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Review of battery models and experimental parameter identification for lithium-ion battery equivalent circuit models

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ABSTRACT

The growing use of electric vehicles has led to an ever-increasing demand for efficient and reliable management systems to control the behavior of lithium-ion batteries, especially with respect to heat generation and state-of-charge. Understanding these patterns constitutes a major new challenge for these batteries, as remaining ignorant of their behavior can result in decreased performance, shorter service life and even safety dangers. This review provides an overview of the different modeling techniques applied to simulate battery behavior. Different methods using equivalent electrical circuit models are discussed, covering both simple battery models and more complex equivalent electrical circuit models, with a focus on the 2RC-Thévenin circuit model. In this context, parameter approach methods for these systems are reviewed. In addition, laboratory tests are run to identify the various model parameters for a lithium-ion battery. This comprehensive study is designed to guide scientists and engineers in the selection and use of suitable tools for state-of-charge and battery health studies.

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NOMENCLATURE

R_s : Series resistance of the battery
I_b : Charging or discharging battery current
U_b : Battery terminal voltage
E_b : Open circuit voltage of the battery
R_{PC} : Resistance due to chemical reactions
C_{PC} : Capacitor dynamic behaviour of battery cell
C_n : Plate capacitance

1. INTRODUCTION

Lithium-ion batteries are becoming increasingly embedded in the normal daily lives of the majority of the population, powering a range of commonly employed devices, from cell phones and renewable energies to more advanced systems such as electric vehicles [1]–[3]. As a result, there is an ongoing demand to develop these batteries to satisfy the ever-increasing needs of technological progress, and this requires special attention [4]. One of the most critical requirements is the efficient and effective electrical behavior modeling of lithium-ion batteries [5]. In fact, simulating battery voltage with an accurate model can offer crucial feedback for selecting the optimum battery type based on application needs [6], [7]. In addition, an accuracy battery modeling can increase the efficiency and reliability of the battery management system (BMS) by anticipating the electrical behavior of batteries in real time [8].

Lithium-ion battery models are usually classed in terms of the way in which their electrical behavior is represented, into two different classes: equivalent circuit models (ECMs) and physics-based models (PBMs) [9]. ECMs are essentially based on the adaptation of cell voltage behaviour using time-domain (TDM) or frequency-domain (FDM) measurements [10], [11]. More precisely, TDM-based ECMs can streamline the BMS and be helpful in a range of applications [12], [13]. It should be noted that ECM-based methods provide the advantages of high efficiency and low computing power to identify the dynamic and steady-state characteristics of lithium-ion batteries. Even though these ECMs only consider the diffusion performance of the battery, treating other physical phenomena as ohmic, they still provide crucial information for estimating battery behavior, such as state-of-charge [14], [15], while keeping implementation simple. As a result, they can be easily deployed in low-cost microcontrollers for practical real-time engineering applications, such as in the context of electric vehicles [16].

In this article, the ECMs discussed range from the simple (Rint model, Thevenin model) to the complex (partnership for a new generation of vehicles (PNGV) model, 2RC-thevenin circuit). The latter involves two series-connected resistors and two parallel RC branches. The two series resistors account for high- and medium-frequency power losses caused by ohmic and interfacial losses, respectively. The parallel RC branches cover low-frequency losses such as those related to diffusion effects. The parameters of this ECM extend over the whole frequency range of battery function, and take into consideration changes in state-of-charge (SoC) and charge-discharge current. The identification of the parameters and the efficiency of the ECM of the 2RC-thevenin circuit have been tested experimentally on an array of cylindrical 3.25 Ah lithium-ion battery cells.

The rest of the article is structured as follows: in section 2, an overview is presented and characteristics of batteries, particularly lithium-ion batteries. Section 3 introduces the various ECMs characterizing batteries. Section 4 is dedicated to the procedure for identifying model parameters through experimental methods for the 2RC-thevenin circuit ECM model. Section 5 discusses and compares the results. Section 6 concludes the paper.

2. DEFINITION AND CHARACTERISTIC QUANTITIES

A battery is a reversible physico-chemical system able to transform chemical energy into electrical energy by redox reactions [17], [18]. The electrical energy is stored in the form of chemical energy when the system is in accumulator mode (the system is in charge mode) and then restored in the form of electrical energy when it is in generator mode (the system is in discharge mode). A battery is generally characterized by the association of several cells [19], [20].

