Power Electronics Reliability Research @ Aalborg University

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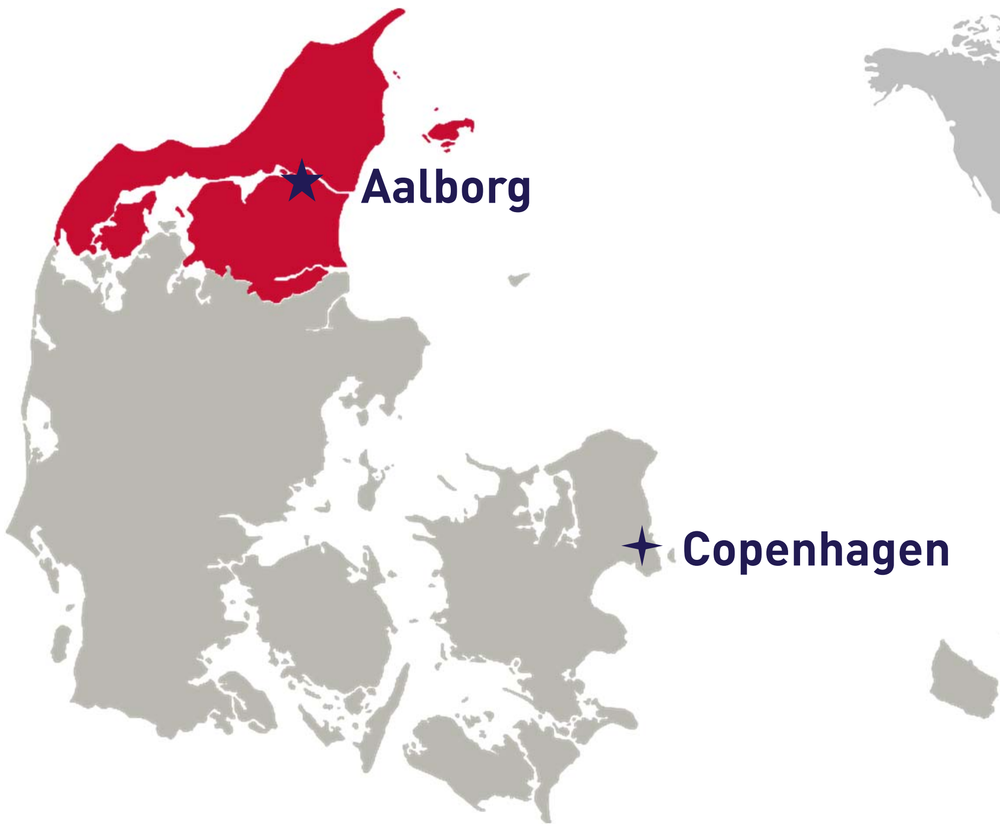
AALBORG UNIVERSITY
DENMARK

CORPE

► Aalborg University, Denmark



USNEWS 2018
Engineering
No. 8 globally
No. 1 in Europe
No. 1 in normalized citation impact globally

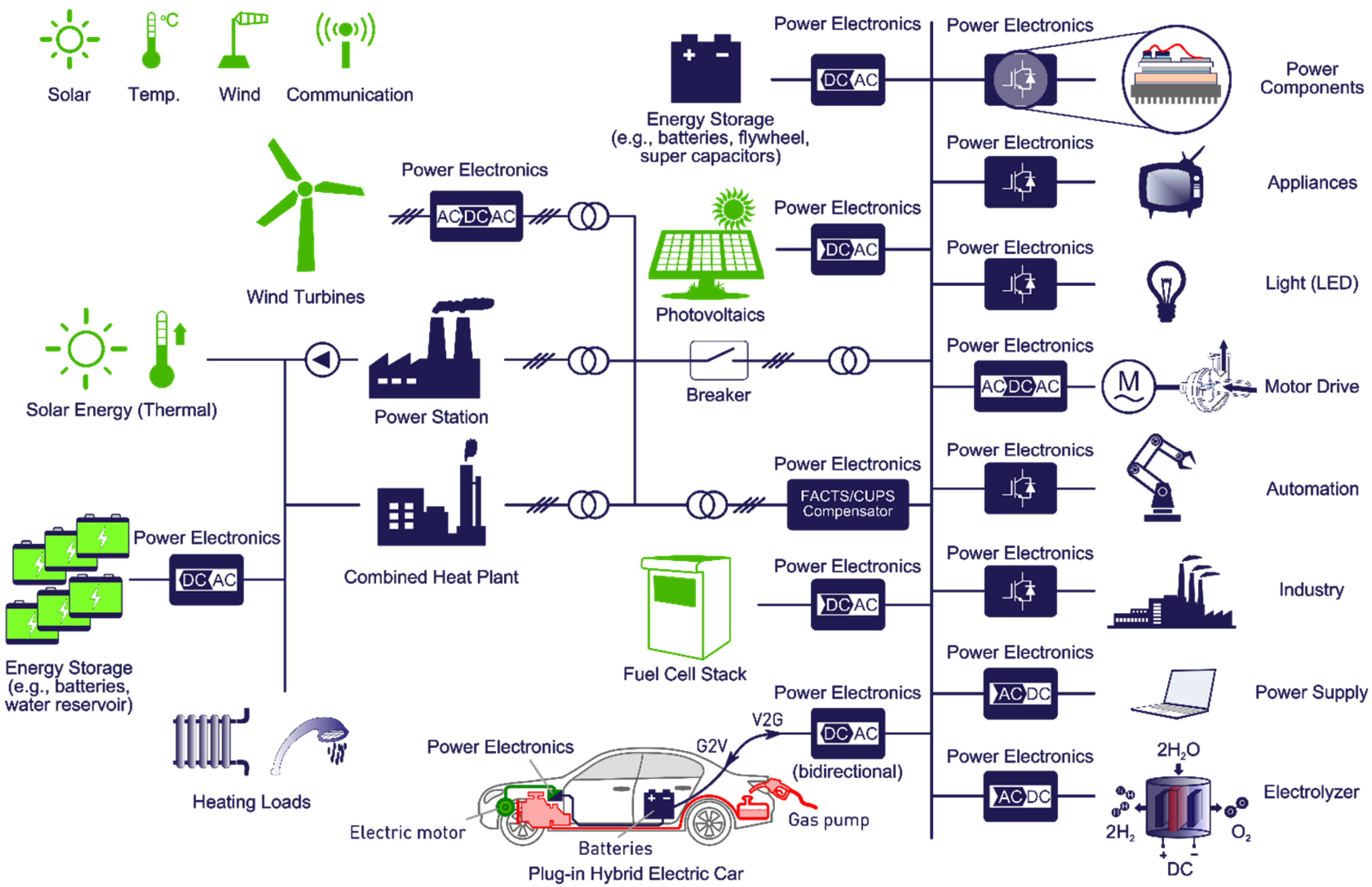
Source: https://www.usnews.com/education/best-global-universities/engineering?int=994b08

Established in 1974
22,000 students
2,300 faculty

PBL-Aalborg Model
(Problem-based learning)

▶ Energy Technology Department at Aalborg University

40+ Faculty, 100+ PhDs, 30+ RAs & Postdocs, 20+ Technical staff, 30+ visiting scholars
60% of manpower on power electronics and its applications



▶ Energy Technology Department at Aalborg University

Research and Education Sections at Department of Energy Technology, Aalborg University

- Electric Power Systems
- Power Electronic Systems
- Electrical Machines
- Fluid Power and Mechatronic Systems
- Thermo Fluids
- Thermal Energy Systems
- Esbjerg Energy Section

Multi-disciplinary Research Programs

Core power electronics research program

- Efficient and Reliable Power Electronics

Programs of power electronics intensive applications

- Wind Power Systems
- Photovoltaic Systems
- E-Mobility and Industrial Drives
- Microgrids

Programs of power electronics related applications

- Fuel Cell and Battery Systems
- Intelligent EnergySystems and Active Networks
- Modern Power Transmission Systems
- Offshore Energy Systems
- Green Buildings
- Thermoelectrics

- Fluid Power in Wind and Wave Energy
- Biomass

Department in total

40+ Faculty members
100+ PhD students
30+ Research assistants and postdocs
30+ Visiting scholars and students
20+ Technical and administrative staff
4 In-house company divisions

60%+ of the above manpower are in power electronics and its applications.

3 in-house company divisions heavily involve in power electronics.

More information: Huai Wang and Frede Blaabjerg, Aalborg University fosters multi-disciplinary approach to research in efficient and reliable power electronics, *How2power today*, issue Feb. 2015.

▶ Efficient and Reliable Power Electronics Program

Mission

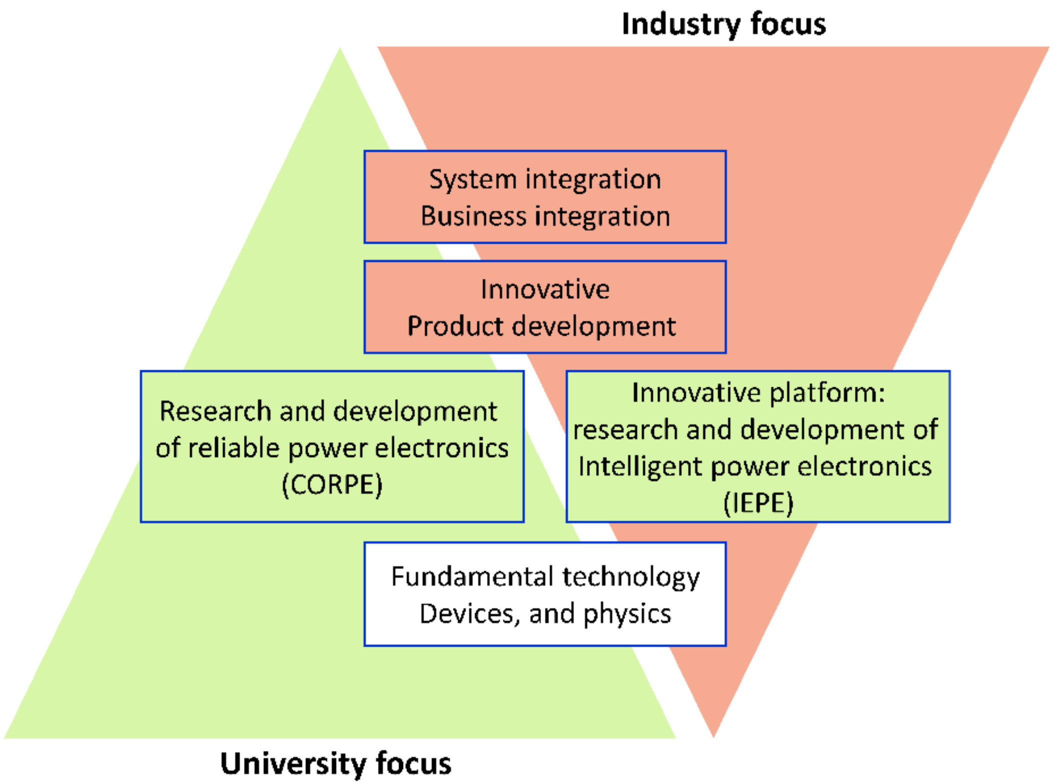
To develop innovative power electronic converters and systems to all relevant applications, which are efficient, reliable and cost-competitive by means of reduction in manufacturing, maintenance and operational costs. It addresses the following core challenges:

