



Reliability of Modern Power Electronic Based Power Systems

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AALBORG UNIVERSITY
DENMARK

► Where Are We Located ?

Aalborg University, Denmark

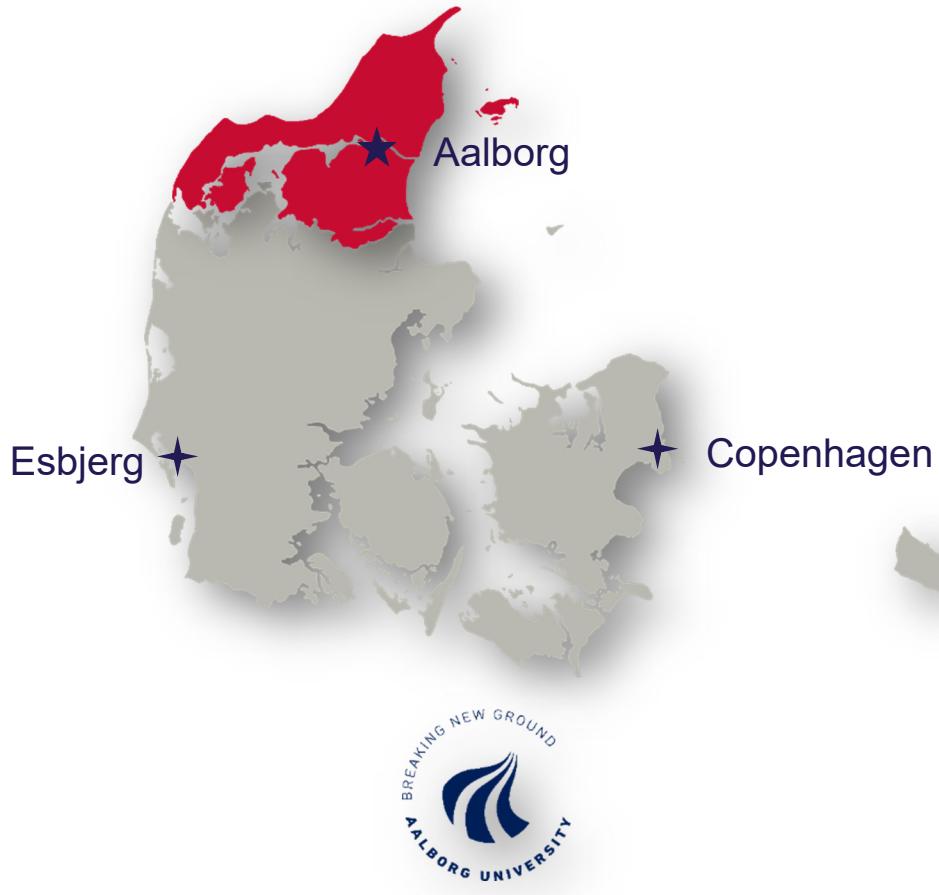
One university, three campuses



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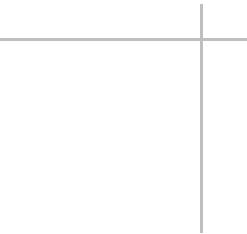
One university, three campuses



► Outline

- **Introduction**
- **Reliability Definition in PEPS**
- **Reliability Modeling in PE**
- **Reliability Analysis**
- **Reliability Enhancement**
- **Summary**





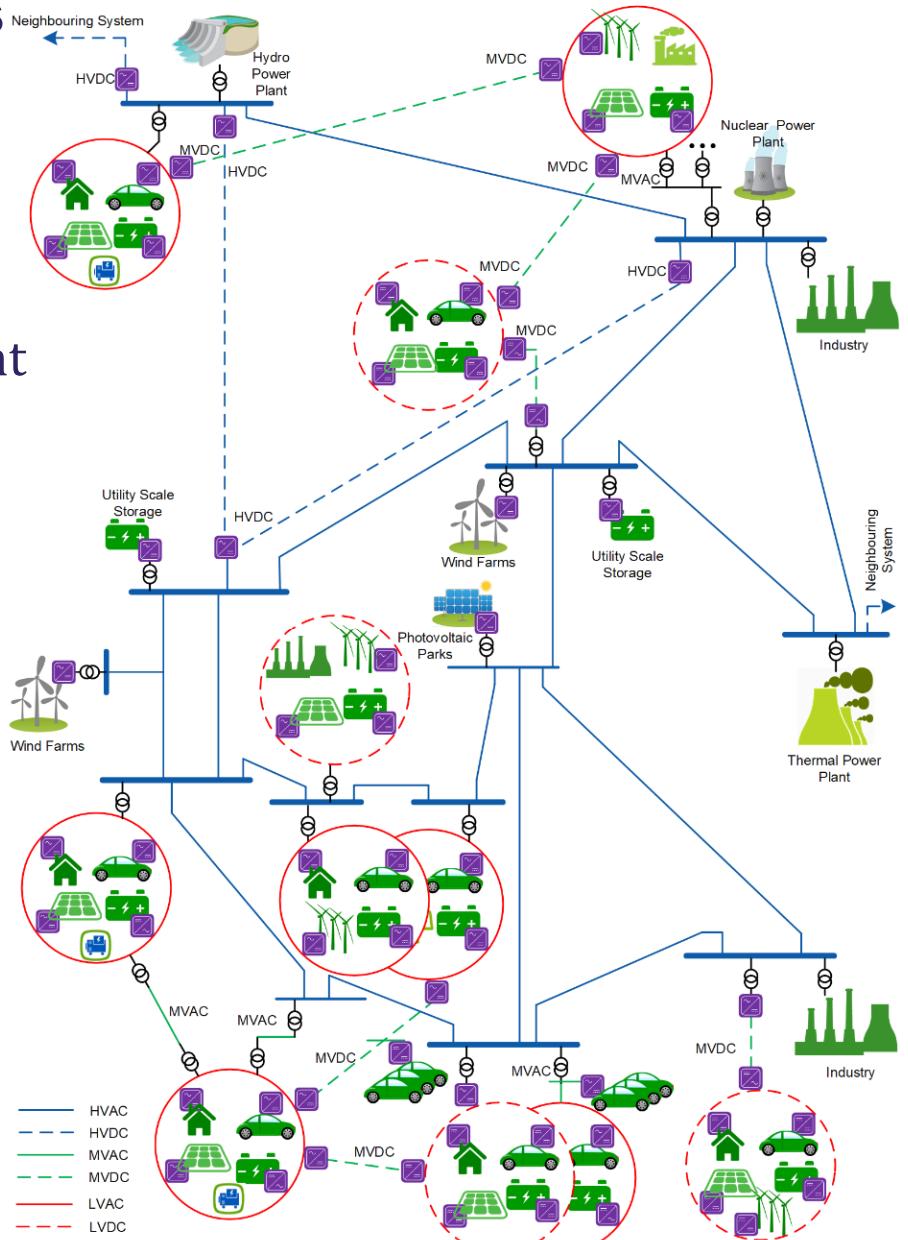
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► Introduction

Power electronics in power systems

- From large-scale power plants to distributed generations
- From central power/energy management to distributed/decentralized control
- 100% renewable generations
- Utility-scale energy storage
- Microgrids
- HVDC/MVDC transmission systems
- Electric vehicles (V1G, V2G, ...)

Power converters underpinning technology for power system modernization

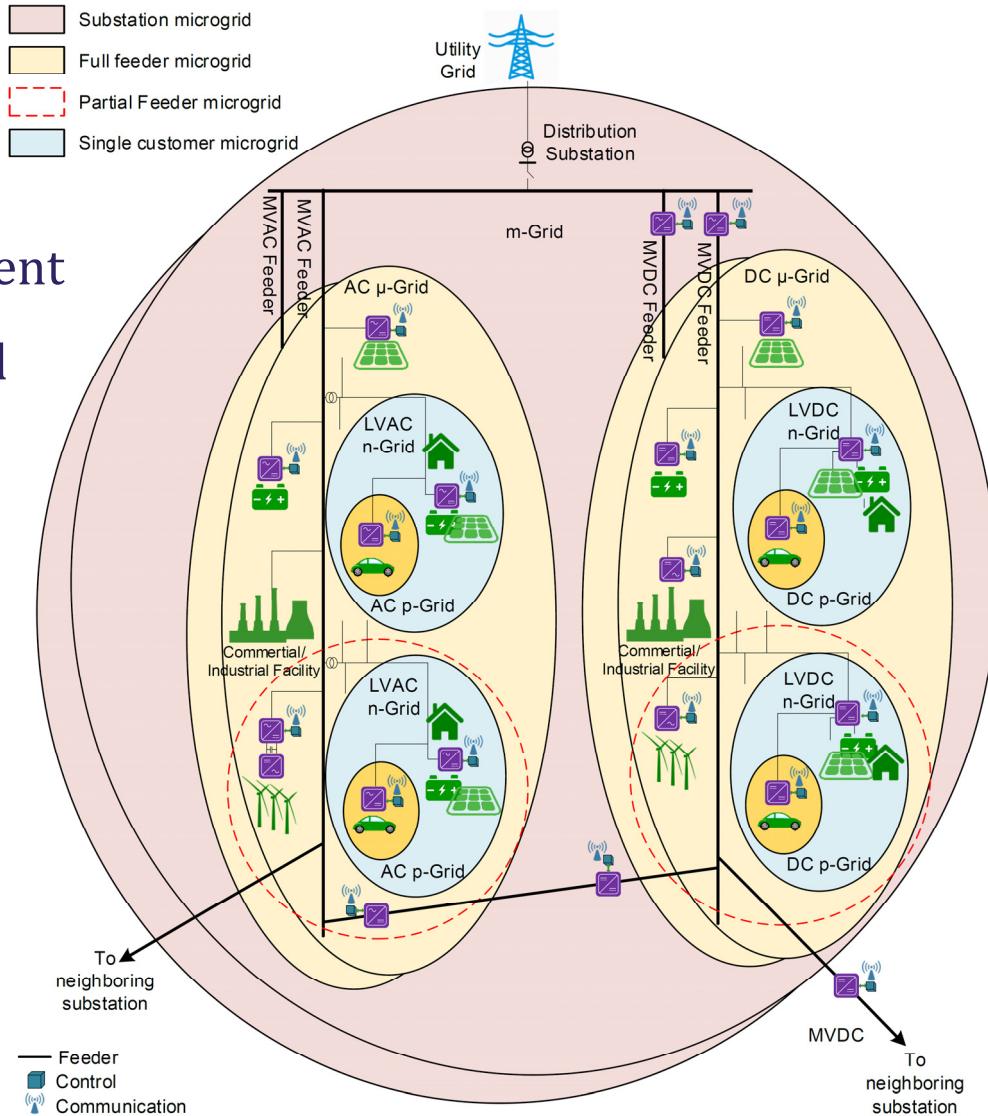


► Introduction

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Power converters underpinning technology for power system modernization



