Reliability of Power Electronics in Photovoltaic Systems:

Design and Control Solutions

Ariya Sangwongwanich

Department of Energy Technology
Aalborg University, Denmark
ars@energy.aau.dk

REPEPS
REliable Power Electronic based Power System

AALBORG UNIVERSITY
DENMARK

CORPE

VILLUM FONDEN

About the presenters

Ariya Sangwongwanich received the M.Sc. and Ph.D. degree in energy engineering from Aalborg University, Denmark, in 2015 and 2018, respectively. He is currently working as an Assistant Professor at the Department of Energy Technology, Aalborg University, where he is a Vice-Leader of Photovoltaic Systems research program. His research interests include control of grid-connected converters, photovoltaic systems, reliability in power electronics, and multi-level converters.

He was a Visiting Researcher with RWTH Aachen, Aachen, Germany from September to December 2017. Dr. Sangwongwanich was the recipient of the Danish Academy of Natural Sciences' Ph.D. Prize and the Spar Nord Foundation Research Award for his Ph.D. thesis in 2019.

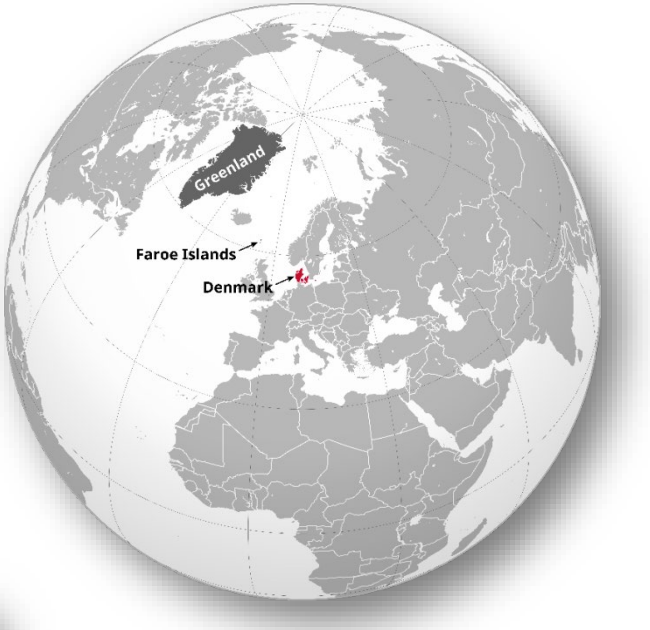
Research:

- ☐ Control and reliability of power electronics systems
- ☐ Photovoltaic systems and battery integration
- ☐ Multi-level power converters
- ☐ https://vbn.aau.dk/en/persons/132201

Teaching:

- ☐ PhD course: Photovoltaic power systems, Reliability of power electronics in PV systems, etc.
- ☐ MSc course: Control of grid connected PV and WT Systems
- ☐ Bachelor course: Power electronics

Aalborg University - Denmark



Inaugurated in 1974
22,000 students
2,300 faculty

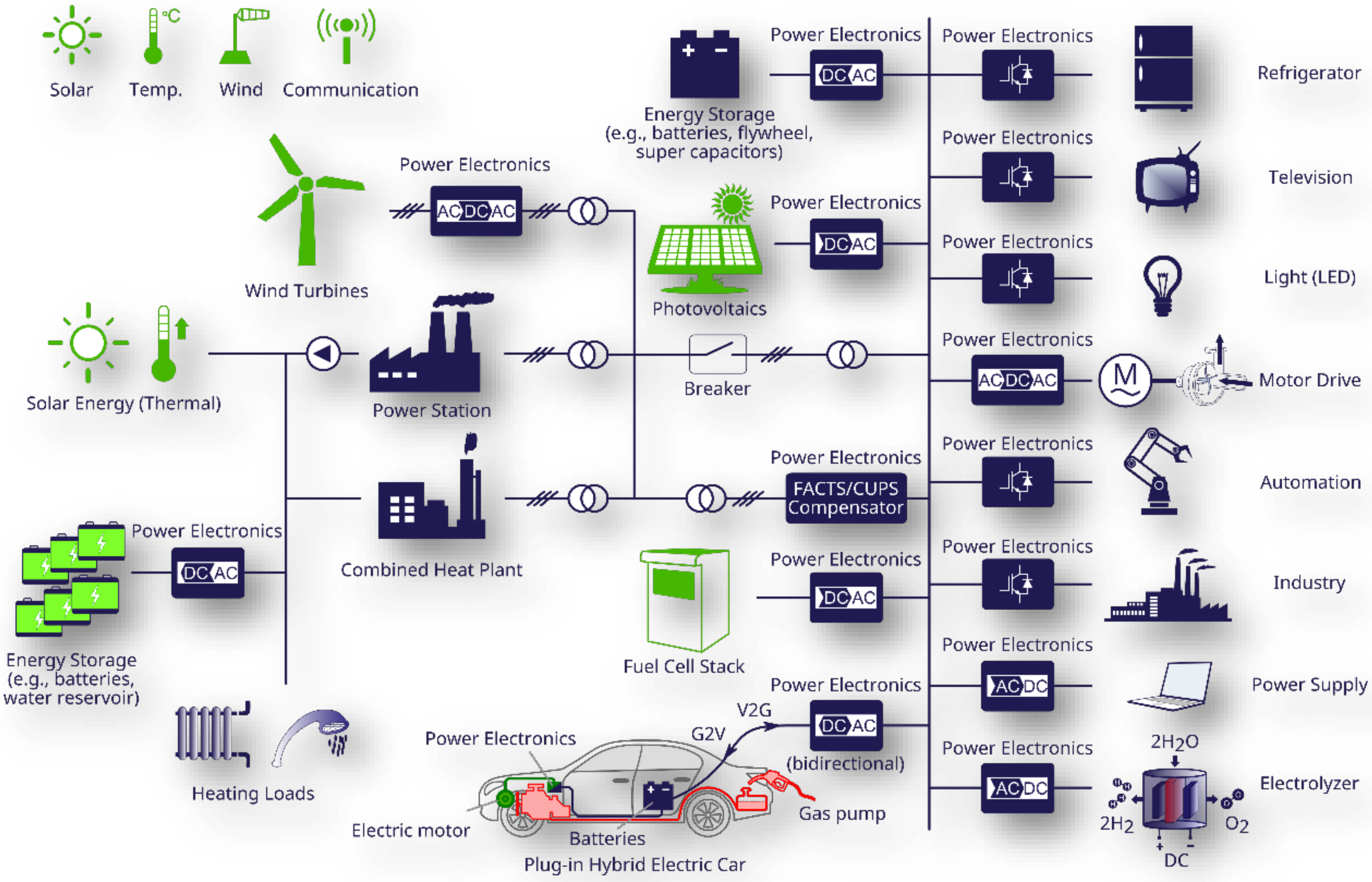
PBL-Aalborg Model
(Problem-based learning)

Adapted from Wikimedia Commons: https://upload.wikimedia.org/wikipedia/commons/c/c1/Denmark_regions.svg

Aalborg University - Campus

Aalborg University - Campus

Department of Energy Technology



Energy Production | Distribution | Consumption | Control

PV Systems Research Program

4 QUALITY EDUCATION
7 AFFORDABLE AND CLEAN ENERGY
11 SUSTAINABLE CITIES AND COMMUNITIES
13 CLIMATE ACTION

SUSTAINABLE DEVELOPMENT GOALS

Focus areas:

- Control and topologies of PV inverters
- Grid integration of PV power
- Reliability of PV inverters
- PV and energy storage integration
- Electrical characterization and fault detection in PV panels and arrays
- Electroluminescence and infrared thermography - based diagnostics

www.pv-systems.et.aau.dk

Research Infrastructures

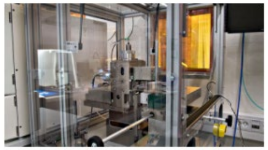
X-POWER

A world-class testing center.
Supporting fundamental research, PoC and facilitate development and validation of industry products.

+

POWER ELECTRONICS CONVERTER LABORATORY

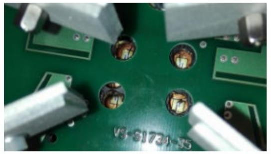
POWER ELECTRONICS PACKAGING



PV SYSTEMS LABORATORY

BATTERY SYSTEMS TEST LABORATORY

POWER ELECTRONICS RELIABILITY LABORATORY



POWER ELECTRONICS POWER DISTRIBUTION LABORATORY

PV OUTDOOR TEST AND MONITORING PLATFORM

DRIVES TEST LABORATORY

POWER ELECTRONICS COMPONENT ANALYSIS LABORATORY

ADVANCED CONTROL OF POWER CONVERTERS FOR FUTURE ENERGY SYSTEMS

EMC LABORATORY

DRIVES CONTROL LABORATORY

and More…

http://www.et.aau.dk/laboratories/

Outline

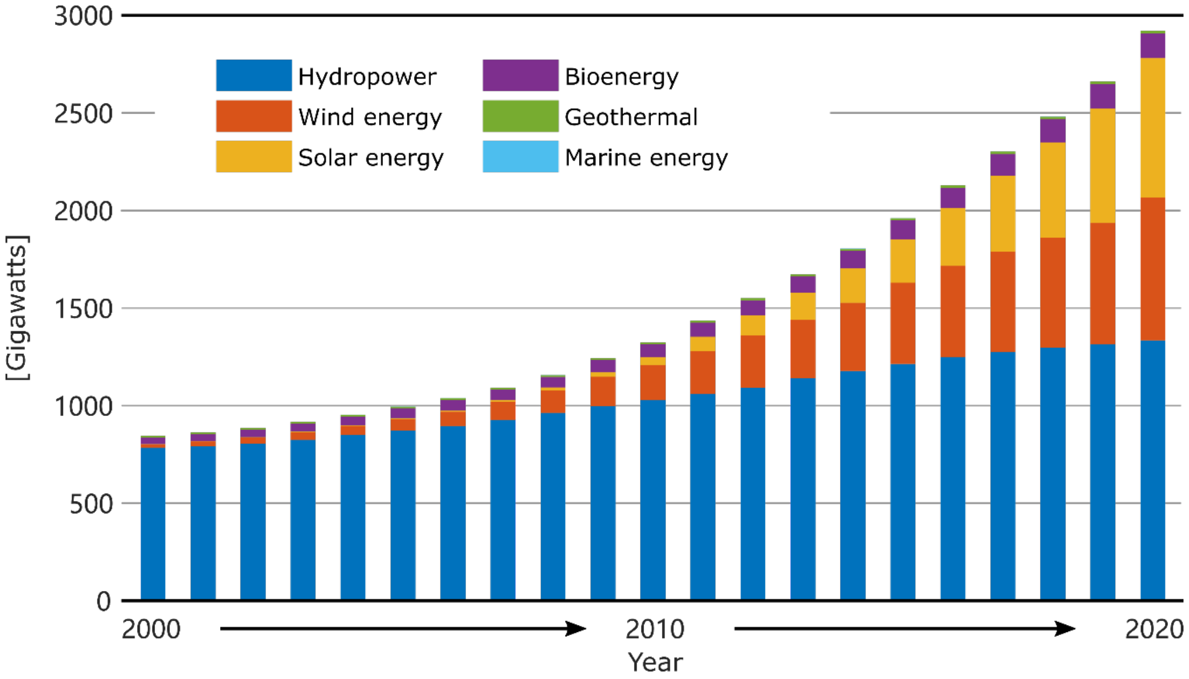
- Introduction
- Reliability of power electronics in PV systems
- Design for Reliability
- Practical/Industry application
- Conclusion

Outline

Reliability of power electronics in PV systems

- Demands to lower LCOE
- Failures in PV systems
- Wear-out of components

State of the Art – Renewable Evolution



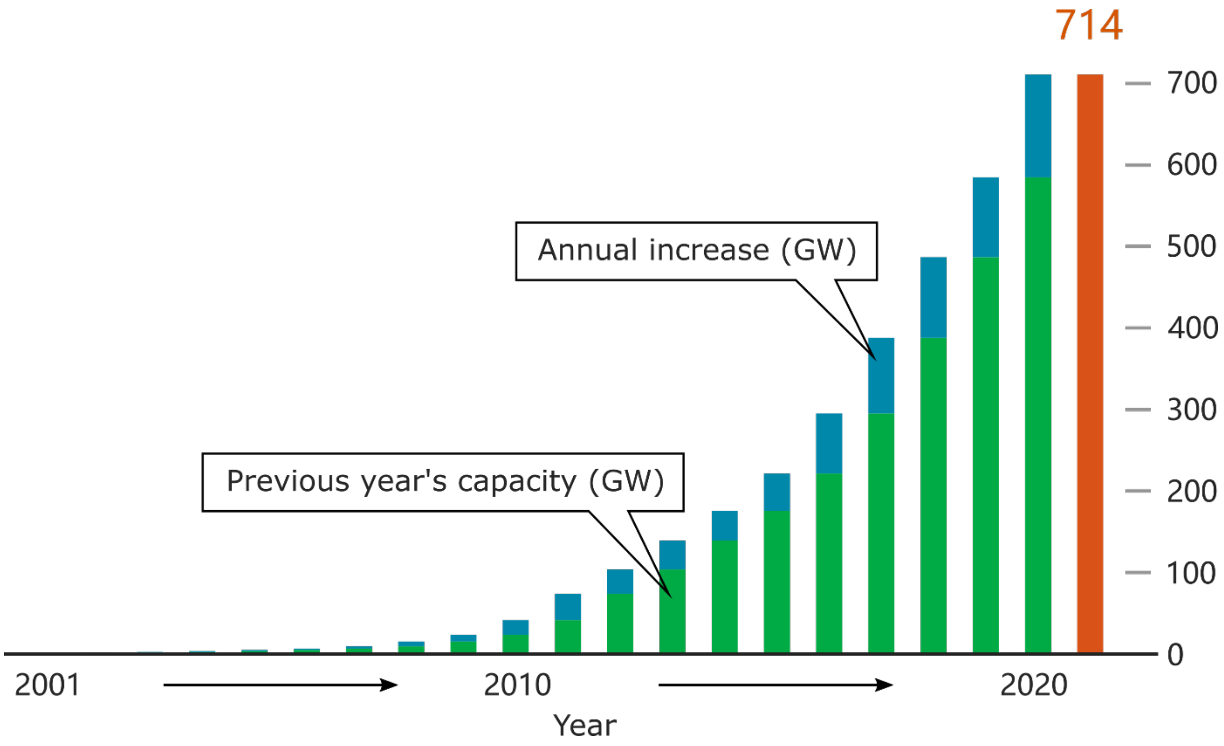
Global Renewable Energy Annual Changes in Gigawatt (2000-2020)

(close to **3000** GW in total)

1. Hydropower also includes pumped storage and mixed plants;
2. Marine energy covers tide, wave, and ocean energy
3. Solar includes photovoltaics and solar thermal
4. Wind includes both onshore and offshore wind energy

(Source: IRENA, “Renewable energy capacity statistics 2020”, http://www.irena.org/publications, March 2020)

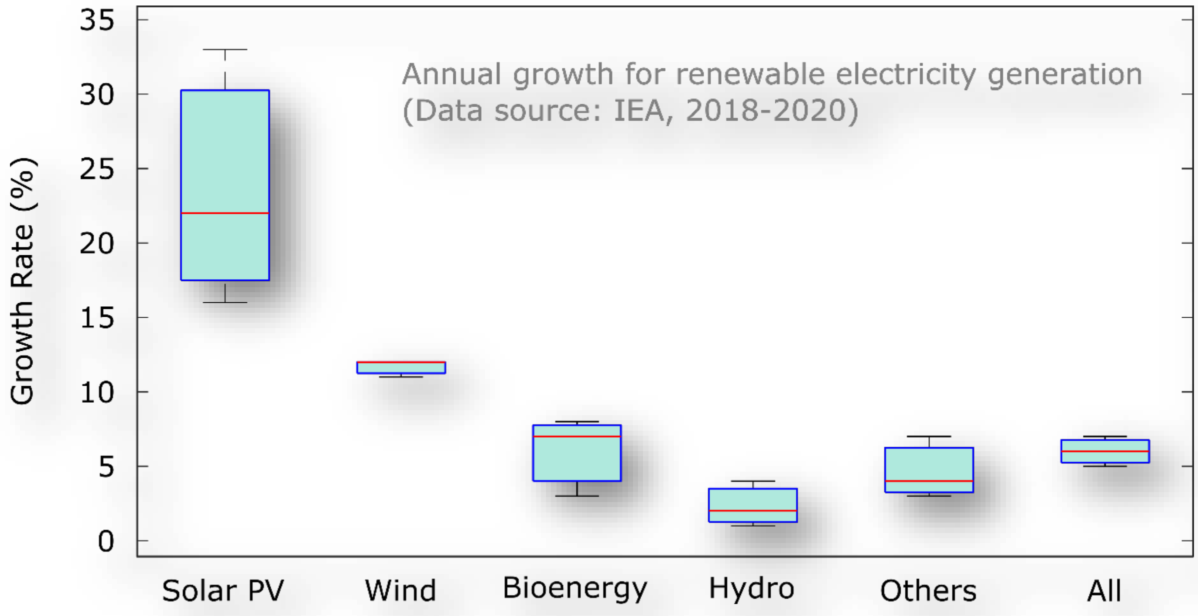
State of the Art Development – PV Power



Global installed solar PV capacity (until 2020): **714** GW, 2020: **127** GW

- More significant total capacity (45 % non-hydro renewables).
- Fastest growth rate (22 % between 2018-2020, 33% in 2018).

