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Machine Learning and Digital Twins for RUL Prediction of DC Semiconductor Circuit Breakers

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Machine Learning and Digital Twins for RUL Prediction of DC Circuit Breakers

Outline

- Motivation
- Digital Twin Framework
- RUL Prediction MOSFET Reference Dataset
- Demonstrator Setup
- Conclusion and Outlook

Motivation

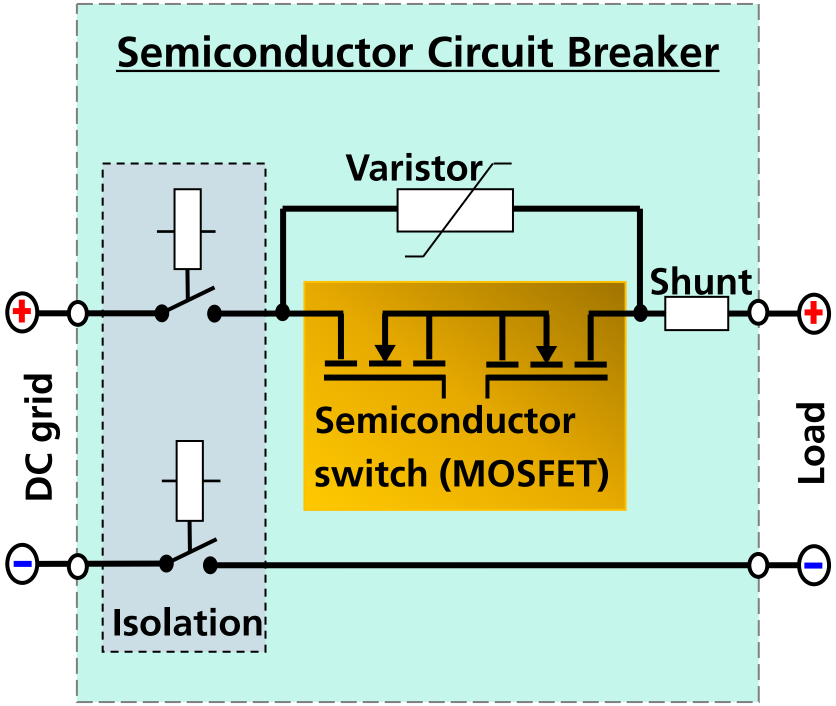
Need for RUL Prediction of DC Semiconductor Circuit Breakers

- DC Networks
  - Increasingly utilized for e.g., integrating renewable energy.

- DC Circuit Breakers
  - Requirements: Interrupt DC currents without zero-crossing in short times.
  - Types: Mechanical, Semiconductor (SCCB) and Hybrid.
  - SCCBs interrupt currents in a range of microseconds.

- Challenges
  - High currents / voltages and harsh environmental conditions stress especially the semiconductor modules of the SCCBs.

Electric schematic of a DC semiconductor circuit breaker



Remaining Useful Life (RUL) prediction of SCCBs is essential for reliable operation and efficient usage.

Motivation

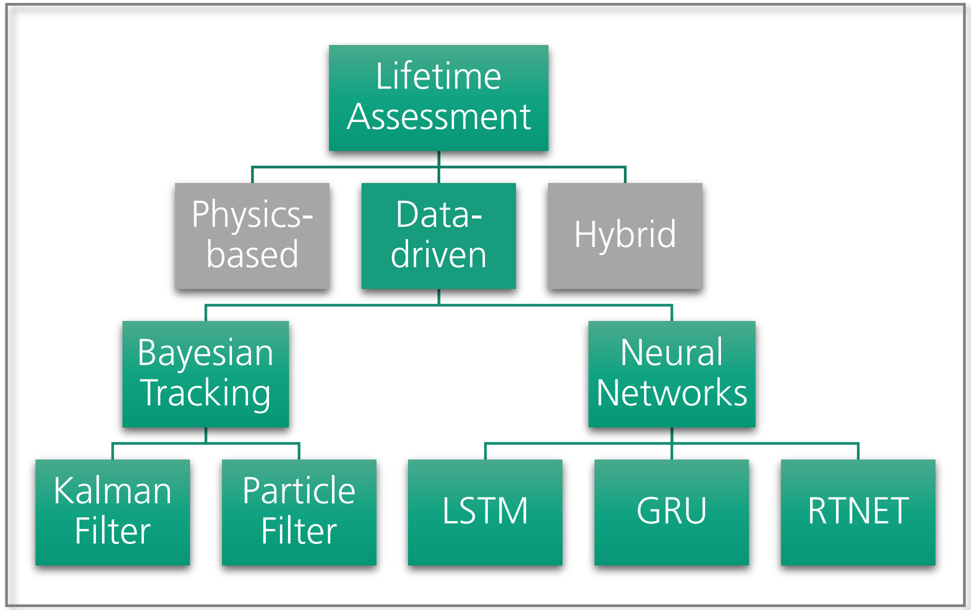
Lifetime Assessment of DC SCCBs

- Lifetime assessment in power electronics
  - Long history and high research interest.
  - In contrast to power converters: less research activity for SCCBs but transfer of methods possible.

- Lifetime assessment methods
  - Physics-based
  - Data-driven
  - Hybrid

- Focus of this work
  - Data-driven RUL prediction of the semiconductor module through forecasting a degradation indicator.

