

Aktive Balancing-Systeme für Lithium-ionen Batterien und deren Auswirkungen auf die Zellalterung

Promotionsvortrag

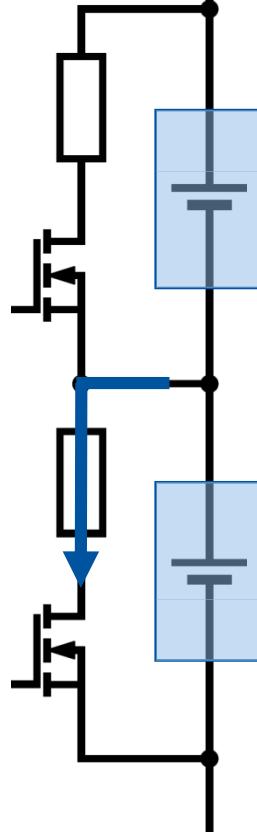
30.06.2017

Manuel Brühl

Passives Balancing

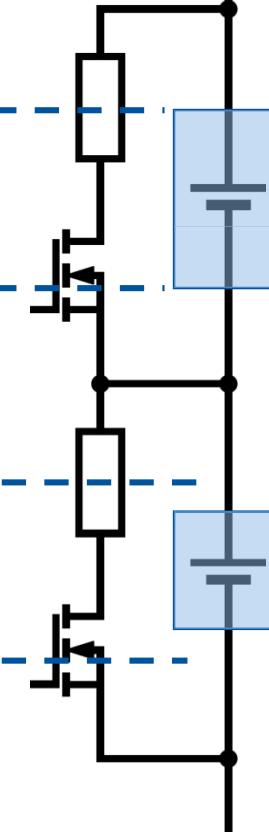
SOC Ausgleich

Ladung



ΔC Ausgleich nicht möglich!

Entladung



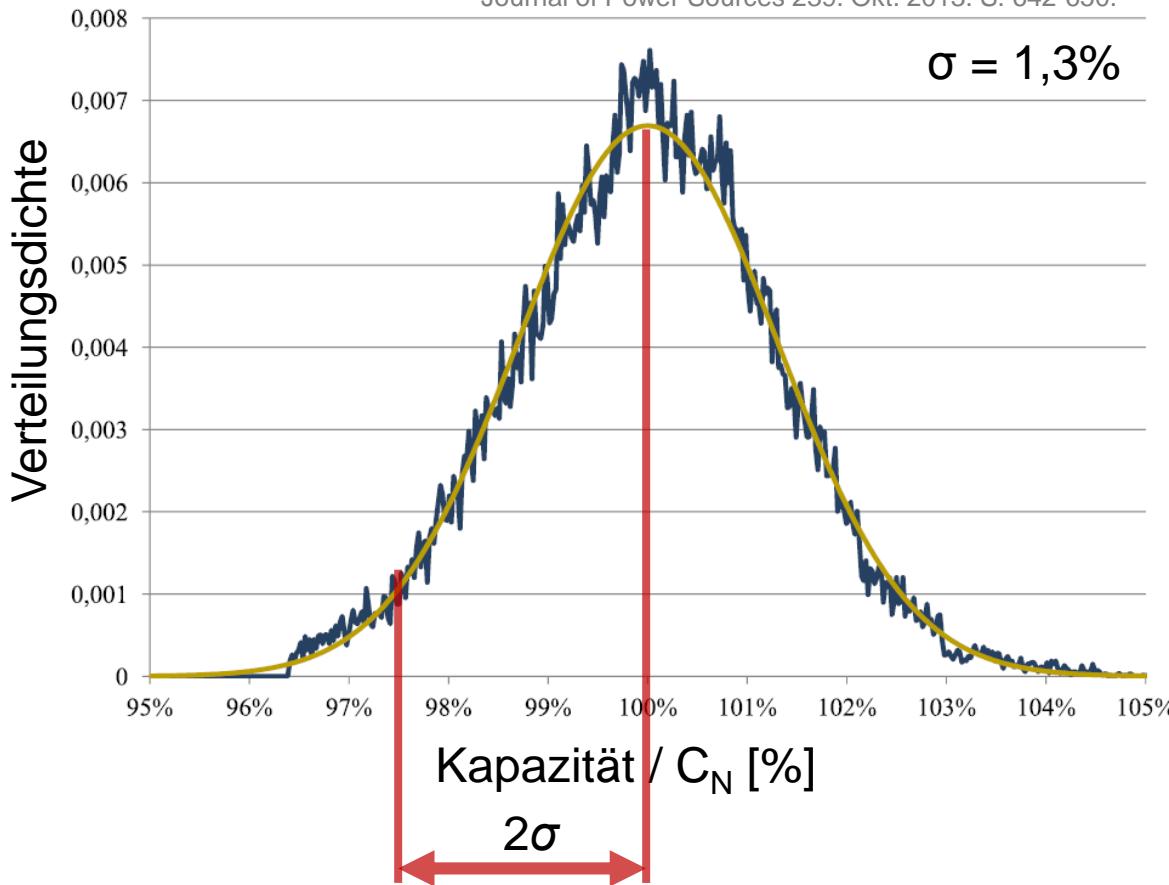
Ungenutzte
Kapazität!

Aktives
Balancing

Welche Zellstreuung ist zu erwarten?

Kapazitäten von 20.000 neuen Zellen

Journal of Power Sources 239. Okt. 2013. S. 642-650.



$$\sigma = 1,3\%$$

Wahrscheinlichkeit, dass eine Zelle $x < \mu - 2\sigma$
 $P_1 = 2,3\%$

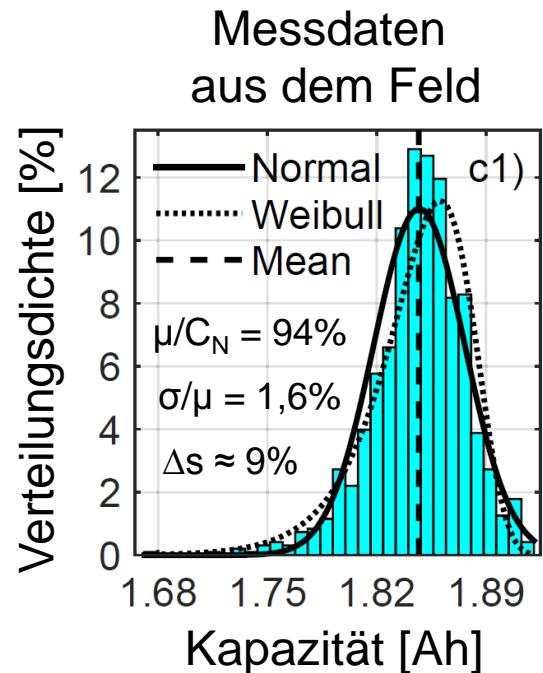
Wahrscheinlichkeit bei 100 Zellen, dass min eine Zelle $x < \mu - 2\sigma$
 $P_{100} = 1 - (1 - P_1)^{100} = 90\%$

Stärkere Ausreißer sind bei vielen Zellen in Serie sehr wahrscheinlich!

Einfluss auf die Streuung und deren Reduktion



- Verbesserte Produktionsqualität
- Aussortieren von schlechten Zellen
- Verbesserte Kühlung
- Erkennen von Ausreißern und austauschen von Zellen bzw. Modulen
- Mittelung durch Parallelschaltung von Zellen
- **Beeinflussung der Zellalterung durch Veränderung der Zellbelastung**
- **Umladen der Zellen im Betrieb durch aktives Balancing**

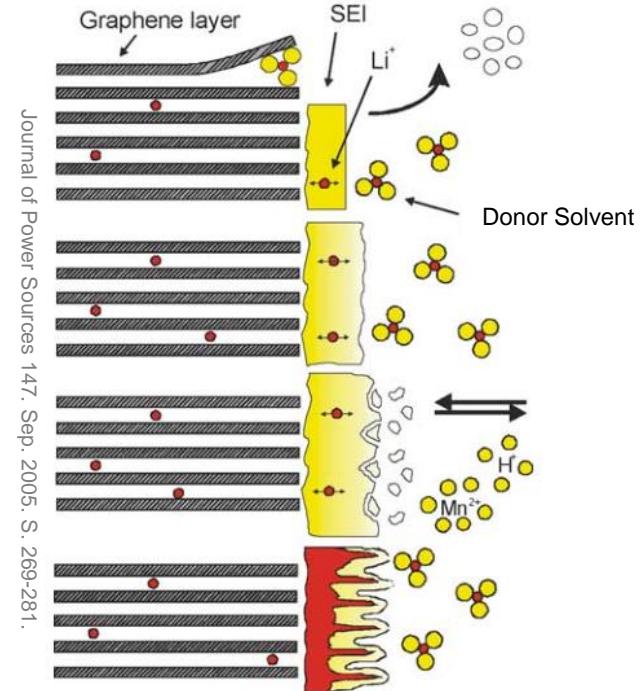
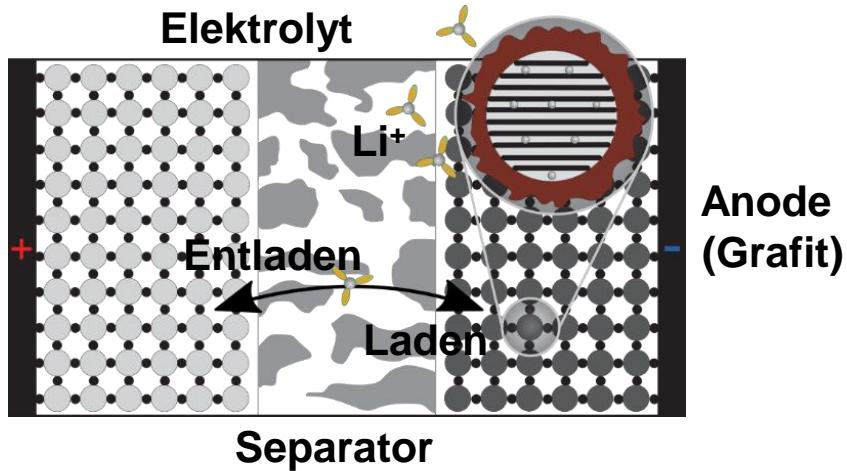


Journal of Power Sources 297.
Nov. 2015, S. 242-251.

Zellaufbau und Alterungsmechanismen

Kathode
(z.B. LiCoO_2)

Käbitz, S. Diss.
RWTH Aachen, 2016.

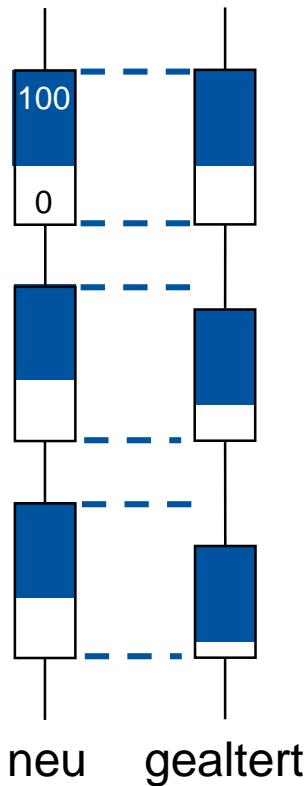


■ Verstärkte Alterung

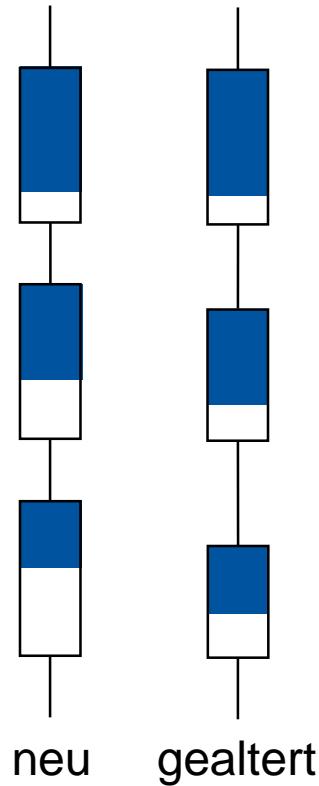
- hohe Entladetiefen (DODs)
- hohe Zellspannungen bzw.
Ladezustände (SOCs)
- hohe Temperaturen

Fragestellung – Zellalterung im Serienbetrieb?

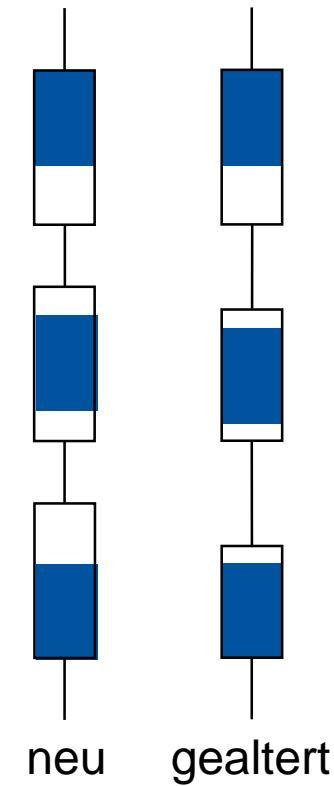
Referenz-
Test



DOD (Entladetiefe)-
Anpassung

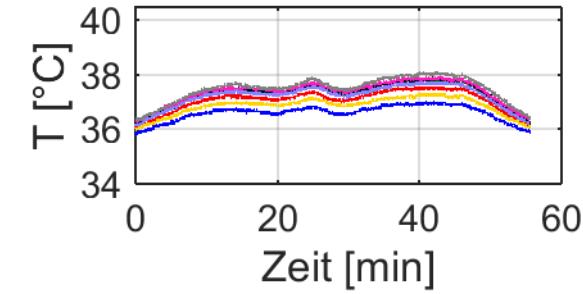
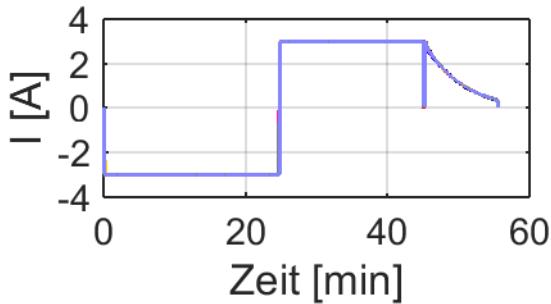
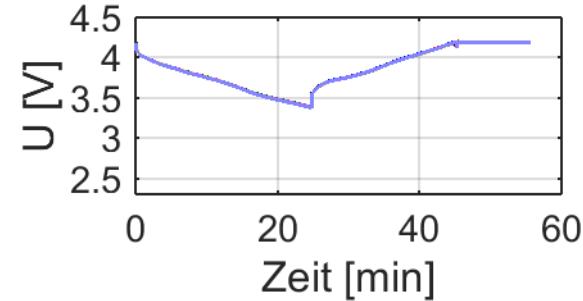


ΔU -
Anpassung

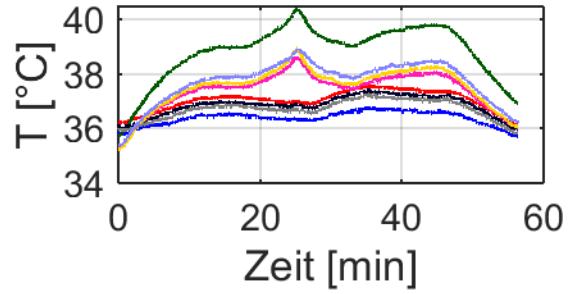
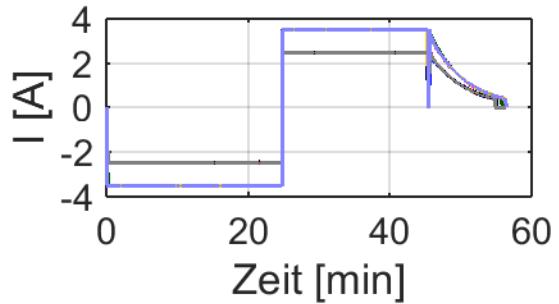
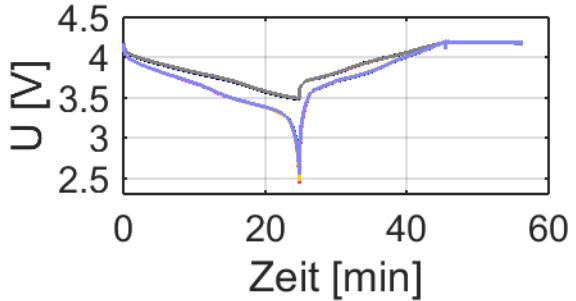


Beispiel-Zyklus der drei Tests

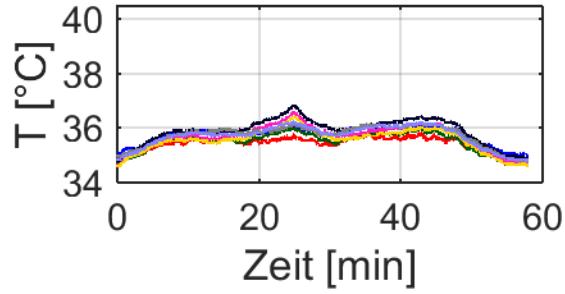
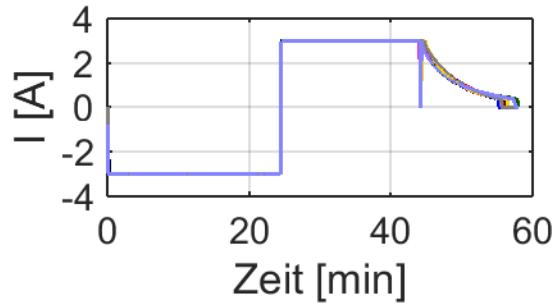
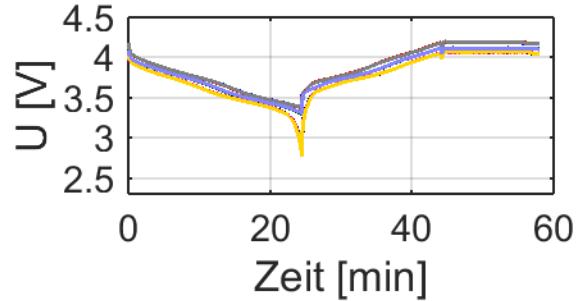
Referenz-
Test