The Li-ion battery's fundamental cell comprises various components, including two electrodes as mentioned in Figure 1 (negative and positive) separated in distinct compartments, linked by an external circuit, current collectors (aluminum for the positive and copper for the negative) connected to terminals, an ionic conductive electrolyte (lithium salt in an organic solvent facilitating Li+ ion movement), a porous separator preventing direct electrode contact, and a rigid or flexible case enclosing the system. In the described operation, considering a graphite negative electrode and a manganese oxide positive electrode, the charging process involves lithium-ion reduction and insertion into graphite on the negative side (cathode) and oxidation of litigated manganese oxide on the positive side (anode), releasing Li+ ions and electrons. During discharge, these reactions are reversed, with lithium ions leaving the graphite anode and manganese oxide undergoing reduction on the cathode [21]–[23].

A battery is defined by its electromotive force (fem), denoted as Eb (SoC), measured in volts and determined by the oxidation-reduction couples of the materials and the reaction progress. It represents the difference in working potentials between the two electrodes. Another crucial characteristic is capacity (Q), measured in coulombs or more commonly in ampere-hours (Ah), dependent on the redox couples' nature and the quantities of species involved in the reactions.

Batteries are typically assessed using specific energy, expressed in Wh/kg (or Wh/L), a product of fem and capacity, indicating the energy delivered per unit of mass (or volume). Specific capacity, expressed in mAh/g, represents the electrical charge the battery can provide per unit of mass during a complete charge and discharge. Battery life is evaluated through cyclability, indicating the number of continuous charge/discharge cycles it can perform. To operate efficiently, electric vehicles and electronic devices, in general, require a source of energy, typically supplied by a battery. Table 1 offers an overview of the primary battery technologies, ranging from lead-acid batteries to lithium-ion batteries.

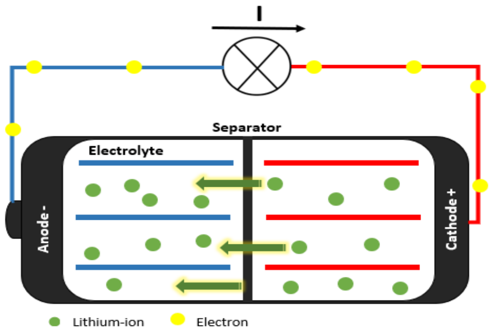


Figure 1. Working principle of a lithium-ion battery-during the charge

Table 1. Comparison of battery technologies: features, advantages, and limitations [24], [25]

Battery technology	Overview	Advantages	Disadvantages	Applications
Lead-acid batteries	Invented in 1859, used until the 1980s in electric cars. Large size and weight, low storage capacity, inexpensive, and easy to produce or recycle. No longer used for traction.	Inexpensive, easy to produce, and recycle.	Low storage capacity, heavy.	Accessories or equipment specific to the thermal world (e.g., starter motor).
Nickel-cadmium (NiCd) batteries	Used in the 90s for electric vehicles but banned due to cadmium toxicity. High storage density, 500-1,000 recharge cycles, but affected by memory effect.	High storage density, long lifespan.	Memory effect, cadmium toxicity.	Previously used in electric vehicles.
Nickel-metal hydride (Ni-MH) batteries	Dominated the hybrid vehicle market in the early 2000s. Economical and successful due to the absence of heavy metals.	Economical, absence of heavy metals.	Moderate energy density.	Hybrid vehicles in the early 2000s.
Lithium-ion batteries	Developed in the early 1990s, gradually became the preferred technology. Long service life, high energy density, no memory effect. Requires precise conditioning and control. Multiple electrode materials available.	High energy density, long service life, multiple electrode materials.	Requires precise conditioning, control, and can be expensive.	Widely used in electric vehicles, consumer electronics.
Lithium polymer batteries	Variant of lithium-ion technology with gel-based electrolyte. Less dangerous and more stable but more expensive. Requires a special charger.	Less dangerous, more stable.	More expensive, requires a special charger.	Consumer electronics, where safety is a priority.
All-solid-state batteries	Conceptualized for the distant future. Replaces liquid electrolyte with a solid material (plastic polymer, compacted inorganic powders). Promises increased energy density and stability, simplifying thermal management. Currently at the laboratory prototype stage.	Increased energy density, stability.	In early development, not yet commercially available.	Potential future use in automotive and electronics.

