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Brief Report

Thévenin's Battery Model Parameter Estimation Based on Simulink

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Abstract: Lithium-ion batteries (LIB) proved over time to be one of the best choices among rechargeable batteries. Their small size, high energy density, long life, and low maintenance need make them a prominent candidate for the role of the most widespread energy storage system. They have the potential to monopolize the green technology sector. An accurate definition of the parameters defining the behaviour of the battery in different operating conditions is thus essential, as their knowledge proves crucial in certain fields such as those that involve electric vehicles. This paper proposes the estimation of the values of the parameters of the Thévenin equivalent circuit of a LIB commercial cell. Experimental data obtained through constant current charge/discharge cycles are analysed through a Simulink model, and results are obtained as a function of the state of charge (SOC) for a fixed and controlled temperature value. The results achieved with the proposed model can monitor the salient parameters of the equivalent circuit with an error between 7 and 10%.

Keywords: parameter estimation; lithium-ion batteries (LIB); battery models; equivalent circuit model (ECM)



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1. Introduction

In recent years, the growing concern for both environmental issues related to atmospheric pollution and for the use of fossil fuels paved the way for a new “idea” of energy, green, ecologic, and economic, whose consolidation represents an important goal for the social and economic development of most countries. One of the main problems with this kind of energy is the difficulty with its storage. The development of production technologies is strictly connected to the progress in storage technology. The extensive use of renewable resources due to their highly uncertain nature needs the continuous use of electrical storage systems. Lithium-ion batteries in this context are an issue in the literature [1–3]. Being among the most advanced rechargeable batteries, they have drawn much attention from researchers and companies in the last decades. Li-ion batteries show significant benefits in terms of power and energy density, estimated life, working temperature range, and capacity [4–6]. Beginning with the production of the first rechargeable Li-ion battery in 1976, in approximately a decade the technological issues were addressed. The ceaseless evolution of these devices led to an extension of the fields of application of LIBs, starting from mobile phones in the early 1990s, to digital cameras, personal computers, and finally to the transport sector, both in electric and in hybrid vehicles [7]. This implied a substantial increase in the demand for LIBs, a trend which—according to previsions—will protract for the rest of the decade [8]. It is almost immediate to notice the importance held by the development of these batteries when we think of the ever-increasing functionalities of mobile phones, tablets, and personal computers, as well as the safety performance and low cost required to operate in electric vehicles. Furthermore, LIBs employment is strongly increasing for energy storage, to moderate the impact of the discontinuous and

fluctuating green energy supply from renewable sources on the electricity grid and to store excess energy produced in times of high supply and low demand. In this context, the cost for production of large-scale Li-ion batteries for grid application will need to be strongly cut down.

Intensive research is still being conducted on various types of materials for the electrodes, the electrolyte, and the separator, as well as on the physical behaviour and on the computer-aided monitoring of the batteries.

A key point towards carbon neutrality, the decarbonization of the transport sector is an issue that is currently being addressed worldwide by both public and private bodies. Although the diffusion of electric motors in the heavy transport sector is still irrelevant (with an exception being busses and trams for public transport)—and even less so for the aviation and maritime sectors—important progress was made in the last decades for light vehicles; either cars, motorcycles and scooters, or bikes.

LIBs are the energy source for electric vehicles; thus, their development determines the speed and the quality degree at which EVs grow. To date, an efficient and reliable battery monitoring system (BMS) is the key to grant a safe operation of LIBs. The central operator of lithium-ion batteries, the BMS must be able to balance the cells, ensuring uniformity between the individual elements in terms of nominal capacity, internal resistance, and self-discharge. The possibility of parameterising the battery elements is an important simplifying aspect of the operation process. There are various steps in the making of a BMS, as the analysis of requirements, the modelling and simulation, the research for a control strategy and the hardware experimentation all need an efficient model to identify the characteristic parameters of li-ion batteries [9–12]. Chen et al. studied lithium-ion batteries via an equivalent circuit model by varying the state of charge (SOC). The proposed model is third order in the RC network in Thévenin's model. Some physical evaluations were included, and the proposed model was validated using Simulink with experimental data [13]. Ding et al. proposed an improved first-order Thévenin model for LIB cells with an accuracy of around 1% with experimental data [14].

This study aims at determining the value of those parameters for the Thévenin equivalent circuit (1st and 2nd order) of a commercial LIB cell, whose experimental data were obtained through charge/discharge cycles at a fixed and controlled temperature and for different values of current.