State of the Art Development – PV Power



Global installed solar PV capacity (until 2020): **714** GW, 2019: **127** GW

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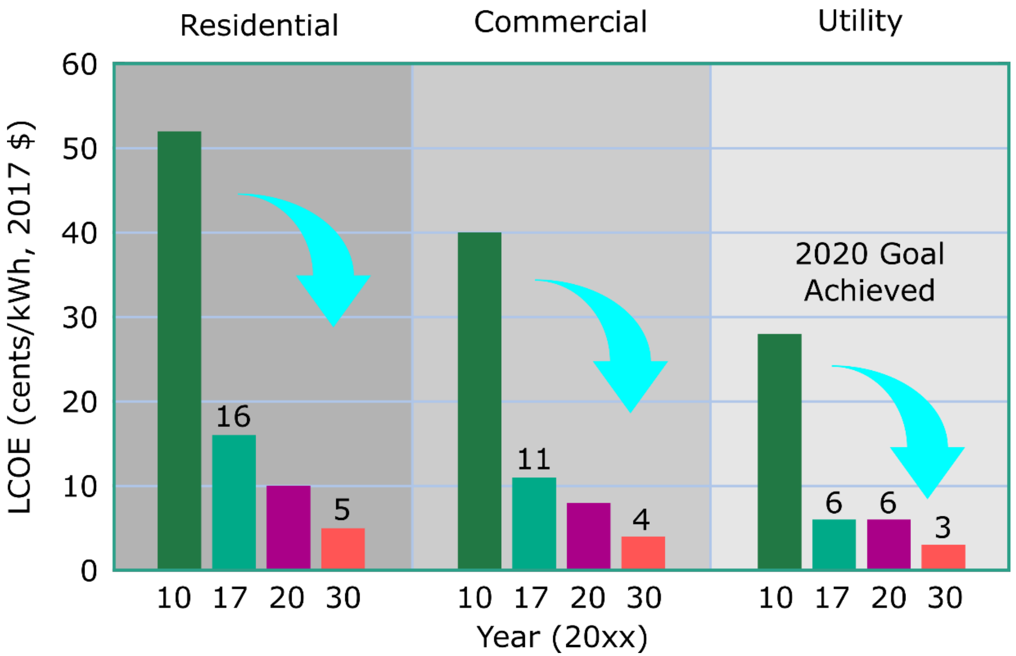
Future Target

Increasing competitiveness by lowering **Cost of Energy**

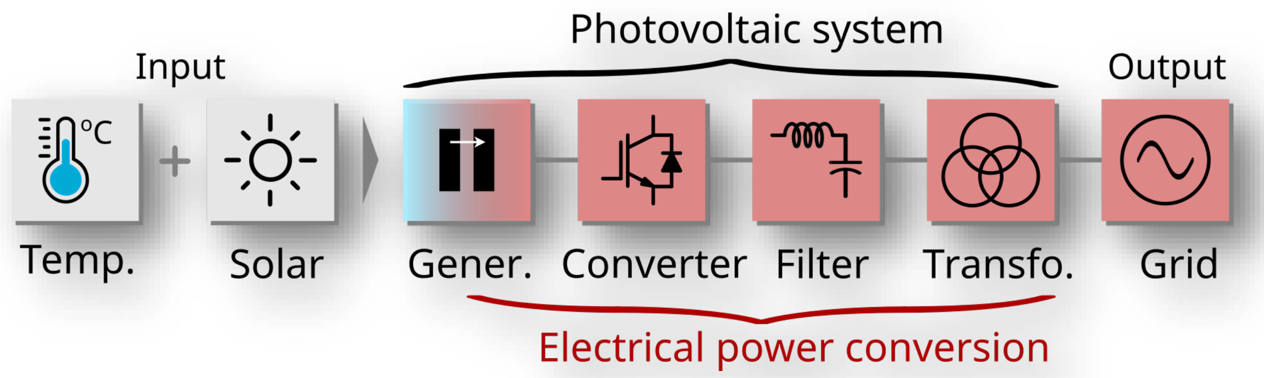


In 2017, DOE's Solar Energy Technologies Office (SETO) announced that the industry had achieved the 2020 cost goal for utility-scale solar of 6¢ per kilowatt hour (kWh).

*Levelized cost of electricity (LCOE) progress and targets are calculated based on average U.S. climate and without the ITC or state/local incentives. The residential and commercial goals have been adjusted for inflation from 2010–17.

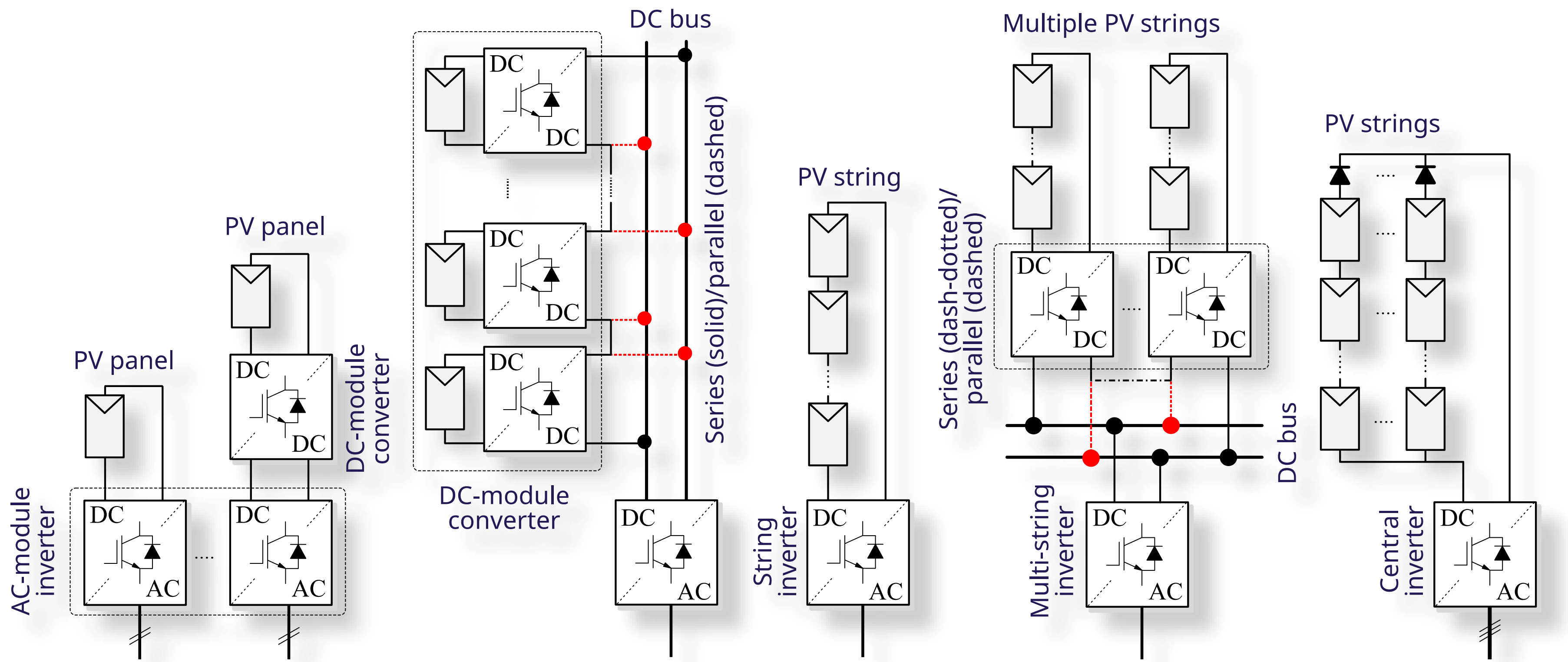
How to integrate?

General Photovoltaic power conversion (grid integration)



- **Photovoltaic Effect**
  Power generation is dependent on the ambient conditions
- **Power Electronics**
  Power converters are essential to realize the power transfer
- **Power Grid**
  Synchronous generator governed system with fixed freq. and voltage

PV inverter system configurations



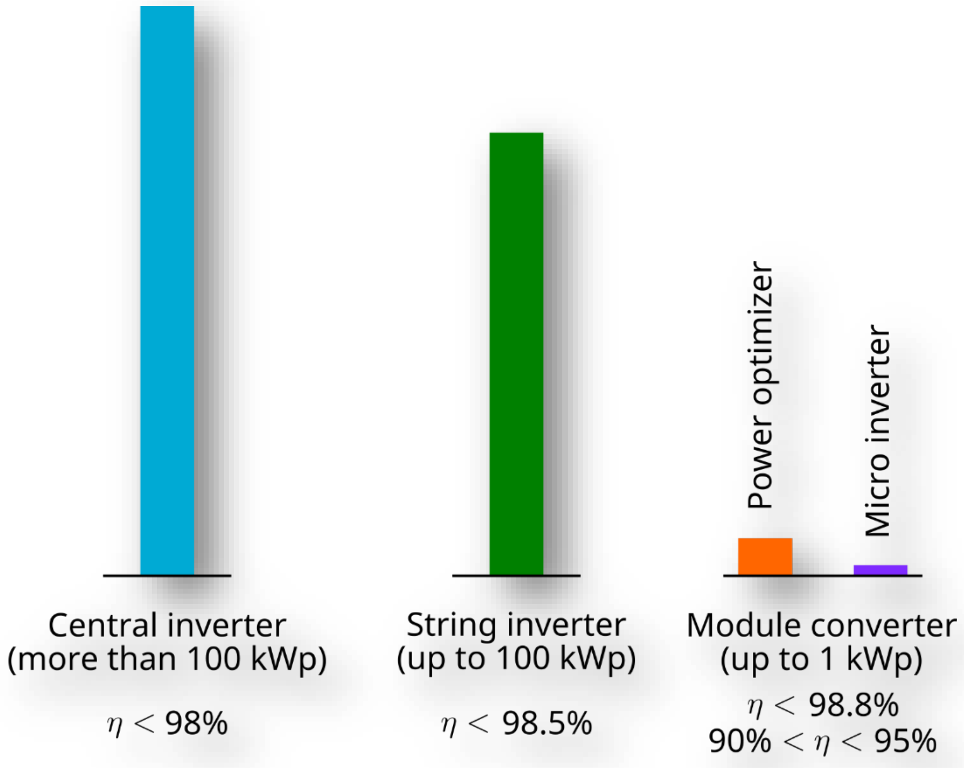
Module Converter	DC Grid	String/Multistring Converter	Central Inverter
Single-phase Hundreds watts Small systems	DC grid → AC grid Single-/three-phase Several kilowatts Small systems / resisdential	Single-/three-phase 1~30 kW applications Residential/commercial	Three-phase 30~ kW Commercial / utility-scale

Chapter 03 in *Renewable energy devices and systems with simulations in MATLAB and ANSYS*, Editors: F. Blaabjerg and D.M. Ionel, CRC Press LLC, 2017

Market size of different PV configuration

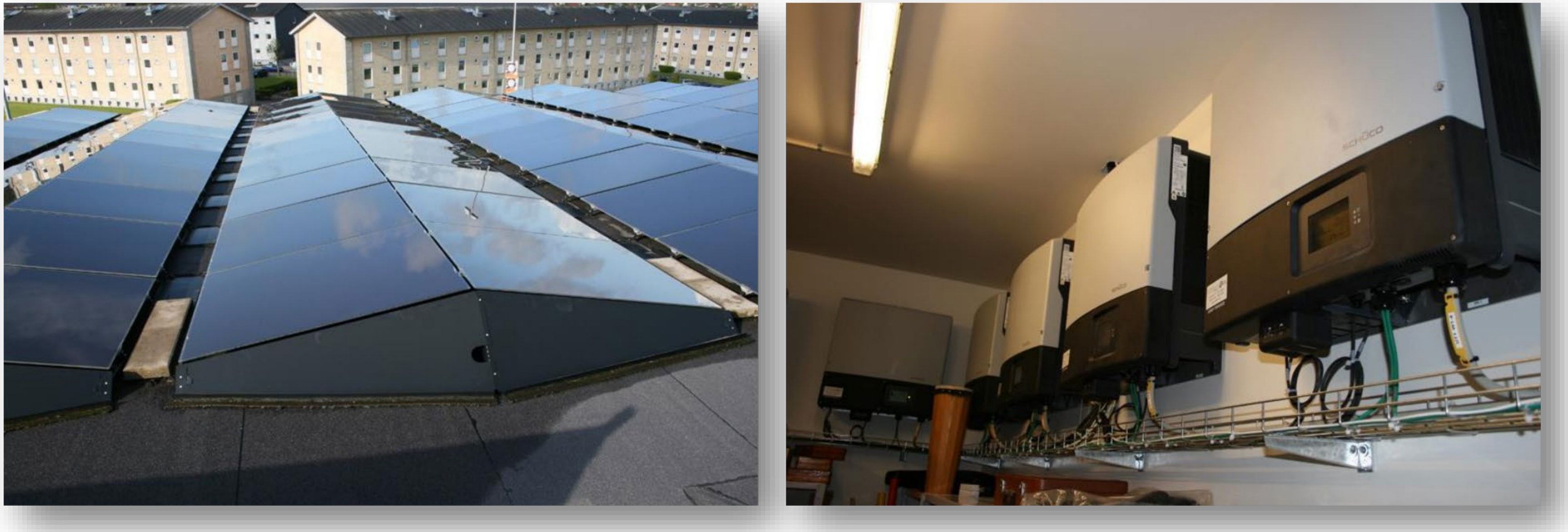
Center and String Inverters are dominating the market