3. BATTERY MODELING

3.1. Electrical circuit of lithium-ion batteries

Battery modeling consists of developing a set of equations or rules to describe a phenomenon in a reproducible and simulatable way. The model resulting from the modeling is used to predict the behavior of the battery and to better understand its operation according to known solicitations. It is also a good way to control its complexity and ensure its consistency [22], [23], [26].

The modeling of an information system allows to obtain consolidated representations under different levels. It leads to efficiency gains, reduces risks and optimizes the budget. It also makes it possible to limit the redundancy of certain data as much as possible, which makes the use of the accumulator easier to manage. It allows to deduce models from others and to prioritize the models describing a given phenomenon, according to their complexity, speed, taking into account all the characteristics and precision.

3.2. The R_{int} model

The equivalent circuit diagram for this model is provided in Figure 2. The R_{int} model is a extremely practical one, involving an ideal voltage source $E_b(SoC)$ that describes the open-circuit voltage of the battery in series with a simple internal resistance R_s is connected to all the components that make up the battery, and covers: the resistance of the active electrode, the electrolyte resistance, as well as the contact resistance between cells and electrodes. I_b is the charge current, with a positive value on discharge and a negative value on charge, U_b is the terminal voltage. Because of its low precision, it cannot reflect the impact of the electrochemical process inside the cell; and it is based on a linear model, which is unsuitable for estimating the SoC in a practical application.

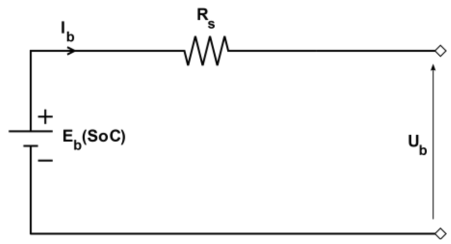


Figure 2. The Rint model of battery

when completely charged, the terminal voltage E_b may be determined by measuring the open circuit voltage, and R_s can be determined by connecting a load and detecting both the terminal voltage and current.

The electrical behavior of the circuit can be expressed by the (1),

$$E_b(SoC) = U_b + I_b R_s \tag{1}$$

3.3. Thevenin model

Based on the R_{int} model, a parallel RC cell is incorporated into the equivalent Thevenin model Figure 3 to simulate the effect of polarization in the charge and discharge process of Li-ion batteries, R_{PC} resistance due to chemical reactions C_{PC} represents dynamic behaviour of cell. Otherwise, it can partially represent the dynamic characteristics of Li-ion batteries, which compensates for the limitations and shortcomings of the R_{int} model.

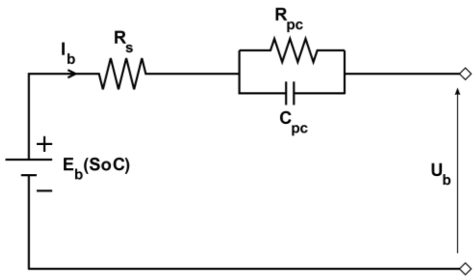


Figure 3. The hevenin model of batterie

The electrical behavior of the Thevenin model of the Figure 3 can be expressed by the (2) and (3):

$$\frac{\mathrm{d}U_p}{dt} = -\frac{U_p}{R_{pc}C_{pc}} + \frac{I_b}{C_{pc}} \tag{2}$$

$$E_b(SoC) = U_b + U_p + I_b R_s \tag{3}$$

However, in view of the complexity of actual battery behaviour, the dynamic performance of a single RC system is limited and unable to take into account the impact of polarization or other factors that affect the battery.

3.4. The PNGV model

PNGV model, as illustrated in Figure 4, adds a plate capacitance C_n in series based on Thevenin's equivalent circuit model to describe the open circuit voltage change generated in the charging current accumulation time. Therefore, its accuracy is higher than that of Thevenin's model [27].

