



Article

Novel Method for Battery Design of Electric Vehicles Based on Longitudinal Dynamics, Range, and Charging Requirements

Ralph Biller^{1,*}, Erik Ketzmerick², Stefan Mayr² and Günther Prokop¹

¹ Chair of Automobile Engineering, University of Technology Dresden, George-Bähr-Straße 1b, 01069 Dresden, Germany

² AUDI AG Ingolstadt, Auto-Union-Straße 1, 85057 Ingolstadt, Germany

* Correspondence: ralph.biller@tu-dresden.de

Abstract

VDI/VDE 2206 introduces the “V-Model”, a standard in the field of automotive development that uses systems engineering to derive requirements for (sub-)systems and components based on vehicle characteristics. These characteristics, which are directly experienced by drivers, are crucial in the concept phase, where virtual methods are increasingly applied. Regarding the battery electric vehicle’s energy storage, commonly a lithium-ion battery, vehicle metrics, especially for charging, range, and longitudinal dynamics, are of particular relevance. This publication will demonstrate a method to derive the requirements for the battery system based on those metrics. The core of the method is a static battery model, which considers the needed effects and dependencies in order to adequately represent the defined vehicle metrics, e.g., the battery’s open-circuit voltage and internal resistance. This paper also discusses the necessity of the relevant effects and dependencies and also why some of them can be ignored at this particular vehicle development stage. The result is a consistent method for requirement definition, from vehicle level to battery system level, applicable in the concept phase of the vehicle development process.

Keywords: battery-electric vehicles; battery design; virtual vehicle development; vehicle requirements



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1. Introduction

In the early development stages of battery electric vehicles (BEVs), it is essential to define system requirements based on vehicle characteristics. This approach ensures targeted performance, efficiency, and user satisfaction. The VDI/VDE 2206 [1] guideline introduces the V-Model, a systems engineering framework that supports the derivation of component-level requirements from overall vehicle behavior. This approach is especially relevant, as virtual methods increasingly replace physical prototypes in early design phases.

Despite its importance, battery design in current design methods like [2–7] are often, rather, approached in reverse: instead of deriving battery requirements from vehicle-level metrics, the battery is typically designed first, based on the cell or module characteristics, often obtained through physics-based models [8–11]. These models can later be integrated into the vehicle, potentially using data-driven techniques [10,12] or AI-based models [12,13] to accelerate computation, allowing for the assessment of the battery’s impact on overall vehicle performance. However, this sequence can lead to iterative design loops, increased development time, and misalignment between battery capabilities and vehicle requirements. Moreover, employing physics-based models during the concept phase

is generally inefficient due to their high computational demands [10] and the need for extensive parametrization [9,11]. While data-driven methods offer faster computation [10], they are not ideal for requirement derivation in the concept phase. These models function as black boxes, lacking transparent physical relationships, and are heavily dependent on the quality and scope of their training data. Consequently, they may introduce errors when applied to operating conditions outside of the training dataset [12,13].

This paper presents a novel method for battery design that focuses on driver perception and vehicle level, rather than cell or module level. Therefore, the method integrates directly into the decomposition and requirement definition of the V-Model methodology [1] using virtual development methods [14,15] and supports the model-based systems engineering [16,17] in conjunction with characteristics-based vehicle development [17,18]. The primary objective of this paper is twofold:

1. To develop an electrical battery model that captures key vehicle-level metrics for longitudinal dynamics, range, and charging behavior. These metrics are used to parameterize the model and to derive the essential electrical requirements for the battery system.
2. To ensure that the model remains as simple as possible for efficient use during the concept phase, where a rough concept and conceptual flexibility are crucial [18].

To balance simplicity with accuracy, a maximum deviation of 5% from the measurement data or a validated reference simulation model is considered acceptable (for comparison, Ref. [19] states a common maximum absolute deviation of 10% for comparing simulation to a measurement or to a reference model; by contrast, Ref. [20] allows for a maximum absolute deviation in the used measurement devices for energy consumption of 1% in the final energy consumption determination for a BEV on a test bench). In summary, the method and the model contribute to the development of a digital twin [21].

Temperature effects are analyzed in terms of their influence on electrical properties, such as internal resistance and open-circuit voltage. However, within the scope of the proposed method, a constant temperature of 23 °C is assumed, and no temperature variation is considered. Therefore, the design of a thermal management system for the battery is not a subject that will be covered within this paper.

The effects regarding long-term battery degradation are excluded from this work, as it will instead focus on the concept phase in the vehicle development process.

By identifying which physical effects must be considered and which can be reasonably excluded at this stage, the proposed method offers a consistent and efficient pathway from vehicle characteristics to battery system requirements. This contributes to the requirement-based simulation [14] and a more integrated battery design process in the context of modern BEV development.

2. Materials and Methods

The following sections exhibit the materials and methods relevant to this publication. Starting with the previously mentioned vehicle characteristics, which are described as objective metrics on vehicle level, common battery charging methods are introduced. Subsequently, vehicle measurements pertaining to all of the metrics relevant to this publication are presented. Section 2.4 discusses the necessary battery model data, as well as the battery test bench that has been employed to validate the proposed design method.

2.1. Metrics for Longitudinal Dynamics of Battery Electric Vehicles

The starting point for this method is a set of vehicle-level metrics defined in [22]. These metrics cover a broader scope. However, for the purpose of this publication, the relevant metrics (Table 1) are grouped into the following three main topics:

- Longitudinal dynamics (acceleration);
- Range;
- Charging requirements.

In the first topic, **longitudinal dynamics**, mainly three metrics are of particular relevance for this paper. The first metric is *residual acceleration*, defined as the acceleration that the vehicle still reaches at 120 km/h. The maneuver here is a full-load acceleration from 0 to a minimum of 130 km/h at 23 °C and 80% state-of-charge (SOC). As defined in [22], the SOC corresponds to the value shown in the driver's cockpit for this manuscript which is the usable SOC range or the net energy content. The second metric is *residual acceleration at 10% SOC*, where the defined maneuver is a full-load acceleration from 100 to 140 km/h at 23 °C and 10% SOC. The third metric is *residual acceleration at −7 °C*, where the defined maneuver is a full-load acceleration from 100 to 140 km/h at −7 °C and 80% SOC. For the latter, it is recommended to use a climate dynamometer as test facility for an optimal tempering. Both *residual acceleration at 10% SOC* and *residual acceleration at −7 °C* are evaluated at 120 km/h analogously to the metric *residual acceleration*.

The second topic, **range**, is defined by two metrics: the BEV's *range* itself and its *energy consumption* at 23 °C and 80% SOC. As defined in [22], the basis maneuver for range is the Worldwide harmonized Light vehicles Test Cycle (WLTC) [20]. Both metrics are referred to the WLTC, which are used in the following to calculate the battery's energy content.

Lastly, **charging** metrics are used to define the charging behavior of the vehicle. The maneuver here is a DC charging process using the maximum available power defined in the standard Combined Charging System (CCS) [23,24]. The metrics include *DC charging time from 10 to 80% SOC* and *max. recharged range in 10 min* regarding the WLTC range and consumption. An alternative to the latter metric would be the maximum charging power. In addition to the charging metrics presented in [22], it is essential to consider another metric, namely, the *residual charging power at 80% SOC*.

Table 1. Summary of relevant metrics based on [22].

ID	Topic	Objective Metric	Unit
1.1	Longitudinal dynamics	Residual acceleration	m/s ²
1.2		Residual acceleration at 10% SOC	m/s ²
1.3		Residual acceleration at −7 °C	m/s ²
2.1	Range	Range	km
2.2		Energy consumption	kWh/100 km
3.1	Charging	DC charging time from 10 to 80%	min
3.2		Max. recharged range in 10 min	km/10 min
3.3		Residual charging power at 80% SOC *	kW

* This metric was not considered in [22], but it is relevant in this publication.

2.2. Battery Charging Methods

In order to calculate the charging time of the battery, it is necessary to select an appropriate charging method. The most common one is “constant current-constant voltage” (CC-CV) [25,26], which consists of a constant current phase until the cut-off voltage U_{const} is reached, followed by a constant voltage phase at U_{const} . This method is illustrated in Figure 1 left schematically. A related method is “const power-constant voltage” (CP-CV). The key difference between this and CC-CV is that the constant current phase is replaced by a constant power phase, which can be seen schematically in the middle figure of Figure 1. In addition to other methods, “a number of more complex variable current profiles [(VCP)] have also been proposed for fast charging” [25]. The VCP method, as illustrated in Figure 1 right, is more variable than the previous mentioned approaches. It can also be interpreted

as a resulting current profile if the current is limited by the battery management system (BMS) due to temperature monitoring or by the grid, for instance. It is essential that a charging method is defined in advance to the method. All three of these methods are needed in this work.

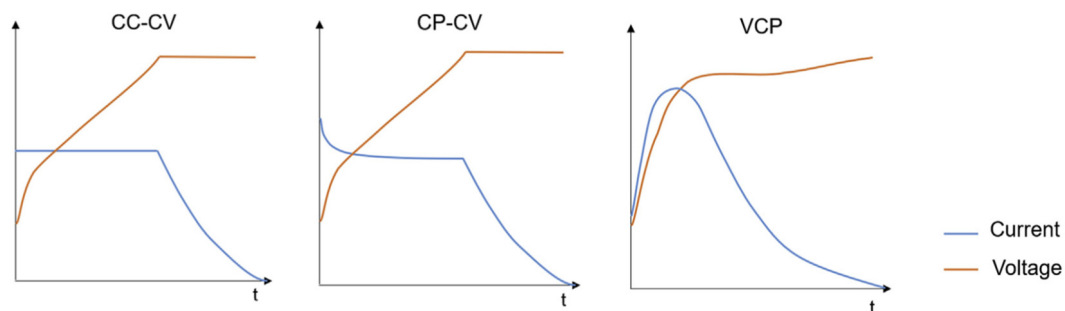


Figure 1. Schematic overview of common charging methods [25].

2.3. Vehicle Measurements for Acceleration and Charging

Measurements on vehicle level are conducted for all metrics. An upper mid-range electric vehicle with a battery of 100 kWh energy content and a maximum propulsion power of 270 kW is used. In addition to the other variables, the following relevant variables are measured over time:

- Longitudinal vehicle acceleration and speed;
- Battery current and voltage;
- Battery SOC;
- Battery temperature.

Table 2 shows the mean values of three measurements related to longitudinal dynamics (see definition in Section 2.1), and Table 3 shows their corresponding operating points. IDs 1.1 and 1.2 were measured on a proving ground. ID 1.3 was conducted using a climate dynamometer, whose load was set to the driving resistances of the vehicle. Additionally, the entire vehicle was conditioned until the target battery temperature of $-7\text{ }^{\circ}\text{C}$ was reached.

