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Fakultät für Elektrotechnik und Informationstechnik

Arbeitsgebiet Bordsysteme

TransformationsHub LEITUNGSSATZ

Transient Disturbances in eFuse-based Power Distribution Systems

M. Sc. Michael Gerten, Prof. Dr.-Ing. Stephan Frei | Arbeitsgebiet Bordsysteme, Technische Universität Dortmund

Vortragender

Michael Gerten

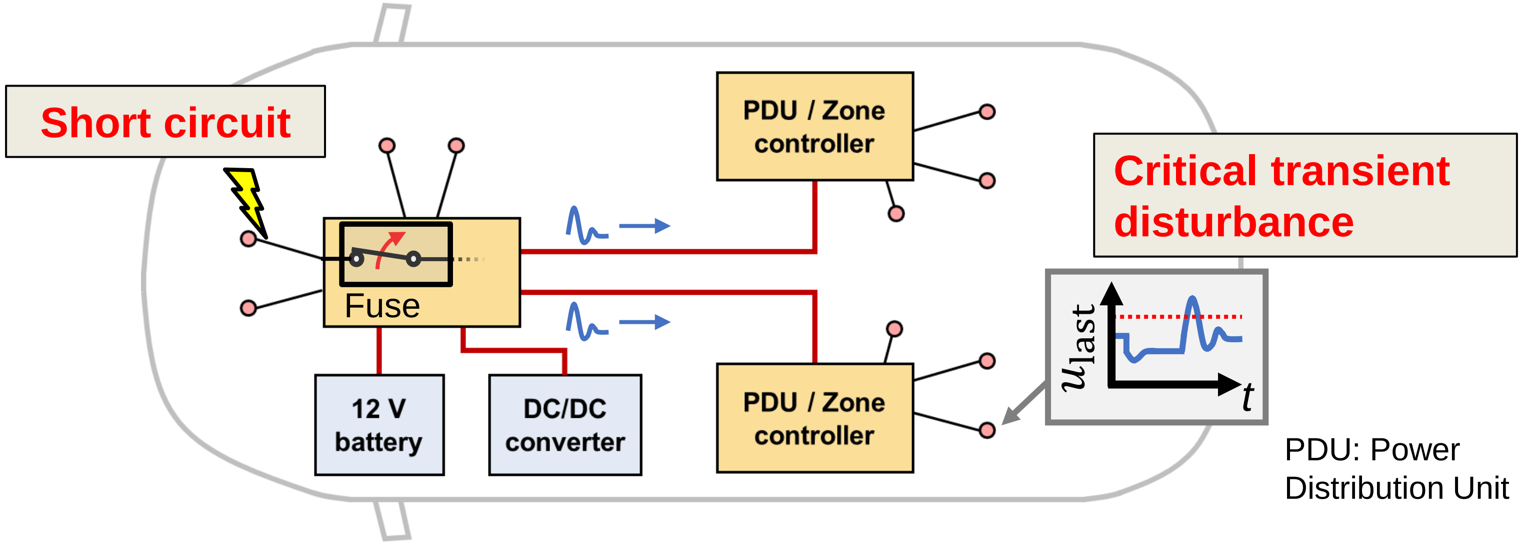
- **2019:** M. Sc. in Elektrotechnik und Informationstechnik,
  TU Dortmund
- **2020-heute**: Wissenschaftlicher Mitarbeiter am
  Arbeitsgebiet Bordsysteme, TU Dortmund
- **Vsl. 2025:** Promotion im Bereich stabiler Kfz-Energiebordnetze

Outline

- Motivation
- Comparison of Melting and Electronic Fuses
  - Selectivity in complex distribution systems
  - Transient impact on other components
- Efficient Frequency-Domain Analysis of Transient Stability
  - Identification of critical disturbances
  - Systematic stabilization
- Conclusion

Motivation

- New **zonal system architecture** and **electronic fusing**
- Highly **increased safety requirements** due to automated driving
  - No mechanical fallback level
  - Functional safety required even in case of fault → Fail-operational
  - Reduncancy concepts



PDU: Power Distribution Unit

- **Transient disturbances can lead to critical failures**
- Need to be analyzed during development process

- Impact of electronic fusing on the system stability?
- Systematic model-based analysis and stabilization method?

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Comparison of Melting and Electronic Fuses

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Why electronic fuses?

Source: Infineon

Source: STMicroelectronics

Conventional Melting Fuses

- Simple operating principle
- Well-established and standardized
- Not resettable
- Slow reaction time
- Only offers simple wire protection

Automated Driving
- Functional safety and
- Diagnostics needed

Electronic Fuses (eFuses)

- Repeated switching capabilities
- Voltage and current measurements
- Semiconductor protection
  - Overcurrent
  - Overtemperature
  - Undervoltage
  - ➢ **Fast reaction time (< 100 µs)**
- Enhanced wire protection possible
  - Wire temperature calculations
  - ➢ Cross-section reduction

Source: Littelfuse

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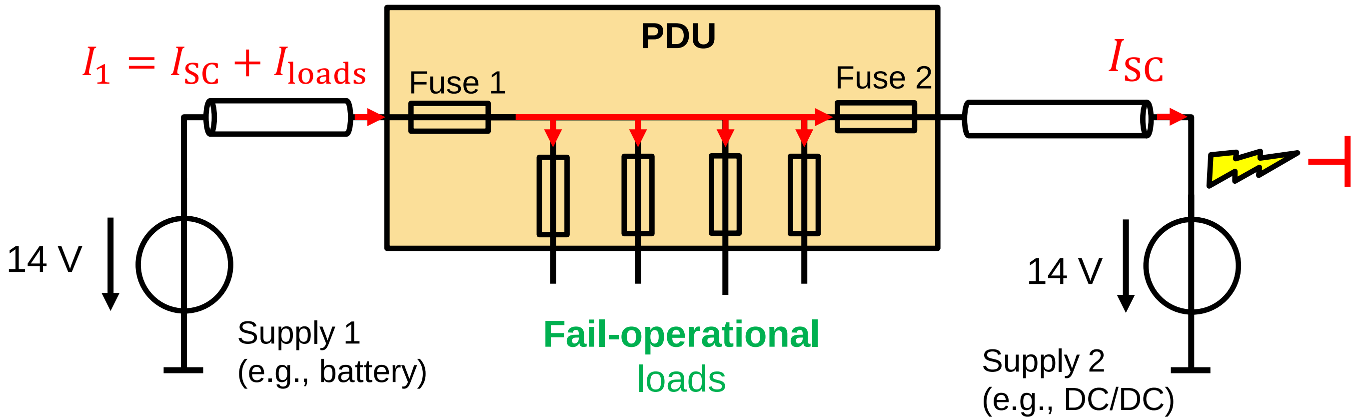
Comparison of Melting and Electronic Fuses