► Introduction

Scientific Challenges



Power module failure



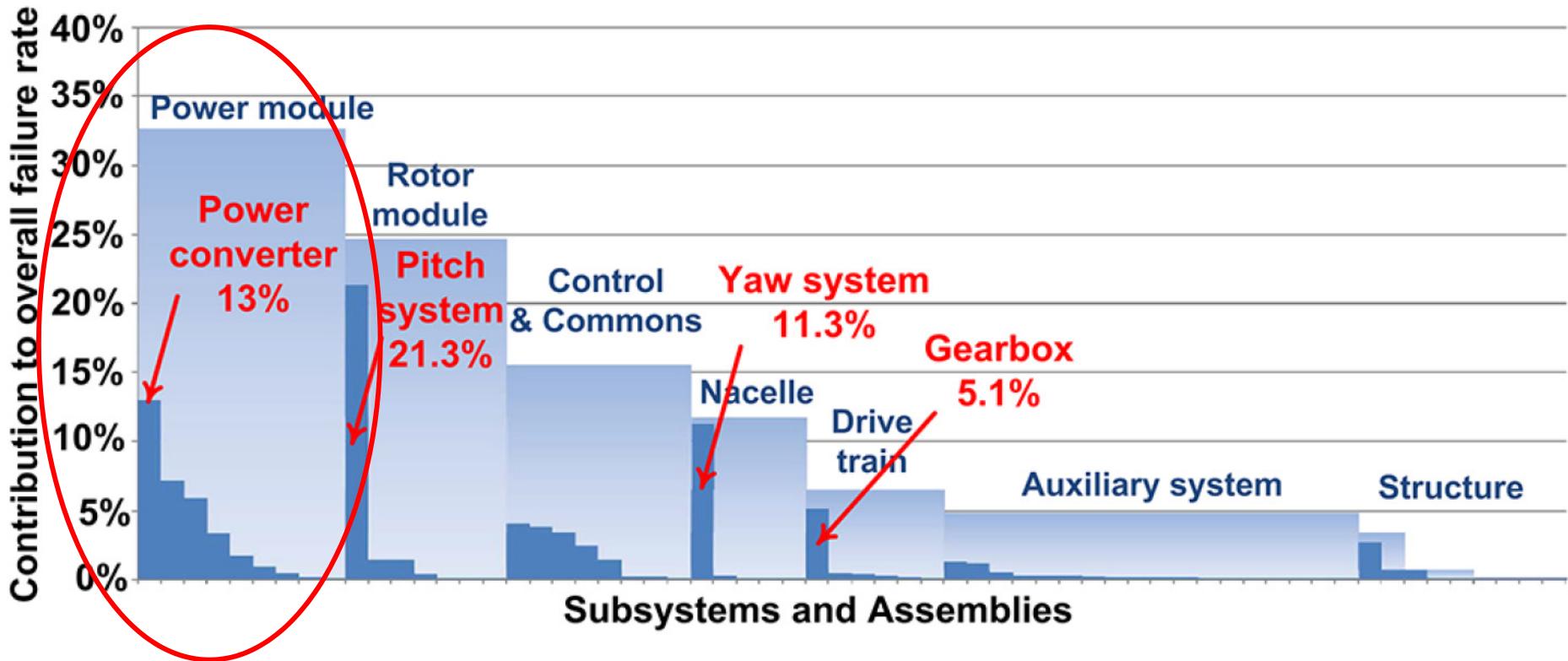
Capacitor failure (bottom)

Source: <https://sites.google.com/site/metropolitanforensics/cause-and-contributing-factors-of-failure-of-wind-turbines>

**Sub-system/system level
failure (illustration only)**

► Introduction

Field experiences of wind turbine systems

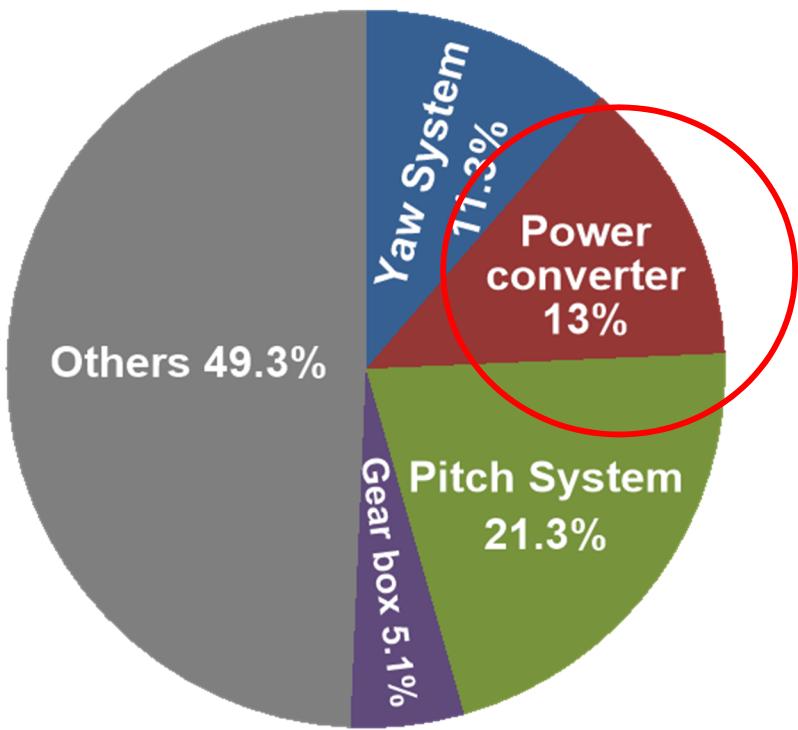


Contribution of subsystems and assemblies on the overall failure rate of wind turbines.

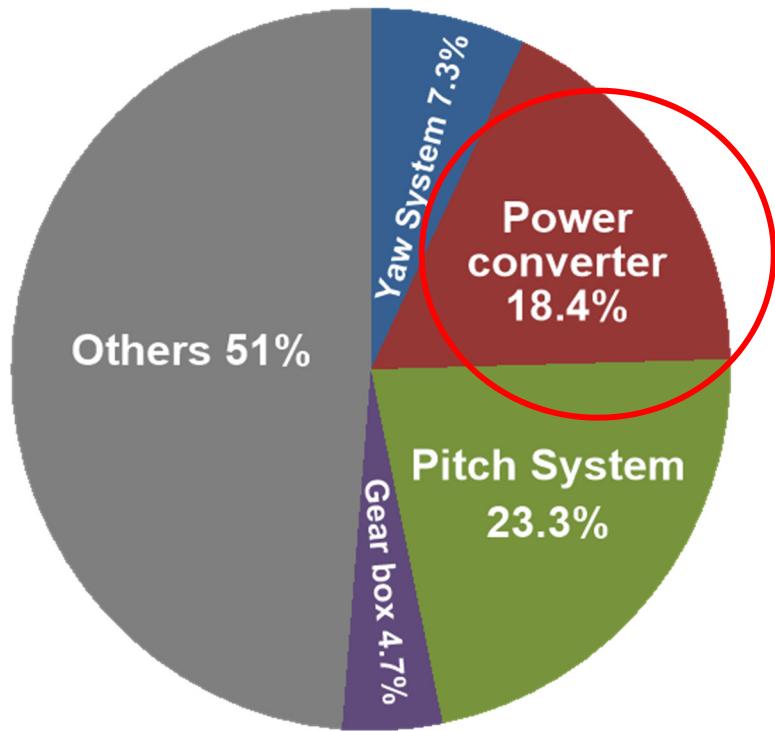
Source: M. Wilkinson and B. Hendriks, *Report on Wind Turbine Reliability Proles*. Reliawind, 2011.

► Introduction

350 onshore wind turbines in varying length of time (35,000 downtime events)



Contribution of subsystems and assemblies to the overall **failure rate** of wind turbines.



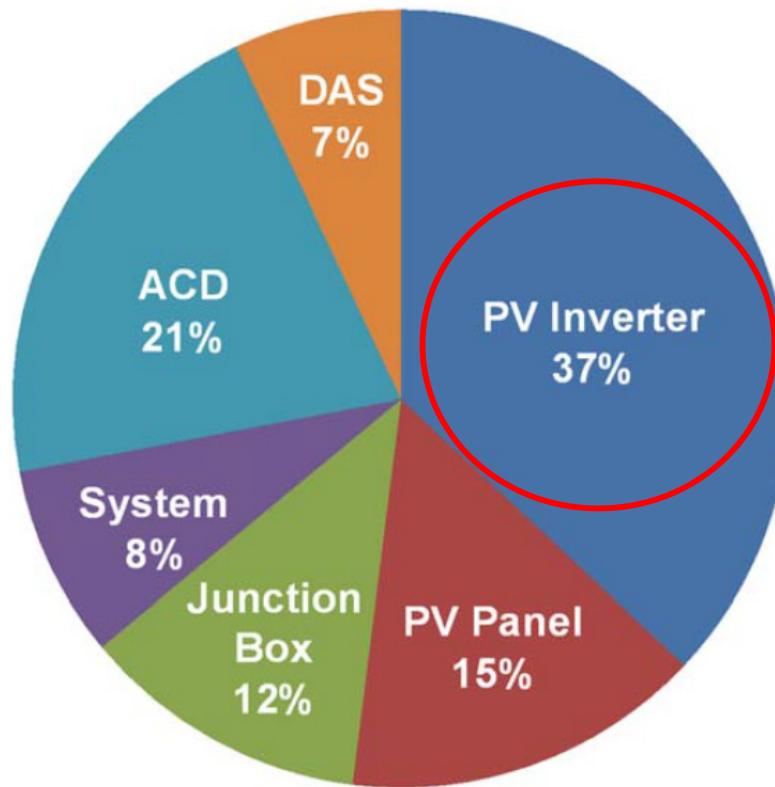
Contribution of subsystems and assemblies to the overall **downtime** of wind turbines.

Source: Reliawind, Report on Wind Turbine Reliability Profiles – Field Data Reliability Analysis, 2011.



