Hochschule Karlsruhe
University of
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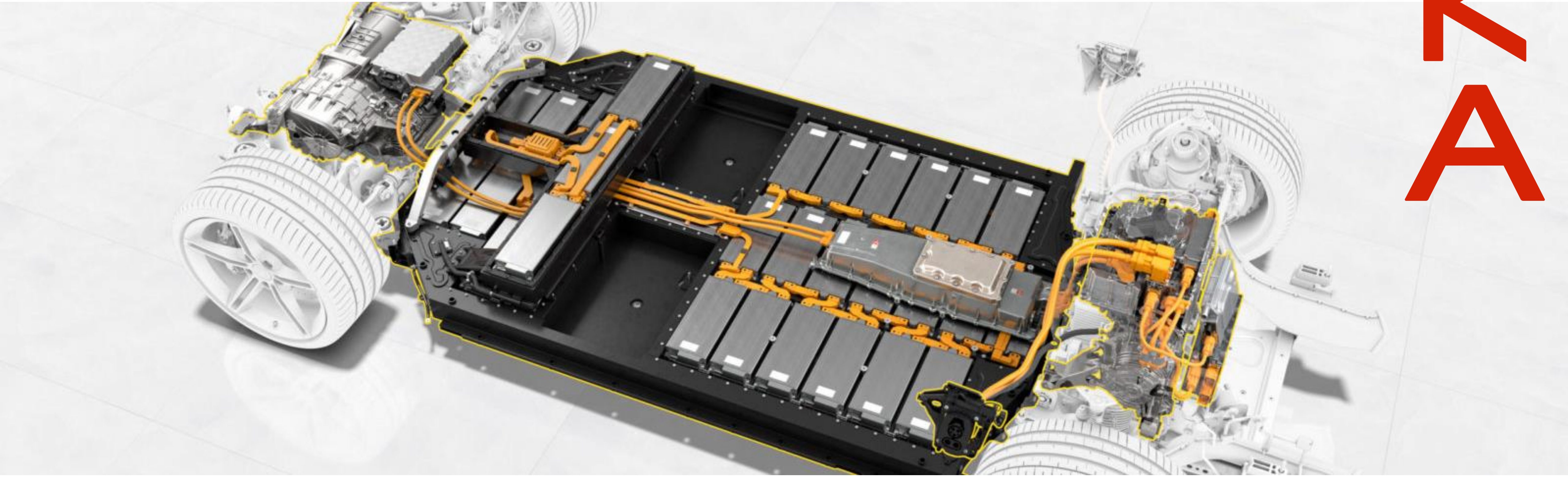
Concept of a Hybrid Energy Storage System for Energy Management System Development



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Agenda

- **Objectives**
  - Presentation of the topology of the Hybrid Energy Storage System developed in the project
- **Model of Li-Ion Cell**
  - Concept of the equivalent circuit model
  - Presentation of the subsystems that are part of the Li-ion cell model
  - Adaptation of the Li-Ion cell model into a battery model
- **Model of Supercapacitor Cell**
  - Concept of the equivalent circuit model
  - Presentation of the subsystems that are part of the supercapacitor model
- **Model of Bidirectional DC/DC Converter**
  - Topology and operation of the bidirectional converter
  - Modes of operation of the bidirectional DC/DC converter
- **Energy consumption of the BMW i3 vehicle on the route Bruchsal-Karlsruhe-Bruchsal**