- Future power electronics products target for ppm level of return rate, with optimized life-cycle performance in terms of energy efficiency and cost
- Undesirable harmonics and resonances in local electrical network and power systems
- Lack of design tools for efficiency, reliability and cost oriented power electronics design
- Emerging applications of power electronics under harsh environments and long operation hours
- Emerging active devices and passive components need paradigm shifts in packaging technology and power electronics design

▶ Efficient and Reliable Power Electronics Program

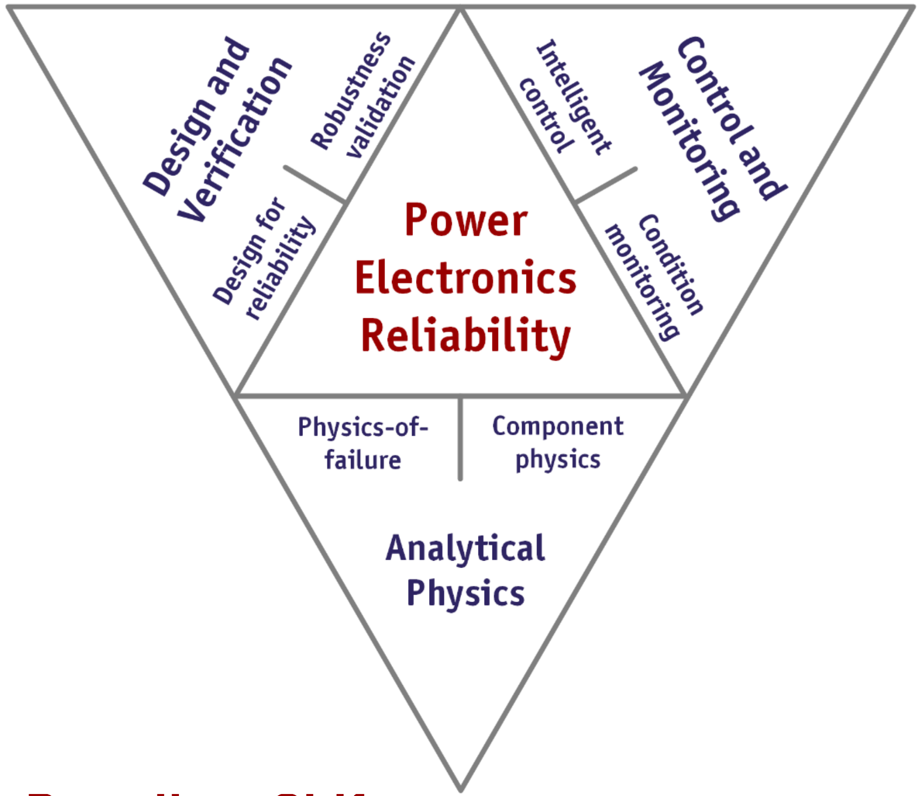
Examples of University-Industry Collaboration

- 1990s – Danfoss Professor Program
- 2000s – Vestas Power Program
- 2010s – CORPE and IEPE



▶ Overall Research Scope on Power Electronics Reliability

50+ million Euro funding during 2012-2023 from government and industry to address the research



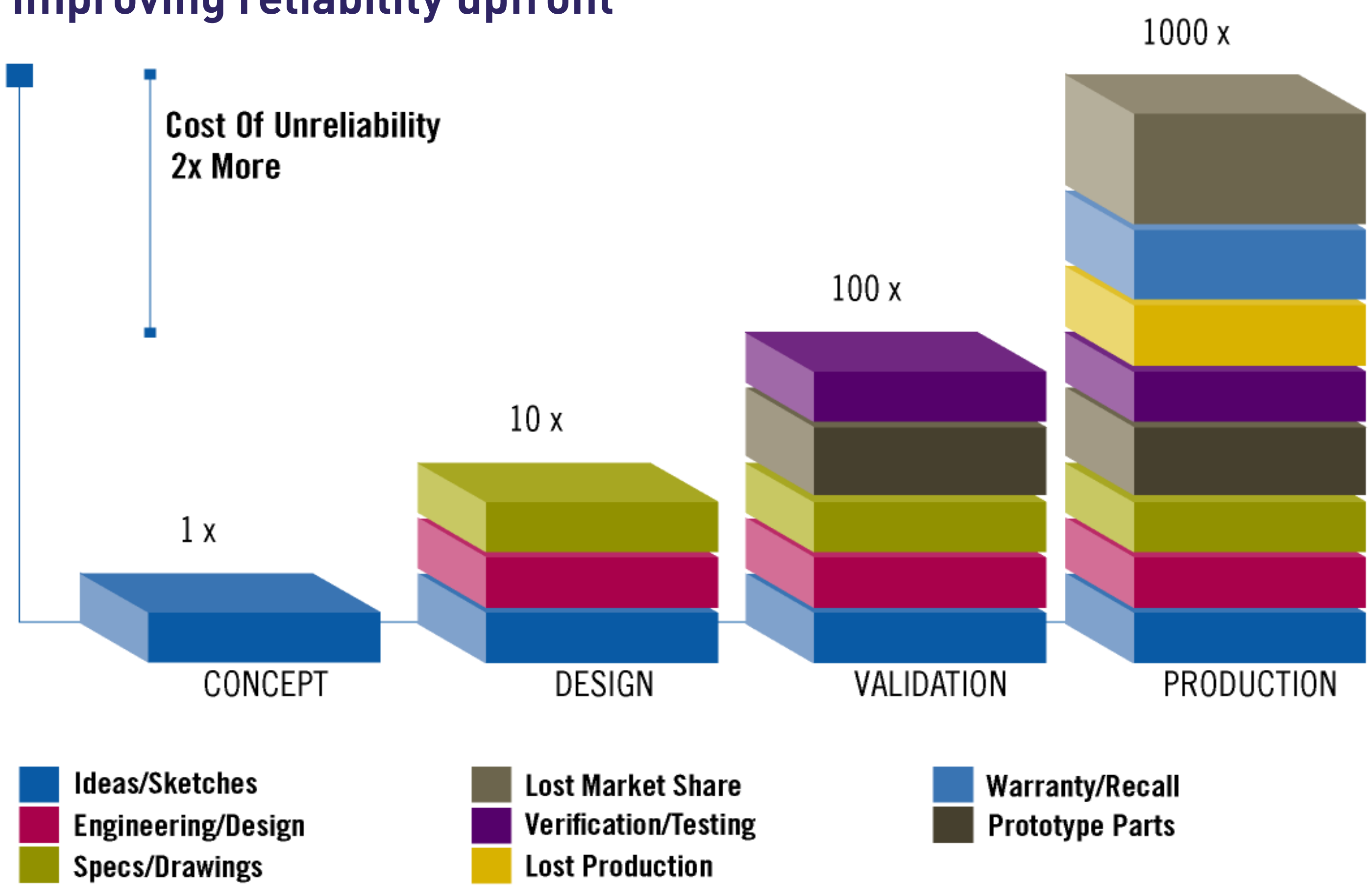
Paradigm Shift

- From components to failure mechanisms
- From constant failure rate to failure level with time
- From reliability prediction to robustness validation
- From microelectronics to also power electronics

Source: H. Wang, M. Liserre, F. Blaabjerg, P. P. Rimmen, J. B. Jacobsen, T. Kvisgaard, J. Landkildehus, "Transitioning to physics-of-failure as a reliability driver in power electronics," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 2, no. 1, pp. 97-114, Mar. 2014.

▶ Motivation for Reliability-Oriented Design

Reduce costs by improving reliability upfront



Source: DfR Solutions, Designing reliability in electronics, CORPE Workshop, 2012.

► The Reliability Challenges in Industry

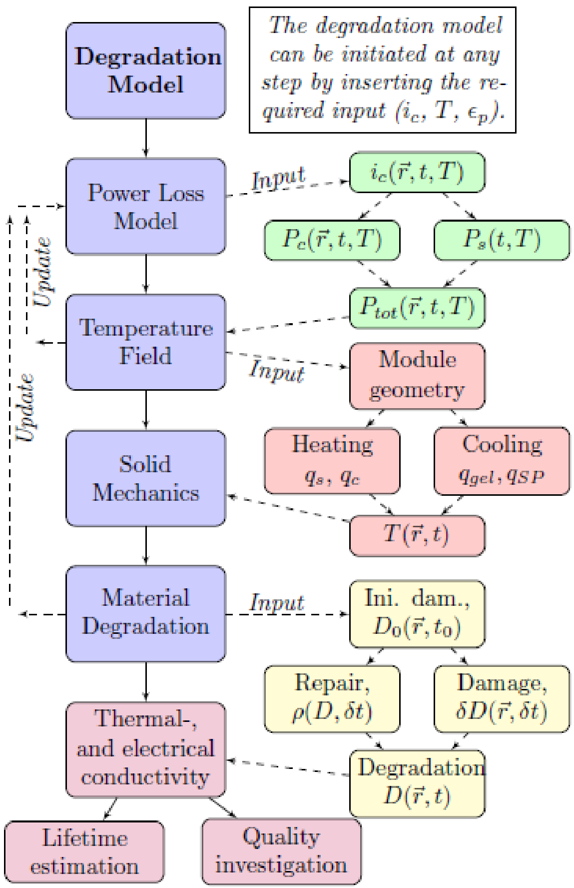
	Past	Present	Future
Customer expectations	✧ Replacement if failure ✧ Years of warranty	✧ Low risk of failure ✧ Request for maintenance	✧ Peace of mind ✧ **Predictive maintenance**
Reliability target	✧ Affordable returns (%)	✧ Low return rates	✧ **ppm return rates**
R&D approach	✧ Reliability test ✧ Avoid catastrophes	✧ Robustness tests ✧ Improve weakest components	✧ **Design for reliability** ✧ Balance with field load
R&D key tools	Product operating tests	✧ Testing at the limits	✧ **Understanding failure mechanisms,** field load, root cause, ... ✧ Multi-domain simulation ✧ ...

