WIDE-BANDGAP TECHNOLOGIES FOR TOMORROW‘S HIGHLY EFFICIENT

AND RELIABLE AUTOMOTIVE MOBILITY SOLUTIONS

“How to Boost Power Electronics Limits While Ensuring Reliability? ”

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Sajib Chakraborty (Vrije Universiteit Brussel)

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Chips JU

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Center for Micro and Nano Technologies

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Center for Micro and Nano Technologies (ZfM)

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Group Leader: Component Reliability

www.zfm.tu-chemnitz.de www.tu-chemnitz.de

Chemnitz – European Capital of Culture in 2025

251.605 inhabitants
(10/2023)

Chemnitz University of Technology: 7 Faculties
Approx. 9200 students (11/2022)

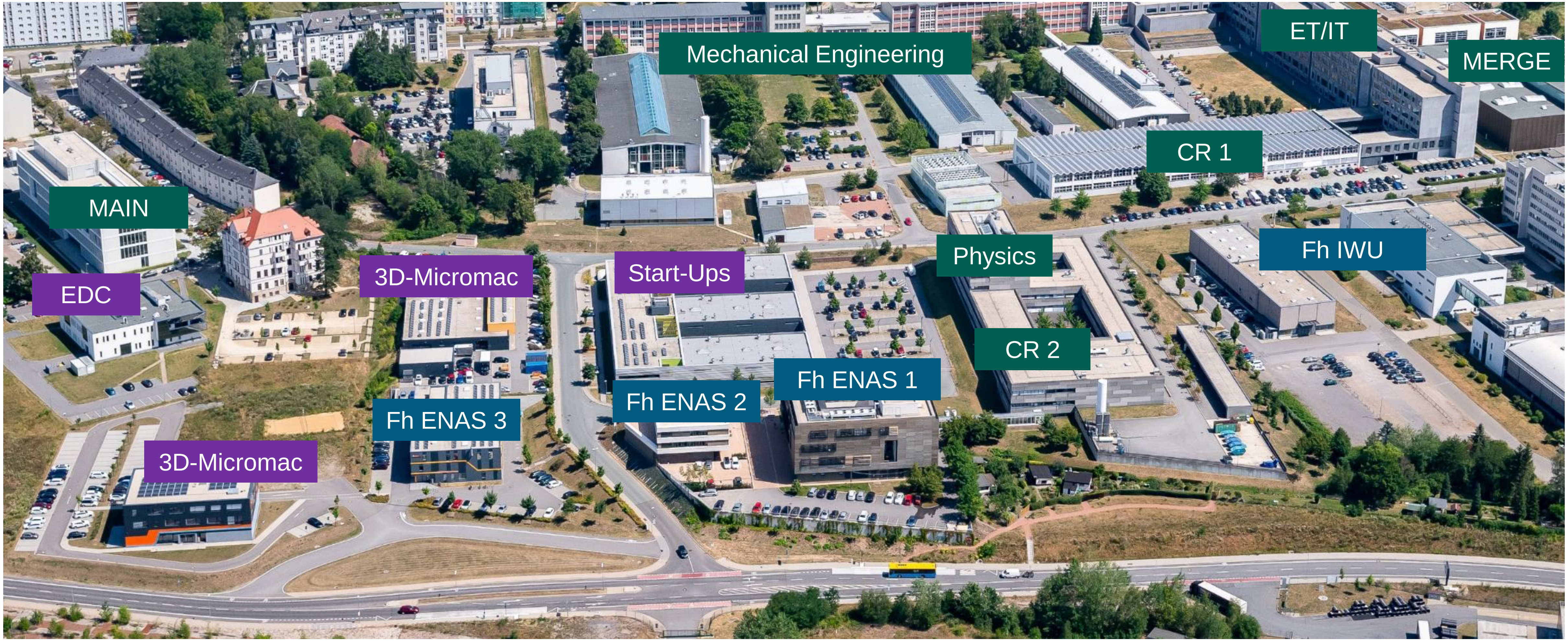
Just under 16,000 companies
(07/2023)

Non-academic RTOs:
Fraunhofer IWU, Fraunhofer ENAS, Sächsisches Textilforschungsinstitut e.V. (STFI)

Key sectors:
automotive, metal and mechanical engineering

Leading R&D place for micro system technology, sensors and textile

Smart Systems Campus Chemnitz – Reichenhainer Str.



Buildings of Chemnitz University | Fraunhofer institutes | Start-Ups and companies

5 Research Group

VUB mobi ELECTROMOBILITY RESEARCH CENTRE

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MOBI-EPOWERS IN NUMBERS

EPOWERS Research Portfolio

Power Electronics

Charging Systems
Inverters & multi-level converters
DC/DC converters & Active Front-End (AFE)
Battery Management Systems (BMS)

Electrical Machines

Design and Optimization
System Control
Performance Assessment

Vehicle Powertrains

Digital Twin Powertrain
Codesign Optimization Framework
ECO-energy management strategies
Fleet Electrification

Smart Green Grid Solutions

Design, Optimization and Sizing of Green assets
Energy-Thermal Management and Control system
Optimal Charging & V2X (V2G, V2B, V2H, V2D) Strategies

Digital Twin and Reliability

Virtual prototyping and validation of PE converters
Virtual vehicles simulation and Fleets management
Lifetime testing/ALT testing and RUL estimation

Team Lead: Dr. Sajib Chakraborty

15+ EU funded projects

4 Top-Notch Labs

40+ Members

5 Research Tracks

MAIN CONTACTS

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Head of EPOWERS

Part I: Streamlined Power Electronics Optimization with "Design for Reliability (DfR)"

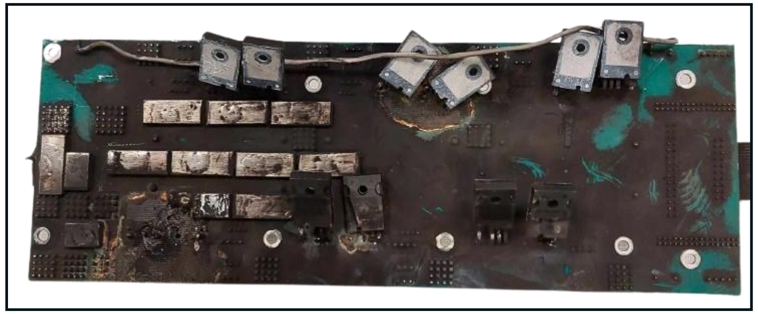
The Critical Role of "Design for Reliability" in the Early Design Phase

Reported Reliability issues

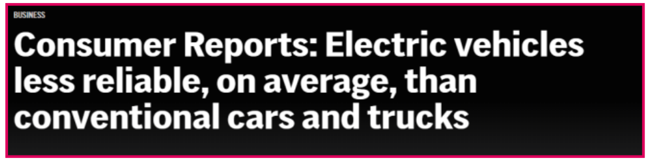
- Σ 1.9 million cars recalled to fix batteries overheating [1]
- Σ Nearly 130K+ EVs recalled for overheating of processors [2]
- Σ Over 120K+ EV/PHEVs were recalled due to a risk fire by a Capacitor [3].
- Σ 400k+ cars recalled due to unexplained overheating of inverter [4]

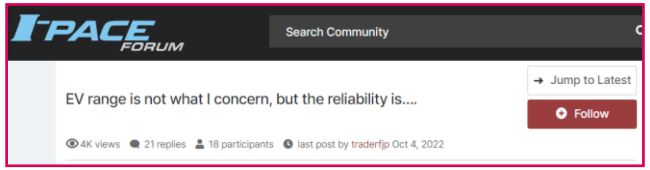
Significances of poor Reliability

- Σ Revenue loss
- Σ Customer dissatisfaction
- Σ Long delivery delay
- Σ Disrupted services



A Consequence of Semiconductor Failures in a DC Fast Charger

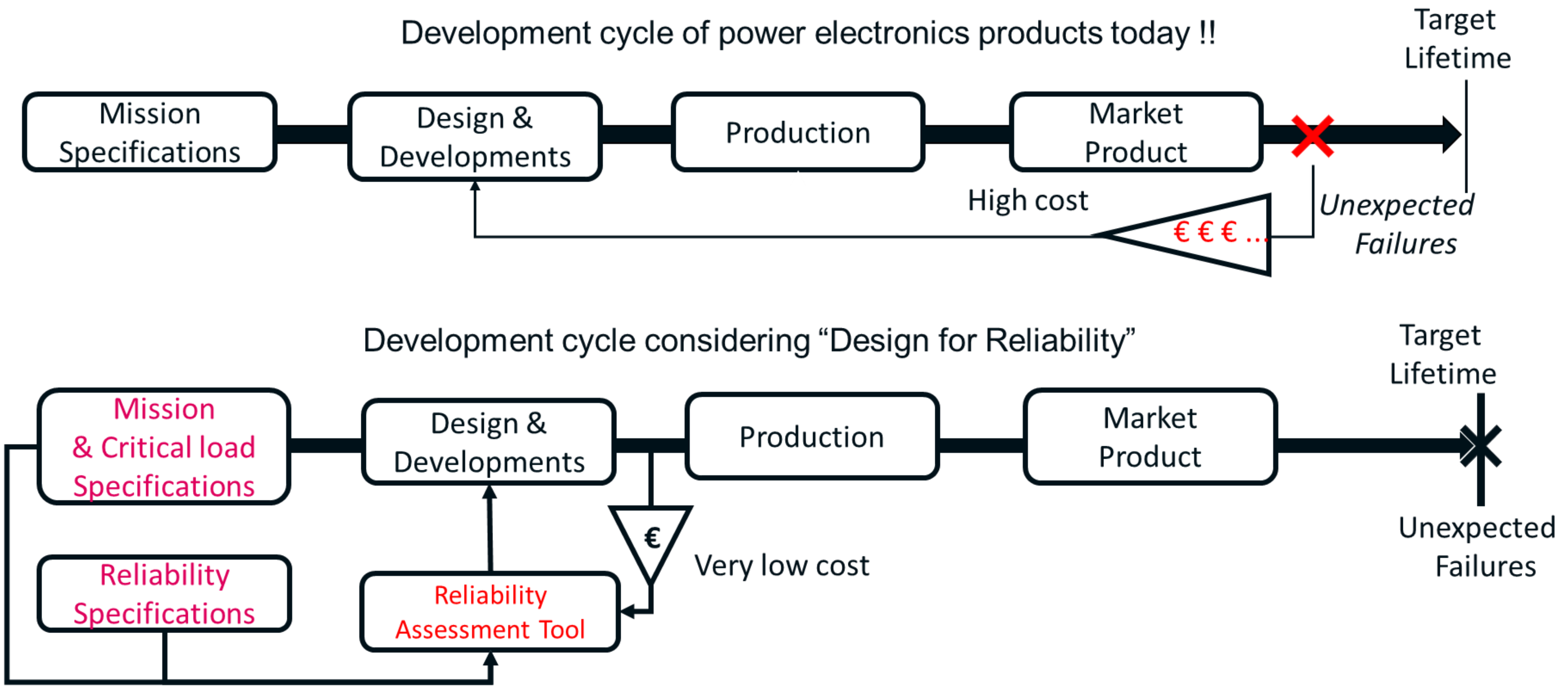




➔ Trend from **8000** hours to **100,000** hours of operation time, due to EV grid connection