Table 2. Measurement results for ID 1.1, 1.2, and 1.3.

ID	Objective Metric	Value	Unit
1.1	Residual acceleration	2.73	m/s^2
1.2	Residual acceleration at 10% SOC	2.23	m/s^2
1.3	Residual acceleration at $-7\text{ }^{\circ}\text{C}$	2.51	m/s^2

Table 3. Operating points for ID 1.1, 1.2, and 1.3.

ID	Objective Metric	Voltage in V	Current in A
1.1	Residual acceleration	682.503	413.206
1.2	Residual acceleration at 10% SOC	572.672	453.072
1.3	Residual acceleration at $-7\text{ }^{\circ}\text{C}$	620.048	443.486

The same climate dynamometer was used for the topic range. Table 4 shows the results for IDs 2.1 and 2.2. The values presented here are the mean values of three measurements.

Regarding the topic charging, the vehicle was charged from 10 to 80% at maximal power using a DC charging station which illustrated in the blue line in Figure 2. The measurement and the IDs 3.1, 3.2, and 3.3 can be seen in Figure 2 and Table 5. In Figure 2, the red line represents the recharged range, ID 3.2, and the yellow line applies for charging

time and, hence, for ID 3.1. The measurement can be interpreted as VCP, as the current is limited by the BMS due to high temperature above 30% SOC. It is needed for the validation in Section 3.2.

Table 4. Measurement results for ID 2.1 and 2.2.

ID	Objective Metric	Value	Unit
2.1	Range ¹	542.86	km
2.2	Energy consumption ²	17.59	kWh/100 km

¹ This value is calculated using a net energy content of ≈ 95.5 kWh. ² Although the speed profile is based on WLTC, the value is not suitable for homologation.

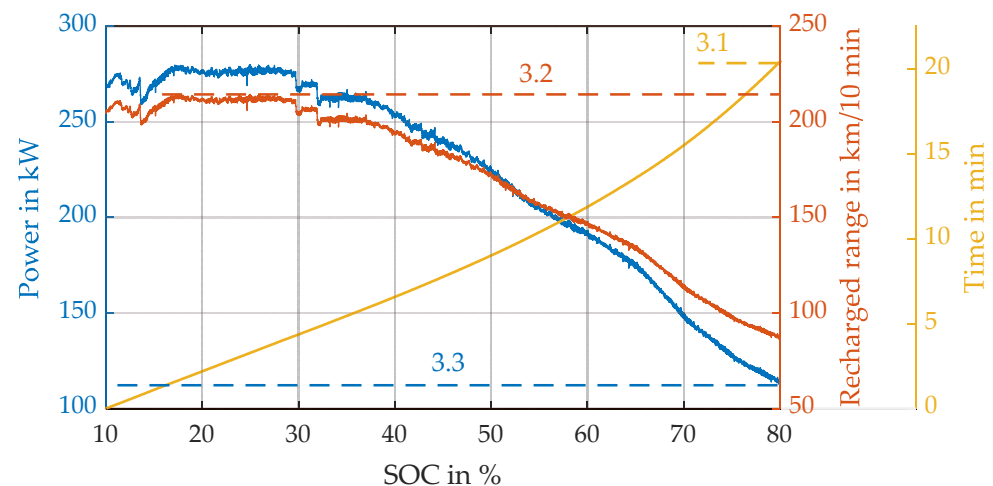


Figure 2. DC charging measurement.

Table 5. Measurement results for ID 3.1, 3.2, and ID 3.3.

ID	Objective Metric	Value	Unit
3.1	DC charging time from 10 to 80%	20.5	min
3.2	Max. recharged range in 10 min	214.0	km/10 min
3.3	Residual charging power at 80% SOC	113.3	kW

2.4. Battery Data and Measurement

In this paper, four validated simulation models of battery cells are used. The basic battery cell specifications are shown in Table 6. For each cell, an open-circuit voltage (OCV) and internal resistance map are available, both dependent on SOC and temperature.

Table 6. Battery cell specification.

Battery	1	2	3	4
Cell chemistry	NMC	NMC	LFP	LFP
Nominal voltage in V	3.700	3.700	3.200	3.300
Capacity in Ah	151	152	148	37

Cell 1 is further measured at system level using a battery pack test bench (Figure 3), which, in addition to the others, is able to control the battery current up to 400 A. Similar test setups were used in [27–30]. From the battery's perspective, the current I_{bat} for charging is negative, which is controlled by a current source. In addition to the others, the BMS decides based on the measurement of voltage U , current I , temperature T , and SOC if the main switch is opened or closed. The battery's environment in the climate chamber and the

battery itself can be tempered via the cooling plate by a thermal management system (TMS), which controls the mass flowrate $\dot{m}$ and its temperature. The goal of this is to analyze the general battery behavior, compare it to the cell simulation models, and validate the method. Therefore, OCV and internal resistance are additionally measured, both on system level. Furthermore, the defined method is applied for this battery using the test bench in Section 3.2.

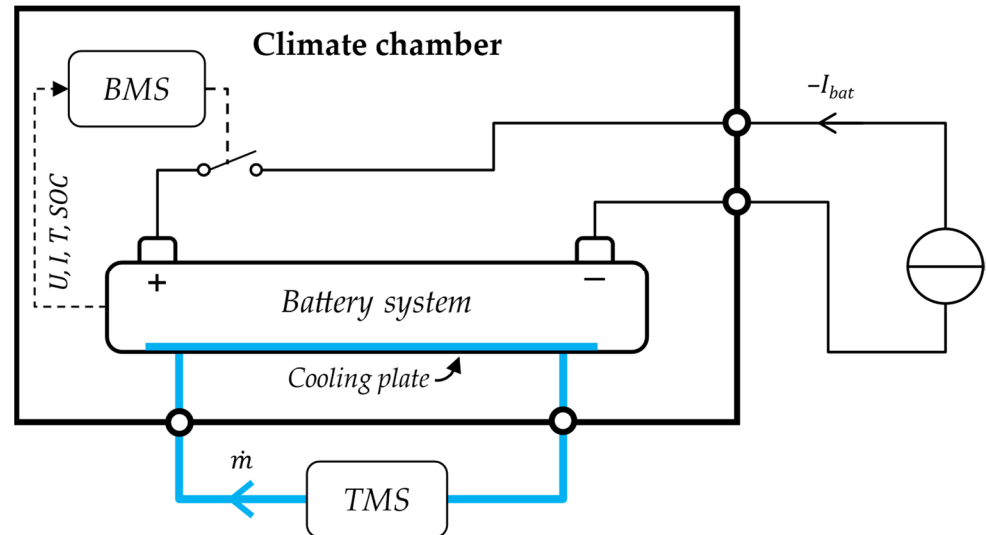


Figure 3. Battery pack test bench setup.

3. Method for Battery Design of Electric Vehicles

The following sections present the developed method for battery design of electric vehicles in the concept phase based on the charging, range, and longitudinal dynamic metrics introduced in Section 2.1. The core of the method is a static battery model (Section 3.1), combined with the design method (Section 3.2), which is validated in Section 3.3 using both the vehicle-level measurements presented in Section 2.3 and the system-level measurements utilizing the test bench presented in Section 2.4.

3.1. Battery Model

In the literature, various battery models exist for simulating the electrical characteristics of batteries [31–39]. Within the concept phase of vehicle development based on the V-Model methodology, the main goal of a battery model is its ability to simulate, at minimum, all defined metrics. In other words, the model should only incorporate a minimum number of parameters necessary to simulate the metrics defined in Section 2.1. It is standard practice to use electrical equivalent circuit models (ECMs). The basic model considers an OCV with an internal resistance in series at a minimum, cf. [33,36,40]. Resistor-capacitor circuit elements (RC) can be added to simulate the dynamic behavior of the battery [33,35,36,40]. Other elements can be added in order to simulate the battery more precisely, cf. [33,36]. However, these additions also need more effort for parameterization. Therefore, the basic model serves as a starting point for this paper and is extended if required.

The basic model is displayed in Figure 4. Here, the OCV is U_{OCV} and the voltage over the resistor is U_{Ri} . R_i equals the battery's internal resistance. The battery voltage U_{bat} is given by Equation (1) and the battery current by Equation (2). The charged or discharged power P_{OCV} is calculated by Equation (3) and the terminal power P_{bat} by Equation (4):

$$U_{bat} = U_{OCV} - U_{Ri} \quad (1)$$

$$I_{bat} = \frac{U_{Ri}}{R_i} \quad (2)$$

$$P_{OCV} = U_{OCV} \cdot I_{bat} \quad (3)$$

$$P_{bat} = U_{bat} \cdot I_{bat} \quad (4)$$

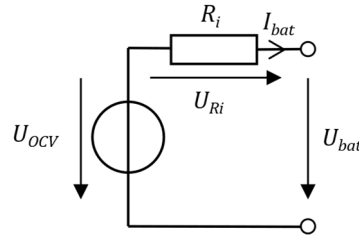


Figure 4. Basic battery model.

The characteristics of batteries are typically dependent on SOC and temperature [41,42]. Both the OCV and the internal resistance can be modeled dependent on SOC and temperature. However, as demonstrated in other publications, for example [42,43], it has been determined that the internal resistance is not significantly SOC dependent. Therefore, the following paragraph will analyze which dependencies must be added to the basic battery model based on vehicle and battery measurements. As none of the defined metrics listed in Table 1 exceed 80% or fall below 10% SOC, the relevant SOC range is predefined between 10 and 80%. The relevant temperature range is assumed to be -7 to 23 °C, as outlined in [22], which defines both metrics: *residual acceleration* and *residual acceleration at -7 °C*.

The OCV is first analyzed. Figure 5 presents the OCV maps for each battery listed in Table 6, showing their dependency on SOC and temperature. These maps were gathered from a validated simulation model, which was parameterized based on the cell data provided by the respective battery suppliers. The model consists of an ohmic resistance with three RC elements connected in series, as previously applied in [39,44], and serves as the reference for this analysis. The voltage of the OCV maps is normalized to their upper cut-off voltage. The operating points for the three metrics of residual acceleration are also shown.