2. Battery Model

To design an important system such as a battery monitoring system and for it to properly work, a suitable battery model—including charging/discharging characteristics, state of charge (SOC) and state of health (SOH) estimation, and real-time simulation—is indispensable. Different battery models were proposed through the years: thermal, electrochemical, multi-physics coupled, equivalent circuit models (ECMs), and machine learning models. Li-ion batteries' performance and safety depend on both internal and external parameters, such as temperature, vibrations, ageing, and self-discharge. A suitable model is chosen to allow the identification of the characteristics describing the battery, and it is the base for the estimation of its state. In the modelling section, three scales are considered: material level, cell level, and battery pack level. The first one is used to describe microscopic phenomena related to charge transfer, and diffusion of the lithium ions; the second one deals with transport, thermodynamic, mechanical, and kinetic phenomena; the third one considers the complete set of cells and studies its behaviour during operation.

ECMs are widely used, thanks to their efficient online implementation and modest computational cost, although their calculations are not always accurate to the highest degree [15]. Equivalent circuits consist of voltage sources, resistors, and capacitors which simulate the dynamic characteristics of the battery, to describe the relationship between tension and current shown when the battery is working [7,16–18]. The two most common circuits in literature are the first and second order Thévenin equivalent circuit and the PNGV (Partnership for a New Generation of Vehicles) [14,19,20]. These models offer two

significant benefits: they are not excessively complex, while still representing adequately the static and dynamic characteristics of LIBs. Therefore, they can be implemented without problems and their parameters can be found easily.

A schematic of the three circuits is shown in Figure 1. In all of them, the tension V_{oc} is the open circuit voltage (OCV), which varies non-linearly with the SOC, R_0 is the ohmic resistance of the electrolyte and the battery connection resistance, R_i is the polarization resistance, C_i is the polarization capacitance, and V_L is the load voltage [7,21]. The RC branch describes the non-linear polarization of LIBs. In the second order Thévenin circuit, two RC branches are present, while in the PNGV circuit there is an added capacitance term related to the OCV, $1/V'_{oc}$.

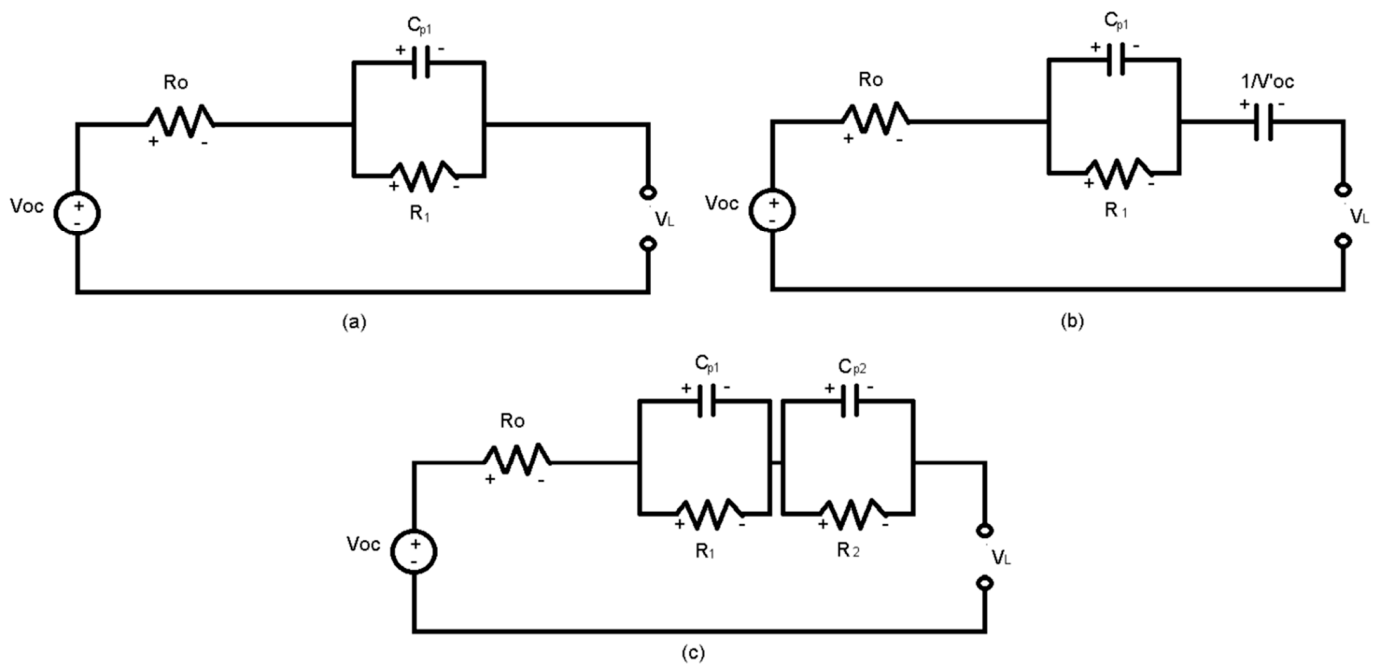


Figure 1. (a) First-order Thévenin, (b) PNGV, (c) Second order Thévenin.