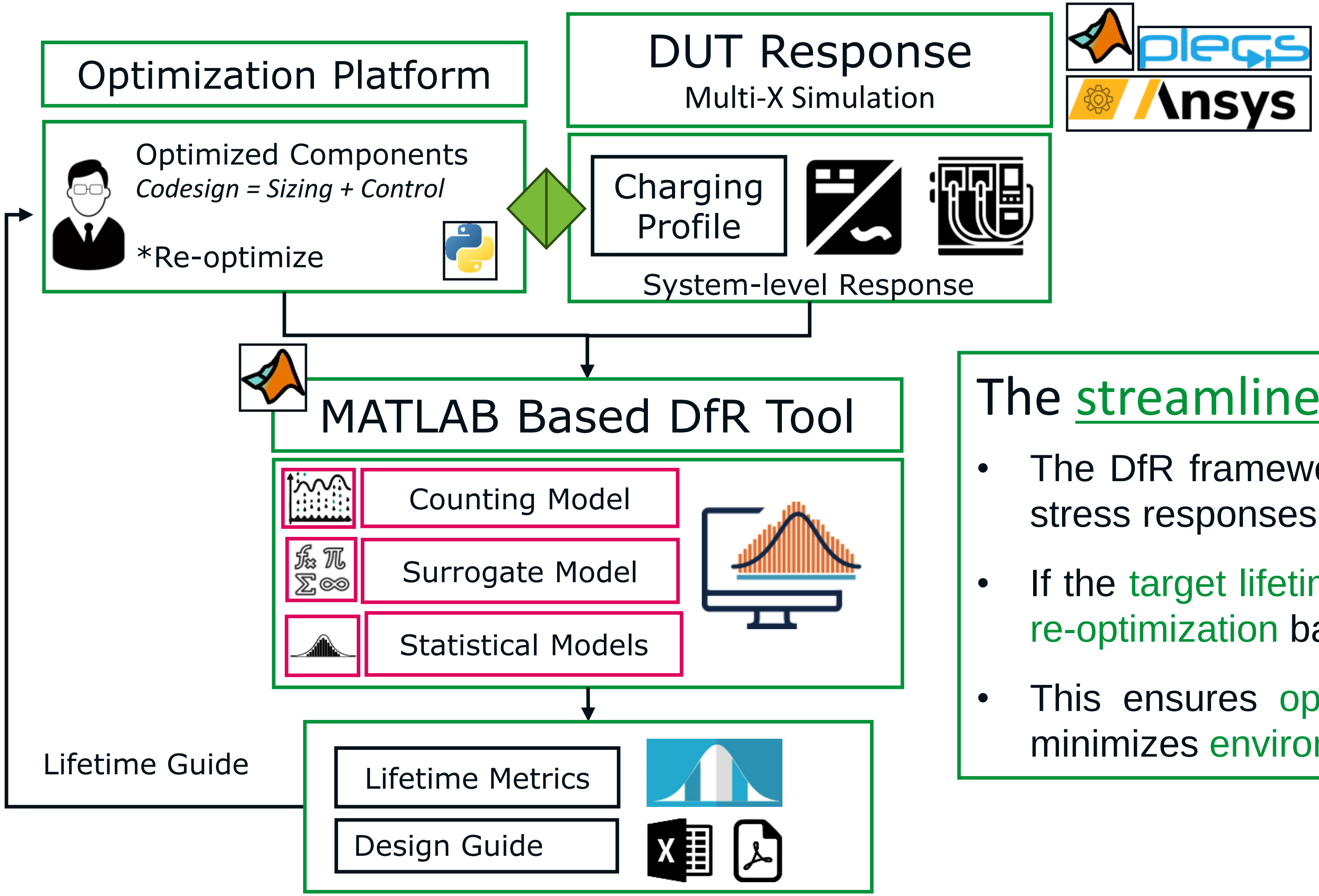
Source:
1. https://www.cnbc.com/2023/11/02/toyota-recalls-nearly-1point9-million-rav4s-to-fix-batteries-that-can-move-during-hard-turns-and-cause-a-fire.html
2. https://www.theverge.com/2022/5/10/23065987/tesla-recall-130000-vehicles-fix-touchscreen-issues-caused-overheating-cpu-amd-ryzen
3. https://movemnt.net/why-have-270000-vehicles-been-recalled-in-past-week/
4. https://www.latimes.com/local/california/la-fi-prius-overheat-inverter-defect-20190414-story.html

Improvement considering " Streamlined Design for Reliability (DfR) Approach"



Source: [Design for reliability and robustness tool platform for power electronic systems]

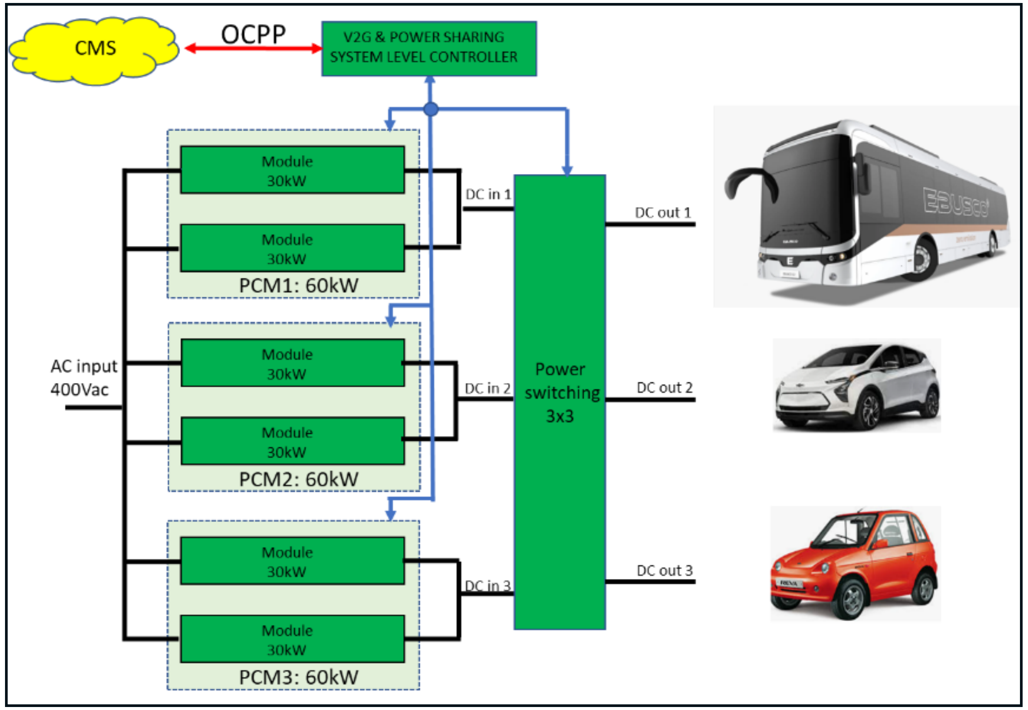
Methodology of Streamlined Optimization with "Design for Reliability (DfR)"

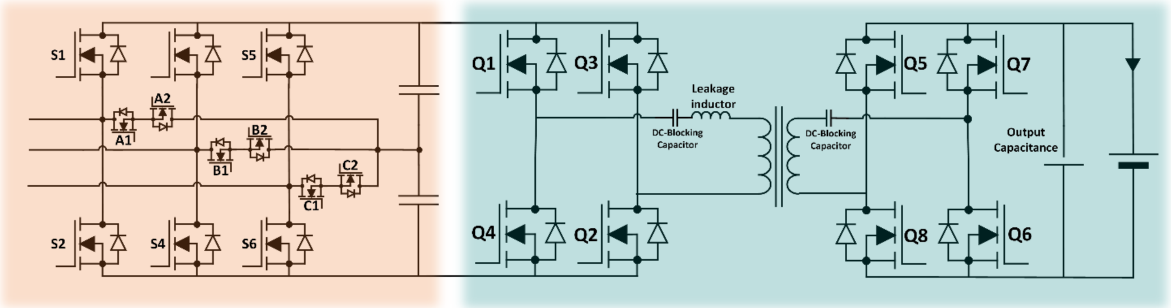


The streamlined DfR framework functions as follows:

- The DfR framework evaluates DUT lifetime based on electro-thermal stress responses from optimized designed prototypes
- If the target lifetime isn't met, it provides feedback to the optimizer for re-optimization based on a reliability scorecard
- This ensures optimal component sizing, reduces over-engineering, minimizes environmental impact, and extends component life

HIEFFICIENT Use Case Definition & Specification





Description	Values
Input voltage	3ph 230V
Output voltage	200V to 1000V
Output power	30kW @ 40°C
Max DC output current	30kW/350V=86A
Bidirectional	Yes

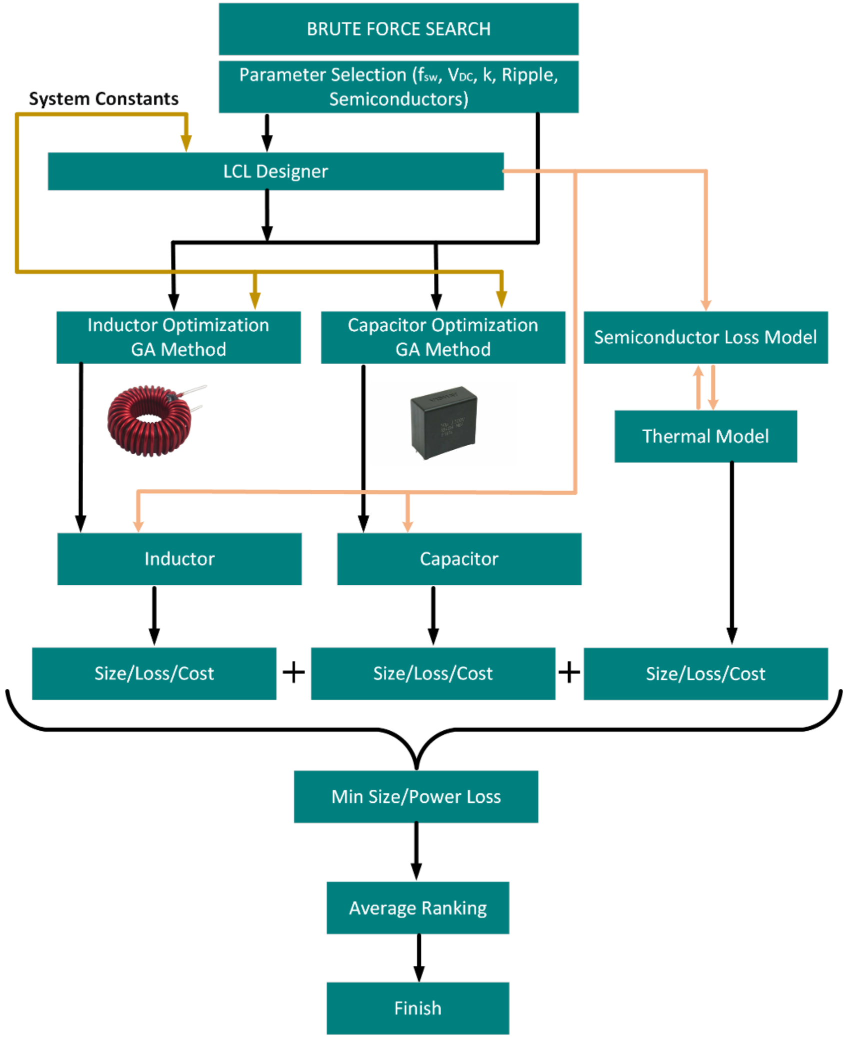
Use Case Lifetime Target:

1. Efficiency:

- 97% @ (30kW 40°C 350V and 1000V)
- 98.5% efficiency AFE
- 98.5% efficiency DAB

2. System Lifetime > *150 thousand hours (MTBF)*

Multi-objective Design and Optimization



DC-Link Capacitor (x4)

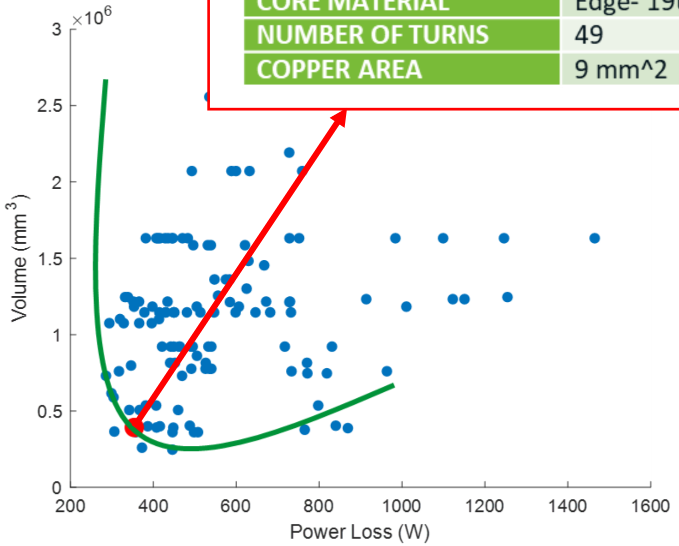
PARAMETER	VALUE
PART NO	'MKP1848C66012JY5'
CAPACITANCE	60uF
PARALLEL	1
LIFETIME	151kHr

AFE Side LCL Filter Inductor

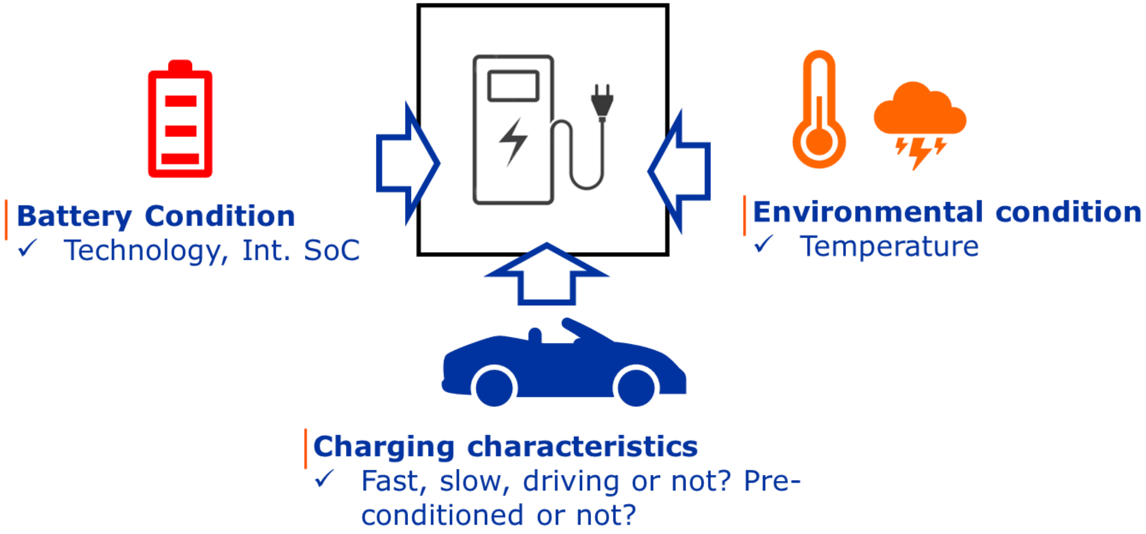
PARAMETER	VALUE
INDUCTANCE	65 uH
CORE SHAPE (PART NO)	906
CORE MATERIAL	Edge- 19u
NUMBER OF TURNS	49
COPPER AREA	9 mm^2