It can be seen that the gradient of the normalized OCV in the SOC direction is qualitatively higher than in direction of temperature T . However, Equation (7) is used for a quantitative evaluation in both directions for all three metrics of residual acceleration. In order to compare both directions equally, both gradient maps are normalized using the minimum and maximum value of SOC and temperature between 0 and 1. The normalizations are SOC_{norm} , Equation (5), and T_{norm} , Equation (6).

$$SOC_{norm} = \frac{SOC - \min(SOC)}{\max(SOC) - \min(SOC)} \quad (5)$$

$$T_{norm} = \frac{T - \min(T)}{\max(T) - \min(T)} \quad (6)$$

$$\nabla U_{OCV} = \left(\frac{\partial U_{OCV}}{\partial SOC_{norm}}, \frac{\partial U_{OCV}}{\partial T_{norm}} \right) \quad (7)$$

Table 7 shows the results of the gradient evaluation in the direction of SOC in volts per normalized SOC, and Table 8 in the direction of temperature in volts per normalized temperature. It can be seen that the absolute values of the gradient in the direction of temperature are significantly smaller compared to the absolute values of the gradient in direction of SOC, being on average 163 times lower for both NMC batteries and 56 times lower for both LFP batteries. Therefore, the OCV will be modeled as SOC-dependent only.

A comparison of OCV on battery system level between 23 °C and −7 °C using the test bench of Section 2.4 and battery 1 from Table 6 can be found in Appendix A.1, which underlines this conclusion. It is noteworthy that, for both NMC batteries, the gradient in direction of SOC is higher than for the two LFP batteries. The reason for this is that LFP batteries show, in general, a lower OCV increase dependent on SOC, cf. [45–47].

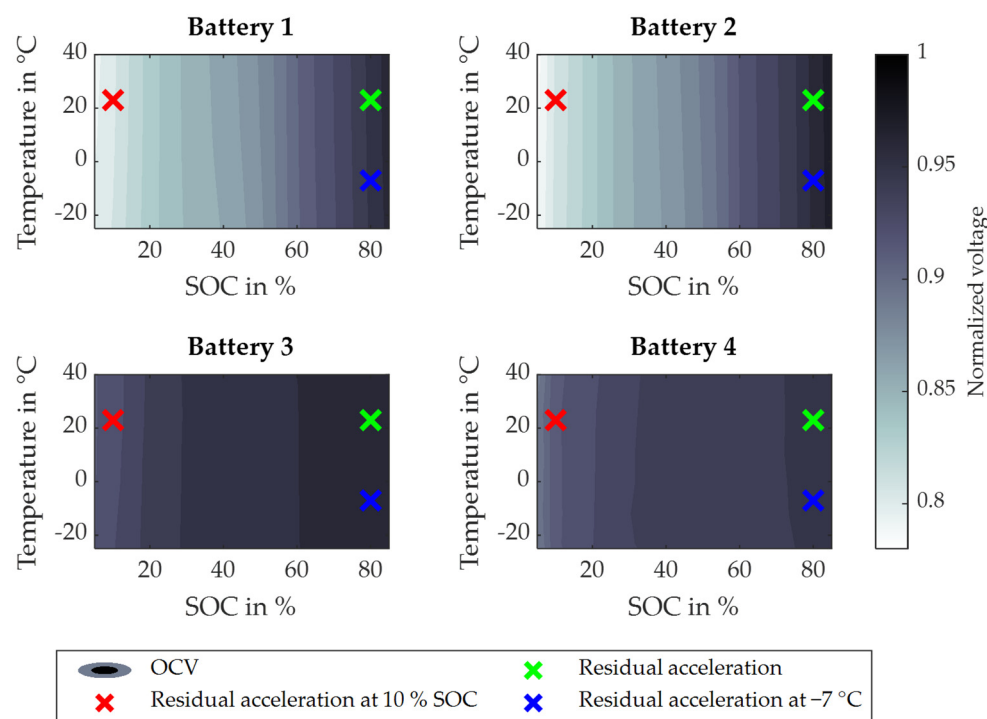


Figure 5. OCV maps of batteries dependent on SOC and temperature.

Table 7. Normalized gradient evaluation of OCV in direction of SOC in V/−.

Battery	1	2	3	4
Residual acceleration	1.017	1.096	0.011	0.070
Residual acceleration at 10% SOC	1.041	1.552	0.179	1.095
Residual acceleration at −7 °C	1.010	1.088	−0.048	0.059

Table 8. Normalized gradient evaluation of OCV in direction of temperature in V/−.

Battery	1	2	3	4
Residual acceleration	0.005	0.006	0.001	0.001
Residual acceleration at 10% SOC	−0.009	−0.008	−0.009	−0.005
Residual acceleration at −7 °C	0.010	0.006	0.003	0.024

Another simplification can be made if it is assumed that, in the context of the battery design, only the range from 10 to 80% SOC is relevant. This assumption is underlined by the metrics defined in Table 1. As a result, the OCV is linearized by Equation (8). Here, the linear factor k in $\frac{V}{\%}$ is introduced. The theoretical voltage at 0% SOC is U_0' .

$$U_{OCV}(SOC) = k \cdot SOC + U_0' \quad (8)$$

Figure 6 shows the comparison between the measured/simulated OCV (solid lines) alongside their linear approximations (dashed lines) for all four batteries. Table 9 provides

a quantitative comparison between the actual and approximated values. Three evaluation criteria were used:

- Pearson correlation coefficient R ;
- Mean relative error (MRE);
- Root-mean-square error (RMSE).

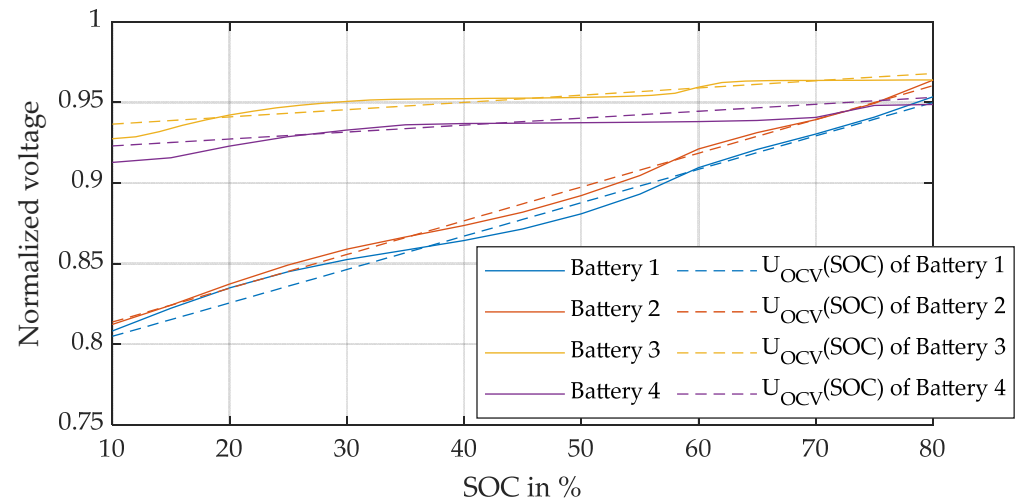


Figure 6. OCV of measurement/simulation and their linear approximation.

Table 9. Comparison of OCV between measurement/simulation and their linear approximation.

Battery	1	2	3	4
R	0.995	0.998	0.933	0.928
MRE in %	0.440	0.282	0.305	0.333
RMSE in V	0.019	0.013	0.012	0.013

Table 9 demonstrates that the linear approximation yields accurate results, particularly for the two NMC batteries (battery 1 and 2), with correlation coefficients of 0.995 and 0.998, respectively. Even for the LFP batteries (battery 3 and 4), the correlation remains above 0.92, indicating that the linear model is suitable across different chemistries. The MRE is below 0.5% for all batteries, with the LFP batteries showing intermediate values between the two NMC batteries. In relation to the nominal voltage of 3.7 V for battery 1 shown in Table 6, the RMSE is low, reaching only 0.019 V for battery 1. These results confirm that the linear approach provides sufficient accuracy and can be reliably used within the proposed design methodology. As mentioned above and calculated in Table 7, LFP batteries show a lower SOC gradient than NMC batteries. Based on the similar error values for all batteries shown in Table 9 combined with the SOC-limitation between 10 and 80%, no higher error rates are expected for LFP compared to NMC.

Second, the battery's internal resistance R_i is analyzed. This is conducted in a similar manner as for OCV. Figure 7 shows the normalized internal resistance for the batteries of Table 6, dependent on SOC and temperature. Similarly to OCV, these maps were gathered from a validated simulation model, which was parameterized based on the cell data provided by the respective supplier. The model consists of an ohmic resistance with three RC elements connected in series as previously applied in [39,44], and serves as the reference for this analysis. The normalization is performed by using the maximum resistance. Battery dynamics or a differentiation for charging and discharging is not considered here. In Figure 7, the sum of the ohmic resistance and the three resistors of the RC elements was used. The operating points for the three metrics of residual acceleration are also shown.

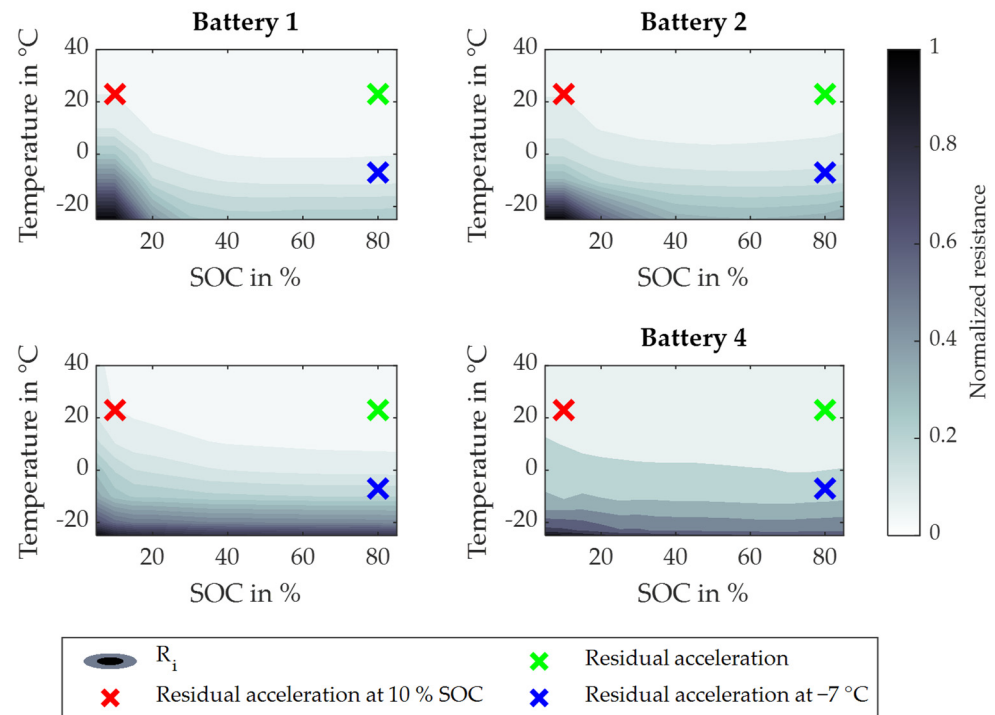


Figure 7. Internal resistance of batteries dependent on SOC and temperature.