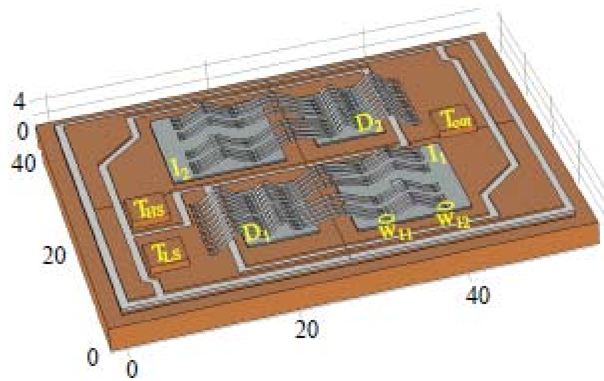
Product + Service

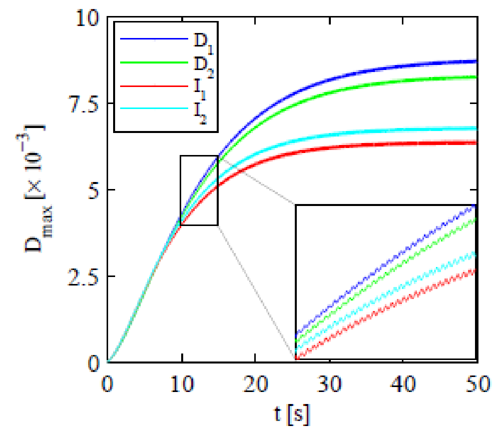
Data + Physics of Failure

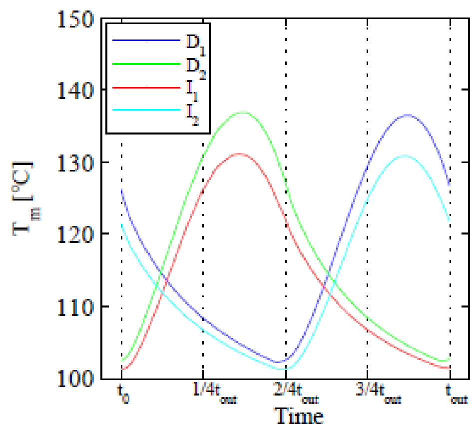
▶ Example - Multiphysics Simulation

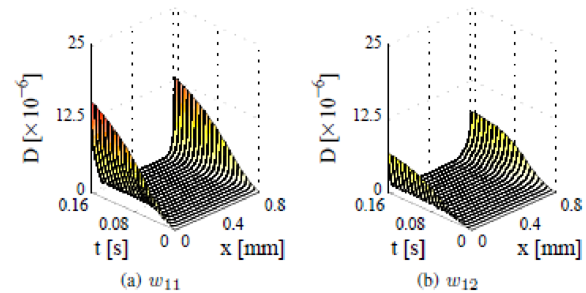
Degradation of IGBT modules based on physics-of-failure simulations











Simulation results are consistent with micro-sectioning analysis and four-point probing results of degraded modules

Source: Kristian Bonderup Pedersen, IGBT Module Reliability. Physics-of-Failure based Characterization and Modelling, PhD Dissertation, CORPE, Aalborg University, 2015

▶ Example – Application-Oriented Degradation Testing

Power Cycling Testing on IGBT Modules

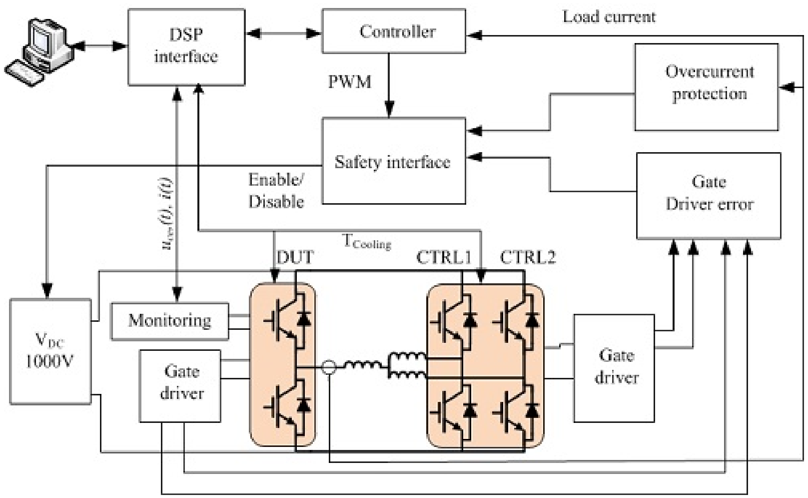
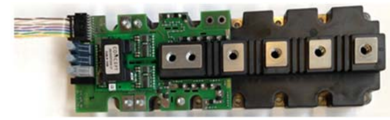
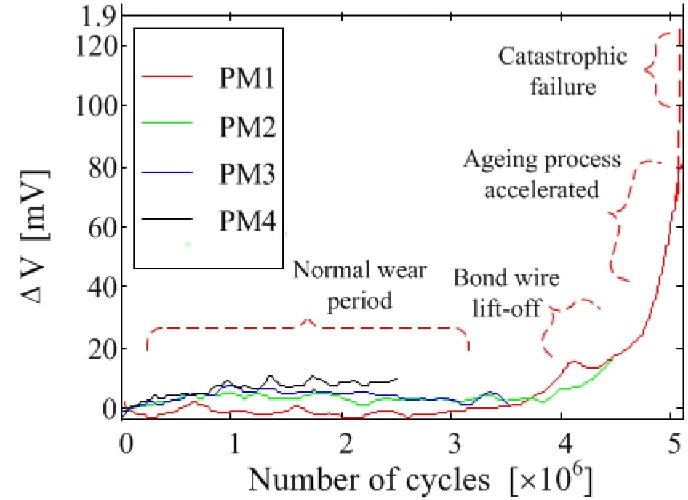
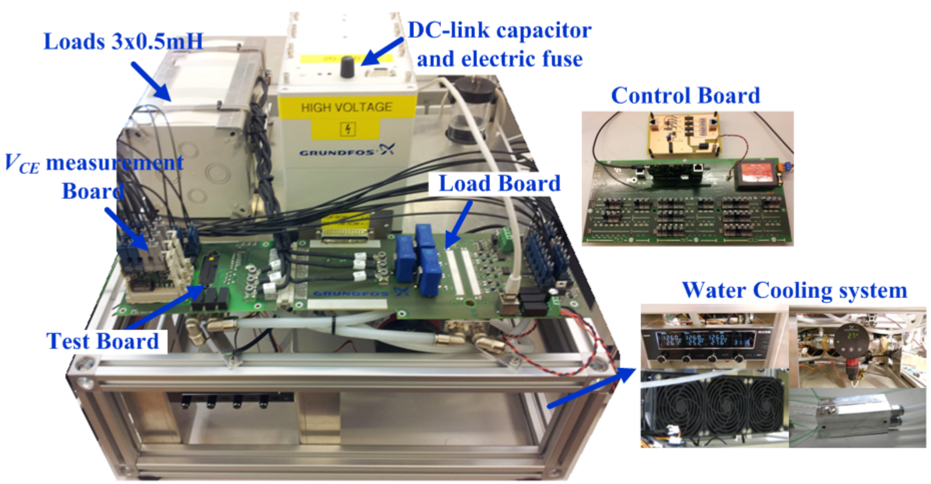