Grid Side LCL Filter Inductor

PARAMETER	VALUE
INDUCTANCE	19.5 uH
CORE SHAPE (PART NO)	906
CORE MATERIAL	Edge- 19u
NUMBER OF TURNS	27
COPPER AREA	9 mm^2

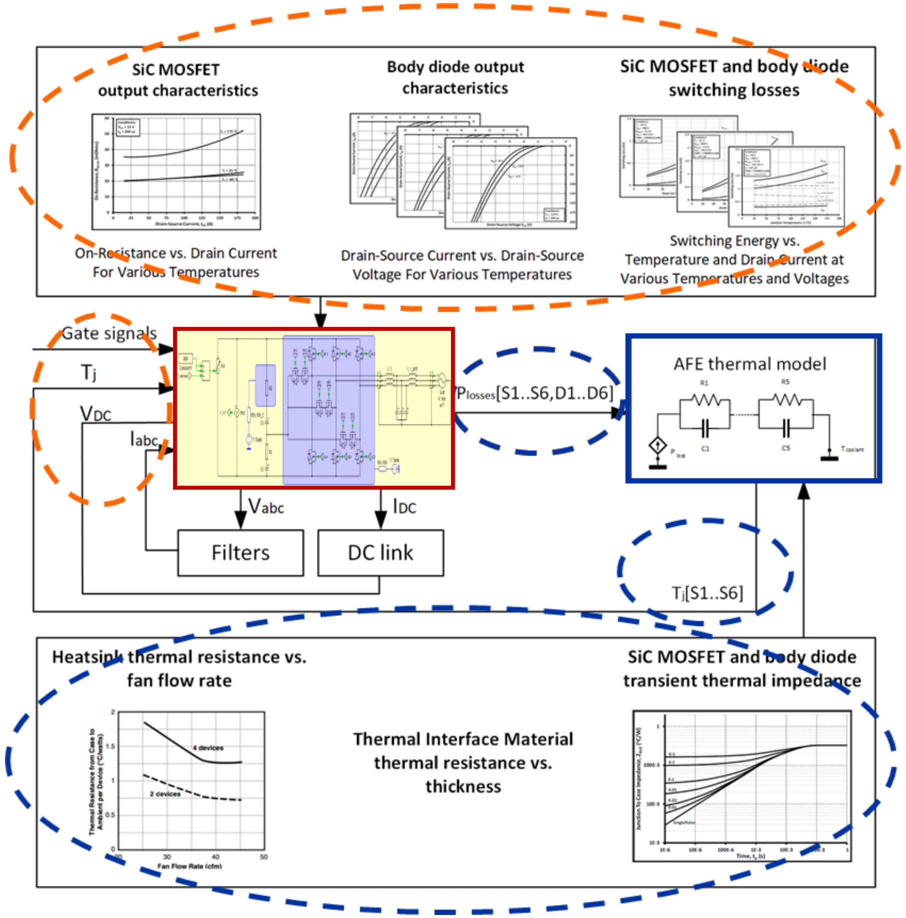


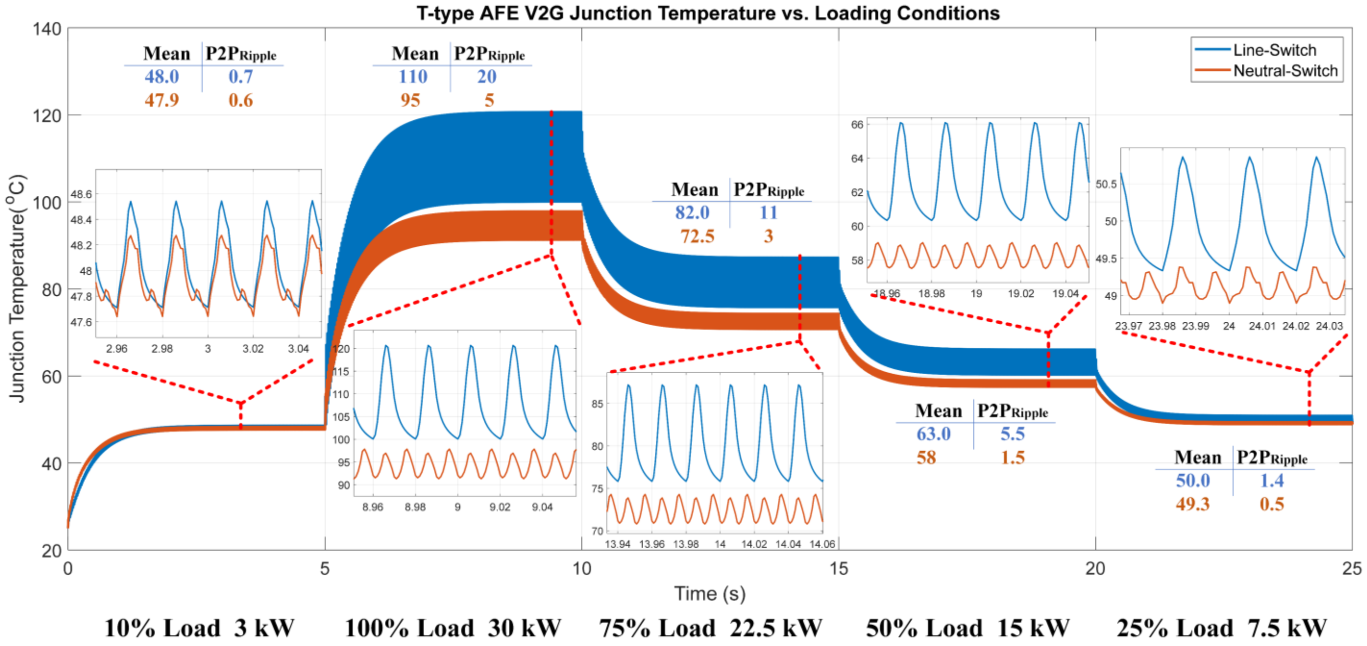
Charging-Profile Definition



Condition	Cabinet Temperature (^{0}C)	Charging cycle description
Critical mission Profile (CMP)	**45**	- 12 minutes CC (30 kW) - 5 minutes CV - 20 minutes of constant discharge (30 kW)
Adjusted Mission Profile (AMP)	**45**	- 12 minutes CC (30 kW) - 5 minutes CV - 10 minutes of constant discharge (30 kW)
Heliox defined Mission Profile (HMP)	**45**	- 12 minutes CC (68% load) - 5 minutes CV - 20 minutes of constant discharge (68% load)

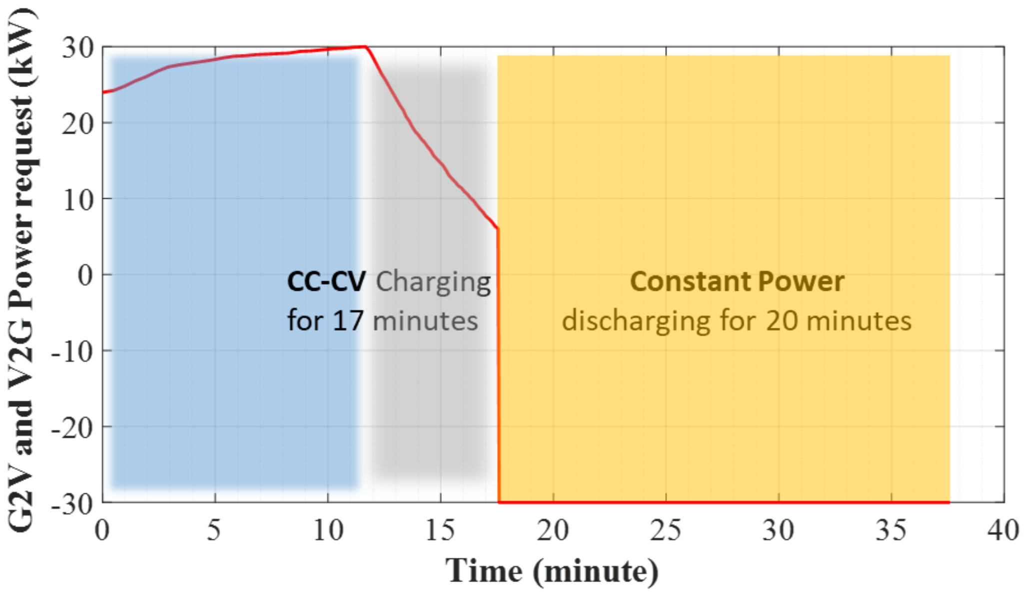
Charging Profile Based Multi-X Simulation