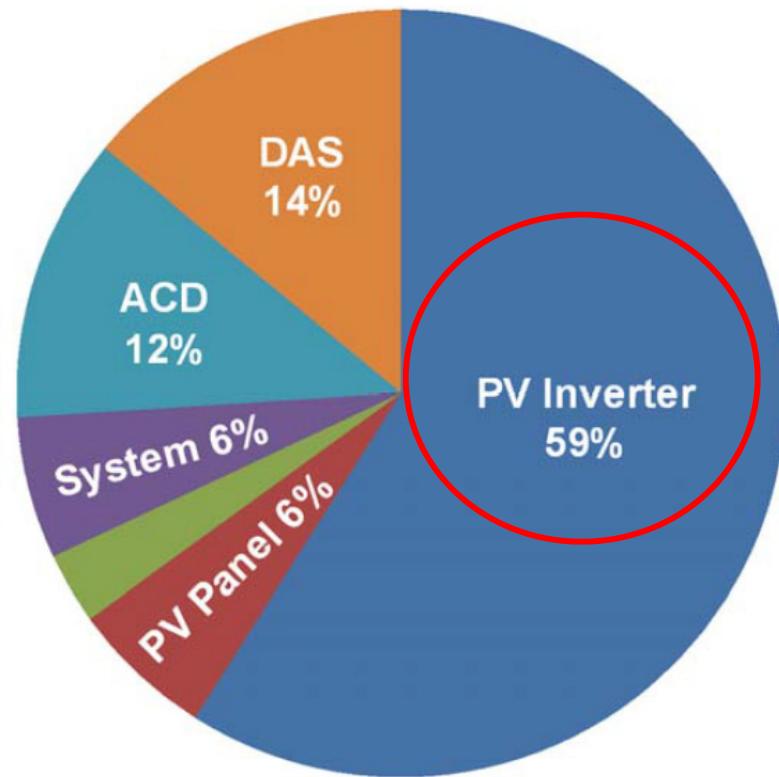
► Introduction

Field experiences of wind turbine systems



(a)

(a) Unscheduled maintenance events and (b) unscheduled maintenance costs



(b)

Source: L. M. Moore and H. N. Post, "Five years of operating experience at a large, utility-scale photovoltaic generating plant," *Prog. Photovolt., Res. Appl.*, vol. 16, no. 3, pp. 249-259, May 2008.

► Introduction

Field returned data on the aging of PE based units

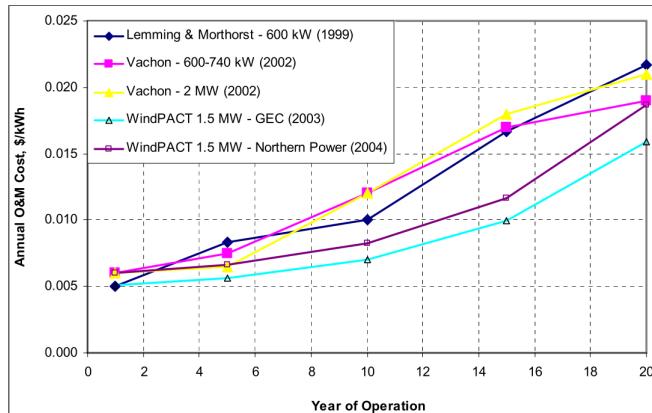


Figure 3. Total Operations and Maintenance Costs Increase with Age Due to Wear-Out Related Failures.

Source: SANDIA REPORT SAND2008-0983 Unlimited Release Printed February 2008

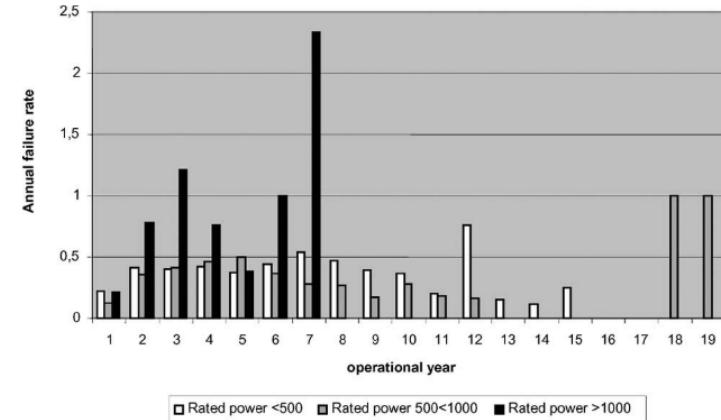
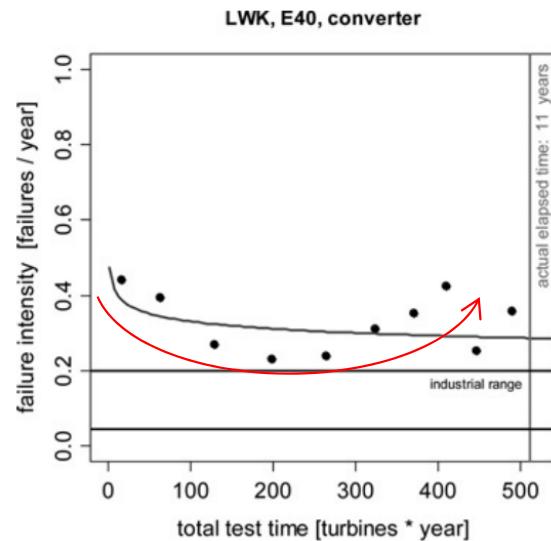
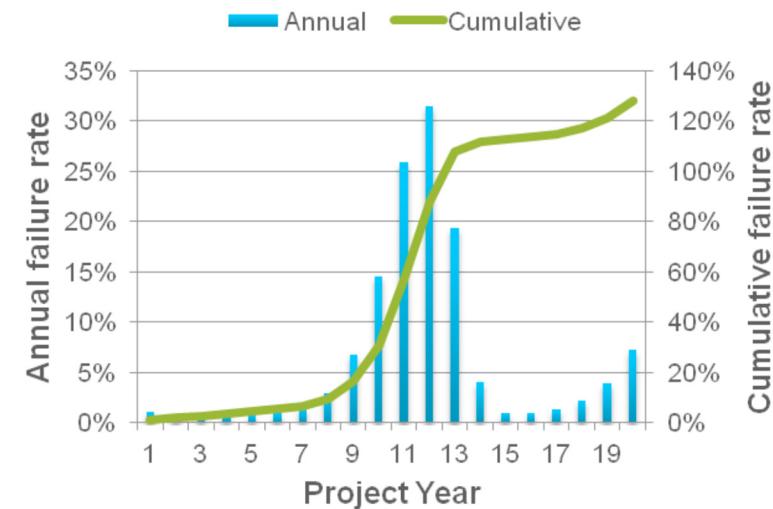


Fig. 6. Failure rate in respective rated power group versus operational year.

Survey of Failures in Wind Power Systems With Focus on Swedish Wind Power Plants During 1997–2005



Source: DOI: 10.1049/iet-rpg.2008.0060



Source: Solar Access to Public Capital Working Group

► Introduction

California 2016 – 1200 MW - Solar

NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report

Southern California 8/16/2016 Event
June 2017

RELIABILITY | ACCOUNTABILITY

Analysis and Findings

The analysis revealed that the largest percentage of inverter loss (~700 MW) was due to the inverter phase lock loop (PLL) control detecting a frequency less than 57 Hz and initiating an instantaneous inverter trip. Frequency measuring network (FNET) data from this disturbance (see Figure 2.3) shows that the Western Interconnection frequency did not actually reach 57 Hz; the lowest recorded frequency only dropped to 59.867 Hz before arresting and recovering. Near instantaneous frequency change measurement of localized fault voltage waveforms does not always exactly represent the true system frequency. To ensure that a more accurate representation of the system frequency measurement is used for inverter controls, a minimum delay for frequency detection and/or filtering should be implemented.