Diagram of an advanced power cycling testing system

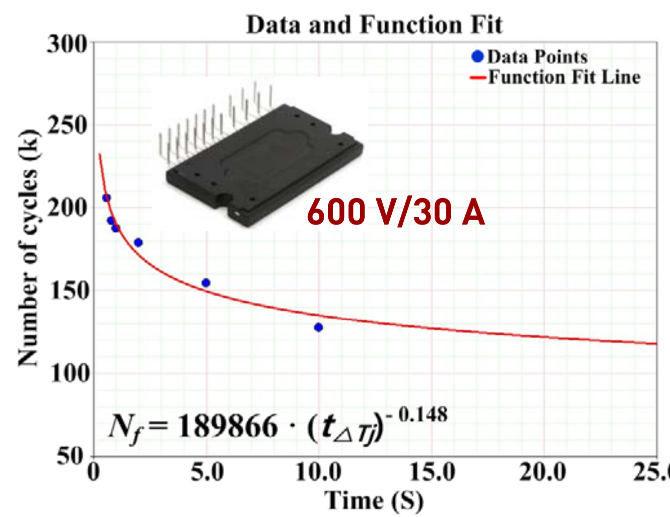


1700 V/1000 A



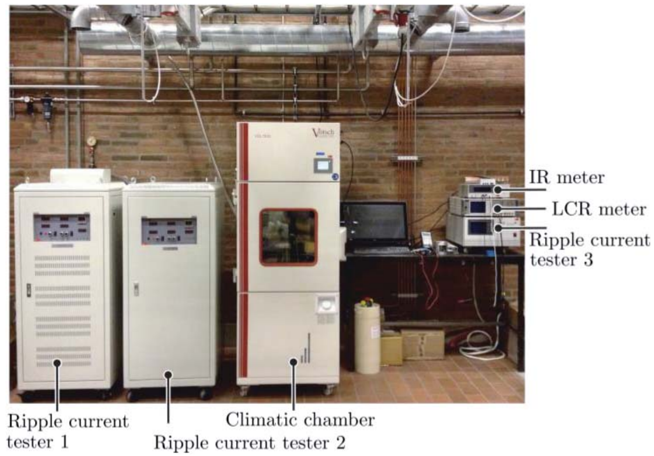


A low-power power cycling testing setup

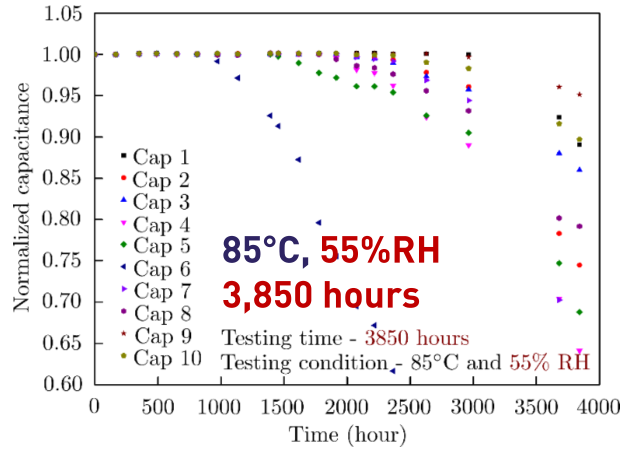


► Example – Application-Oriented Degradation Testing

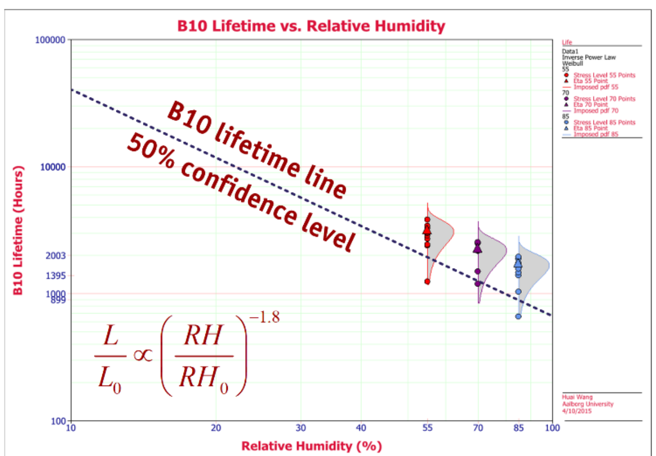
Degradation Testing of DC Film Capacitors under Humidity Conditions



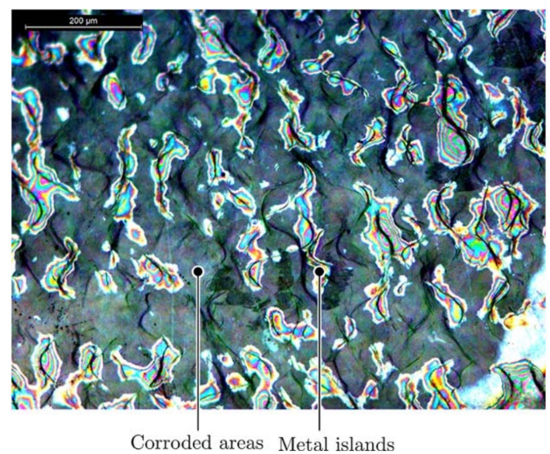
Capacitor degradation testing setup



Degradation curve of one group of testing



A humidity-dependent lifetime model

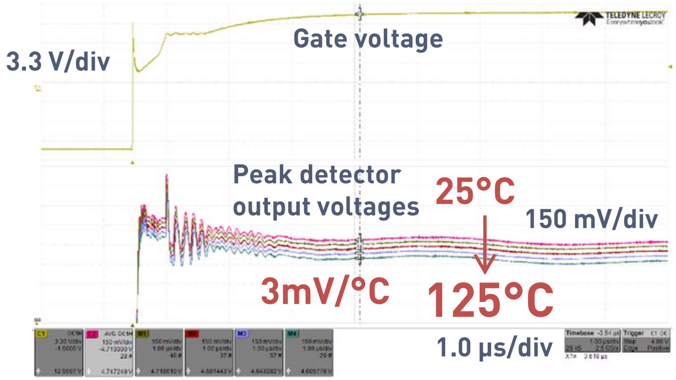


Optical microscopy investigation of one of the degraded samples

Source: H. Wang, D. A. Nielsen, and F. Blaabjerg, "Degradation testing and failure analysis of DC film capacitors under high humidity conditions," Microelectronics Reliability, 2015

▶ Example – Condition Monitoring of Power Components

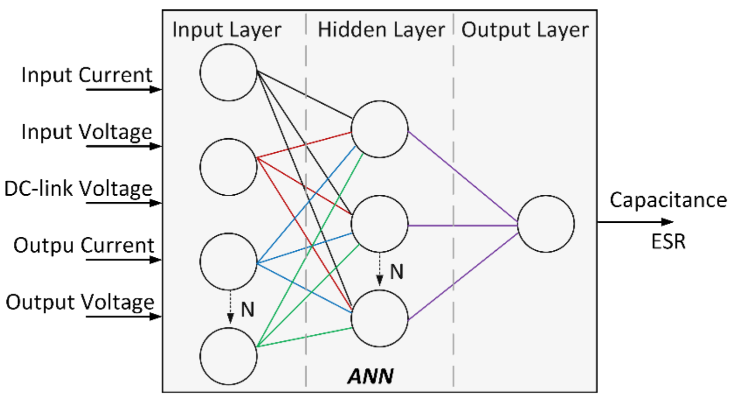
Gate Peak Current based IGBT Junction Temperature Monitoring



Outcome

- Experimentally verified and calibrated
- Gate voltage compensation

Condition Monitoring and Remaining Lifetime Prediction of Capacitors

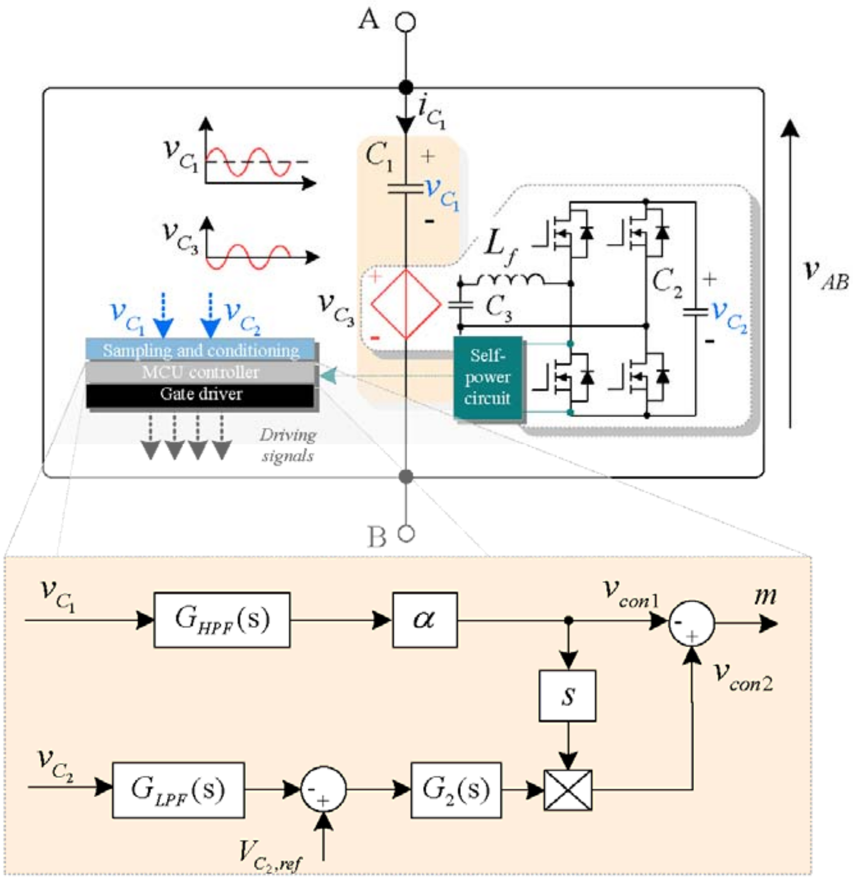


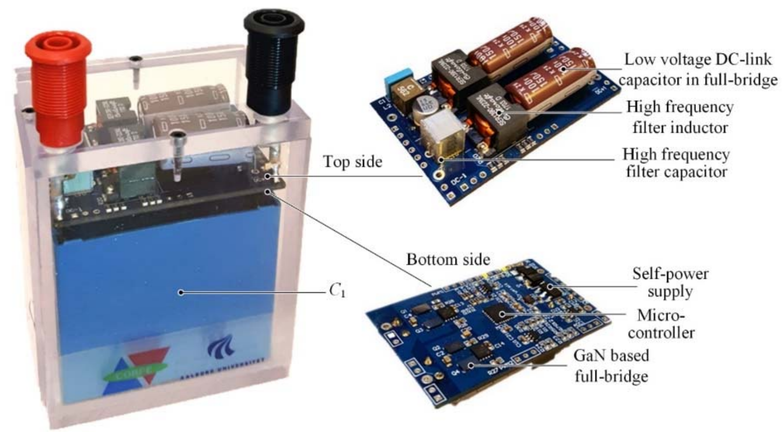
Outcome

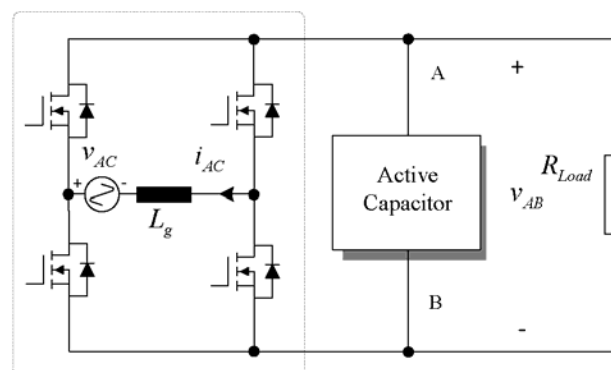
- An Artificial Neural Network (ANN) based method is applied for estimation of capacitance
- Based on existing available information, pure software solution