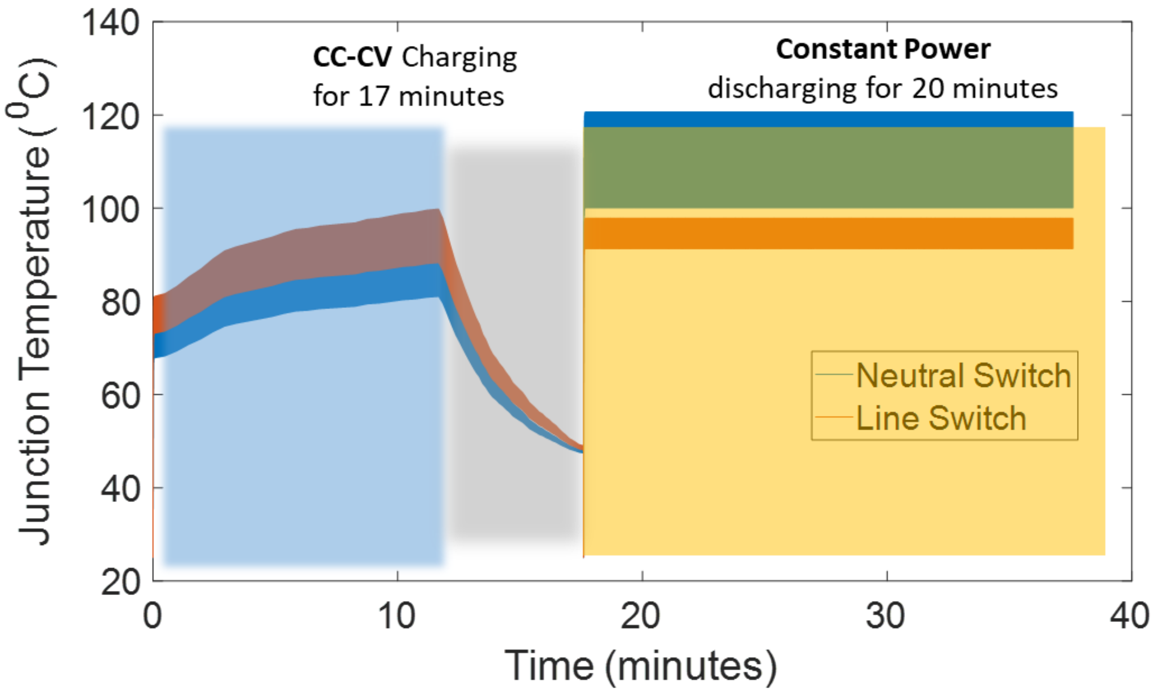




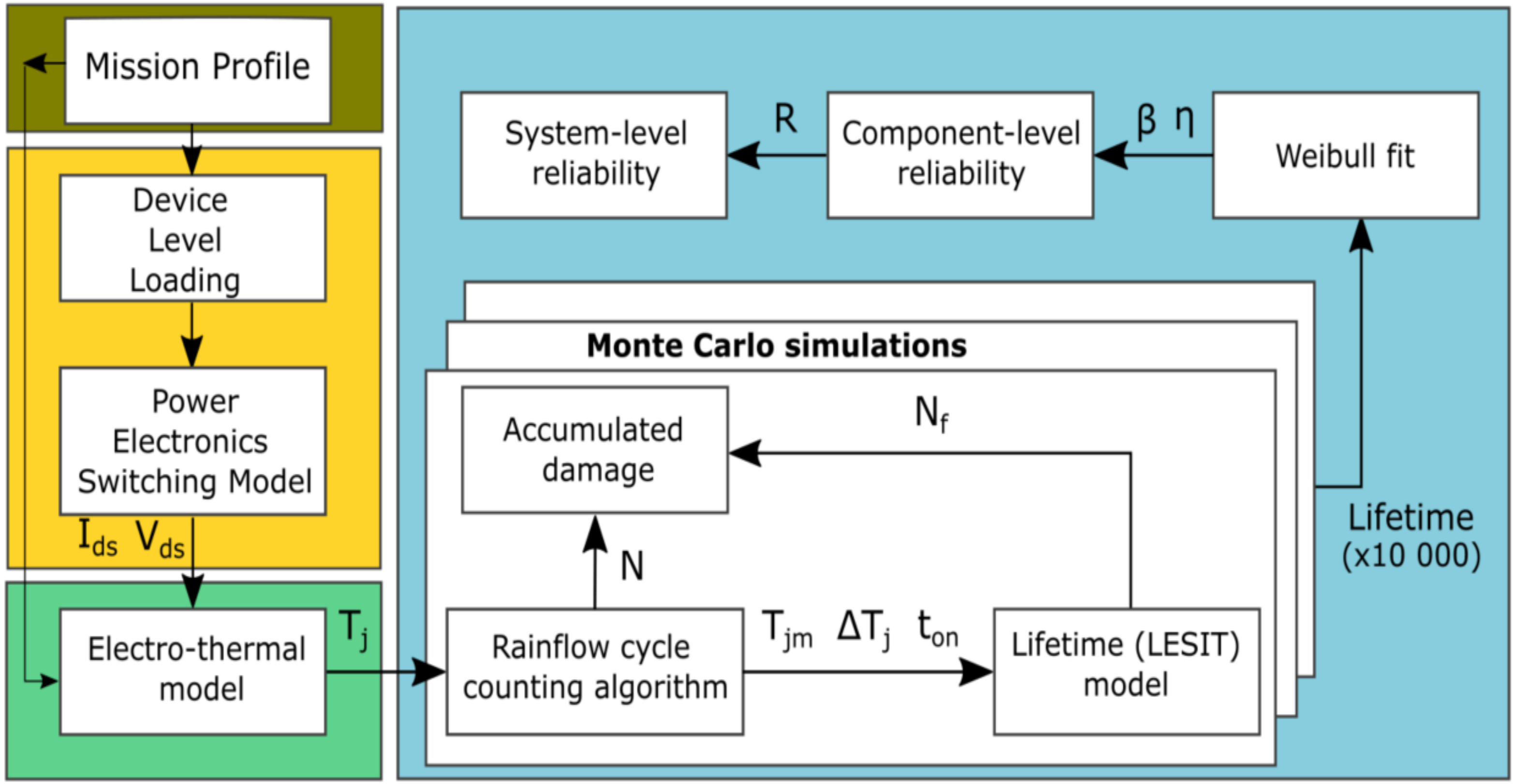
Multi-X Simulation Analysis: Based on detailed Electro-thermal simulation we found that the **Mean Junction Temperature** (Tjmean) and **Junction temperature swings** (ΔTj) are ~ **2.5 times** more aggressive in the **T-type AFE** compared to **DAB** throughout all operating conditions. **Results**→ Hence the Critical DUT is **T-type AFE**

Mission Profile to Thermal Stress Translation





Lifetime Assessment Framework



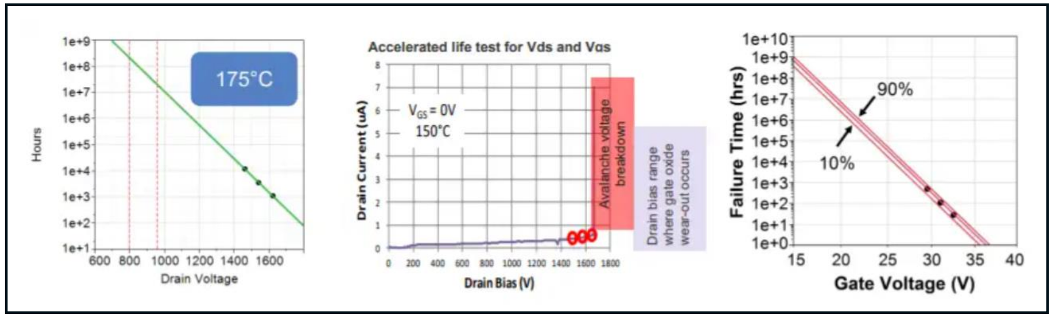
***MREL**: connected Mission profile-oriented RELiability assessment tool*

Source: S. Chakraborty et al., "Real-Life Mission Profile-Oriented Lifetime Estimation of a SiC Interleaved Bidirectional HV DC/DC Converter for Electric Vehicle Drivetrains," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 10, no. 5, pp. 5142-5167

Lifetime Model Parameters

	Parameters	Value	Unit	Experimental condition
SiC MOSFET	$\boldsymbol{A}$	3.4368×10^{14}	-	
	$\boldsymbol{\alpha}$	-4.983	-	$64K \leq \Delta T_j \leq 113K$
	$\boldsymbol{\beta_1}$	-9.012×10^{-3}	-	$0.19 \leq ar \leq 0.42$
	$\boldsymbol{\beta_0}$	-1.942	-	$0.19 \leq ar \leq 0.42$
	$\boldsymbol{C}$	1.434	-	$0.07s \leq t_{ON} \leq 63s$
	$\boldsymbol{\gamma}$	-1.208	-	
	$\boldsymbol{f_{diode}}$	0.6204	-	
	$\boldsymbol{ar}$	0.31	-	
	$\boldsymbol{E_a}$	0.06606	eV	$32.5°C \leq T_{jm} \leq 122°C$
	$\boldsymbol{k_b}$	8.61733×10^{-5}	eV/K	
DC Link Capacitor	$\boldsymbol{L_f}$	*5,000*	hr	*@ 85⁰C*
	$\boldsymbol{T_f}$	*358*	K	-
	$\boldsymbol{V_f}$	*1200*	V	*DC*

According to © 2018 Cree, Inc. the power cycling reliability performance is comparable between discrete SiC and Si devices.



Number of field hours for CREE SiC discrete devices subject to various drain voltages (on the left) and gate voltages (on the right). Drain bias range where avalanche voltage breakdown and gate oxide wear out occurs is far beyond the rated 1,200 V (middle).

Reliability Matrix: target > 150 thousand hour

For lifetime estimation, we consider that the T-Type AFE converter will be subjected to 10 same profiles/day during its entire life cycle, which means daily the charger will operate a minimum of 4 hours 30 minutes and a maximum of 6 hours 10 minutes each day. And the ambient temperature will remain the same at 45^{0}C facilitated by pre-conditioning before each charging cycle.

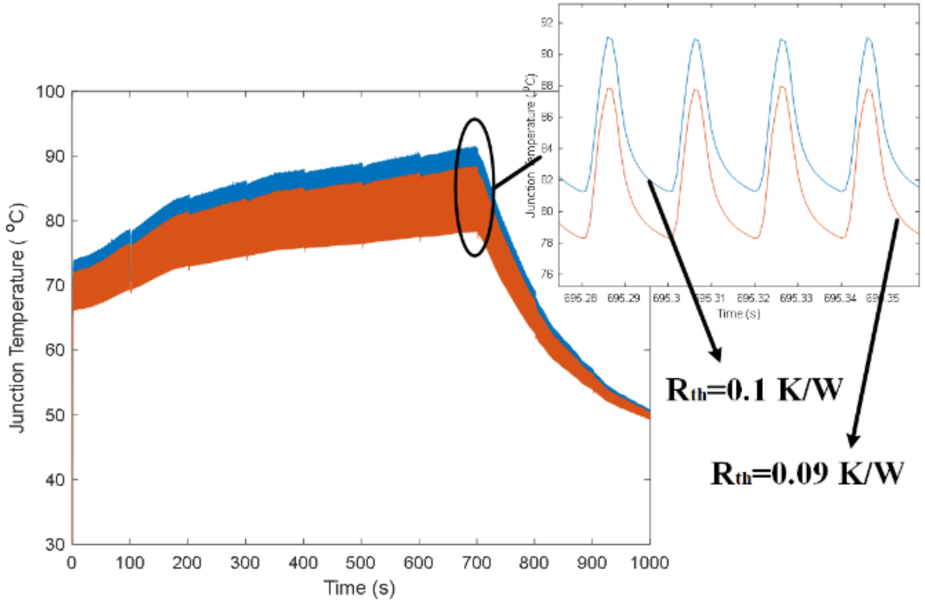
Scenario Condition	Operational cycles/day	MTBF in thousand hours	MTBF in thousand hours With 2% less ΔTj	MTBF in thousand hours With 10% less ΔTj
Critical mission Profile (CMP)	10 cycles Total 6hr 10 min	103 (F)	114 (F)	165 (P)
Adjusted Mission Profile (AMP)	10 cycles Total 4hr 30 min	141 (F)	153 (P)	-
CPO Mission Profile (CpMP)	10 cycles Total 6hr 10 min	380 (P)	-	-

MTBF of the UC4 charging system, P= pass to meet design criteria, F= fail to meet design criteria

Re-optimization to reduce ΔTj by 10%

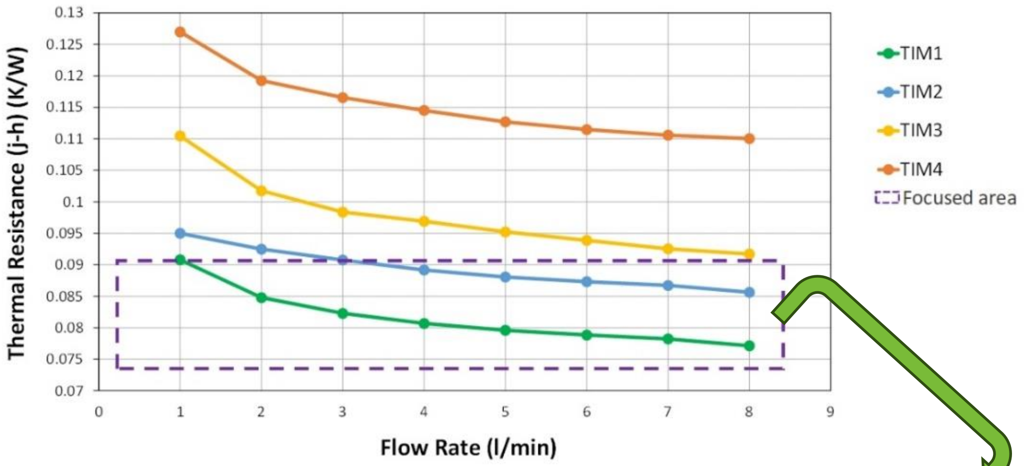
The results from the lifetime study show that to achieve the project KPI of 150khr operation time for **CMP**, junction-to-heatsink resistance should be reduced from 0.1 W/K to 0.09 W/K (10% decrease). This decrease can be achieved by a few methods:

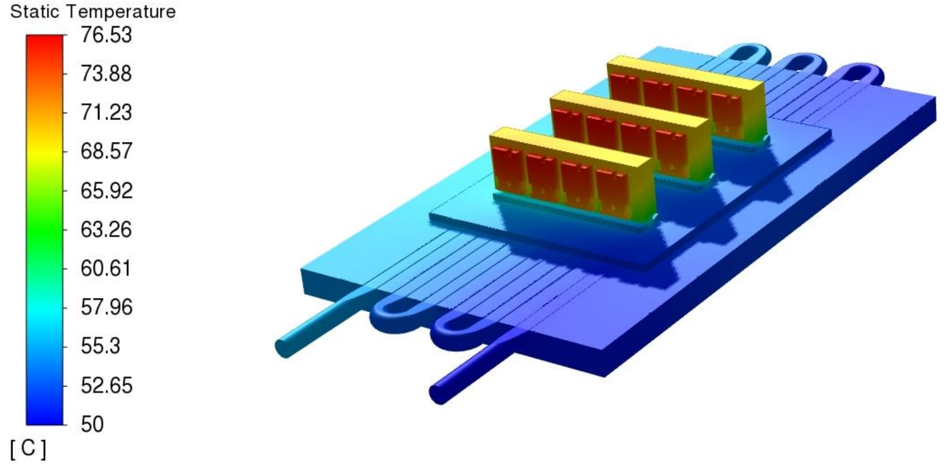
- changing the semiconductors
- using different heatsink materials or changing the thermal design
- changing cooling parameters such as flow rate and coolant temperature
- using thermal interface materials with lower thermal resistance



Design Guide To Match Lifetime KPI

Definition	Product Type	Thickness (mm)	Thermal Properties (W / m K)
TIM1	Ceramic	0.635	200
TIM2	Ceramic	0.635	25
TIM3	Silicone Free Thermal Gap Filler	0.5	10
TIM4	Ceramic	2.03	15





CFD simulation results showing overall temperature distribution with TIM1 at 2L/min at extreme condition