Selectivity in complex distribution systems

- Ring structures or redundant supply
  → bidirectional current flow
- How can such structures be protected using fuses?

Short-circuit fault in redundant supply structure

Steady state: $I_1 > I_{SC}$



<u>Supply side fault: Steady state</u>

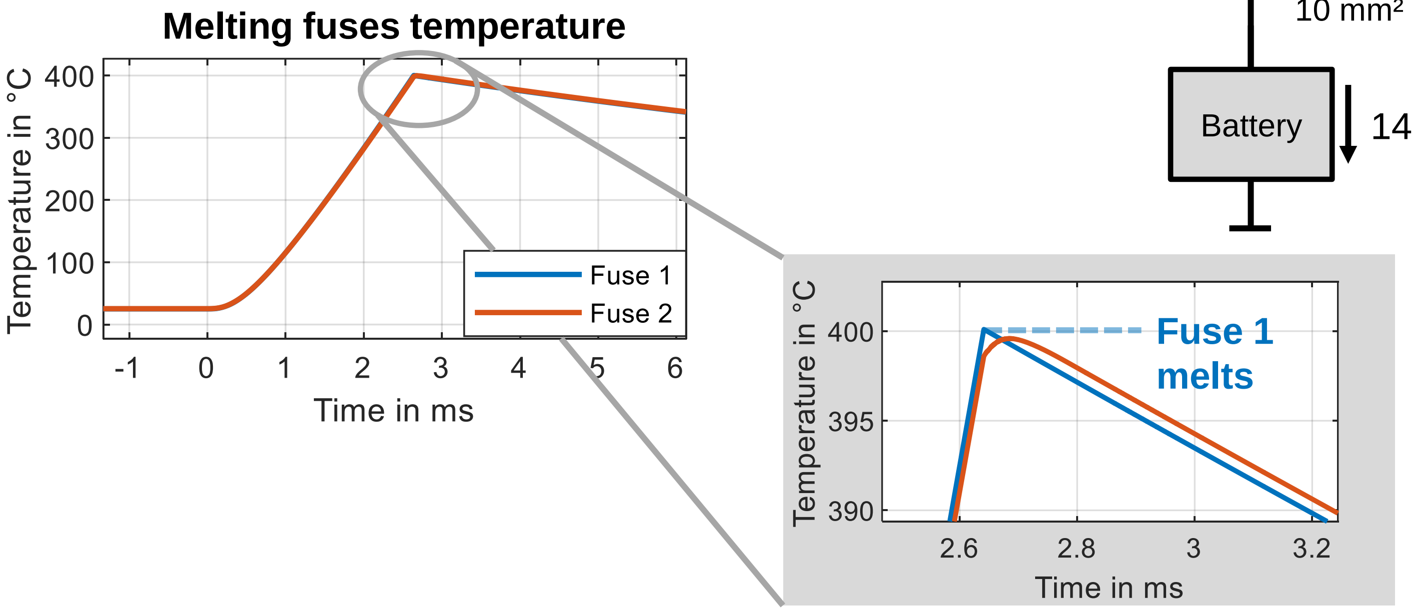
- Fuse at opposite supply carries larger current
- ➢ In case of similar fuse dimensioning, wrong could trip

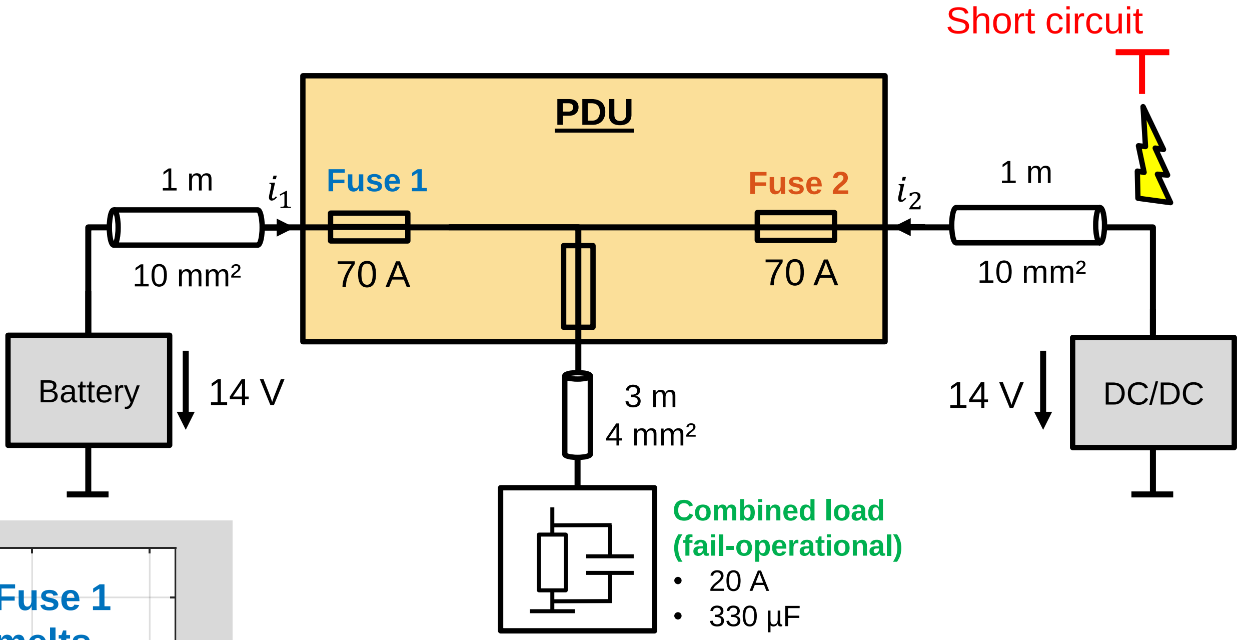
➢ **Transient behavior of both fuse types?**