In this study, the first- and second order Thévenin equivalent circuits were analysed, and their parameters were obtained as functions of the SOC, for different operative conditions during the discharge phase (constant current $1C$, $2C$ and $C/3$) fixing the temperature.

3. Experimental Set-Up

The battery under investigation is an NMC 811 cathode ($\text{LiNi}_{0.8}\text{Mn}_{0.1}\text{Co}_{0.1}\text{O}_2$) and graphite anode for a voltage window of 2.8–4.25 V. Data were extracted from an experimental study already published by Ma et al. (2016) [22]. The rated tension designed was fixed to 3.7 V, while the specific capacity ranged around 215 mAh/g at 4.2 V, as reported from Li-Fun Technology (Xinma Industry Zone, Golden Dragon Road, Tianyuan District, Zhuzhou City, Hunan Province, PRC, 412000).

The battery underwent two equal consecutive charge/discharge cycles, starting from a completely discharged state. It was initially charged at a constant current up to the rated tension, then the charging phase continued at constant tension until the SOC reached 100%. It was conducted at a constant current, and the test was repeated for different values of current, namely ($1C$), ($\sim 2C$), and ($C/3$). The second cycle started immediately after the null value of SOC had been reached. The tests were conducted with the internal temperature of the battery fixed at 25 °C. The temperature was fixed with a calorimeter even if the battery temperature could increase during the operation. This has a non-negligible effect on the parameters, and on the internal resistance; it depends not only on the SOC but also on the temperature.

4. Results and Validation

The results obtained through the Equivalent Circuit simulation have undergone a curve fitting—realized with the dedicated Matlab tool—according to the Ordinary Least Squares method. The first order Thévenin model (see Figure 1a) and the second order Thévenin model (see Figure 1c) were implemented in Matlab-Simulink [23]. The scheme implemented in Simulink is reported in Figure 2 where the terminal Voltage is implemented in Figure 3 as a submodule. The State of Charge (SOC) calculation is implemented in Figure 4. Looking at the estimated parameters (Table 1, Figures 5 and 6), one can see that the obtained data and the trends reported are comparable to those published in the literature with even third order Thévenin models [15,21,24].

Table 1. Estimated parameters—First order Thévenin model.

| | | 1C | | |
|---------|--------------|---------------------|---------------------|-------------|
| SOC (%) | V_{oc} (V) | R_0 (m Ω) | R_1 (m Ω) | Cp_1 (kF) |
| 20 | 3.853 | 9.143 | 0.472 | 58.55 |
| 60 | 3.979 | 6.112 | 0.399 | 68.25 |
| 100 | 4.157 | 2.315 | 0.201 | 290.9 |
| | | 2C | | |
| SOC (%) | V_{oc} (V) | R_0 (m Ω) | R_1 (m Ω) | Cp_1 (kF) |
| 20 | 3.941 | 6.891 | 0.412 | 65.2 |
| 60 | 4.021 | 4.960 | 0.313 | 124.0 |
| 100 | 4.135 | 2.572 | 0.180 | 350.9 |
| | | C/3 | | |
| SOC (%) | V_{oc} (V) | R_0 (m Ω) | R_1 (m Ω) | Cp_1 (kF) |
| 20 | 3.752 | 15.73 | 0.655 | 15.29 |
| 60 | 3.903 | 8.727 | 0.493 | 19.88 |
| 100 | 4.165 | 3.791 | 0.359 | 143.5 |

