolyte and electrodes, accelerating wear and reducing the battery's overall lifespan [6].



(a) Battery overheats while charging.



(b) Battery with a fault caused by an external heating source.

Fig. 1: Battery overheating caused by different factors.

The design of a battery inherently involves a delicate tradeoff between performance and safety, where pushing the limits of energy density and power output can increase the risk of overheating-related issues. Simulation is a powerful tool in this context to accelerate the design process, enabling engineers to optimize battery performance while ensuring safety [7]. By replicating various, even extreme, operating conditions in a virtual environment, simulation facilitates evaluating and validating safety levels, thus contributing to developing more robust and reliable energy storage systems. This paper analyzes the description of a circuit model of a lithium-ion battery, introducing fault models related to both electrical and thermal components. The injection of such faults inside the circuits representing the battery behavior allows us to simulate the system under several scenarios. The main points of this paper

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are:

- Modeling the behavior of batteries as electrical circuits, which can be used both to design and to model already existing battery cells;
- The injection of fault models [8] into the equivalent circuit for simulating dangerous conditions related to overheating;
- Discussion related to the presented methodology based on simulation results: fault simulation helps test the batteries even in the worst conditions, sharpening their design phase.

This paper is organized as follows: Section II introduces how to model batteries' electrical and thermal aspects using electric equivalent circuits. Section III presents the simulation setup and the results achieved through fault injection. Section IV draws partial conclusions and describes planned future developments.

II. BATTERY MODELING

Let us now see how to model a battery and its thermal components through equivalent electrical circuits. With this representation, we can handle fault injection directly, thus easily simulating many scenarios.

A. Equivalent Circuits for Batteries

Lithium-ion batteries are components of several elements that generate an electrochemical reaction, thus delivering the stored energy upon a current demand. Studying the structural components of the battery in detail is the key element of its design: different amounts of certain elements rather than others will shift the balance of the construction compromise of this kind of battery. On the one hand, considering a specific volume occupied by the battery, filling up most of the space to increase energy storage enhances the battery's performance. On the other hand, battery safety is threatened, as there is no longer much space left for a potential cooling system. However, modeling all the chemical processes in detail is complex and unnecessary if one only wants to analyze battery behavior. Electrical equivalent circuit models are widely used for representing the dynamic behavior of batteries due to their simplicity, flexibility, and computational efficiency [7]. Modeling a battery using equivalent electrical circuits, as shown in Figure 2, involves representing its dynamic electrical behavior with components like resistors, capacitors, and voltage sources [9]. Specifically, the circuit branch on the left side shows the section devoted to the evolution of state-of-charge (SOC), represented with V_{SOC}, and the capacitor C_B represents the charge stored in the battery. It is discharged by the I_B load current, i.e., that required from the battery. In the right branch of Figure 2, we can see the nonlinear dependence between the voltage delivered by the battery and the SOC. The R_S resistance models the voltage drop due to the inherent ohmic losses of the battery itself and is also affected by SOC. This dynamic relationship can be easily derived from the battery datasheet if multiple SOC vs. voltage curves are reported. This approach provides a simplified and effective way to capture key characteristics of the battery, such as open-circuit voltage (OCV), internal resistance, transient responses, and SOC dependencies. By capturing the electrochemical processes in an abstracted electrical framework, electrical equivalent circuits provide a practical way to analyze and predict battery performance under various operating conditions. They are particularly effective for applications requiring real-time simulations, such as battery management systems (BMS) in electric vehicles, where speed and accuracy are critical. Those equivalent models can also be extended to include thermal and aging effects, enabling a more comprehensive evaluation of battery performance and safety over its lifecycle. This approach facilitates optimization and validation during the design phase, supporting the development of efficient and reliable energy storage systems.

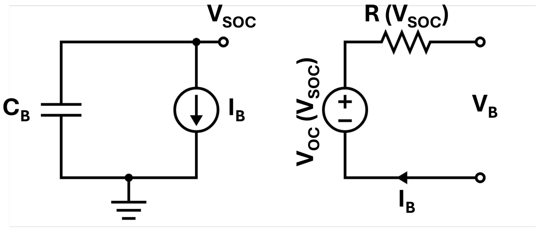

Fig. 2: Equivalent Circuit for modeling the behavior of a lithium-ion battery.

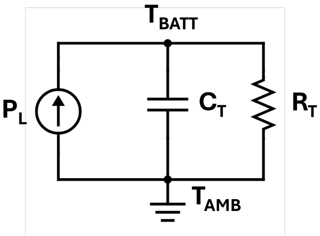

Fig. 3: Thermal Equivalent Circuit for measuring the temperature of a lithium-ion battery.