DOD-
Anpassung

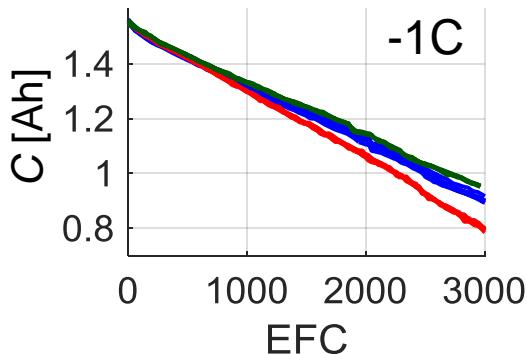


ΔU -
Anpassung

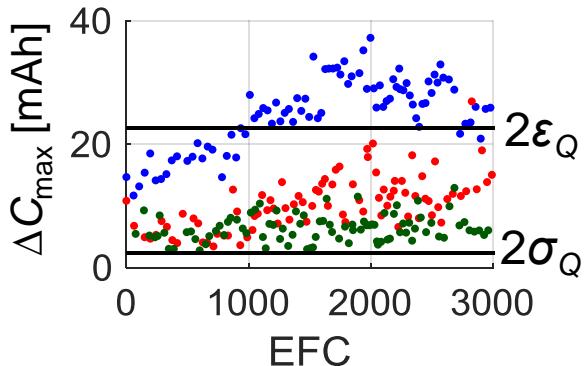


Verlauf der Entlade-Kapazitäten und deren Streuung

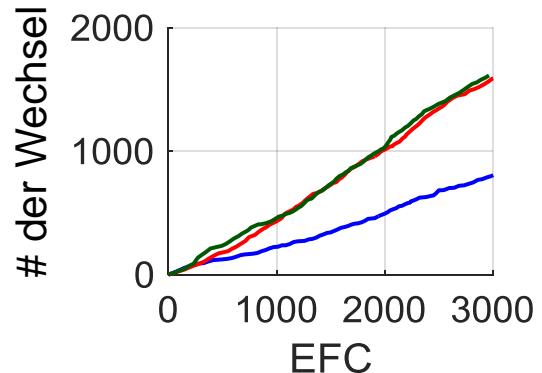
Referenz



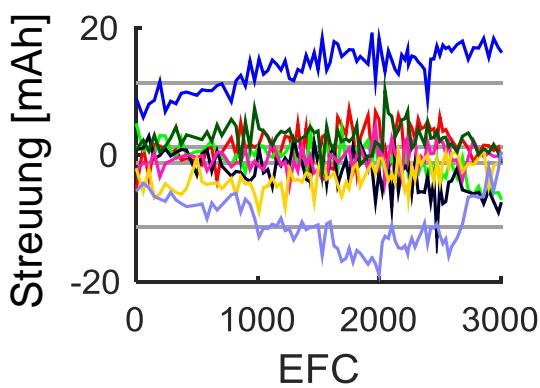
DOD



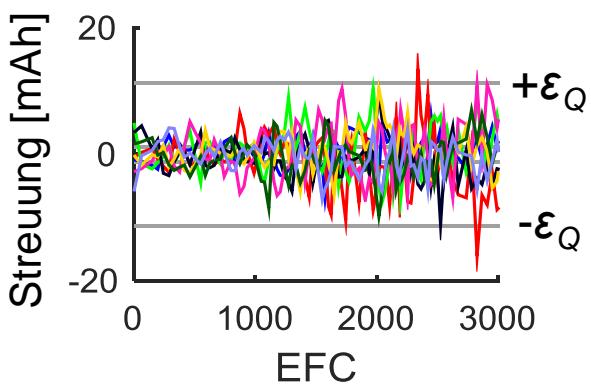
ΔU



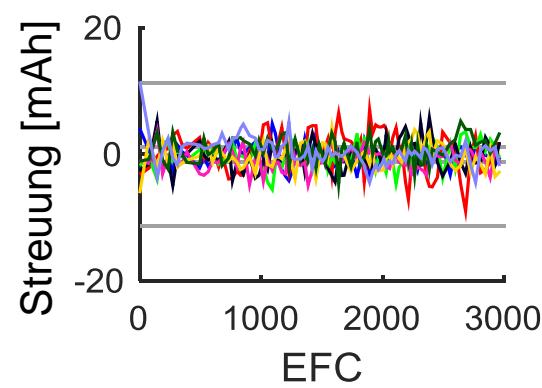
Referenz



DOD



ΔU

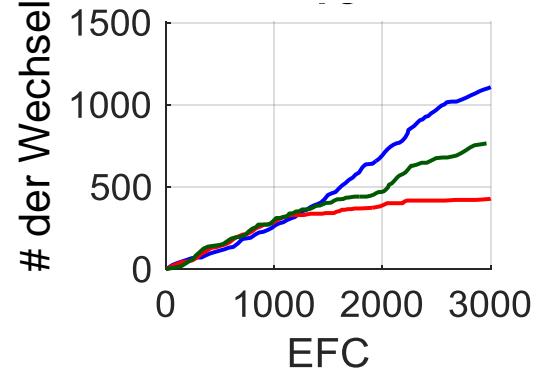
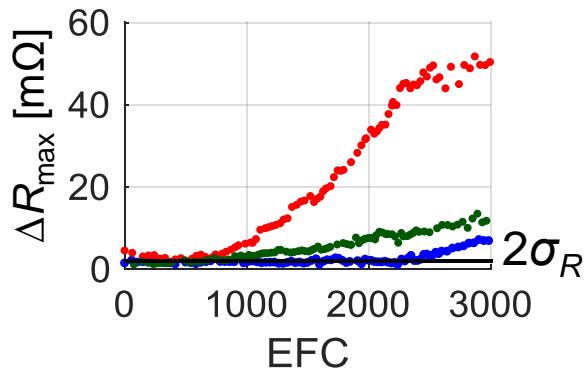
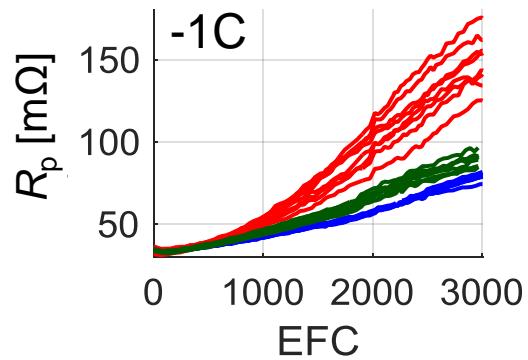
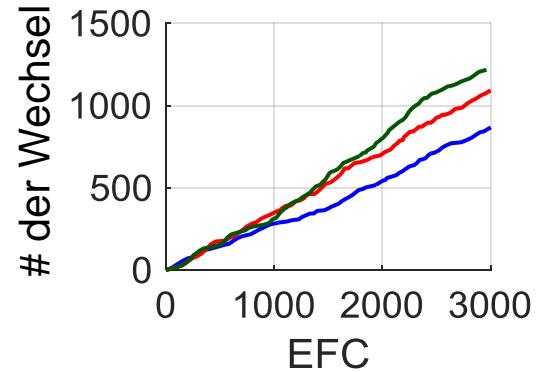
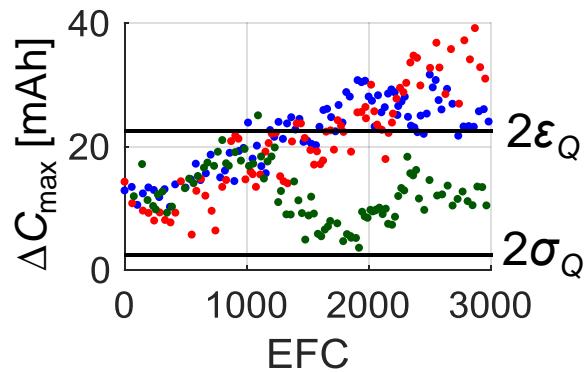
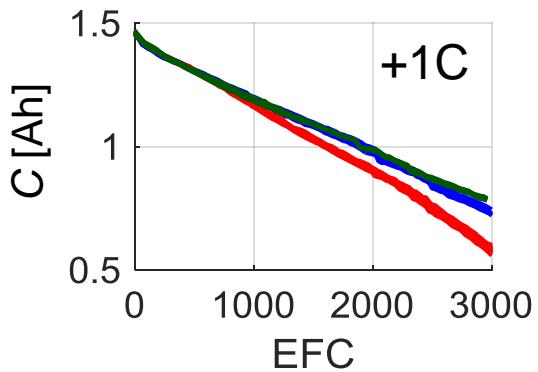


Verlauf der Lade-Kapazitäten und Entlade-Pulswiderstände

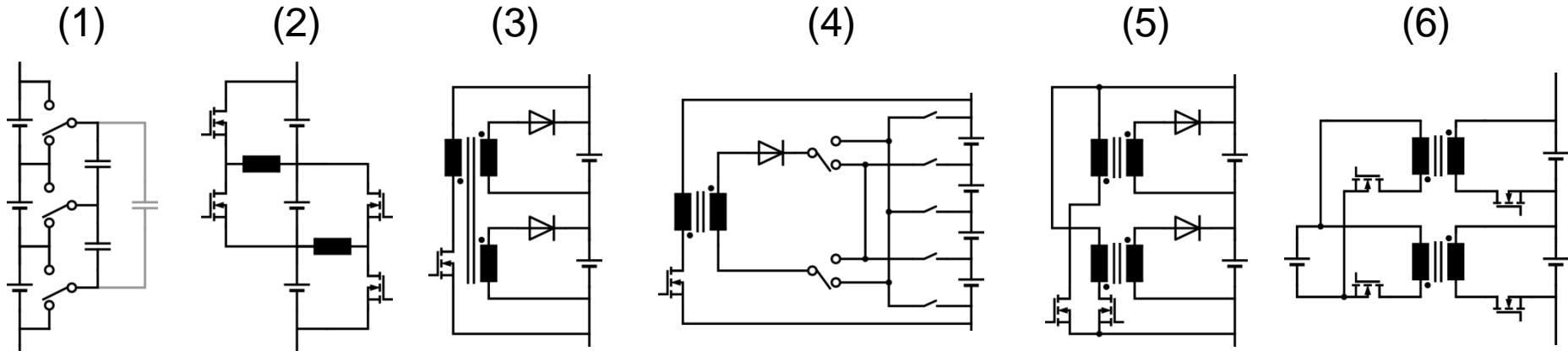
Referenz

DOD

ΔU



Anforderungen an das aktive Balancing



■ Basis-Anforderungen zum SOC-Abgleich

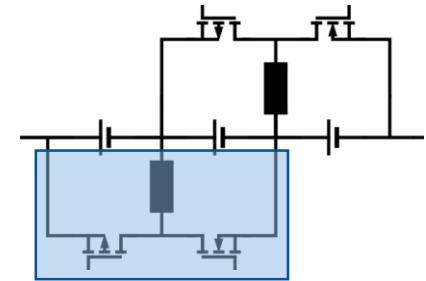
- Robust gegen kritische Fehler (Zellkurzschluss, Zellüberladung)
- Umladen auch zwischen Modulen möglich
- günstig, klein, (leicht)
- Modular erweiterbar (für große Zellstränge), einfach kontaktierbar
- gleichmäßige Bauteilbelastung (Spannungsfestigkeit)

■ Anforderung zum Ausgleich von Kapazitätsunterschieden im Betrieb

- Zellspannungsunabhängiges Umladen
- schnelles Ausgleichen von schlechten Zellen
- hoher Wirkungsgrad

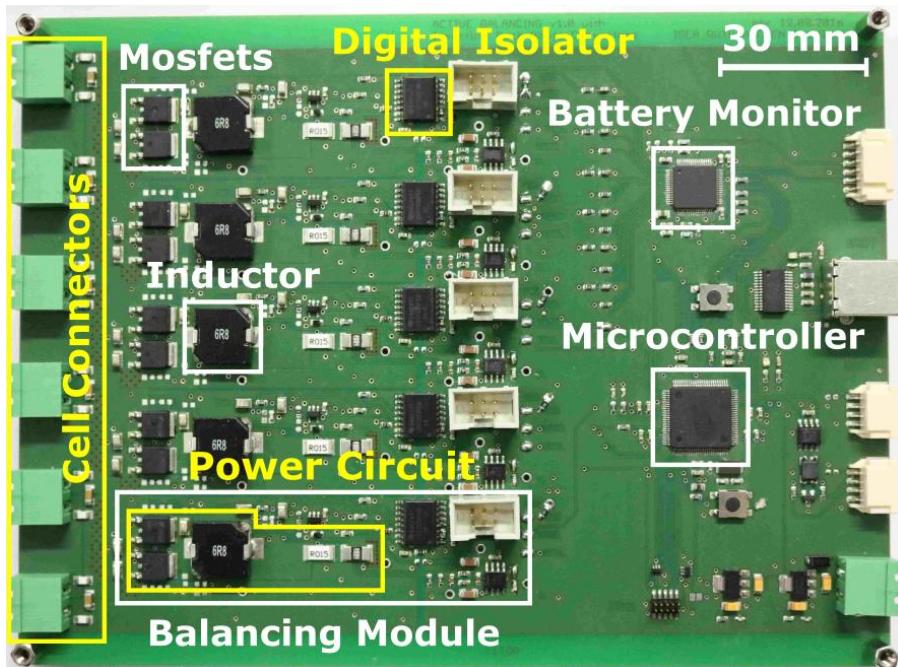
Hardware-Entwicklung der Zelle \leftrightarrow Zelle Topologie

- Ziele:
 - hoher Wirkungsgrad
 - Konverter-Ansteuerung

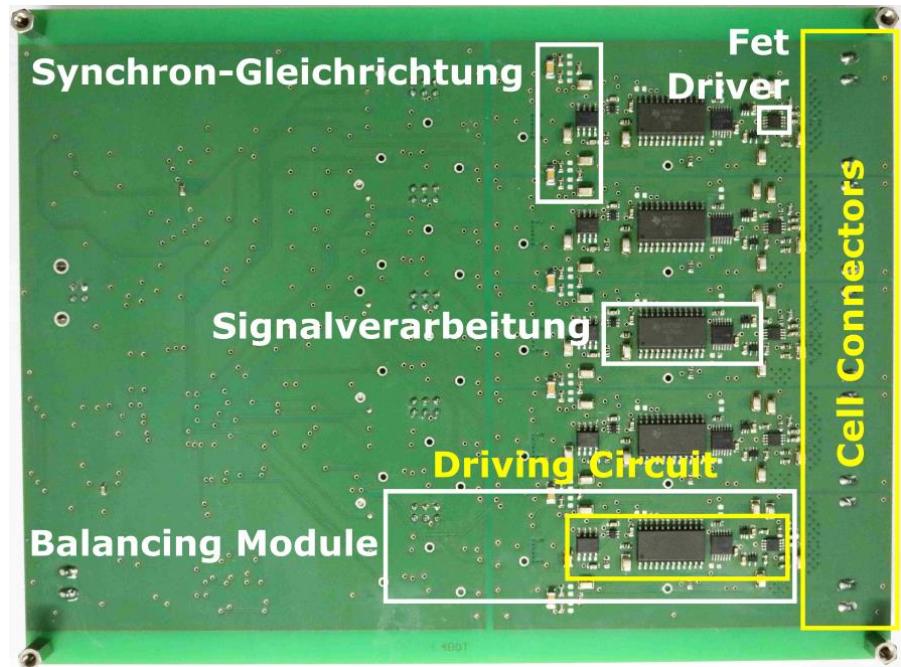


Balancing-Module

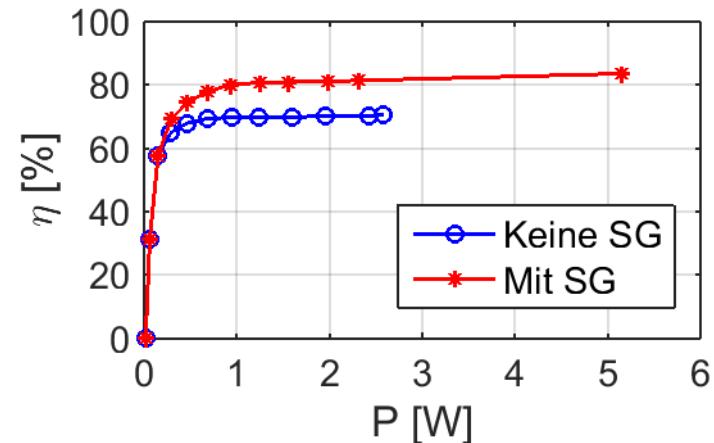
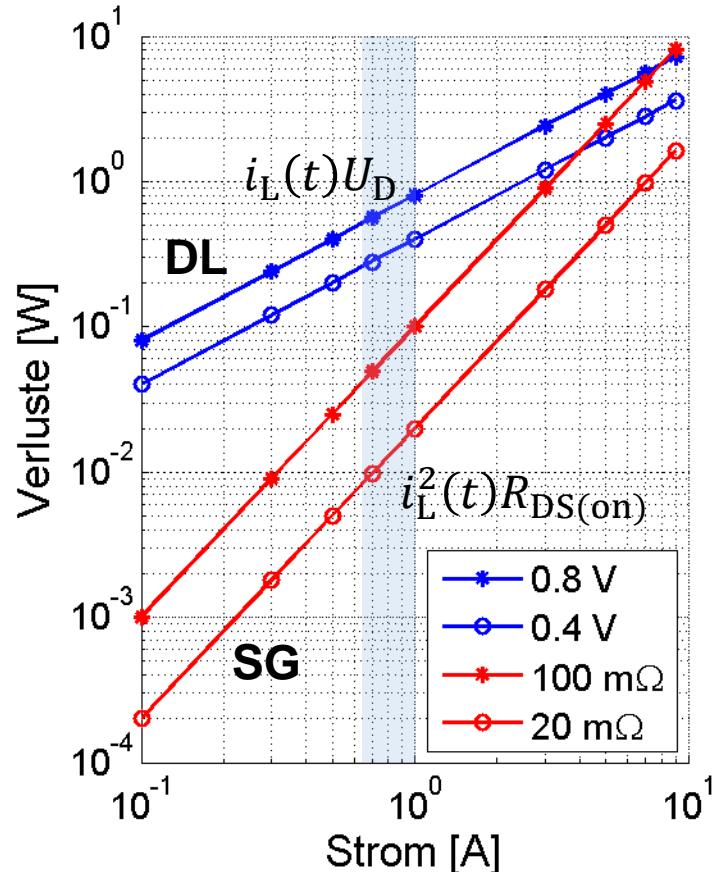
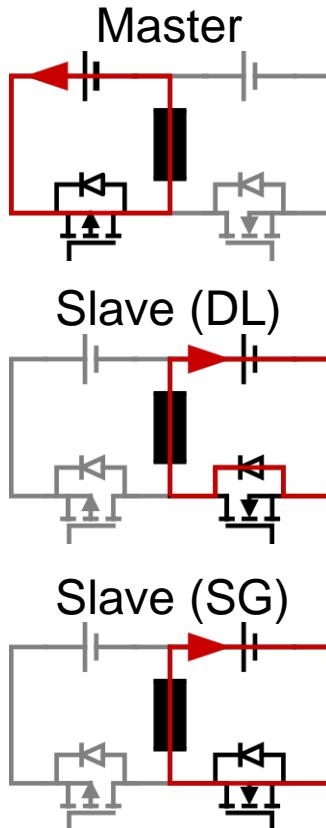
TOP