Objectives: Topology of the HESS developed in this project

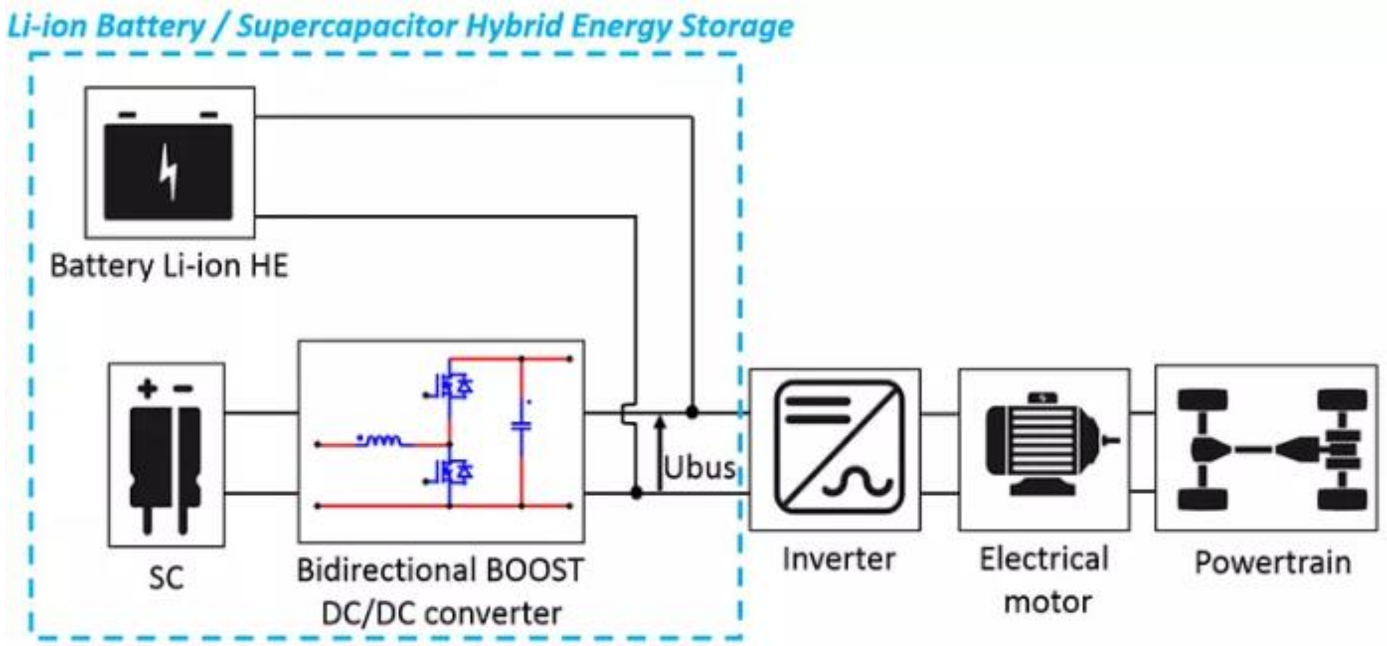


Figure 1. Topology of the Hybrid Energy Storage System

- Li-Ion battery 60Ah BMW i3
- Pack of Supercapacitor MAXWELL 3000F
- Bidirectional DC/DC Converter

Battery Cell	
Manufacturer	Samsung SDI
Rated voltage	3.7 V
Rated capacity	60 Ah
Min./Max. voltage	2.70/4.10 V
Battery Pack for the vehicle BMW i3	
Number of Cells (serial connection)	96
Rated voltage	355 V
Max. Battery energy	22 kWh
Max. Power (EM)	125kW

Table 1. . Characteristic values of the cell and battery of the BMW i3 vehicle li-ion battery cells [1]

Supercapacitor Cell BCAP3000	
Manufacturer	Maxwell
Rated Voltage	2.7 V
Capacitance	3000F
Stored Energy	3.04 Wh
Supercapacitor Pack	
Number of Cells (serial connection)	67
Rated voltage	180 V
Energy	204 Wh

Table 2. Characteristic values of the cell and pack of the Supercapacitor BCAP3000 [2]

[1] I. N. Laboratory, „2014 BMWi3 with range Extender (REx) Advanced Vehicle Testing-Baseline Vehicle testing Results
[2] Maxwell Technologies, "Datasheet K2 Ultracapacitors – 2.7V Series,"

Model of Li-Ion Cell: Concept of the equivalent circuit model

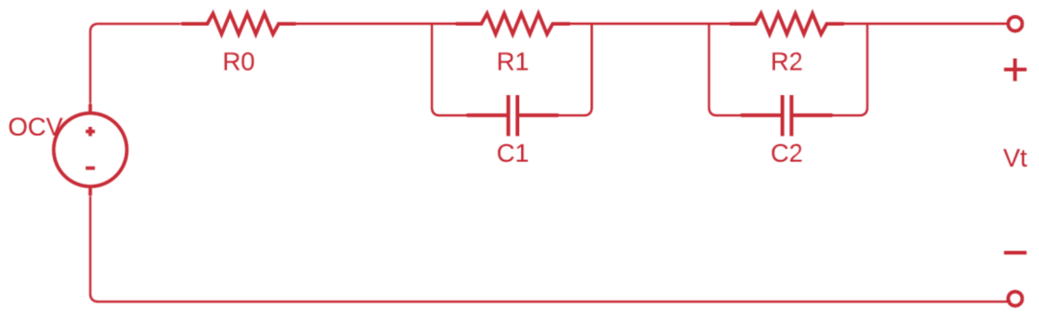


Figure 2. Equivalent circuit model of the Battery [3]

$$V_t = OCV - V_1 - V_2 - V_0 \quad \textbf{(1)}$$

- The model provides a reliable state-of-charge estimate of the cell as well as the open-circuit voltage
- The RC parallel circuits are used to model the battery relaxation effects
- With one RC parallel circuit modeling the battery relaxation effect, non-ignorable modeling error exists and while two series connected RC parallel circuits are used, the modeling error is reduced dramatically