Comparison of Melting and Electronic Fuses

Selectivity in complex distribution systems

- Parameterized example system
- Transient simulation considering melting fuses





- Small deviation between both fuses → Unpredictable behavior with realistic tolerances
- ➢ **Selectivity cannot be assured with conventional protection**

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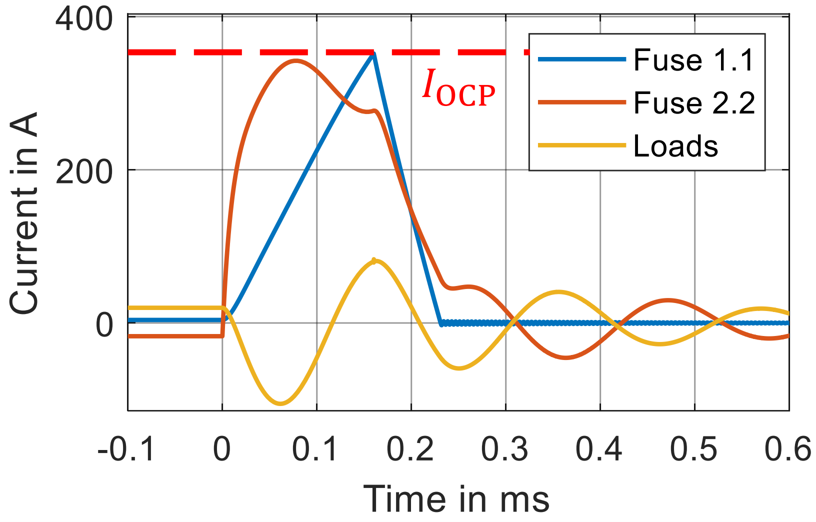
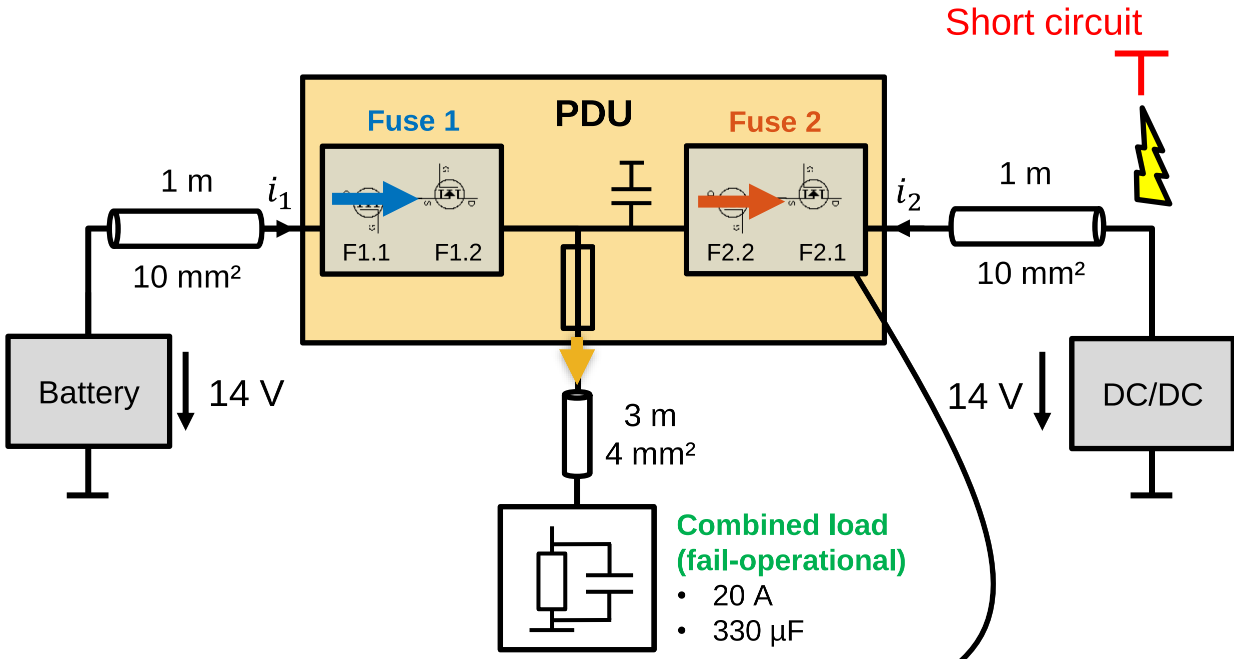
Comparison of Melting and Electronic Fuses

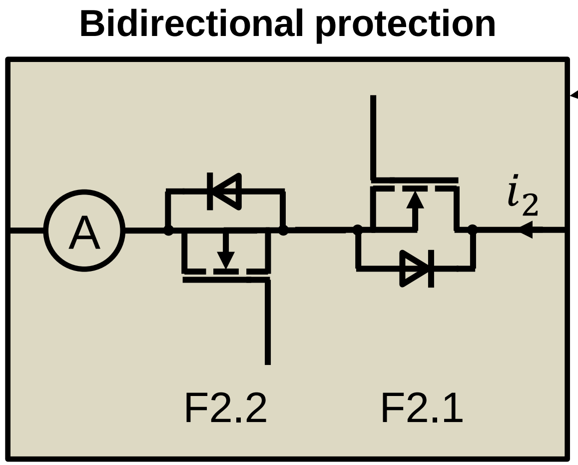
Selectivity in complex distribution systems