B. Thermal Battery Modeling

As anticipated in the previous section, extending the model of a battery with its thermal component facilitates its analysis and study from a safety perspective. Modeling the thermal equivalent circuit of a battery is highly useful because it provides a simplified and effective way to understand and predict how a battery manages heat during operation. Batteries generate heat due to internal resistance and electrochemical processes, and if not properly managed, this heat can lead to performance degradation, safety risks, and reduced lifespan. In this context, the concept of equivalent circuits returns to be the focus of this important modeling phase of batteries. In fact, the thermal component is modeled through an electrical circuit, exploiting the analogy between the electrical and thermal domains. In this way, we can easily model a heat flow through a flow of current, the thermal resistance of materials as electrical resistance, and the thermal capacity through electrical capacitors. An example of this type of thermal model is depicted in Figure 3, where the current generator P_L indicates the power dissipated by the battery, which will then be converted into emitted heat. R_T and C_T are the thermal resistance and capacitor of the battery, describing how the battery handles the heat produced. If we measure the voltage across this circuit, we obtain the temperature difference against the ambient. Then, feedback on the voltage of temperature on the electrical side of the model is provided according to [10].

III. THERMAL FAULT ANALYSIS OF BATTERIES

In this section, several faults that can affect batteries, both electrical and thermal components, are presented. Afterward, these fault models are applied to a case study based on the model shown in the previous section.

A. Multidomain Fault Modeling

One of the worst problems with lithium batteries is the risk of thermal runaway. This phenomenon occurs when the amount of heat the battery produces is greater than the amount of heat dissipated. This fatal consequence can happen for multiple reasons: an insufficient cooling system for the properties of the battery and extreme user conditions such as very high ambient temperature. Other causes may be exaggerated stresses on the battery, i.e., with too fast charge and discharge cycles. Thermal runaway is particularly problematic because it can cause battery fires or, in worst cases, explosions. There are other problems due to overheating of batteries besides thermal runaway: capacity losses, battery swelling due to gases produced by the heat, leakages due to an electrolyte breakdown, and internal short circuits [11, 12]. In this context, several fault models that can cause thermal runaway are injected into the equivalent thermal circuit. The first one is a parametric fault with respect to the value of the battery thermal resistance, varying from the nominal conditions. This fault can be caused by multiple scenarios, such as an inefficiency of the cooling system, assuming that our battery is part of a larger and, therefore, cooled battery pack. A change in the geometry of the battery due to an external impact can also lead to this fault. These circumstances do not allow the battery to dissipate heat normally, and thus we have a temperature increase as an effect. This fault is injected by raising or lowering the resistance value in the equivalent thermal circuit, thus changing the structural properties of the battery. Another fault that can cause battery overheating is the battery's exposure to external heat, perhaps produced by external agents or nearby components. The unintended heat source could then raise the temperature of our battery, thus changing its performance. This fault is modeled by injecting a source of electric current (equivalent to heat) into the equivalent thermal circuit, affecting the measured voltage (equivalent to temperature) value.

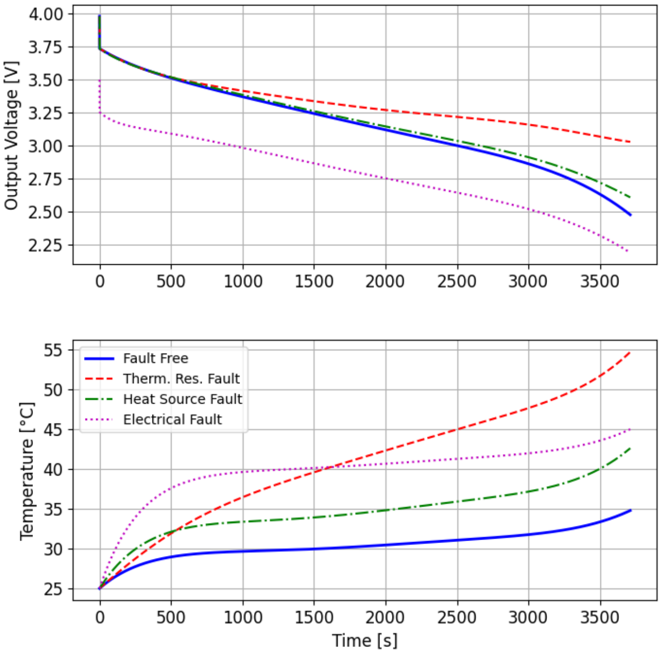

Fig. 4: Simulation of the battery model for a complete discharge cycle at 1C rate.

After analyzing the possible thermal scenarios, let us see what types of faults can affect the battery from a purely electrical point of view. Since the battery is represented through an electrical circuit, electrical faults that can be injected are state of the practice, constituting several standards such as ISO26262. An open-circuit fault occurs when electrical continuity is disrupted, preventing current flow. Causes include physical breaks, overheating, aging, or manufacturing defects. This fault is simulated by introducing a high-value resistor at the fault location. A short-circuit fault arises when normally separate circuit points make contact, creating an unintended low-resistance path. This allows excessive current to bypass the load, often due to insulation failure, external objects, or faulty components. It is modeled by adding a new branch between two nodes. In batteries, short circuits can lead to fires by damaging internal components. Additional fault models include voltage or current sources to simulate external influences and parametric faults, which alter nominal circuit element values.