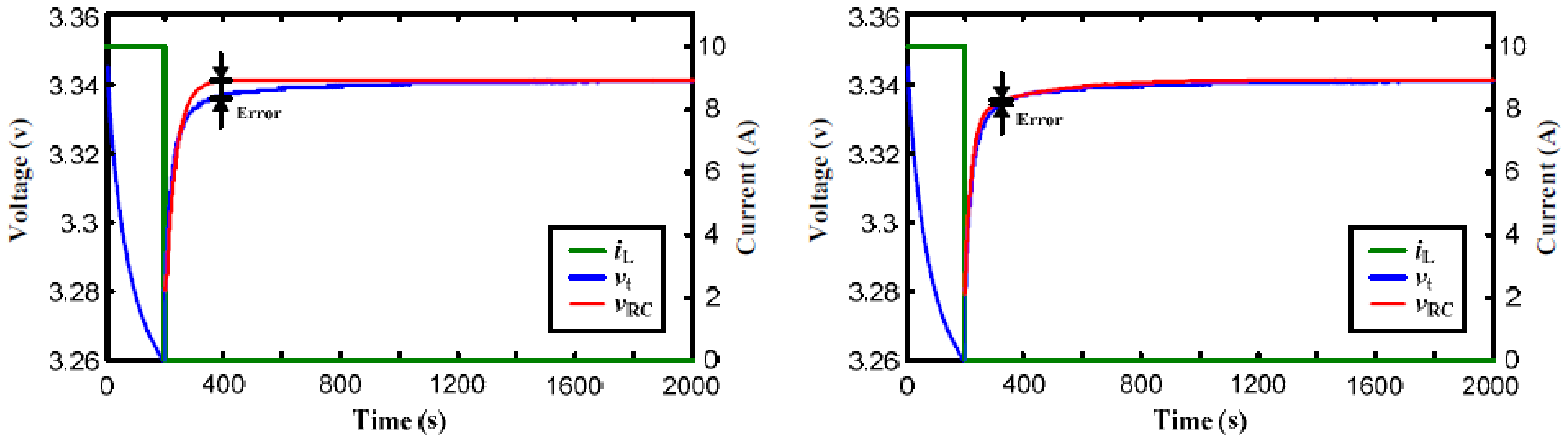


Figure 3 Relaxation effect modeling whit one RC parallel circuit and relaxation effect modeling with two series connected RC parallel circuits [4]

[3] M. Chen and G. Rincon-Mora, „Accurate electrical battery model capable of predicting runtime and I-V performance
[4] H. Zhang and M. Chow, „Comprehensive Dynamic Battery Modeling for PHEV Applications“

Model of Li-Ion Cell: Subsystems of Li-Ion cell model

- **Subsystem for the calculation of the usable capacity**
  - Peukert equation: $Q_0 = \left(\frac{I_{BT}}{I_{BT,rated}}\right)^{1-n} * Q_{o,rated} * Kf$ (2)
- **Subsystem for the calculation of the state of charge**
  - Coulomb- Counting: $SoC = SoC_{init} - \int \frac{I_{BT}}{Q_{0*3600}} dt$ (3)
- **Subsystem for calculation of open circuit voltage**
  - Polynomial equation seventh order: cftools
- **Subsystem for calculation of the voltage V_0**
  - Ohm's law: $V_0 = R_0 * I_{BT}$ (R_0, Look-up-Table) (4)
- **Subsystem for calculation of the RC elements R_1, R_2, C_1, C_2**
  - Time constant: $\tau_1 = R_1 * C_1 = -\frac{t_2 - t_1}{ln\left(\frac{V_2}{V_1}\right)}$ (5)
  - Ohm‘s law: $R_1 = \frac{V_1 - V_2}{I_{BT}}$ (6)
- **Subsystem for calculation of the Voltages V_1 and V_2**
  - S-domain RC connection: $V_1 = \left(\frac{1}{s}\right)\left[\frac{1}{C} - \frac{V}{RC}\right]$ (7)