(market share in respect to the central inverter – the base value)



Examples

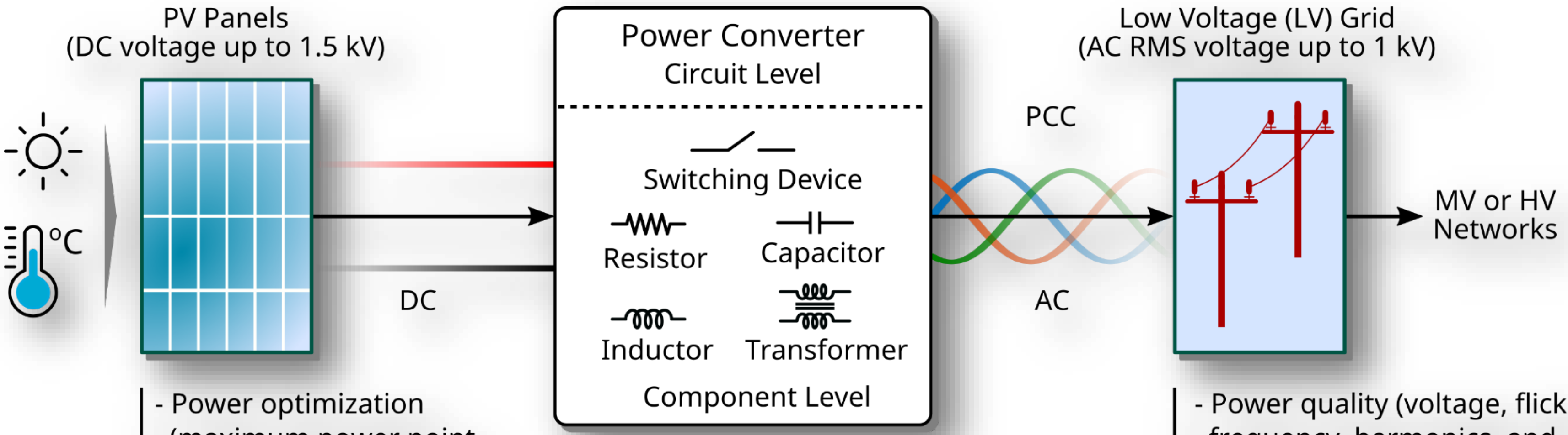
String inverter solution



Rooftop-installed PV systems: (a) PV arrays with a total rating of 60 kW installed on the roof of Aalborghus High School in Denmark and (b) power electronic converters with the schematic are installed within the building and are connected to the AC grid.

Demands on PV Systems

Power converter – key enabling technology for PV integration



PV Panels
(DC voltage up to 1.5 kV)

°C

DC

Power Converter
Circuit Level

Switching Device

Resistor

Capacitor

Inductor

Transformer

Component Level

PCC

AC

Low Voltage (LV) Grid
(AC RMS voltage up to 1 kV)

MV or HV
Networks

- Power optimization (maximum power point tracking - MPPT)
- DC voltage/current control
- Monitoring and diagnosis

- Converter controllability
- Conversion efficiency
- Reliability
- Thermal management
- Energy management
- Islanding detection/protection
- Response to grid recovery
- Monitoring and safety
- Communication

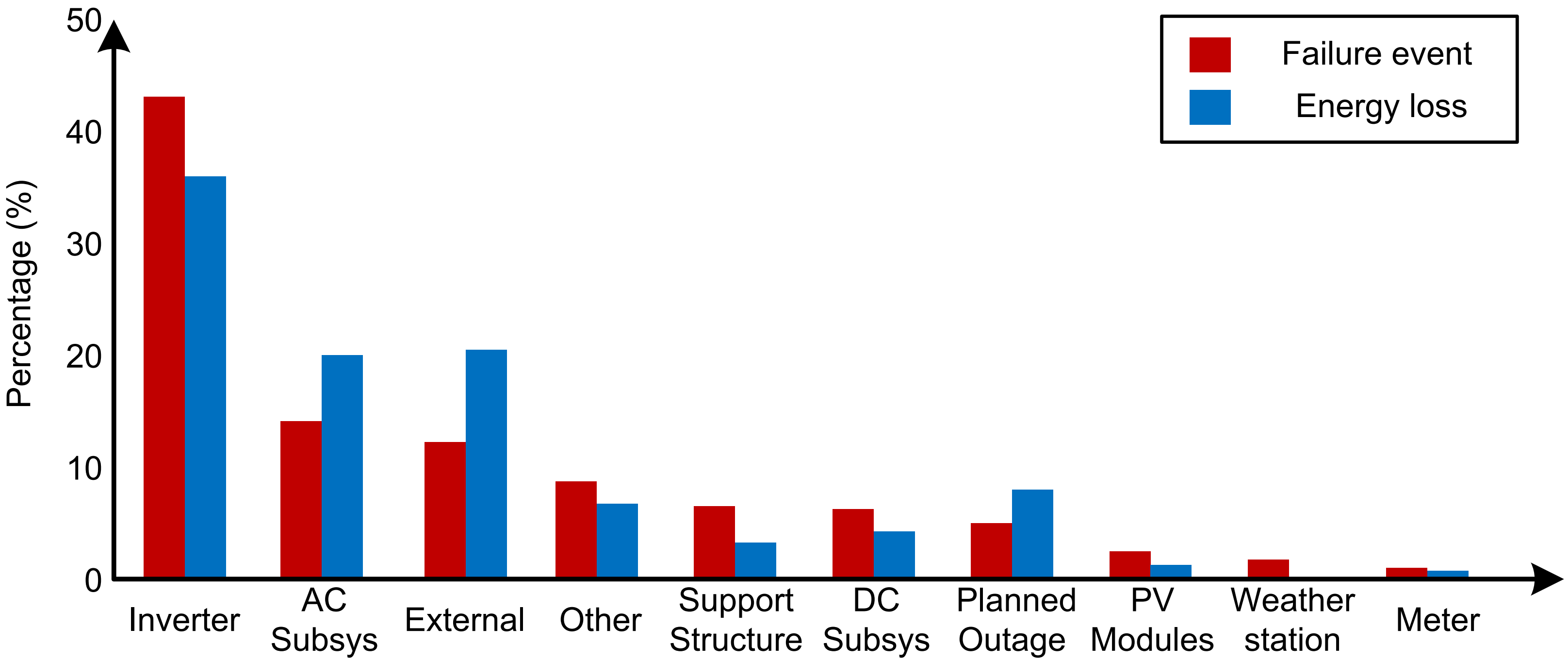
- Power quality (voltage, flicker, frequency, harmonics, and power factor)
- Power flow controllability

Supportive Schemes for MV/HV

- Frequency-Watt control
- Voltage-VAr control
- Fault ride-through
- Grid-forming
- Inertia provision

Failure in Photovoltaic systems

Inverters are accounted for a majority of failure event & energy loss

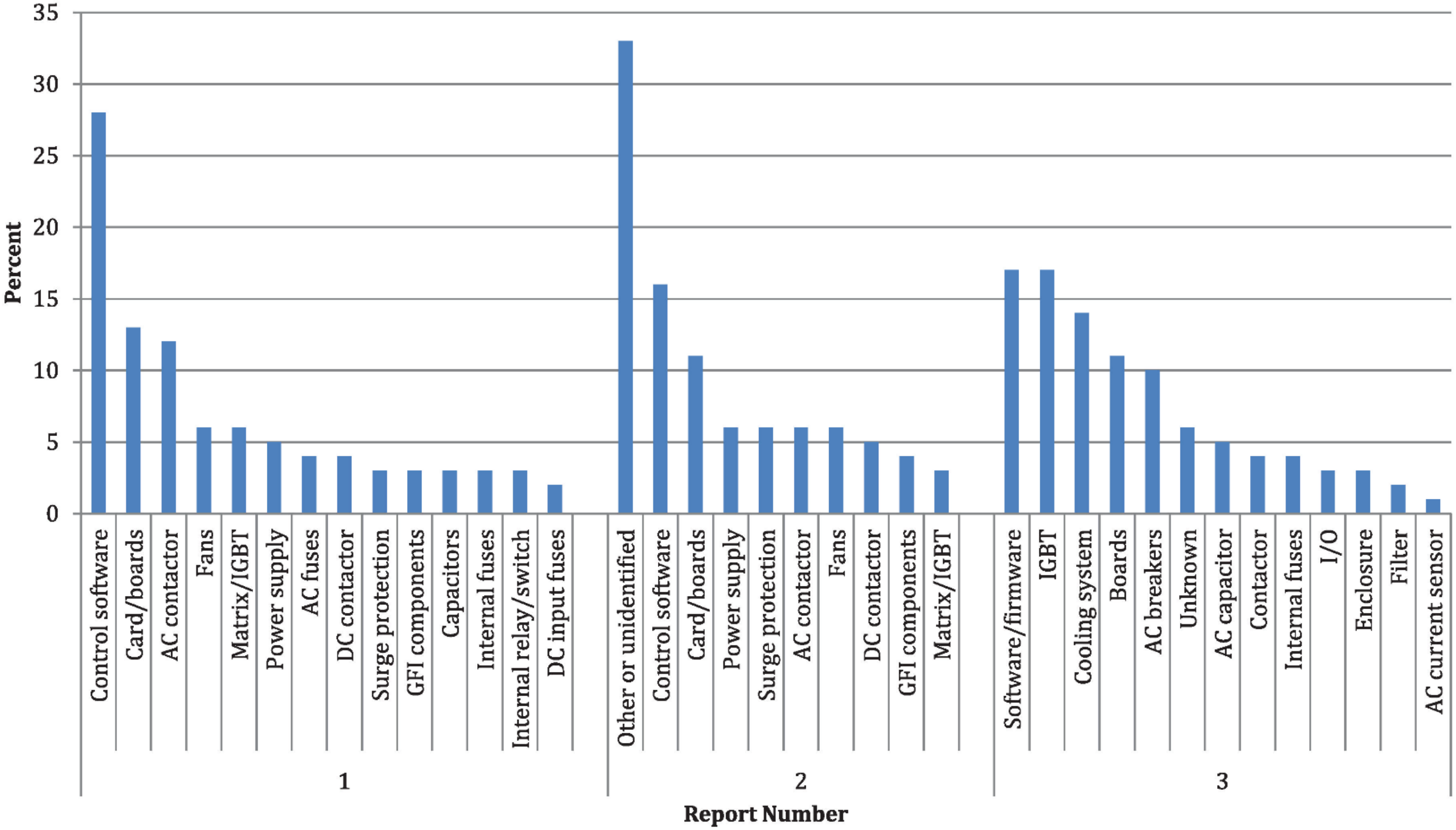


- Reliability (availability) is the key performance parameter of PV systems

[1] **“PV System Reliability—An owner’s perspective”** SunEdison 2012.

An example of field experiences in PV application

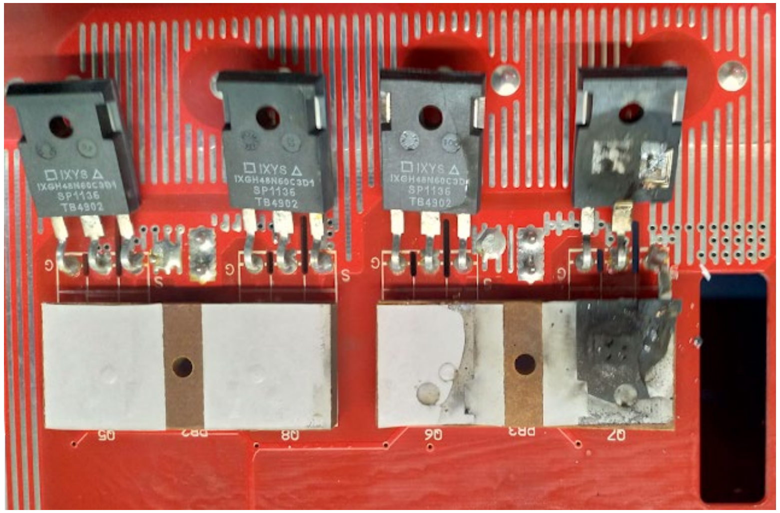
Source: P. Hacke, S. Lokanath, P. Williams, A. Vasan, P. Sochor, G. TamizhMani, H. Shinohara, and S. Kurtz, "A status review of photovoltaic power conversion equipment reliability safety and quality assurance protocols", Renewable and Sustainable Energy Reviews, vol. 82, no. 1, pp. 1097-1112, Feb. 2018.



PV Inverter failure component breakdown from three reports (in percentage), primarily for central inverters. (IGBT-Insulated gate bipolar transistors, GFIs – around fault interrupters)

Failure in power electronics systems

Real-field examples – it does not look good…

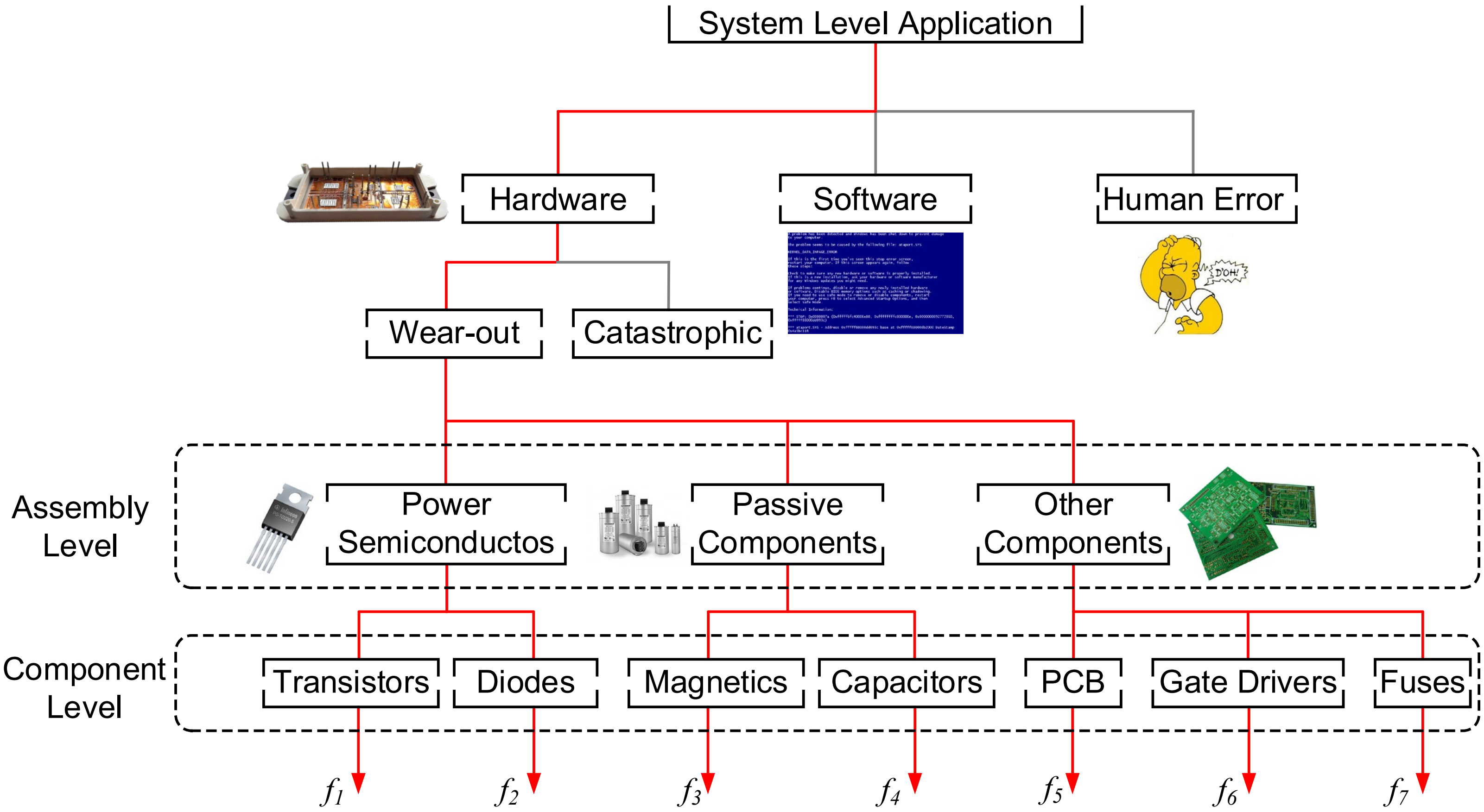


- Failure of small component can have a significant impact
- Cost, safety, reputation, etc.