- How about eFuses?
- **O**ver**c**urrent **p**rotection Fuse 1 & 2: $I_{OCP} = 350\ \mathrm{A}$



- ➢ Selectivity problem possible <u>in some cases</u>
- ➢ Especially depends on wire lengths and system capacitances

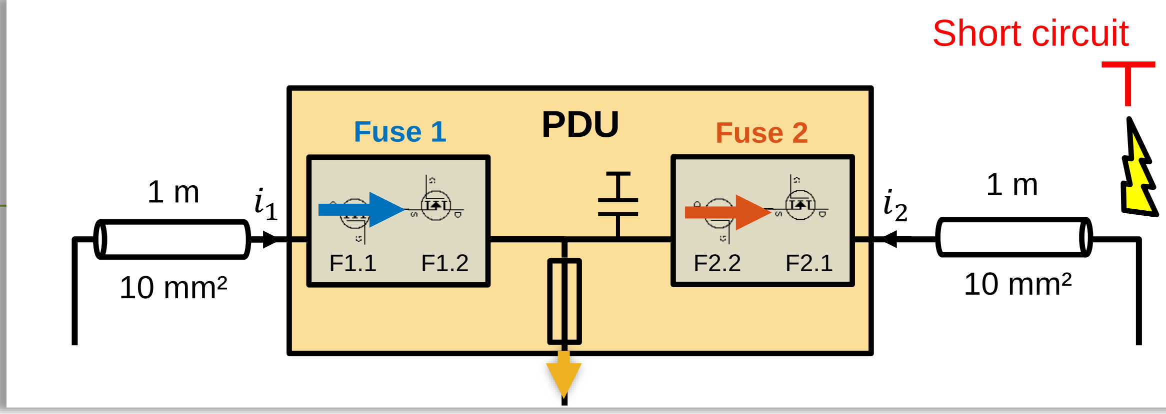




<u>Overcurrent protection</u>

- F2.1 trips, if $i_2 > I_{OCP}$
- F2.2 trips, if $i_2 < -I_{OCP}$

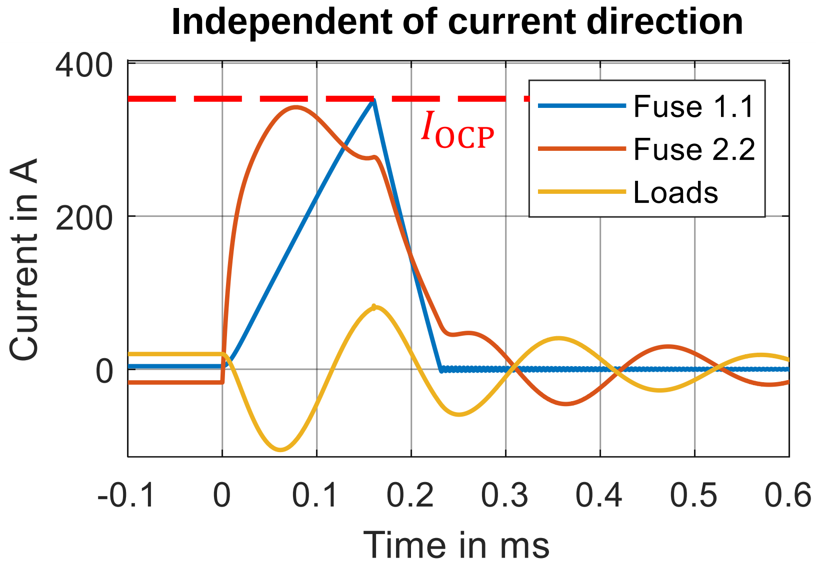
Comparison of Melting and Electronic Fuses

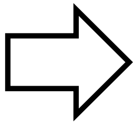


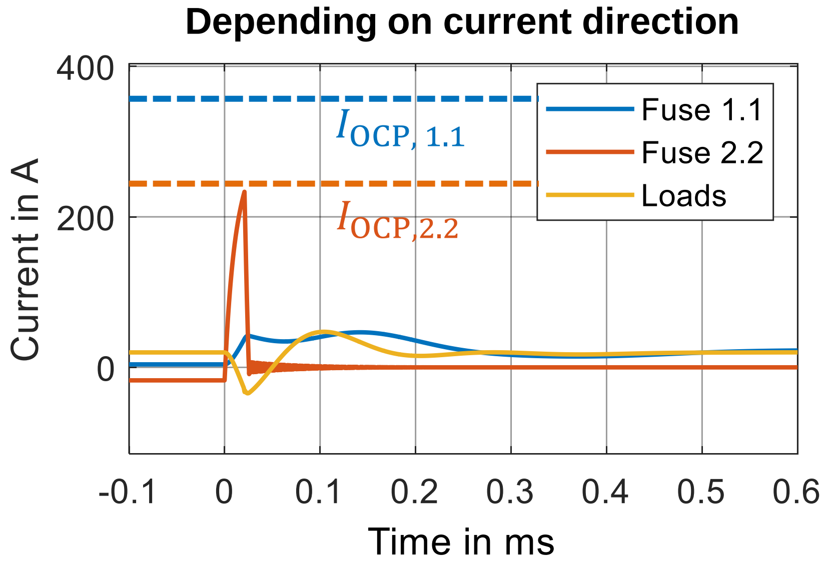
Selectivity in complex distribution systems

- Countermeasures?