BOTTOM



Dioden-Leitung (DL) vs. Synchron-Gleichrichtung (SG)



	Body-Diode	Schottky-Diode
U_D	0,8 bis 1 V	0,4 bis 0,5 V
I_{leck}	< 1 μA	> 100 μA

Zusammenfassung und Ausblick

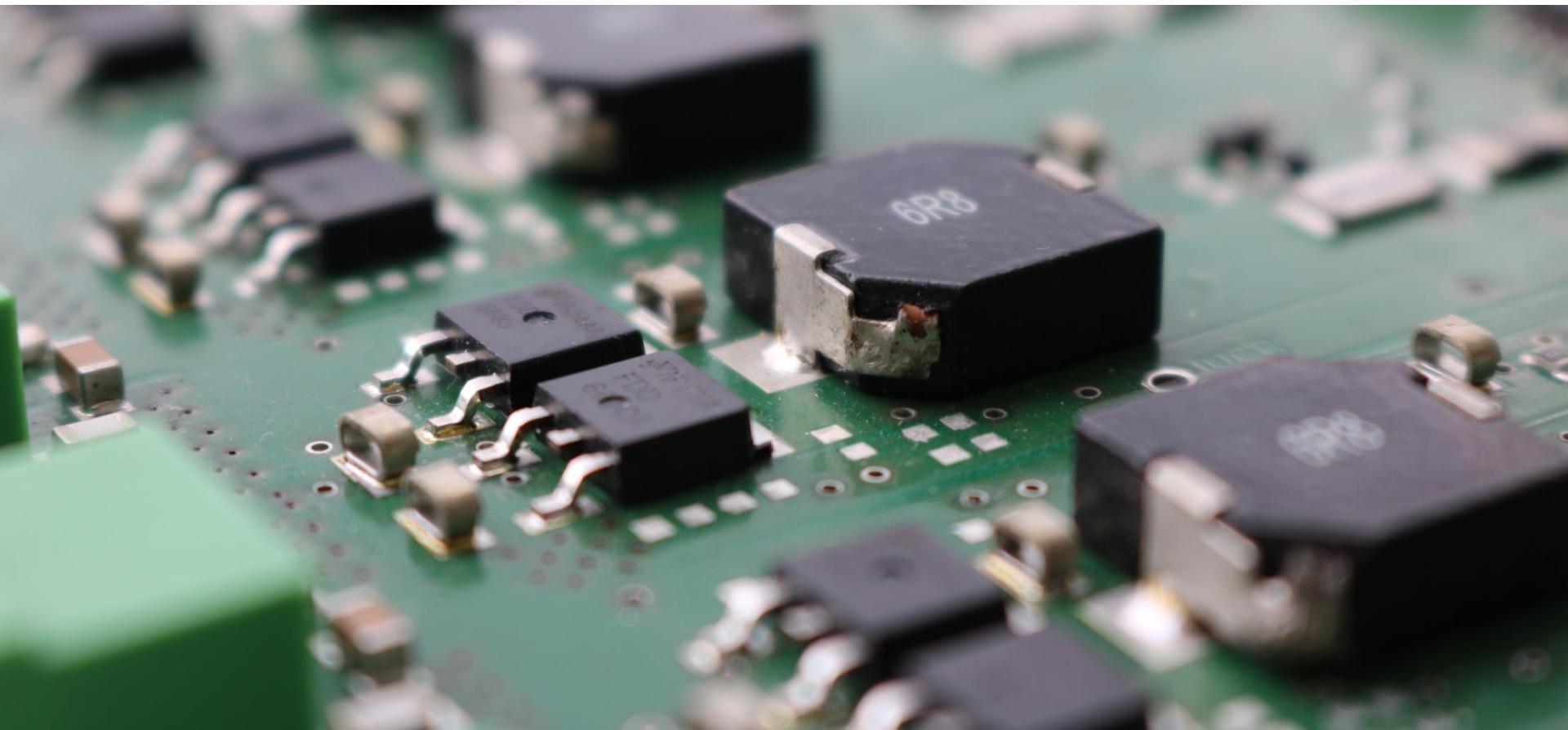
■ Zellstreuung

- Streureduktion funktionierte nur eingeschränkt
 - mit umgekehrter Sortierung
 - ohne erreichen der Zellbetriebsgrenzen
- Zellstreuung bei diesen Zellen sehr gering ($\Delta s < 1,5\%$)
 - mit Pouchzellen?
- Einzelzellzustandsschätzung mit Angabe der Fehlergrenzen
 - Zellstreuung im Feld und Detektieren von Ausreißern

■ Aktives Balancing

- Hardware-Entwicklung: $\eta = 80\%$
 - Wirkungsgrad im realen Betrieb?
 - Einfluss des Stromrippels auf Zellalterung?
 - Vereinfachung der Spannungsversorgungen und PWM-Übertragung

Vielen Dank für Ihre Aufmerksamkeit





Aktive Balancing-Systeme für Lithium-Ionen Batterien und deren Auswirkungen auf die Zellalterung

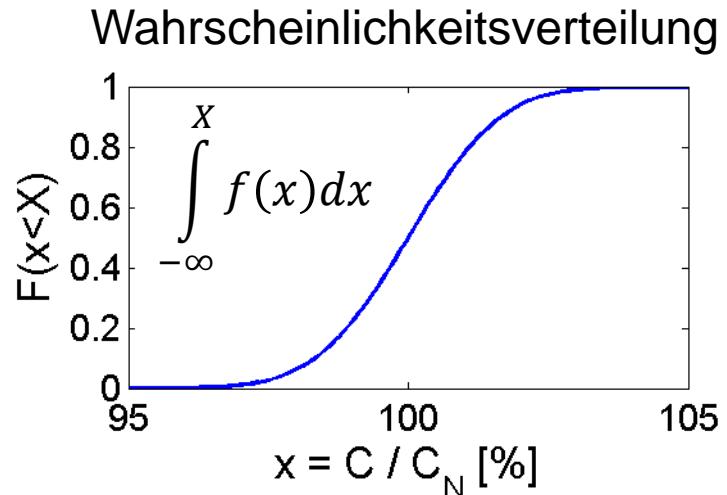
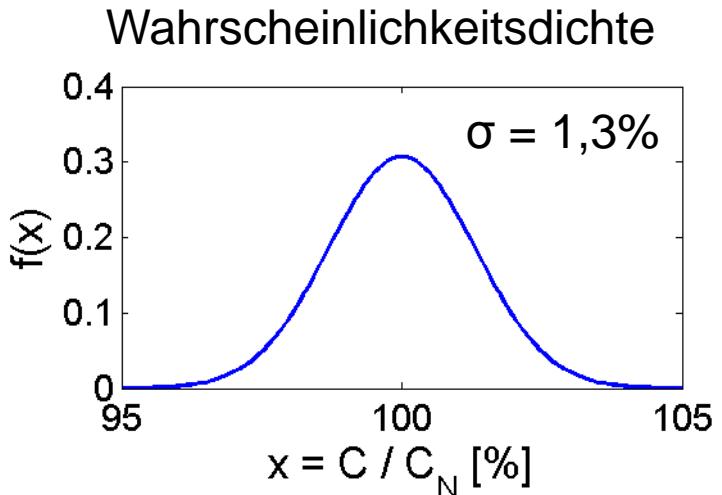
Promotionsvortrag

30.06.2017

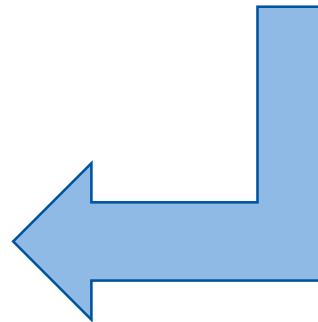
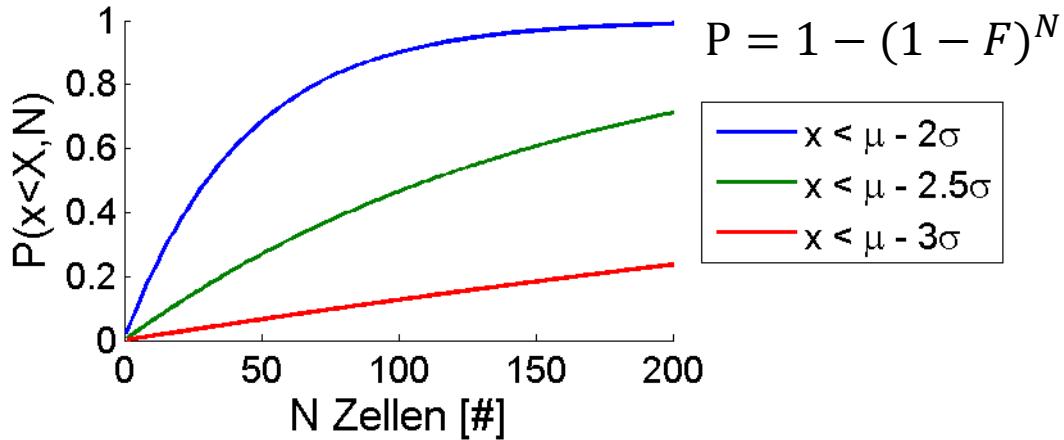
Manuel Brühl

ANHANG

Welche Zellstreuung ist zu erwarten?

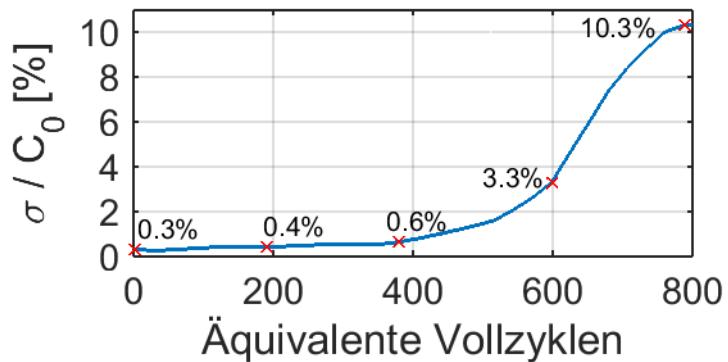
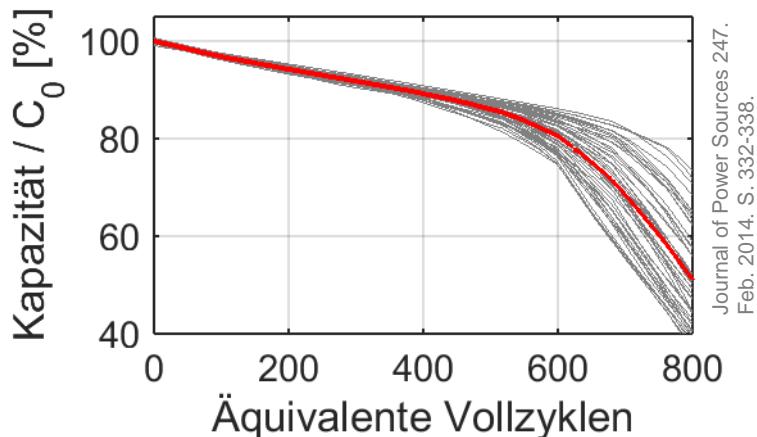


P für einen Ausreißer bei N Zellen

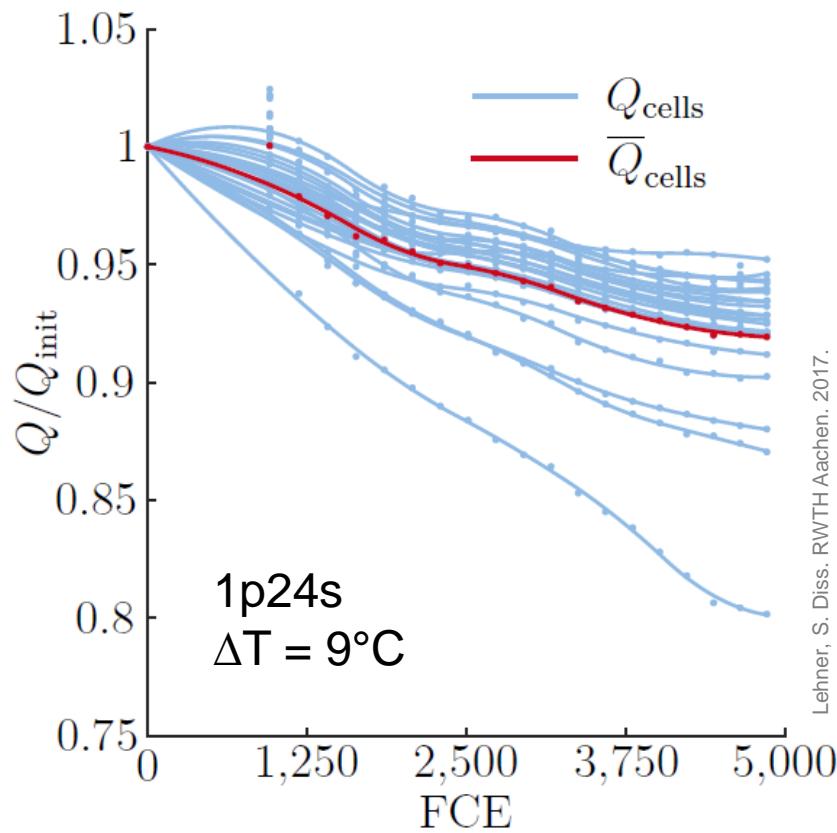


Experimentelle Alterungsuntersuchungen zur Zellstreuung bei zyklischer Belastung

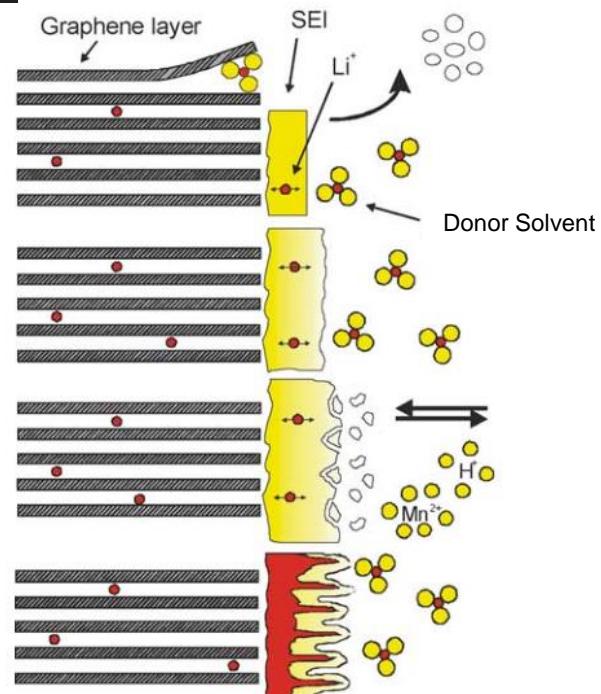
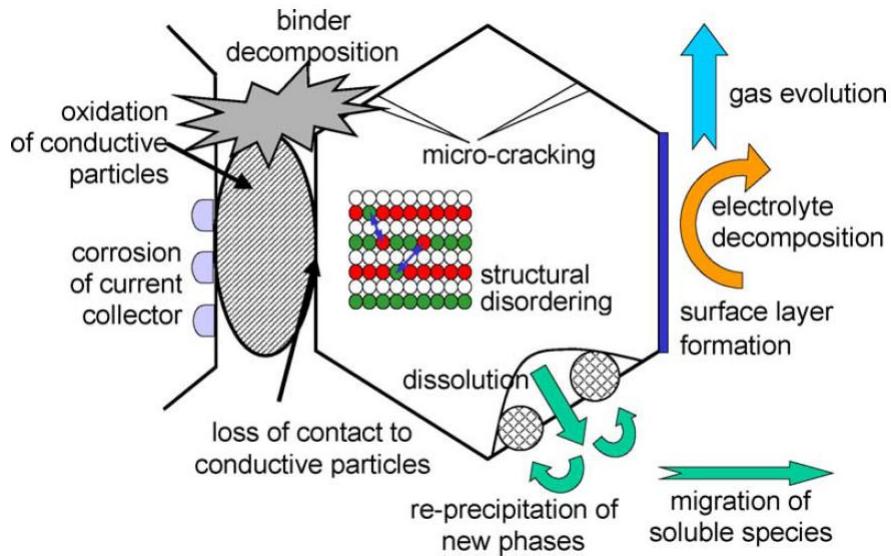
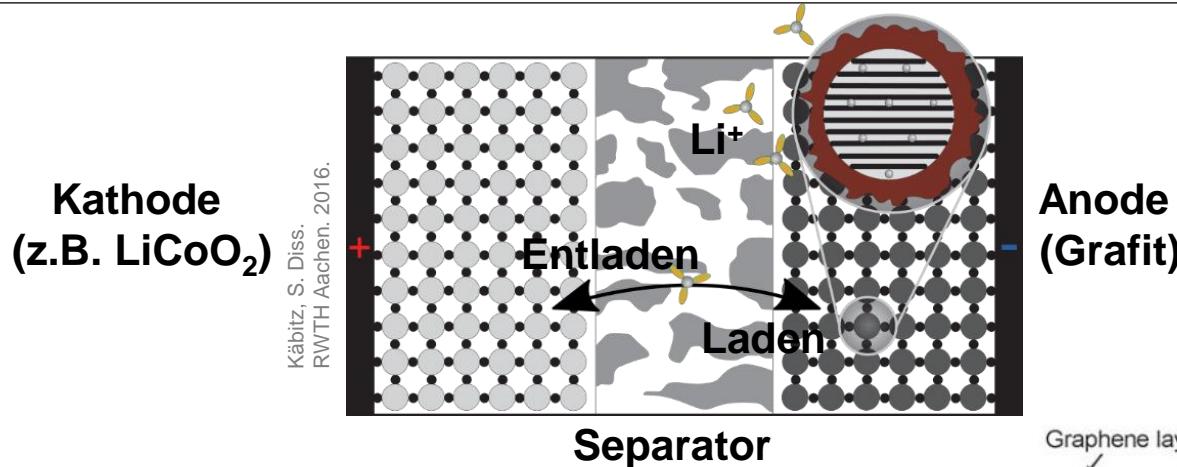
Natürliche Streuung während der Alterung



Streuung wegen Temperaturgradient



Zellaufbau und Alterungsmechanismen



Journal of Power Sources 147. Sep. 2005. S. 269-281.