[1] **https://twitter.com/roystonfire/status/993074938063015936/photo/1**
[2] **https://blog.logisense.com.au/2020/09/growatt-sungold-3000-failure.html**

Scientific challenges

Multi-components/multi-failure sources



System Level Application

Hardware

Software

Human Error

Wear-out

Catastrophic

Assembly Level

Power Semiconductos

Passive Components

Other Components

Component Level

Transistors

Diodes

Magnetics

Capacitors

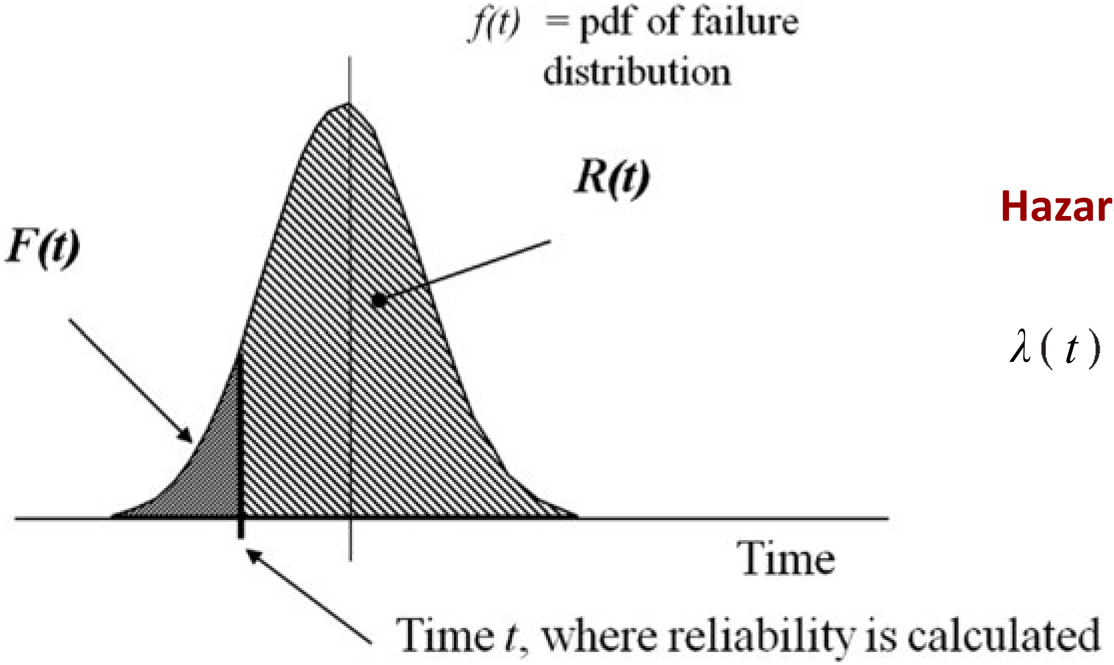
PCB

Gate Drivers

Fuses

f_1 f_2 f_3 f_4 f_5 f_6 f_7

Reliability, Unreliability, and Failure rate



Probability Density Function (pdf) and its application to reliability.

Hazard rate

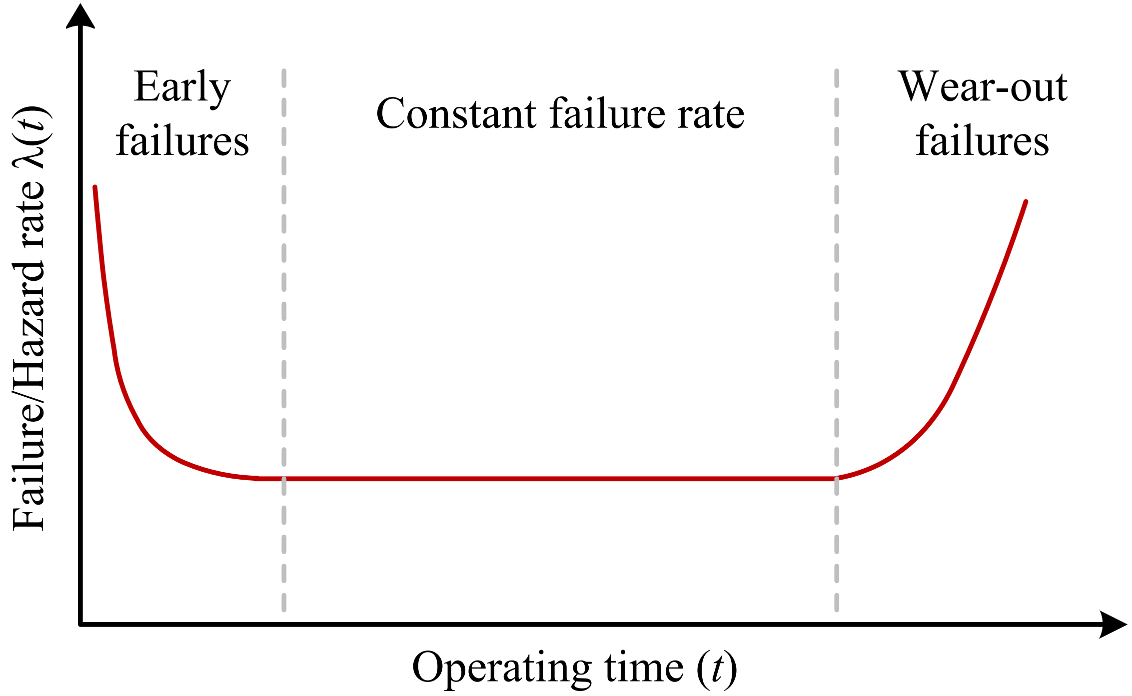
$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1 - F(t)}$$

Reliability Function

$$R(t) = 1 - F(t) = \int_{t}^{\infty} f(t)\,dt = 1 - \int_{-\infty}^{t} f(t)\,dt$$

Why do we have failure?

Bathtub curve



Start-up/Commissioning

- Decreasing failure rate
- Infant mortality

Normal operation

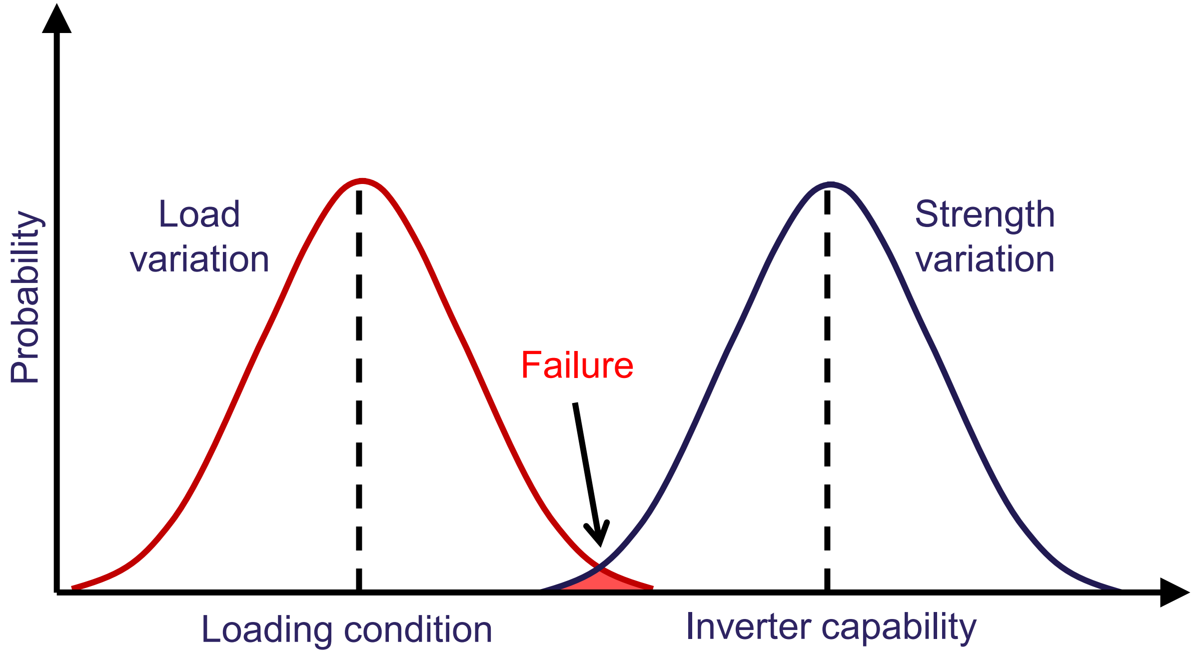
- Constant failure rate
- Random failures

End-of-life

- Increasing failure rate
- Wear-out

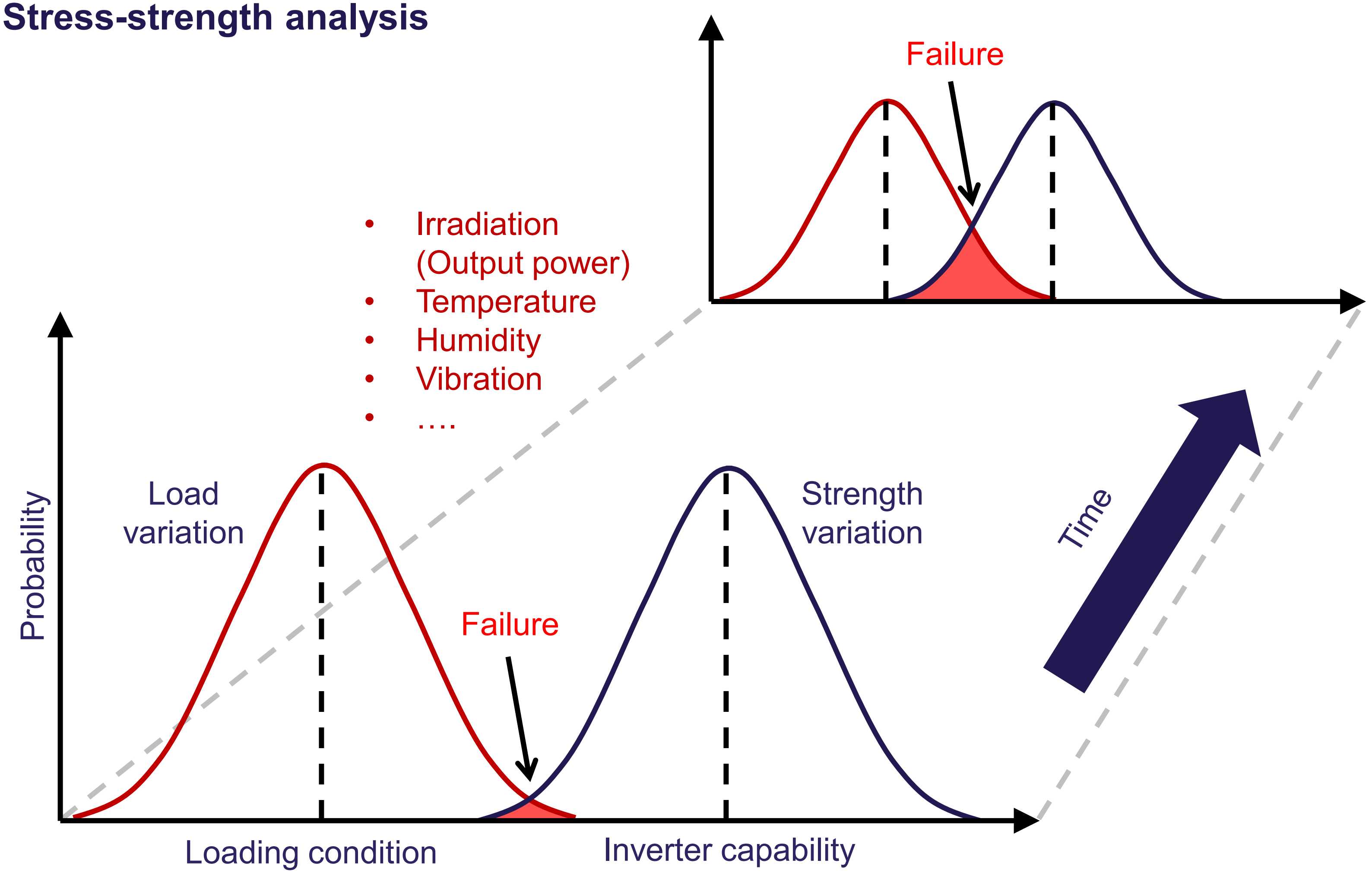
Component degradation

Stress-strength analysis



Component degradation

Stress-strength analysis



- Irradiation (Output power)
- Temperature
- Humidity
- Vibration
- ….