- Fuse parameterization depending on current direction → $I_{\text{OCP, 1.1}} = 350\text{ A}$, $I_{\text{OCP,2.2}} = 230\text{ A}$







➢ Selectivity is maintained in every investigated parameter combination

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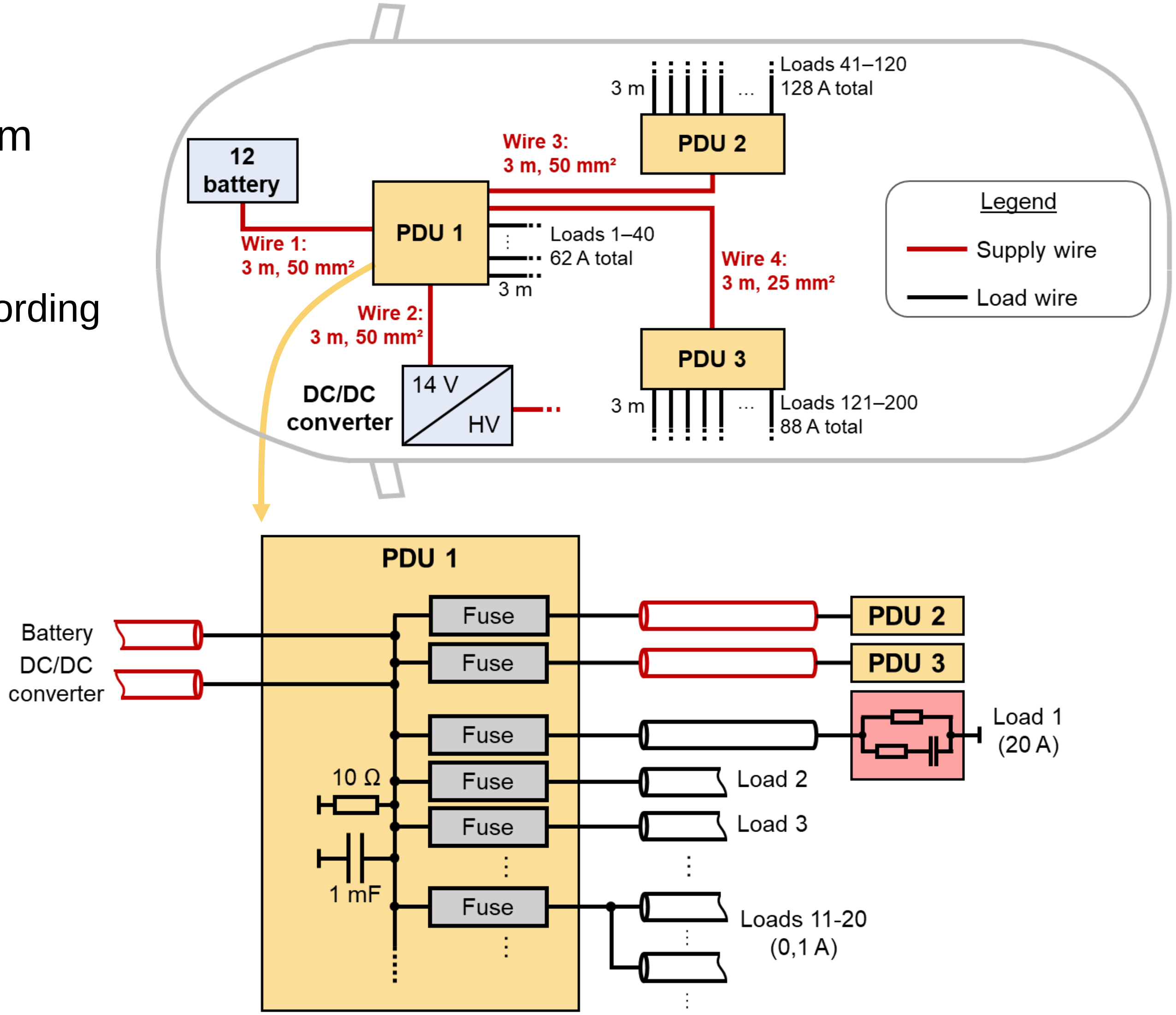
Comparison of Melting and Electronic Fuses

Transient impact on other components

- Exemplary investigation in larger distribution system
  - 3 Power distribution units (**PDU**s)
  - 200 loads
  - Dimensioning of wires, fuses and load capacitors according to nominal currents
  - Overvoltage threshold 27 V
  - Undervoltage threshold 6 V for >100 µs

PDU 1		PDU 2		PDU 3	
Load No.	Current	Load No.	Current	Load No.	Current
1	20 A	41	50 A	121	40 A
2–3	10 A	42	20 A	122	20 A
4–6	5 A	43–44	10 A	123	10 A
7–10	1 A	45–48	5 A	124	5 A
11–40	0,1 A	49–60	1 A	125–130	1 A
		61–120	0,1 A	131–200	0,1 A



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Comparison of Melting and Electronic Fuses

