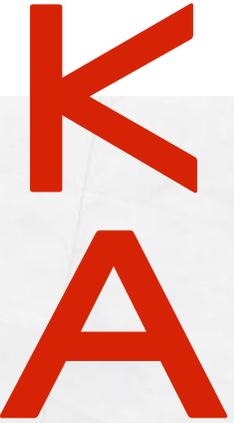




Concept of a Hybrid Energy Storage System for Energy Management System Development





- **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**

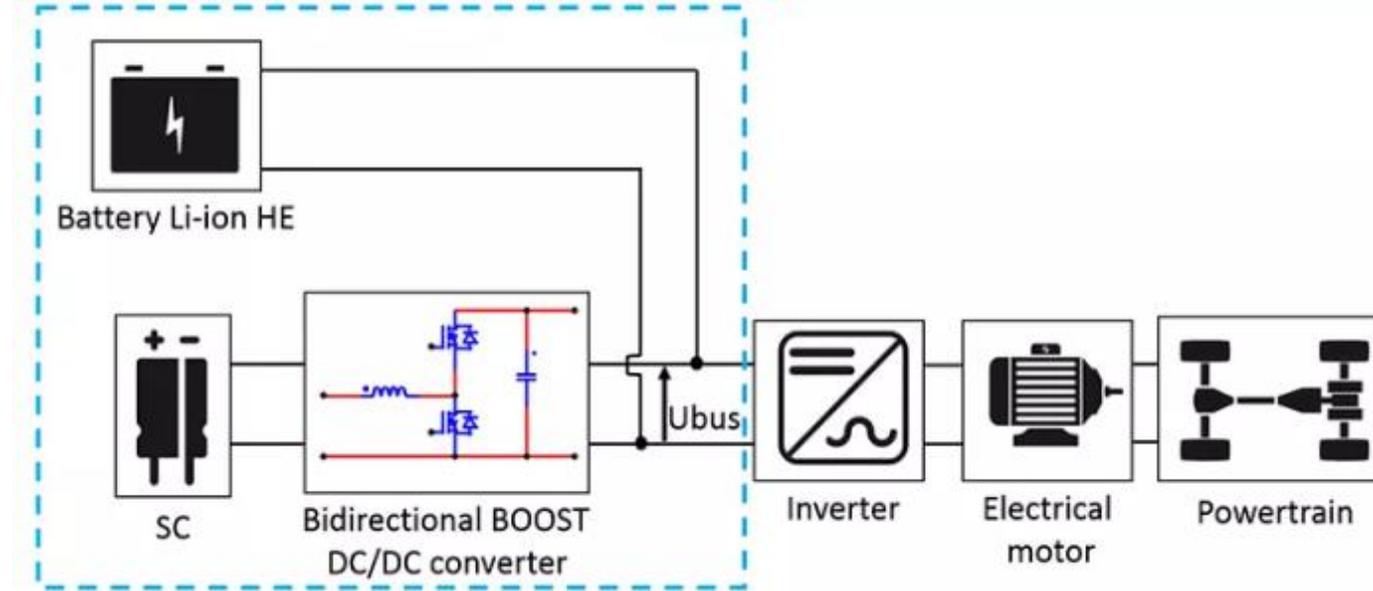
- Topology and operation of the bidirectional converter
- Modes of operation of the bidirectional DC/DC converter

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

Objectives: Topology of the HESS developed in this project



Li-ion Battery / Supercapacitor Hybrid Energy Storage



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]

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

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

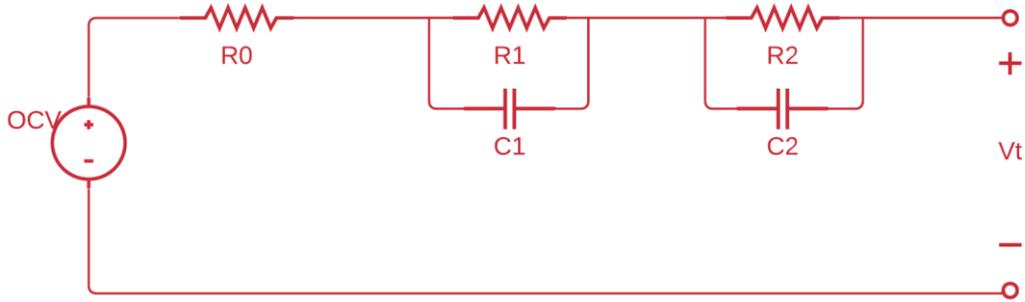


Figure 2. Equivalent circuit model of the Battery [3]