Outline

Design for Reliability

- Mission profile
- Electro-thermal modelling
- Reliability evaluation

Motivation for more reliable product design

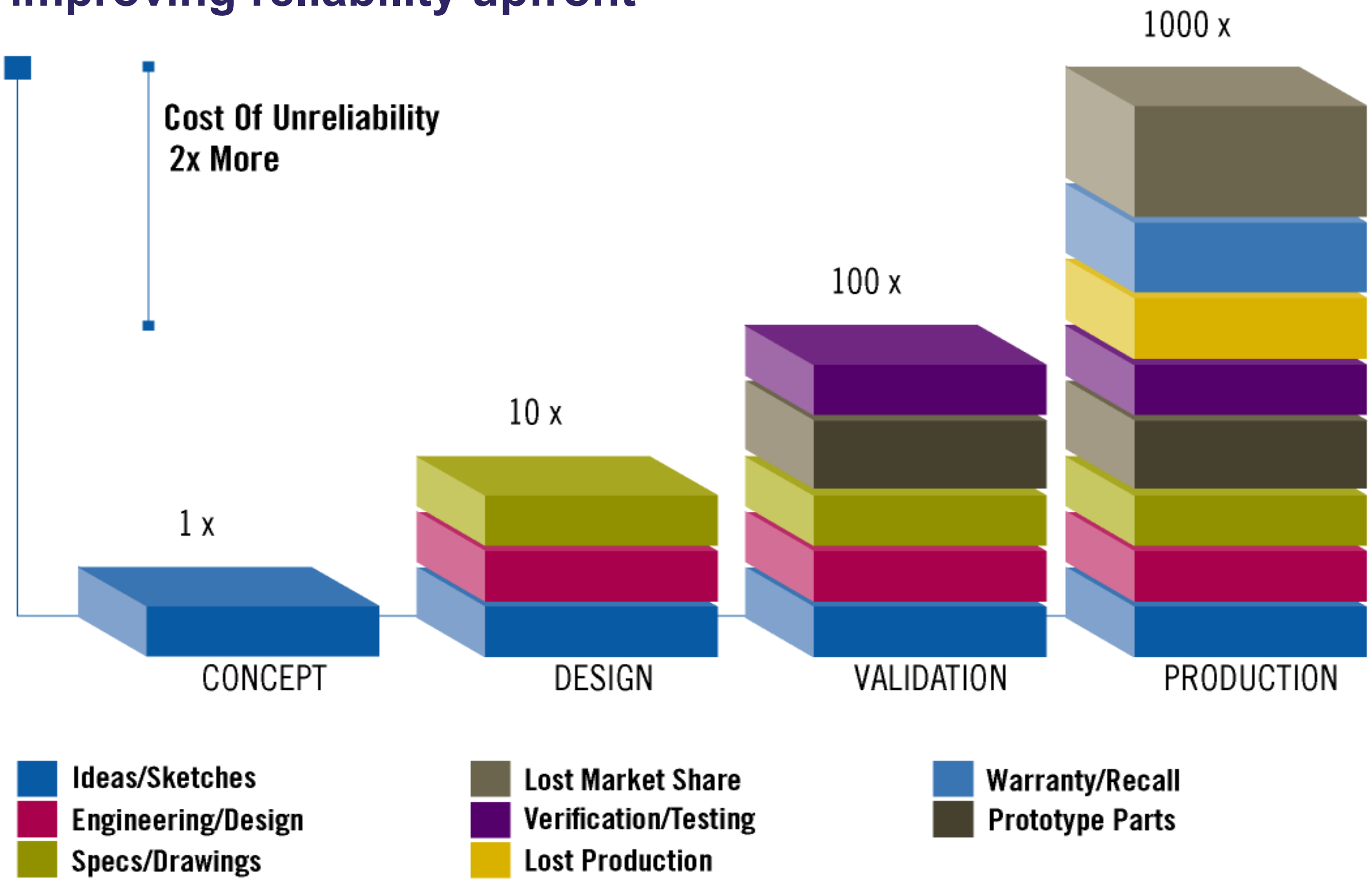
	Past	Present	Future
Customer expectations	➢ Replacement if failure ➢ Years of warranty	➢ Low risk of failure ➢ Request for maintenance	➢ Peace of mind ➢ **Predictive maintenance**
Reliability target	➢ Affordable returns (%)	➢ Low return rates	➢ **ppm return rates**
R&D approach	➢ Reliability test ➢ Avoid 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

Motivation for more reliable product design

Reduce costs by improving reliability upfront

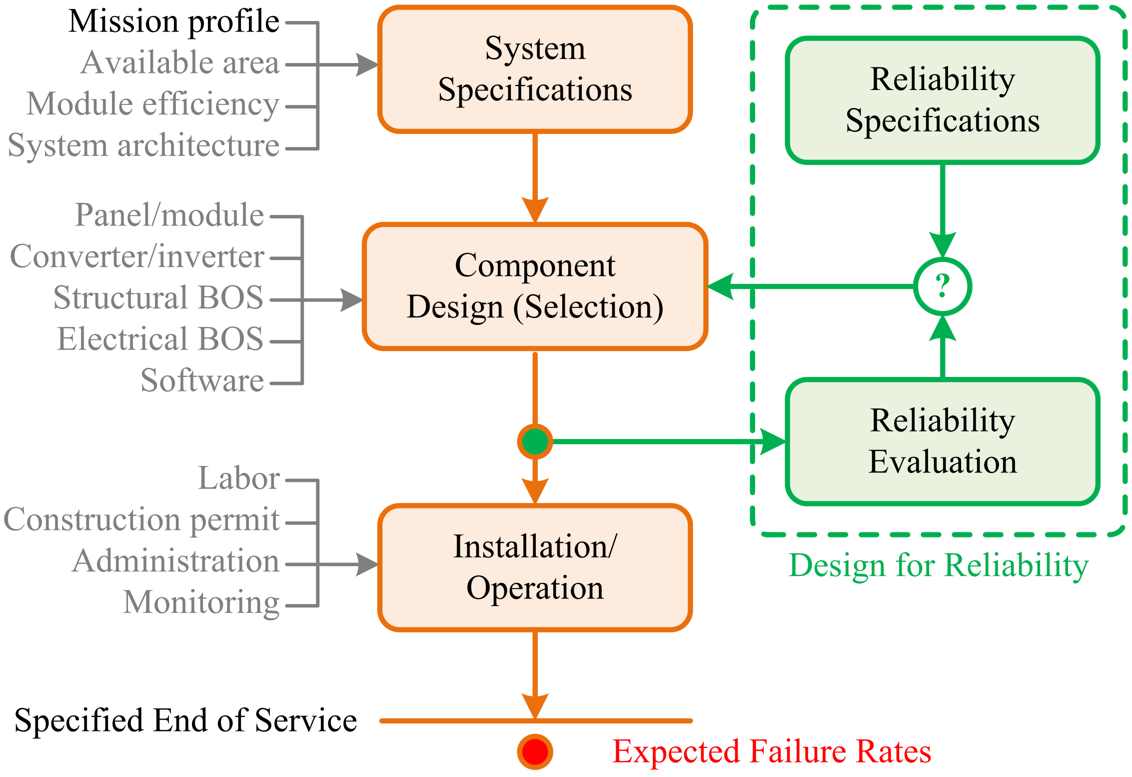


Source: DfR Solutions, Designing reliability in electronics, CORPE Workshop, 2012.

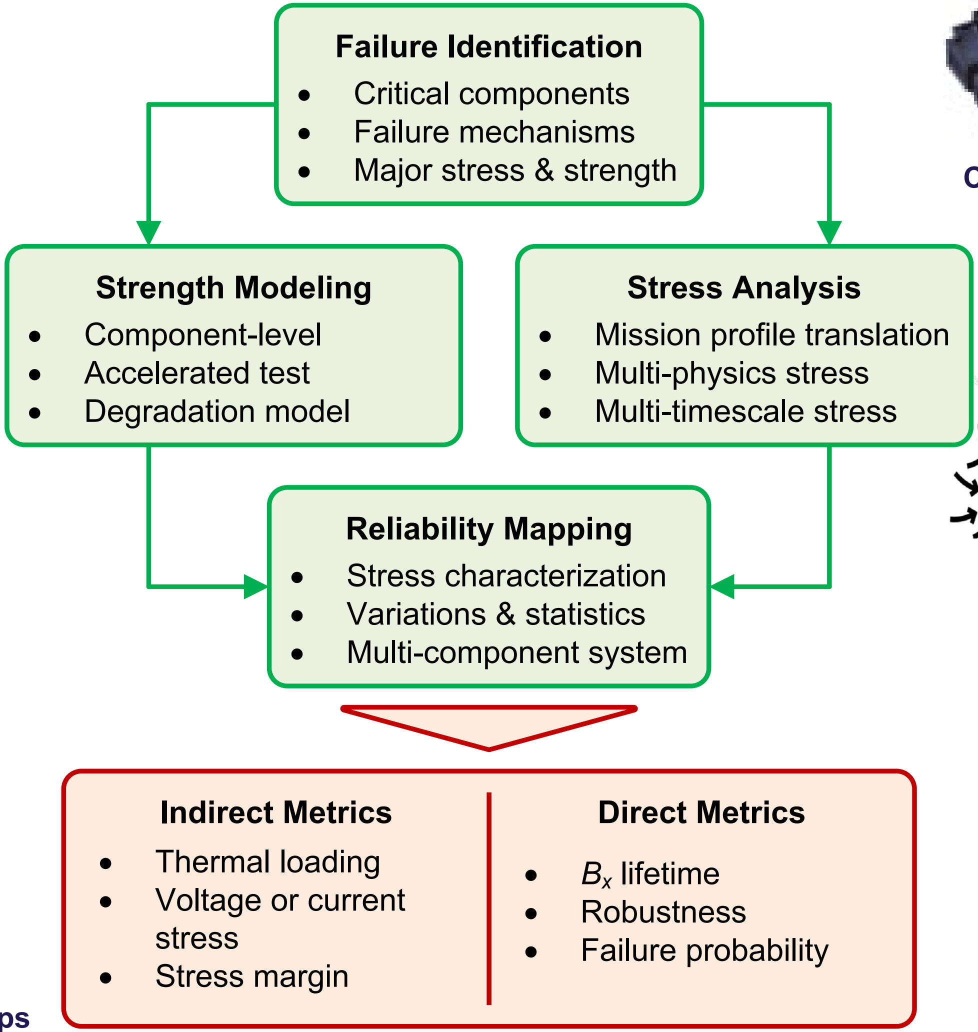
Design for reliability of power electronics

Application of DfR in PV inverter design

- Expected failure at the end of life – reduce O&M cost
- No over-designed – reduce system cost



Key aspects in reliability analysis



Failure Identification

- Critical components
- Failure mechanisms
- Major stress & strength

Strength Modeling

- Component-level
- Accelerated test
- Degradation model

Stress Analysis

- Mission profile translation
- Multi-physics stress
- Multi-timescale stress

Reliability Mapping

- Stress characterization
- Variations & statistics
- Multi-component system

Indirect Metrics

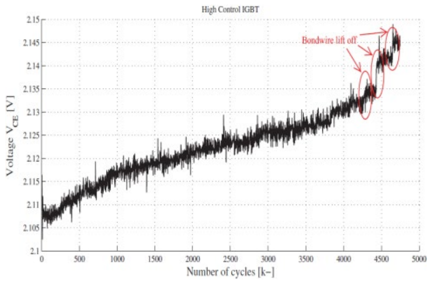
- Thermal loading
- Voltage or current stress
- Stress margin

Direct Metrics

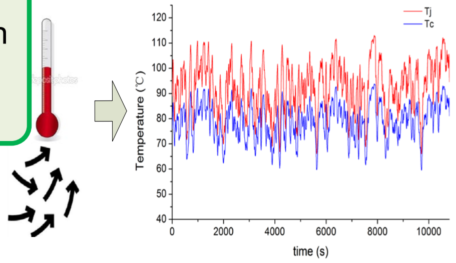
- B_x lifetime
- Robustness
- Failure probability

Reliability Performance

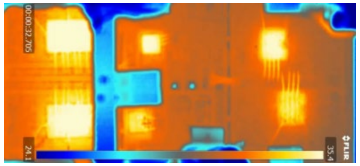
Critical components in Power electronics



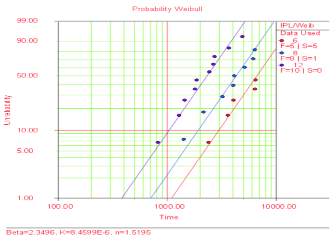
Accelerated test of IGBT



Translate mission profile to device loading



Thermal loading of IGBT chips

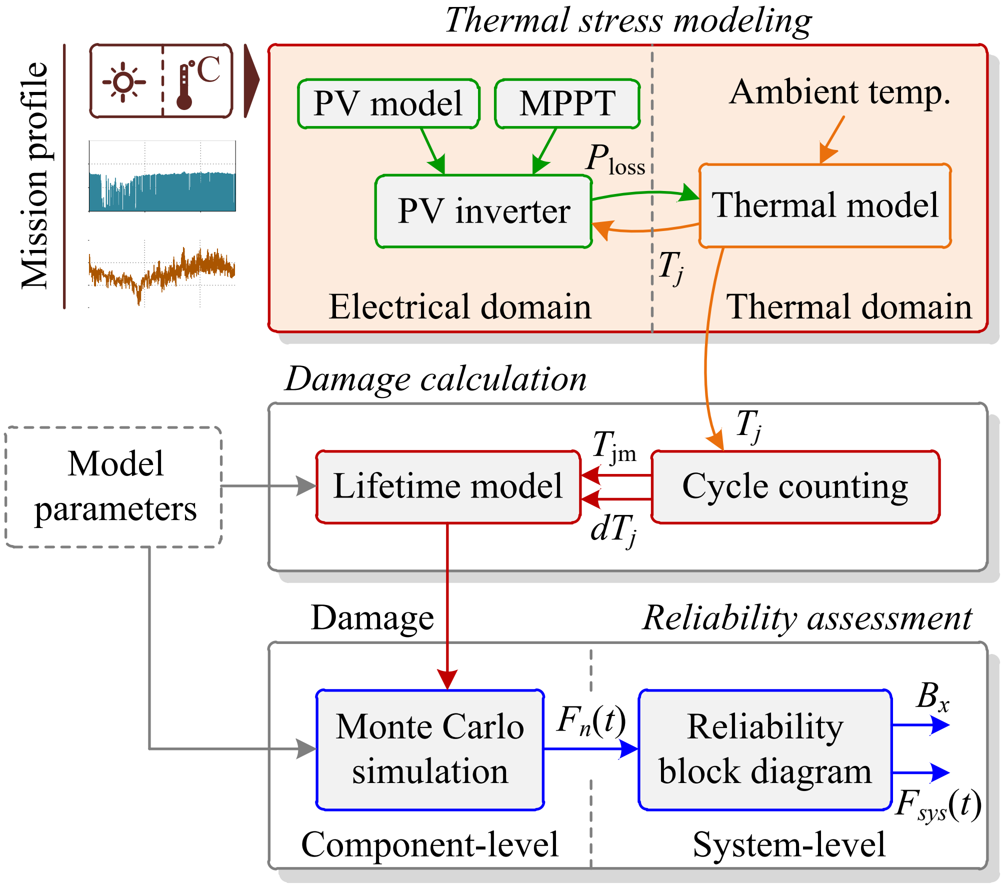


Reliability/unreliability vs. time

[1] F. Blaabjerg and K. Ma, **"Future on Power Electronics for Wind Turbine Systems,"**

Reliability evaluation of PV inverters

Three steps modeling approach



Thermal stress modeling (requirement)

- Mission profile (i.e., solar irradiance, ambient temperature)
- Electrical model (i.e., power losses, control strategy)
- Thermal model

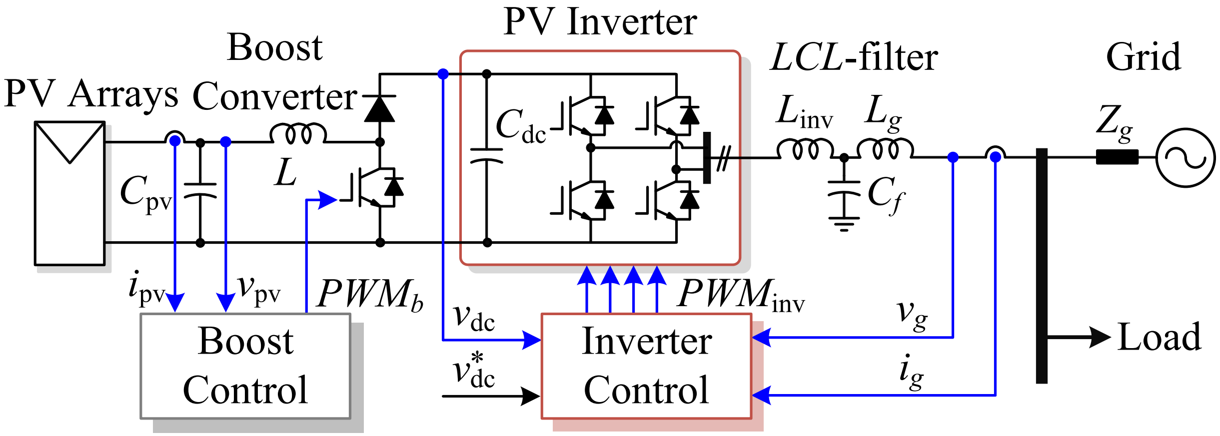
Damage calculation (requirement)