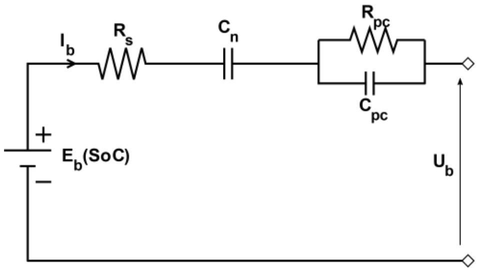


Figure 4. The PNGV model of battery

The electrical behavior of the circuit of the Figure 4 can be expressed by the (4) to (6):

$$\frac{\mathrm{d}U_p}{dt} = -\frac{U_p}{R_{pc}C_{pc}} + \frac{I_b}{C_{pc}} \tag{4}$$

$$\frac{\mathrm{d}U_n}{dt} = \frac{I_b}{Cn} \tag{5}$$

$$E_b(SoC) = U_n + U_p + U_b + I_bR_s \tag{6}$$

however, this model is challenging to identify and involves high computational complexity, making it unsuitable for real-time SoC estimation in practical applications.

3.5. The 2RC-thevenin circuit

An improved circuit model (or 2RC-thevenin circuit) is defined as the dual bias model to refine the description of the bias characteristics and simulate the concentration bias and electrochemical bias separately. This model, as shown in Figure 5, consists of an open circuit voltage E_b(SoC) of internal resistors (R_{pa} and $R_{p'c'}$) to represent the effective resistance characterizing electrochemical polarization and concentration polarization and effective capacitances (C_{pa} and $C_{p'c'}$) that are used to characterize the transient response during power transfer to/from the battery and to describe electrochemical polarization and concentration polarization separately.

The 2RC model simplifies the representation of complex electrochemical processes occurring in a lithium-ion battery. These elements enable the capture of delays associated with the battery's responses during charge and discharge cycles. The specific values of these elements can be determined through model fitting based on experimental measurements.

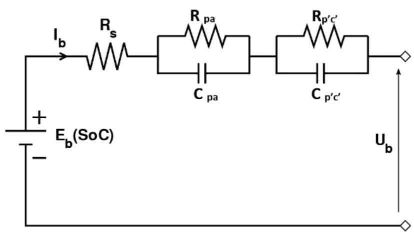


Figure 5. The improved circuit model of battery

Alternatively, the (7) to (9) can be used to express the electrical behavior of the model, as depicted in Figure 5.

$$\frac{\mathrm{d}Upa}{dt} = -\frac{U_{pa}}{R_{pa}C_{pa}} + \frac{I_b}{C_{pa}} \tag{7}$$

$$\frac{\mathrm{d}Up\prime c\prime}{dt} = -\frac{U_{p\prime c\prime}}{R_{p\prime c\prime}C_{p\prime c\prime}} + \frac{I_b}{C_{p\prime c\prime}} \tag{8}$$

$$E_b(SoC) = U_{pa} + U_{pc} + U_b + I_bR_s \tag{9}$$

4. PROCEDURE FOR IDENTIFYING MODEL PARAMETERS THROUGH EXPERIMENTAL METHODS

4.1. Experimental setup

This sequence depicts the different characteristics of the previous ECM so that one can simulate on MATLAB Simulink [5], [28]–[31]. In order to obtain the experimental data needed to identify battery parameters, an automatic acquisition system has been set up using the electronic components shown in Figure 6. The system consists of the following components: the chosen battery is a Li-ion battery with a nominal voltage of 12 V and a capacity of 17 Ah; Load is a 10 Ω resistor with a power of 25 W is used to discharge the battery; LOGBOX SE acquisition board is a data logger with analog and digital inputs, enabling several instruments to be connected simultaneously; an arduino Uno board; relay that used in switching mode to switch between discharge and relaxation modes. With the help of battery’s curve and the set of equations of each equivalent circuit, one can determine the internal parameters of battery for each ECM.