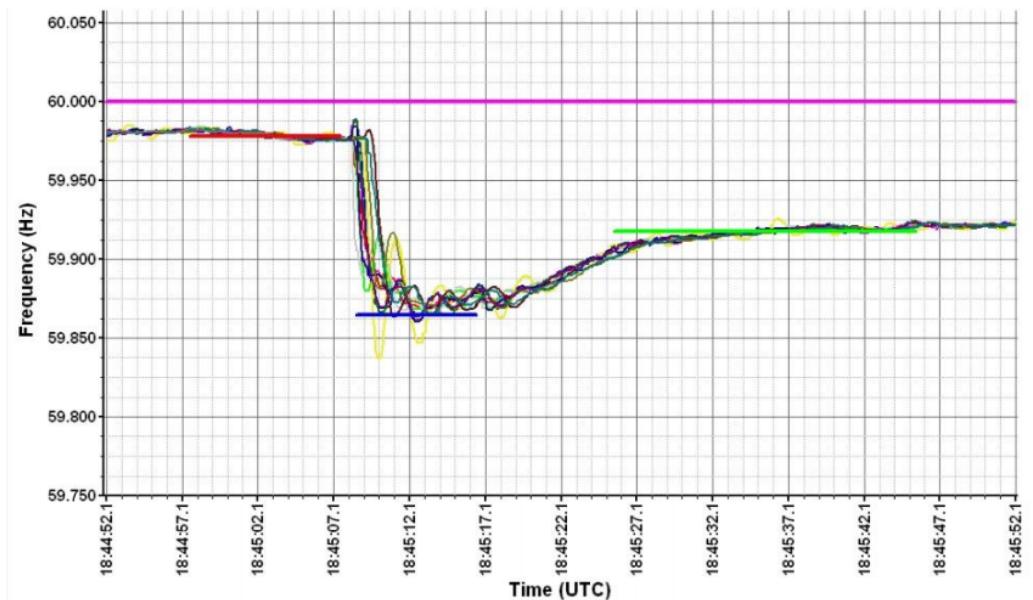
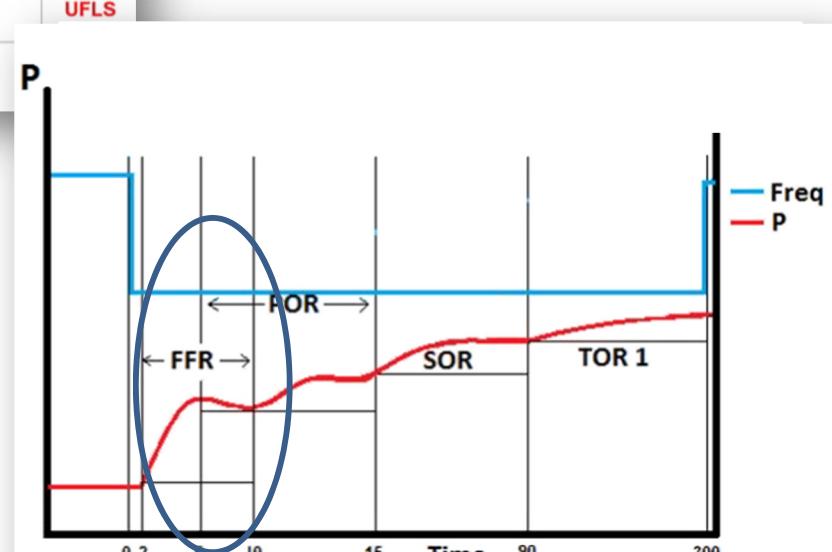
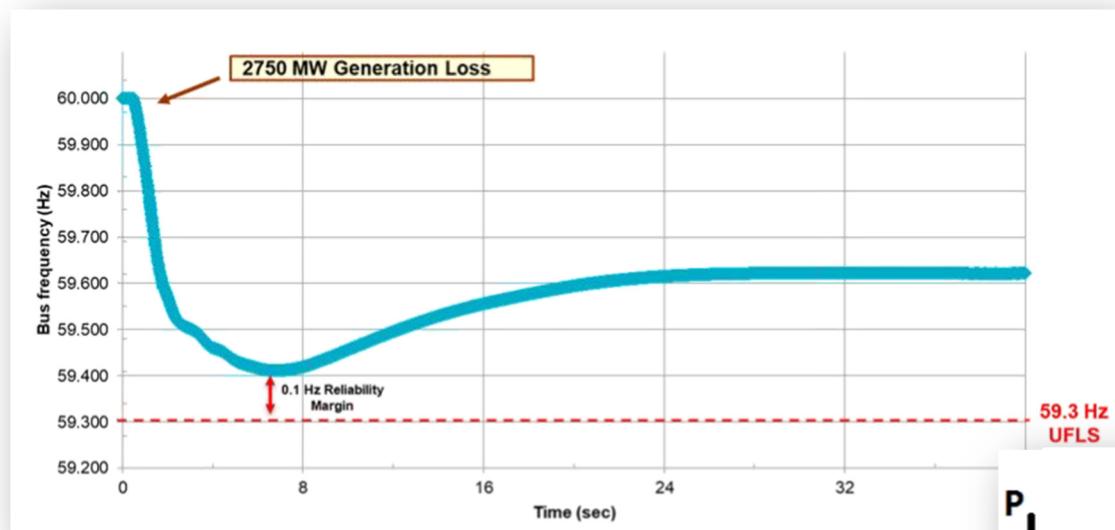


Figure 2.3: FNET Data for Large Resource Loss Event (August 16, 2016)

► Introduction

How can power electronic based units help?



Fast Frequency Reserve (FFR)

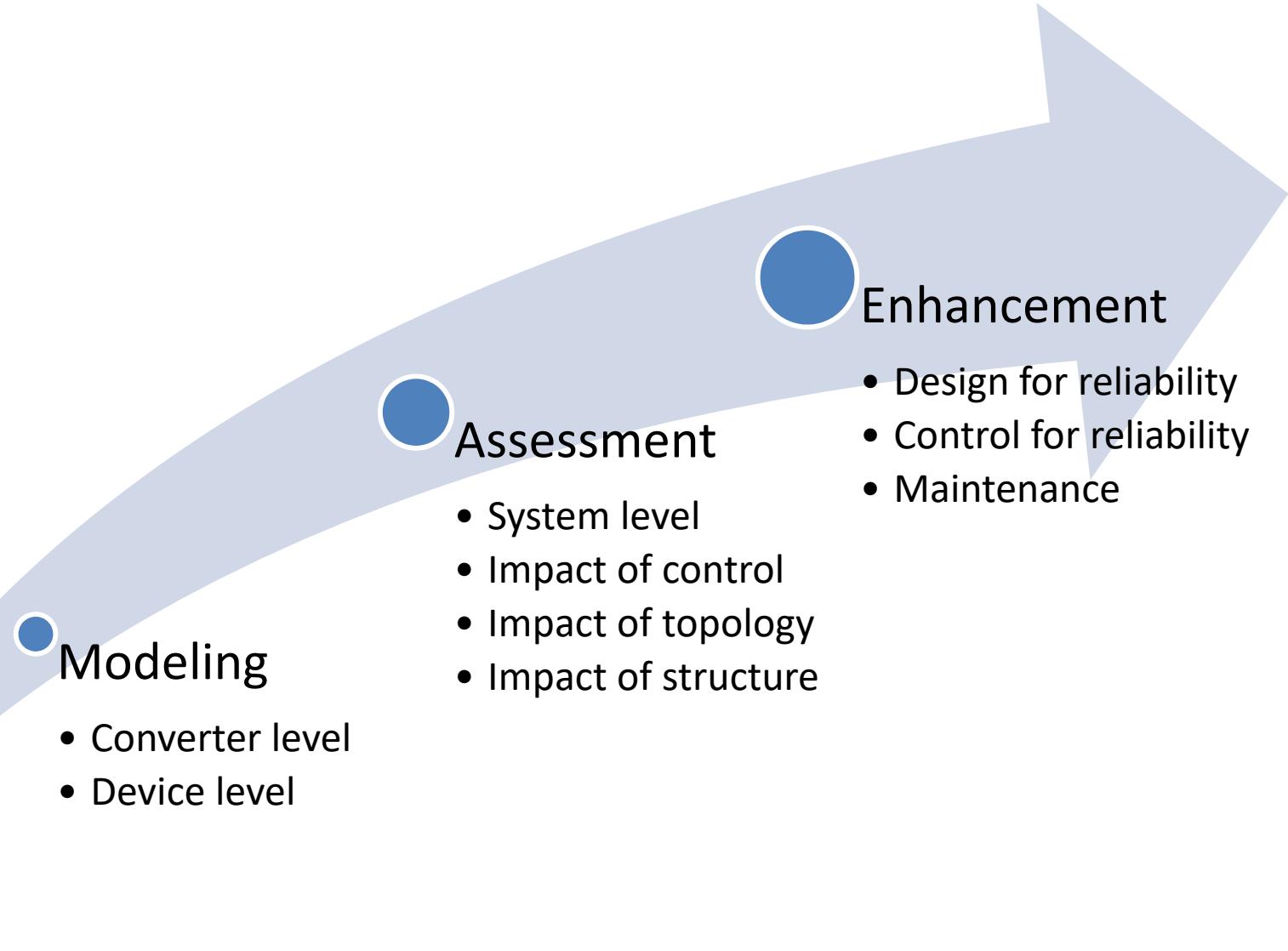
- Nadir
- RoCoF

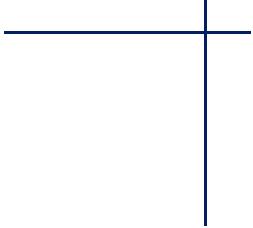
Source: Cigre C2/C4 webinar on the “Impact of high penetration of inverter-based generation on system inertia of networks”

<http://www.eirgridgroup.com/site-files/library/EirGrid/Aggregators-OR-Test-Report-Template.docx>

► Introduction

Need for reliability analysis

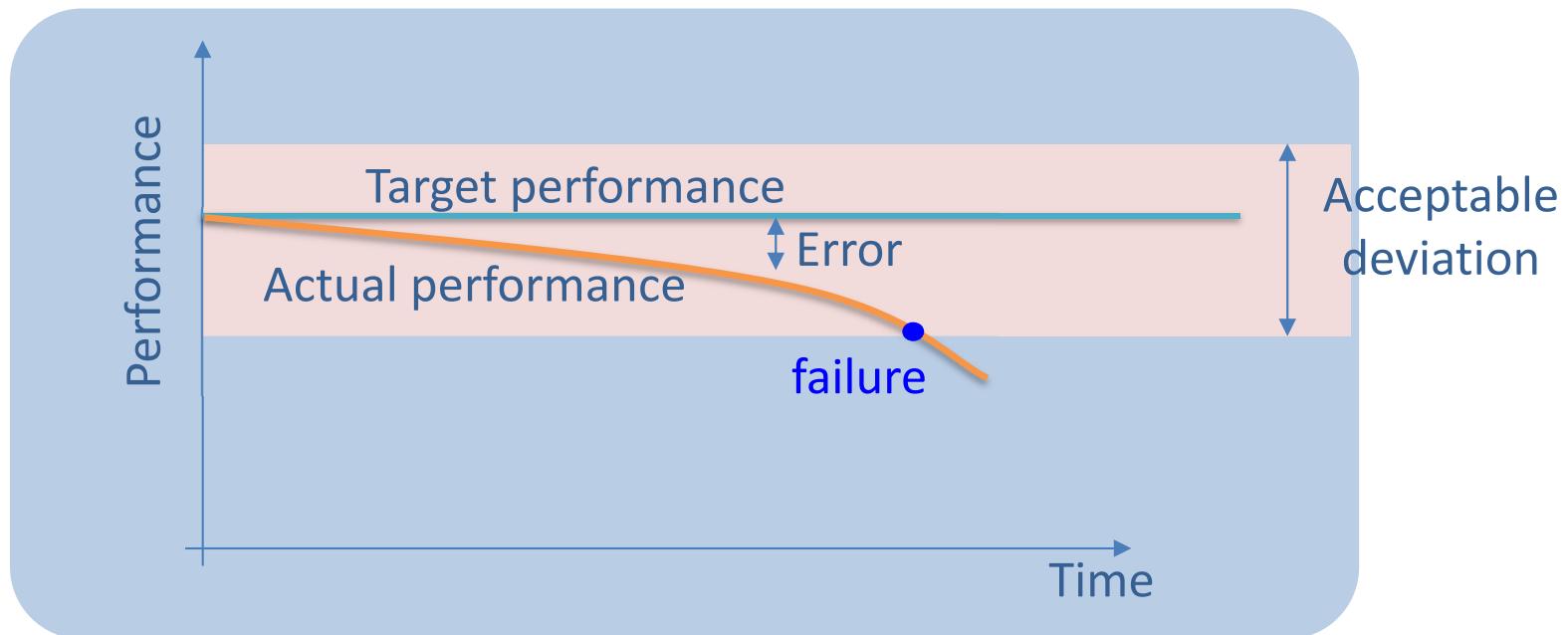


- 
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► Reliability Definition

General Definition

- ❖ Reliability is defined as a **measure of the ability** of a system or an item to **function** under a **desired conditions** within a specific **period of time**. (IEEE Reliability Society)