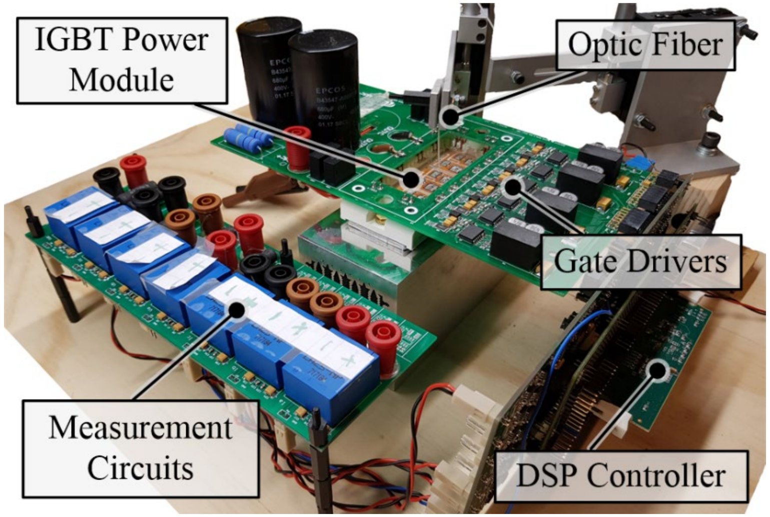
- Physic-of-failure (failure mode)
- Lifetime model
- (Cycle counting)

Reliability assessment (requirement)

- Parameter variation
- Monte Carlo simulation
- Reliability block diagram

Example of PV inverter design

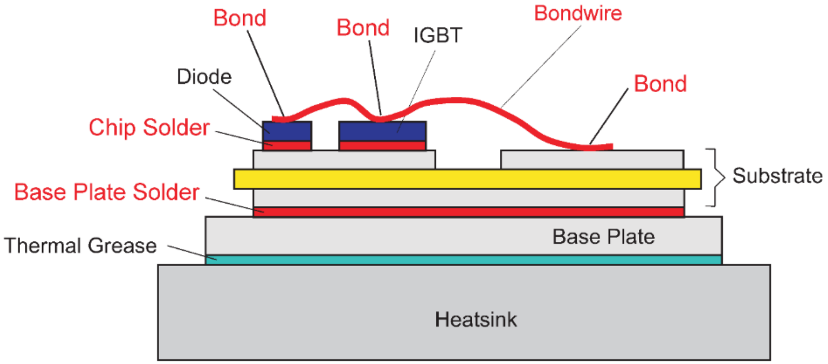




Parameter	Value
PV inverter rated power	6 kW
Boost converter inductor	L = 1.8 mH
DC-link capacitor	C_{dc} = 1100 μF
LCL-filter	L_{inv} = 4.8 mH, L_g = 2 mH, C_f = 4.3 μF
Switching frequency	Boost converter: 16 kHz Full-Bridge inverter: 8 kHz
DC-link voltage	V_{dc} = 450 V
Grid voltage (RMS)	V_g = 230 V
Grid frequency	50 Hz

Lifetime model of components

Power devices (e.g., IGBT)



Insulated-Gate Bipolar Transistor

DC-link capacitors (Al-cap)

Aluminum Electrolytic Capacitors

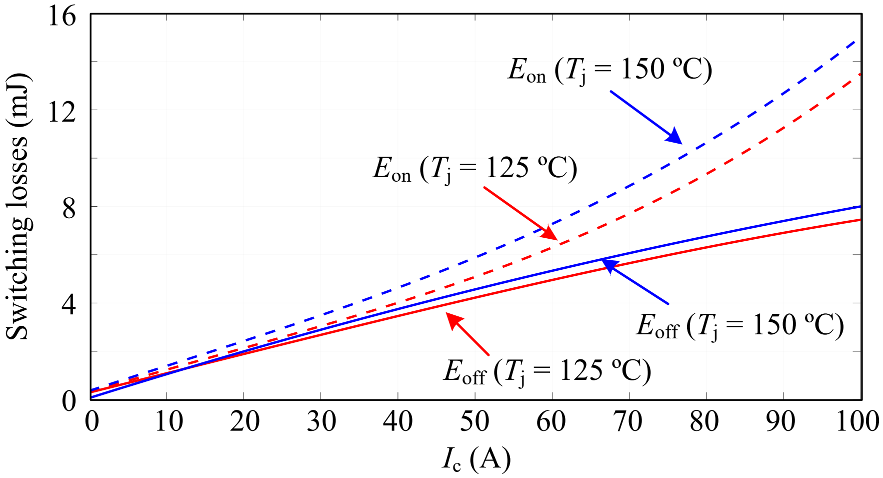
Component	Failure Mechanisms	Stress Factors	Lifetime Model
Power devices (e.g., IGBT)	• Bond wire lift-off • Solder degradation	• **Thermal cycling (ΔT_j)** • Mean temperature (T_{jm}) • Cycle period (t_{on})	*Cycle to failure:* $N_f(\Delta T_j, T_{jm}, t_{on})$
DC-link capacitors (Al-cap)	• Electrolye vaporization • Increase of leakage current	• **Hotspot temperature (T_h)** • Operating voltage (V_{dc})	*Time to failure:* $L_f(T_h, V_{dc})$

Power losses modeling

IGBT characterization

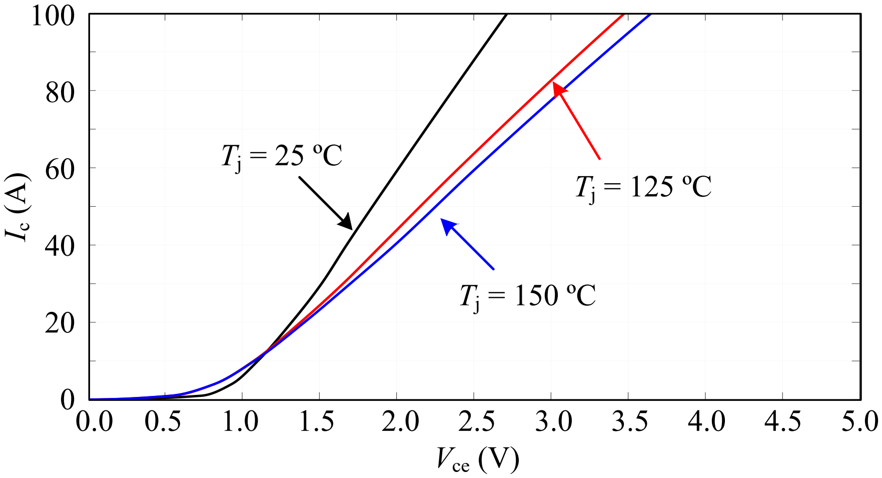
- 1200V/50A IGBT from Infineon (FS50R12KT4_B15)
- Datasheet parameter (also verified with double-pulse testing)
- Look-up table

Switching losses



$$P_{sw,S} = f_{sw}(E_{on} + E_{off})$$

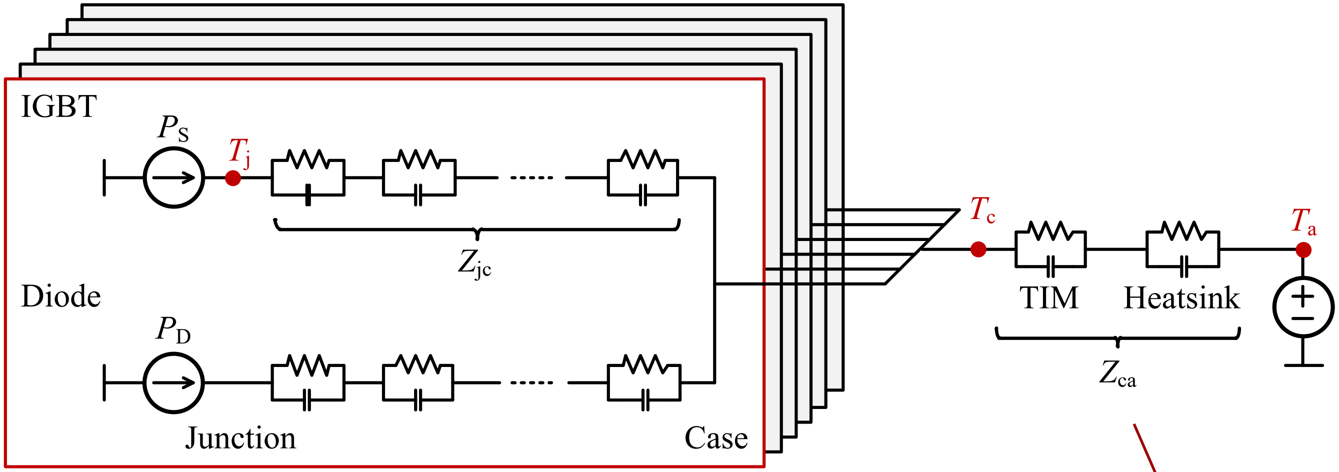
Conduction losses



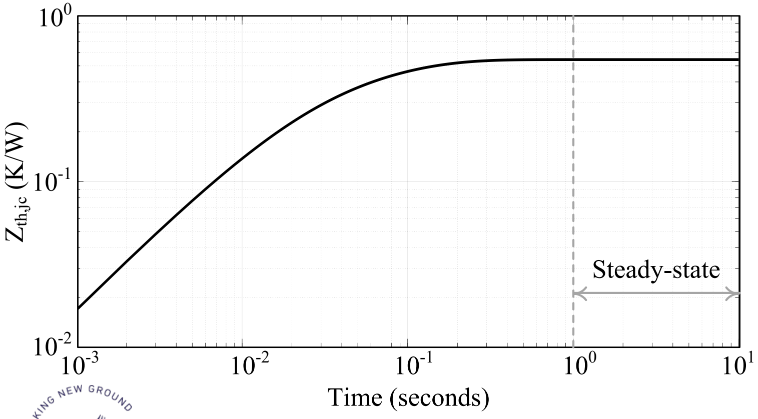
$$P_{con,S} = \frac{1}{T}\int_0^{t_1} i_c(t)\cdot v_{ce}(t)dt$$

Thermal modeling

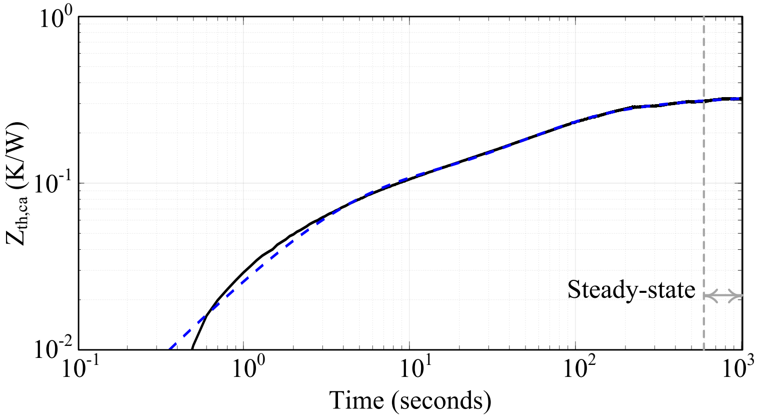
Lumped thermal network (Foster's model)



Z_{jc}: Junction-to-case

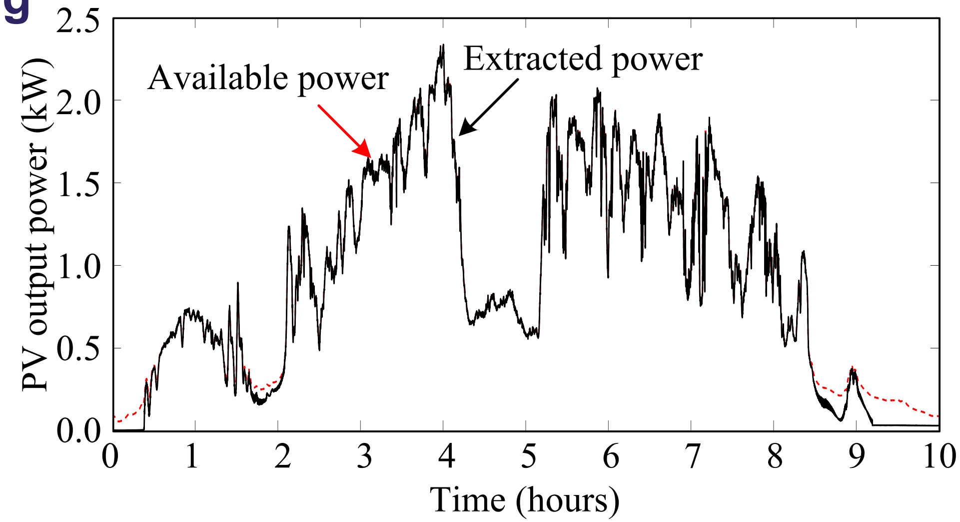


Z_{ca}: Case-to-ambient

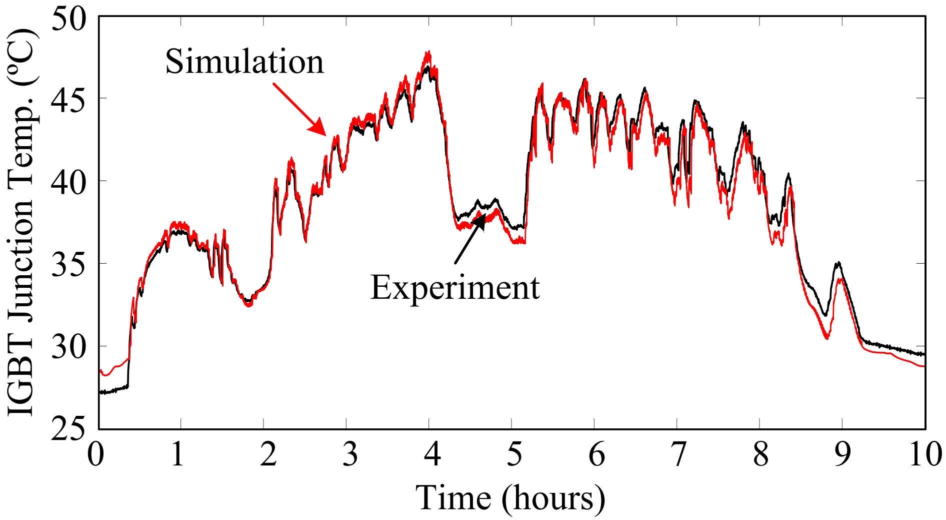


Real-field thermal stress (IGBTs)

Electrical loading
(mission profile)



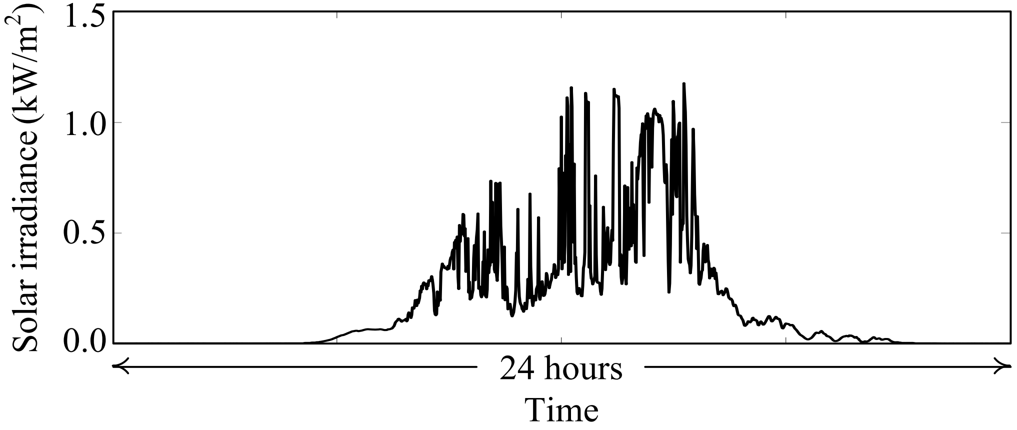
Thermal loading
(Ta = 25 °C)