Prüfstand für den Alterungstest



18650er Zelle von Samsung

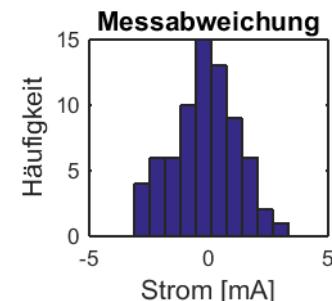
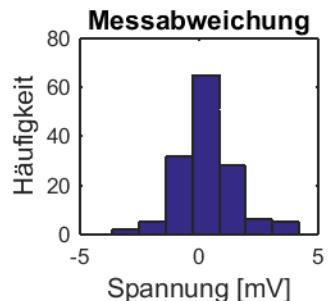
Aktivmaterial	Graphit NMC
Nennkapazität	1.5 Ah
Ladestrom	<4 A (2.7C)
Entladestrom	<18 A (12C)

Temperaturkammer (Binder)

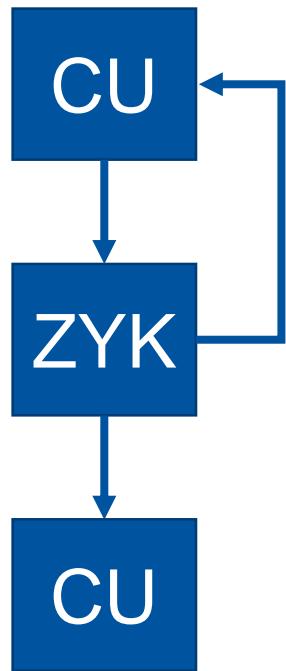
Temperatur	35 °C
Abweichung	±1 K

Zelltester (Digatron)

Messspannung	10 mV bis 5 V
Stell- & Messstrom	40 mA bis 20 A
Abtastzeit	>100 ms



Beeinflussung der Zellalterung zur Zellstreuungsreduktion

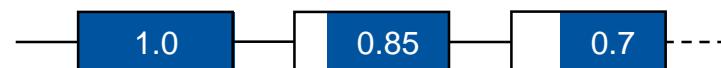


Referenztest
ohne Anpassung

gut mittel schlecht

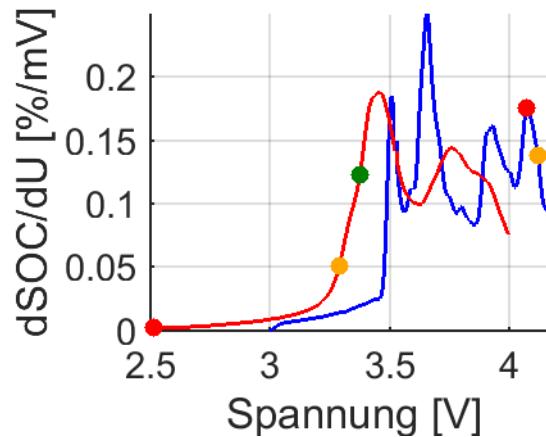
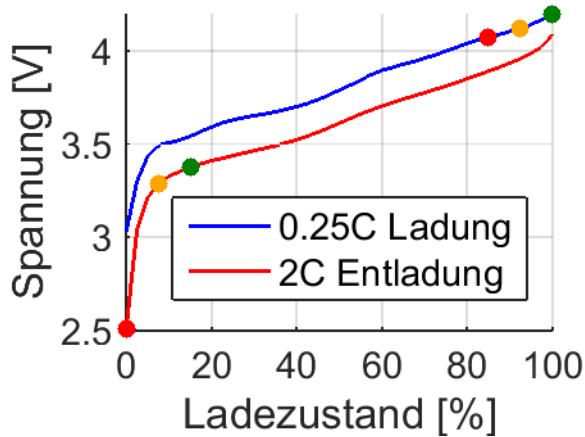
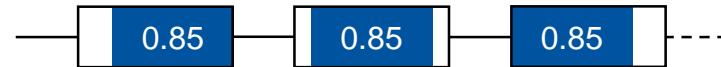


DOD- und I-
Anpassung

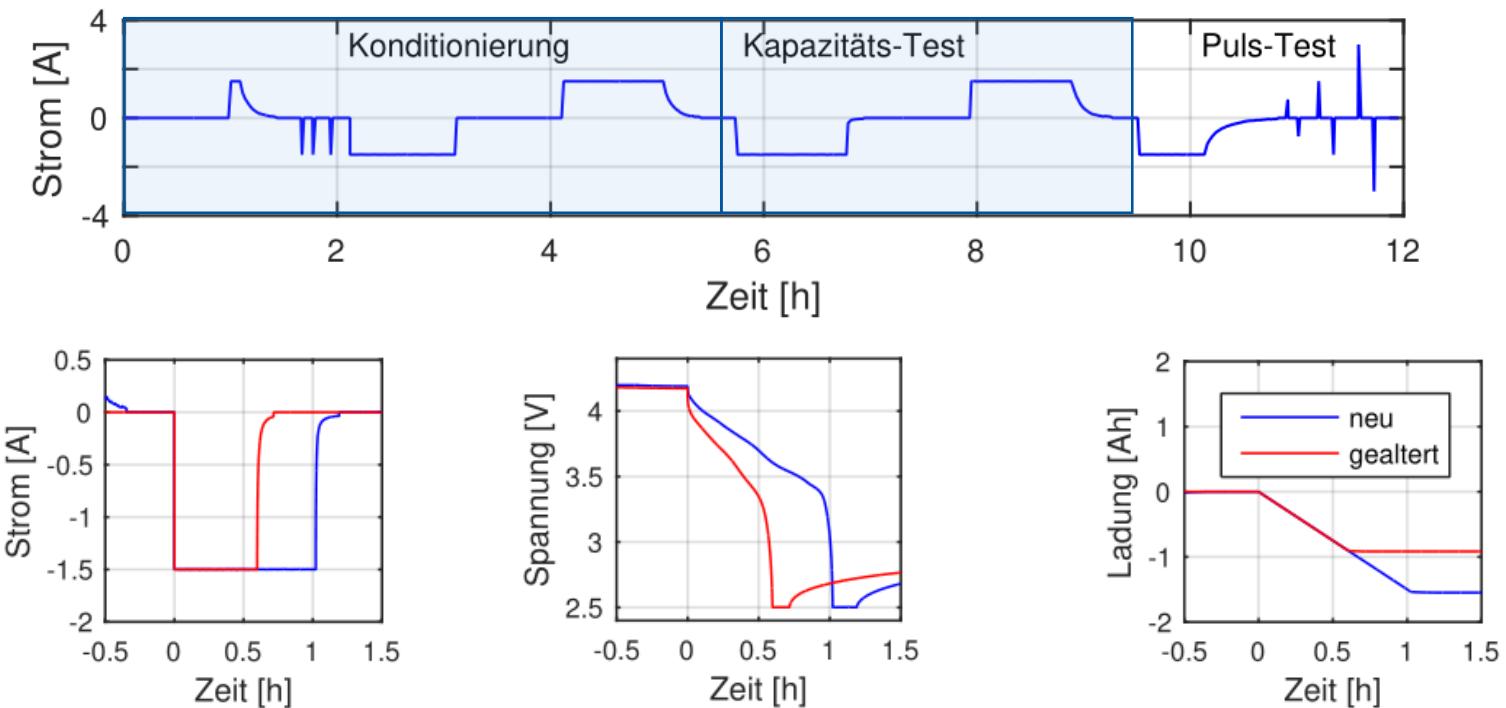


ΔU -Fenster
Anpassung

SOC: 0-100%



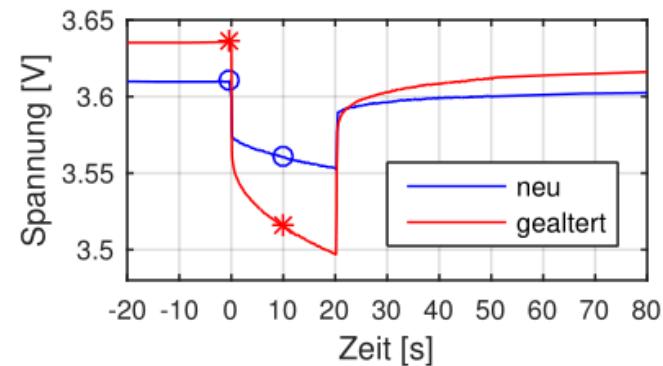
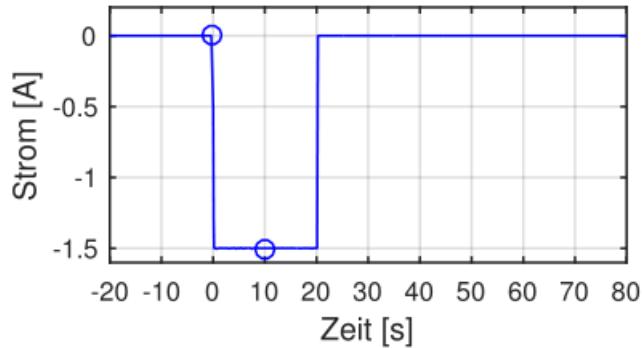
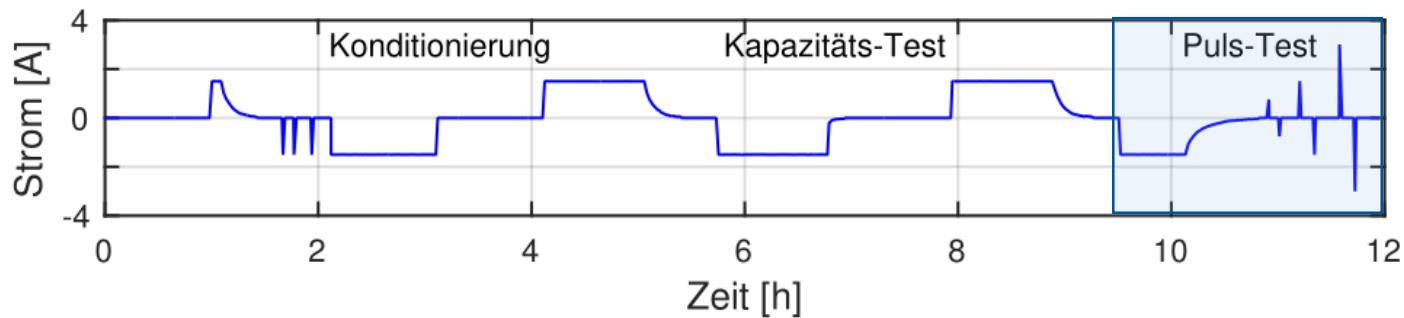
Check-Up-Test



$$Q = \int_0^{t_{\text{end}}} i(t) dt$$

$$\begin{aligned}\varepsilon_Q &\approx \varepsilon_U \frac{\partial Q}{\partial U} + \varepsilon_I \frac{Q}{I} \approx \pm 11,3 \text{ mAh} \approx \pm 1\% C_N \\ \sigma_Q &\approx \sigma_U \frac{\partial Q}{\partial U} \approx \pm 1,2 \text{ mAh} \approx \pm 0,1\% C_N\end{aligned}$$

Check-Up-Test

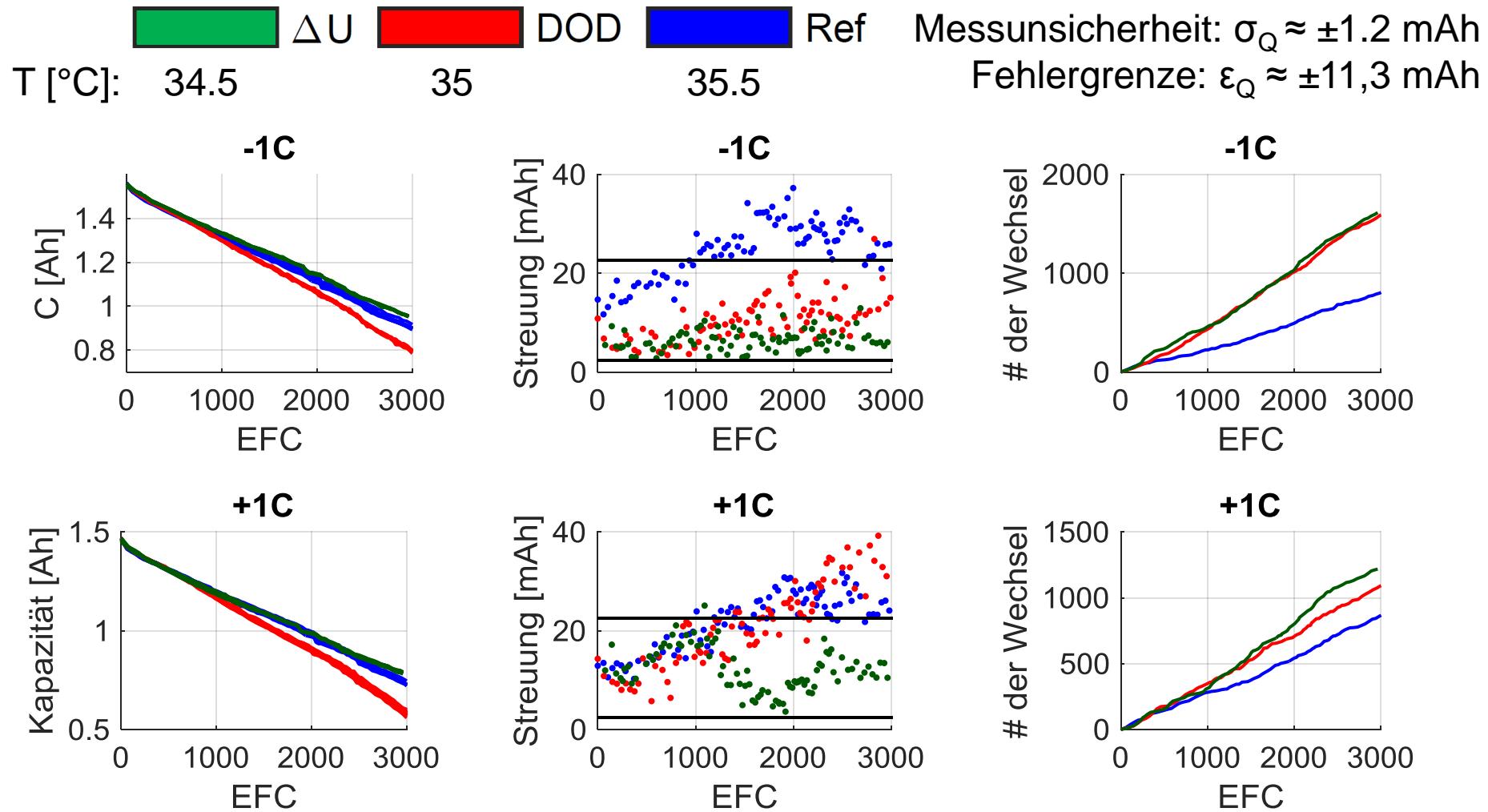


$$R_P = \frac{\Delta U}{\Delta I} |_{\Delta t=t_2-t_1} = \frac{U(t_2) - U(t_1)}{I(t_2) - I(t_1)}$$