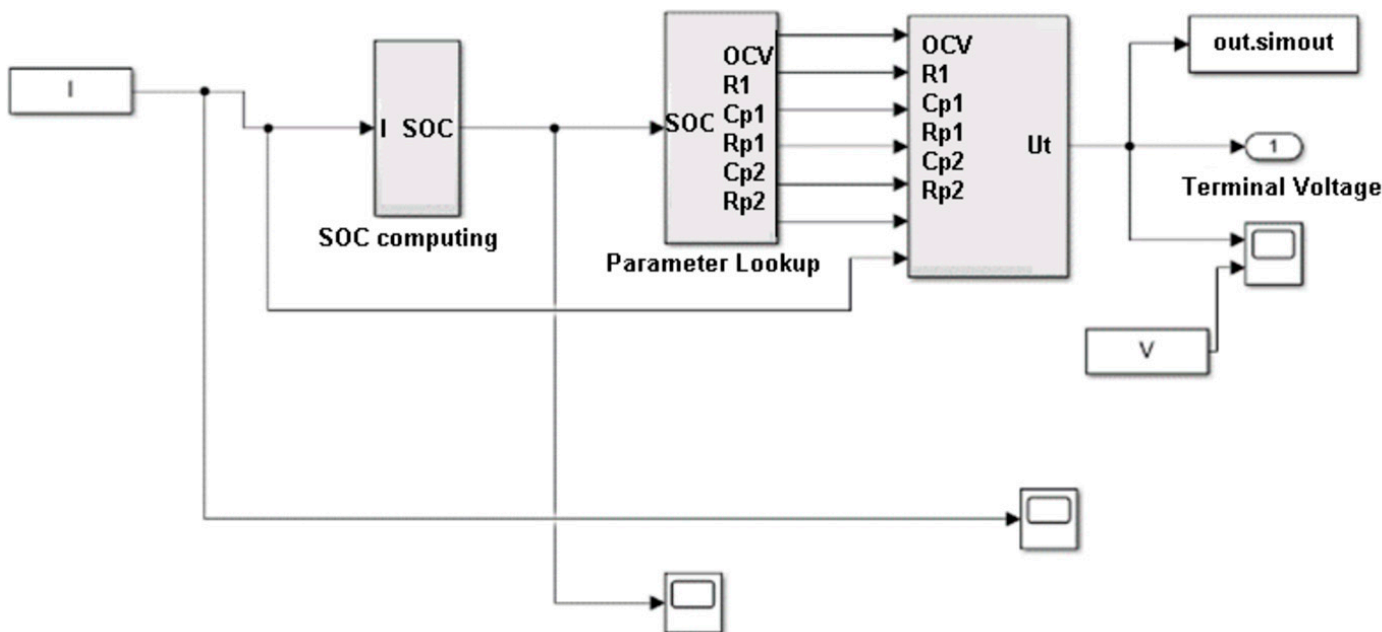


Figure 2. Simulation model for the second order RC circuit.