Any design choice under the dotted area fulfill the lifetime criteria

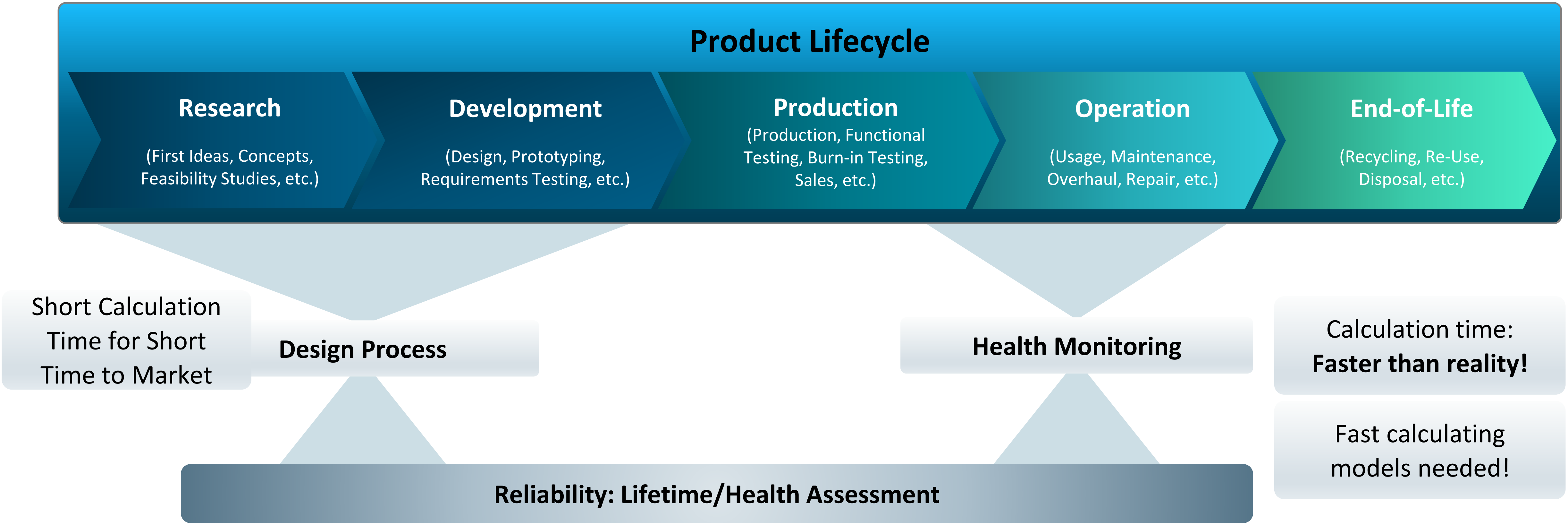
Conclusion

- **WBG Semiconductors** arrived in automotive and charger applications and offer a huge potential for tomorrow's green mobility
- **Optimal Design** to achieve efficiency and cost is not **Enough**!
- **Design for Reliability** is key for the broad application and needs to be considered already in the **design phase**!!

Part II: Application of Deep Physical Modelling for Reliable Designs and Condition Monitoring of Power Electronics

Motivation: Product Lifecycle

Typical processes in the product lifecycle



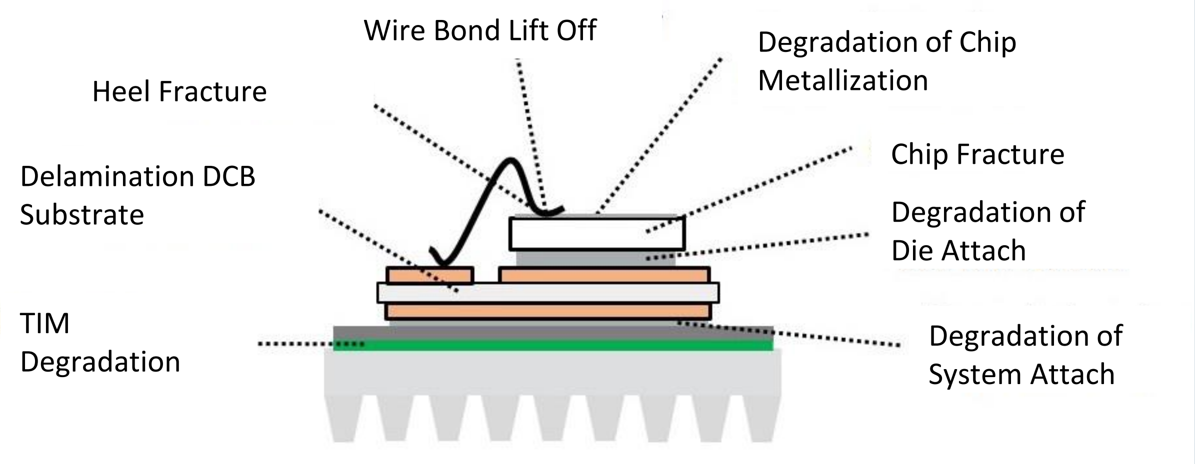
Failure Modes

Failure Cause
In-appropriate design rules and/or material choices, production processes, load condition, harsh environments

Failure Mechanism
Physical, chemical, electrical or other process that results in a failure. It describes how a degradation process preceeds.*

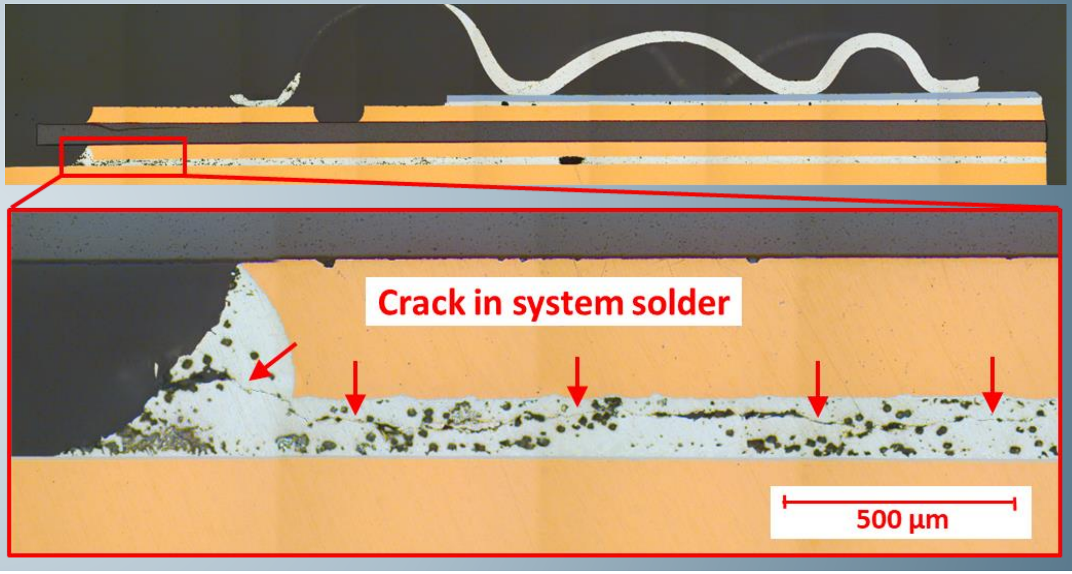
Failure Mode
The effect or manner by which a failure is observed to occur.
It is the effect of the failure mechanism.*

Failure Effect
Deviations of (measurable) device parameters during a test run

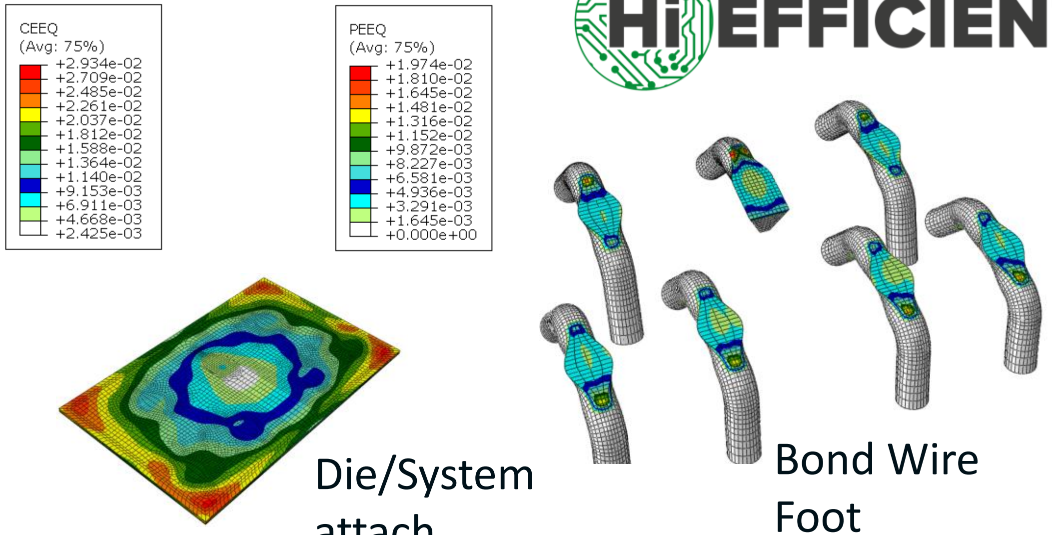


Alexander Otto, Lifetime modeling of discrete power devices under consideration of superimposed power cycling tests, PHD Thesis, TU Chemnitz

Microscopic cross section after TST2 (800 cycles):



Physical Modelling



Die/System attach

Bond Wire Foot

Load → FEM

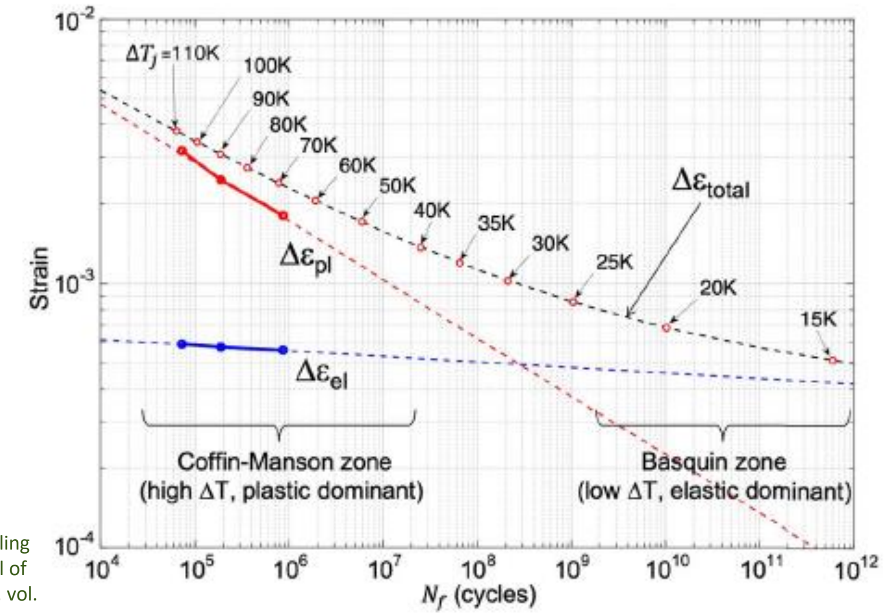
I, f, T, …

$$\varepsilon_a = \varepsilon_a^{pl} + \varepsilon_a^{el} = \varepsilon_f'(2N_f)^c + \left(\sigma_f'/_E\right)(2N_f)^b$$

Coffin-Manson — Basquin

“low cycle fatigue” term for evaluation of fatigue which is controlled by plastic (creep) deformation

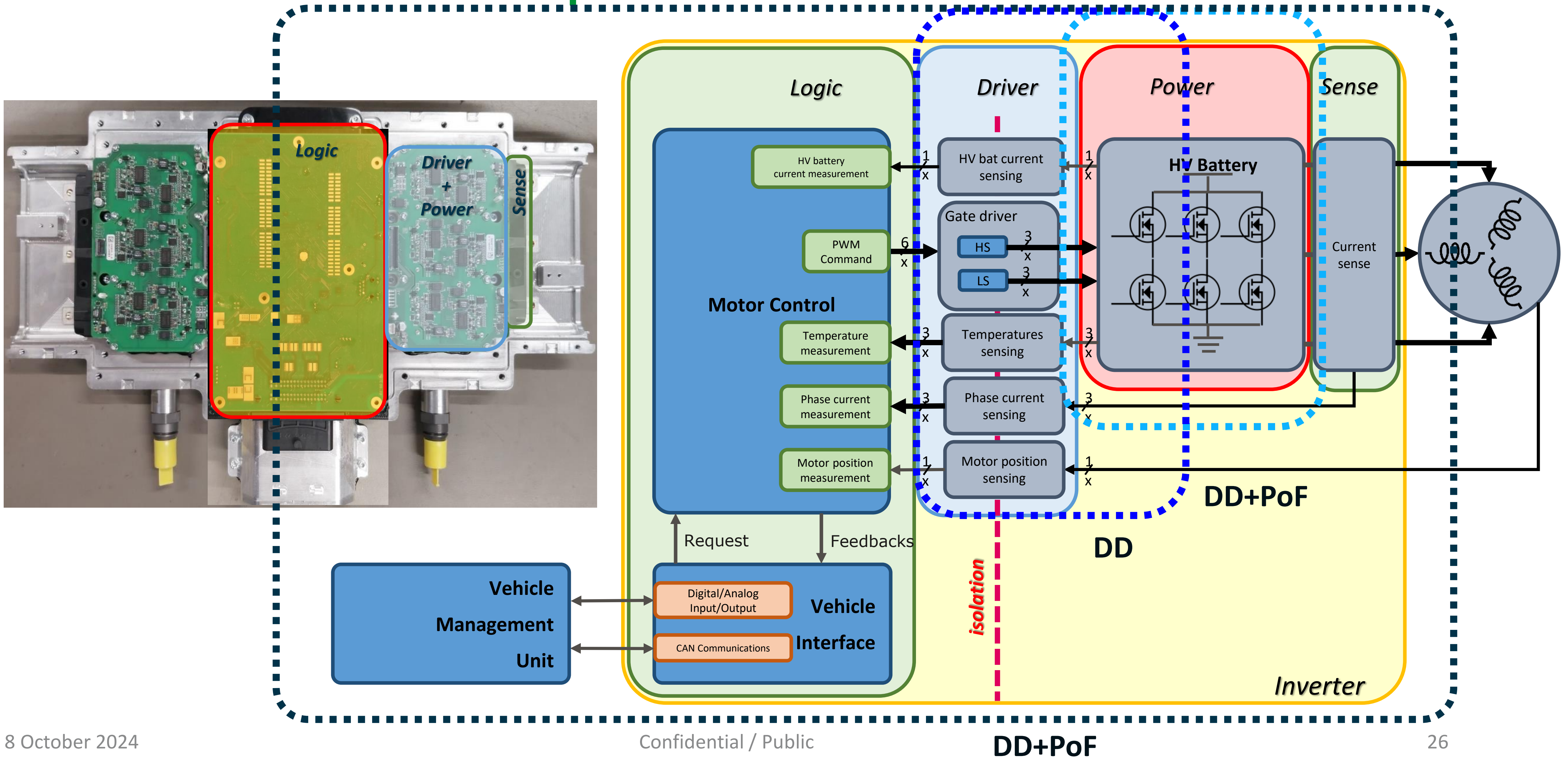
“high cycle fatigue” term for evaluation of fatigue which is controlled by elastic deformation



N. Dornic et al., "Stress-Based Model for Lifetime Estimation of Bond Wire Contacts Using Power Cycling Tests and Finite-Element Modeling," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 7, no. 3, pp. 1659-1667, Sept. 2019, doi: 10.1109/JESTPE.2019.2918941.