It is obvious that the temperature influences R_i qualitatively more than the SOC (Figure 7). To analyze this assumption quantitatively, a similar evaluation as for OCV shall be made by using the normalized gradient in both directions. Equations (5) and (6) apply to this evaluation as well. However, as the internal resistance is evaluated, the normalized gradient calculation must be adapted for it, which is shown in Equation (9).

$$\nabla R_i = \left(\frac{\partial R_i}{\partial SOC_{norm}}, \frac{\partial R_i}{\partial T_{norm}} \right) \quad (9)$$

Based on the gradient evaluations in Tables 10 and 11, the metric *residual acceleration at -7°C* exhibits the highest absolute gradient values in the temperature direction across all batteries. For example, battery 3 shows an absolute gradient of $33.886 \text{ m}\Omega/-$, which is significantly higher than any other value in both tables. In contrast, the corresponding absolute gradient in the SOC direction for the same metric is only $0.616 \text{ m}\Omega/-$, highlighting a pronounced directional difference. The pattern is consistent across all batteries: the gradient in direction of temperature for *residual acceleration at -7°C* is at least nine times higher than the SOC gradient, with battery 3 showing a factor of 55. When comparing the gradients of *residual acceleration* and *residual acceleration at 10%*, the gradients in both directions for each of the metrics do not show such a contrast. This indicates that the influence of SOC on internal resistance is less significant and cannot be clearly distinguished based on gradient behavior for all batteries. Nevertheless, the internal resistance is also dependent on SOC as the gradient in direction of SOC for the metric *residual acceleration at 10%* shows which can result in deviations for low SOC values. In conclusion, the temperature, particularly at -7°C , has the strongest impact on the internal resistance, making *residual acceleration at -7°C* the most sensitive metric. Therefore, the dependency of SOC on resistance is reasonably neglected in the context of the design method. This conclusion is consistent with the results reported in [42,43]. However, as temperature variation was excluded from this publication in the Introduction, a temperature-dependent internal resistance is not further analyzed here.

Table 10. Normalized gradient evaluation of R_i in direction of SOC in mΩ/-.

Battery	1	2	3	4
Residual acceleration	−0.170	0.983	−0.148	0.618
Residual acceleration at 10% SOC	−3.350	−1.917	−7.977	−1.810
Residual acceleration at −7 °C	0.812	1.755	−0.616	1.076

Table 11. Normalized gradient evaluation of R_i in direction of temperature in mΩ/-.

Battery	1	2	3	4
Residual acceleration	−1.328	−0.982	−1.876	−1.320
Residual acceleration at 10% SOC	−3.633	−1.513	−3.821	−1.840
Residual acceleration at −7 °C	−11.493	−9.516	−33.886	−12.222

In order to consider the metrics *range*, *energy consumption*, *DC charging time from 10 to 80% SOC*, and *max. recharged range in 10 min*, the SOC has to be calculated using P_{OCV} , Equation (10). In this instance, the maximum battery energy $E_{Bat,Max}$ in Ws is used, which can be calculated using the defined range r in km and the defined energy consumption η in $\frac{\text{kWh}}{100 \text{ km}}$, Equation (11). By solving Equation (10) for dt , the charging time t_{ch} can be calculated using its integral from SOC_1 to final SOC_2 , Equation (12). Lastly, the maximal recharged range r_{rech} in $\frac{\text{km}}{10 \text{ min}}$ is used to determine a maximal charging power $P_{Ch,Max}$ in W, Equation (13). In combination with the metric *residual charging power at 80% SOC*, a charging curve can be derived based on the charging methods presented in Section 2.3:

$$P_{OCV}(SOC) = E_{Bat,Max} \cdot \frac{dSOC}{dt} \quad (10)$$

$$E_{Bat,Max} = r \cdot \eta \cdot \frac{1000 \cdot 3600}{100} \quad (11)$$

$$t_{ch} = E_{Bat,Max} \cdot \int_{SOC_1}^{SOC_2} \frac{1}{P_{OCV}(SOC)} dSOC \quad (12)$$

$$P_{Ch,Max} = r_{rech} \cdot \frac{1}{10 \cdot 60} \cdot \eta \cdot \frac{1000 \cdot 3600}{100} \quad (13)$$

With the presented model, all defined metrics for the concept phase in the context of longitudinal dynamics, range, and charging are considered. Therefore, no further model enhancements are needed at this point.

3.2. Proposed Design Method

Basis for the design method is the model deduced in Section 3.1. The first step is to calculate the maximum energy content of the battery using Equation (11) and the metrics ID 2.1 and 2.2. The maximum energy content will be the usable net energy analogous to the SOC definition. The maximal charging power using Equation (13) and the metrics ID 2.2 and 3.2 can also be calculated.

The next step in the process is to incorporate the battery model and the operating points, which have been defined by the metrics. The main goal here is to determine values for R_i , k , U'_0 , and I_{const} (CC-CV) or P_{const} (CP-CV), respectively. The three operating points are as follows:

- ID 1.1: Residual acceleration;
- ID 1.2: Residual acceleration at 10% SOC;
- ID 3.3: Residual charging power at 80% SOC.

Current and voltage can be determined for each operating point. For IDs 1.1 and 1.2, either a measurement, for instance Table 3, or a backward-calculating longitudinal dynamics model can be used. Using a simulation model is especially useful in the early concept development; this is previewed in [14] and will be presented in a future publication. Current and voltage for ID 1.1 are $I_{ID1.1}$ and $U_{ID1.1}$ and for ID 1.2 are $I_{ID1.2}$ and $U_{ID1.2}$. ID 1.2 is always defined at 10% SOC. Usually, ID 1.1 is defined at 80% SOC; however, it can also be defined at other SOC values, given that the 80% definition is rather regarded as a “worst case” design. This SOC value is $SOC_{ID1.1}$. For the third operating point ID 3.3 P_{80} , it is assumed that the constant voltage U_{const} is valid. Therefore, the current at this point can be calculated as follows:

$$I_{80} = \frac{P_{80}}{U_{const}} \quad (14)$$

It should be noted that, for VCP, the current at this point is given by the profile. Therefore, ID 3.3 is needed only for CC-CV or CP-CV. For CC, the constant current is calculated by

$$I_{const} = \frac{P_{Ch,Max}}{U_{const}} \quad (15)$$

Using CP, power is constant; therefore, P_{const} equals $P_{Ch,Max}$. If VCP is used, neither current nor power have to be constant, because current is given by the profile. Using Equations (1), (2) and (8), a system of three linear equations in the form $A \cdot x = B$ is deployed, which can be solved for U'_0 , k and R_i :

$$A = \begin{pmatrix} 1 & SOC_{ID1.1} & -I_{ID1.1} \\ 1 & 10\% & -I_{ID1.2} \\ 1 & 80\% & -I_{80} \end{pmatrix}, x = \begin{pmatrix} U'_0 \\ k \\ R_i \end{pmatrix}, B = \begin{pmatrix} U_{ID1.1} \\ U_{ID1.2} \\ U_{const} \end{pmatrix} \quad (16)$$

The parameterization process is shown in Figure 8 by using an example. As demonstrated in Section 3.1, the internal resistance, which is the slope of each line, remains equal for all operating points. First, ID 1.1 *residual acceleration* is considered at its defined SOC (1. in Figure 8). Second, ID 3.3 *residual charging power at 80% SOC* defines another line with the same slope and adding the constant voltage U_{const} (2. in Figure 8). Third, ID 1.2 *residual acceleration at 10% SOC* is considered as the third line, adding the theoretical voltage at 0% SOC U'_0 (3. in Figure 8). The displacement in voltage is considered by the linear factor k . Equation (16) can also be interpreted as a plane in three-dimensional space, as shown in 4. in Figure 8.

The last step is to consider the charging time, ID 3.1, using Equation (12) in order to achieve the desired constant voltage U_{const} in the CV phase. In this case, $P_{OCV}(SOC)$ depends on the chosen charging method (Section 2.2). Equations (17)–(19) show the charging time calculations split in CC (t_{CC}), CV (t_{CV}), and CP (t_{CP}). The constant current in Equation (17) is I_{const} , the constant voltage in Equation (18) is U_{const} , and the constant power in Equation (19) is P_{const} . The detailed derivation of the equations can be found in Appendix A.2 (CC), 3 (CV), and 4 (CP).

$$t_{CC} = -\frac{E_{Bat,Max}}{I_{const} \cdot k} \cdot \log\left(\frac{U'_0 + k \cdot SOC_x}{U'_0 + k \cdot 10\%}\right) \quad (17)$$

$$t_{CV} = -\frac{2E_{Bat,Max}R_i}{\sqrt{-4k^2U'_0(U_{const}-U'_0)-k^2(U_{const}-2 \cdot U'_0)^2}} \cdot \left[\tan^{-1}\left(\frac{-2 \cdot k^2 \cdot 80\% + k(U_{const}-2 \cdot U'_0)}{\sqrt{-4k^2U'_0(U_{const}-U'_0)-k^2(U_{const}-2 \cdot U'_0)^2}}\right) - \tan^{-1}\left(\frac{-2 \cdot k^2 \cdot SOC_x + k(U_{const}-2 \cdot U'_0)}{\sqrt{-4k^2U_{0SOC0}(U_{const}-U'_0)-k^2(U_{const}-2 \cdot U'_0)^2}}\right) \right] \quad (18)$$

$$t_{CP} = \frac{1}{2k} \frac{E_{Bat,Max}}{P_{const}} \left[\sqrt{(k \cdot SOC_x + U'_0)^2 + 4P_{const} \cdot R_i} - 2\sqrt{P_{const} R_i} \left(\tanh^{-1} \left(\frac{\sqrt{(k \cdot SOC_x + U'_0)^2 + 4P_{const} \cdot R_i}}{2\sqrt{P_{const} \cdot R_i}} \right) - \tanh^{-1} \left(\frac{\sqrt{(k \cdot 10\% + U'_0)^2 + 4P_{const} \cdot R_i}}{2\sqrt{P_{const} \cdot R_i}} \right) \right) + k(SOC_x - 10\%) - \sqrt{(k \cdot 10\% + U'_0)^2 + 4P_{const} R_i} \right] \quad (19)$$