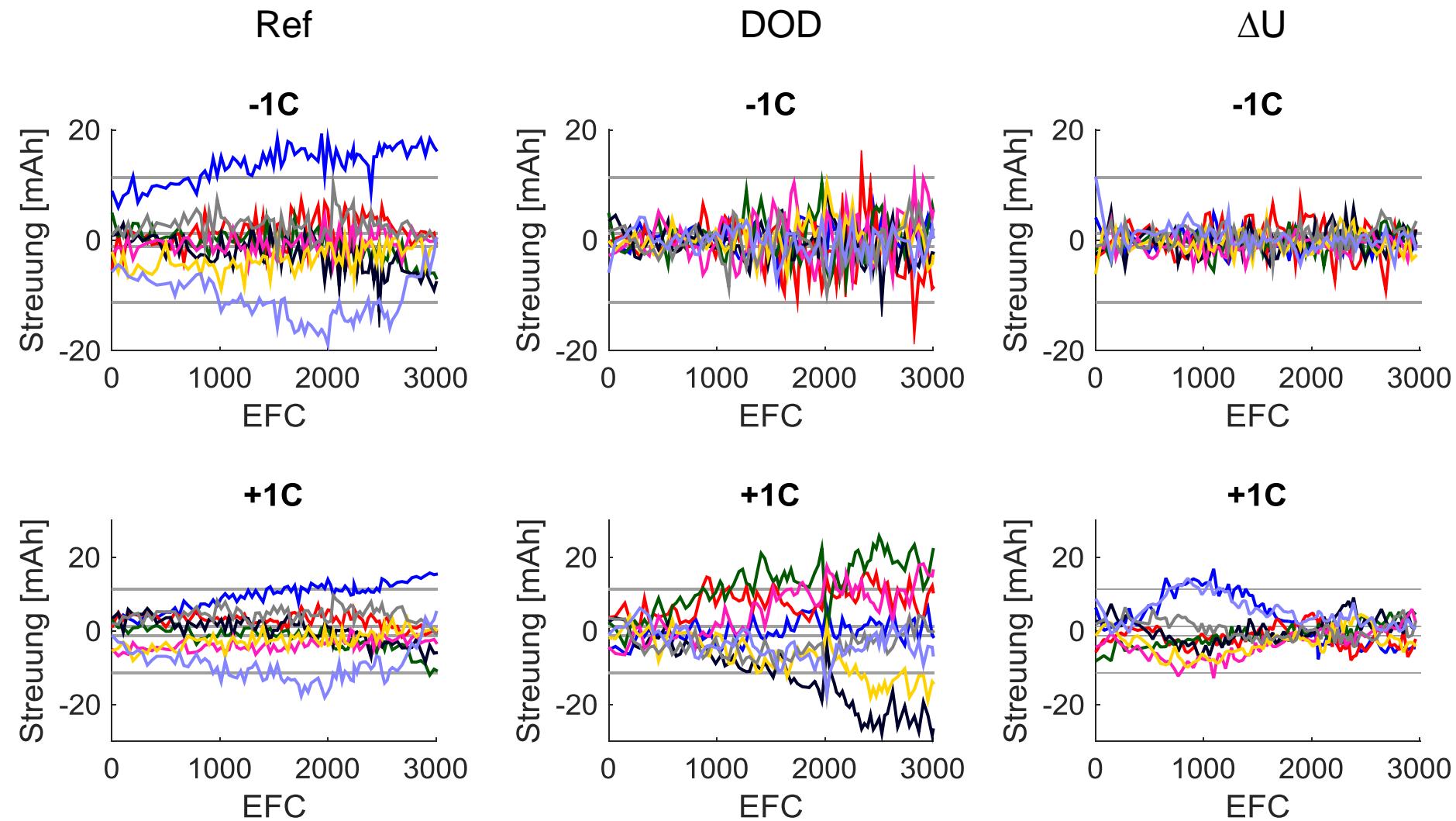
$$\varepsilon_{R_P} = \left(\frac{\varepsilon_{\Delta U}}{\Delta U} + \frac{\varepsilon_{\Delta I}}{\Delta I} \right) \cdot \frac{\Delta U}{\Delta I} \approx 0$$

$$\sigma_{R_P} = \sqrt{\left(\frac{\sigma_{\Delta U}}{\Delta U} \right)^2 + \left(\frac{\sigma_{\Delta I}}{\Delta I} \right)^2} \cdot \frac{\Delta U}{\Delta I} \approx \pm 1 \text{ m}\Omega \approx \pm 3\%$$

Verlauf der Lade-Kapazitäten und Entlade-Pulswiderstände

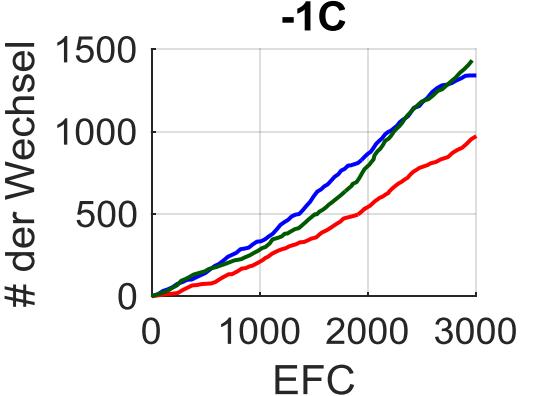
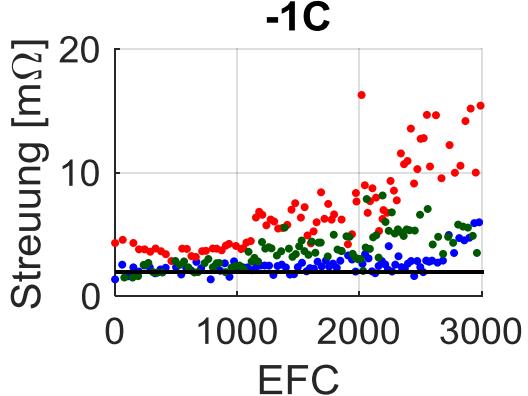
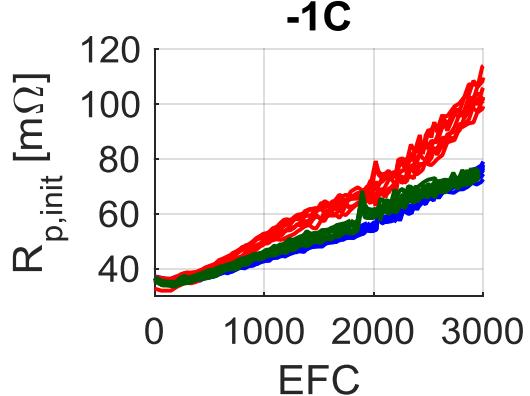
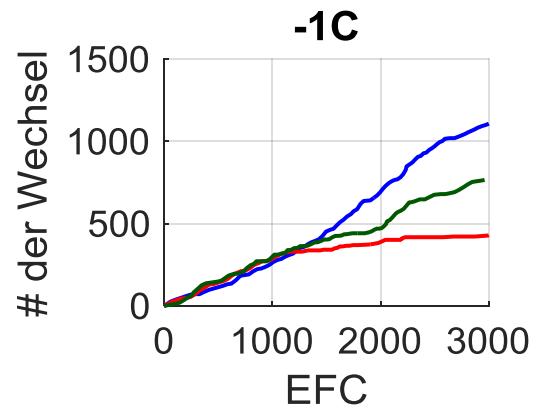
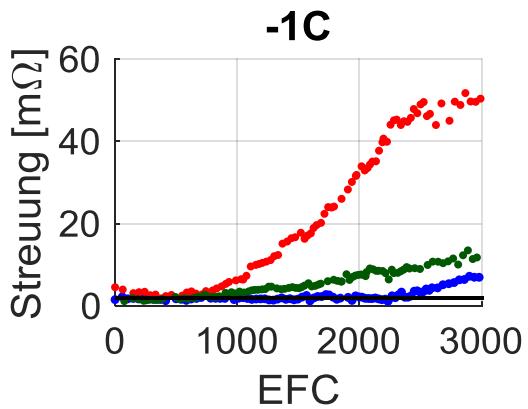
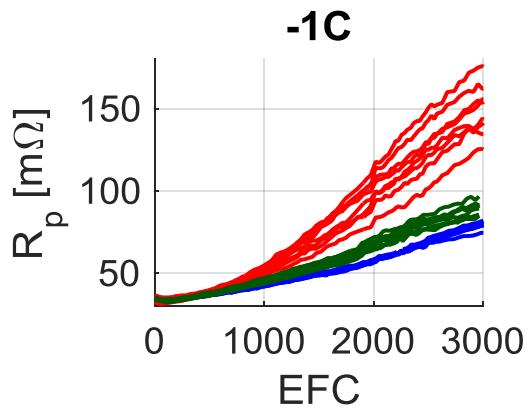


Mittelwertfreie Streuung der Kapazitäten (Dch/Cha)



Zunahme des Puls-Widerstands

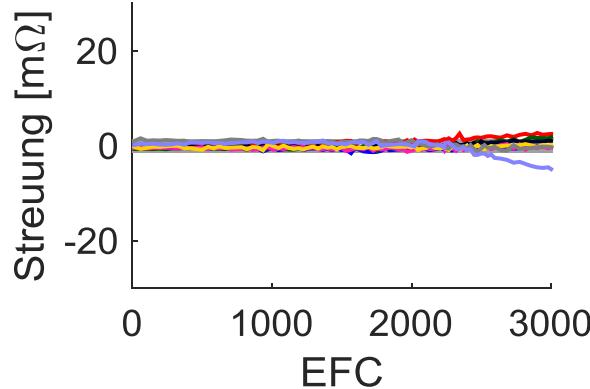
 Messunsicherheit: $\sigma_Q \approx \pm 1 \text{ m}\Omega$



Mittelwertfreie Streuung der Puls-Widerstände

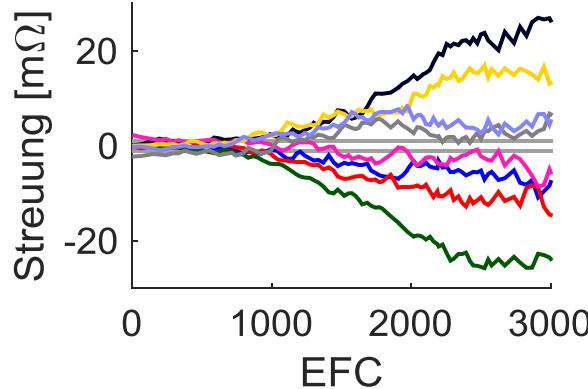
Ref

-1C



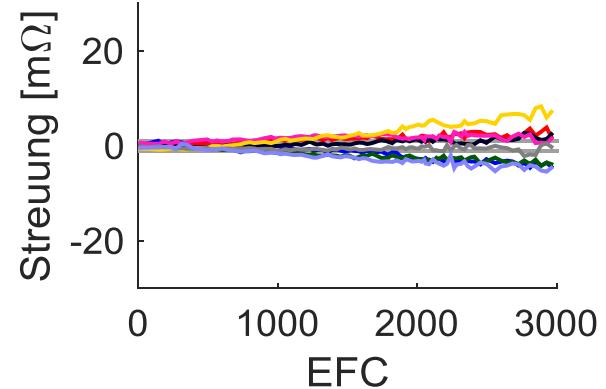
DOD

-1C

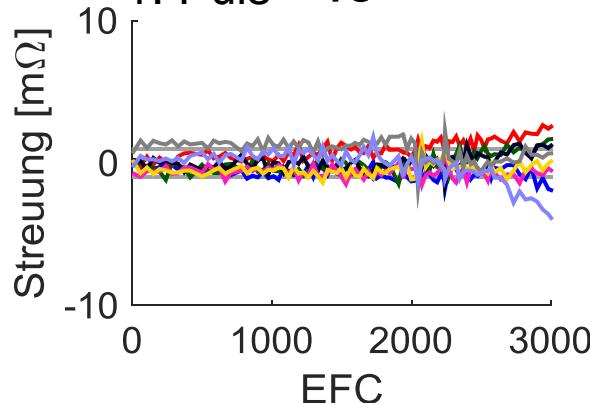


ΔU

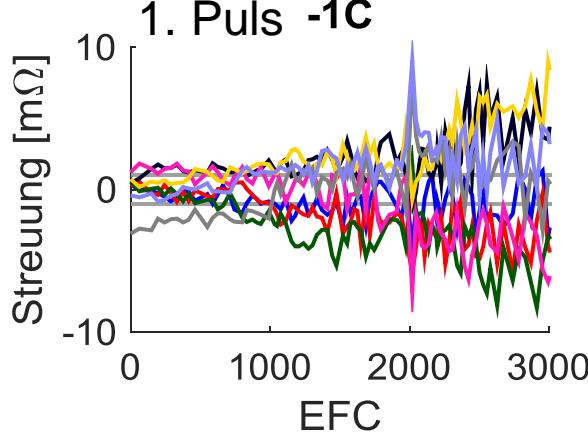
-1C



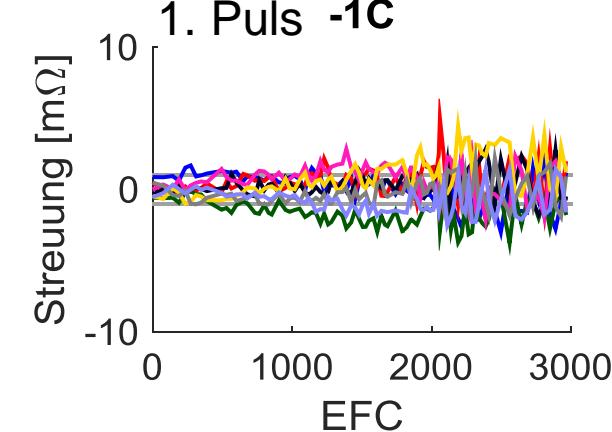
1. Puls -1C



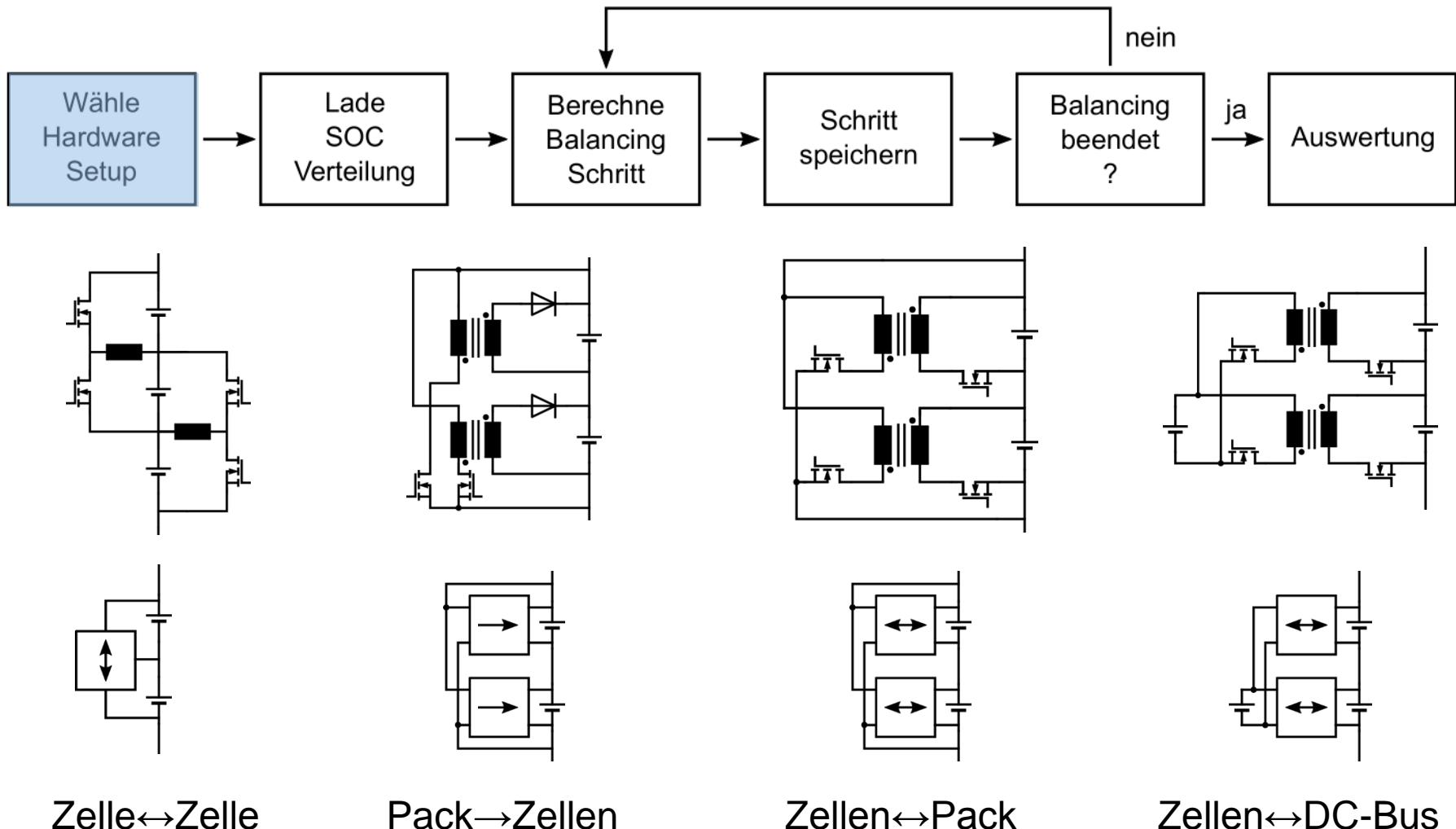
1. Puls -1C



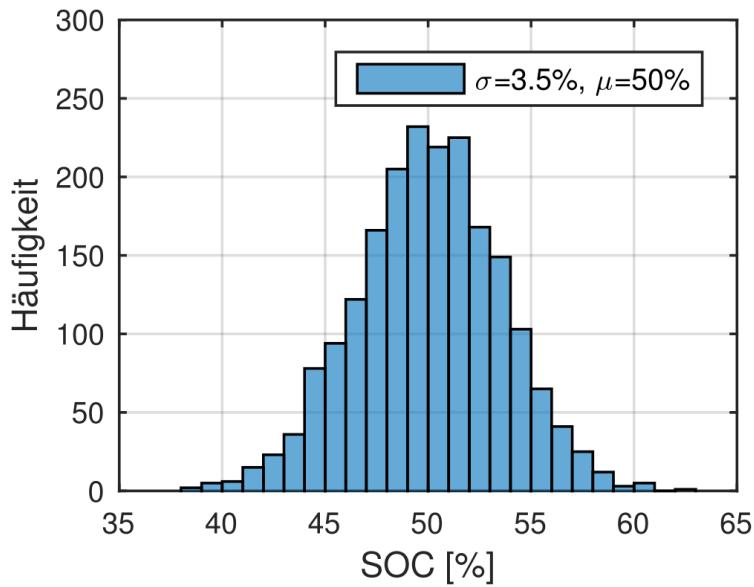
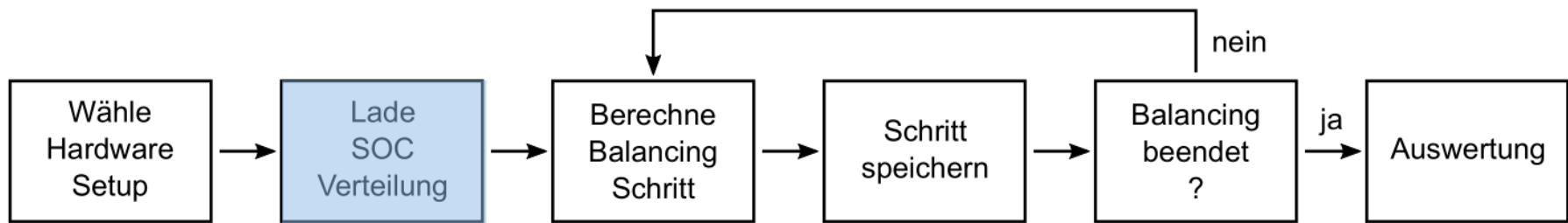
1. Puls -1C