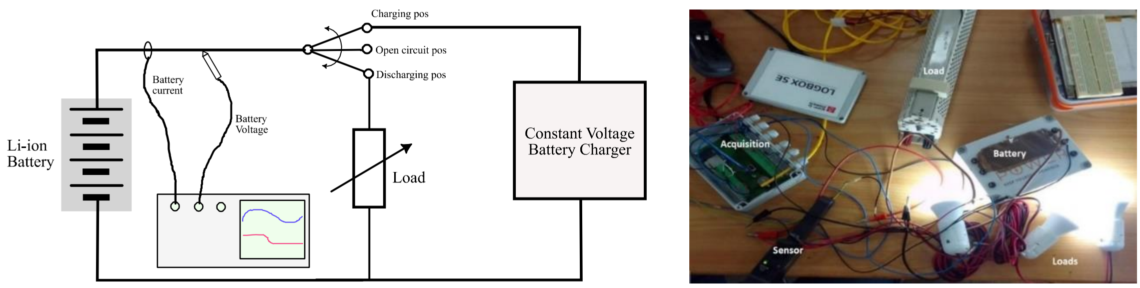
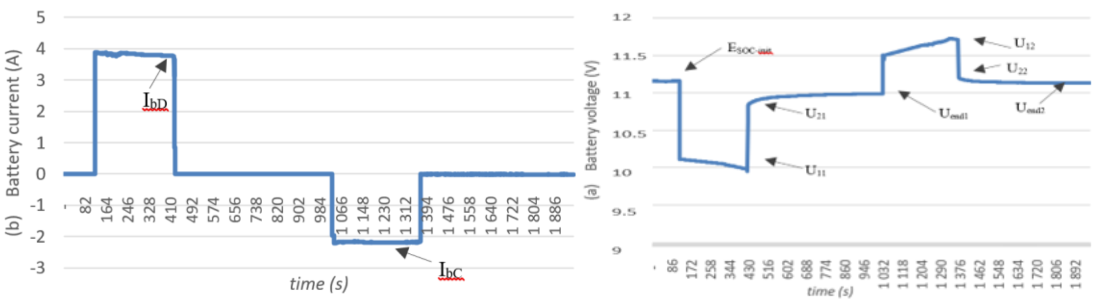


Figure 6. Experimental set-up

4.2. Measurement results

In the context of an experiment on a lithium-ion battery aimed at determining the parameters of the ECM, Figure 7 depicts the behavior of the battery during a charge/discharge test. As illustrated in Figure 7(a), a discharge cycle was initiated by subjecting the battery to a load for 372 seconds. Subsequently, a charging phase was initiated, utilizing a constant current for 322 seconds. Following this current profile, the voltage across the battery terminals is given in Figure 7(b). The voltage and current curves observed during these cycles, as shown in Figure 7, represent crucial data points for extracting parameters in the 2RC-Thévenin ECM model. This in-depth analysis aims to enhance our understanding of the battery's behavior under different operational conditions, providing valuable insights into the broad field of energy storage and management.



(a) (b)

Figure 7. Measured terminal voltage battery (a) and current (b) during charge and discharge phases test

4.3. Series resistance identification

First, we will determine the series resistance R_S, which is the common parameter of all models considered in this study, by (10) and (11):

$$R_{SD} = \frac{U_{21} - U_{11}}{I_{bD}} \quad (10)$$

$$R_{SC} = \frac{U_{22} - U_{12}}{I_{bC}} \quad (11)$$

From the Figure 7, with R_{SD} and R_{SC} are the series resistances determined during the battery discharge (from U11 to U21) and charge (from U_{12} to U_{22}) periods respectively. The difference of a few milliohms between the R_{SD} and R_{SC} values can just as easily be ignored in certain applications.

4.4. Identification of RC network parameters

The RC model parameters are determined from the measured voltage signals generated during the subsequent battery (U_{21} to U_{end1}) and charge (U_{22} to U_{end2}) intervals. Figure 7(a) represents the recuperation interval after discharging the battery. The RC system parameters are taken from (2) and (3) as (12) and (13).

$$R_{pcD} = \frac{A}{I_{bD}(1 - e^{-\frac{t}{\tau}})}, \quad C_{pcD} = \frac{\tau}{R_{pcD}} \quad (12)$$

$$U_b = U_{end1} - Ae^{-\frac{t}{\tau}} \quad (13)$$

with A and τ the factors of the exponential correspondence formula in Figure 8, and I_{bD} the discharge current. The RC parameters for the battery charging interval are determined in a related way, as are the RC parameters.