▶ Example - the Activation of Passive Components

A Two-terminal Active Capacitor

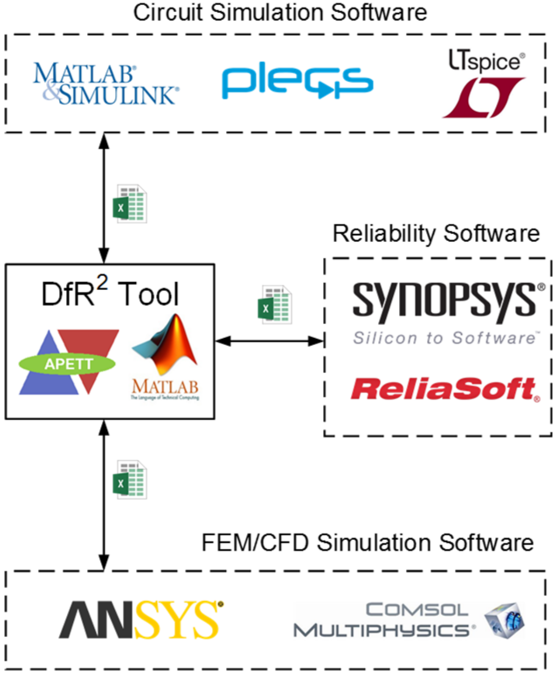




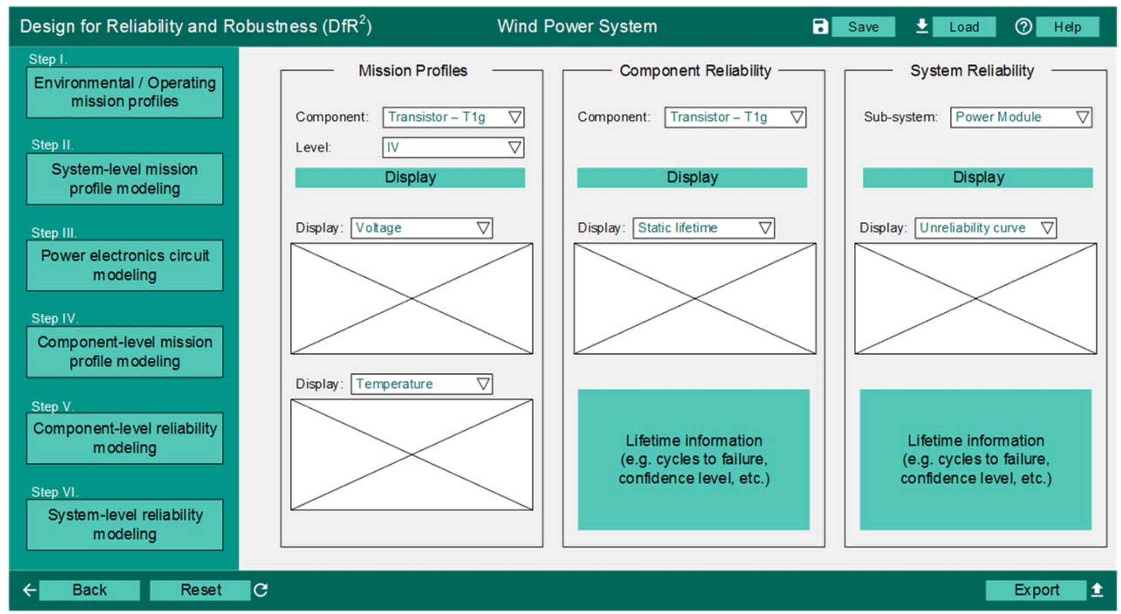


▶ Example - DfR^2 Tool Platform at CORPE

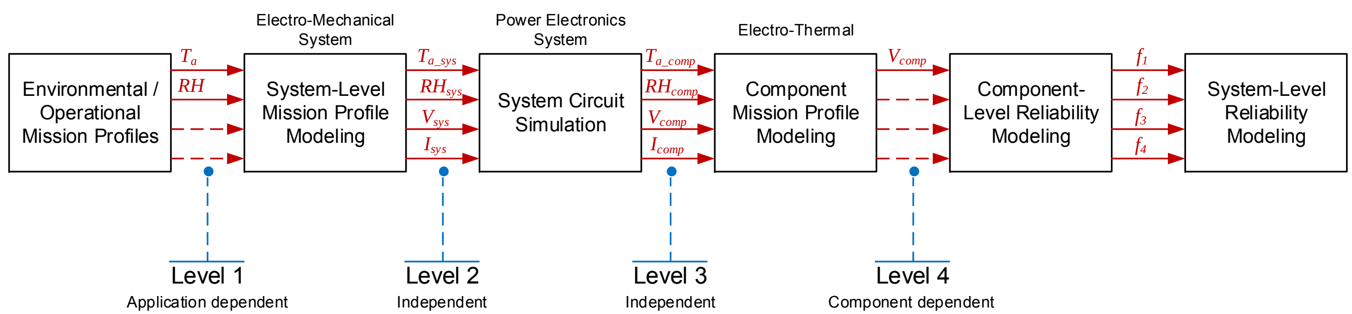
Design for Reliability and Robustness (DfR^2)