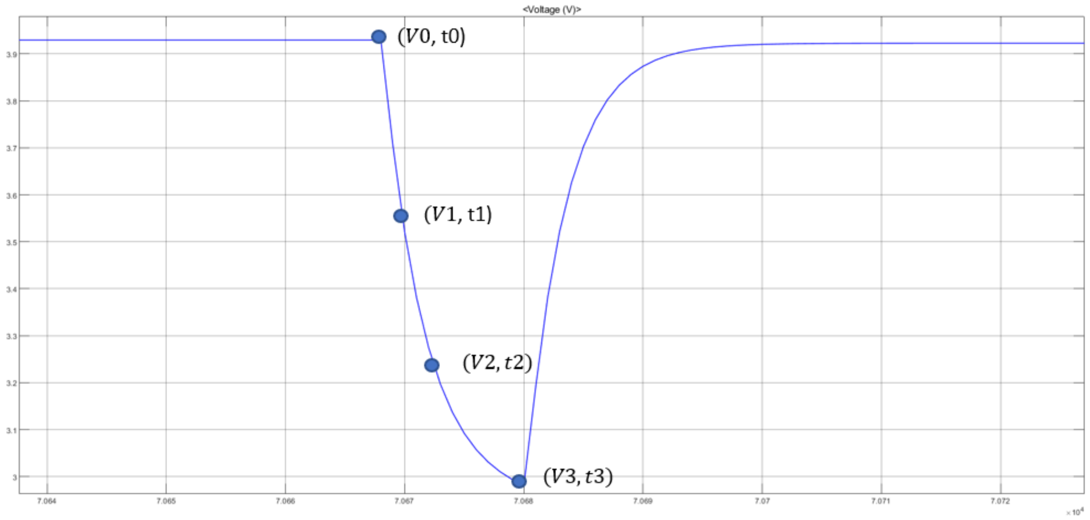


Figure 4. Transient behavior of the cell after a pulse discharge

Model of Li-Ion Cell: Adaptation of the Li-Ion cell model into a battery model

- **Calculation of the battery´s amount of charge AOC**

$$Q(t) = SoC * Q_{max} \qquad (8)$$

- **Calculation of the voltage of the battery V_{BT}**

$$V_{BT} = N_{zelle} * V_{t,zelle} \qquad (9)$$

- **Calculation of the energy of the battery E_{BT}**

$$E_{BT} = V_{BT}(t) * Q(t) \qquad (10)$$

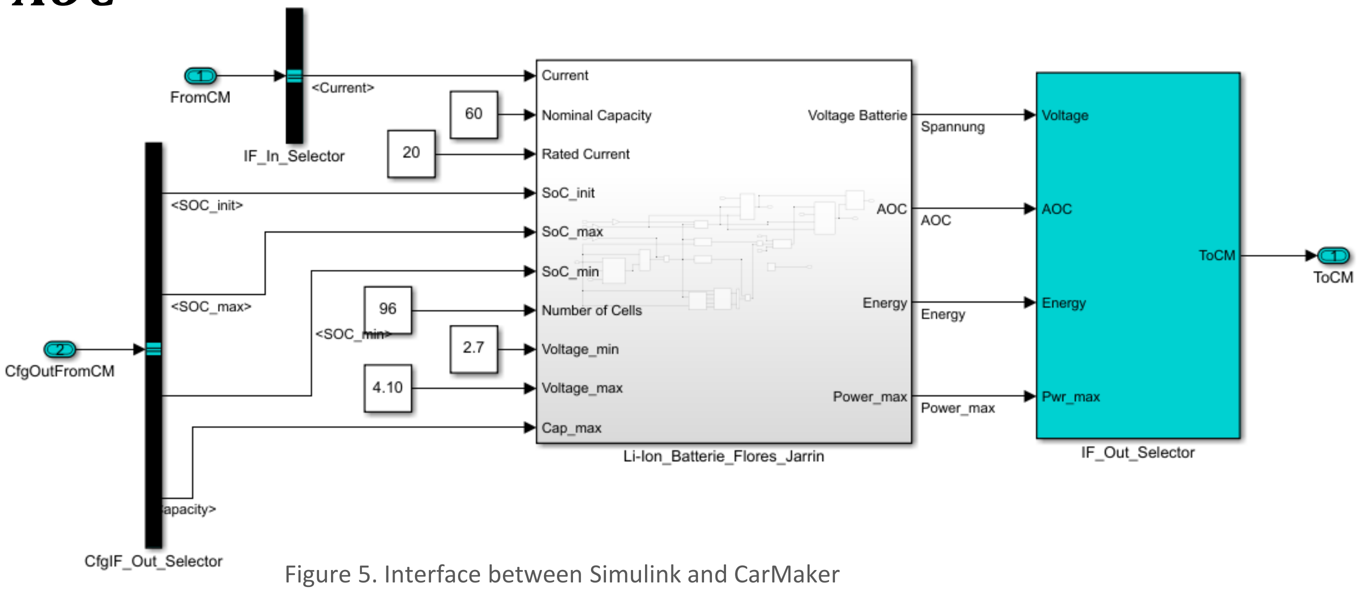


Figure 5. Interface between Simulink and CarMaker

Model of Supercapacitor Cell: Concept of the equivalent circuit model

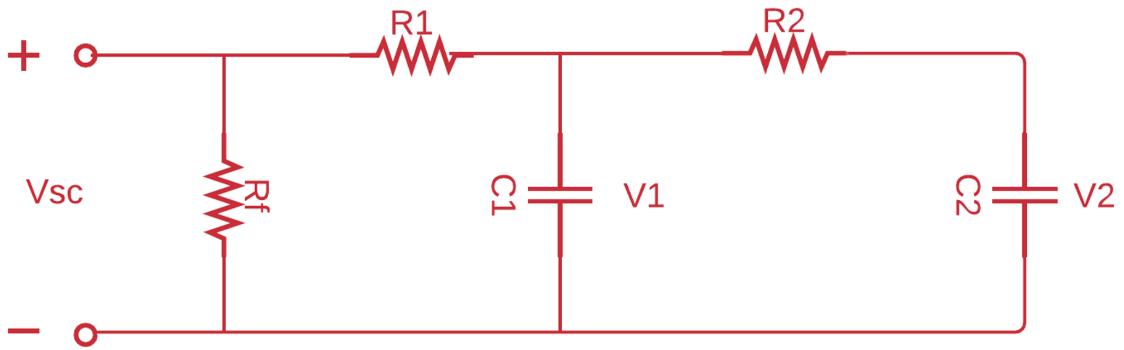


Figure 6. Equivalent circuit model of the Supercapacitor [5]