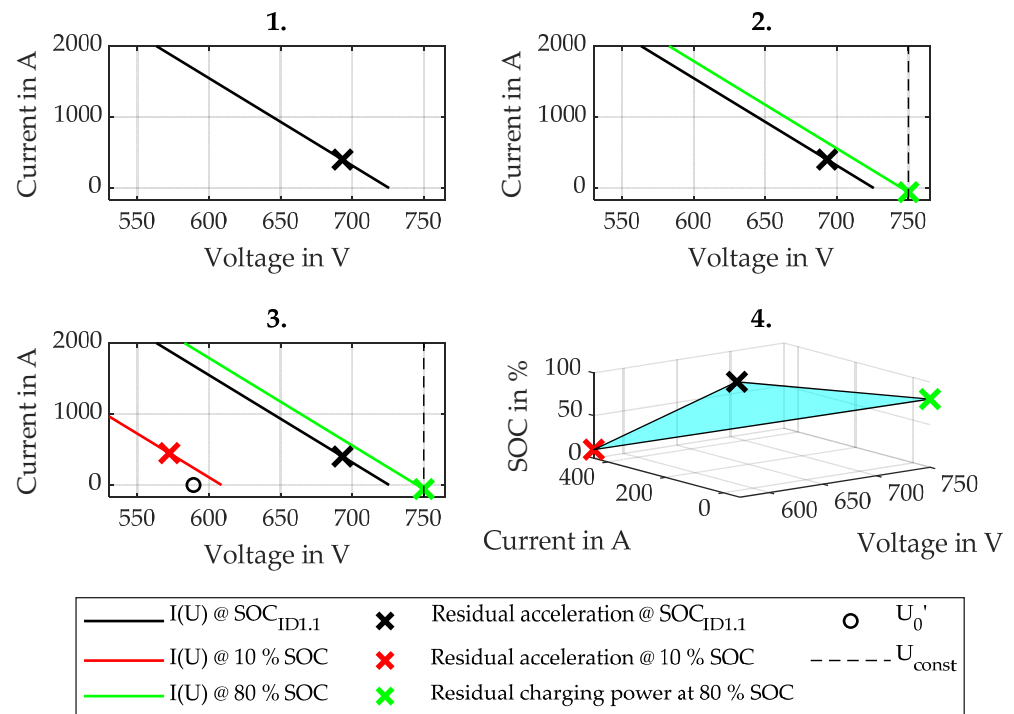


Figure 8. Exemplary parameterization process for U'_0 , k and R_i .

In Equations (17)–(19), SOC_x is the transition from CC or CP to CV. For CC-CV, the value is determined by the intersection between CC and CV:

$$U_{const} = U'_0 + k \cdot SOC_x - R_i \cdot I_{const} \quad (20)$$

$$SOC_x = \frac{U_{const} - U'_0 + R_i \cdot I_{const}}{k} \quad (21)$$

For CP-CV, the value is determined by the intersection between CP and CV:

$$P_{const} = U_{const} \cdot I_{bat} = U_{const} \cdot \frac{U_{const} - (U'_0 + k \cdot SOC_x)}{R_i} \quad (22)$$

$$SOC_x = \frac{-\frac{R_i \cdot P_{const}}{U_{const}} + U_{const} - U'_0}{k} \quad (23)$$

Finally, the complete charging times can be determined by adding the particular charging times:

$$t_{CCCV} = t_{CC} + t_{CV} \quad (24)$$

$$t_{CPCV} = t_{CP} + t_{CV} \quad (25)$$

For VCP, the defined current profile $I_{VCP}(SOC)$ can directly be used for Equation (12):

$$t_{VCP} = E_{Bat,Max} \cdot \int_{10\%}^{80\%} \frac{1}{U_{OCV}(SOC) \cdot I_{VCP}(SOC)} dSOC \quad (26)$$

As all of the methods cannot be solved for U_{const} and Equations (17)–(19) and (26) are non-linear, a non-linear root-finding algorithm, e.g., Newton's method or False-position method [48,49], is used to find the desired value for U_{const} .

3.3. Validation

Firstly, this section compares the method with the existing vehicle measurement, shown in Figure 2. The method used mean measured operating points for the longitudinal dynamics metrics, as measured in Table 2, are presented in Table 3. The remaining measured metrics are listed in Table 4 for range and Table 5 for charging. All of these metrics and their operating points are inserted into the model in order to apply the design method, in this case the one using VCP. The simulation's VCP is equivalent to the measured current. The result of this DC charging maneuver in comparison to the measurement can be seen in Figure 9.

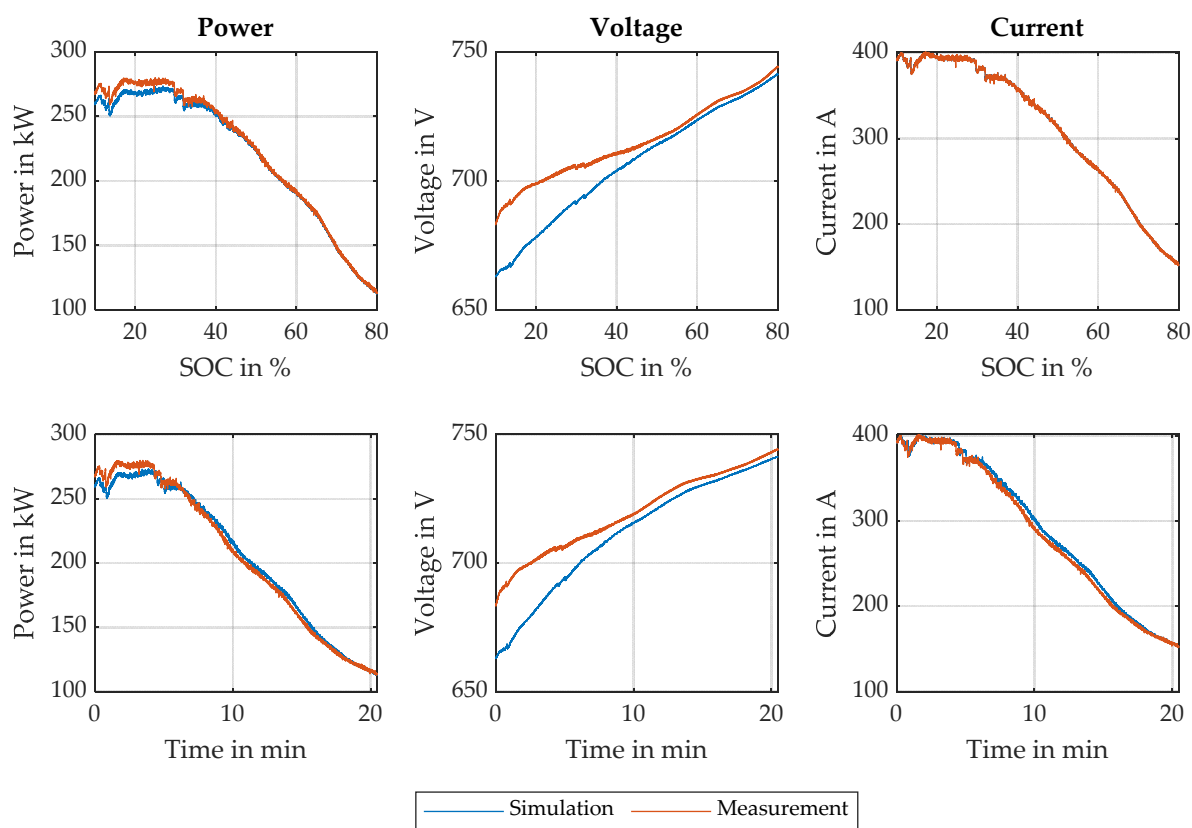


Figure 9. Comparison between simulation and measurement for VCP.

It is obvious that the current (Figure 9 right) is almost identical, as it is predefined. However, voltage differs from the measurement, especially below 40% SOC (Figure 9 middle). Consequently, the terminal power also differs below 45% SOC (Figure 9 left). The underlying cause of this is that neither battery dynamics nor the SOC dependency of the internal resistance at low SOC levels are modeled. This tradeoff has already been mentioned in Section 3.1. However, if one compares time-dependent measurements and simulations quantitatively using R , MRE, and RMSE (Table 12), it can be seen that this

method achieves a good first estimation for DC charging in the concept phase. R is close to 1 for current, voltage, and power, indicating a high correlation between measurement and simulation. The MRE remains below 1.1% for all parameters, with the lowest deviation observed for current and slightly higher values for voltage and power. These low error rates confirm the reliability of the simulation in capturing the key characteristics of the charging process. Lastly, the RMSE values are within acceptable ranges for early-phase estimations when compared to the maximal values shown in Figure 9.

Table 12. Comparison between simulation and measurement using VCP.

	Power	Voltage	Current
R	0.999	0.986	1
MRE in %	1.023	0.993	0.235
RMSE	3.969 kW	10.192 V	0.879 A

Secondly, both CC-CV and CP-CV are used to design a virtual battery. The resulting parameters are validated. However, during the publication's creation process, it was impossible to create an entirely new battery for validation. Therefore, battery 1 of Table 6 served as the target design, as it was available for measurement and validation. The first step is to find a solution for the battery parameters using CC-CV and CP-CV, respectively, that matches with the parameters identified by the DC charging maneuver from Figure 9. This is achieved by using an optimization algorithm. In the second step, the identified current profiles are applied to the battery test bench, prescribed as input current. In the final step, the measured data is compared to the simulation results for each charging method. These comparisons are illustrated in Figures 10 and 11. It should be noted that the metric *DC charging time from 10 to 80%* does not match the value shown in Table 5. The reason for this is that the value in Table 5 would require a current profile exceeding 400 A, which surpasses the maximum current limit of the test bench, as specified in Section 2.4. Therefore, this metric was adjusted to 21.7 min to comply with the test bench limitations. This adjustment does not affect the validity of the comparison between the measurement and simulation. It should be noted that another unavoidable effect is evident in the measurement, especially with regard to the voltage. At about 41% and 54% SOC, the charging process had to be stopped for cooling because the battery reached its maximum temperature. Otherwise, the BMS would throw an error and open the main switch. The cooling sections are excluded from the diagrams. In this case, the battery's environment and the battery itself were initially conditioned at 23 °C by the TMS. However, during the charging process, the cooling liquid was set to 15 °C to delay the reaching of the battery's maximum temperature. Regarding OCV or internal resistance, the cooling has almost no influence, as both do not vary significantly above 23 °C in combination with $\text{SOC} \geq 45\%$, cf. Figures 5 and 7 in combination with Figures 10 and 11. However, it can be seen that, for both CC-CV and CP-CV charging, the dynamics have an influence on the voltage, especially below 45% SOC, where the internal resistance varies additionally.