Overview of lifetime assessment methods



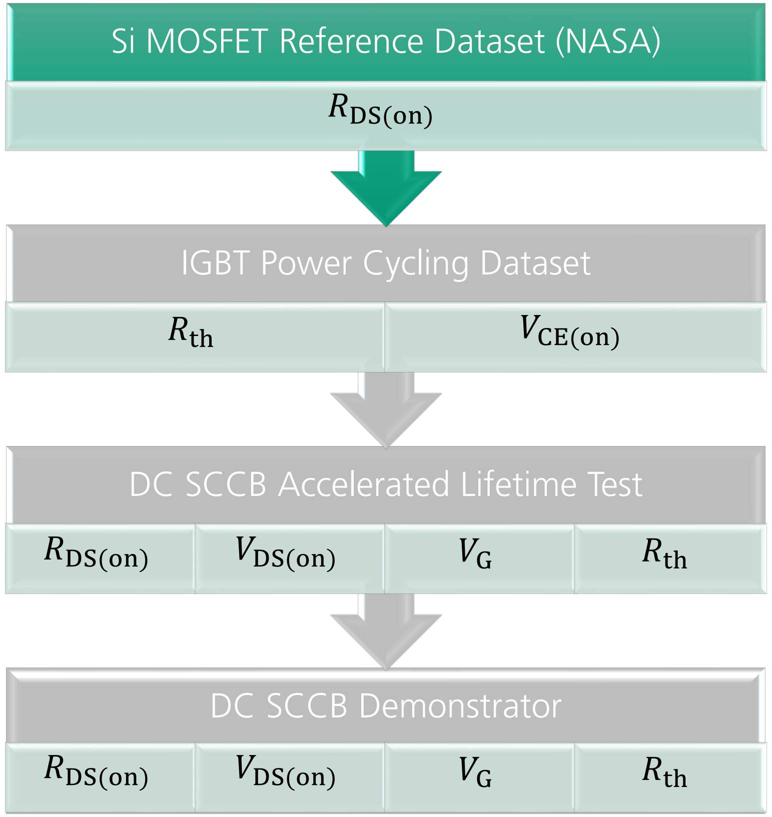
Digital Twin Framework

Approach

- Develop a digital twin framework for
  - Degradation indicator-based RUL prediction according to sensor measurements.
  - Application in lifetime tests, real-word industrial applications, and research on devices.

- Requirements
  - Continuous tracking of multiple degradation indicators.
  - Integration of historical and real-time data.
  - Providing digital services to support predictive maintenance.

Overview of data sources for the training of RUL prediction models



Si MOSFET Reference Dataset (NASA)

$R_{\mathrm{DS(on)}}$

IGBT Power Cycling Dataset

R_{th} | $V_{\mathrm{CE(on)}}$

DC SCCB Accelerated Lifetime Test

$R_{\mathrm{DS(on)}}$ | $V_{\mathrm{DS(on)}}$ | V_{G} | R_{th}

DC SCCB Demonstrator

$R_{\mathrm{DS(on)}}$ | $V_{\mathrm{DS(on)}}$ | V_{G} | R_{th}

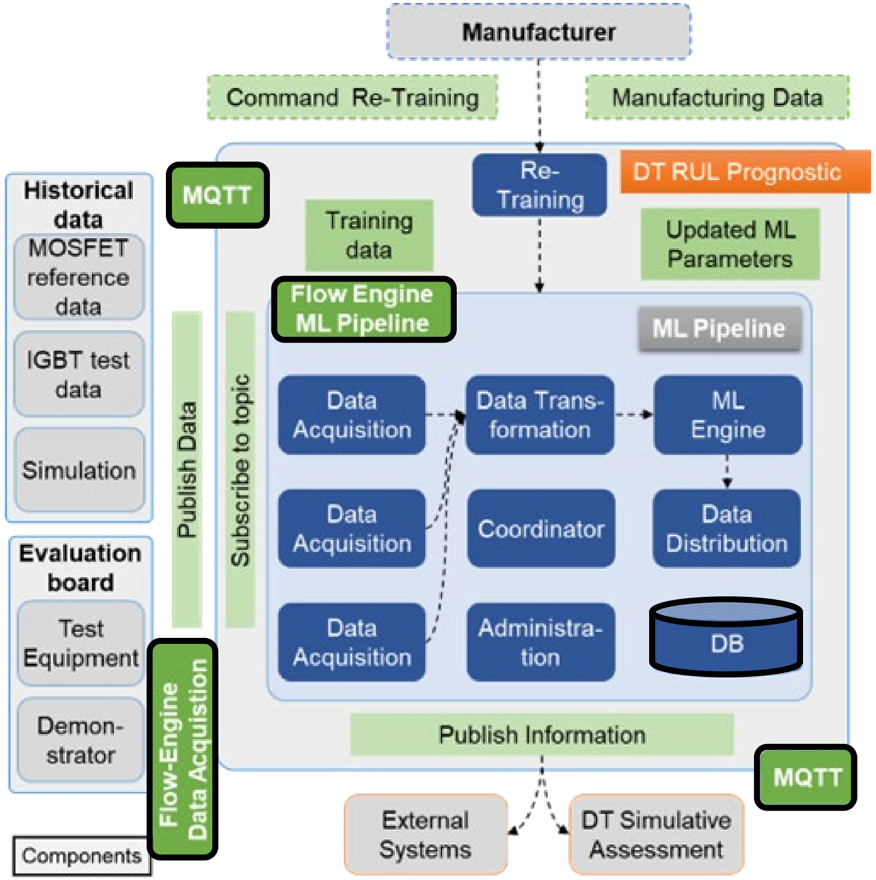
Digital Twin Framework

Architecture and Components

- Architecture
  - Design for seamless integration of different data sources.
  - Distributed edge-cloud architecture to monitor degradation indicators of multiple SCCBs during real-time operation across various production sites.