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

- 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

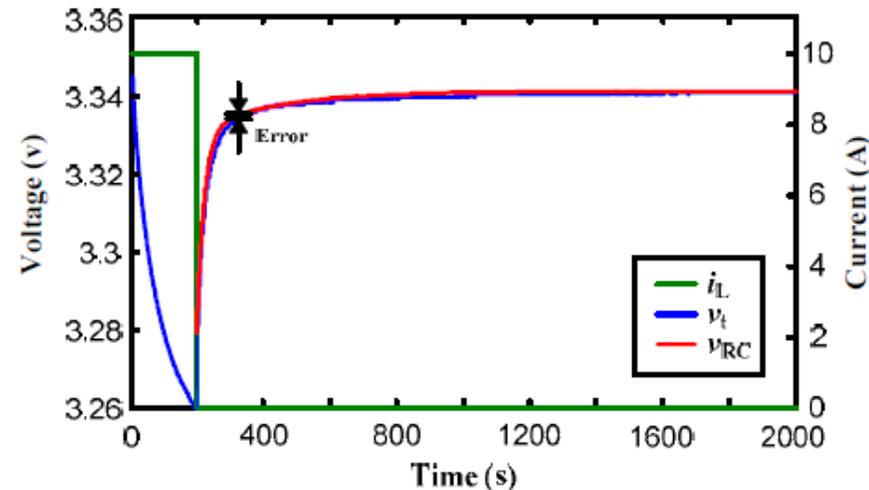
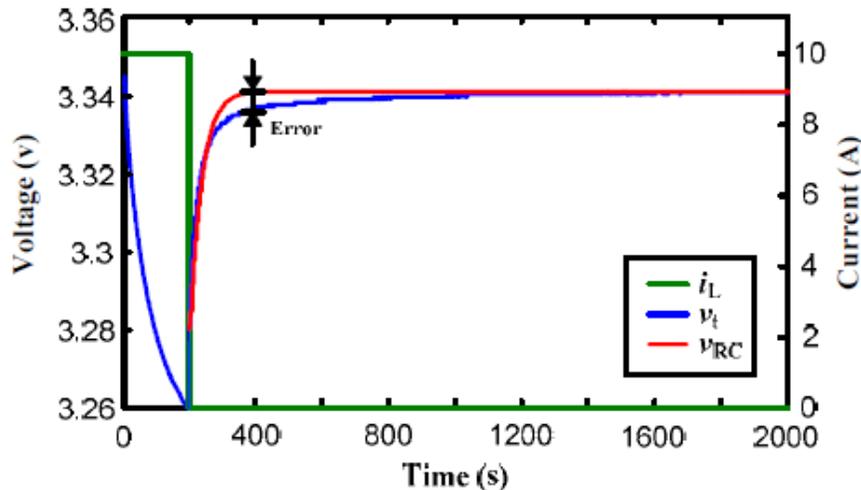


Figure 3 Relaxation effect modeling with one RC parallel circuit and relaxation effect modeling with two series connected RC parallel circuits [4]

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



- **Subsystem for the calculation of the usable capacity**

- Peukert equation: $Q_0 = \left(\frac{I_{BT}}{I_{BT, rated}} \right)^{1-n} * Q_{0, rated} * Kf$

- **Subsystem for the calculation of the state of charge**

- Coulomb- Counting: $SoC = SoC_{init} - \int \frac{I_{BT}}{Q_0 * 3600} dt$

- **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)

- **Subsystem for calculation of the RC elements R_1, R_2, C_1, C_2**

- Time constant: $\tau_1 = R_1 * C_1 = - \frac{t_2 - t_1}{\ln\left(\frac{V_2}{V_1}\right)}$

- Ohm's law: $R_1 = \frac{V_1 - V_2}{I_{BT}}$

- **Subsystem for calculation of the Voltages V_1 and V_2**

- S-domain RC connection: $V_1 = \left(\frac{1}{s} \right) \left[\frac{1}{C} - \frac{V}{RC} \right]$

(2)

(3)

(4)

(5)

(6)

(7)