Interfaces to other software



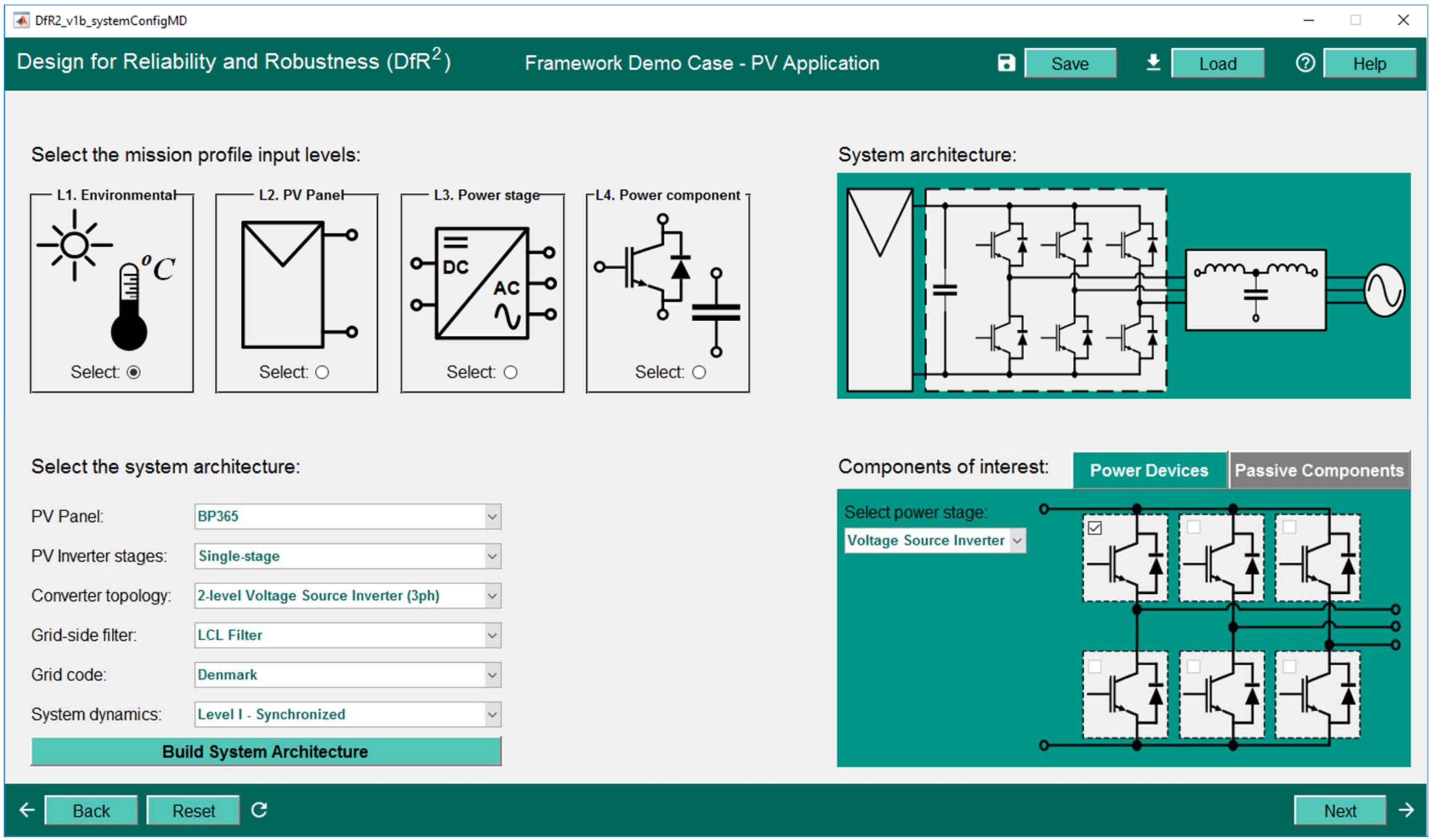
Main GUI panel



Modeling Framework

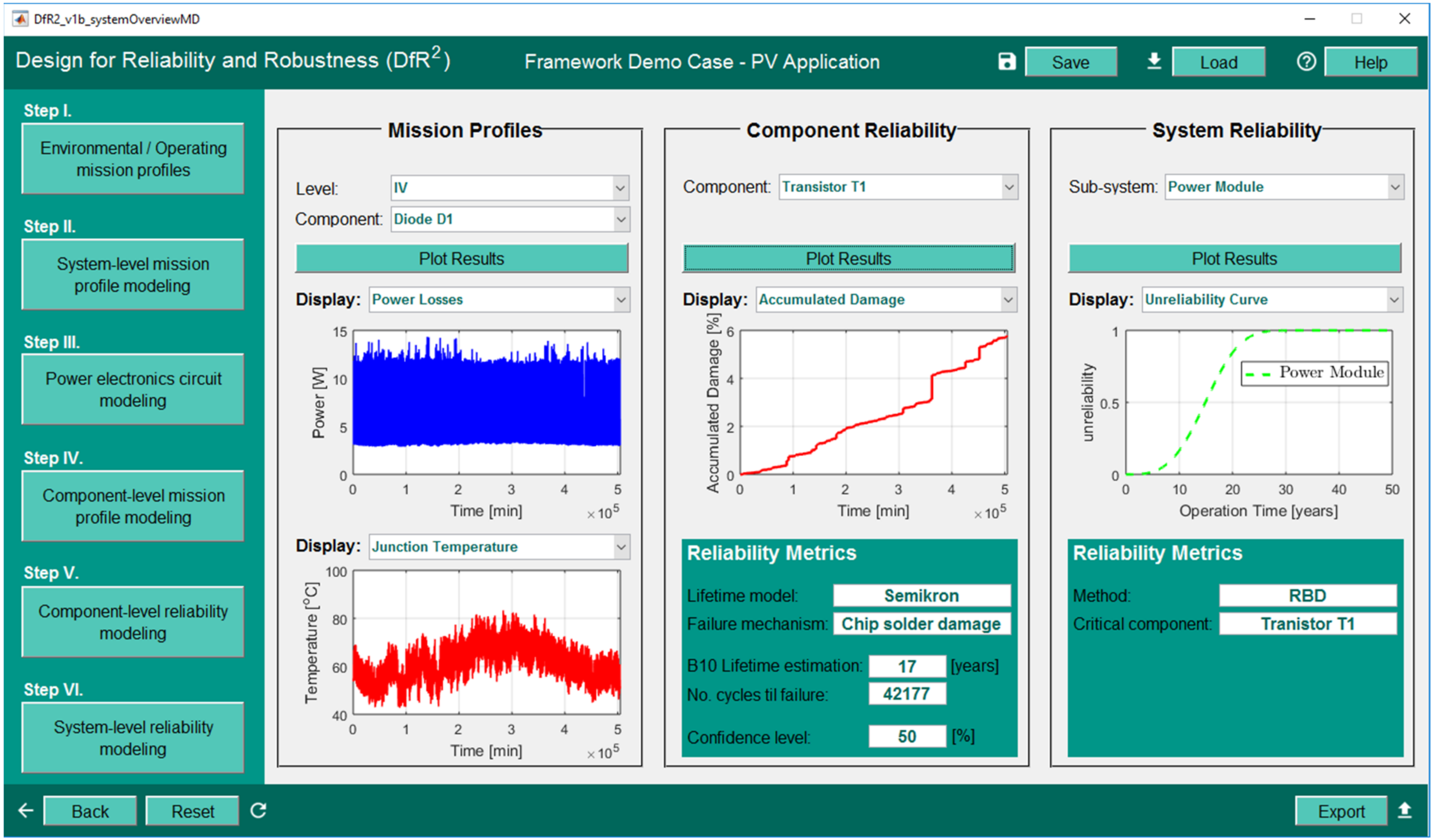
▶ Example - DfR² Tool Platform at CORPE

Design for Reliability and Robustness (DfR²)



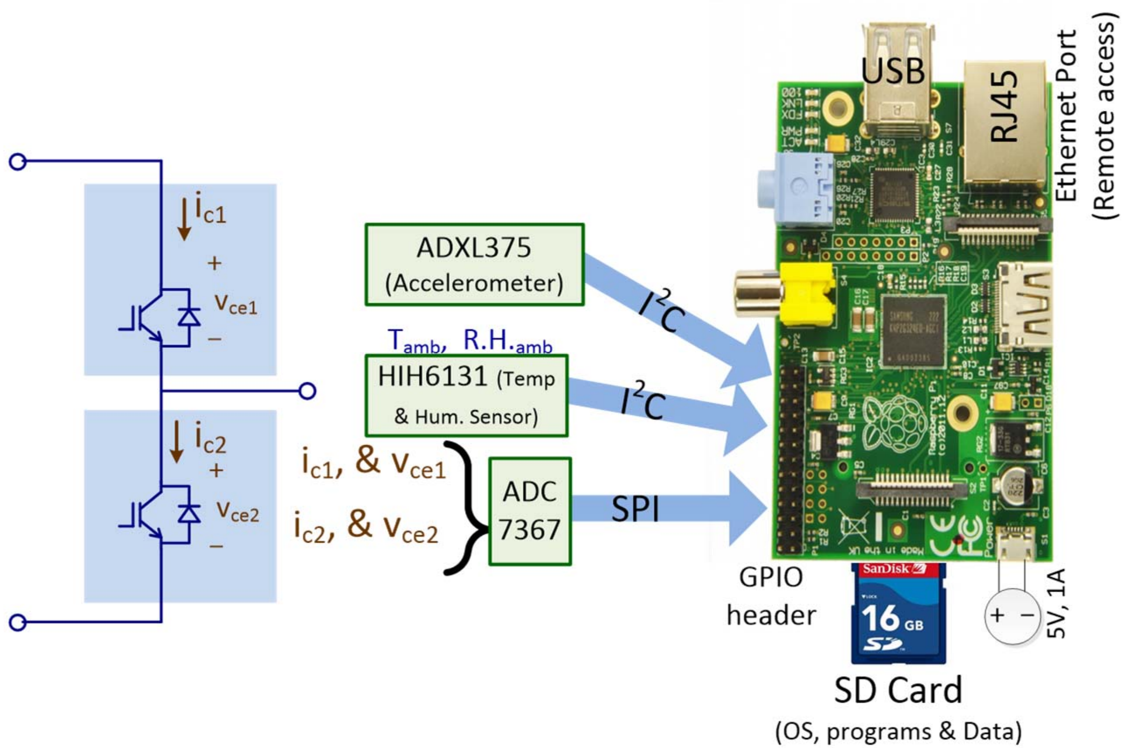
▶ Example - DfR^2 Tool Platform at CORPE

Design for Reliability and Robustness (DfR^2)



▶ Example - Mission Profile Logger

Mission Profile Logger Developed at CORPE, Aalborg University

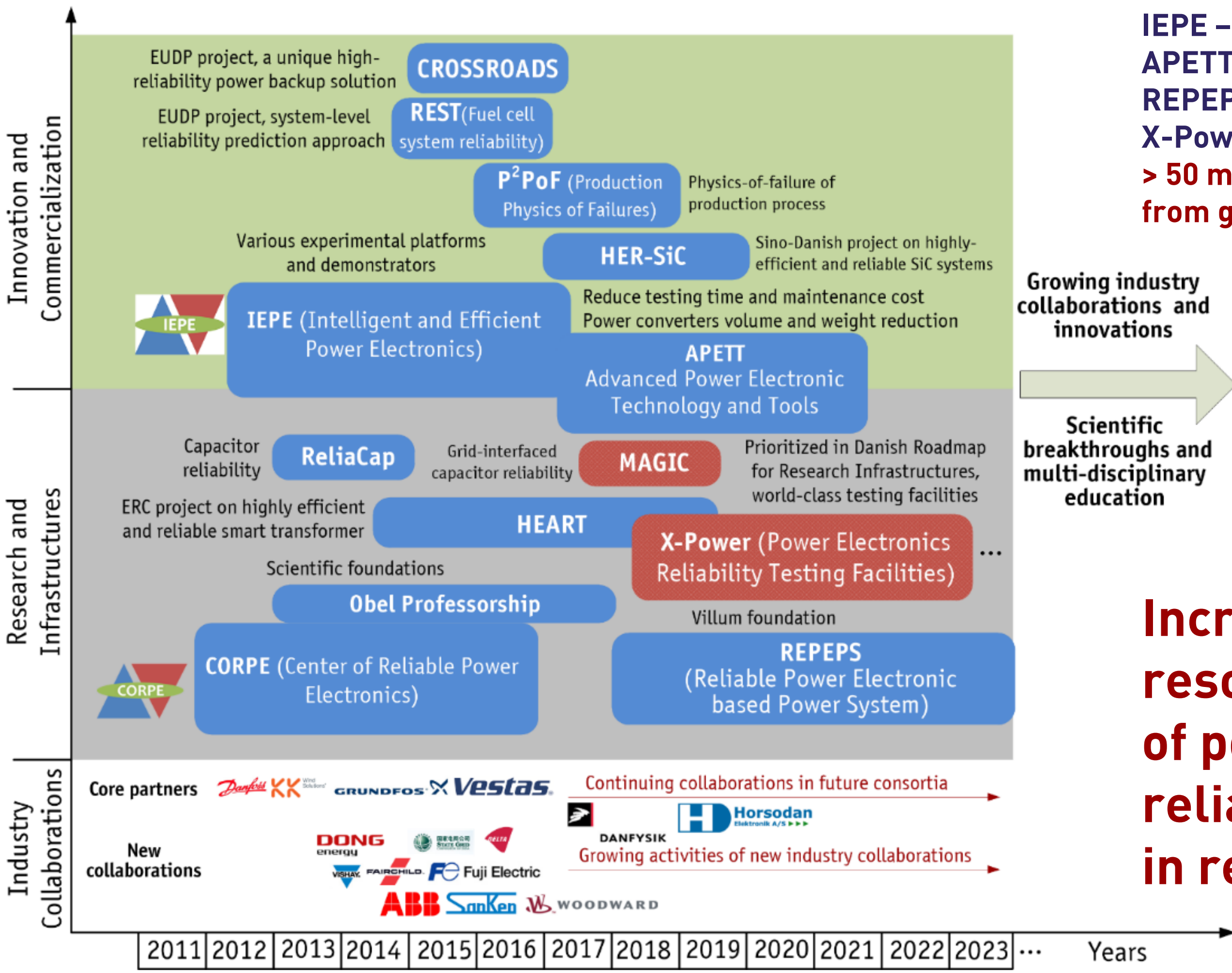


86×56 mm^2
512 MB RAM

Instantaneous data
Average data
Extreme data
Processed data

A mission profile logger for measuring environmental and operational conditions

▶ Project Roadmap on Power Electronics Reliability



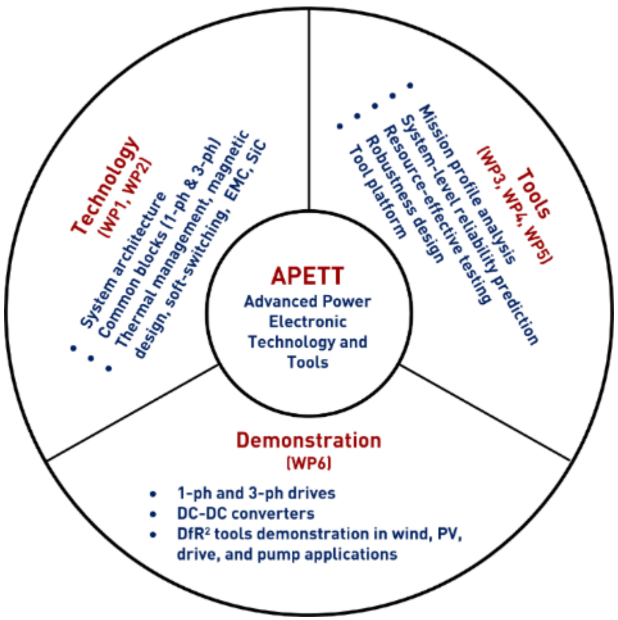
Project roadmap at Center of Reliable Power Electronics (CORPE)