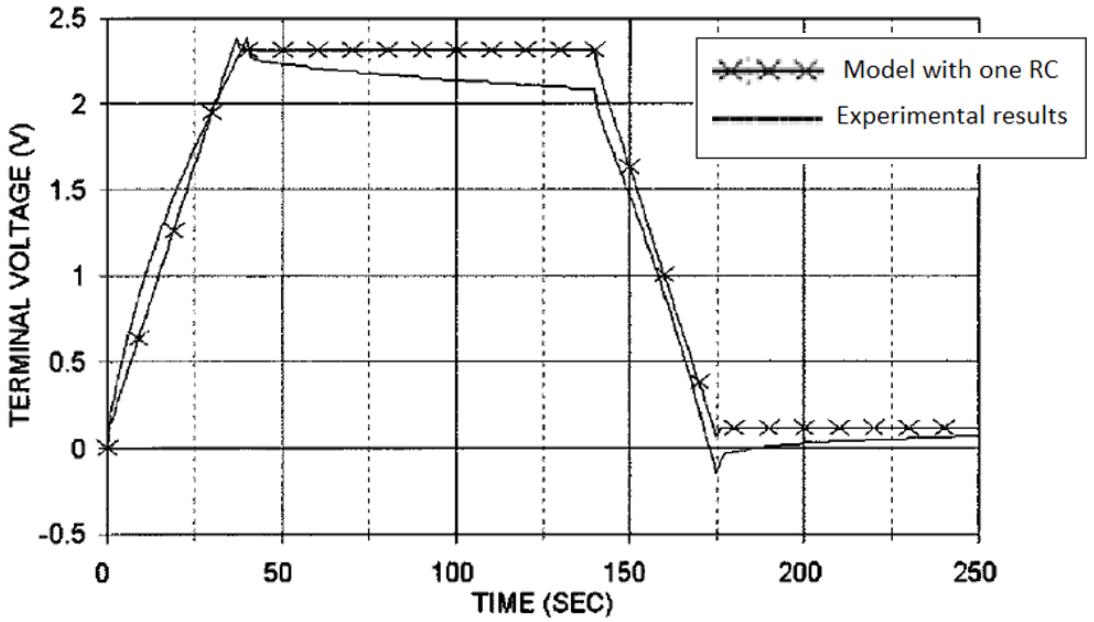


Figure 7. Comparation between experiments and simple RC modeling [6]

- The decision about the number of RC circuits of the equivalent circuit model depends on the time span of the transient response to be covered
- A two branches model dominates the terminal behavior in the range of minutes

[5] M. Sahin, F. Blaabjerg and A. Sangwongwanich, „Modelling of Supercapacitors Based on Simplified Equivalent Circuit"
[6] L. Zubieta and R. Bonert,"Characterization of Double-Layer Capacitors for Power Electronics Applications"

Model of Supercapacitor Cell: Subsystems of Supercapacitor cell model

- **Subsystem for the calculation of the voltage V_1**

$$V_1 = \frac{-C_0 + \sqrt{{C_0}^2 + 2C_v Q_1}}{C_v} \qquad (12)$$

- **Subsystem for the calculation of the voltage V_2**

$$V_2 = \frac{1}{C_2}\int i_2 dt = \frac{1}{C_2}\int \frac{1}{R_2}(V_1 - V_2)dt \qquad (13)$$