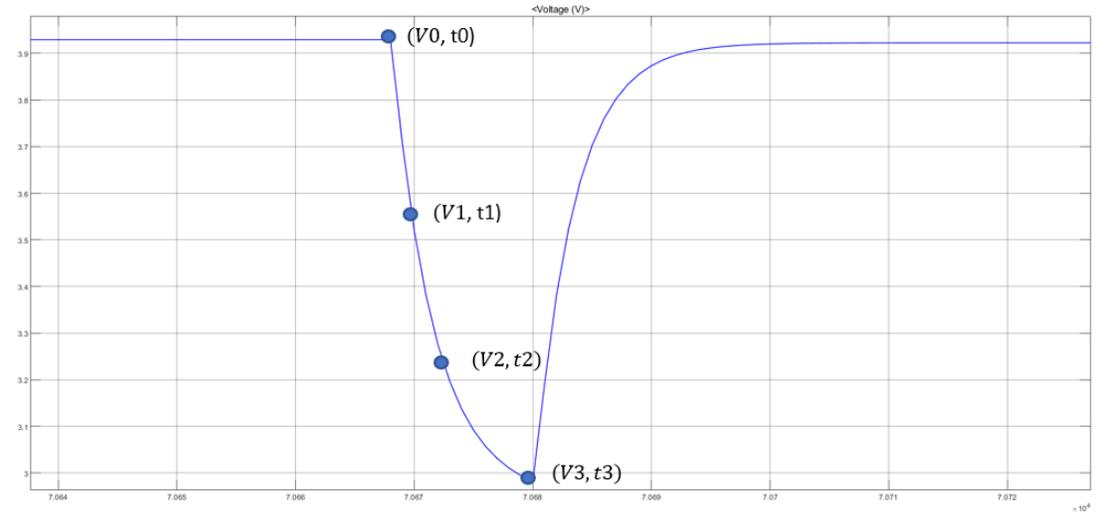


Figure 4. Transient behavior of the cell after a pulse discharge



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

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

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

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

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