Real-field thermal stress (DC-link capacitors)

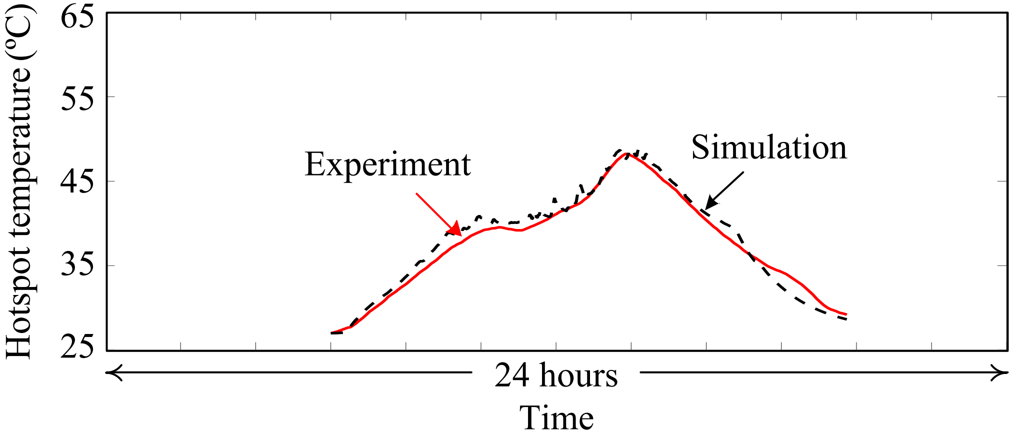
Electrical loading

(mission profile)



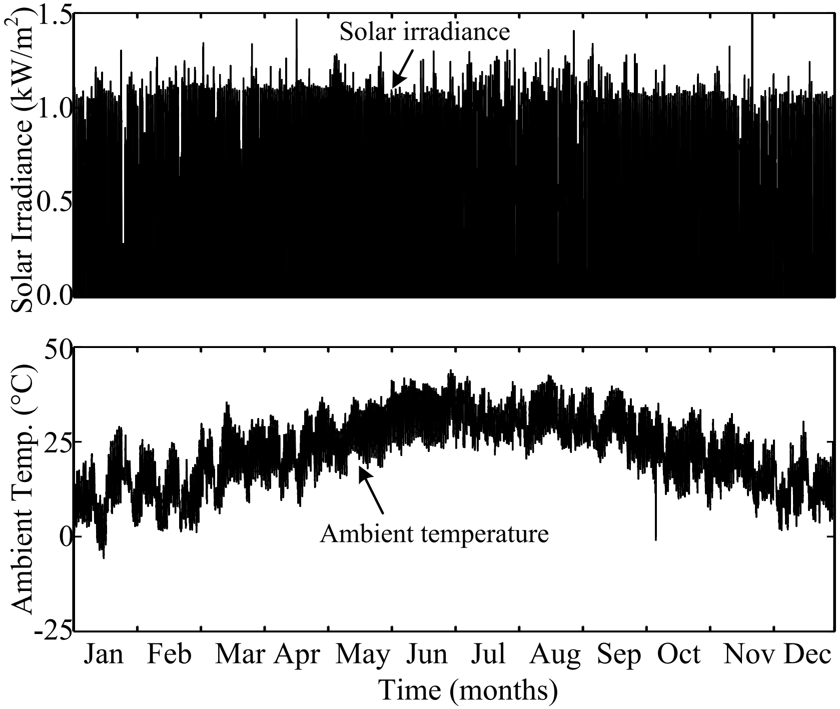
Thermal loading

(Ta = 25 °C)

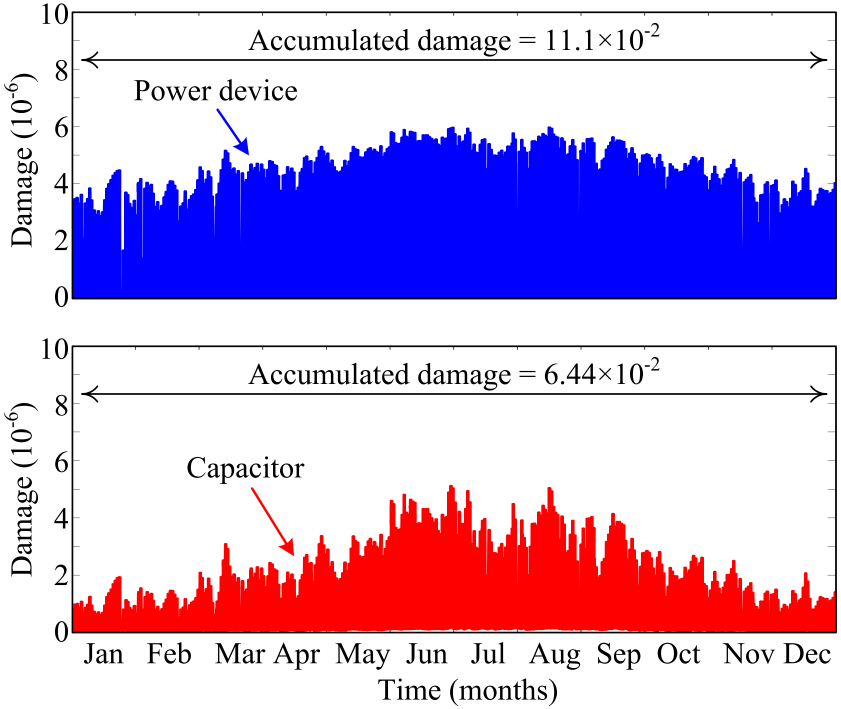


Component-level analysis

Mission profile is translated into damage in components



Mission profile (one year)

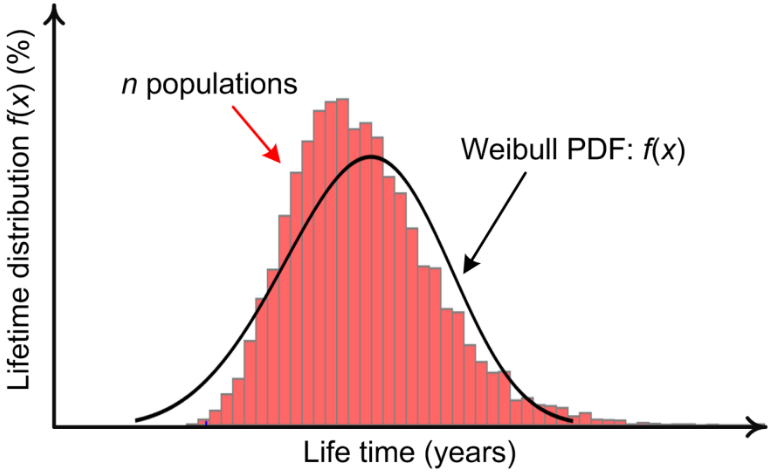


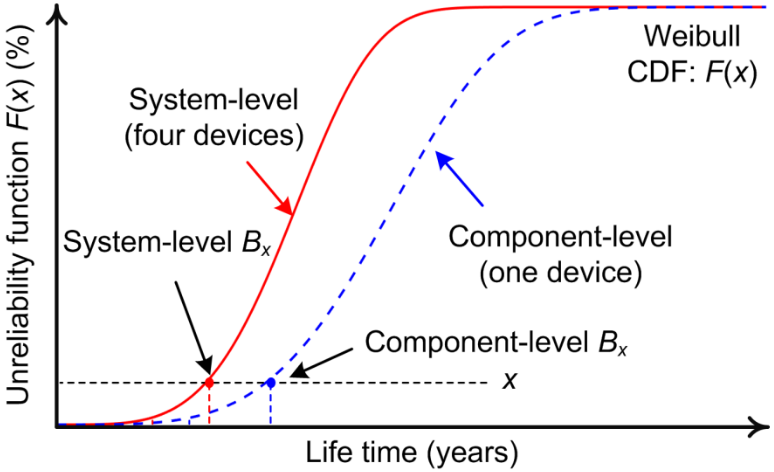
Corresponding damage in the component

The reliability can be determined from the weakest component in the system (e.g., the highest accumulated damage)

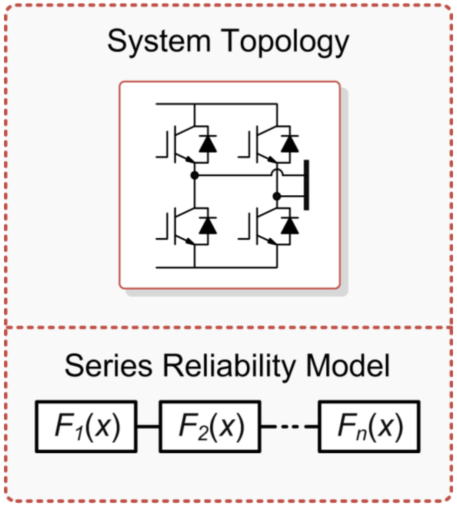
Converter-level analysis

Weibull Analysis





- ► Represent development of failure rate overtime (e.g., from 0 % to 100 % failure)
- ► B_x lifetime: Time when x % of population have failed
- ► From component-level to system-level assessment

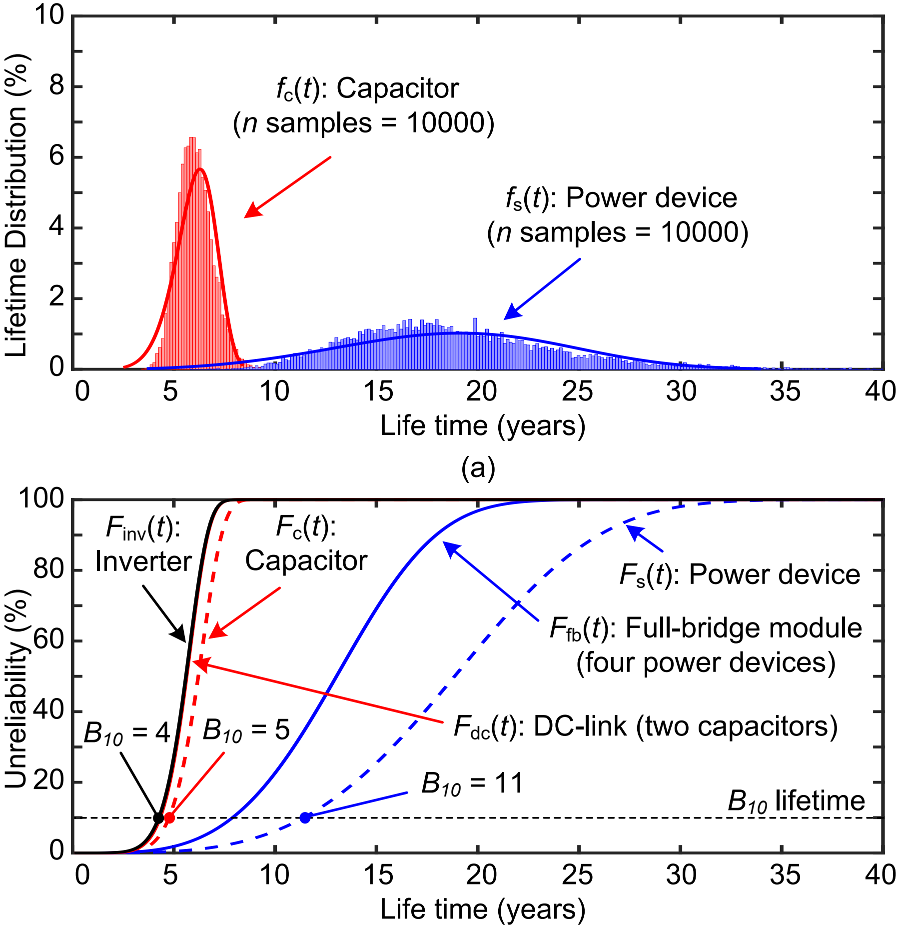


Reliability Block Diagram: System-level

$$F_{tot}(x) = 1 - \prod_{n=1}^{4} (1 - F_n(x))$$

Converter-level analysis

Parameter variation: Lifetime distribution ⇨ Unreliability function



(a)

(b)

Outline

Practical/Industry Application

- Microinverter Case Study
- Impact of PV module size

Micro-Inverter Case Study

Appearance of the PV Micro-Inverter

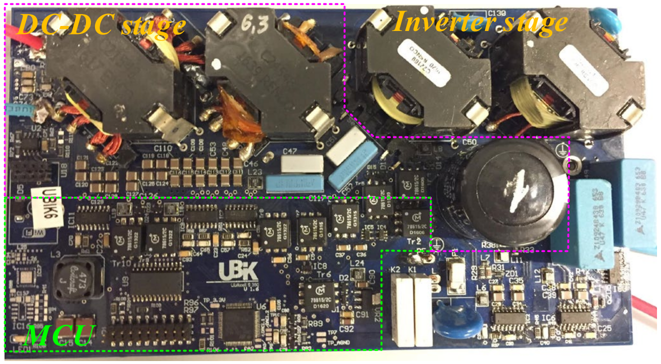
Configuration of a PV micro-inverter system

Advantages:

- Module-level maximum power point tracking
- Module-level monitoring and troubleshooting
- Lower amperage wires
- Higher safety

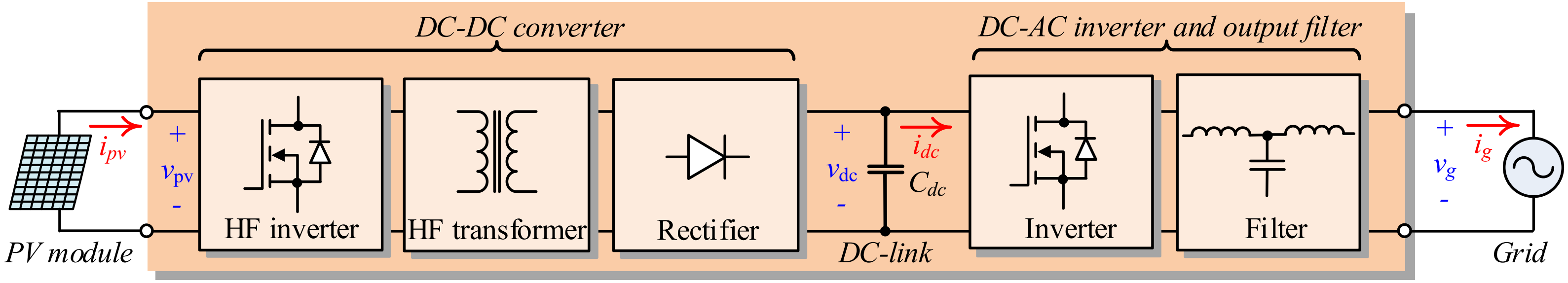
Challenges:

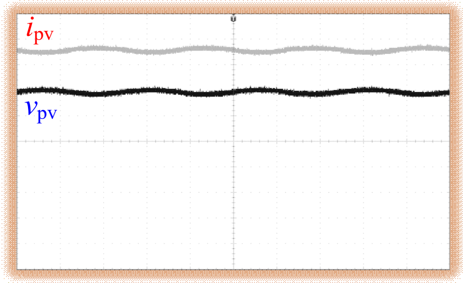
- Higher cost-of-energy
- Reliability?