- Key components
  - Flow engines: data acquisition and ML pipeline.
  - MQTT broker: data transmission and return of results.
  - Central database (DB): stores data, models, and model parameters.

Digital twin architecture including main components and interfaces for data transformation and ML pipeline



Digital Twin Framework

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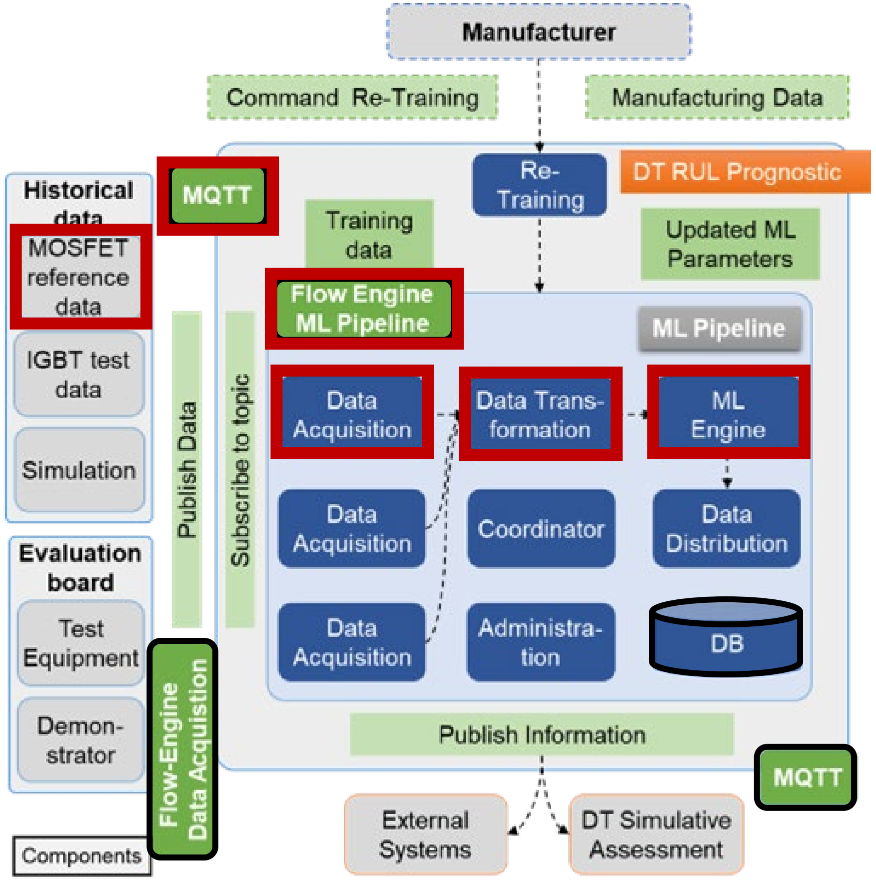
□ Components base implementation

Digital twin architecture including main components and interfaces for data transformation and ML pipeline



RUL Prediction for a MOSFET Reference Dataset

Dataset and Data Transformation

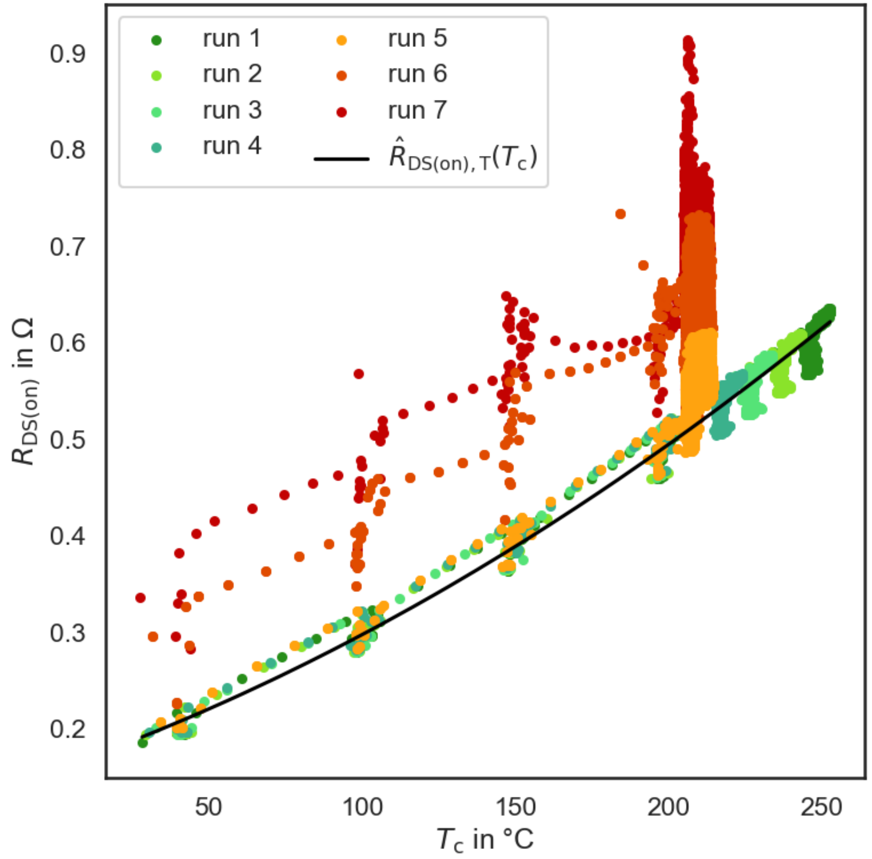
- MOSFET Reference Dataset
  - NASA's Prognostics Data Repository.
  - Thermal and power cycling of Si MOSFETs.
  - 42 different IRF520Npbf MOSFETs in a TO-220 package.
  - $R_{\mathrm{DS(on)}}$ as degradation indicator.
- Data transformation: Normalization of $R_{\mathrm{DS(on)}}$
  - Temperature and degradation dependent.
  - Temperature dependency as quadratic relationship:

$$\hat{R}_{\mathrm{DS(on)},\,T} = a \cdot T^2 + b \cdot T + c. \qquad (1)$$

  - Normalization according case temperature:

$$R_{\mathrm{DS(on),norm},k} = R_{\mathrm{DS(on)},k} - \hat{R}_{\mathrm{DS(on)},\,T,\,k}. \qquad (2)$$

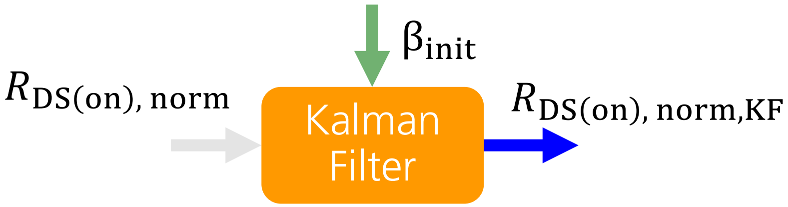
$\mathrm{R_{DS(on)}}$ vs temperature for run 1-7 of device 9



RUL Prediction for a MOSFET Reference Dataset

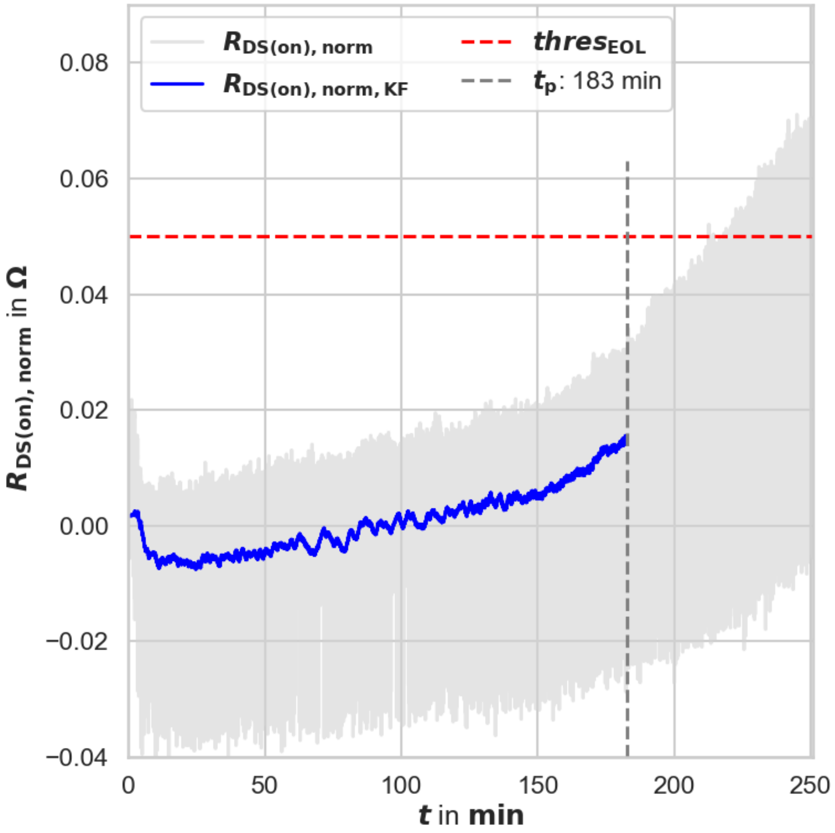
Implementation of RUL Algorithm

- Exponential degradation model + Kalman filter to forecast $R_{\mathrm{DS(on),norm}}$.
  - $R_{\mathrm{DS(on),\,norm}}(t) = \alpha \cdot e^{(\beta \cdot t)}$ (3)
  - $R_{\mathrm{DS(on),\,norm},\,k+1} = \underbrace{(1 + \beta \cdot \Delta t)}_{\text{state matrix } F} \cdot R_{\mathrm{DS(on),\,norm},\,k}$ (4)



- KF predict step: $x_{\mathrm{pred},\,k} = F_k x_{\mathrm{KF},k-1} + \cancelto{0}{B_k} u_k$ (5)
- KF correct step: $x_{\mathrm{KF},\,k} = x_{\mathrm{pred},k} + K_k\left(z_k - H x_{\mathrm{pred},\,k}\right)$ (6)
  - $x_{\mathrm{KF},\,k} = R_{\mathrm{DS(on),\,norm,\,KF},\,k}$
  - $z_k = R_{\mathrm{DS(on),\,norm},\,k}$