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

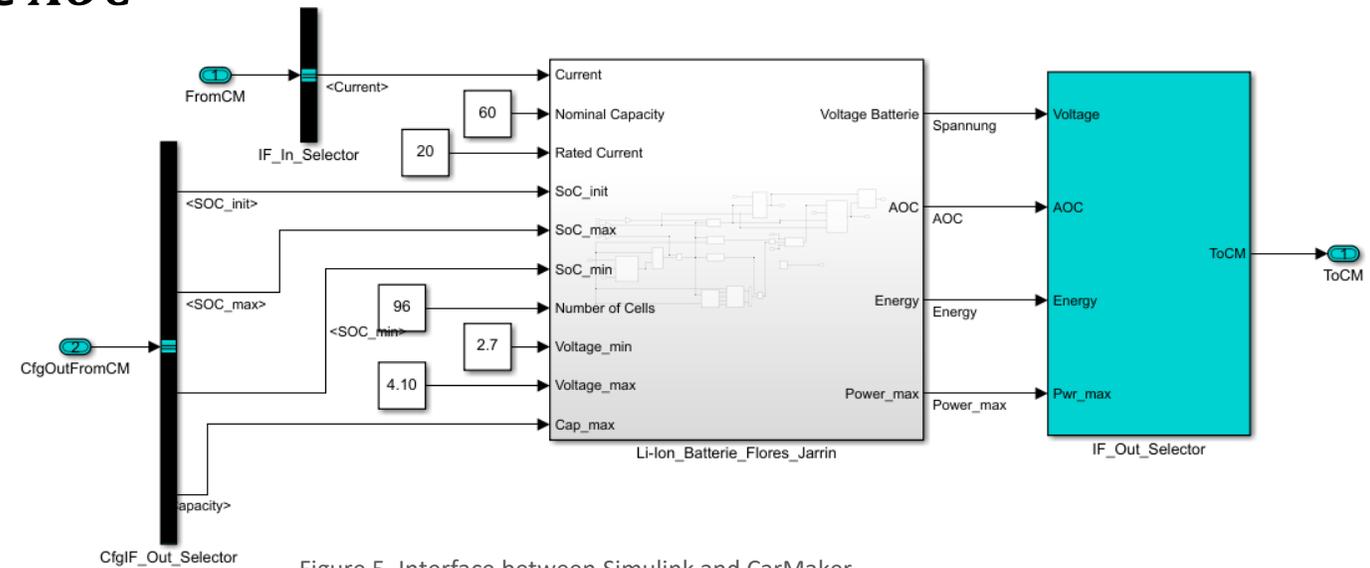


Figure 5. Interface between Simulink and CarMaker

Model of Supercapacitor Cell: Concept of the equivalent circuit model

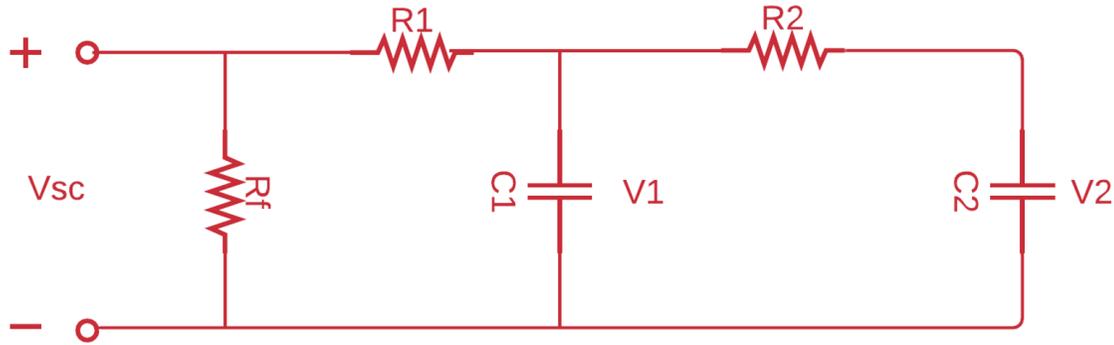


Figure 6. Equivalent circuit model of the Supercapacitor [5]

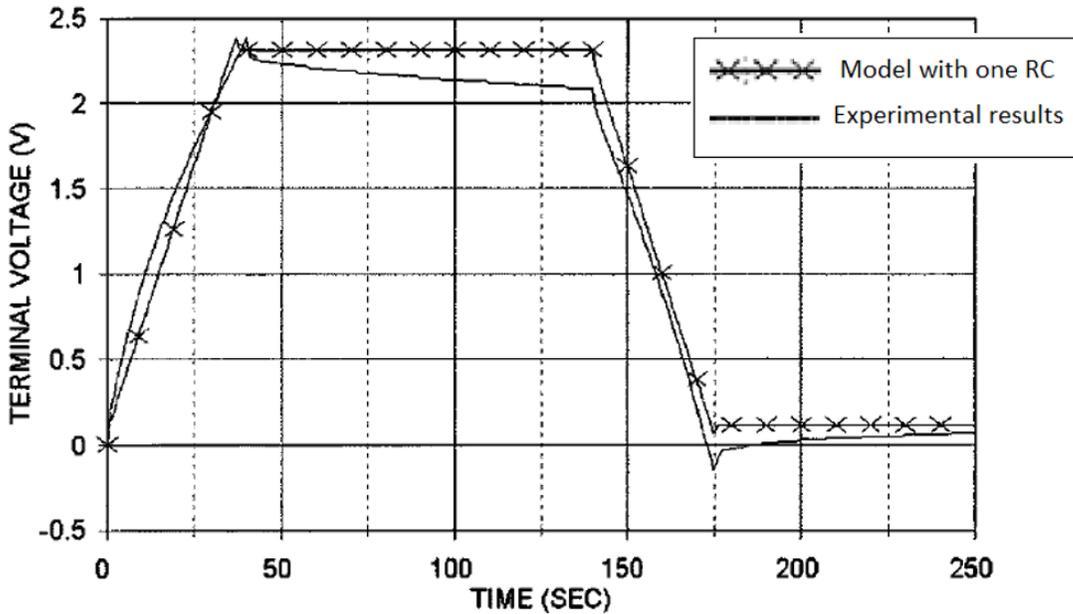


Figure 7. Comparison between experiments and simple RC modeling [6]