CORPE – 12 million Euro
IEPE – 14 million Euro
APETT – 7 million Euro
REPEPS – 5 million Euro
X-Power – 8 million Euro (budget)
> 50 million Euro funding 2012-2023 from government and industry

Increasing research resources in the area of power electronics reliability worldwide in recent years!

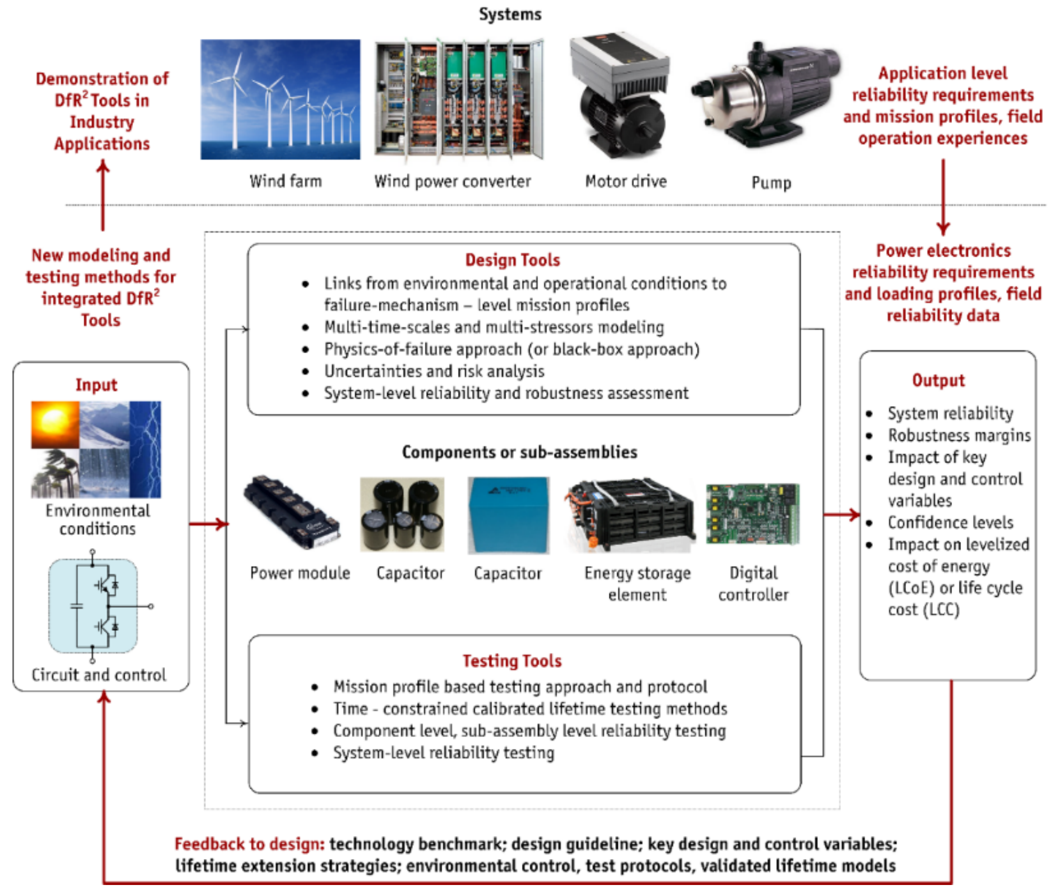
▶ Current Project Example 1 - APETT

APETT - Advanced Power Electronic Technology and Tools (2017-2021)



Work packages and scopes of APETT

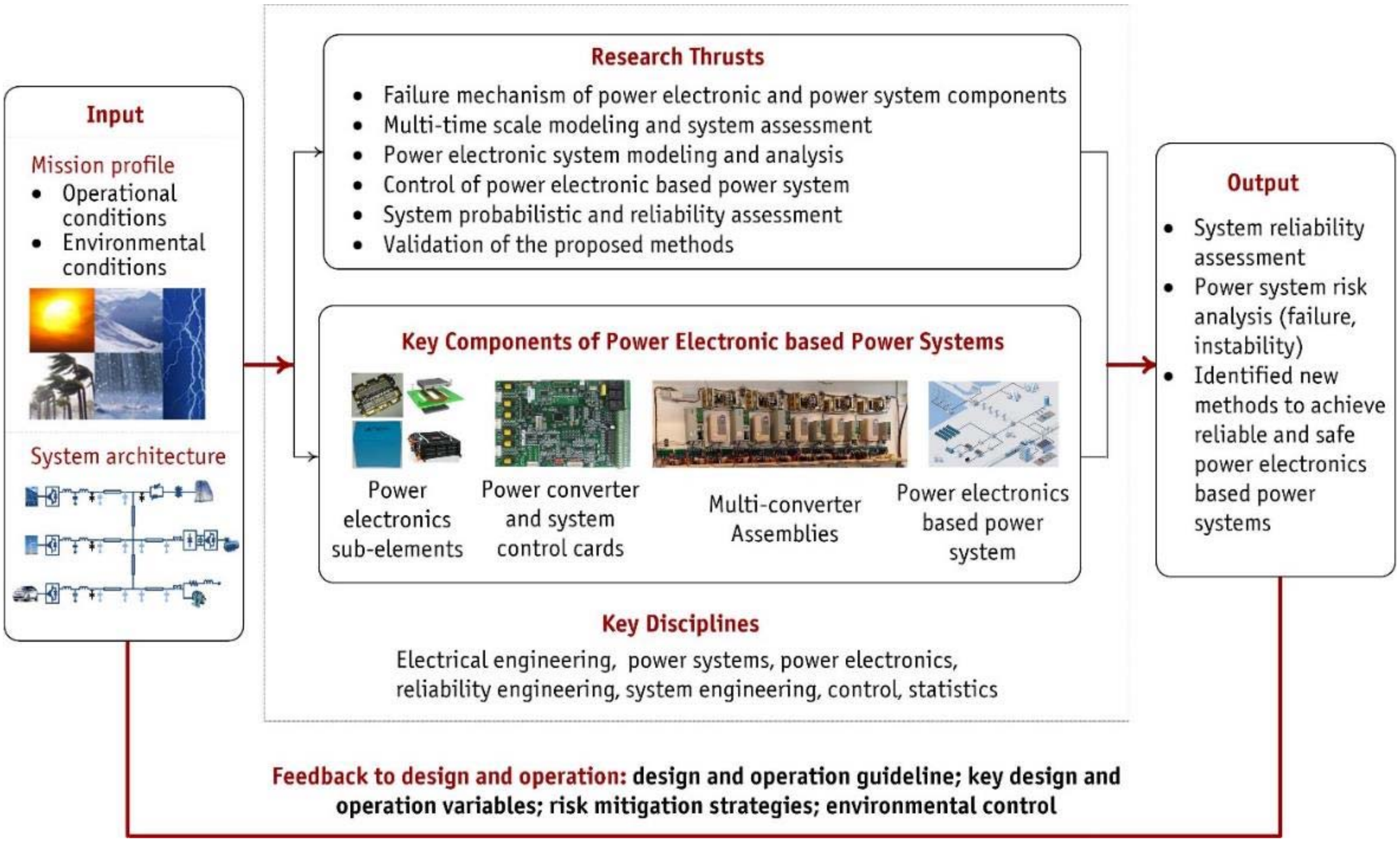
3 University partners + 6 industry partners



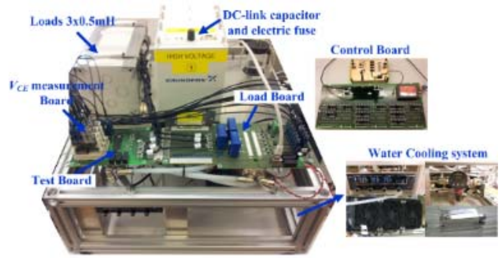
Key research activities in reliability tools

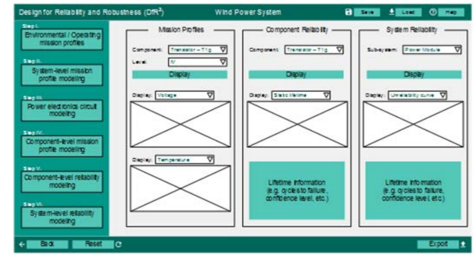
▶ Current Project Example 2 - REPEPS

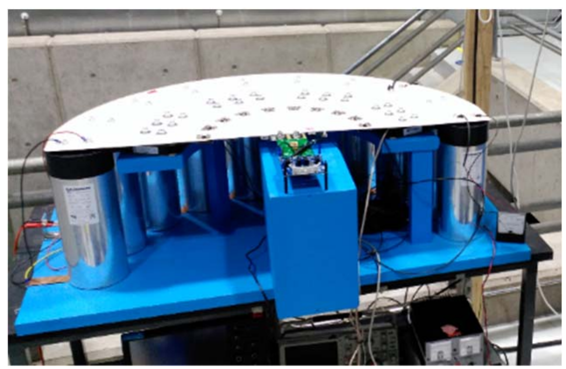
REPEPS - Reliable Power Electronic based Power System (2018-2023)



▶ Part Examples of Research Infrastructures







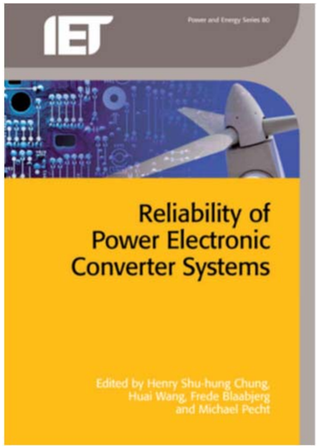
▶ Introduced New Courses in Energy Technology

Industrial/PhD Courses

- Reliability in power electronics systems (3 days, since 2013)
- Modern power semiconductors and their packaging (3 days, since 2016)
- Capacitors in Power Electronic Applications (2 days, since 2017)
- D-FMEA (Design Failure Mode and Effect Analysis) (4 days, 2017 workshop, since 2018 becomes a course)
- ...