Compared to VCP, CC-CV and CP-CV measurements indicate better values for R , MRE, and RMSE, as demonstrated in Tables 13 and 14, respectively, for the time-dependent values. As with VCP, for both CC-CV and CP-CV current was predefined and, hence, it correlates with $R = 1$. Voltage achieves a value for R only near to 1 because of the unconsidered effects of internal resistance dependency at low SOC. This is also reflected in a worse MRE for the voltage compared to the current. However, compared to the absolute maximum values, the RMSE is low for power, voltage, and current. In conclusion, all of the analyzed charging methods, VCP, CC-CV, and CP-CV, show a high reliability for early-phase estimations. Especially in the concept phase, where precise real-world data

may not yet be available, these results demonstrate that the method provides a robust first approximation.

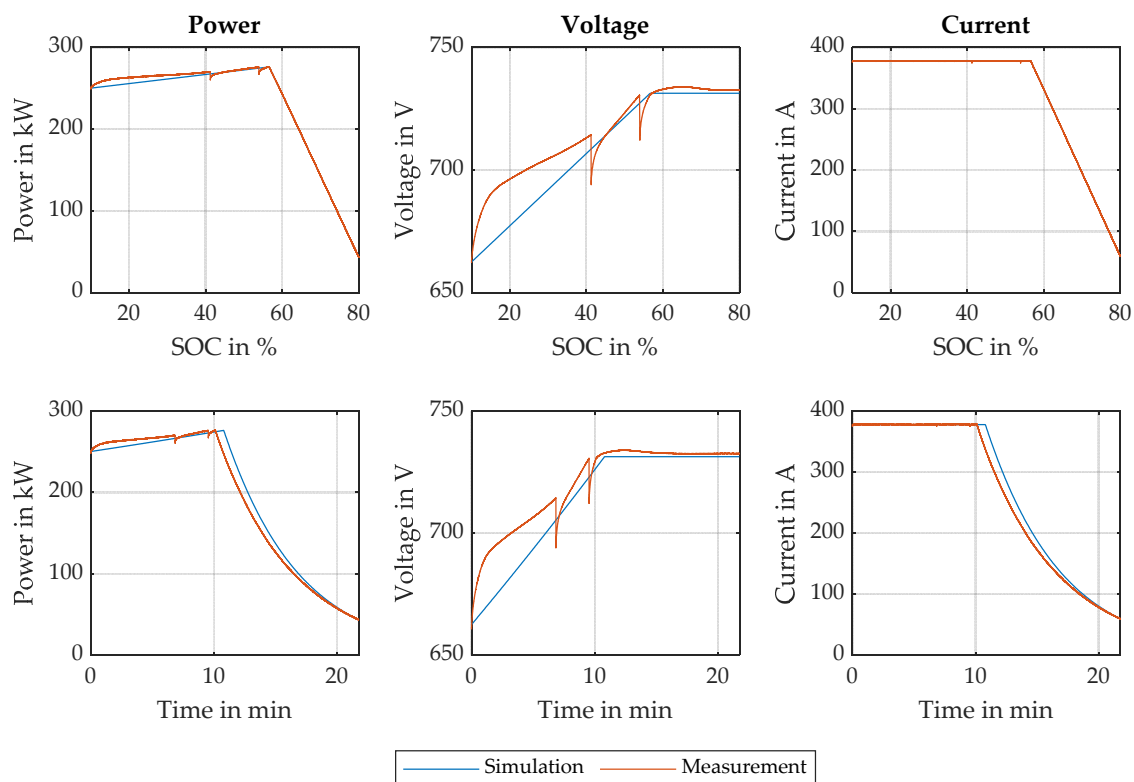


Figure 10. Comparison between simulation and measurement for CC-CV.

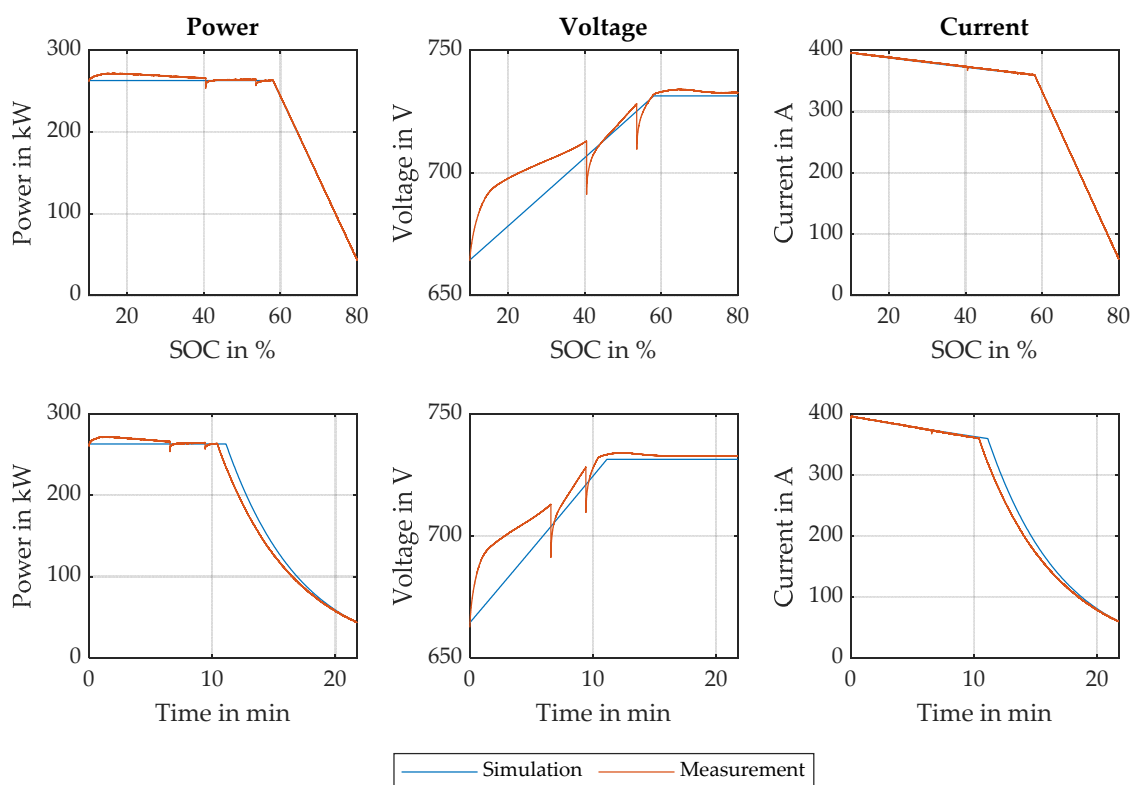


Figure 11. Comparison between simulation and measurement for CP-CV.

Table 13. Comparison between simulation and measurement using CC-CV.

	Power	Voltage	Current
R	1	0.981	1
MRE in %	0.819	0.780	0.147
RMSE	3.258 kW	8.505 V	0.373 A

Table 14. Comparison between simulation and measurement using CP-CV.

	Power	Voltage	Current
R	1	0.977	1
MRE in %	0.916	0.793	0.201
RMSE	3.571 kW	8.516 V	0.657 A

4. Discussion

This section discusses the benefits of the presented method for the concept phase in the vehicle development process using the V-Model methodology and concludes with a summary of the method's limitations.

4.1. Benefits of the Method for Vehicle Development Process

The primary objective of this publication was to develop a method capable of deriving battery system requirements based on the longitudinal dynamics, range, and charging metrics, as introduced in Table 1. The method is specifically tailored for the concept phase within the V-Model. In contrast to other battery design approaches such as [5,6], the proposed method eliminates iterative loops during the concept phase by utilizing a static battery model that incorporates the battery's OCV and the internal resistance.

A key benefit of the method's model lies in its simplicity and efficiency. The OCV is modeled as temperature-independent based on gradient evaluations in SOC (Table 7) and temperature direction (Table 8), which showed no significant influence. This finding was further validated at the battery system level for battery 1 in Table 6 (Appendix A.1). Moreover, many established battery models also neglect temperature dependency in OCV modeling, e.g., [32,34,35,37,47], supporting the validity of this simplification. Within a applicable SOC range from 10 to 80%, the OCV can be effectively linearized by using Equation (8), further streamlining the modeling process. The battery's internal resistance was identified as rather temperature-dependent, a finding that is consistent to those reported in [42,43]. As temperature is neglected in this method, the internal resistance is constant. This simple battery model allows for a fast and efficient first battery design in the concept phase.

By applying the method described in Section 3.2, which uses the presented battery model, requirements can be derived in a fully backward manner according to the V-Model, using a requirement-based simulation approach. The method requires the load points at the battery based on the metrics of Table 1 as input. It is possible to use a default charging profile (CC-CV or CP-CV) or to incorporate a predefined charging profile in VCP, which allows us to consider battery limitations regarding the temperature or grid, for instance. It outputs the OCV, R_i , and U_{const} . Consequently, the presented method ensures that the battery design is both fast and efficient in the concept phase, where usually only few data is available. This allows for further analyses in the development process without the necessity for a fully developed battery. Overall, the proposed method offers a number of key advantages:

- Reduction in development loops: Eliminates iterative redesigns by enabling direct requirement derivation.

- Model simplicity: Uses a static model with linearized OCV and constant R_i , reducing computational complexity.
- Early applicability: Enables battery system design even with minimal input data, supporting early-phase decision-making.
- Time and cost efficiency: Accelerates the concept phase and reduces resource consumption by avoiding detailed simulations and measurements.

4.2. Limitations of the Method

Despite the advantages of the proposed method for fast and efficient battery system design in the concept phase, several limitations must be acknowledged to ensure the proper application and interpretation of the results.

The method is based on a static battery model with constant internal resistance and a simplified representation of the OCV. Battery dynamics using RC elements or Warburg impedances [33] are not captured, which leads to deviations when comparing with measured charging curves (Figures 9–11). The discrepancy is highest below 45% SOC. Furthermore, temperature effects are not taken into consideration. While the OCV showed minimal temperature sensitivity within the evaluated range, internal resistance is known to vary significantly with temperature, which is confirmed in Section 3.1, especially in Figure 7 and Table 11. However, temperature variation in the internal resistance was excluded from the Introduction. Furthermore, due to the losses in the internal resistance, the battery warms up itself, which is not included in the method, but it must be considered later during the development process, especially in the design of a TMS for the battery. Therefore, the method must be expanded for temperature consideration in future research, which starts with involving the metric *residual acceleration at -7°C* . Appendix A.4 addresses the simplifications made in the model for internal resistance and compares it to a validated reference simulation model for battery 1 using CC-CV.