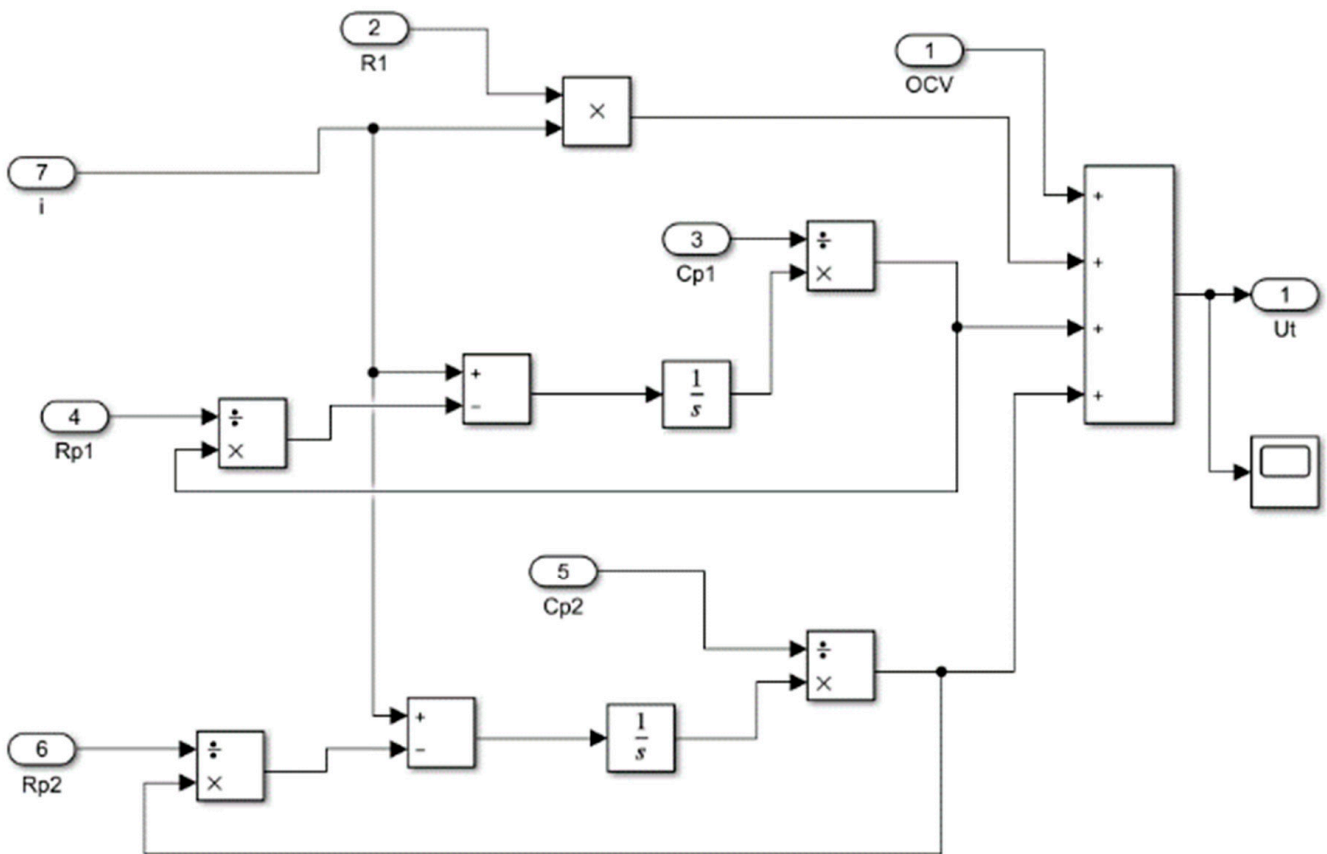


Figure 3. Terminal voltage calculation submodule of the second-order RC circuit.

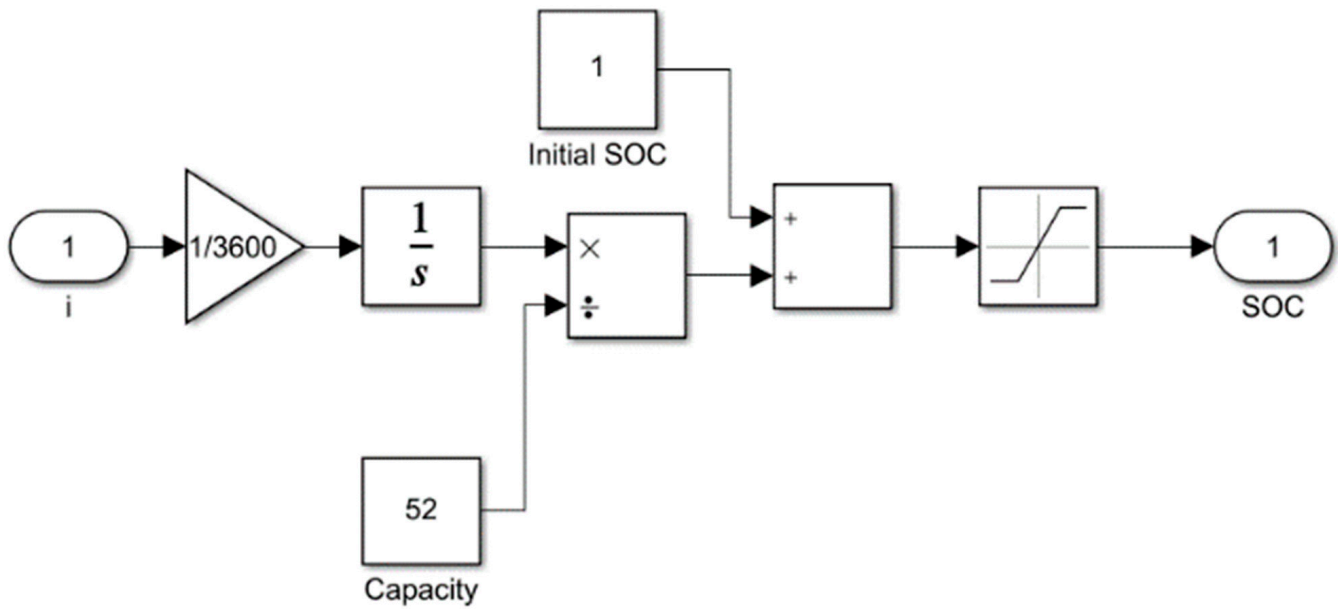


Figure 4. Simulation model for the SOC calculation.