Kalman filter estimates $R_{\mathrm{DS(on),norm,\,KF}}$ until t_{p}



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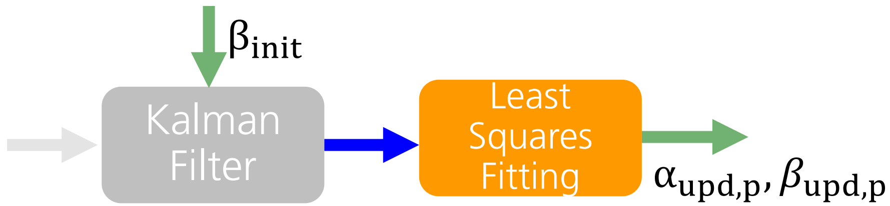
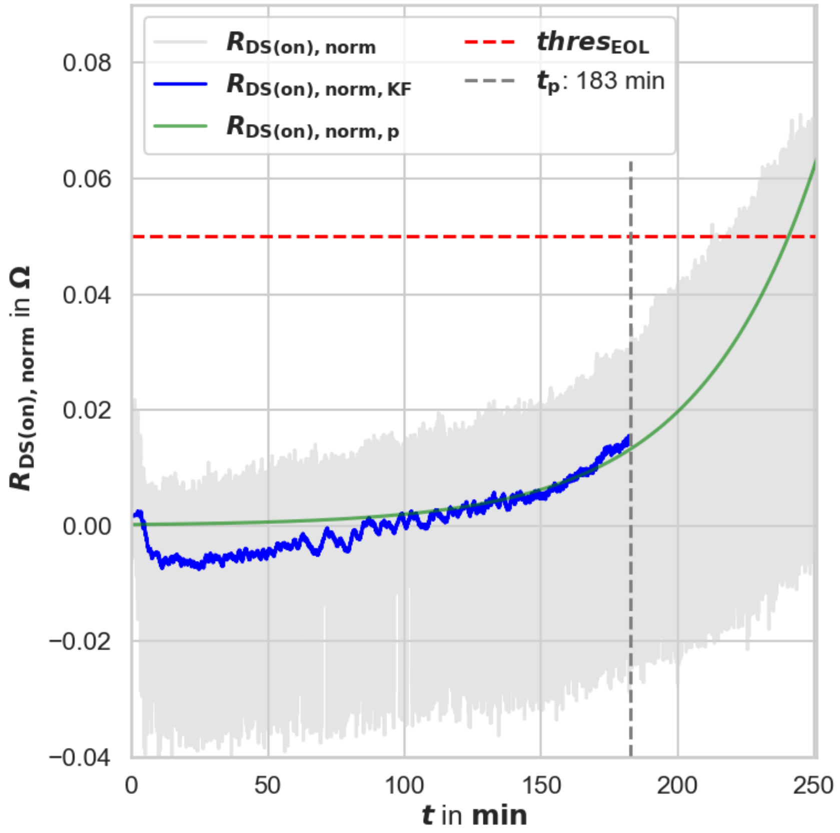


Forecast $R_{\mathrm{DS(on),norm,p}}$ based on Kalman filter estimates



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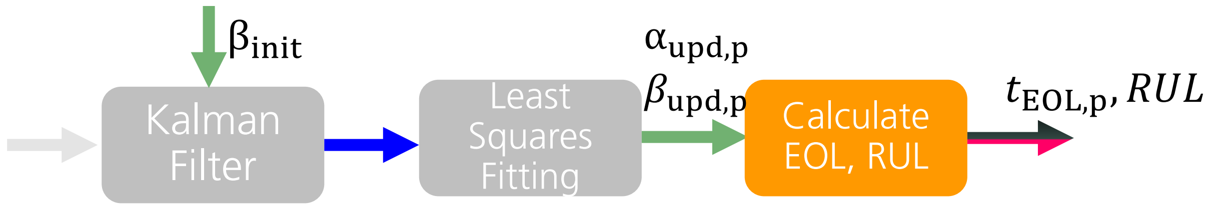
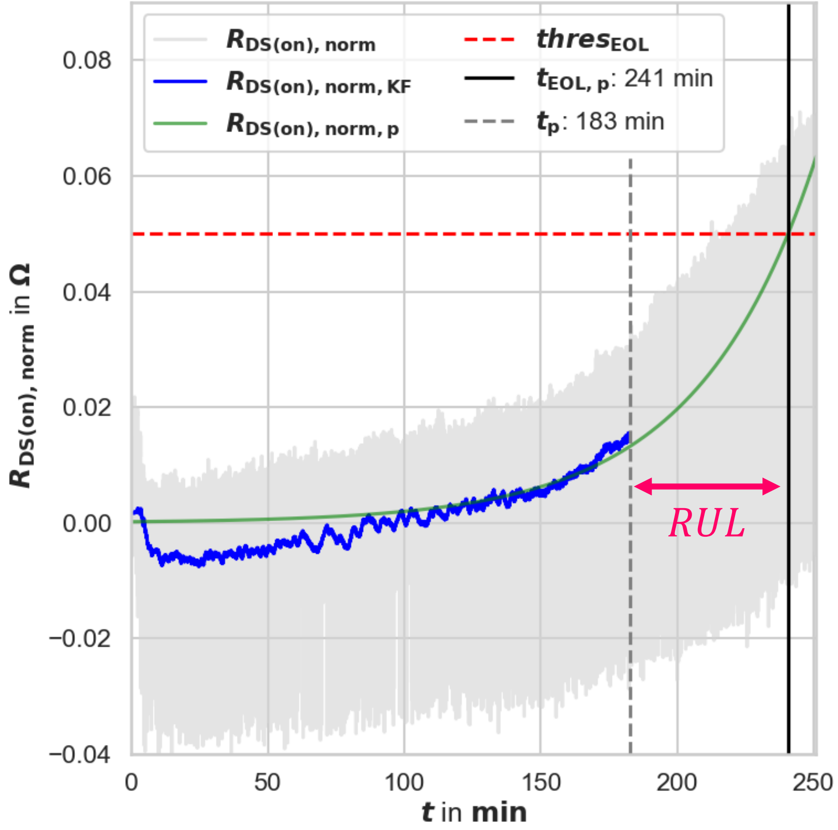