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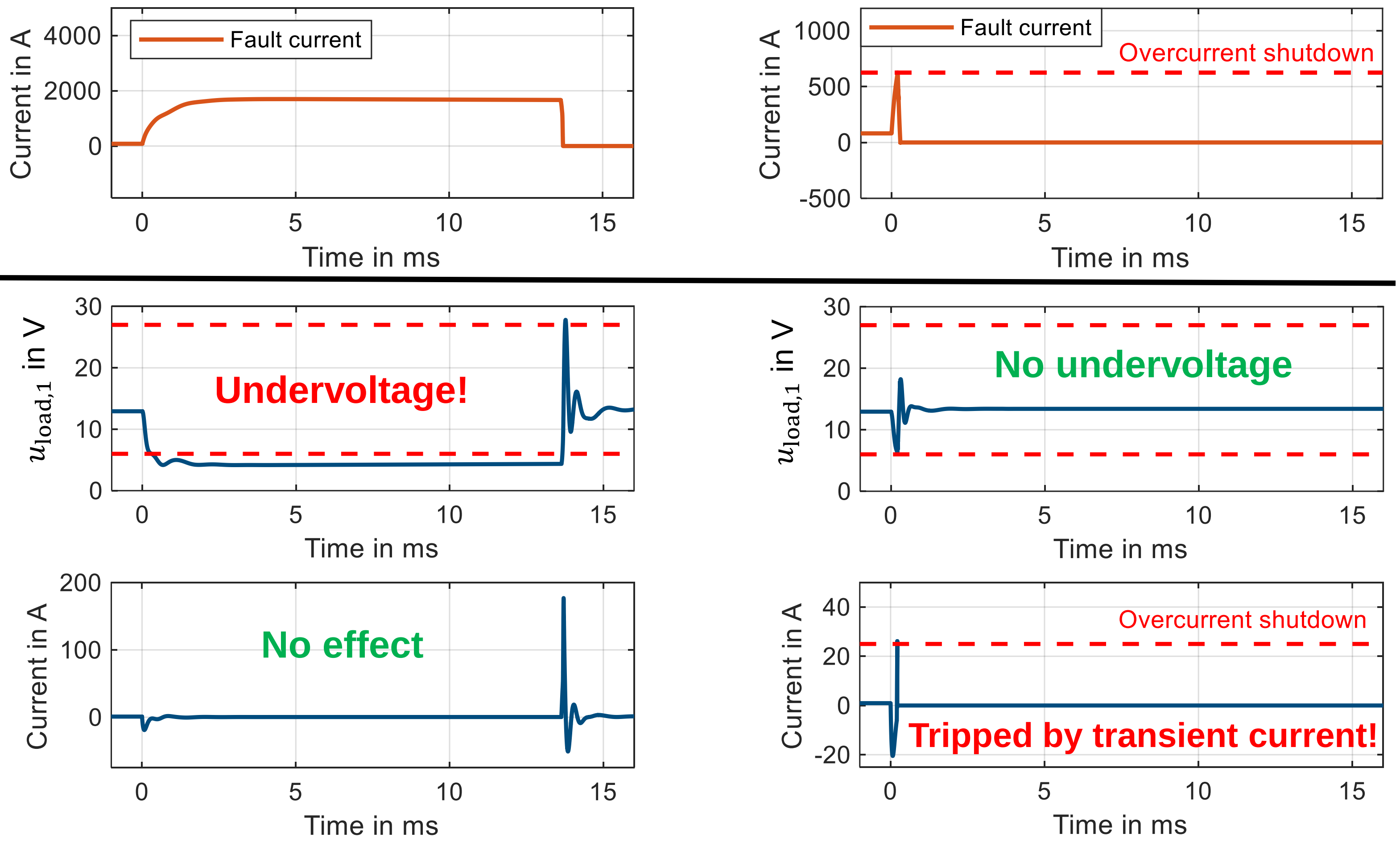
- Scenario: **Short circuit at Wire 4** – Effect on exemplary components

Melting Fuses | **eFuses**

Short circuit

Voltage Load 1

Current Fuse 11



Conclusion

- eFuses <u>necessary</u> to rapidly isolate faults
- <u>Can be tripped unintendedly by transient currents!</u>

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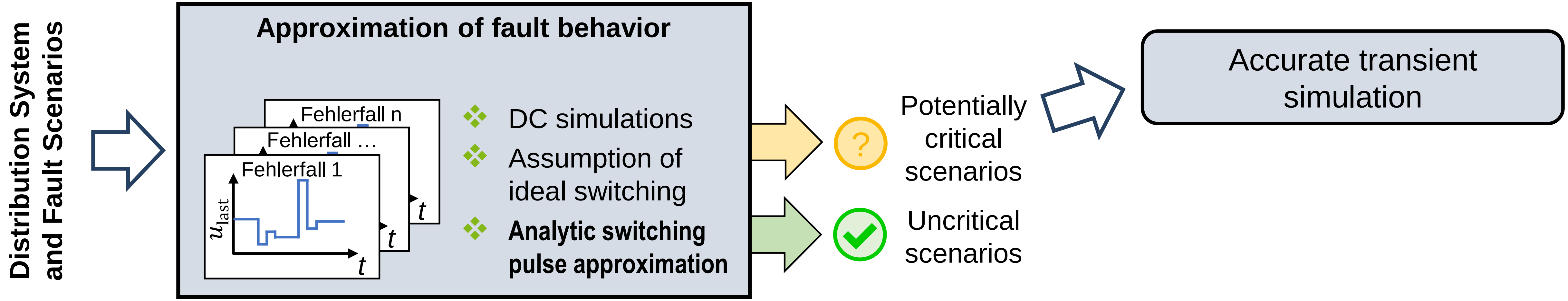
Efficient Frequency-Domain Analysis of Transient Stability

- Critical transient pulses can occur in eFuse-based distribution systems
- How can they be efficiently identified?

- Transient short-circuit simulation: 173 s
- Example: 173 s · 411 Fault scenarios · 1000 system operating points = 822 days
- **More efficient methods needed for stability analysis!**

Idea: Preselection of potentially critical scenarios by approximation of fault behavior



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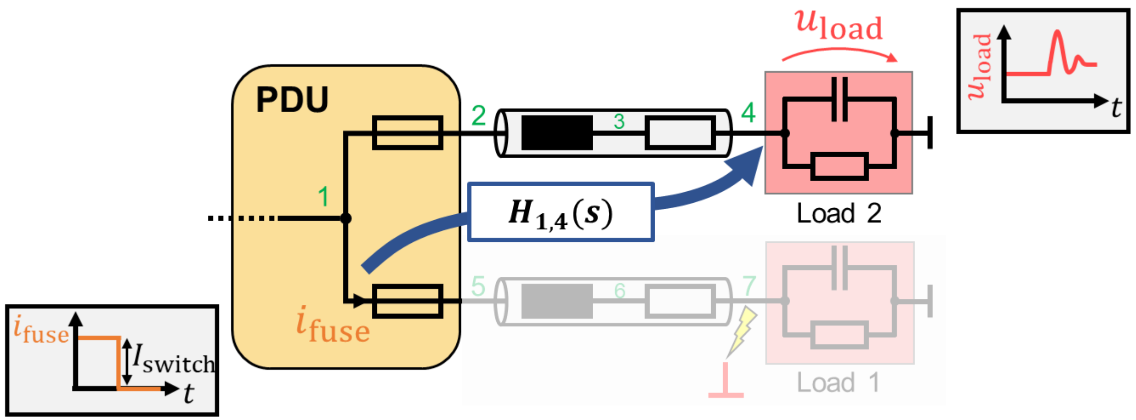
Frequency-Domain Identification of Critical Disturbances