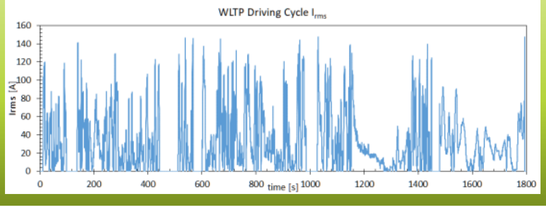
N_f	mean cycles to
σ_f'	the cyclic stress amplitude (can be replaced by elastic strain amplitude)
ε_a^{pl}	cyclic plastic strain amplitude
ε_a^{el}	cyclic elastic strain amplitude

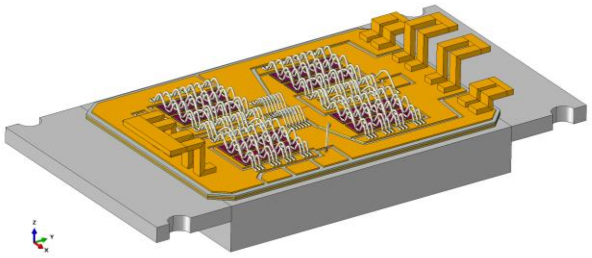
UC2 Multidrive e-powertrain

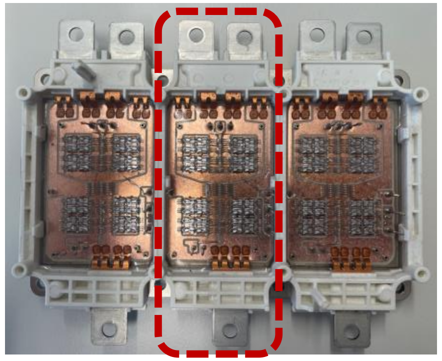


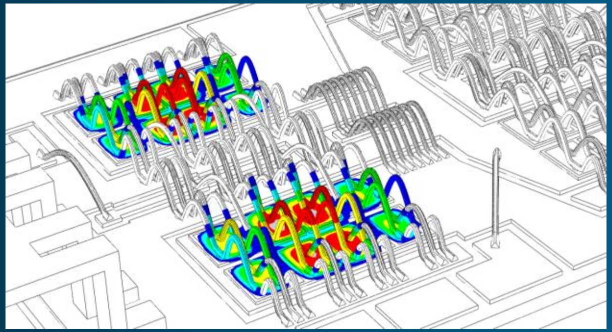
Framework: FEM

Load Case Scenario
Standard test profile
Mission profile

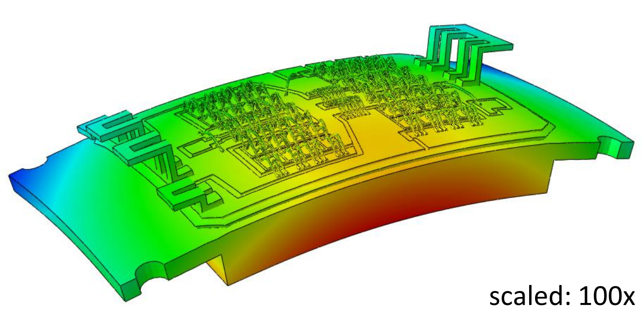




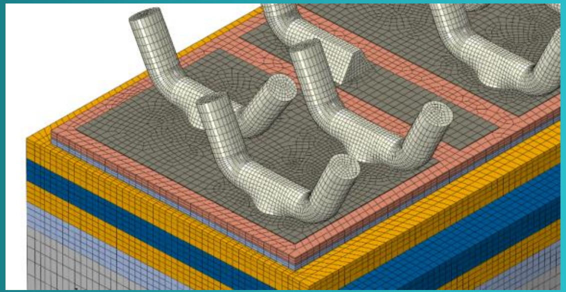




Electric-Thermal Simulation
- Electrostatic analysis



Global Thermal-Mechanical Simulation
- Mechanical behaviour for validation (warpage)

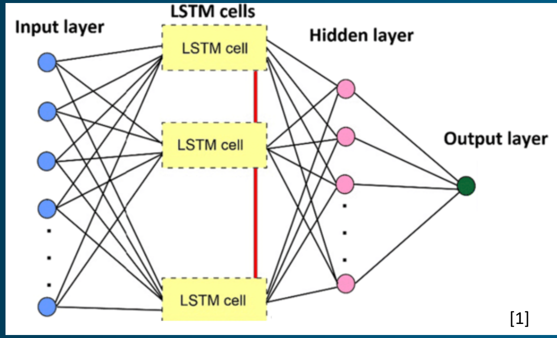


Local Thermal-Mechanical Simulation
- Mechanical stress and strain

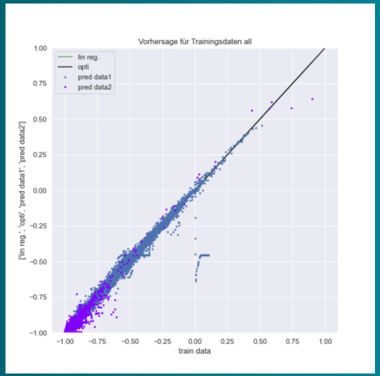
Creating virtual training data by means of validated electro-thermo-mechanical simulation models

Framework: Surrogate Model

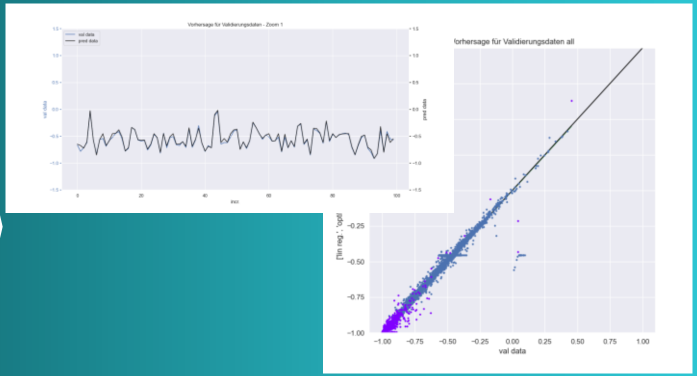
Virtual training



Surrogate Model
- LSTM, MOP



Train Surrogate Model

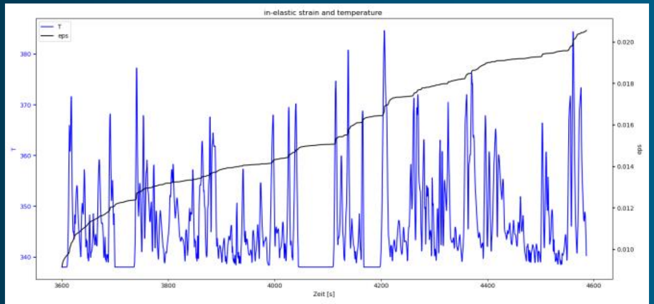


Model Verification

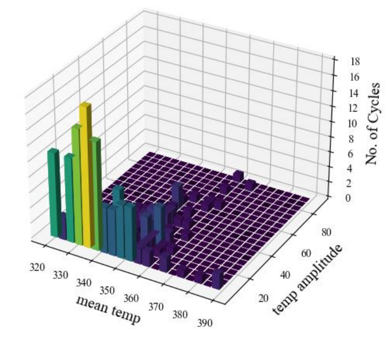
Verified Model

Framework: Health State Assessment

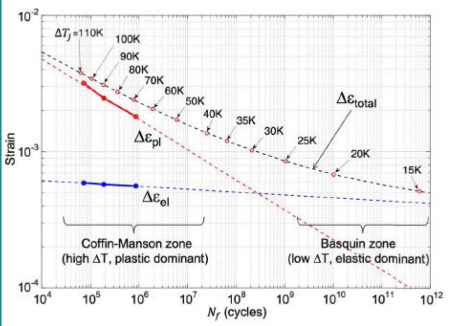
Verified Model



Application on field data
- LSTM, MOP



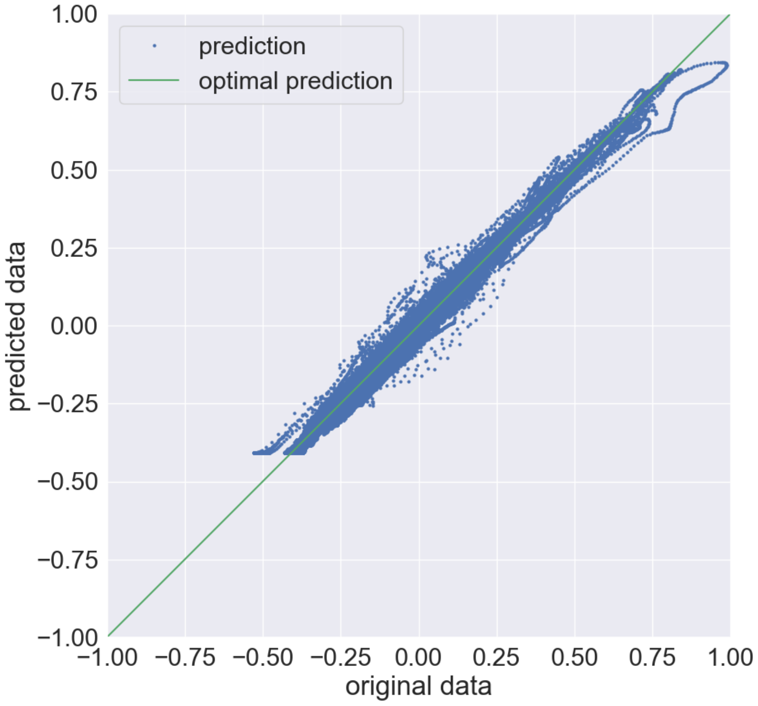
Rainflow Counting
- Allocate stress to cycles