- $t_{\mathrm{EOL,p}} = (\log(thres_{\mathrm{EOL}}) - \log(\alpha))/\beta$ (7)
- $RUL = t_{\mathrm{EOL,p}} - t_{\mathrm{p}}$ (8)

Forecast $R_{\mathrm{DS(on),norm,p}}$ based on Kalman filter estimates



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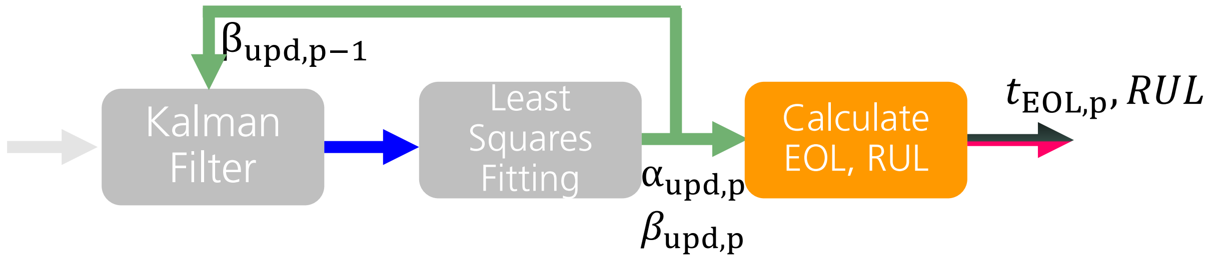

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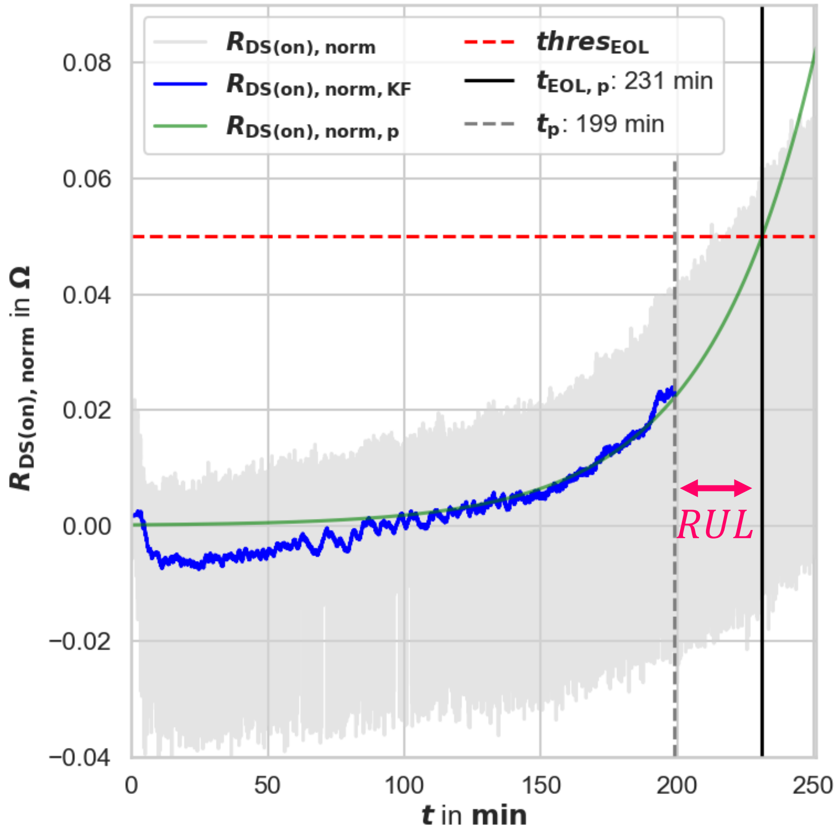


RUL Prediction for a MOSFET Reference Dataset

Results

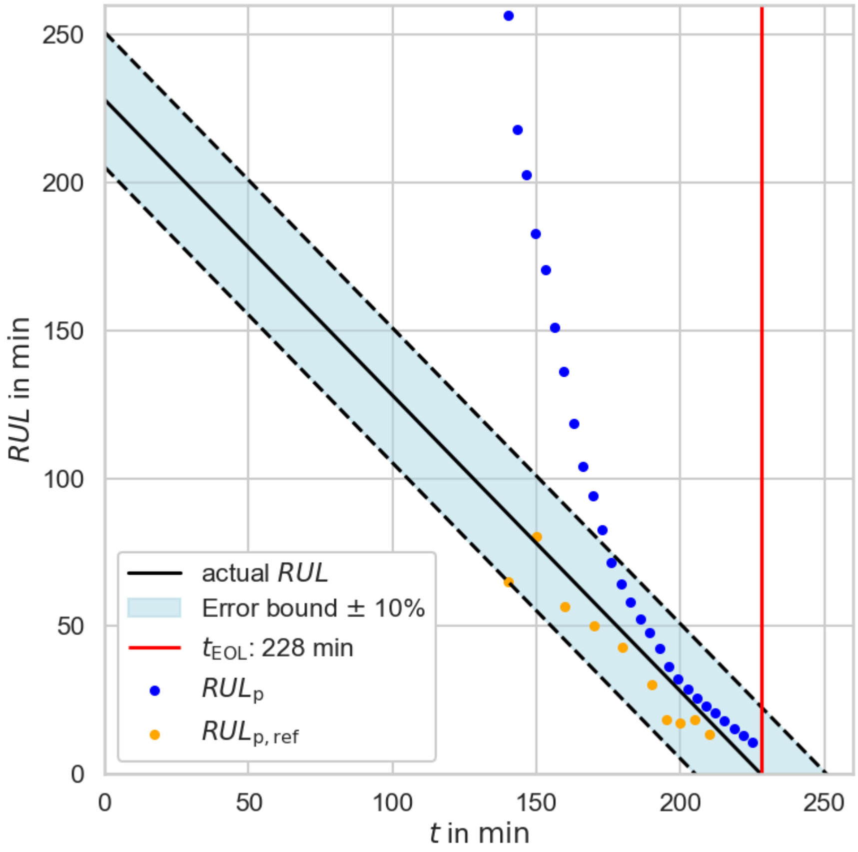
- Base implementation
  - Best RUL predictions: 199 - 206 minutes, absolute error: 4 min.
  - Afterwards: results slightly diverge.
  - Comparable to reference implementation, thus satisfactory.