The method has been validated for both NMC and LFP battery chemistries. A distinction between these chemistries is not made due to the scope of the concept phase in the vehicle development process. Consequently, specific effects associated with each chemistry, such as hysteresis behavior observed in LFP batteries [39], are not considered. Applicability to other lithium ion chemistries, such as lithium ion manganese oxide or lithium nickel cobalt aluminum oxide, is expected to be feasible, as [45] demonstrates that similar ECMs can be reasonably applied to these chemistries as well. The method may also be suitable for sodium-ion batteries, given that several successful applications of ECMs for this chemistry have been reported [50–52]. Regarding solid-state batteries, which represent another emerging technology for BEV, a similar assessment can be made. Multiple studies, e.g., [53–55], have employed ECMs to simulate solid-state battery behavior. Nevertheless, a definitive decision regarding the method's applicability to other chemistries and whether adaptations of the method are necessary remains open and will require further validation.

The derived battery configuration represents a minimum requirement set based on driver-relevant metrics. If a more capable battery is selected due to modularity goals or platform strategies, the validity of the method is not compromised. However, other essential design constraints, such as packaging space, weight, cost, or thermal management, are not included and must be addressed in separate development stages.

The method is tailored to specific vehicle-level input parameters. In instances where alternative or additional metrics are used, a modification of the method may be necessary. Moreover, unrealistic or inconsistent vehicle-level inputs can result in implausible battery system outputs, emphasizing the need for careful input validation. Additionally, the method does not explicitly account for constraints imposed by charging standards like CCS [23,24]. Therefore, results must be critically assessed for plausibility.

5. Outlook

Future work has to focus on extending the proposed method to incorporate temperature effects on acceleration, range and charging behavior, as defined in the metrics in [22]. In particular, the temperature dependency of the internal resistance should be considered, as demonstrated in the gradient analysis in Section 3.1 and discussed in detail in Section 4. Prior studies [42,43] have shown that the internal resistance exhibits an exponential relationship with temperature. Additionally, accurate range estimation at lower temperatures requires accounting for the reduction in usable capacity under cold conditions.

Another key development will be the integration of the method into a comprehensive design process for BEVs' longitudinal dynamics and powertrain. This includes coupling with a backward-calculating longitudinal dynamics model, as previewed in [14], which enables a comprehensive virtual and requirement based system design of BEV. The application and validation of this extended approach will be presented in an upcoming publication.

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Abbreviations

The following abbreviations are used in this manuscript:

BEV	Battery electric vehicle
BMS	Battery management system
CC	Constant current
CCS	Combined charging system
CP	Constant power
CV	Constant voltage
DC	Direct current
ECM	Equivalent circuit model
LFP	Lithium-Iron-Phosphate
MRE	Mean relative error
NMC	Nickel-Mangan-Cobalt
RMSE	Root-mean-square error
R	Pearson correlation coefficient
SOC	State-of-charge
TMS	Thermal management system
VCP	Variable current profile
WLTC	Worldwide harmonized Light vehicles Test Cycle

Appendix A

Appendix A.1. Comparison of OCV at Battery System Level

Using the test bench from Figure 3, two OCV measurements were conducted at 23 °C and −7 °C. Both are displayed in Figure A1. The charging process at −7 °C was stopped periodically in order to hold the temperature as the battery warms up because of its internal resistance while charging. With $R > 0.999$ and $RMSE < 0.002$ normalized voltage, it can be concluded that the temperature dependency is neglectable in the concept phase.

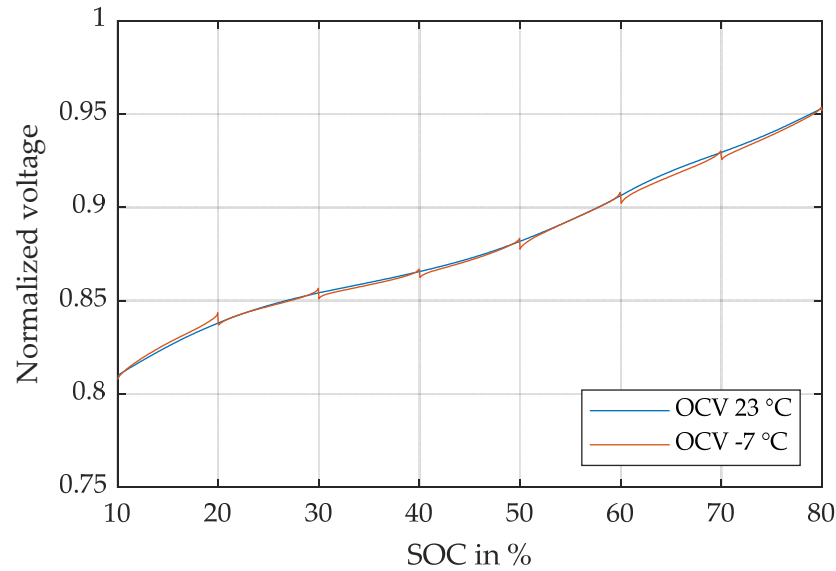


Figure A1. Comparison of OCV between 23 °C and −7 °C.

Appendix A.2. Derivation of CC

In CC, the constant current is I_{const} , which is defined positive for discharging. Using Equations (3) and (8), P_{OCV} can be derived:

$$P_{OCV}(SOC) = U_{OCV}(SOC) \cdot (-I_{const}) = -(k \cdot SOC + U'_0) \cdot I_{const} \quad (A1)$$

By inserting Equation (A1) in (12), the following integral can be solved for SOC from 10% to the transition to CV at SOC_x :

$$\begin{aligned} t_{CC} &= E_{Bat,Max} \int_{10\%}^{SOC_x} \frac{1}{-(k \cdot SOC + U'_0) I_{const}} dSOC \\ &= -\frac{E_{Bat,Max}}{I_{const}} \int_{10\%}^{SOC_x} \frac{1}{k \cdot SOC + U'_0} dSOC \\ &= -\frac{E_{Bat,Max}}{I_{const} \cdot k} [\log(k \cdot SOC + U'_0) + C]_{10\%}^{SOC_x} \\ &= -\frac{E_{Bat,Max}}{I_{const} \cdot k} [\log(U'_0 + k \cdot SOC_x) - \log(U'_0 + k \cdot 10\%)] \\ &= -\frac{E_{Bat,Max}}{I_{const} \cdot k} \cdot \log\left(\frac{U'_0 + k \cdot SOC_x}{U'_0 + k \cdot 10\%}\right) \end{aligned} \quad (A2)$$

Appendix A.3. Derivation of CV

In CV, the constant voltage is U_{const} , which replaces U_{bat} . The following equation for P_{OCV} can be determined by using Equations (1)–(3):

$$P_{OCV}(SOC) = U_{OCV}(SOC) \cdot \frac{U_{const} - U_{OCV}(SOC)}{R_i} = \frac{U_{OCV}(SOC) \cdot U_{const} - U_{OCV}(SOC)^2}{R_i} \quad (A3)$$

With Equation (8), P_{OCV} becomes

$$P_{OCV}(SOC) = \frac{(k \cdot SOC + U'_0) \cdot U_{konst} - (k \cdot SOC + U'_0)^2}{R_i} \quad (A4)$$

By inserting Equation (A4) in (12), the following integral can be solved for SOC from the transition to CV at SOC_x to 80%:

$$\begin{aligned} t_{CV} &= E_{Bat,Max} \int_{SOC_x}^{80\%} \frac{R_i}{(k \cdot SOC + U'_0) \cdot U_{konst} - (k \cdot SOC + U'_0)^2} dSOC \\ &= E_{Bat,Max} \int_{SOC_x}^{80\%} \frac{R_i}{k \cdot SOC \cdot U_{konst} + U'_0 \cdot U_{konst} - k^2 \cdot SOC^2 - 2k \cdot SOC \cdot U'_0 - (U'_0)^2} dSOC \\ &= E_{Bat,Max} R_i \int_{SOC_x}^{80\%} \frac{1}{-k^2 \cdot SOC^2 + SOC \cdot k(U_{konst} - 2 \cdot U'_0) + U'_0(U_{konst} - U'_0)} dSOC \\ &= \left[-\frac{2E_{Bat,Max} R_i}{\sqrt{-4k^2 U'_0(U_{konst} - U'_0) - k^2(U_{konst} - 2 \cdot U'_0)^2}} \right. \\ &\quad \cdot \tan^{-1} \left(\frac{-2 \cdot k^2 \cdot SOC + k(U_{konst} - 2 \cdot U'_0)}{\sqrt{-4k^2 U'_0(U_{konst} - U'_0) - k^2(U_{konst} - 2 \cdot U'_0)^2}} \right) \Big]_{SOC_x}^{80\%} \\ &= -\frac{2E_{Bat,Max} R_i}{\sqrt{-4k^2 U'_0(U_{konst} - U'_0) - k^2(U_{konst} - 2 \cdot U'_0)^2}} \\ &\quad \cdot \left[\tan^{-1} \left(\frac{-2 \cdot k^2 \cdot 80\% + k(U_{konst} - 2 \cdot U'_0)}{\sqrt{-4k^2 U'_0(U_{konst} - U'_0) - k^2(U_{konst} - 2 \cdot U'_0)^2}} \right) \right. \\ &\quad \left. - \tan^{-1} \left(\frac{-2 \cdot k^2 \cdot SOC_x + k(U_{konst} - 2 \cdot U'_0)}{\sqrt{-4k^2 U'_0(U_{konst} - U'_0) - k^2(U_{konst} - 2 \cdot U'_0)^2}} \right) \right] \end{aligned} \quad (A5)$$

Appendix A.4. Derivation of CP

In CP, the constant power is P_{const} , which is defined as the power at the battery terminals. By using Equations (3) and (4),

$$P_{OCV}(SOC) = U_{OCV}(SOC) \cdot I = U_{OCV}(SOC) \cdot \frac{P_{const}}{U_{bat}} \quad (A6)$$

Using Equations (1) and (2), the terminal voltage U_{bat} can be determined:

$$U_{bat} = U_{OCV}(SOC) - R_i \cdot I = U_{OCV}(SOC) - R_i \cdot \frac{P_{const}}{U_{bat}} \quad (A7)$$

Equation (A7) results in a quadratic equation for U_{bat} with two solutions. The only plausible solution is

$$U_{bat} = \frac{1}{2} \left(U_{OCV}(SOC) + \sqrt{-4 \cdot R_i \cdot P_{const} + U_{OCV}(SOC)^2} \right) \quad (A8)$$