Damage Assessment
- Coffin-Manson lifetime model

Health State Assessment

Surrogate Model: T

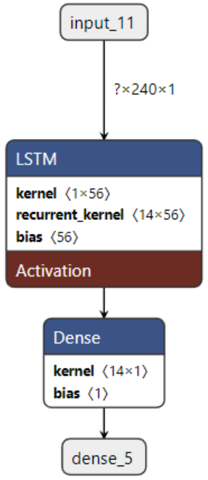


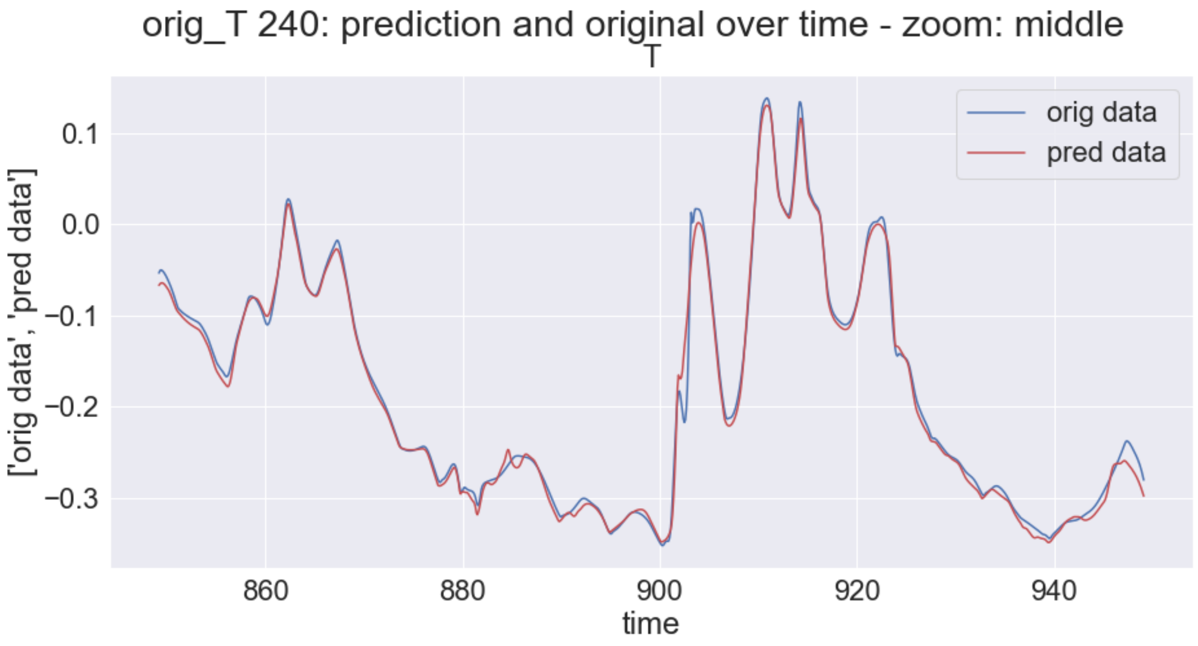

```
Datensatz: all
MSE: 0.0736 %
MAE: 1.6617 %
mean: 0.4042 %
std: 2.6824 %
```

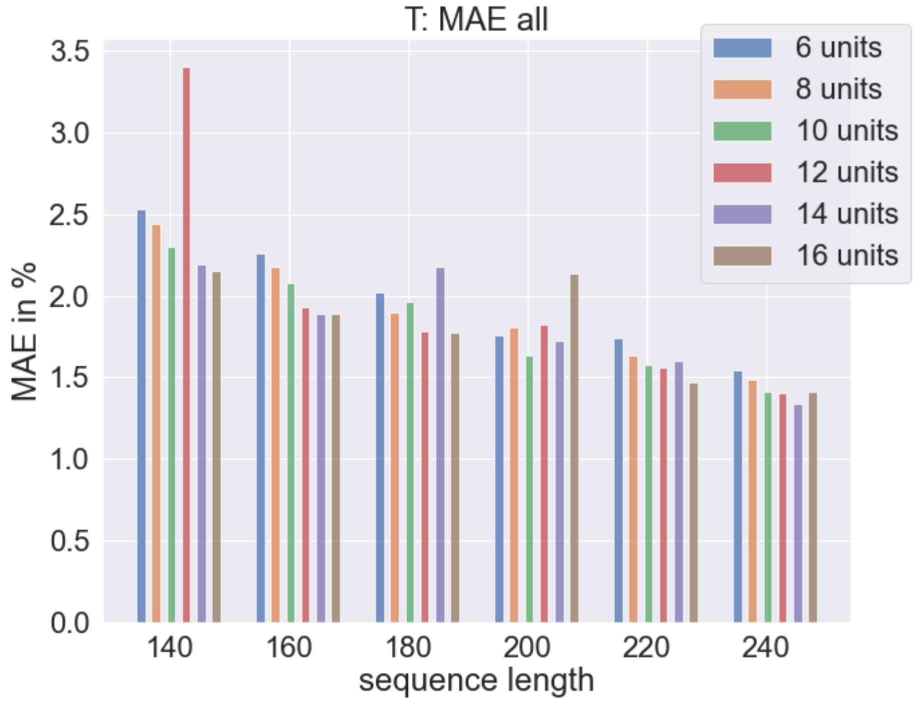
$I \Rightarrow T$

14 units, 1 layer,
150 epochs training

$seq_{len} = 240$

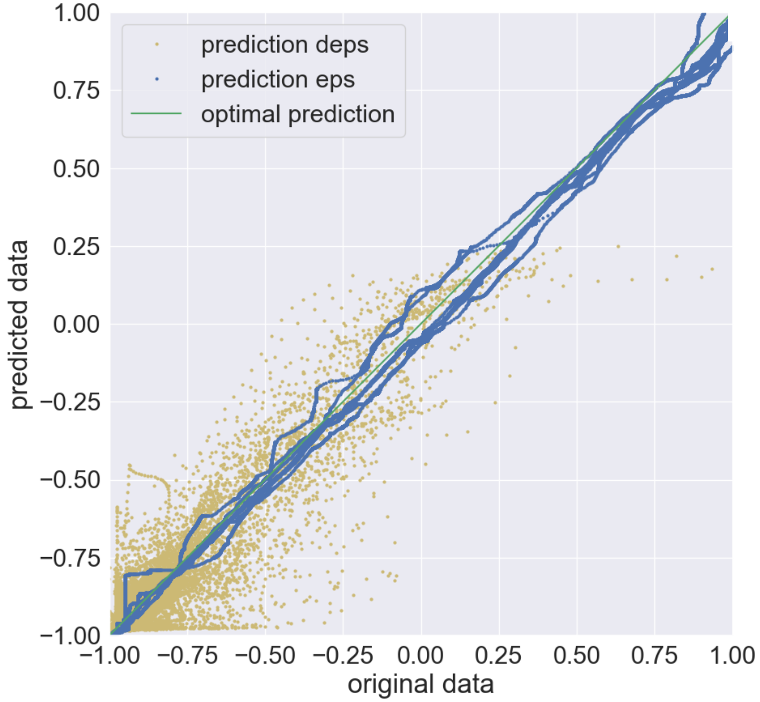






T. Horn et. al, "Influence of reducing the load level of mission profiles on the remaining useful life of a TO220 analyzed with a surrogate model", PHM Society European Conference. Vol. 8. No. 1. 2024 https://doi.org/10.36001/phme.2024.v8i1.3979

Surrogate Model: Creep



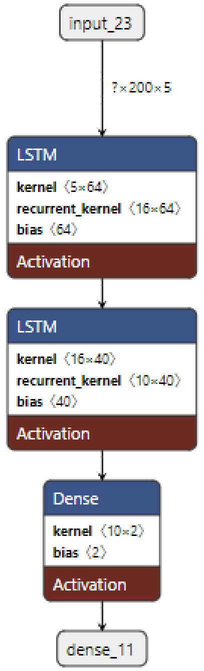

```
Datensatz: all
MSE: 0.2733 %
MAE: 4.1237 %
mean: -2.7570 %
std: 4.4422 %
```

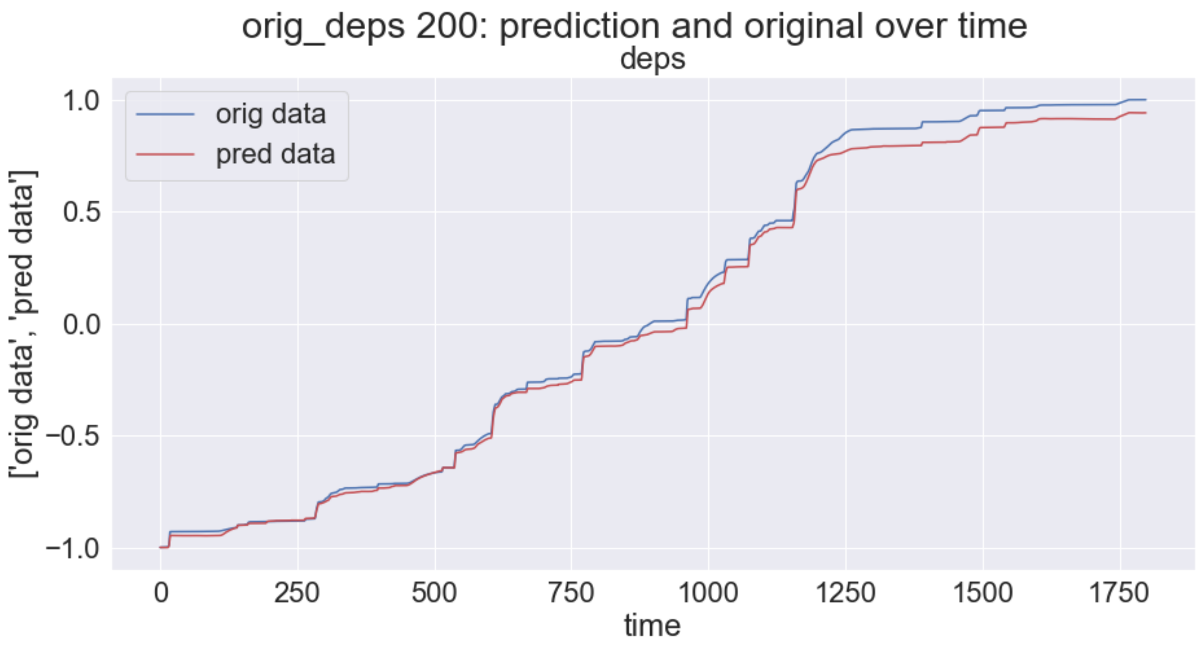
$$I, \frac{dI}{dt}, \frac{d^2I}{dt^2}, T, \frac{dT}{dt} \Rightarrow \sigma, \frac{d\varepsilon^{cr}}{dt}$$

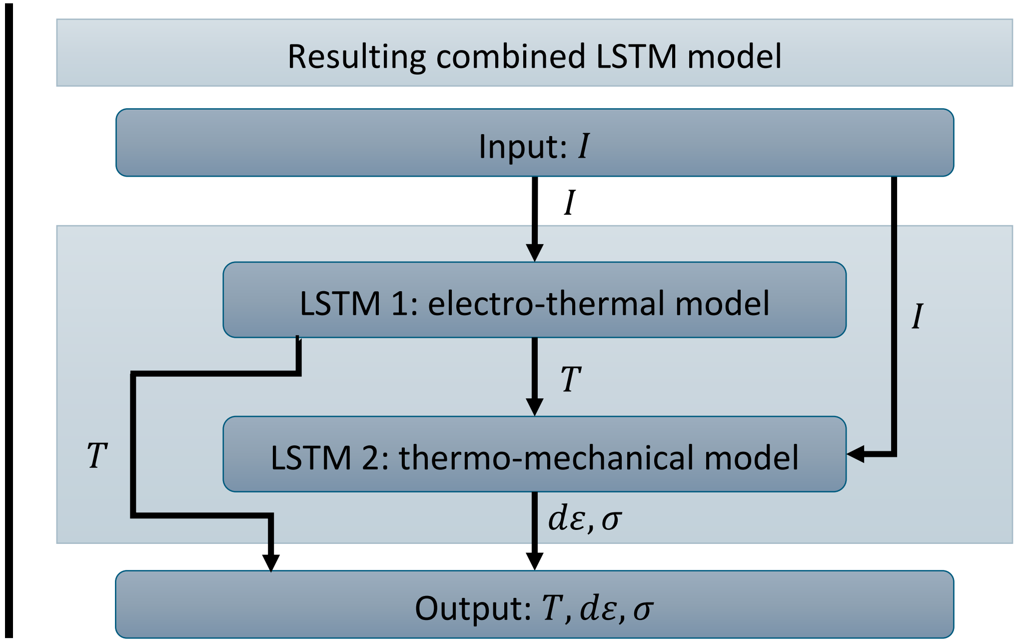
16 units, 10 units

150 epochs training

$seq_{len} = 200$







1800s load

~20s
calculation
time

HiEFFICIENT

Framework

FE simulation model: creation + validation

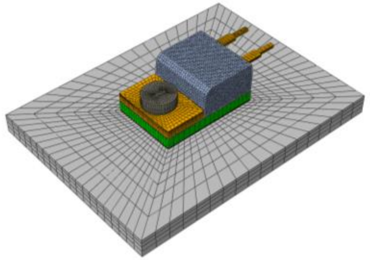
Creating training data: FE simulations

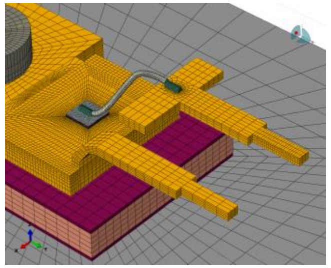
Training the model

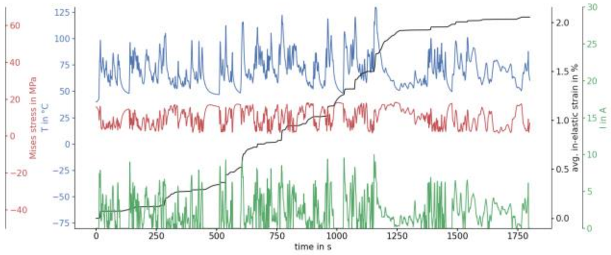
Rainflow counting and calculation of SoH