- Reference implementation (extended Kalman filter)
  - Signal is filtered with mean filter before.
  - Best RUL prediction:150 min, absolute error: 2 min.

- Planned developments
  - Improve prediction at pristine state.
  - Generalize algorithms for accelerated lifetime tests and real-world applications.

- Data from accelerated lifetime tests do not capture all operating conditions ➔ future work will incorporate real-world field data.

RUL predictions of base implementation and reference implementation



Demonstrator Setup

Motivation

- Enable testing for real-world conditions of DC grids to gather practical aging behavior data.

- DC networks can vary significantly:
  - Grounding systems: TN-S, AC-sided grounding, IT (floating high ohmic midpoint grounding).
  - Load dynamics: Fast (e.g., welding) vs slow (e.g., PV).
  - Grid characteristics: cable length ➔ variations in inductances and resistances.
  - Faults: Low/high resistive short circuits, ground faults, arc faults.

Parameter ranges of the demonstrator

Parameter	Value Range
Voltage	≤ 1500 V
Nominal current	≤ 100 A
Short-circuit current	≤ 10 kA
Power grid replication	Inductance ≤ 400 µH Resistance ≤ 20 mΩ
Capacitance	108 mF up to 850 V 54 mF up to 1500 V

A testing system is developed that can flexibly replicate the diversity of DC grids and potential faults.