- 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

Model of Supercapacitor Cell: Subsystems of Supercapacitor cell model



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

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

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

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

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

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

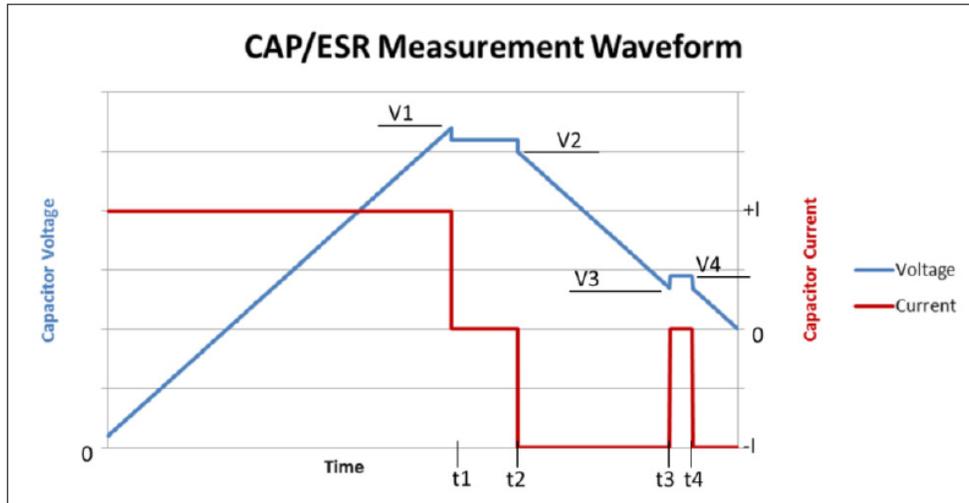
$$Q_1 = \int i_1 dt \quad (15)$$

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

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

$$V_{SC} = N_{SSC} \left(V_1 + R_1 \frac{I_{SC}}{N_{PSC}} \right) \quad (17)$$

Model of Supercapacitor Cell: Validation of the cell model



$V1 = V_{rated}$ $t2 - t1 = 15$ seconds $Capacitance = I \times (t3 - t2) / (V2 - V3)$
 $V3 = 0.5 \times V_{rated}$ $t4 - t3 = 5$ seconds $ESR = (V4 - V3) / I$

Figure 8. Supercapacitor BCAP3000 Measurement Waveform [2]