- **Subsystem for calculation of the current i_1 and quick charge Q_1**

$$i_1 = i_{SC} - i_2 \qquad (14)$$

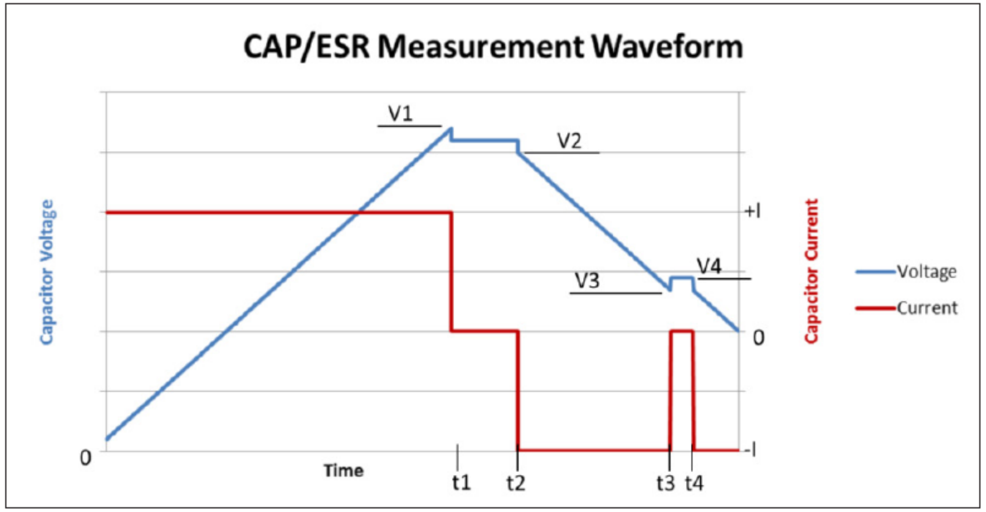
$$Q_1 = \int i_1 dt \qquad (15)$$

- **Subsystem for calculation of the state-of-charge SoC_{SC}**

$$SoC_{SC} = \frac{V_{SC}}{Rated\ voltage} \qquad (16)$$

$$V_{SC} = N_{S_{SC}}\left(V_1 + R_1 \frac{I_{SC}}{N_{P_{SC}}}\right) \qquad (17)$$

Model of Supercapacitor Cell: Validation of the cell model



$V1 = V_{rated}$ $\quad$ t2 - t1 = 15 seconds $\quad$ Capacitance = I x (t3-t2)/(V2-V3)

$V3 = 0.5 \times V_{rated}$ $\quad$ t4 - t3 = 5 seconds $\quad$ ESR = (V4 - V3)/I

Figure 8. Supercapacitor BCAP3000 Measurement Waveform [2]

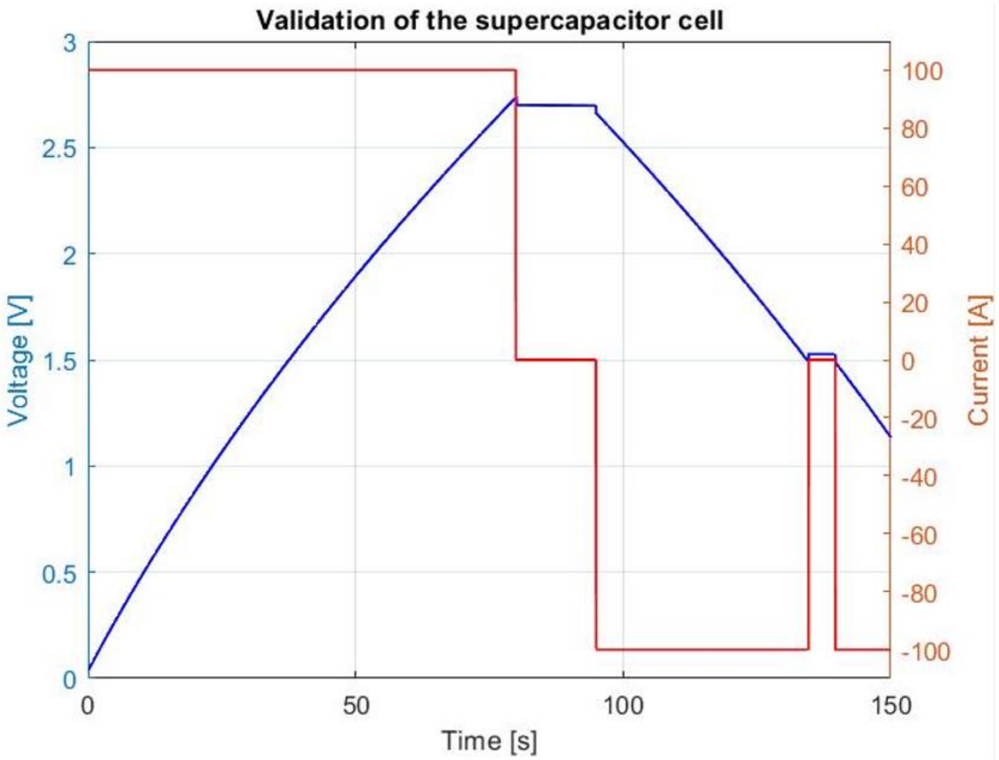


Figure 9. Supercapacitor BCAP3000 Model Measurement

[2] Maxwell Technologies, “Datasheet K2 Ultracapacitors – 2.7V Series,”