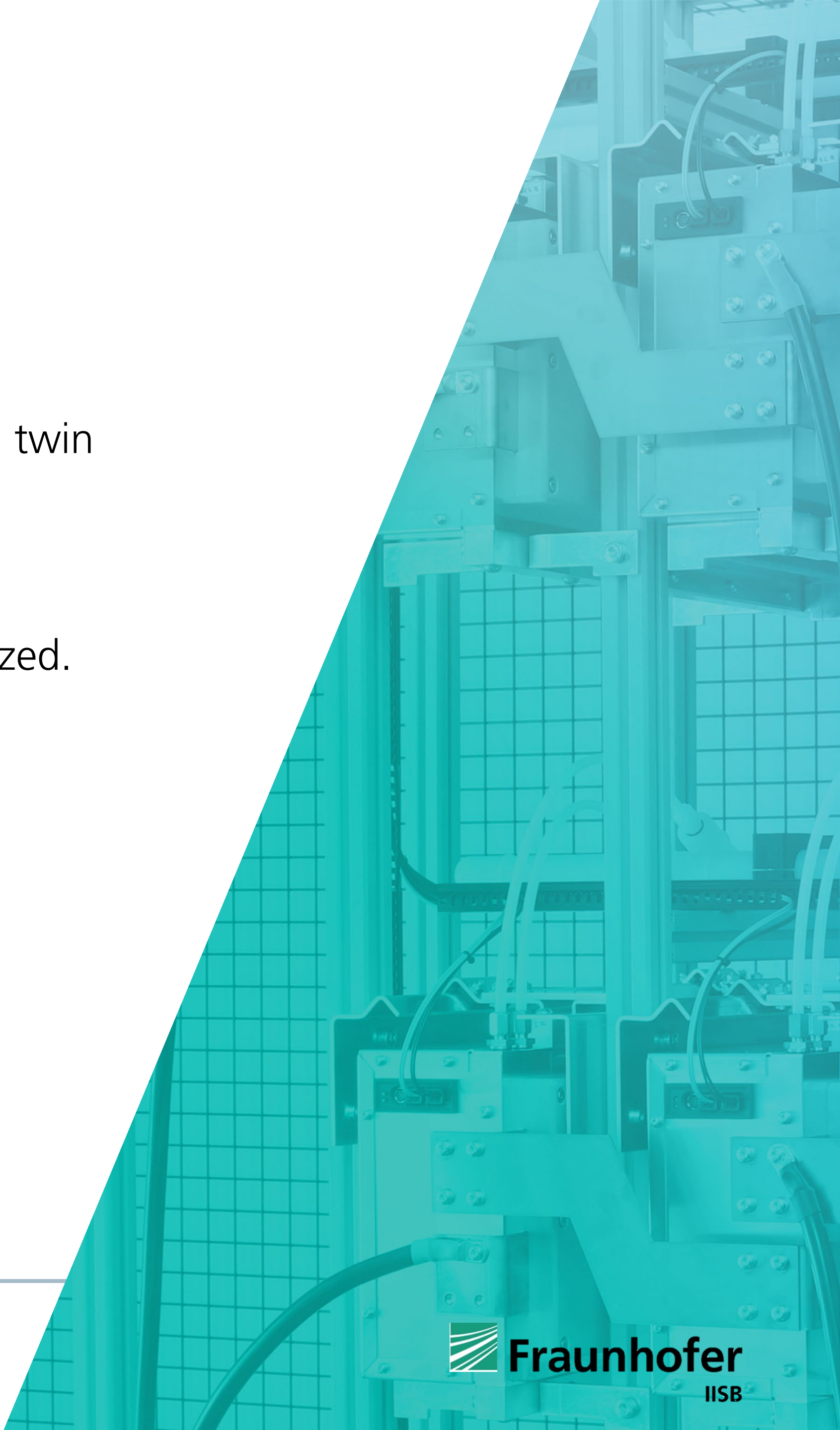
Conclusion and Outlook

- Objective
  - Ensure reliability of DC SCCBs through accurate RUL predictions and digital twin services.

- Achievements
  - Base implementation of an RUL prediction in a digital twin framework realized.
  - Concept and design phase for a real-world demonstrator completed.

- Future work will include RUL prediction for
  - IGBT power cycling data,
  - Testing of SCCBs with integrated SiC MOSFETs,
  - Data for real-world load profiles collected on the demonstrator setup.

- Challenges
  - Generalize models for the different data sets and applications.
  - Develop additional ML algorithms to further enhance prediction accuracy.



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Thank you for the attention!

I‘m pleased to answer your questions.
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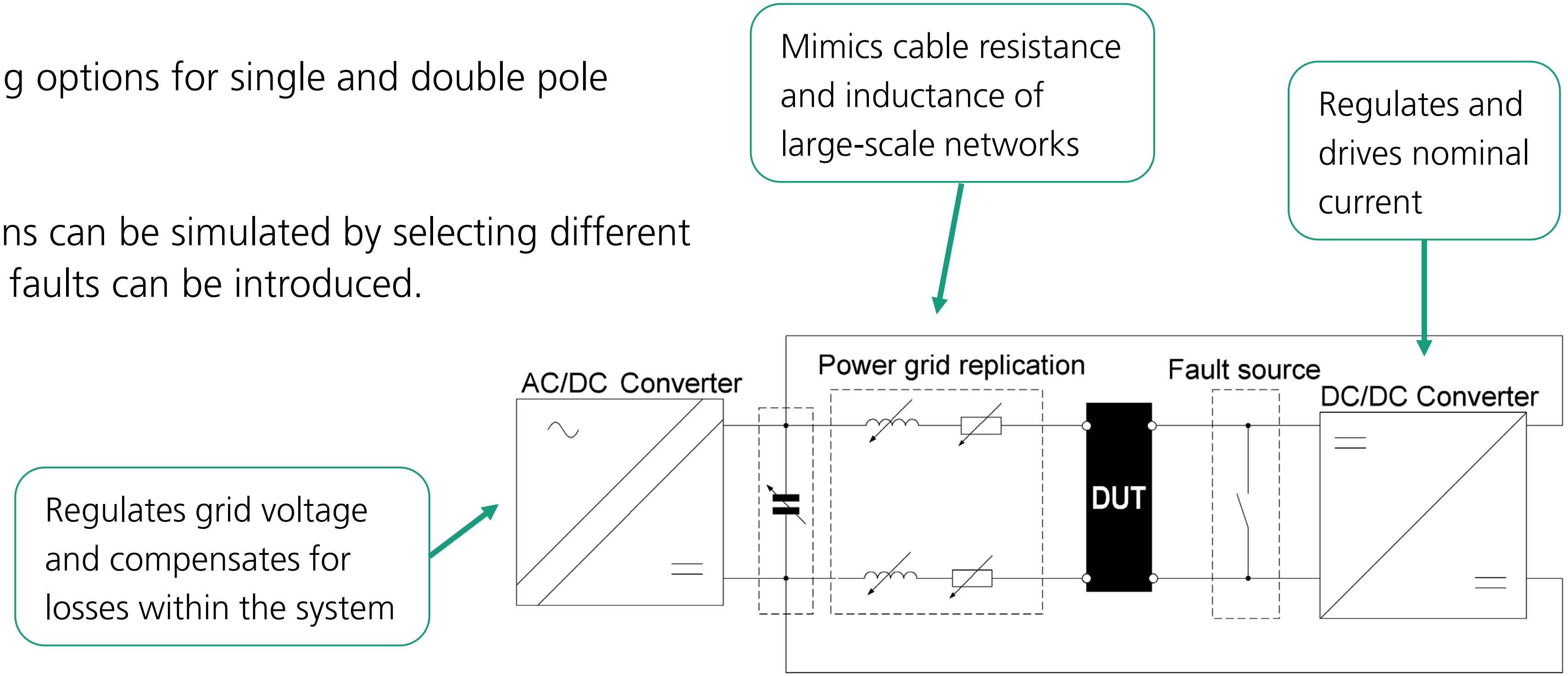
Messe Frankfurt Group

Demonstrator Setup

Hardware Realization

- The demonstrator operates as a single DC line in a sink-source configuration (bidirectional energy flow is possible).
- Integration and testing options for single and double pole circuit breakers.
- Various DC applications can be simulated by selecting different load profiles and grid faults can be introduced.



Mimics cable resistance and inductance of large-scale networks

Regulates and drives nominal current

Regulates grid voltage and compensates for losses within the system

Electric schematic of the demonstrator setup