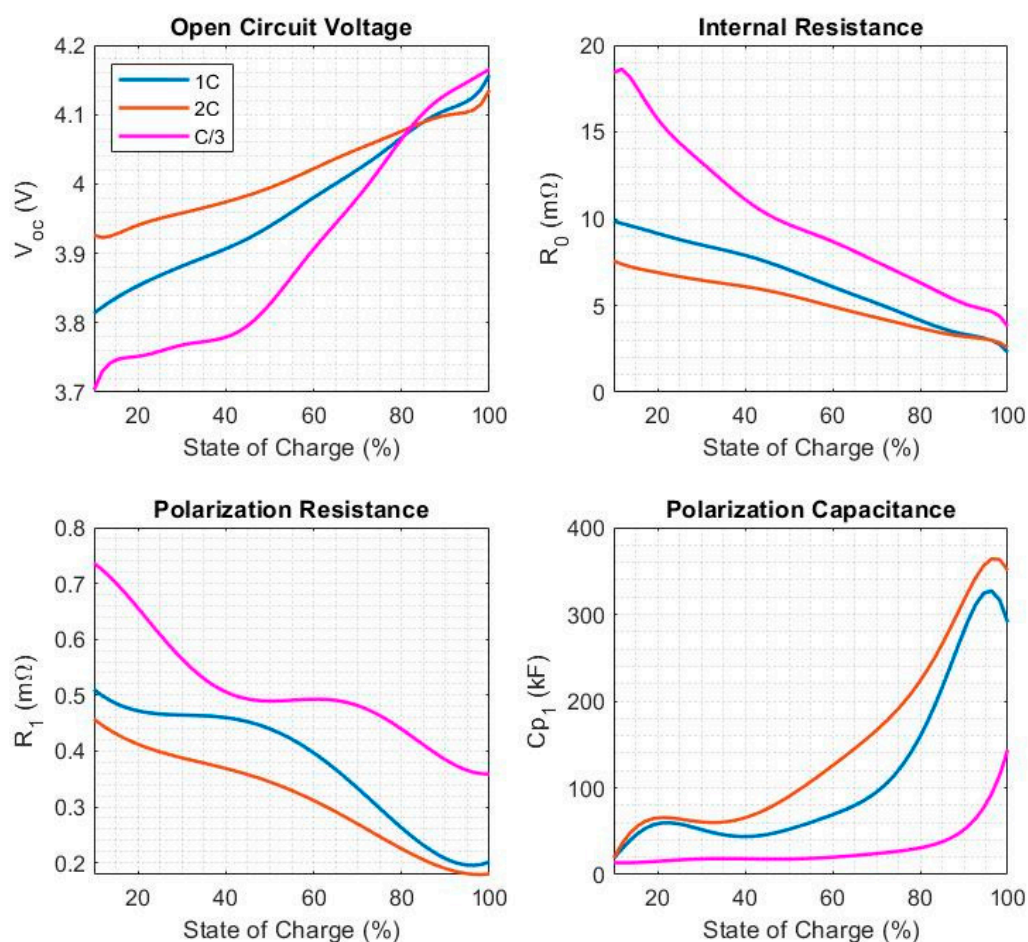


Figure 5. Estimated parameters—First order Thévenin model.

It is immediately apparent that the behaviour of the open-circuit voltage follows the discharge voltage; and thus, a decrease in the state of charge corresponds to a decrease in the open-circuit voltage (OCV). The internal resistance R_0 strongly depends on both the state of charge and the C-rate. Both are supported by the literature [24–26], and such a strong variation is also tied to the temperature rise during the test [27]. Similar considerations can be made for polarisation resistances R_1 and R_2 whose values, as for the internal resistance, increase when the discharge current is lower and with lower SOC. Yuan et al. focused on the BMS to control the LIB system. It was found that with increasing SOC values, the time constant and the polarization resistance decreased accordingly [28].

The polarisation capacitance parameters C_{p1} and C_{p2} behave oppositely with increasing the C-rate. In the initial phase of the discharge process (with a high SOC value), these parameters are high and decrease rapidly as the residual charge decreases. These values are following the study of Dongliang [29]. The polarization phenomenon plays a key role in the battery discharge process, and the initial moments are undoubtedly the most critical, as the current instantly goes from zero to the nominal value, instead of gradually increasing. If it is also considered that chemical reactions are not completely balanced in the initial stages, it is possible to justify such polarization behaviour for high SOC values. After obtaining the parameter values necessary to describe the equivalent circuits (Figures 2 and 3), it is possible to implement—again in Simulink—a model to check the consistency of the results with the experimental data, as proposed by Zhang et al. [7]. The model for the second-order circuit is shown in Figure 4 where both the terminal Voltage and the State of Charge (SOC) calculations are implemented as submodules and shown in Figure 6 and in Figure 5, respectively.