Model of Bidirectional DC/DC Converter: Topology of the bidirectional converter

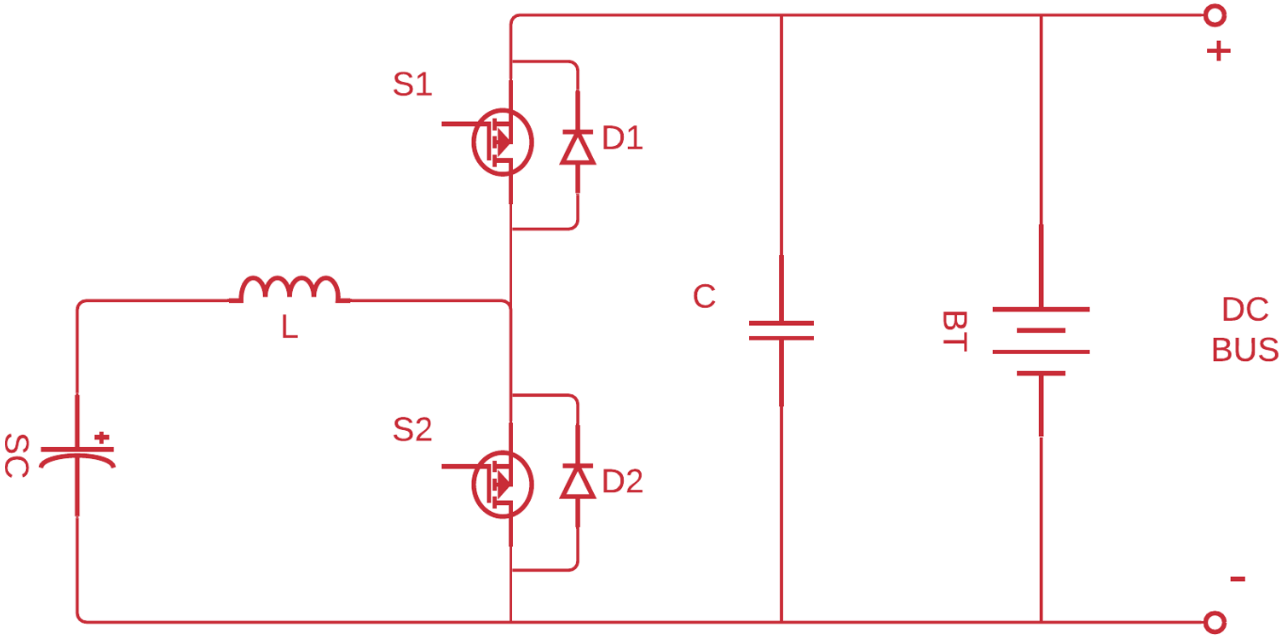


Figure 10. Half-Bridge bidirectional converter [7]

- Semi-Active topology, only one of the two energy storage elements is actively controlled
- Combination of a buck and boost converter
- Requires only one inductor: higher efficiencies since it has lower inductor conduction, lower switching and conduction losses on active components

[7] J. Shen, „Energy Management of a Battery-Ultracapacitor Hybrid Energy Storage System in Electric Vehicles"

Model of Bidirectional DC/DC Converter: Modes of operation of the bidirectional DC/DC converter