► Reliability Definition

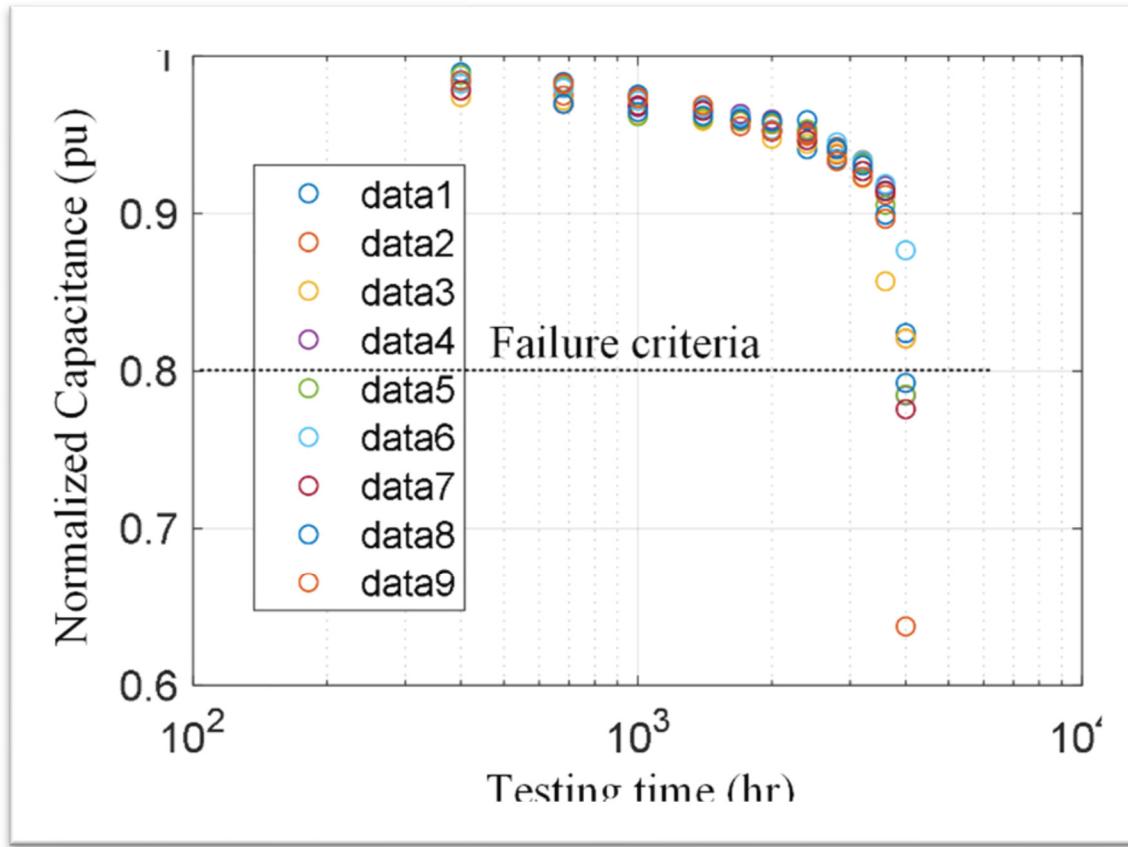
Reliability Definition

Performance measures:

- ❖ Probability of failure: $F(t)$ – e.g., in space craft
 - ✓ $R > 99.9999\%$
- ❖ THD in converters
 - ✓ $THD < 5\%$
- ❖ Availability in a maintainable system – e.g., transformer
 - ✓ $A > 98\%$
- ❖ LOLE, EENS, SAIFI, EENP, ... in power systems
 - ✓ $LOLE < 6\text{hr/yr}$