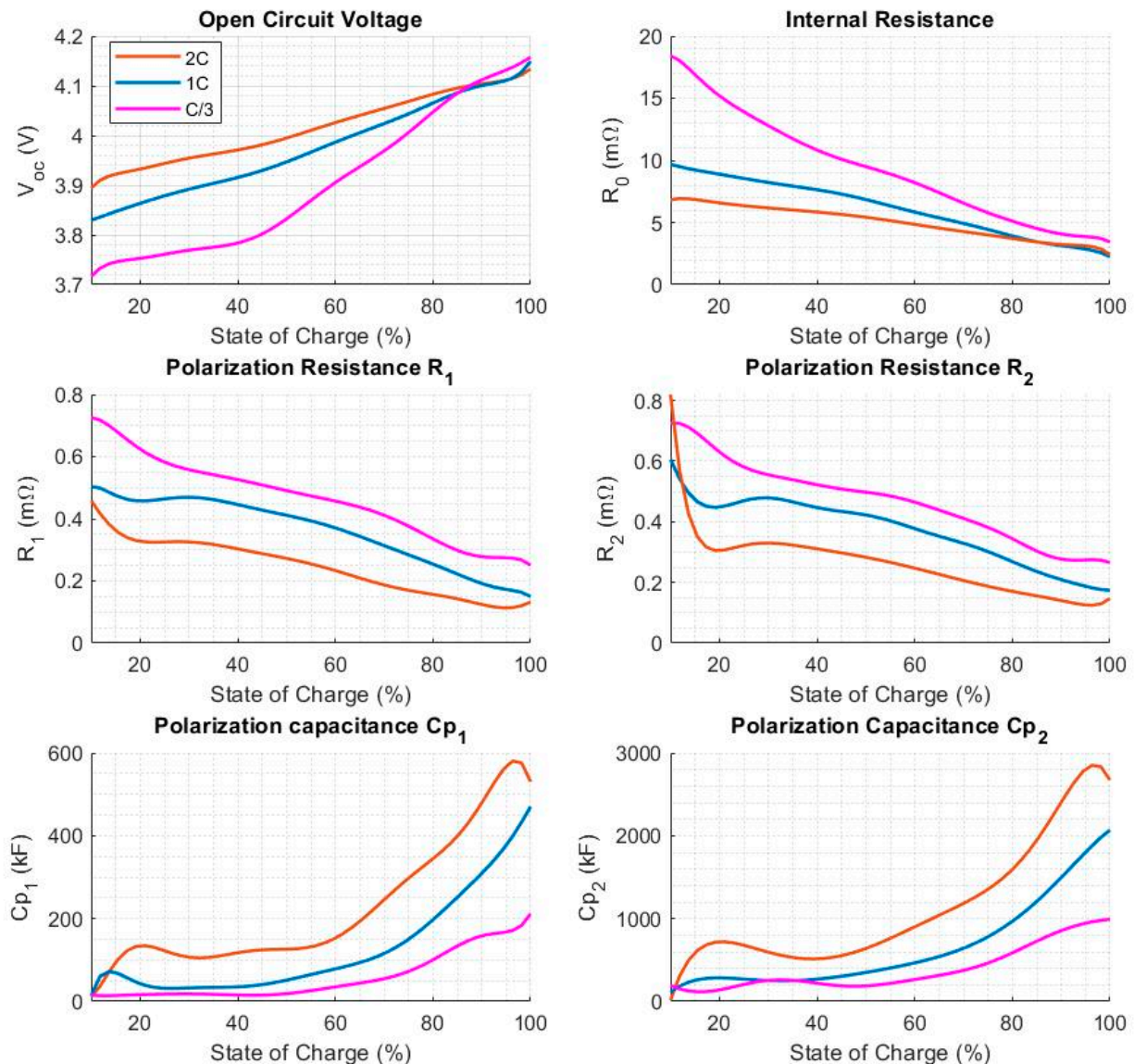


Figure 6. Estimated parameters—Second order Thévenin model.

To perform a comparison between the experimental and the simulated behaviour, the relative error of the voltage is reported in the following figure (Figure 7). It is possible to notice that the deviation is almost negligible in the intermediate phases, while it is more relevant in the starting and ending phases of the discharge process. Increasing the C-rate, with all other variables being equal, means that more current is available. With the first and final stages removed, there is an increase in the simulation error as the C rate increases. This increase is linked to the greater value of available current and the fact that this value can vary continuously over time, so there is a greater variability.