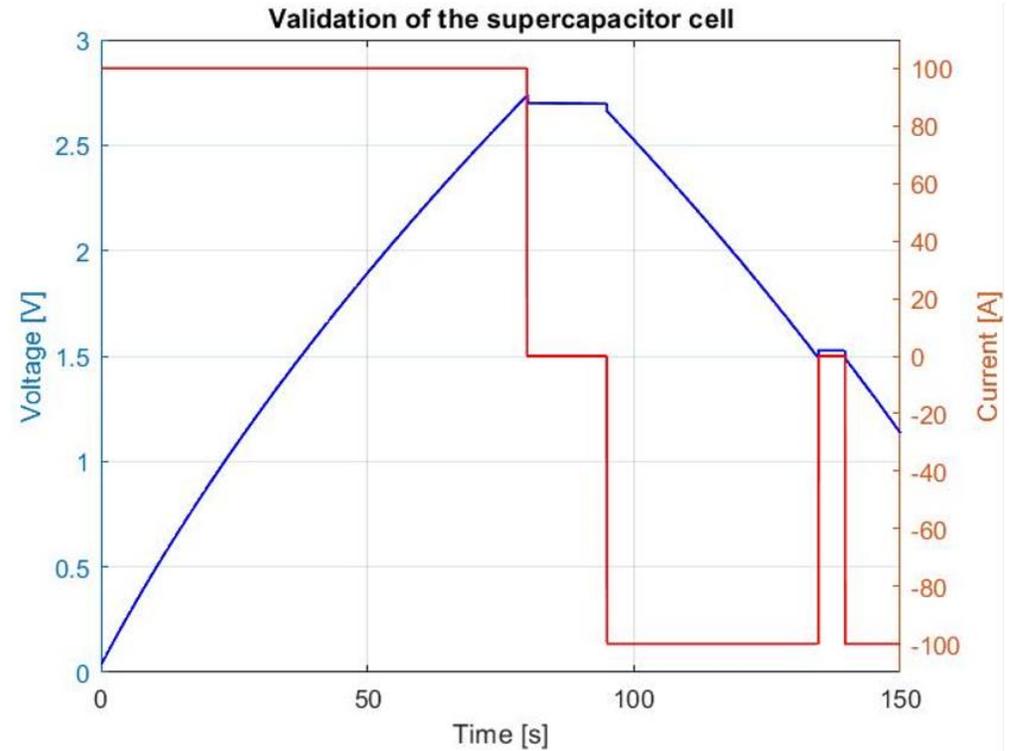


Figure 9. Supercapacitor BCAP3000 Model Measurement

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

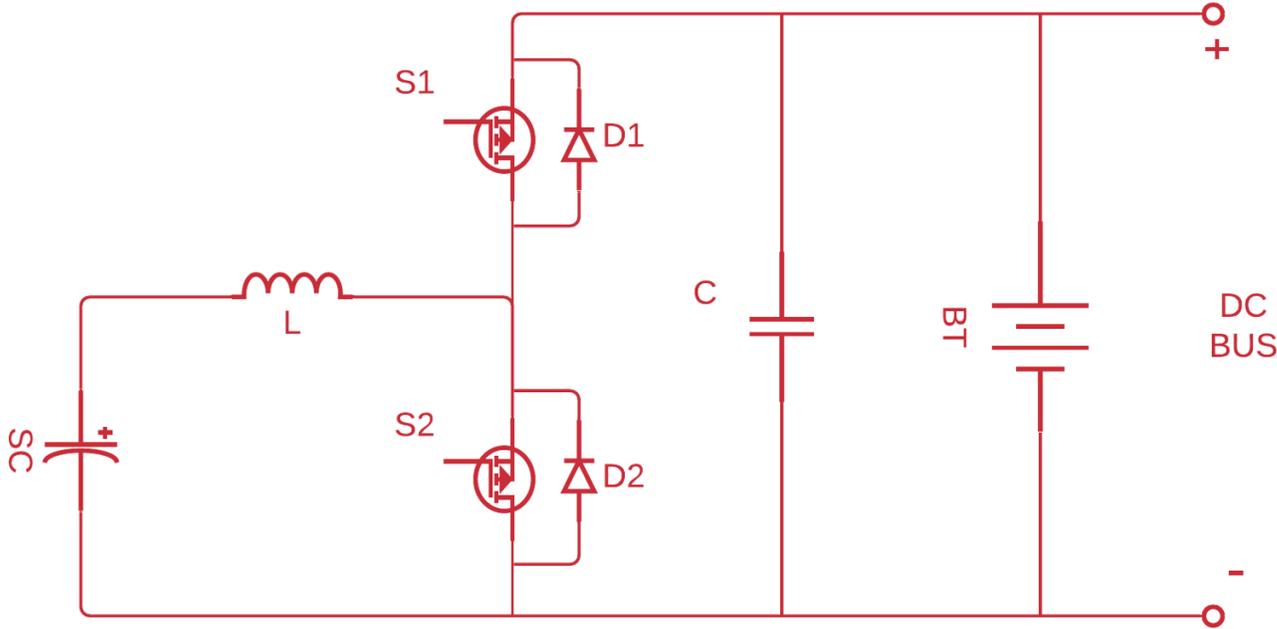


Figure 10. Half-Bridge bidirectional converter [7]