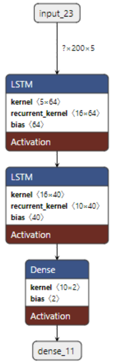
Application

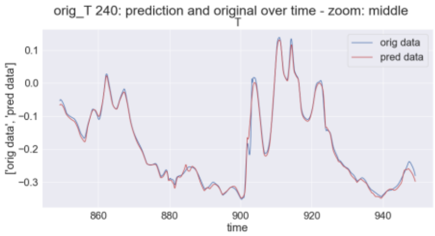
Rectifier: TO220

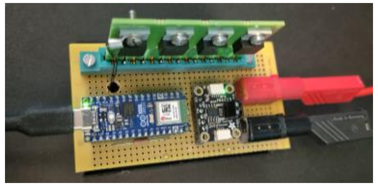


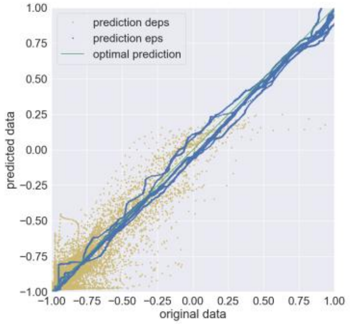






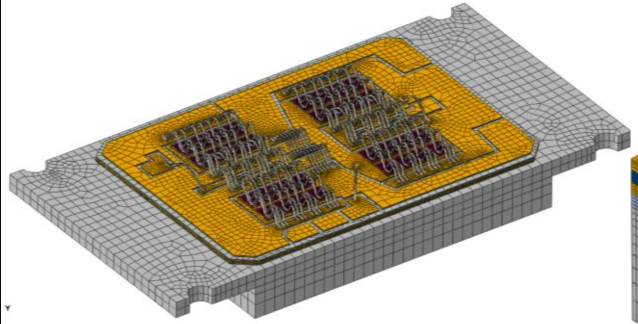


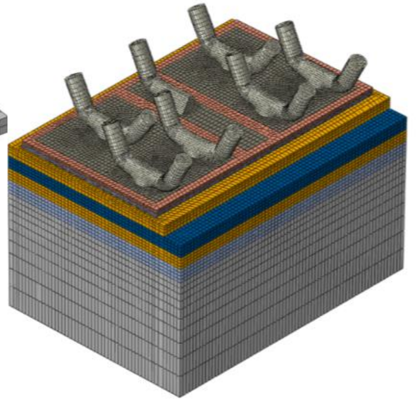


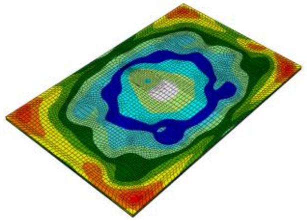


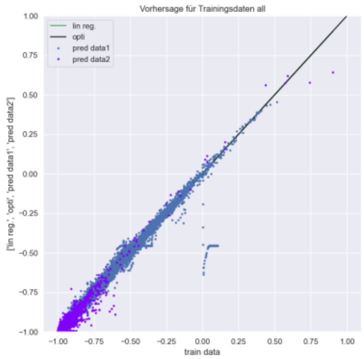
J. Albrecht, T. Horn, S. Habenicht and S. Rzepka, "Mission Profile related Design for Reliability for Power Electronics based on Finite Element Simulation," 2023 IEEE 25th Electronics Packaging Technology Conference (EPTC), Singapore, 2023, pp. 722-726, doi: 10.1109/EPTC59621.2023.10457766.

Module: FS03





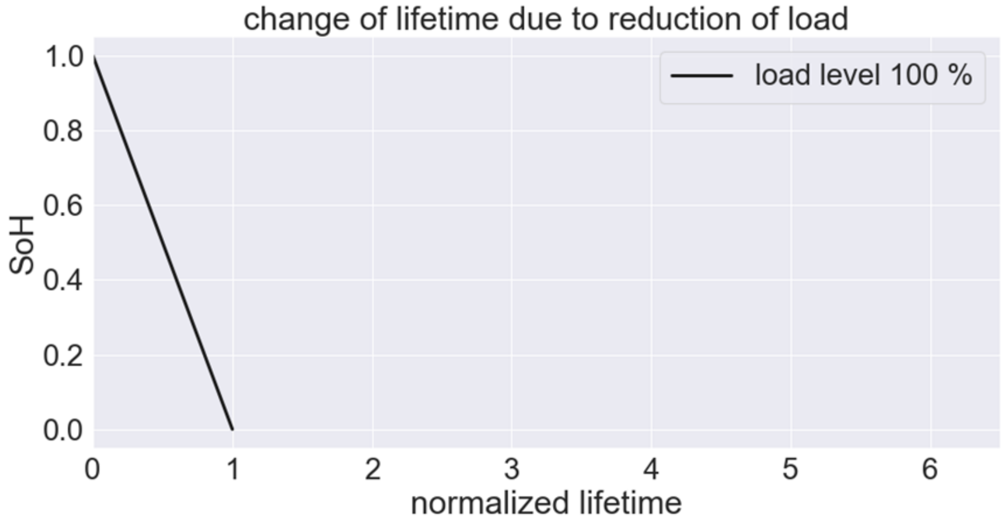


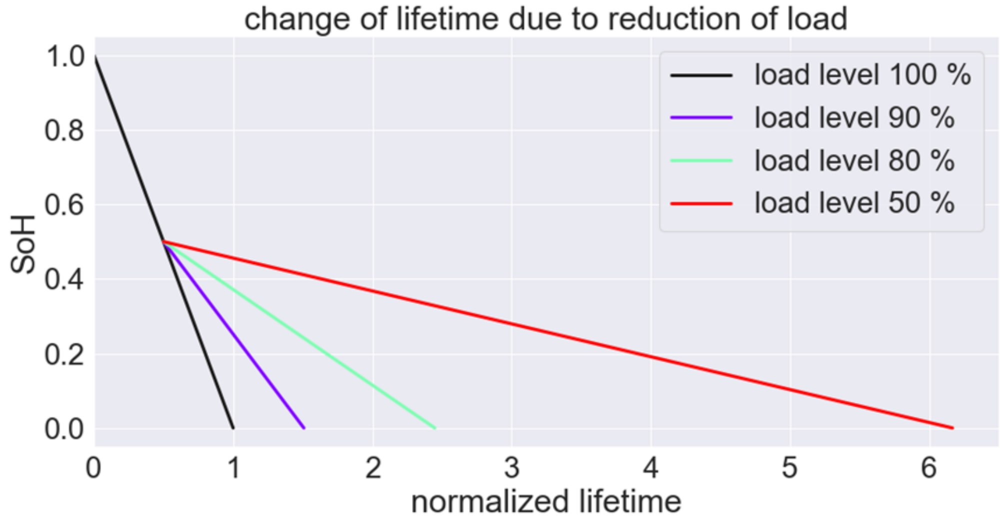


Functional Mock-up Interface

T. Horn et. al, "Influence of reducing the load level of mission profiles on the remaining useful life of a TO220 analyzed with a surrogate model", PHM Society European Conference. Vol. 8. No. 1. 2024, https://doi.org/10.36001/phme.2024.v8i1.3979

State of Health and Life-Time Estimation



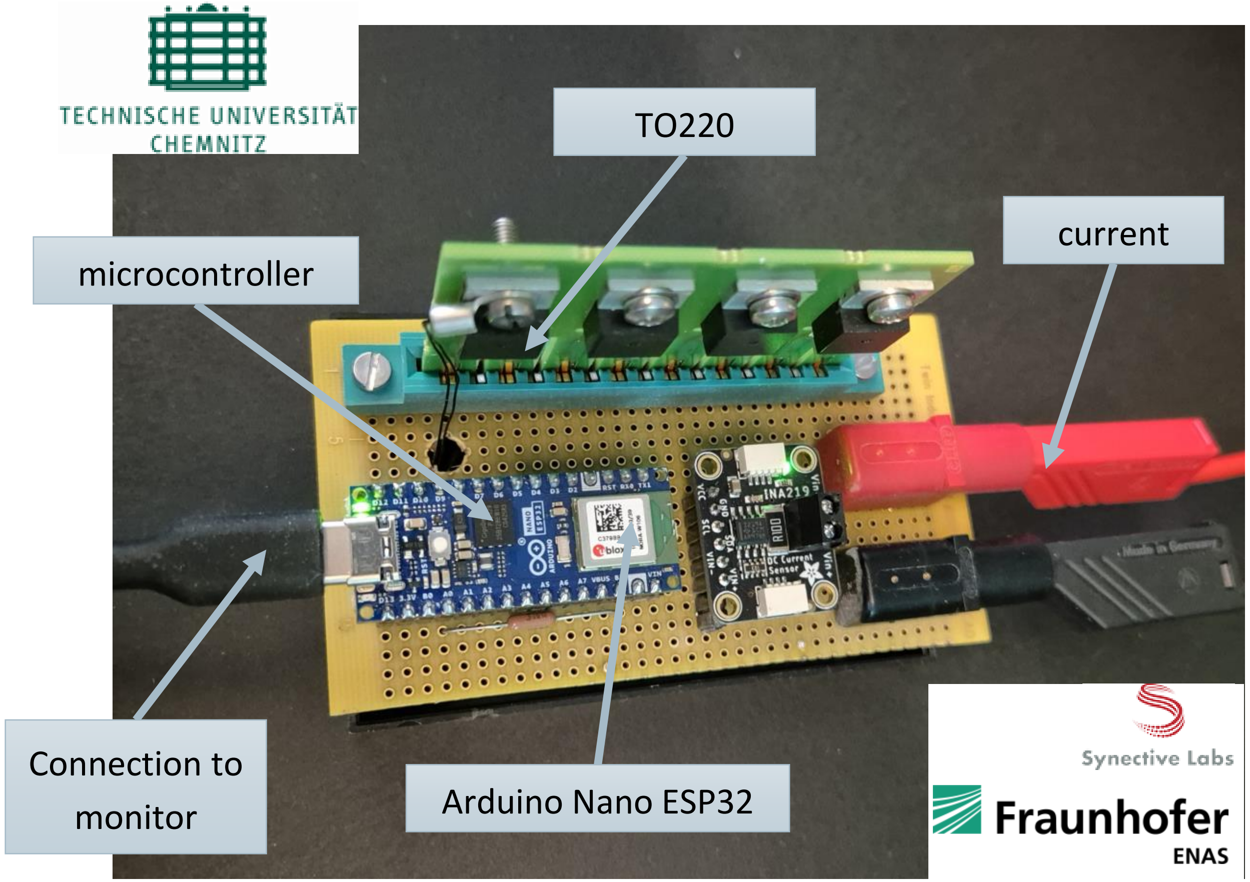


Lifetime extension by reducing the level of stress based on an a priori assessment of the state of health

T. Horn et. al, "Influence of reducing the load level of mission profiles on the remaining useful life of a TO220 analyzed with a surrogate model", PHM Society European Conference. Vol. 8. No. 1. 2024, https://doi.org/10.36001/phme.2024.v8i1.3979

Applications

LSTM model is running on a microcontroller

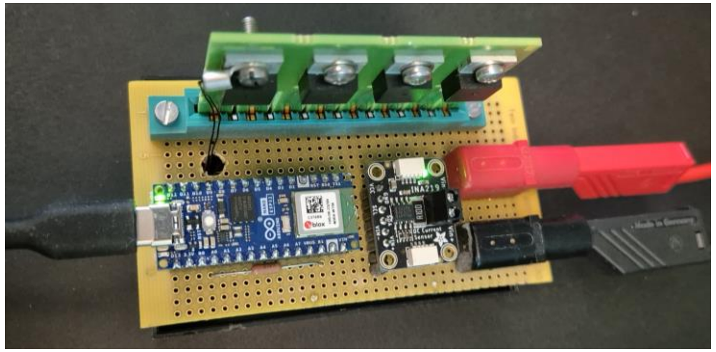


LSTM model is implemented in a .fmu

- Implementation possible in system simulations
- Every program which can read .fmu can use the LSTM model and the SoH calculation

Conclusion and Outlook Part II

- Reduction of the computation time for 1 WLTP (1800s) **from 2x ~1d to 2x ~10s** (for TO220)
- Reduction of the computation time for 1 WLTP (1800s) **from 3x ~1w to 2x ~12s** (for FS03)
- The framework can also be applied to other components and modules
- The calculation is significantly faster than real time
  → It is possible to perform load variation calculations in time
- Application:
  - Condition Monitoring: implementation on microcontroller
  - System simulation: implementation in a .fmu (also .exe possible)



To be done:

- Application to other failure modes
- Including feedback loops in order to cover influence of increasing failure
- Reduction of the required data points in the training data while maintaining good prediction quality
- Comparison of different network structures with regard to prediction quality
- Covering multiple failure modes within one model

Picture source: https://de.m.wikipedia.org/wiki/Datei:Under_construction_icon-yellow.svg

Conclusion

- WBG Semiconductors arrived in automotive and charger applications and offer a huge potential for tomorrow's green mobility
- Optimal Design to achieve efficiency and cost is not Enough
- Design for Reliability is key for the broad application and needs to be considered already in the design phase
- Another key is the trustworthiness of power electronics, which can be achieved through DfR and condition monitoring

HiEFFICIENT contributed with novel frameworks for Design for Reliability (DfR) and Condition Monitoring of power devices/systems

End of Presentation – www.HiEFFICIENT.eu