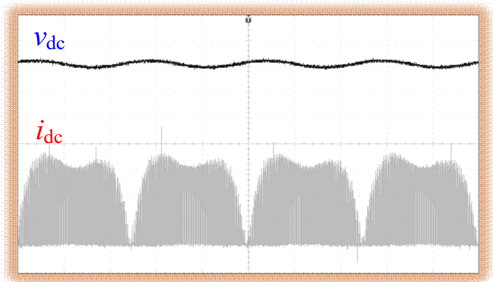


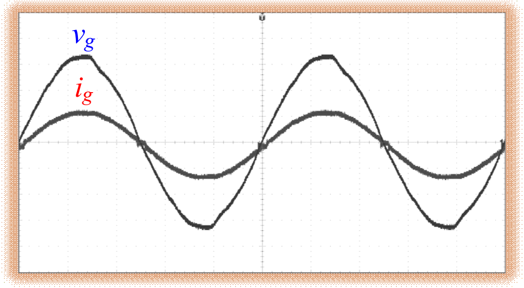
Hardware of the 300-W PV MI

Two-stage micro-inverter









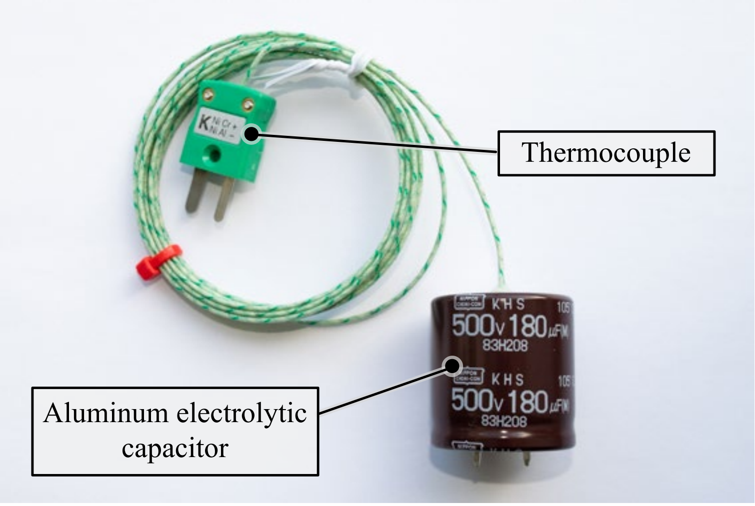
Key parameters:

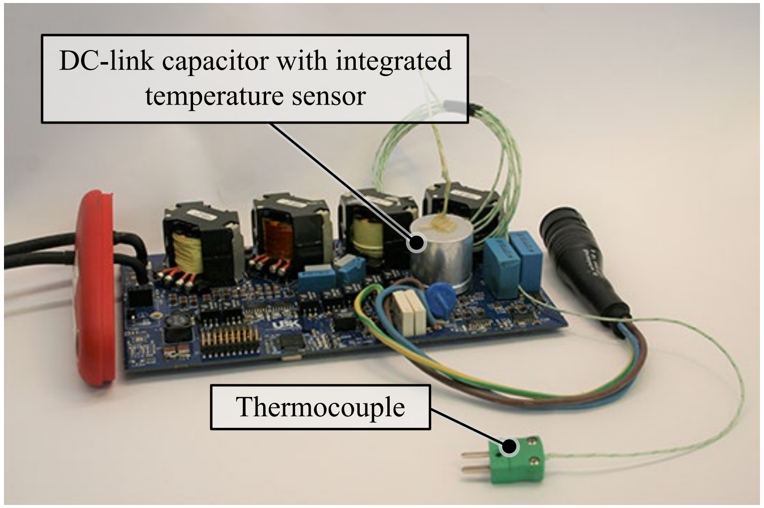
- Rated power: 350 W
- Input voltage range: 8-60 V
- AC grid voltage: 230 V
- Hardware efficiency : 96.2 %
- MPPT efficiency: 99.5 %

Compatibility:

- 72-cell PV module
- 60-cell PV module

Experimental setup



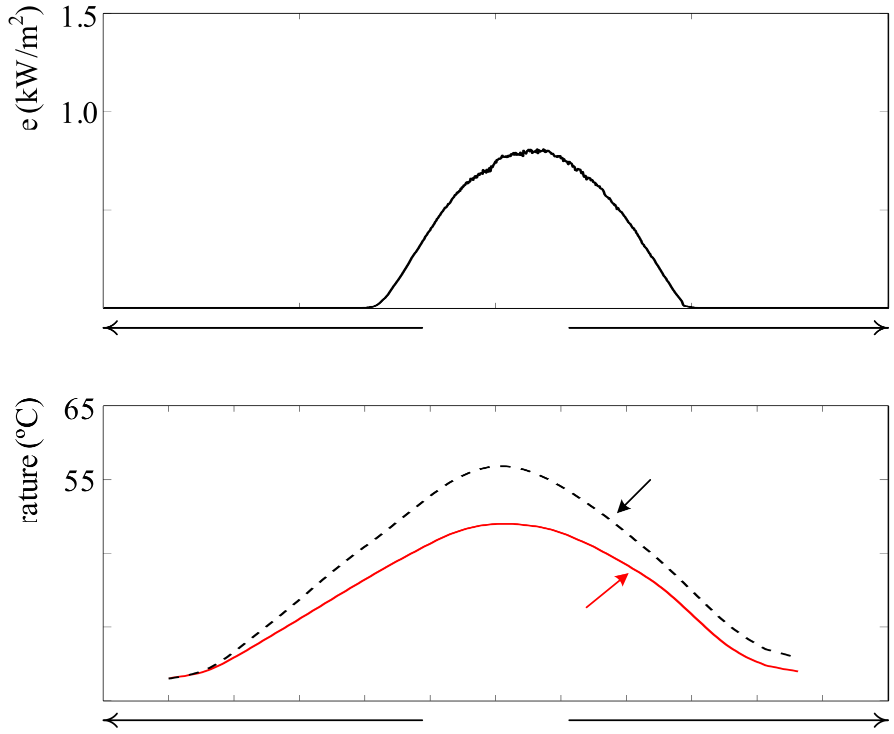


Features

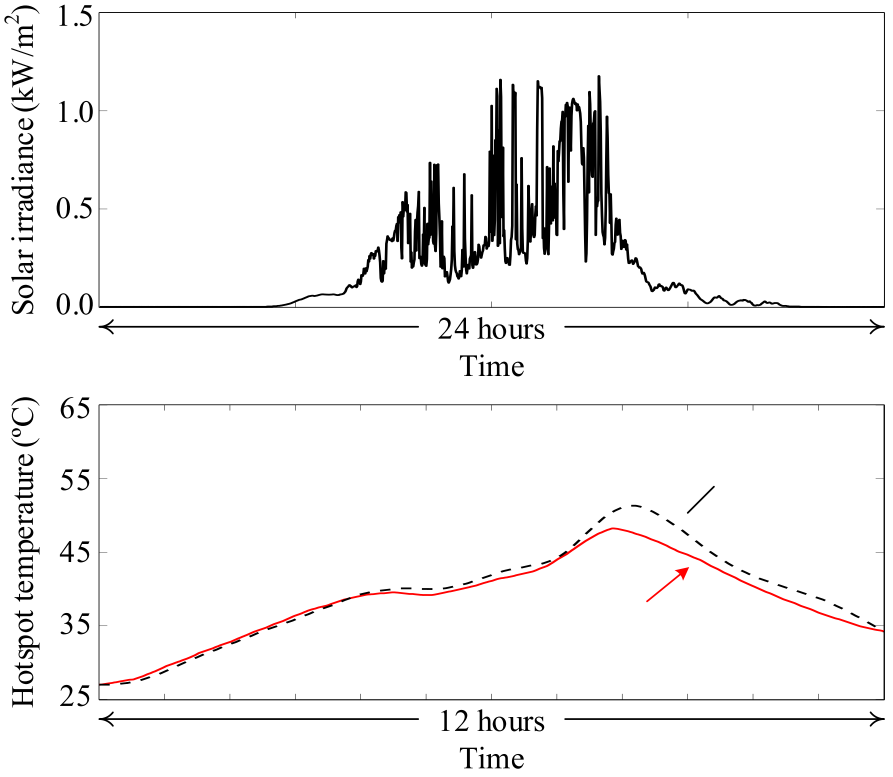
- Test under real operating conditions (inverter-level testing)
- Embedded thermocouple at the core of capacitor
- Direct measurement of hotspot temperature

Thermal stress analysis

Clear-day condition

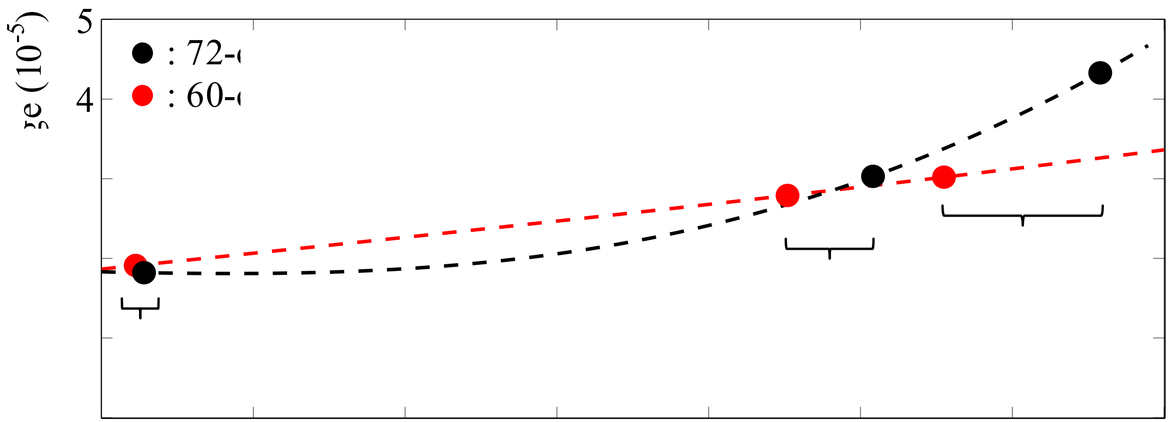


Cloudy-day condition



Reliability evaluation

Accumulated Damage vs. Energy Yield

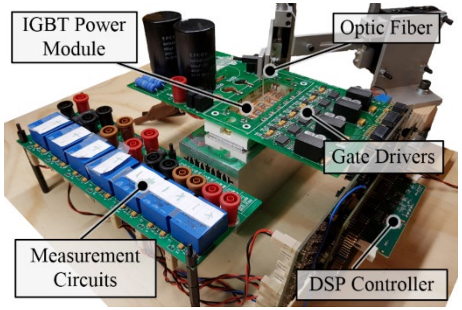


Observation:

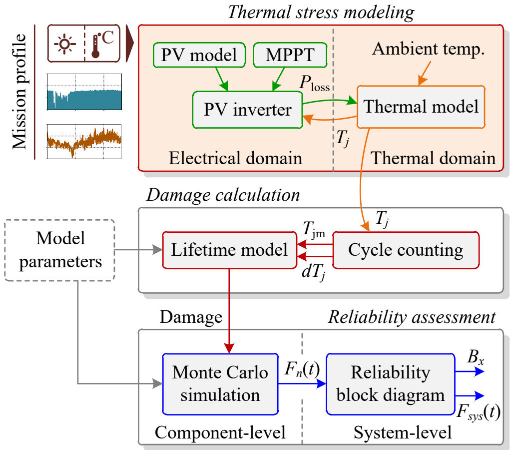
- 60-cell PV module: Linear-dependency between the damage and energy yield
- 72-cell PV module: Exponential-dependency between the damage and energy yield

Summary

- **Reliability of key components in power electronics systems is an important aspect to minimize the cost of renewable energy**
  - Power devices (e.g., IGBTs, MOSFETs)
  - Electrolytic capacitors (e.g., DC-link)
  - Etc. fan, gate driver



- **Long-term degradation induced by thermal stress is the main factor that limit the useful life of power electronics systems – require a proper reliability modeling method**
  - Thermal stress modeling
  - Lifetime estimation (damage calculation)
  - Reliability assessment (uncertainty analysis)



References

Further reading

- H. Chung, H. Wang, Frede Blaabjerg, and Michael Pecht, *Reliability of power electronic converter systems*, IET, 2015.
- 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. (**Open access**)
- H. Wang, M. Liserre, and F. Blaabjerg, “Toward reliable power electronics - challenges, design tools and opportunities,” IEEE Industrial Electronics Magazine, vol.7, no. 2, pp. 17-26, Jun. 2013.
- H. Wang and F. Blaabjerg, “Reliability of capacitors for DC-link applications in power electronic converters – an overview,” IEEE Transactions on Industry Applications, vol. 50, no. 5, pp. 3569-3578, Sep./Oct. 2014. (**Open access**)
- Y. Yang, A. Sangwongwanich and F. Blaabjerg, "Design for reliability of power electronics for grid-connected photovoltaic systems," *CPSS Trans. Power Electron. App.*, vol. 1, no. 1, pp. 92-103, Dec. 2016. (**Open access**)
- A. Sangwongwanich, Y. Yang, D. Sera and F. Blaabjerg, "Lifetime Evaluation of Grid-Connected PV Inverters Considering Panel Degradation Rates and Installation Sites," *IEEE Trans. Power Electron.*, vol. 33, no. 2, pp. 1225-1236, Feb. 2018.
- A. Sangwongwanich, Y. Yang, D. Sera, F. Blaabjerg and D. Zhou, "On the Impacts of PV Array Sizing on the Inverter Reliability and Lifetime," *IEEE Trans. Ind. App.*, vol. 54, no. 4, pp. 3656-3667, July, 2018.
- A. Sangwongwanich, D. Zhou, E. Liivik, and F. Blaabjerg “Mission profile resolution impacts on the thermal stress and reliability of power devices in PV inverters,” *Microelectron. Reliabil.*, Vol. 88-90, pp. 1003-1007, Sep. 2018.
- M. Sandelic, A. Sangwongwanich and F. Blaabjerg, "Reliability Evaluation of PV Systems with Integrated Battery Energy Storage Systems: DC-Coupled and AC-Coupled," *Electronics*, 2019, Status: Published. (**Open access**)
- S. Bouguerra, M. R. Yaiche, O. Gassab, A. Sangwongwanich and F. Blaabjerg, "The Impact of PV Panel Positioning and Degradation on the PV Inverter Lifetime and Reliability," *IEEE J. Emerg. Sel. Topics Power Electron*., Early Access.
- J. He, A. Sangwongwanich, Y. Yang, and F. Iannuzzo, "Lifetime Evaluation of Three-Level Inverters for 1500-V Photovoltaic Systems," *IEEE J. Emerg. Sel. Topics Power Electron*., Early Access.
- A. Sangwongwanich, H. Wang, and F. Blaabjerg, "Reduced-Order Thermal Modeling for Photovoltaic Inverters considering Mission Profile Dynamics," *IEEE Trans. Power Electron*., Early Access. (**Open access**)

REPEPS

REliable Power Electronic based Power System

Thank you for your attention!

Ariya Sangwongwanich
ars@energy.aau.dk

Questions?