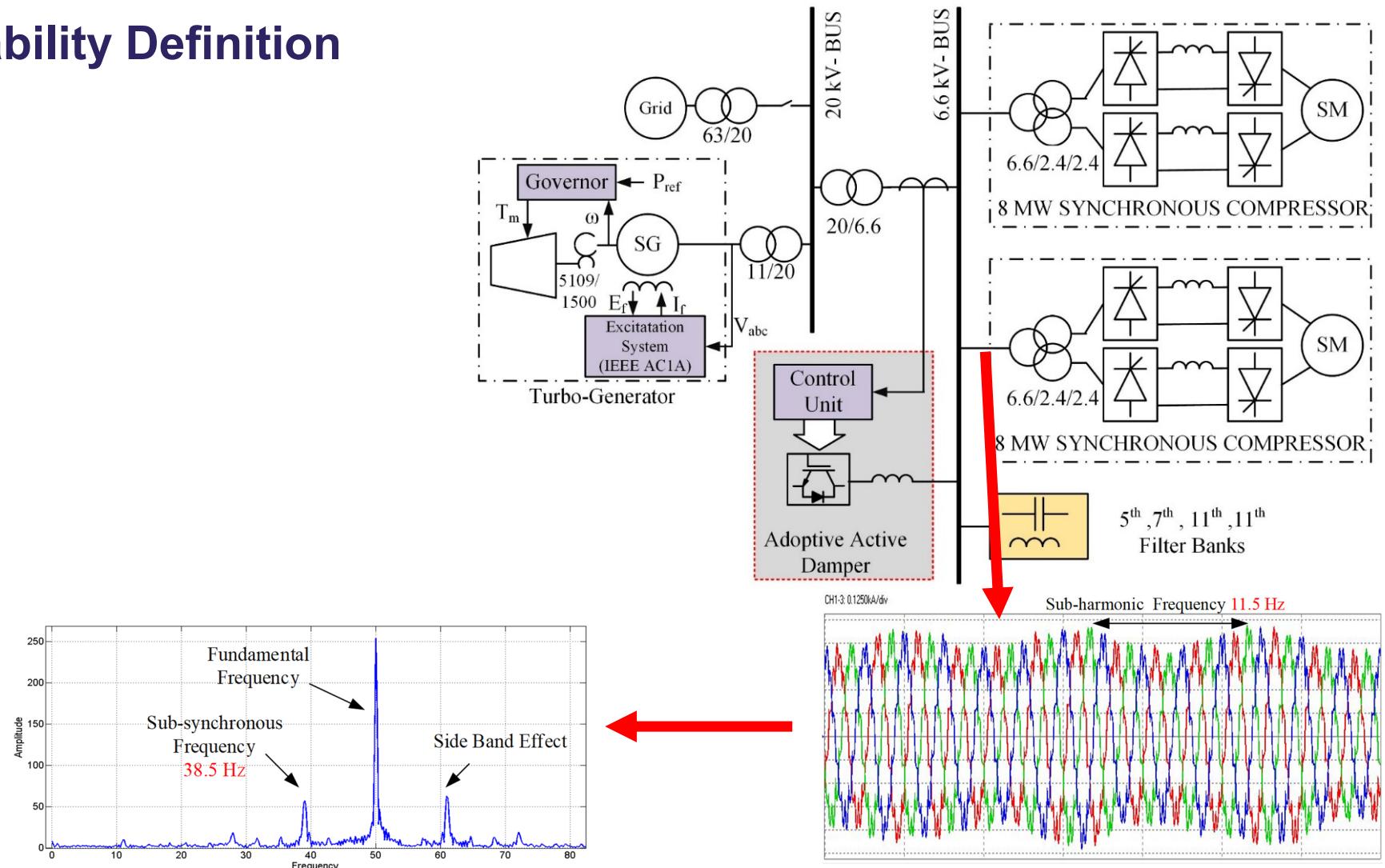
► Reliability Definition

Reliability Definition



► Reliability Definition

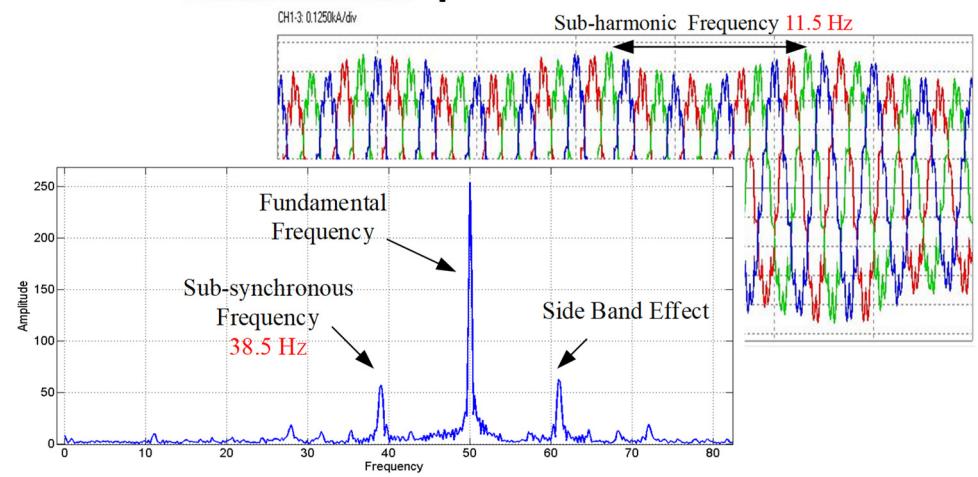
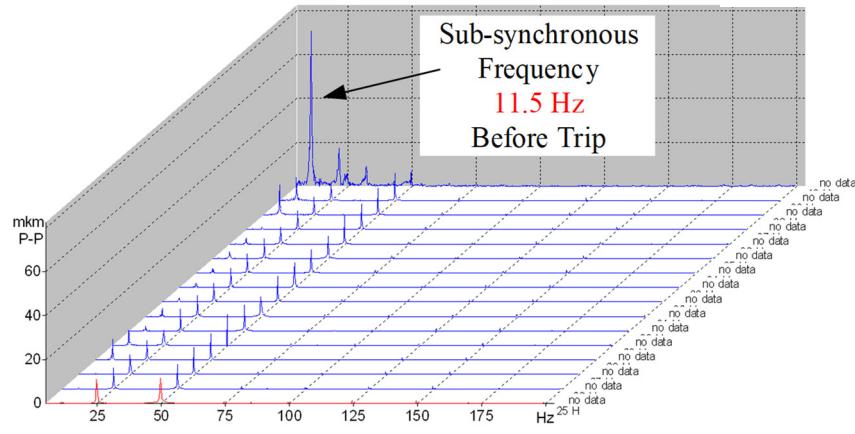
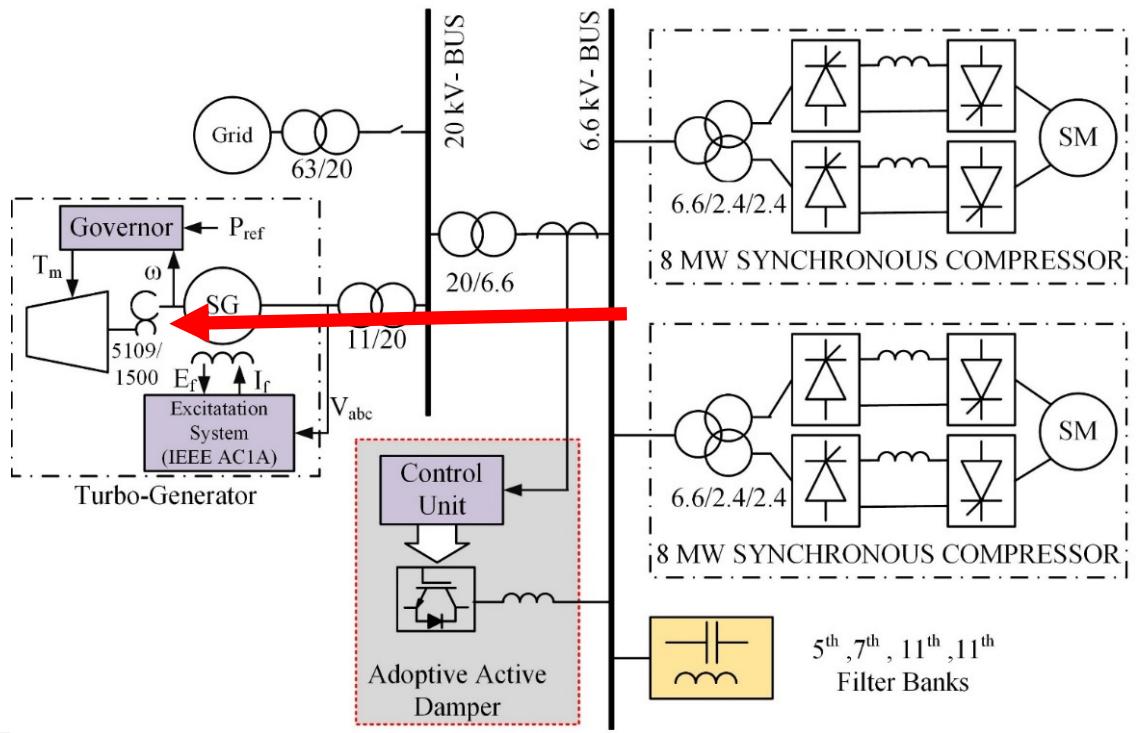
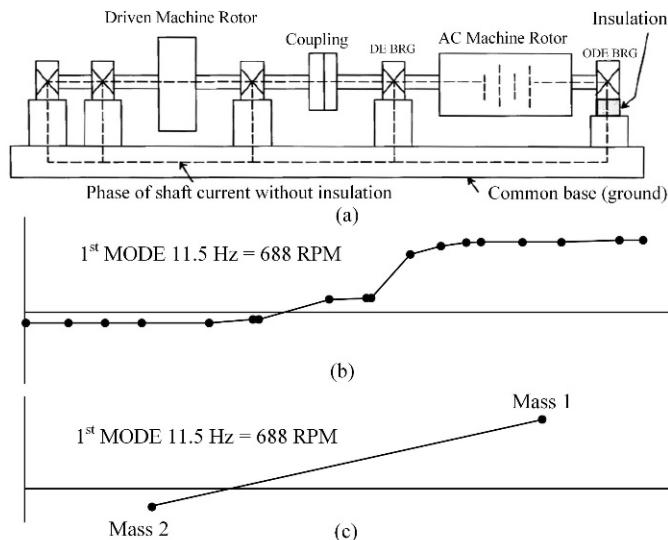
Reliability Definition



S. Peyghami, A. Azizi, H. Mokhtari, and F. Blaabjerg, "Active Damping of Torsional Vibrations due to the Sub-harmonic Instability on a Synchronous Generator," in Proc. IEEE ECCE EUROPE (EPE) 2018, pp. 1-8.

► Reliability Definition

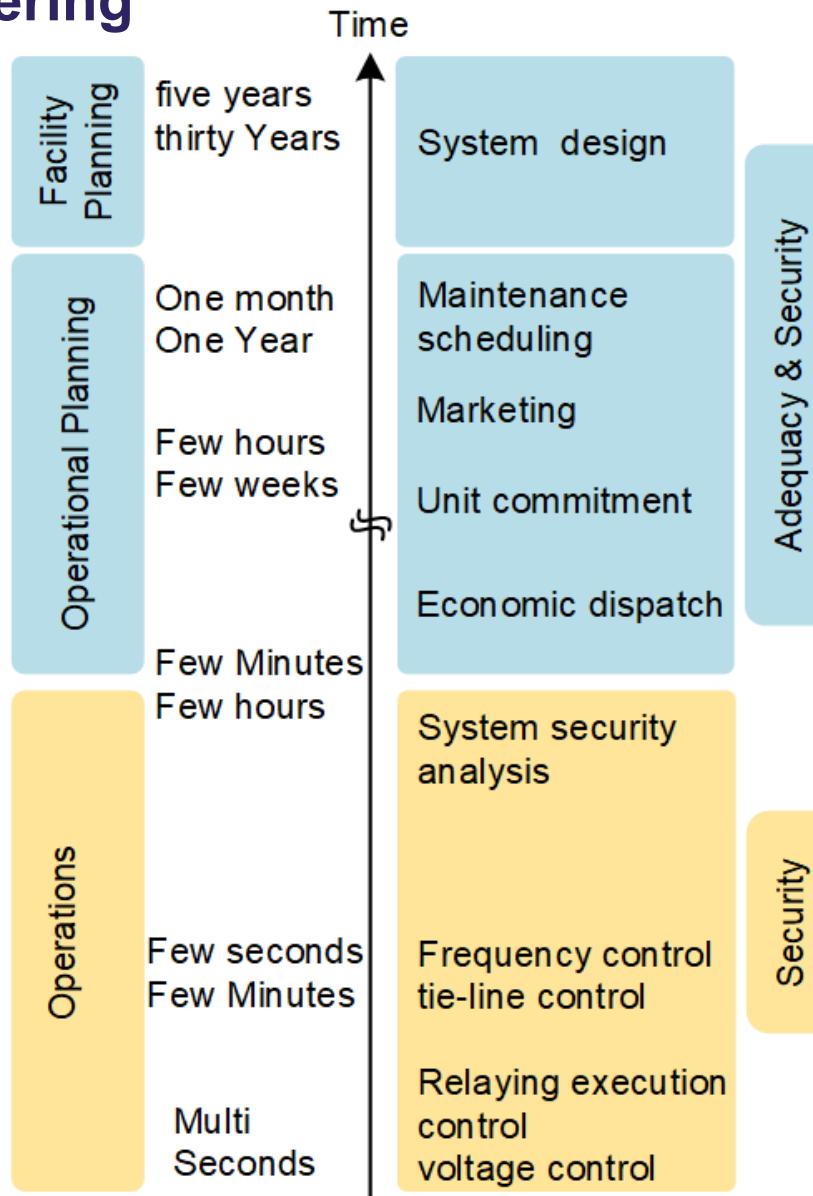
Reliability Definition



S. Peyghami, A. Azizi, H. Mokhtari, and F. Blaabjerg, "Active Damping of Torsional Vibrations due to the Sub-harmonic Instability on a Synchronous Generator," in Proc. IEEE ECCE EUROPE (EPE) 2018, pp. 1-8.

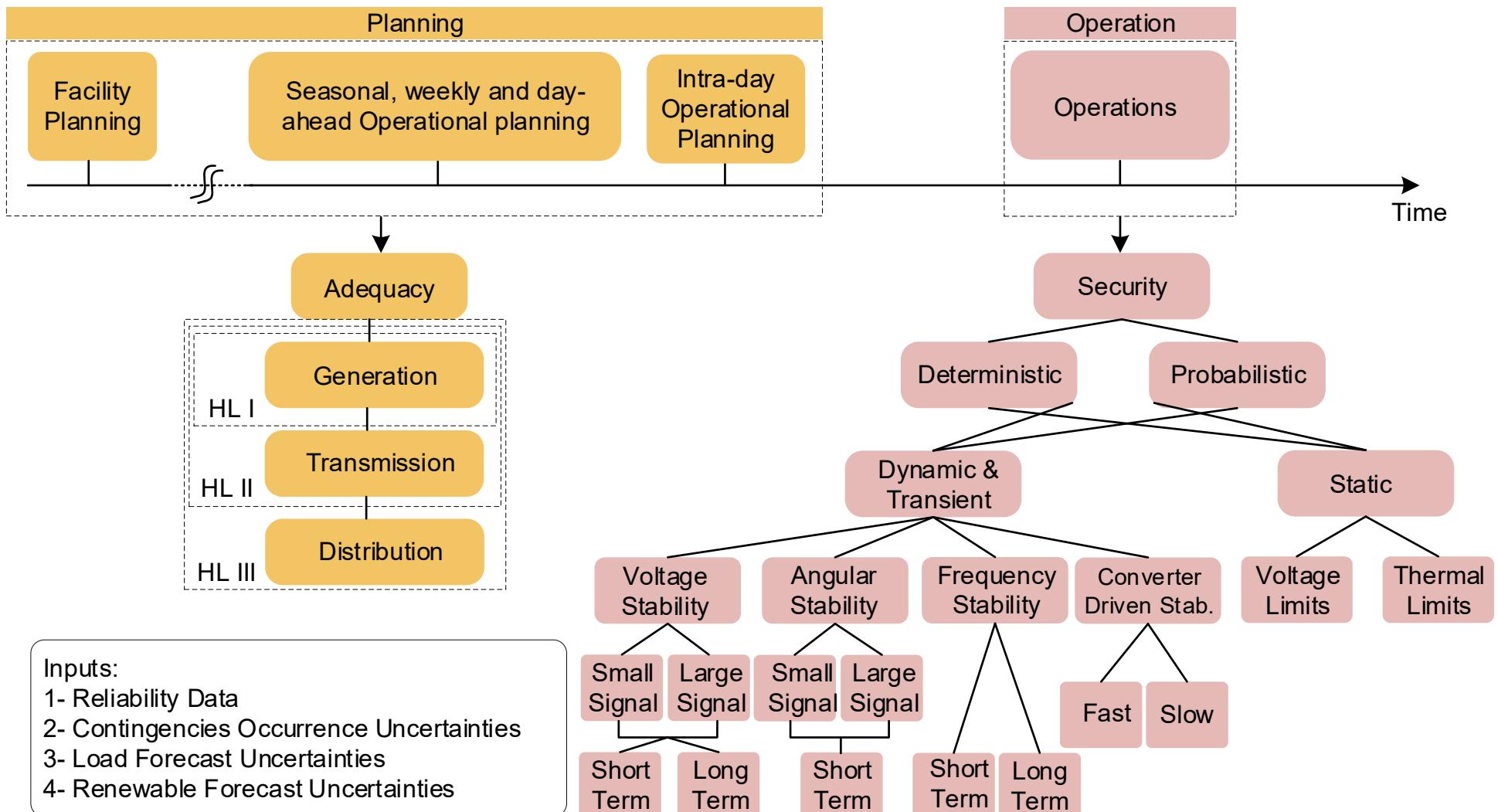
► Reliability Definition

Power system engineering



► Reliability Definition

Power System Reliability



Source: S. Peyghami, P. Palensky and F. Blaabjerg, "An Overview on the Reliability of Modern Power Electronic Based Power Systems," in *IEEE Open Journal of Power Electronics*, vol. 1, pp. 34-50, 2020.