- 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

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

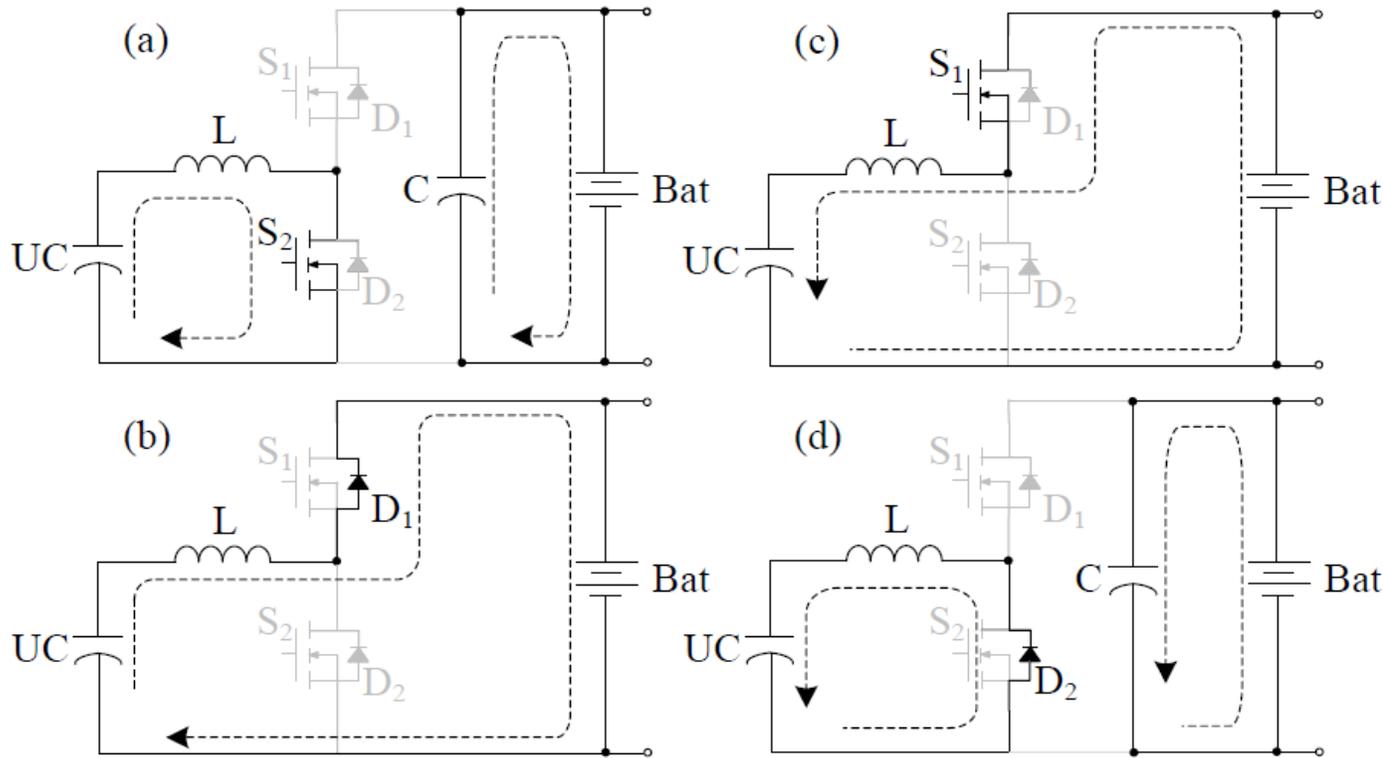


Figure 11. Operation modes of the Bidirectional DC/DC Converter [7]

- **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.

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

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

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

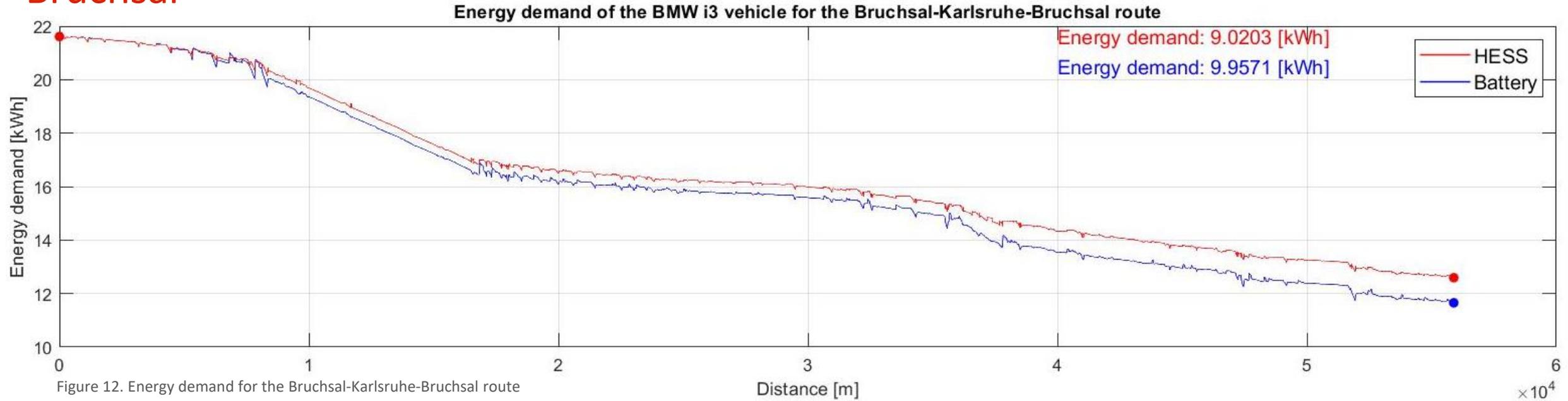


Figure 12. Energy demand for the Bruchsal-Karlsruhe-Bruchsal route

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