- Analytic approximation of switching pulses
- Adapting resonance analysis methods from AC power system
- Transfer function describes the coupling between switching event (eFuse) and affected component:



- Transfer function from modified nodal analysis description
- **Analytic worst-cast estimation of step response possible → Very fast**

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Efficient Frequency-Domain Analysis of Transient Stability

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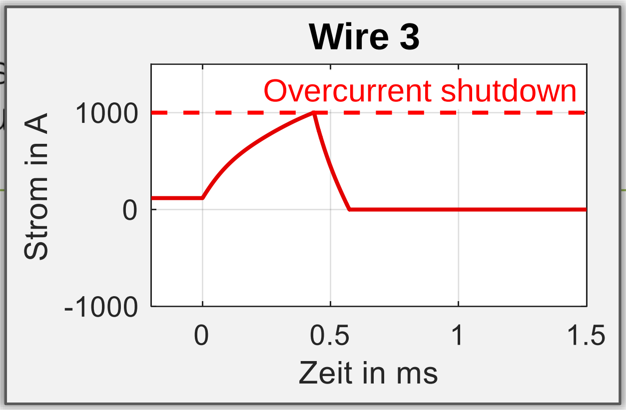
Validation

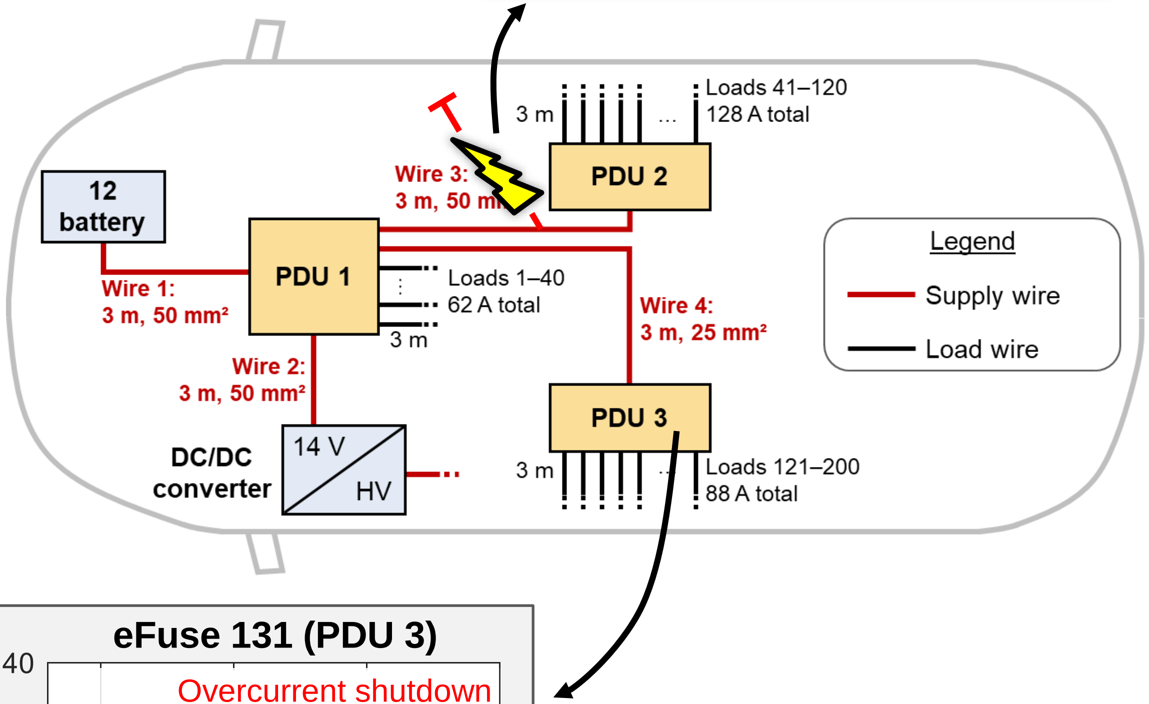
- Analysis of all short-circuit and wire break faults
  - 411 fault scenarios in total

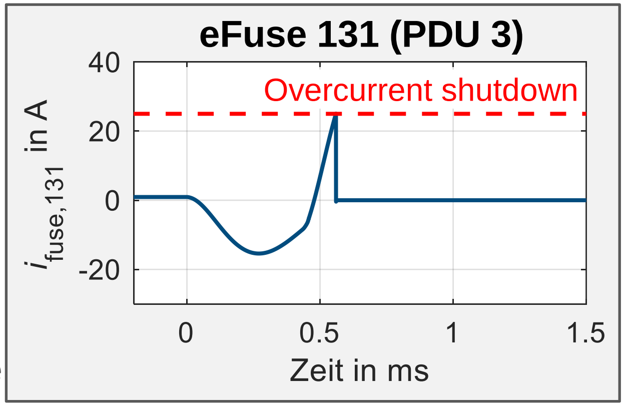
- **9 scenarios** identified as **potentially critical** by approximation

➢ **3 actually critical** in transient Simscape simulation

Critical example scenario







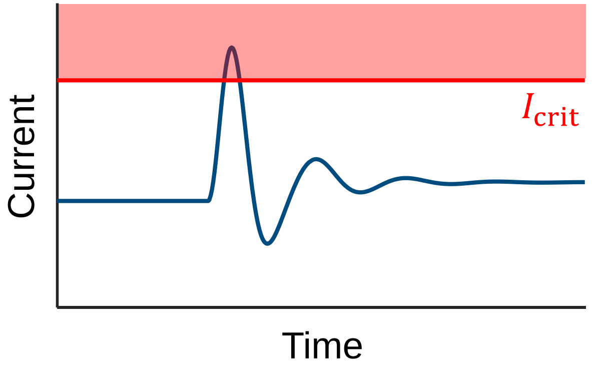
➢ **Failure of safety-relevant load!**

➢ All critical scenarios **successfully identified**

➢ **Runtime reduction of 98 %** compared to Simscape simulations without preselection