Simulationsablauf – Wahl der Topologie & Zellanzahl

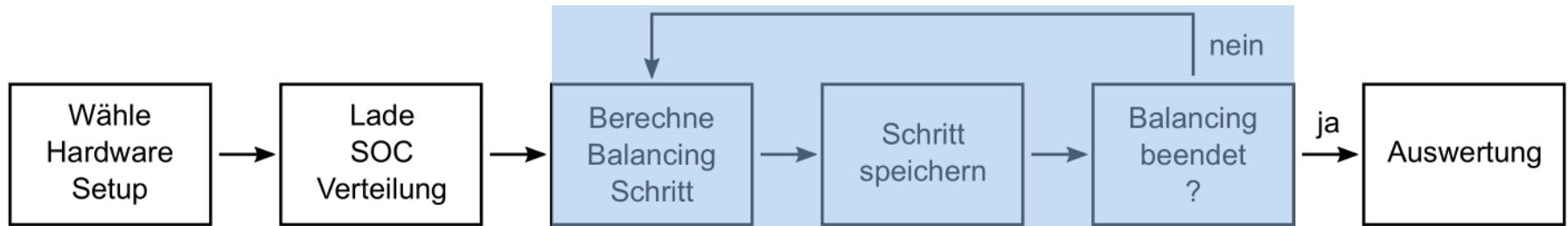


Simulationsablauf – Lade SOC-Verteilung



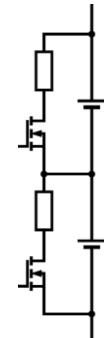
2.000 SOC-Verteilungen
pro Hardware-Setup

Simulationsablauf – Berechne Balancing



■ Zellspannungen konstant

- $U_Z = 3.7V$
- $Q_{soc}(t_i + \Delta t) = Q_{soc}(t_i) + I_Z \Delta t$



$$R = \frac{U_Z}{\bar{I}_{bal}} = \frac{3.7 \text{ V}}{100 \text{ mA}} = 37 \Omega$$

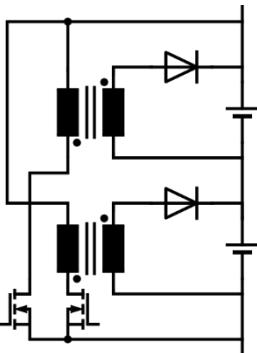
■ Konverter alle gleich

- $P_C = U_Z \bar{I}_{bal} = 3.7 \text{ V} 100 \text{ mA} = 370 \text{ mW}$
- $\eta = 90\%$

$$I_{Z,i} = -\frac{P_{C,i}}{U_Z}$$

■ Balancing-Zielwert

- $Q_{bal,soll,i} = \bar{Q}_{soc} - Q_{soc,i}$



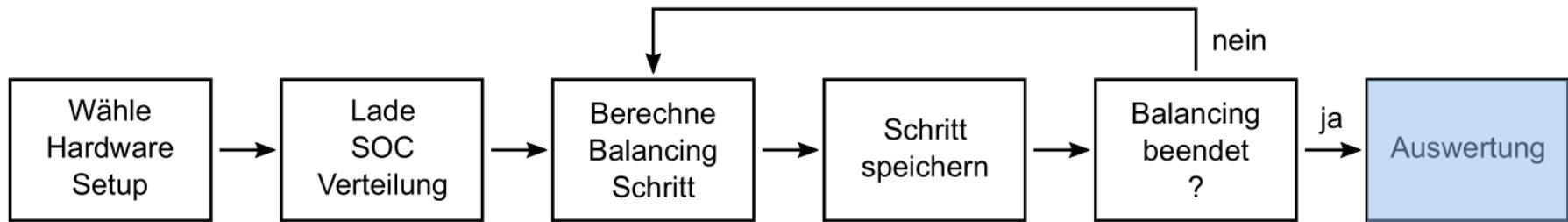
$$L = \frac{U_Z}{2 \bar{I}_{bal}} \times \frac{d^2}{f_s} = 46 \mu\text{H}$$

■ Simulationsabbruch & -schritt

- $\Delta SOC = \frac{\Delta Q_{soc}}{c_N} < 0.1\%$
- $\Delta t \frac{P_C}{U_Z} = \frac{\min\{\max(Q_{bal,soll}), \min(Q_{bal,soll})\}}{100}$

$$I_{Z,i} = \frac{\eta \cdot P_{C,i}}{U_Z} - \frac{1}{N \cdot U_Z} \cdot \sum_{k=1}^N P_{C,k}$$

Simulationsablauf – Auswertung



■ Balancing-Wirkungsgrad

ideales Balancing

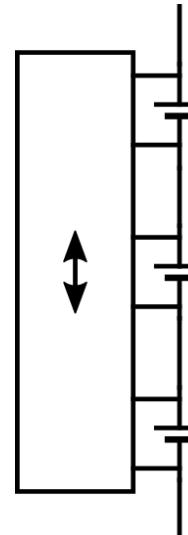
$$\square \eta_{bal} = \frac{\sum Q_{cha}}{\sum Q_{dch}}$$

■ relative Balancing-Zeit

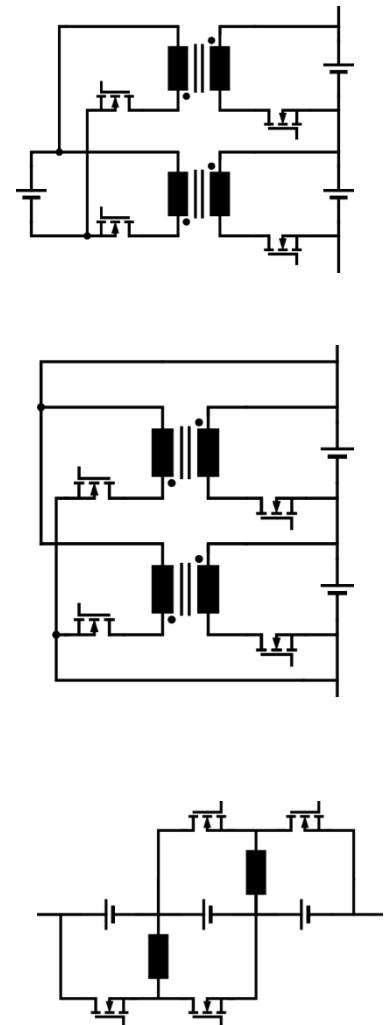
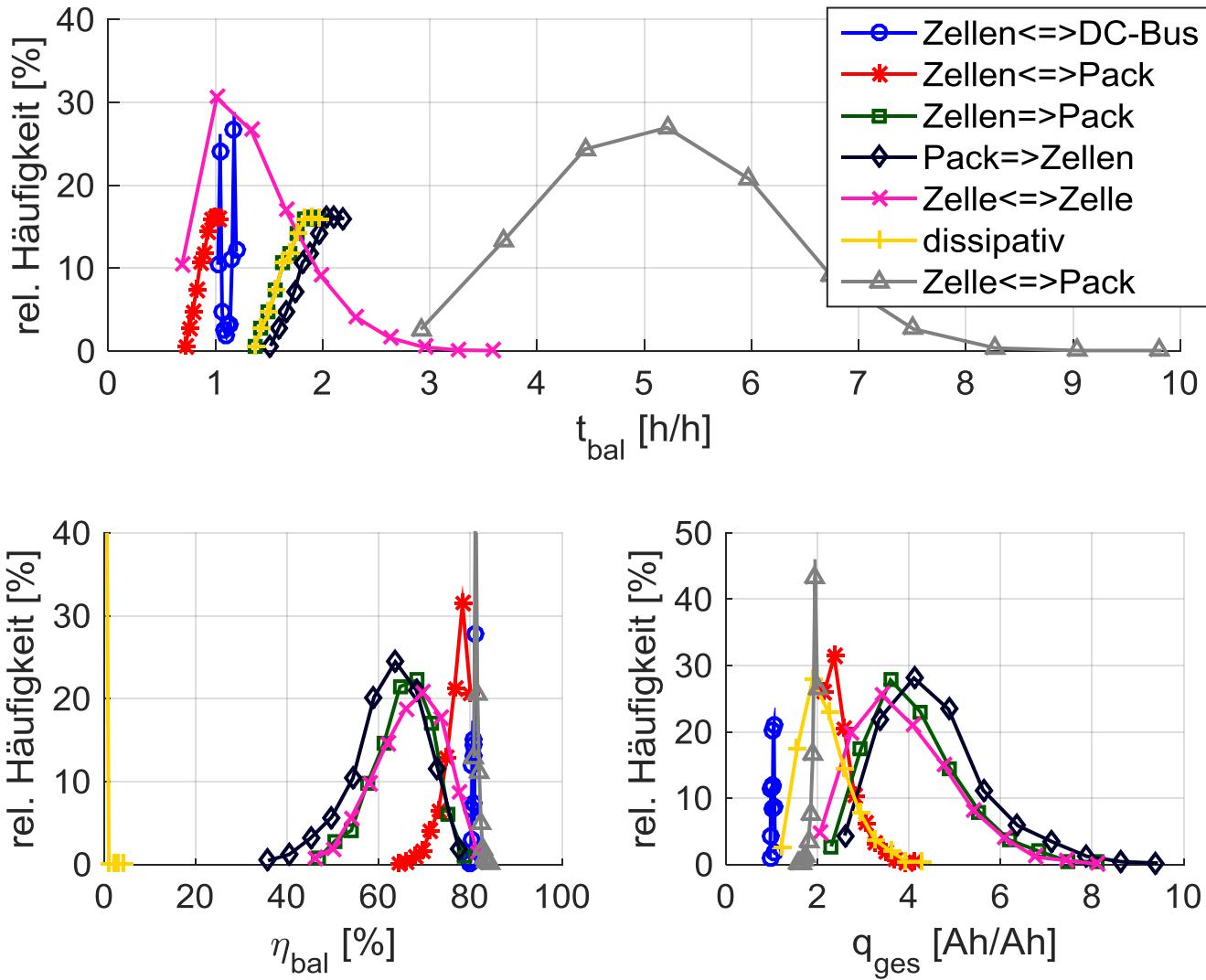
$$\square t_{bal} = \frac{T_{bal}}{T_{bal,ideal}} = \frac{T_{bal}}{\max\{|Q_{bal,soll}|\}} \times \frac{P_C}{U_Z}$$

■ relativer Ah-Durchsatz in den Zellen

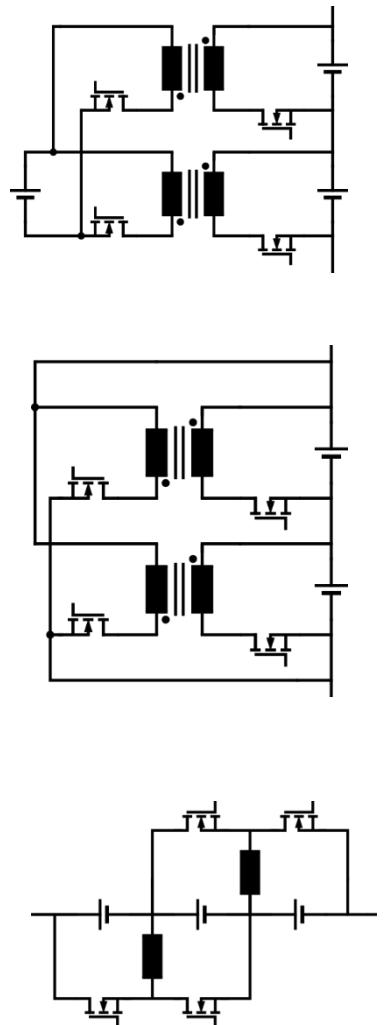
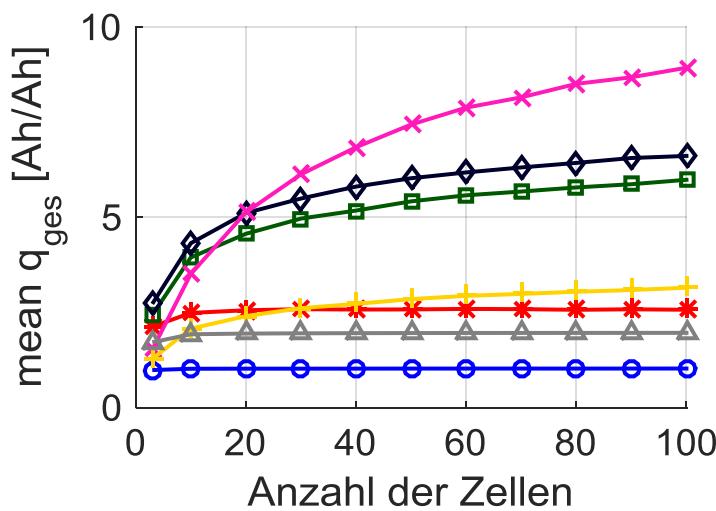
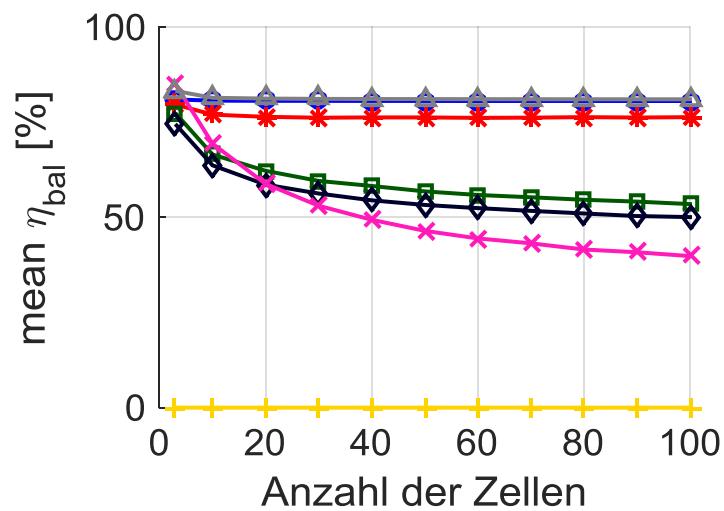
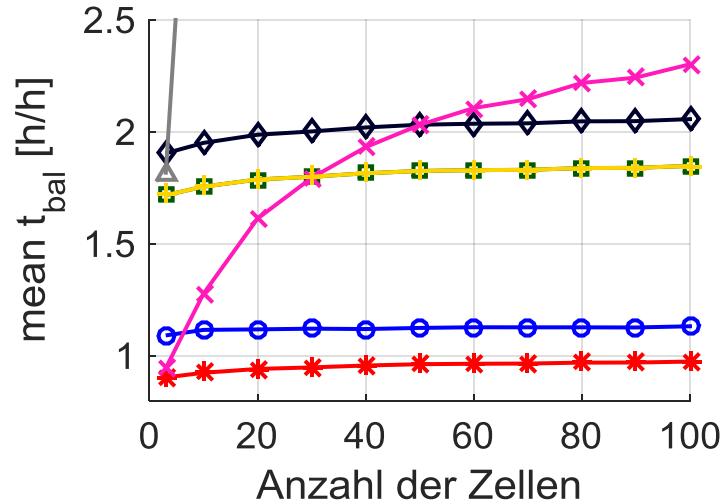
$$\square q_{ges} = \frac{\sum |Q_{bal}|}{\sum |Q_{bal,ideal}|} = \frac{\sum |Q_{bal}|}{\sum |Q_{bal,soll}|}$$