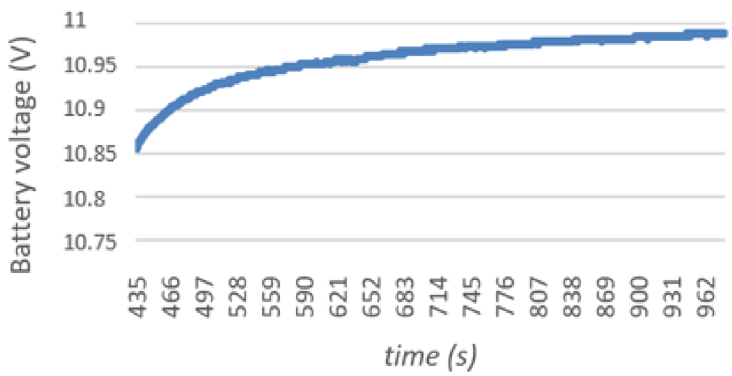


Figure 8. Approximation by a single RC model of the voltage measured at the battery terminals during the recovery interval following battery discharge

Remember that the RC system characteristics identified for Thevenin model are as well applicable to the PNGV system. The RC model response parameters for the DP system are defined by the same recovery answers as in the last example. The case in Figure 8 is provided for the same range of recovery as in Figure 7. The operation is similar to that shown for battery recuperation. The approach is the same as that used for the Thevenin model, alongside the respective parameter equations given (14) and (15).

$$R_{paD} = \frac{A1}{I_{bD}(1 - e^{-\frac{t}{\tau 1}})}, \quad C_{paD} = \frac{\tau 1}{R_{paD}} \quad (14)$$

$$R_{pcD} = \frac{A2}{I_{bD}(1 - e^{-\frac{t}{\tau 2}})}, \quad C_{pcD} = \frac{\tau 2}{R_{pcD}} \quad (15)$$

4.5. Determination of series capacitance

Series capacity is specified as the ramp between load (ΔQ) and voltage variation (ΔU), with ΔQ taken as a product of the battery current and the time period Δt in which the current is being applied. The value ΔU is taken as the open-circuit voltage difference during the entire current period, which includes battery recovery. All these parameters can be obtained from Figure 8 as illustrated (16) and (17).

$$C_{nD} = \frac{I_{bD}\,\Delta t}{E_{SOC-init} - U_{end1}} \quad (16)$$

$$C_{nC} = \frac{I_{bC}\,\Delta t}{U_{end1} - U_{end2}} \quad (17)$$

The addition of the C_{nD} are superior to the C_{nC} indicates that the reliability of of the ECM can be considerably reduced if the dependence of C_n on the battery operating regime is neglected.

4.6. The equivalent model parameters

Based on the measurements and formulas mentioned earlier, Table 2 summarizes the characteristics of the 2RC-Thévenin circuit battery system (7) to (9). The parameter values are as follows: Rs (internal resistance) is 0.226 Ω, R_{pc} (resistance due to chemical reactions) is 0.035 Ω, C_{pc} (capacitor that represents dynamic behaviour of battery cell) is 8.74 kF, C_n (plate capacitance) is 5.32 kF, $R_{p'c'}$ is 0.0312 Ω, Cp'c' is 9.775 kF ($R_{p'c'}$ and Cp'c' model diffusion and reaction phenomena at a finer scale or microscopic level). R_{pa} (resistance of the positive electrode) is 0.022 Ω, and C_{pa} (capacity of the positive electrode) is 0.94 kF. These parameters precisely define the electrochemical approach of the battery according to the 2RC/Thévenin System, providing a solid foundation for a comprehensive understanding of its operation.

Table 2. ECM constant parameter values

Parameters	R_s(Ω)	R_{pc}(Ω)	C_{pc}(kF)	C_n (kF)	$R_{p'c'}$(Ω)	$C_{p'c'}$(kF)	R_{pa}(Ω)	C_{pa}(kF)
Values	0.226	0.035	8.74	5.32	0.0312	9.775	0.022	0.94