B. Fault Simulation inside Batteries

The battery model following the structure shown in Figures 2 and 3 was coded in SystemC AMS, considering the Panasonic NCR18650B battery as a case study. This model was chosen because of the availability of datasheets and its use in multiple areas. The faults were added to the model by parametrization of the components meant to be faulty. A fault selector activates the single fault, choosing the faulty components thanks to a control signal. In the simulations, a full discharge cycle was performed, starting from a 100% charged battery. We simulated this scenario with constant current loads to recreate a linear discharge. The scenario with a current load of 0.5C, i.e., 1.6 A, is shown in Figure 5, while a current load of 1C, or 3.2 A, is applied Figure 4. The two graphs

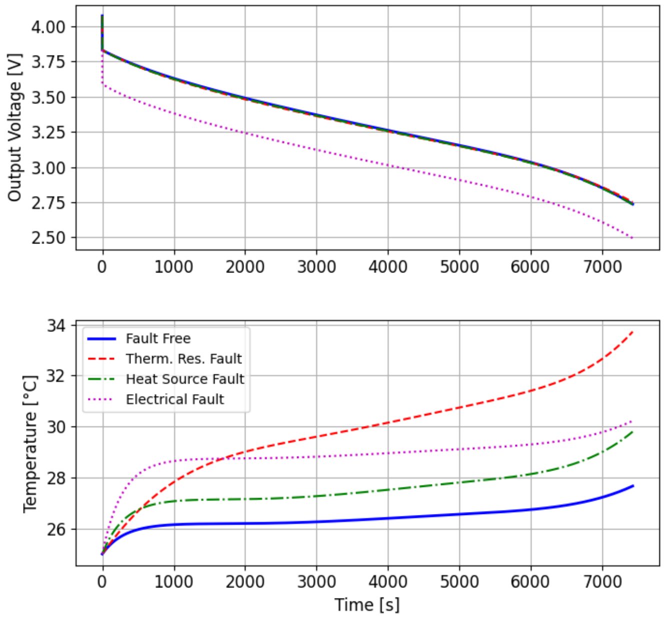

Fig. 5: Simulation of the battery model for a complete discharge cycle at 0.5C rate.

show four simulations each: with the blue color and solid line, the fault-free simulation is identified, which we need to make the comparison with the fault scenarios. The red color with a dashed line represents the thermal resistance fault, which means increasing the value of R_T (Figure 3) from 6.7Ω to 30Ω in both simulations. As an effect, we can see that the battery's temperature rises in both cases, but less heat is generated with a lower required current load. We can also see that the output voltage increases: this is due to the fact that the battery remains in the optimal use temperature range, as higher temperatures enhance ion mobility and reduce the viscosity of the electrolyte, facilitating better charge transport. This phenomenon holds until the optimal temperature range is passed; then, the components start being damaged by excessive heat. As shown in Figure 5, with 0.5C load current, we notice that the voltage is not much subject to this phenomenon, as the temperature rises more slightly compared to the same fault scenario (Figure 4). The green color and dash-dotted line identify the second simulated thermal fault, which is the presence of additional heat from outside. The effect of this fault is obtained by doubling the power loss of the battery, which represents the heat produced by the energy waste. Similar to the previous scenario, the internal battery temperature is increased too, but this time due to additional and constant heat. Although the heat growth appears more pronounced at the beginning, then the growth stabilizes and does not reach the values related to the thermal resistance fault. In multidomain systems, this setting can be very frequent since the heat could come from one or more nearby batteries or other electromechanical components. Last, the magenta color with a dotted line identifies the electrical fault injected. This fault represents the increase in R_S resistance in Figure 2 by 0.15Ω due to multiple possible causes, such as damage to the battery due to impacts, aging, or other defects. The fault shows that increased internal resistance increases the power dissipated by the battery, generating heat. This will cause less power output than normal and, therefore, a higher battery temperature.

IV. CONCLUSIONS AND FUTURE WORK

Batteries are at the center of today's technology research scene, and some technologies, such as lithium-ion, still suffer from many safety problems. Not only is preventing fires and explosions of any scale mandatory, but improving batteries' structural and compositional characteristics would enhance their performance and lifespan. Improving the quality of battery design by introducing tools to perform even severe failure simulations significantly impacts the final product's quality. This work aims to lay the foundation for developing a more advanced framework for testing more complex battery packs and simulating multiple fault scenarios. The proposed methodology already shows that the built model offers the ability to test the behavior of batteries by changing their parameters and exposing them to different fault conditions, depending on the scenario to be investigated. Developing systems for monitoring these batteries through BMS is another research goal.

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