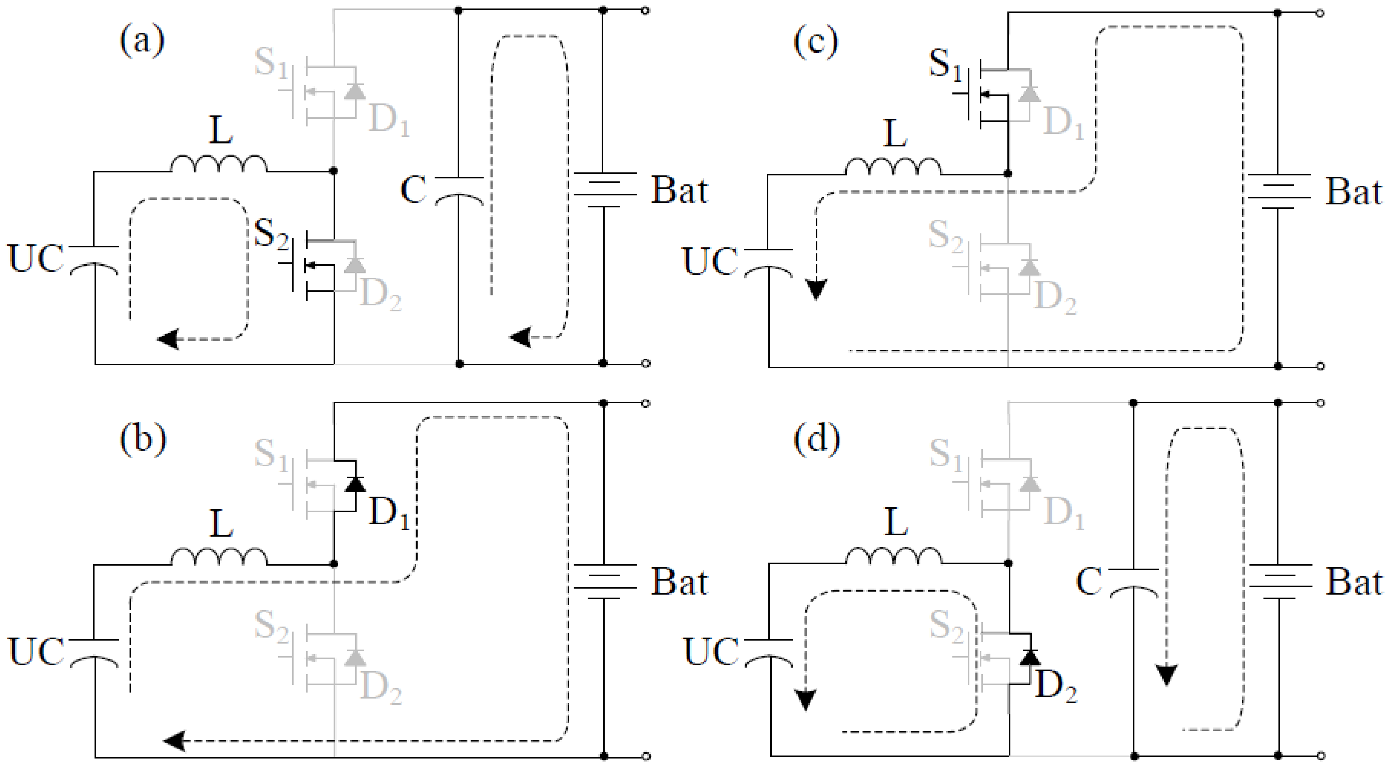


Figure 11. Operation modes of the Bidirectional DC/DC Converter [7]

- **Boost Mode (a) and (b):**
  - Power is transferred from the supercapacitor to the battery/DC-bus
- **Buck Mode (c) and (d):**
  - Power is transferred from the battery/DC-bus to the supercapacitor.

$$i_C = -i_{dmd} + i_L(1 - D) \qquad (18)$$

$$i_C = -i_{dmd} + i_L(D) \qquad (19)$$

[7] J. Shen, „Energy Management of a Battery-Ultracapacitor Hybrid Energy Storage System in Electric Vehicles"

Energy consumption of the BMW i3 vehicle on the route Bruchsal-Karlsruhe-Bruchsal

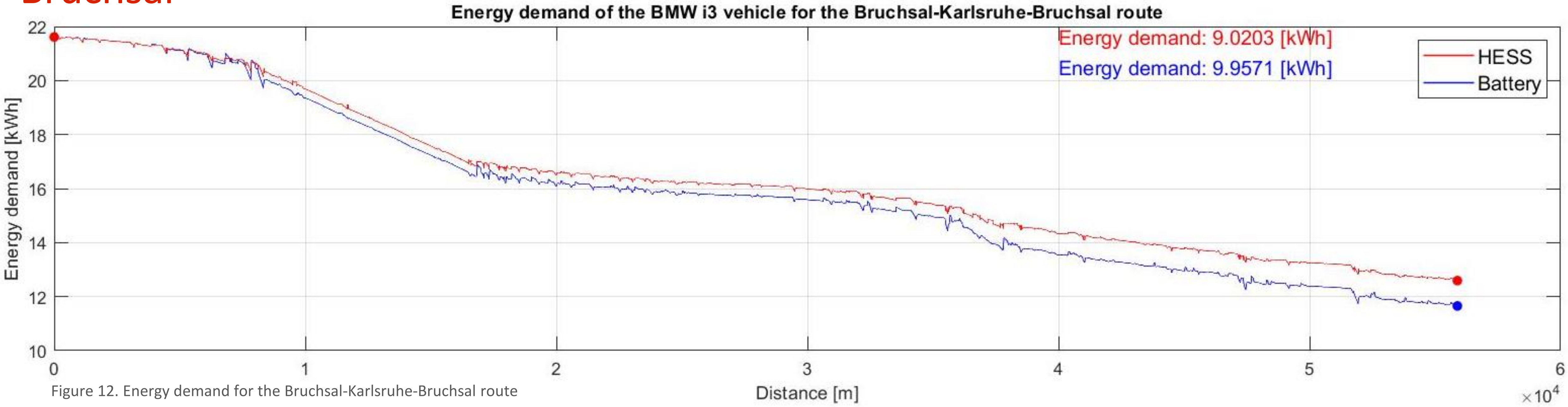


Figure 12. Energy demand for the Bruchsal-Karlsruhe-Bruchsal route

Measurement	Distance	Duration	Average velocity	Energy demand
	km	min	km/h	kWh
Reference value [8]	56,87	56,25	60,67	9,72
Validation battery model	55,90	56,12	59,76	9,95
Variation	**1,70 %**	**0.23 %**	**1.49 %**	**-2,36 %**
Simulation HESS	55,90	56,12	59,76	9,02
Variation ESS-HESS	**-**	**-**	**-**	**9,35 %**

Table 3. Comparison of simulation results with real measurements

[8] C. Gutenkunst, „Prädiktive Routenenergieberechnung eines Elektrofahrzeugs“

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