By inserting Equations (A6) and (A8) in (12), the charging time for CP from 10% to the transition to CV at SOC_x is given:

$$\begin{aligned}
 t_{CP} &= \frac{1}{2} \frac{E_{Bat,Max}}{P_{const}} \int_{10\%}^{SOC_x} \frac{U_{OCV}(SOC) + \sqrt{4 \cdot R_i \cdot P_{const} + U_{OCV}(SOC)^2}}{U_{OCV}(SOC)} dSOC \\
 &= \frac{1}{2} \frac{E_{Bat,Max}}{P_{const}} \int_{10\%}^{SOC_x} 1 + \frac{\sqrt{4 \cdot R_i \cdot P_{const} + (k \cdot SOC + U'_0)^2}}{k \cdot SOC + U'_0} dSOC \\
 &= \frac{1}{2} \frac{E_{Bat,Max}}{P_{const}} \left[\frac{1}{k} \left(\sqrt{(k \cdot SOC + U'_0)^2 + 4P_{const} \cdot R_i} \right. \right. \\
 &\quad \left. \left. - 2\sqrt{P_{const} R_i} \tanh^{-1} \left(\frac{\sqrt{(k \cdot SOC + U'_0)^2 + 4P_{const} R_i}}{2\sqrt{P_{const} R_i}} \right) + k \cdot SOC \right) \right]_{10\%}^{SOC_x} \\
 &= \frac{1}{2k} \frac{E_{Bat,Max}}{P_{const}} \left[\sqrt{(k \cdot SOC_x + U'_0)^2 + 4P_{const} \cdot R_i} \right. \\
 &\quad \left. - 2\sqrt{P_{const} R_i} \tanh^{-1} \left(\frac{\sqrt{(k \cdot SOC_x + U'_0)^2 + 4P_{const} R_i}}{2\sqrt{P_{const} R_i}} \right) + k \cdot SOC_x \right. \\
 &\quad \left. - \left(\sqrt{(k \cdot 10\% + U'_0)^2 + 4P_{const} R_i} \right. \right. \\
 &\quad \left. \left. - 2\sqrt{P_{const} R_i} \tanh^{-1} \left(\frac{\sqrt{(k \cdot 10\% + U'_0)^2 + 4P_{const} R_i}}{2\sqrt{P_{const} R_i}} \right) + k \cdot 10\% \right) \right] \\
 &= \frac{1}{2k} \frac{E_{Bat,Max}}{P_{const}} \left[\sqrt{(k \cdot SOC_x + U'_0)^2 + 4P_{const} \cdot R_i} \right. \\
 &\quad \left. - 2\sqrt{P_{const} R_i} \left(\tanh^{-1} \left(\frac{\sqrt{(k \cdot SOC_x + U'_0)^2 + 4P_{const} R_i}}{2\sqrt{P_{const} R_i}} \right) \right. \right. \\
 &\quad \left. \left. - \tanh^{-1} \left(\frac{\sqrt{(k \cdot 10\% + U'_0)^2 + 4P_{const} R_i}}{2\sqrt{P_{const} R_i}} \right) \right) + k(SOC_x - 10\%) \right. \\
 &\quad \left. - \sqrt{(k \cdot 10\% + U'_0)^2 + 4P_{const} R_i} \right] \tag{A9}
 \end{aligned}$$

Appendix A.5. Comparison of Model Simplifications Regarding Internal Resistance to a Reference Simulation Model

To assess the limitations of the model used in the proposed method, the validated reference simulation model for battery 1 was employed. As described in Section 3, the reference model includes an ohmic resistance and three RC elements in series. All components are dependent on both SOC and temperature (see Figures 5 and 7). Additionally, the model incorporates validated virtual black-box representations of both BMS and TMS.

The following simplifications are simulated using the defined CC-CV charging profile from Section 3.3 as a representative case for comparison:

1. Exclusion of RC elements;
2. Neglecting SOC dependency of all resistor elements ($R(SOC) = \text{const.}$);
3. Neglecting temperature dependency of all resistor elements ($R(T) = \text{const.}$);
4. Exclusion of RC elements and every dependency of the resistors ($R(SOC, T) = \text{const.}$).

The virtual battery was initialized under the same boundary conditions as the validation measurements in Section 3.3: an initial and environment temperature of 23 °C and cooling liquid temperature of 15 °C. The results of all simulations, including the reference simulation, are presented in Figure A2. As in the measurements, all simulations reach the maximum battery temperature, necessitating cooling. These cooling phases are excluded from Figure A2. The current profile is not shown, as it remains identical for all variations. Table A1 summarizes the evaluation criteria for voltage and for each simplification compared to the reference, as voltage exhibited the largest deviations in Section 3.3.

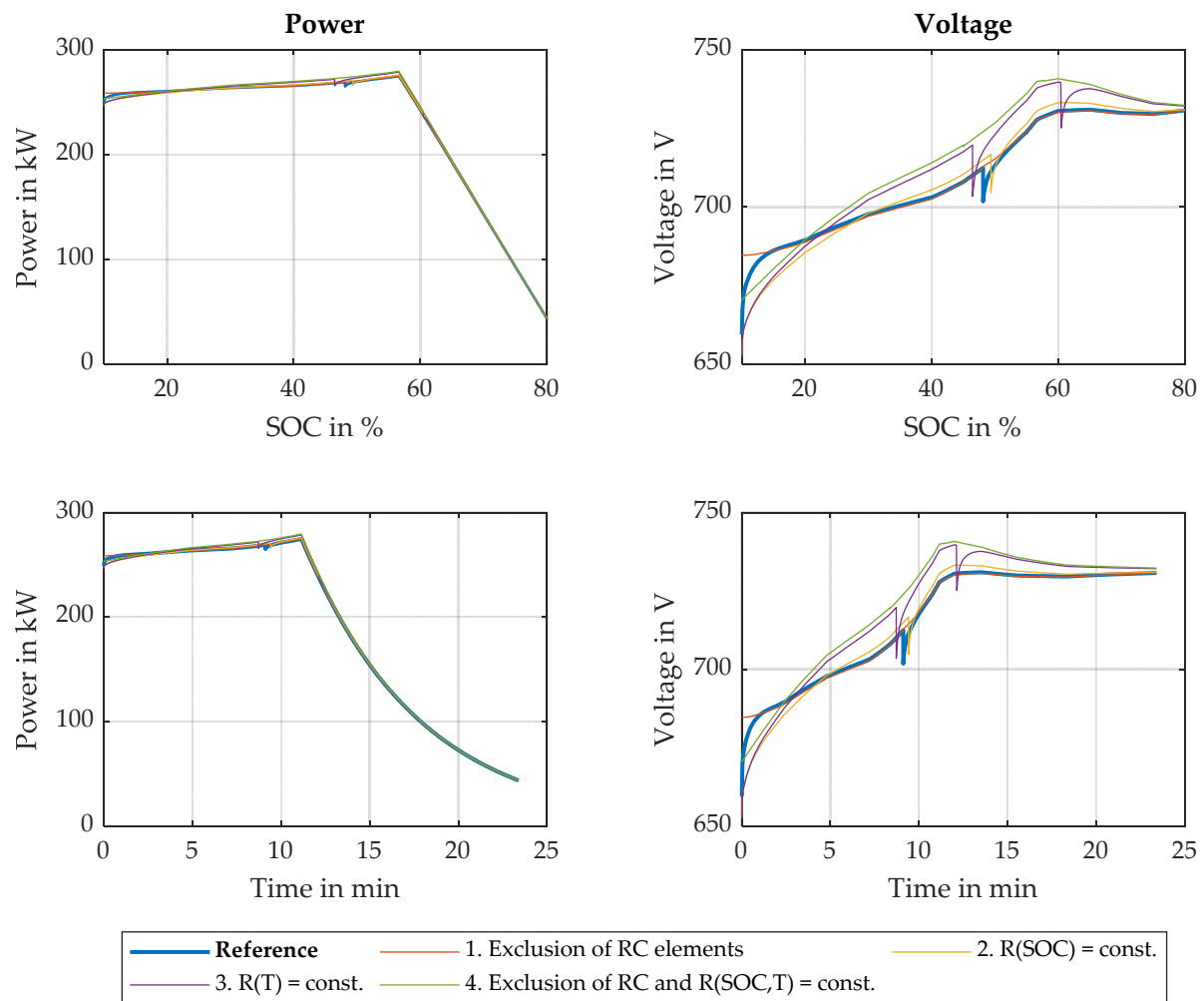


Figure A2. Analysis of model restrictions using a reference battery model.

Table A1. Evaluation criteria of the model restrictions compared to the reference for voltage.

Model Restriction	1.	2.	3.	4.
R	0.996	0.991	0.975	0.967
MRE in %	0.089	0.329	0.764	0.905
RMSE in V	1.634	3.497	6.302	7.506

Analysis of 1.:

Neglecting the RC elements induces errors when the current gradient is non-zero, such as during current switching events. Compared to the reference, the largest voltage deviation occurs at the beginning, reaching a maximum error of 3.812% until the reference reaches its quasi-static value at approximately 15% SOC or 1.19 min, which closely matches the simulation result without RC elements. The mean deviation of 0.089% (see Table A1) remains below the maximum error.

Analysis of 2.:

Ignoring the SOC dependency of the internal resistance results in only minor deviations (MRE: 0.329%, Table A1), supporting the simplification made in Section 3.1. Nevertheless, the voltage starts at a higher level than the reference and increases more slowly over SOC and time, eventually aligning with the reference at 30% SOC or 4.6 min.

Analysis of 3.:

Neglecting the temperature dependency of the internal resistance leads to greater deviations (MRE: 0.764%, Table A1) than ignoring SOC dependency. Additionally, the voltage of the reference is clearly exceeded above 23% SOC or 3 min.

Analysis of 4.:

When all simplifications regarding internal resistance are applied, which are no RC elements, no SOC dependency and no temperature dependency, the highest deviations occur, as expected. The maximum deviation is 3.156% and the mean deviation is 0.905% (Table A1), which remains below the defined maximum deviation of 5%. This result reflects the combined effects of the previous three simplifications: errors during non-zero current gradients, higher initial voltage, slower voltage rise at the beginning, and exceeding the reference above 20% SOC or 2.4 min.

Impact of the simplifications on the method:

Ignoring RC elements (1.) introduces errors when the current gradient is non-zero. Furthermore, since the simplified model considers only a static (ohmic) resistance, only this value can be derived from the method. Ignoring SOC dependency (2.) causes errors particularly at low SOC levels. Additional errors arise from neglecting temperature dependency (3.), which prevents the resistance from decreasing as battery temperature rises during charging.

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