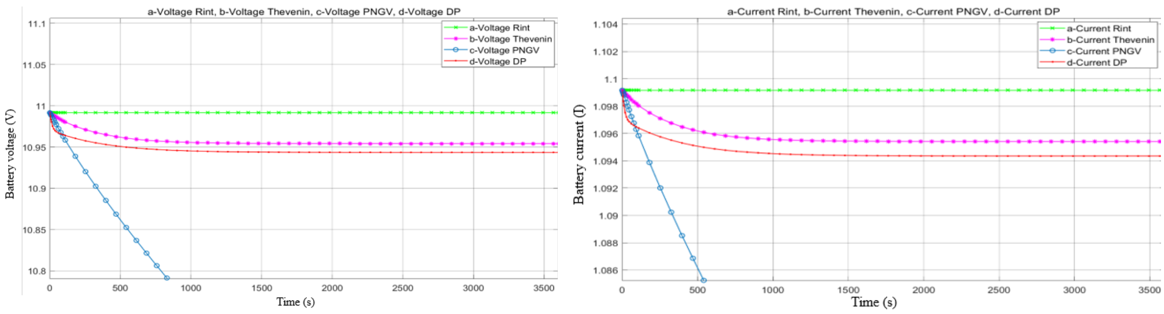
5. SIMULATION OF THE ELECTRICAL CIRCUITS OF LITHIUM-ION BATTERIES: MATLAB SIMULINK

Battery modeling has become a fundamental tool for understanding battery-powered systems. They are applied to battery specification, SoC and state-of-health (SoH) modeling, algorithm engineering, system-level simulation and real-time optimization for the development of battery management systems. The first stage in building an effective battery system is to develop and configure an equivalent circuit that takes into account the non-linear behaviors and temperature, SoC, SoH and current dependencies. These influences are dependent on the chemistry of each particular battery. The simulation ECM models for the batteries under study were created in the MATLAB-Simulink system. For each of the ECM set-ups described previously.

5.1. Results and discussion

Figure 9 shows a simulation of the various battery models in MATLAB-Simulink, of which:

– Curve a: represents the LIB response as a function of voltage and current for the R_{int} system.
– Curve b: represents the LIB response as a function of voltage and current for the Thevenin system.
– Curve c: represents the LIB response as a function of voltage and current for the PNGV system.
– Curve d: represents the LIB response as a function of voltage and current for the DP system (2RC-Thevenin).



Battery voltage (V) Battery current (I)

Figure 9. Simulation of the various battery models battery voltage (V) and battery current (I) responses of the battery ECMs for discharge tests on MATLAB simulink

Comparison of simulations for Li-ion battery with the four typical equivalent circuit models, is summarized as follows: when using the R_{int} model in LIB simulation, the voltage and current characteristics depend on the applied load. However, it cannot reproduce the accuracy of the dynamic polarization characteristics of LIB is limited. The PNGV model is perfectly suited to different working conditions for a short period; yet, over a long-term simulation, the voltage and current behavior caused by the capacitance C_n increases. This model is therefore not suitable for simulating LIB.

In comparison to the PNGV model, the Thevenin model can reflect the polarization of the battery. Simulation current and voltage better reflect actual battery operation. It can also reflect the actual operating characteristics of the LIB, which is appropriate for simulating batteries. Thevenin's model is relatively simple compared with others, so, if necessary, an ECM can be developed by refining Thevenin's model, such as the one from 2RC, which gives simulation results very close to those of the battery.

However, the accuracy of such a model can be improved by adding "RC" networks, which also increases the complexity of the model and the computation time required to solve it. A compromise is therefore necessary between complexity and accuracy. This type of model may be too complex for certain applications, such as electric vehicles, which require real-time modeling of battery characteristics. In such cases, "reduced-order" models can be used to reduce the computational effort required. Accuracy will obviously be reduced compared to the full model. It is also important to consider certain characteristics that can modify battery behavior, such as SOC, temperature, and battery age.

6. CONCLUSION

In conclusion, the integration of lithium-ion batteries into everyday life, powering a wide range of devices from mobile phones to electric vehicles, underscores the critical need for continuous improvement in battery technology. The efficient and low-computational-effort characteristics of ECM make them valuable tools for accurately modeling the electrical behavior of lithium-ion batteries. These models, ranging from simple to complex, provide essential insights into battery diffusion behavior and other physical processes, contributing crucial information such as state of charge. The 2RC-thevenin circuit ECM, with its series resistances and parallel RC branches, proves to be a comprehensive model covering the entire frequency range of battery operation. Experimental verification on cylindrical lithium-ion battery cells demonstrates the effectiveness of this model. The structured exploration of battery characteristics and ECMs in this paper, along with the discussion and comparison of results in Section 6, contributes to advancing our understanding of lithium-ion battery behavior. This research facilitates informed decisions in selecting optimal battery types for various applications, ultimately enhancing the reliability and efficiency of BMS.

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