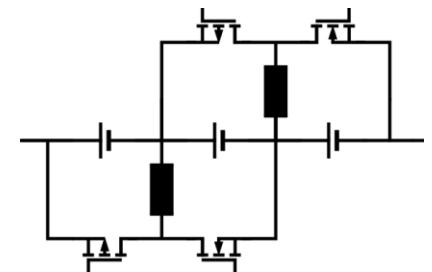
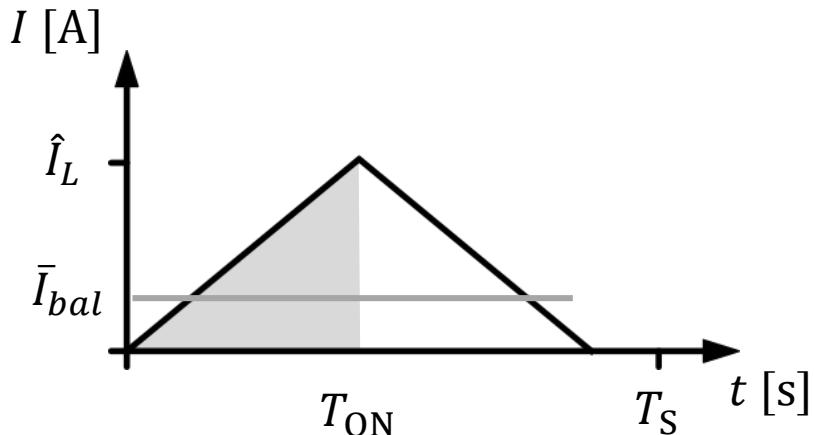
Ergebnis für 12 Zellen in Serie



Ergebnis in Abhangigkeit der Anzahl der Zellen in Serie



Dimensionierung



■ Konverterleistung

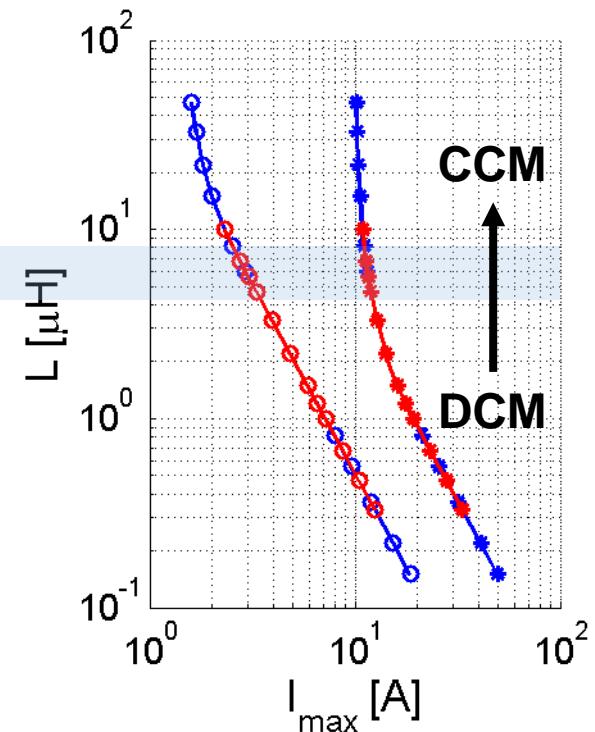
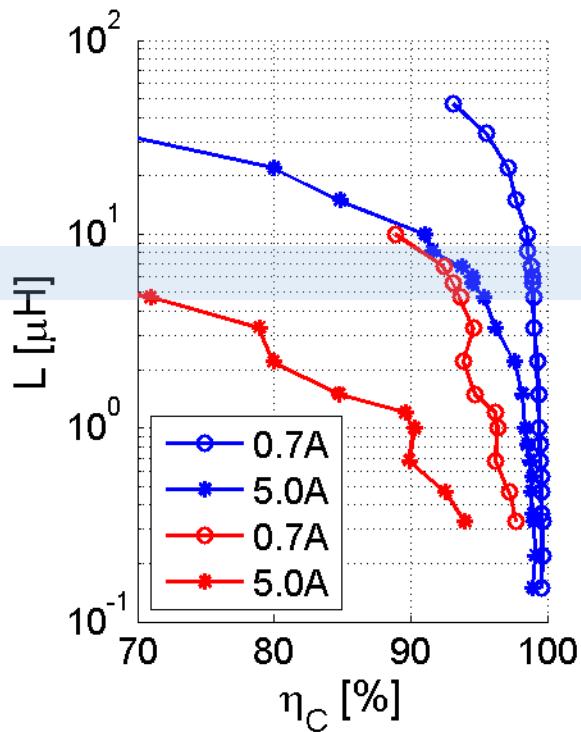
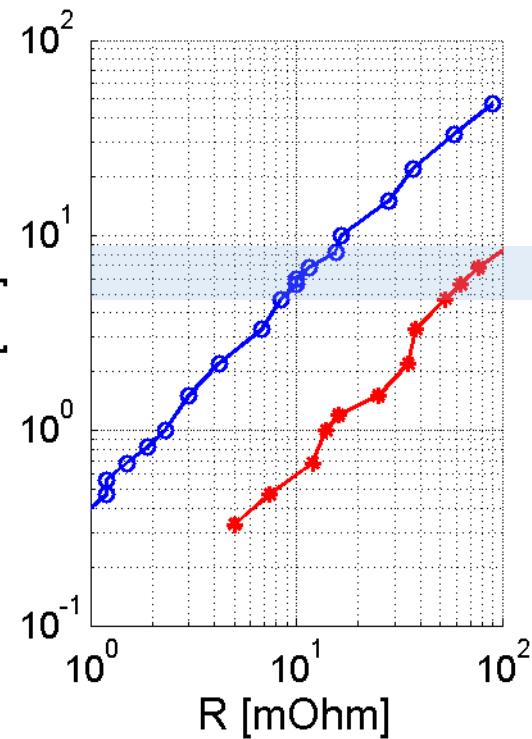
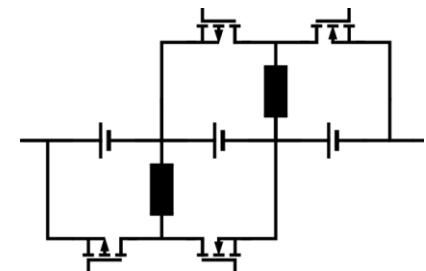
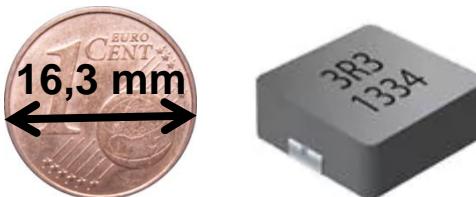
- $P_C = U_N \times C_{\text{rate}} \times C_{\text{akt}} \times \frac{\Delta C}{C_{\text{akt}}} = 3,7 \text{ V} \times \frac{1}{3} \frac{\text{A}}{\text{Ah}} \times 40 \text{ Ah} \times 5\% = 2,5 \text{ W}$
- $\bar{I}_{bal} = \frac{P_C}{U_N} = 675 \text{ mA}$

■ Wahl der Spule für Discontinuous Conduction Mode (DCM)

- $\hat{I}_L = \frac{U_Z \times T_{ON}}{L_{\min}} < I_{\max} = \frac{1}{10} \frac{\text{A}}{\text{Ah}} \times C_{\text{akt}} \rightarrow L_{\min} > \frac{3,7 \text{ V}}{2 \times 100 \text{ kHz} \times 4 \text{ A}} = 4,6 \mu\text{H}$
- $\bar{I}_{bal} = \frac{\hat{I}_L}{2} \times \frac{T_{ON}}{T_S} = \frac{U_{Z,\max}}{2 L_{\max}} \times \frac{(T_{ON})^2}{T_S} \rightarrow L_{\max} < \frac{4,2 \text{ V}}{8 \times 675 \text{ mA}} \times \frac{1}{100 \text{ kHz}} = 7,8 \mu\text{H}$

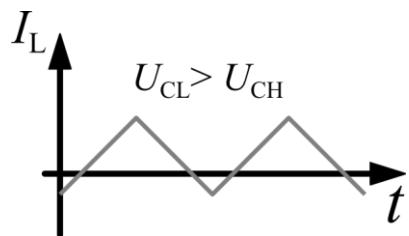
Dimensionierung der Spule

—○— Bourns SRP1265A 13.5x12.5x6.2 mm³
—*— Bourns SRP5030T 5.7x5.2x2.8mm³

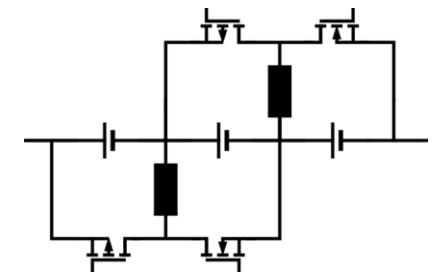
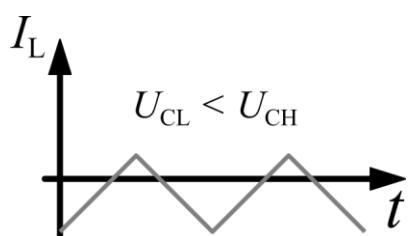
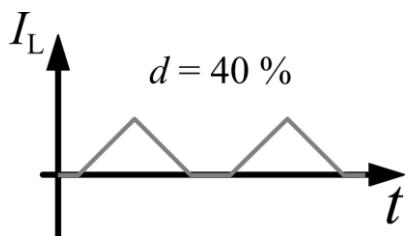
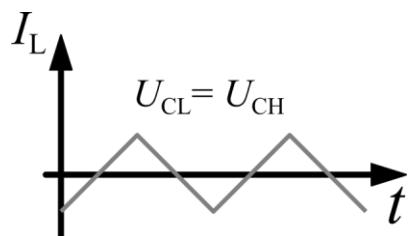
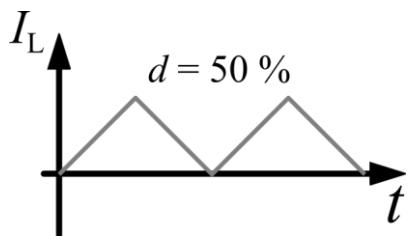


Mosfet-Ansteuerung

Natürliches-
Balancing
 $d = 50\%$

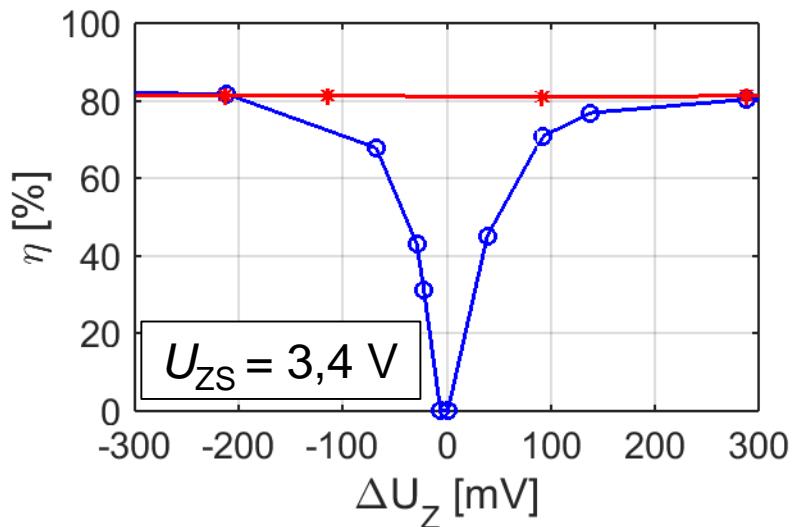


Erzwungenes-
Balancing
 d variabel



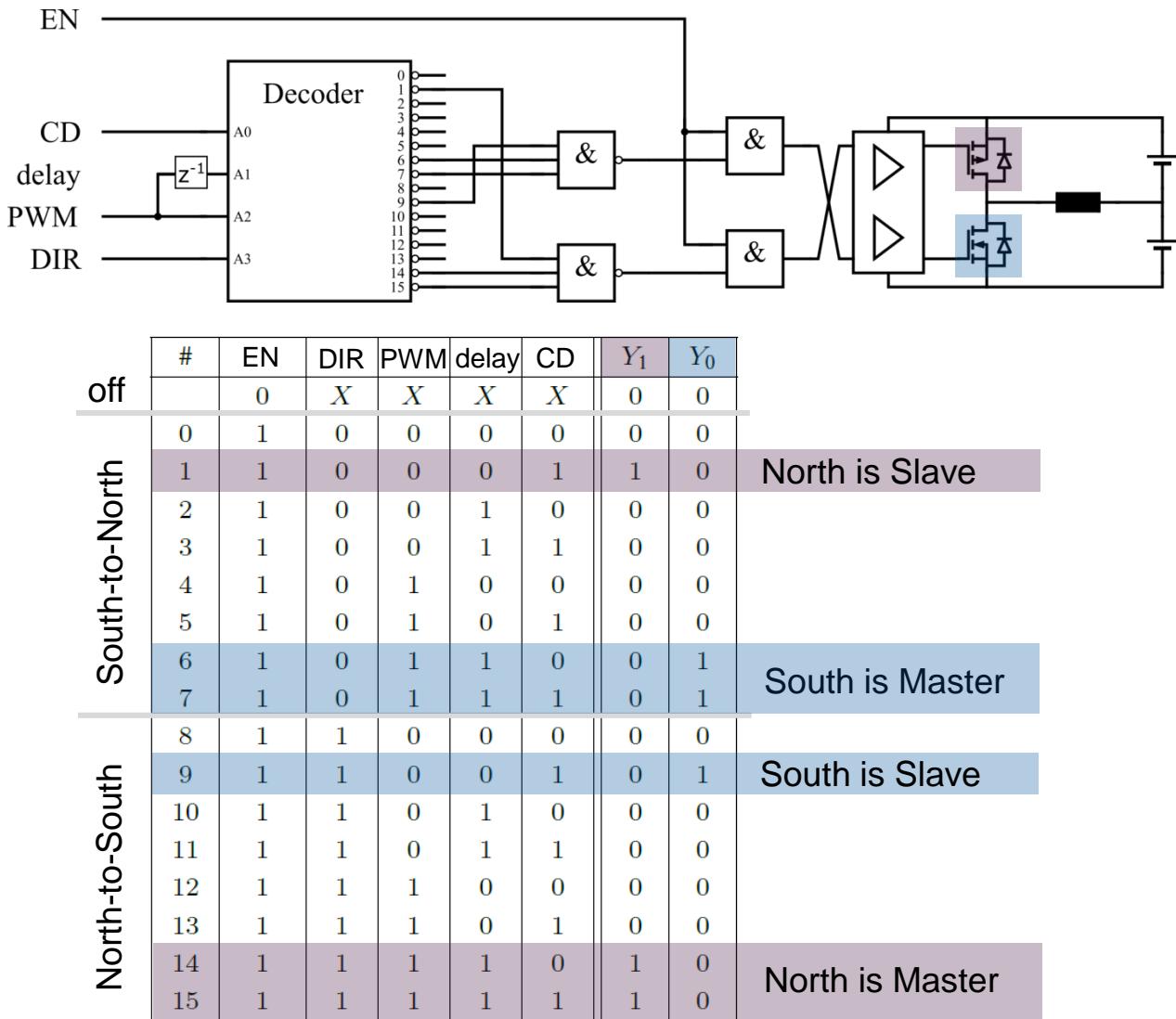
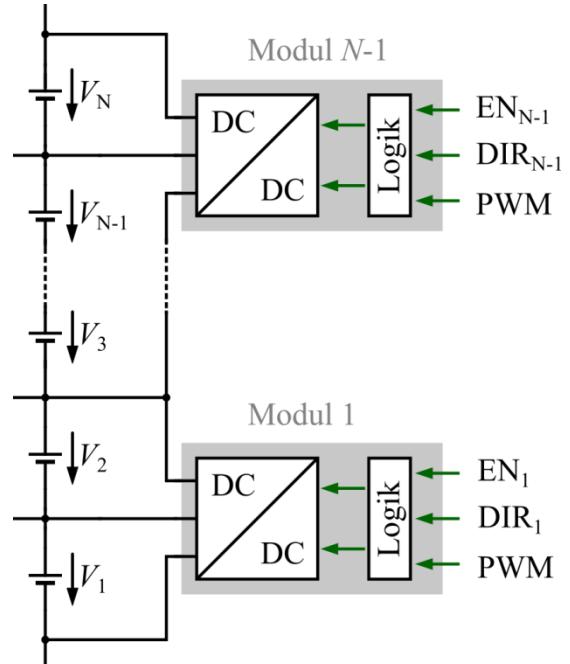
Legend:
— Natürliches Bal.
* Erzwungenes Bal.