As previously stated, this is mainly due to three factors. First, the polarization mechanism plays a key role. Although the current through the battery is constant, it appears as being impulsive in the first moments of the process, varying instantaneously from a null value to the test value. Furthermore, electrochemical reactions in these phases tend to be unbalanced. Finally, there is an important influence of the battery temperature, which will reasonably increase during the discharge, thus reaching a higher value in the last phase.

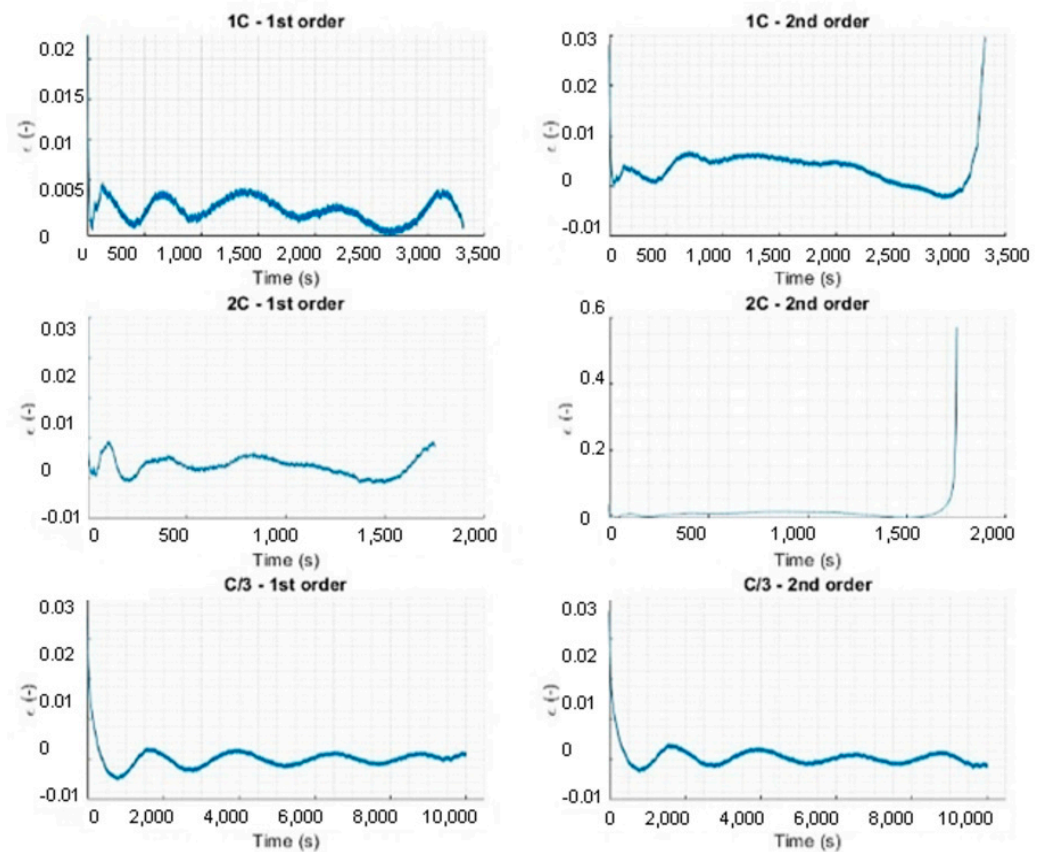


Figure 7. Simulation output error.

5. Conclusions

Various categories of models are generally used to study Li-ion batteries: thermal, electrochemical, multi-physics coupled, equivalent circuit models (ECMs), and machine learning based. Among them, ECMs are widespread, thanks to their efficient implementation and low computational costs. In this work, the parameters characterizing the first- and second-order Thévenin equivalent circuit have been estimated as a function of the state of charge and the discharge current, through a Simulink model at a fixed temperature value. The operating temperature is an important variable for the SOC estimation. The results were then validated using another model, simulating the voltage behaviour during discharge, and comparing it with the experimental data. The estimation error achieved is below 10%. Future studies will be focused on the effect of temperature on the estimation error using a similar model here developed.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

| | |
|---------|--|
| BMS | battery management system |
| Ci | polarization capacitance |
| DOD | depth of discharge |
| ECMs | equivalent circuit models |
| EVs | electric vehicles |
| LIB | lithium-ion batteries |
| OCV—Voc | open circuit voltage |
| PNGV | partnership for a new generation of vehicles |
| R0 | internal resistance |
| Ri | polarization resistance |
| SOC | state of charge (%) |
| VL | load voltage |

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