Master Course

- Modern reliability from a practical approach (one-semester, since 2014)



First book on Reliability of Power Electronic Converter System (IET, 2015)

▶ Course - Reliability in Power Electronics Systems 2018

Description of the course

The course will present the state-of-the-art research results from the Center of Reliable Power Electronics (CORPE) at Aalborg University and the collaborated companies and universities. It was firstly introduced in 2013 as one of the very first courses in its kind in the world. The 2018 version of the course will cover the following aspects:

- Introduction to modern reliability and robustness approach
- Reliability testing methods and testing data analysis (e.g., Weibull)
- Long-term wear out and single-event abnormal operation of active power modules and capacitors
- Design tools and system-level reliability analysis of power electronic converters
- Condition monitoring and thermal control of critical power electronic components

30% of the time of the course will be exercises and hand-on experiments in the field of reliability

Keep yourselves updated at www.et.aau.dk

Fee

6000 DKK for PhD students outside of Denmark and 1500 DKK for PhD students in Denmark, who is not from AAU. 8000 DKK for the Industry.

Credits

3.0 ECTS

Registration

No later than **15 August 2018** by the following link: https://phd.moodle.aau.dk/

Further information

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Phone +45 9940 3816
E-mail: hwa@et.aau.dk

Accommodation

For hotel information and booking, please see our webpage: http://www.et.aau.dk/phd/phd-courses/

Place

Aalborg University, Institute of Energy Technology
Pontoppidanstraede
DK-9220 Aalborg East, Denmark

Language

English

Prerequisites

Basic understanding of power electronics, power semiconductor devices, capacitors, and basic statistics.

Literature

[1] H. Chung, H. Wang, F. Blaabjerg, and M. Pecht, *Reliability of power electronic converter systems*, ISBN: 978-1-84919-901-8, IET, Dec. 2015.

[2] J. W. McPherson, *Reliability Physics and Engineering: Time-To-Failure Modelling*, Springer, 2010.

[3] *Handbook for Robustness Validation of Automotive Electrical/Electronic Modules*, ZVEI, Frankfurt am Main, Germany, Jun. 2013.

September 5, 2018, 08.30-16.30

L0 Course introduction

L1 Training in understanding Weibull

Exc1- Exercises on basic concepts of statistics

L2 Introduction to modern reliability in industry

L3 MCF curve, cost of poor reliability, robustness

L4 Lifetime budgets, degradation

L5 Reliability test facilities, ALT and CALT

Exc2-Lifetime estimation using data provided by companies

L6 Reliability testing from DELTA perspective

September 6, 2018, 08.30-16.30

L7 Reliability of active switching devices (IGBTs)
- Basic semiconductor physics
- Failure mechanisms (wear out; at the edge of SOA)
- Electro-thermal-lifetime modelling
- A lifetime prediction tool for IGBT modules
- Condition monitoring of IGBT modules

L8 Reliability of passive components (capacitors)
- Basic capacitor physics
- Failure mechanisms (wear out; severe conditions)
- Electro-thermal-lifetime modelling
- Active capacitive DC-links
- Condition monitoring of capacitors

September 7, 2018, 08.30-15.40

L9 Reliability challenges in power electronics and design for reliability concept

L10 System-level reliability prediction – approaches and case studies

Exc3-Design of a 10 kW PV inverter with B10 lifetime of 10 years

Tour visit to CORPE facilities

3 Lab Sessions on Sept. 5 – 7, 2018

Lab1 Non-destructive testing of active devices

Lab2 Reliability testing of capacitors

Lab3 Power cycling testing of IGBT modules

Lecturers

- Prof. Frede Blaabjerg, Aalborg University, Denmark
- Associate Prof. Huai Wang, Aalborg University, Denmark
- Advisor Peter de Place Rimmen, Danfoss Power Electronics A/S, Denmark
- Prof. Francesco Iannuzzo, Aalborg University, Denmark

► Course - Capacitors in Power Electronic Applications 2018

Description of the course

Capacitors are one of the key components in typical power electronic systems in terms of cost, volume, and reliability. Power electronics applications are consuming unprecedented quantities of electrolytic capacitors, film capacitors, and ceramic capacitors. This industrial/PhD course will discuss the sizing, modeling, and reliability analysis of capacitors from an application perspective, focusing on both classical and emerging power electronics applications. It is the latest research outcome of several PhD projects and industrial collaboration activities. It was firstly introduced in 2017 as one of the very first courses in its kind in the world. The 2018 version of the course will cover the following aspects:

- Basics of capacitors and its functions in power electronic converters
- Emerging capacitor technologies and latest developments
- Capacitor sizing criteria in power electronics by considering steady-state performance, transient and stability performance under both normal and abnormal operations
- Reliability of electrolytic capacitors, film capacitors, and ceramic capacitors
- Mission profiled based electro-thermal-lifetime modeling of capacitors
- Condition monitoring and protection of capacitors in power electronics applications
- Capacitor minimization techniques in power electronic systems
- Case studies in DC-DC converters, Modular Multi-level Converters (MMC), photovoltaic inverters, and ultra-low inductive capacitor bank design.

30% of the time of the course will be hands-on exercises and lab experiments.

Keep yourselves updated at www.et.aau.dk

Fee

6000 DKK for PhD students outside of Denmark and 1500 DKK for PhD students in Denmark, who is not from AAU. 8000 DKK for the Industry.

Credits

2.0 ECTS

Registration

No later than **1 November 2018** by the following link: https://phd.moodle.aau.dk/

Further information

Prof. Huai Wang
Aalborg University, Department of Energy Technology
Pontoppidanstraede 101, DK-9220 Aalborg, Denmark
Phone +45 9940 3816
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Accommodation

For hotel information and booking, please see our webpage: http://www.et.aau.dk/phd/phd-courses/

Place

Aalborg University, Institute of Energy Technology
Pontoppidanstraede
DK-9220 Aalborg East, Denmark

Language

English

Prerequisites

Basic understanding of power electronics circuits and control

November 22, 2018, 08.30-16.30

L0 Course introduction

L1 Basics of capacitors and emerging capacitor technologies

- Introduction to dielectric materials of capacitors
- Comparisons of different types of capacitors
- Failure mechanisms of capacitors
- Emerging capacitor technologies for power electronic applications

L2 Electro-thermal-lifetime modelling of capacitors

- Capacitor ripple current modelling
- Capacitor thermal modelling
- Lifetime modelling of electrolytic capacitors and film capacitors

Exc 1 - Mission profile based capacitor lifetime modelling

Lab 1 – Capacitor thermal characterization

L3 Accelerated degradation testing of capacitors

Exc 2 - Step-by-step capacitor lifetime data analysis

L4 Condition monitoring of capacitors

November 23, 2018, 08.30-15.30

L5 Capacitor sizing criteria in power electronics

- Steady-state performance related criteria
- Transient and stability related criteria

L6 Active capacitors with semiconductor circuits

- Review of active capacitor concepts
- Two-terminal active capacitors
- Applications of two-terminal active capacitors

L7 Capacitor application case studies

- Capacitor bank optimization in DC-DC converters
- Low-inductive bus bar design
- Capacitor sizing for modular multi-level converter

Exc 3 - Step-by-step capacitor sizing for a PV inverter with specified reliability specifications

Course feedback

Tour visit to CORPE capacitor facilities

Lecturer

- Associate Prof. Huai Wang, Aalborg University, Denmark

► References

1. H. Wang, and F. Blaabjerg, Aalborg University fosters multi-disciplinary approach to research in efficient and reliable power electronics, How2power today, issue Feb. 2015.
2. H. Chung, H. Wang, Frede Blaabjerg, and Michael Pecht, *Reliability of power electronic converter systems*, IET, 2015.
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▶ Short Bio.

Huai Wang is currently an Associate Professor and a Research Thrust Leader with the Center of Reliable Power Electronics (CORPE), Aalborg University, Denmark. His research addresses the fundamental challenges in modelling and validation of power electronic component failure mechanisms, and application issues in system-level predictability, condition monitoring, circuit architecture, and robustness design. In CORPE, he also leads a capacitor research group including multiple PhD projects on capacitors and its applications in power electronic systems, and collaborates with various industry companies across the value chain from manufacturers to end-users of capacitors. Prof. Wang lectures two Industrial/PhD courses on Capacitors in Power Electronics Applications, and Reliability of Power Electronic Systems at Aalborg University. He has given more than 20 tutorials at leading power electronics and reliability engineering conferences (e.g., ECCE, APEC, IECON, PCIM, ESREF, etc.) and a few keynote speeches in the above research areas. He has co-edited a book on Reliability of Power Electronic Converter Systems in 2015, hold 2 patents, and filed another 4 patents in advanced passive component inventions. He has contracted a book with Wiley on Capacitors in Power Electronics Applications: Sizing, Modeling, and Reliability (ISBN: 978-1-119-28734-6).

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