Systematic Stabilization

- Mitigation of critical transient pulses necessary
  - ➢ Sensitivity analysis for efficient optimization



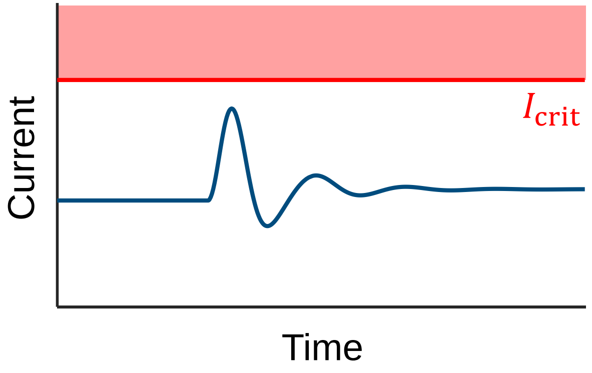
- Normalized sensitivity $S_h^{\hat{\imath}}$ of a current peak $\hat{\imath}$ to parameter x:

$$S_x^{\hat{\imath}} = \frac{x}{\hat{\imath}} \frac{\partial \hat{\imath}}{\partial x}$$

E.g., $S_x^{\hat{\imath}} = 1$:
1 % increase of x
→ 1 % increase of $\hat{\imath}$

Adaptation of system parameter $\boldsymbol{x}$ by $\boldsymbol{y}$ %

→ **Unknown!**



- ➢ Slow calculation in time domain
- ➢ **Fast approximation in frequency domain possible**

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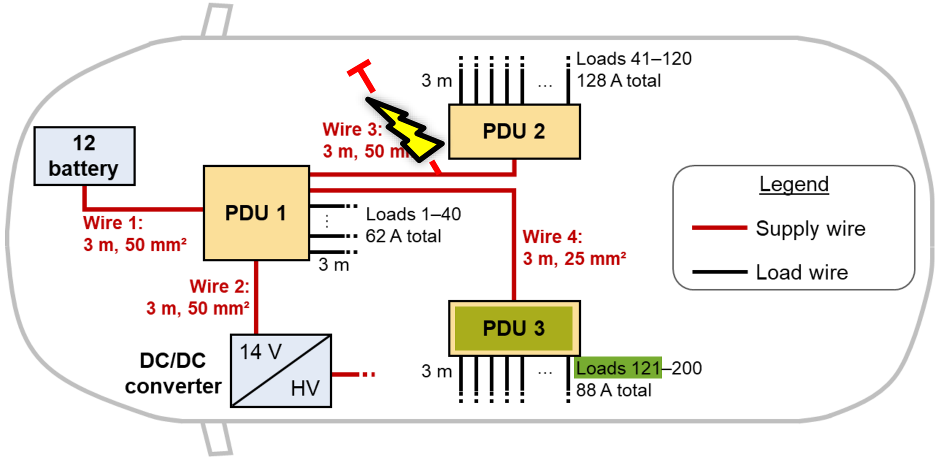
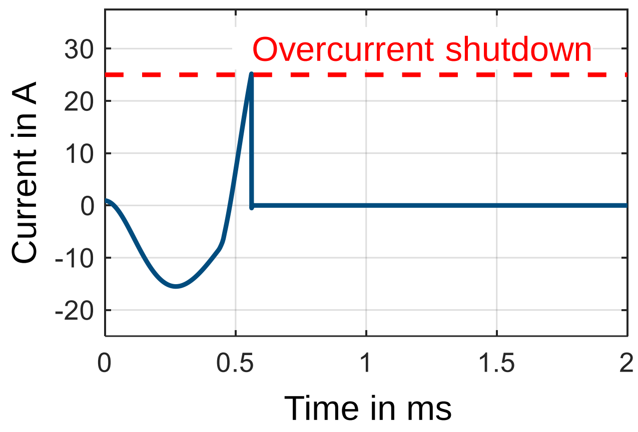
Systematic Stabilization

- Which parameters need to be adapted?
  - ➢ Sensitivities of transfer function resonances
- 1,292 frequency-domain sensitivities of critical scenario calculated



Current eFuse 131 (PDU 3)

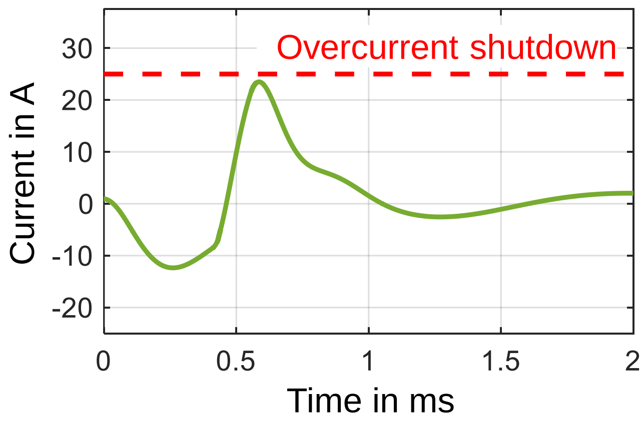


Capacitance increase

$C_{\mathrm{PDU,3}}$: 1 mF → 3.3 mF

$C_{\mathrm{load,121}}$: 680 µF → 2.2 mF

Current eFuse 131 (PDU 3)



➢ Fail-operational

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Conclusion

- eFuses enable protection of complex topologies
- Fast reaction minimizes undervoltage in case of a short circuit

- Transient current pulses and selectivity can be challenges
  - ➢ Investigation of transient behavior
  - ➢ Careful system design

- Efficient stability analysis in the frequency domain
  - – Identification of critical fault scenarios
  - – Stabilization based on sensitivities

Thank you for your attention!

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michael.gerten@tu-dortmund.de

www.bordsysteme.tu-dortmund.de