Low-Side Mosfet ist Master



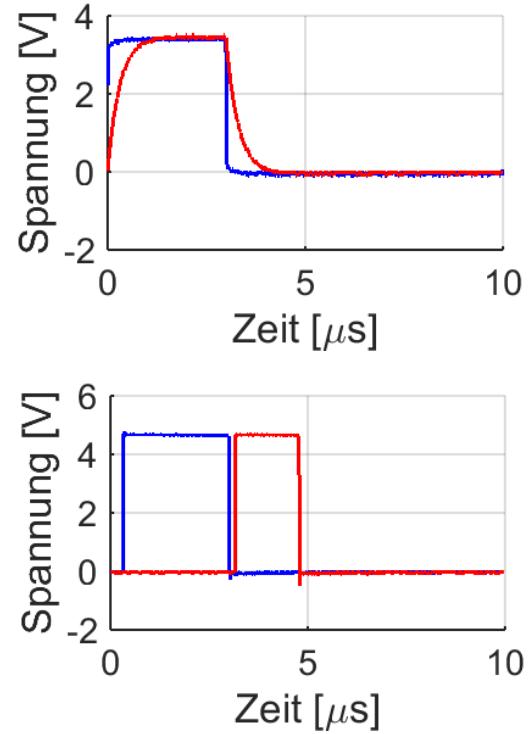
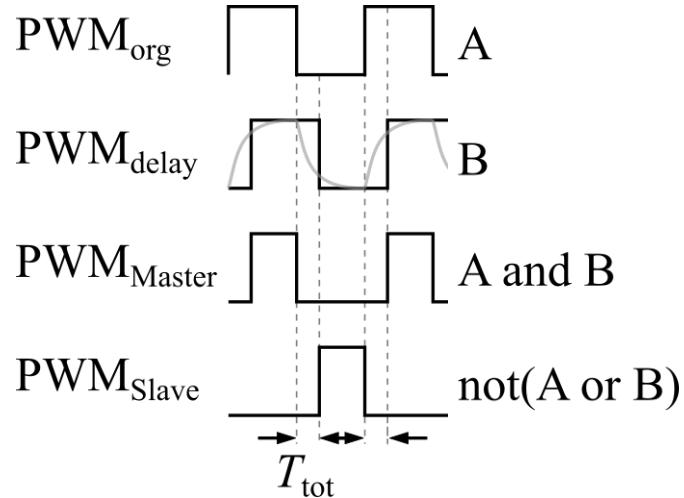
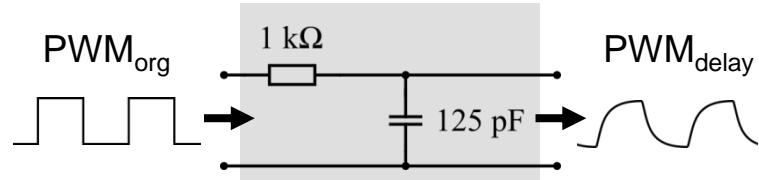
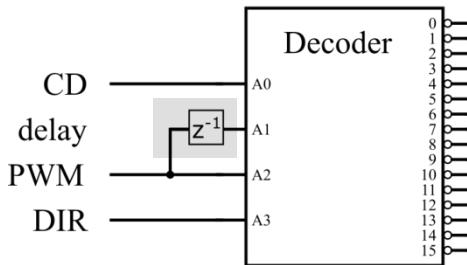
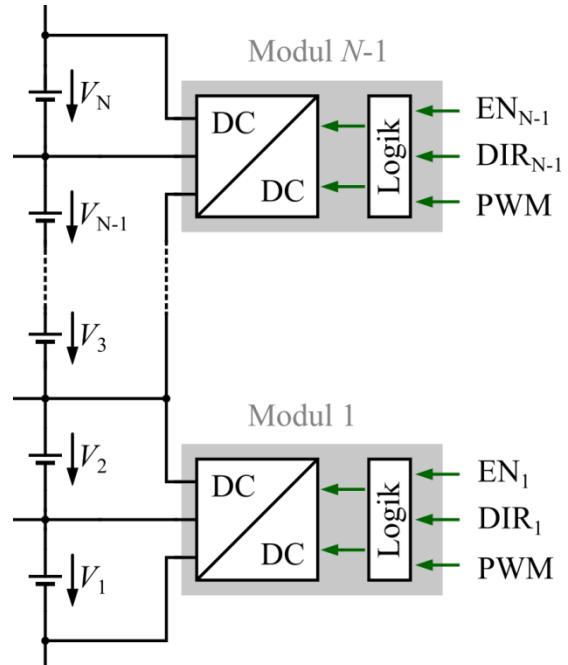
Mosfet-Ansteuerung

- Logik-Schaltung
- PWM-Verzögerung
- Stromerkennung

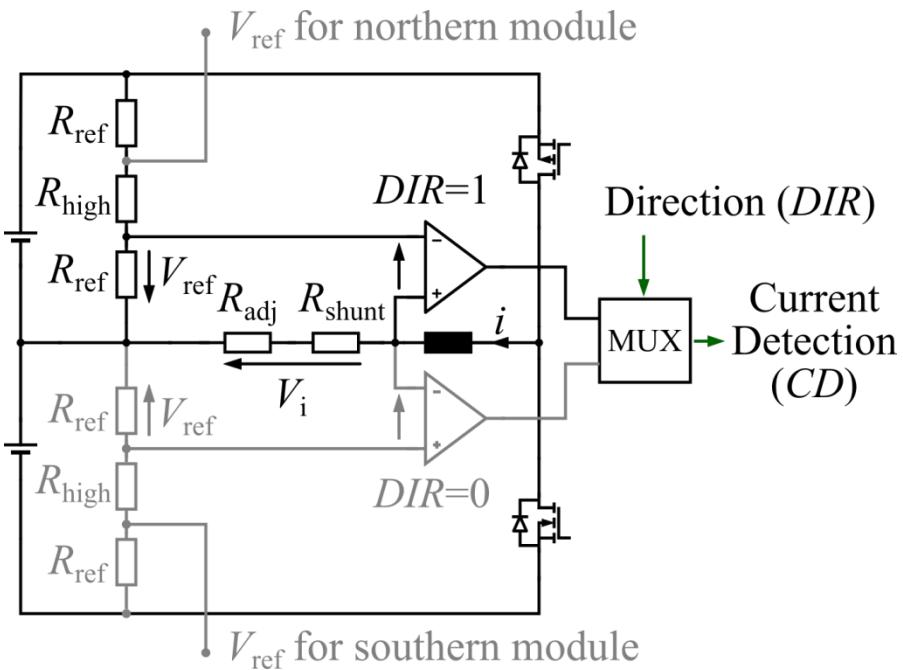


Mosfet-Ansteuerung

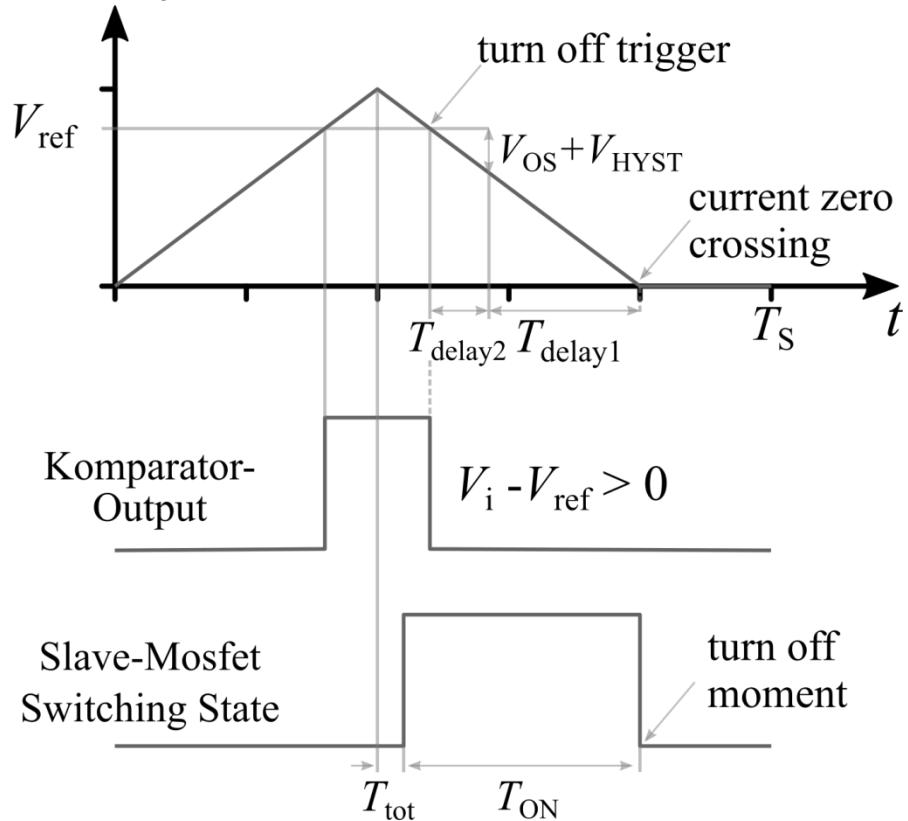
- Logik-Schaltung
- PWM-Verzögerung
- Stromerkennung



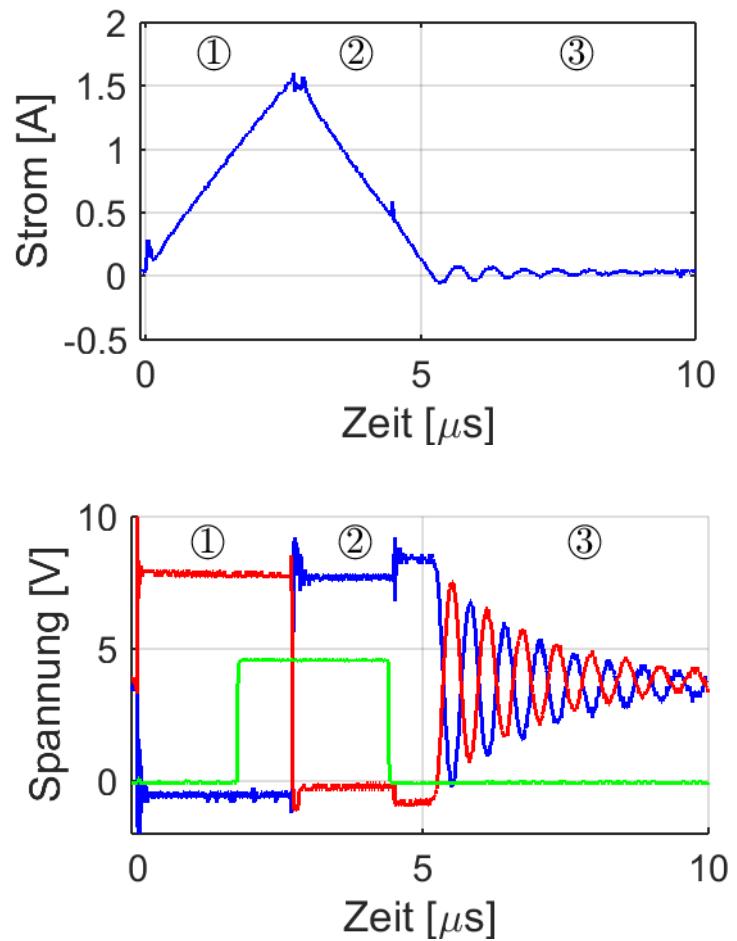
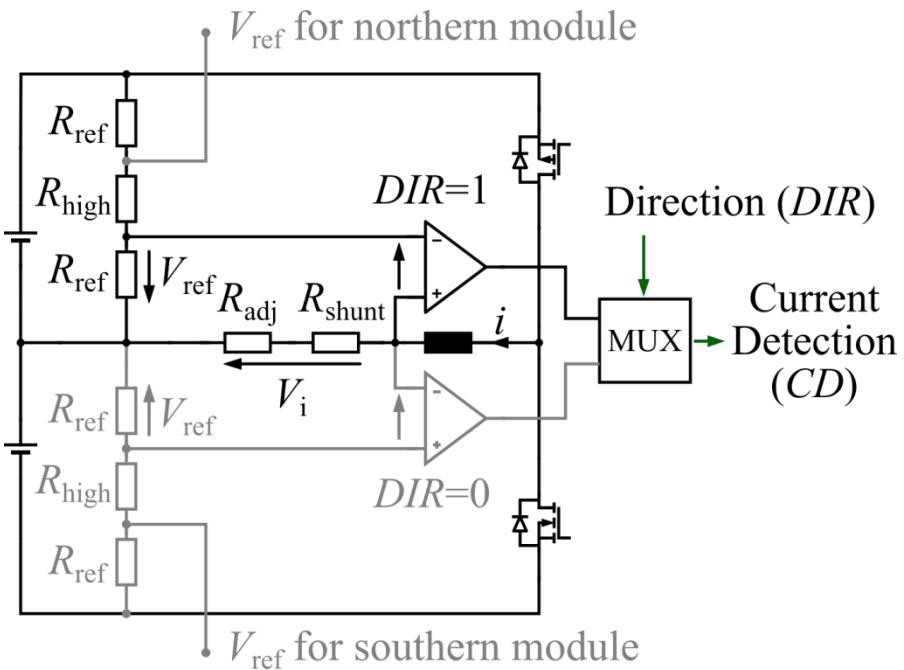
Stromerkennung (CD)



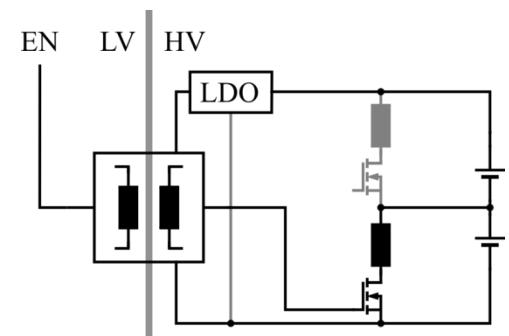
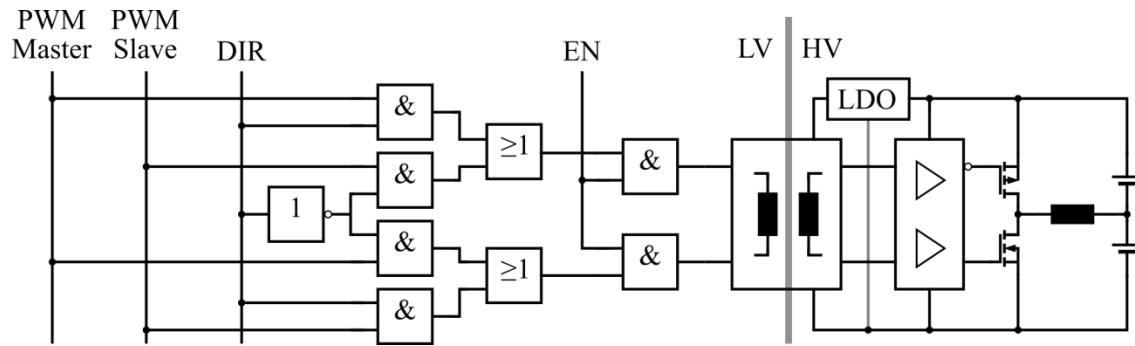
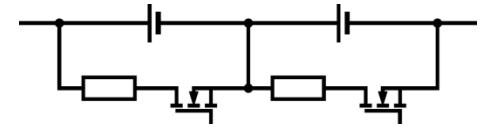
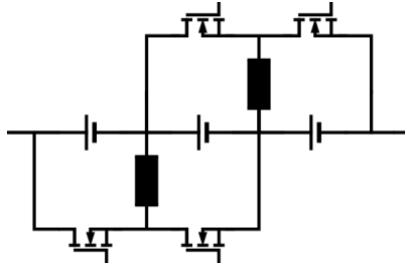
$$V_i = (R_{\text{adj}} + R_{\text{shunt}}) i_L$$



Stromerkennung (CD)

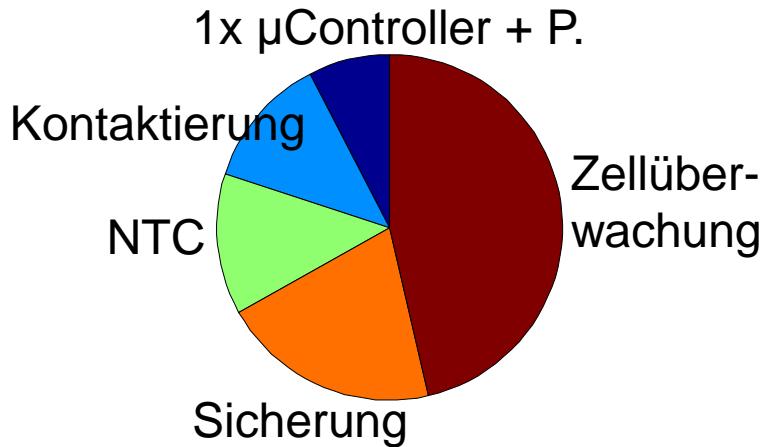


Komponentenvergleich aktives vs. passives Balancing



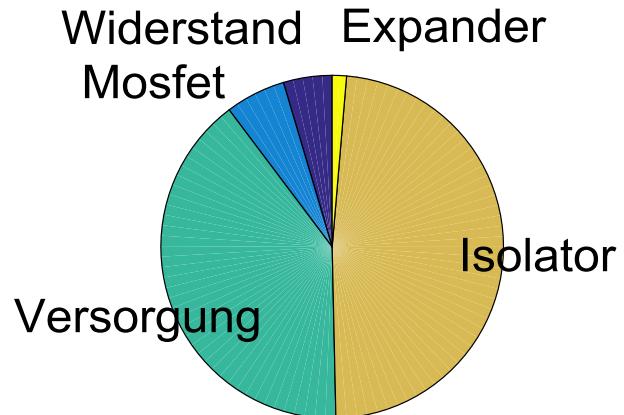
Bauteilkosten für ein Batteriesystem mit 96 Zellen

Basiskosten
377 € (3,9 €/Zelle)



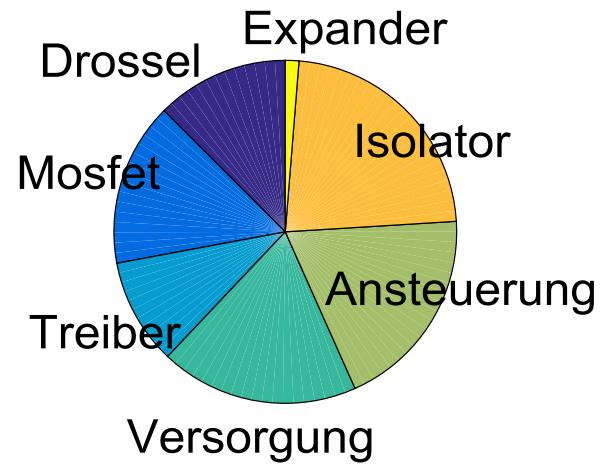
Einzelpreise Farnell
Stand: Mai 2017

Passives Balancing
618 € (6,5 €/Zelle)



Mehrkosten ca.
 $\Delta K = 7€/\text{Zelle}$

Aktives Balancing
1.300 € (13,5 €/Zelle)



Zulässige Mehrkosten des aktiven Balancings

$$\Delta K_{\text{bal}} \leq \eta_{\text{bal}} \cdot \Delta s \cdot U_N \cdot C_N \cdot k_{\text{Zelle}}$$