► Reliability Definition

Reliability—current definition

Reliability

1987: A measure of the ability of a bulk power system to deliver electricity to all points of utilization within accepted standards and in the amount desired.

2002: Electric system reliability can be addressed by considering two basic and functional aspects of the electric system adequacy and security.

Adequacy

The ability of the electric system to supply the aggregate electric power and energy requirements of the customers at all times, taking into account scheduled and unscheduled outages of system facilities.

Investment planning

Security

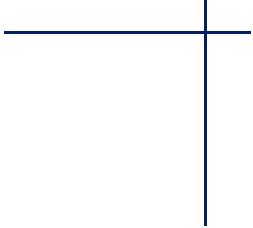
The ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system facilities.

Operation



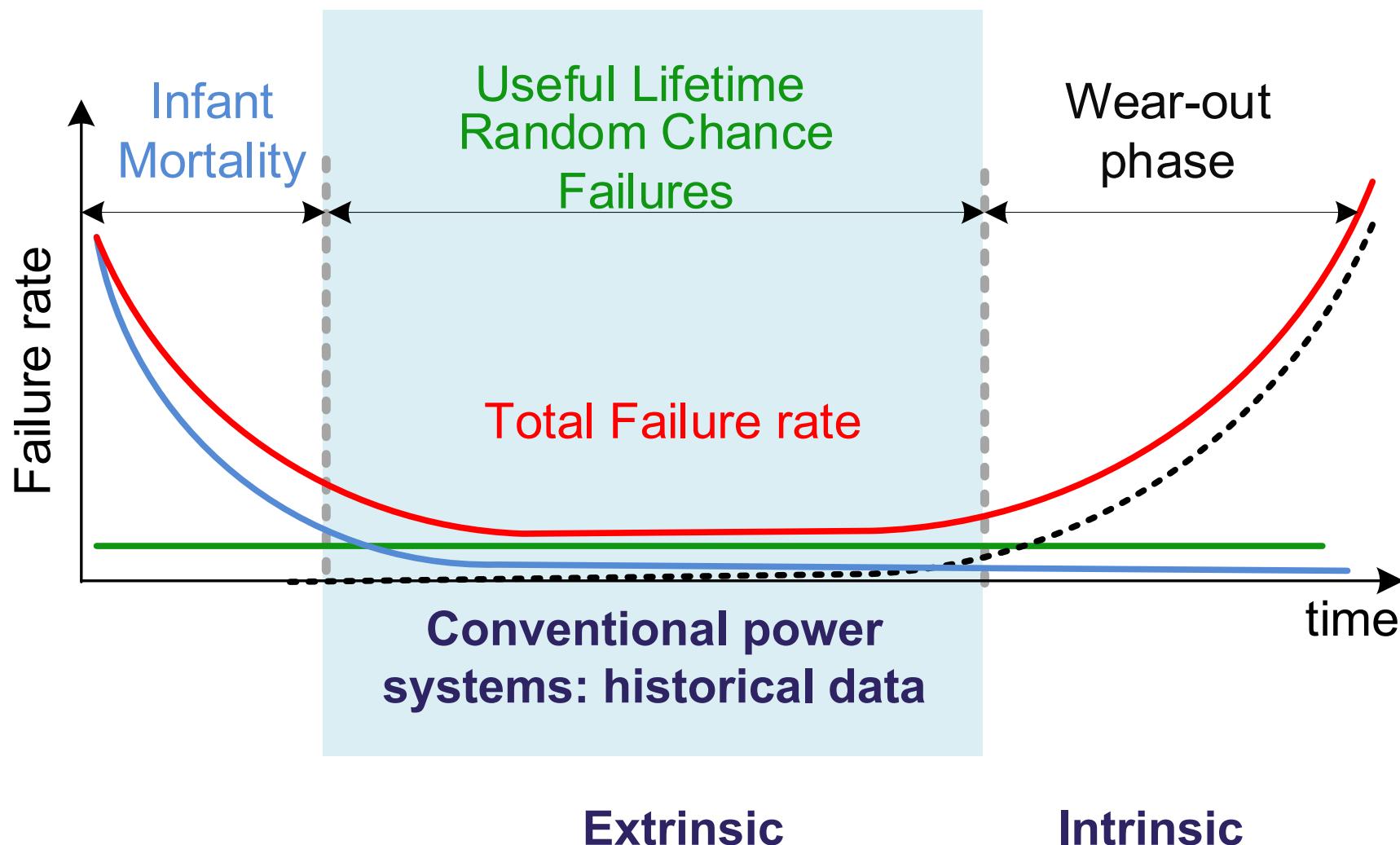
CIGRE Study Committees 37, 38 and 39, Technical Brochure 198,
CIGRE Glossary of Terms Used in the Electricity Supply Industry,
February 2002



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► Reliability Modeling in PE

Failure rates



► Reliability Modeling in PE

Reliability prediction methods

- ❖ Predictions based on field data
- ❖ Predictions based on test data
- ❖ Predictions based on stress and strength models
- ❖ Prediction based on handbooks
 - ✓ MIL-HDBK-217F
 - ✓ Telcordia SR-332
 - ✓ IEC62380
 - ✓ RDF 2000
 - ✓ PRISM
 - ✓ Fides



► Reliability Modeling in PE

Prediction based on handbooks

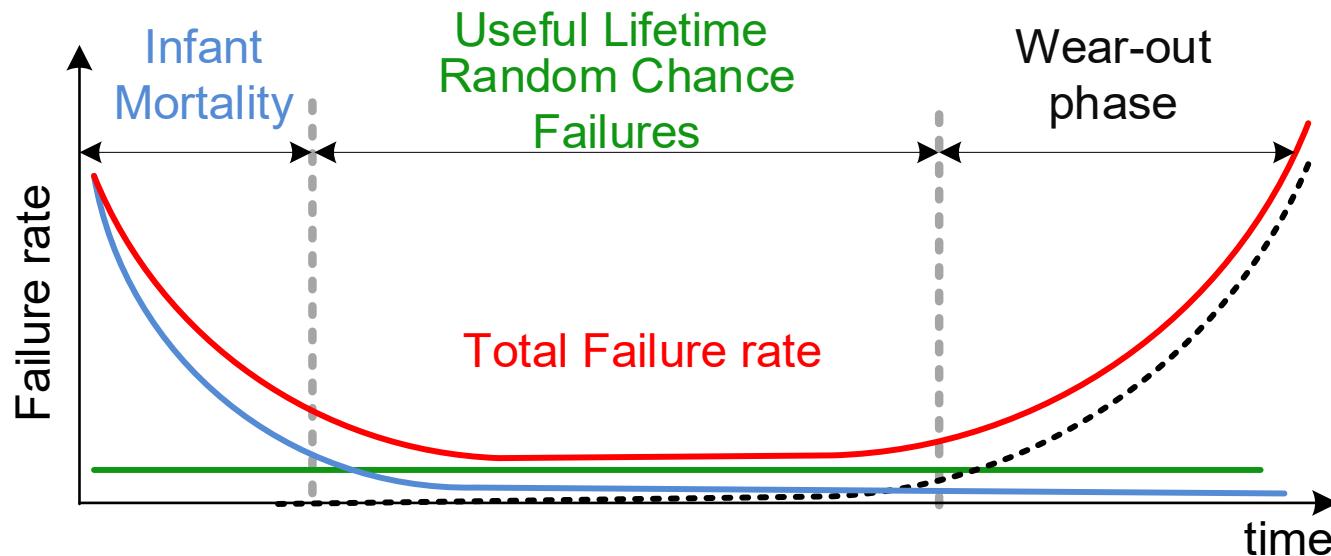
- **Military Handbook 217 (MIL-HDBK-217)**
 - Not be updated
 - No mission profile be considered
 - No physics of failure be considered
- **IEC TR 62380 in 2004**
 - Not be updated
 - No physics of failure be considered
 - Mission profile
- **IEC 61709 in 2017**
 - No physics of failure
 - A general guideline, No failure data available
 - Mission profile
- **FIDES**
 - Mission profile
 - Physics of failure ??
 - Updated data
 - Not suitable for power modules

Withdrawn

Withdrawn

► Reliability Modeling in PE

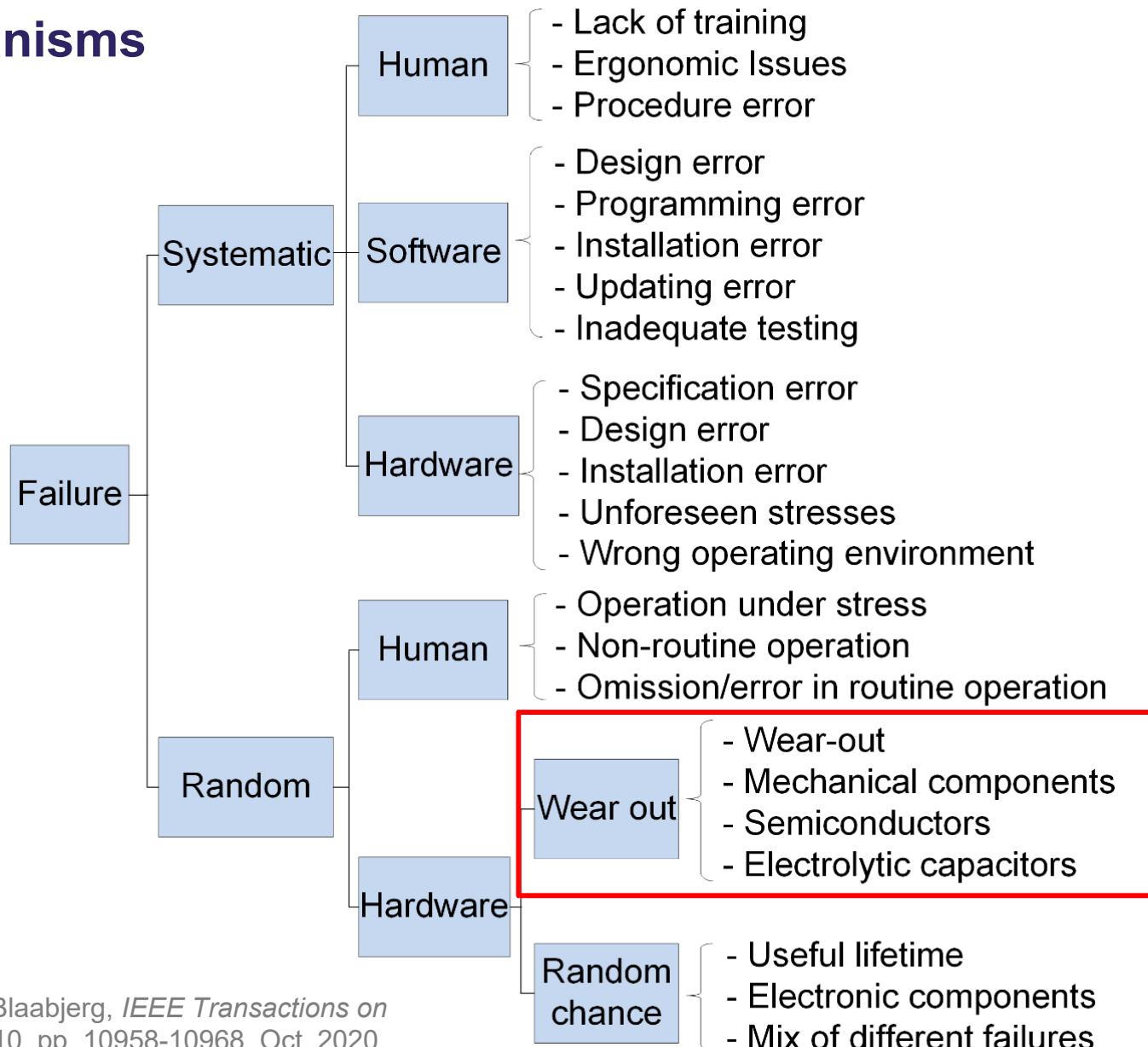
Historical data- what is missed?



- ❖ Are not **accurate**, depend on operation and climate conditions, ...
- ❖ Are not suitable for **new technologies** specially in power electronics
- ❖ Are not useful for **identifying weakest link of systems and reinforcement**
- ❖ Are not useable for **design for reliability**
- ❖ Do not show the **end of life**

► Reliability Modeling in PE

Failure mechanisms



S. Peyghami, Z. Wang and F. Blaabjerg, *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 10958-10968, Oct. 2020

► Reliability Modeling in PE

Failure mechanisms in converter devices

Dev.	Failure type	Failure mode	Failure mechanisms
Semiconductors	Catastrophic failures	Open circuit	Device failure in gate driver, Driver board short-, open-circuit Bond wire lift-off, Bond wire rupture after IGBT short-circuit High voltage breakdown
		Short circuit	Dynamic latch-up Second breakdown Impact ionization High temperature due to power dissipation
	Wear-out failures	Parameter drift	Chip solder joint cracking Baseplate solder joints cracking Wire bonds lift-off/cracking
Al-Caps	Catastrophic failures	Open circuit	Self-healing dielectric breakdown Disconnection of terminals
		Short circuit	Dielectric breakdown of oxide layer
	Wear-out failures	Parameter drift	Electrolyte vaporization Electrochemical reaction
MLPPF-Caps	Catastrophic failures	Open circuit	Self-healing dielectric breakdown Connection instability by heat contraction of dielectric film
			Reduction in electrode area caused by oxidation of evaporated metal due to moisture absorption
		Short circuit	Dielectric film breakdown
			Self-healing due to overcurrent Moisture absorption by film
	Wear-out failures	Parameter drift	Dielectric loss
MLC-Caps	Catastrophic failures	Short circuit	Dielectric breakdown Cracking; damage to capacitor body
	Wear-out failures	Parameter drift	Oxide vacancy migration; dielectric puncture; insulation degradation; micro-crack within ceramic

► Reliability Modeling in PE

Constant failure rates (IEC TR 62380)

CAUTION !

Under cyclic operation, the life time is limited !

Semiconductors

$$\lambda = \left\{ \pi_S \times \lambda_0 \right\} \times \left\{ \frac{\sum_{i=1}^y (\pi_t)_i \times \tau_i}{\tau_{on} + \tau_{off}} \right\} + \left\{ \underbrace{2.75 \times 10^{-3} \times \sum_{i=1}^z (\pi_n)_i \times (\Delta T_i)^{0.68}}_{\lambda_{package}} \times \lambda_B \right\} + \left\{ \underbrace{\pi_I \times \lambda_{EOS}}_{\lambda_{OVERSTRESS}} \right\} \times 10^{-9} / h$$

Elec. Capacitors

$$\lambda = 2.4 \times \left(\left[\frac{\sum_{i=1}^y (\pi_t)_i \times \tau_i}{\tau_{on} + \tau_{off}} \right] + 1.4 \times 10^{-3} \times \left[\sum_{i=1}^j (\pi_n)_i \times (\Delta T_i)^{0.68} \right] \right) \times 10^{-9} / h$$



► Reliability Modeling in PE

Constant failure rates (FIDES)

$$\lambda = \prod_{PM} \prod_{Process} \lambda_{Phy}$$

① Warning: limited life

Semiconductors

FIDES page 120

$$\lambda_{Phy-SD} = \sum_{i=1}^{Phase} \left[\frac{t_{annual}}{8760} \right]_i \left(\begin{array}{l} \lambda_{0TH} \prod_{Thermal} \\ + \lambda_{0TCyCase} \prod_{TCyCase} \\ + \lambda_{0TCySolderjoints} \prod_{TCySolderjoints} \\ + \lambda_{0RH} \prod_{RH} \\ + \lambda_{0Mech} \prod_{Mech} \end{array} \right)_i \left(\prod_{Induced} \right)_i$$

Elec. Capacitors

FIDES page 138

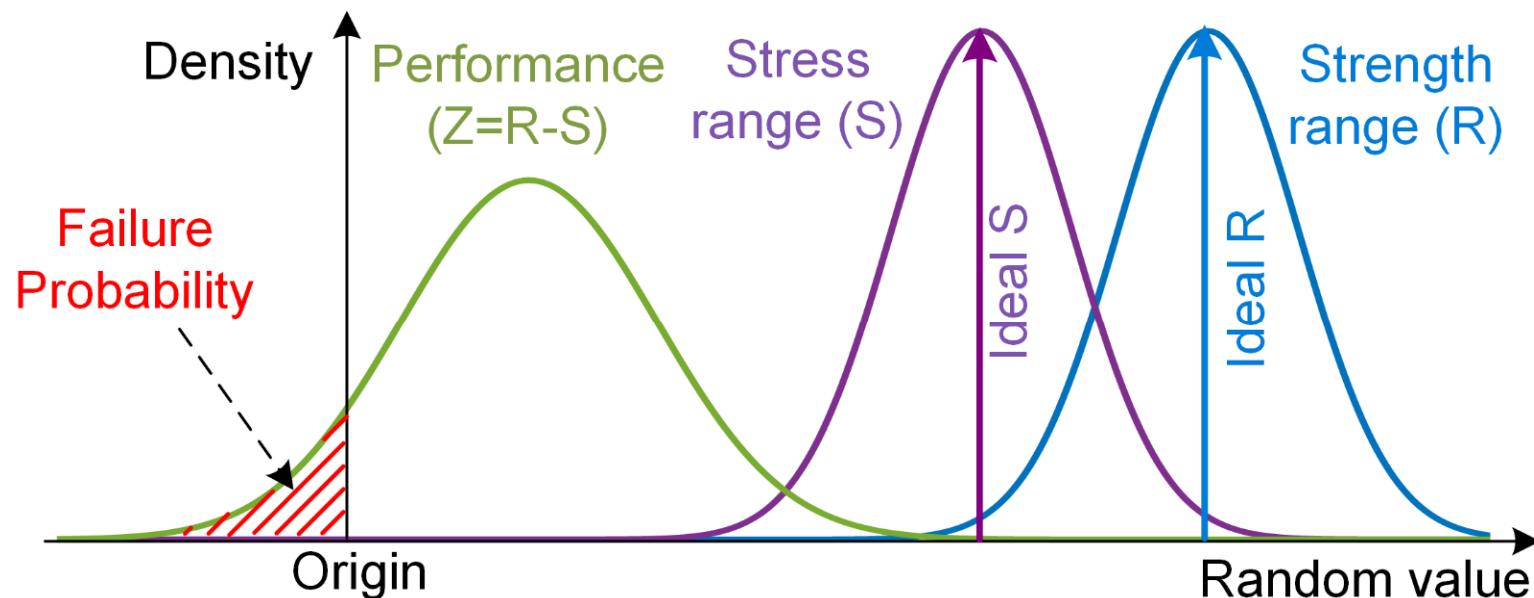
$$\lambda_{Phy-Cap} = \lambda_{0Cap} \sum_{i=1}^{Phase} \left[\frac{t_{annual}}{8760} \right]_i \left(\begin{array}{l} \prod_{Thermo-electrical} \\ + \prod_{TCy} \\ + \prod_{Mechanical} \end{array} \right)_i \left(\prod_{Induced} \right)_i$$

S. Peyghami, Z. Wang and F. Blaabjerg *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 10958-10968, Oct. 2020



► Reliability Modeling in PE

Wear out failure rate prediction – stress-strength analysis



$$Z = R - S$$

$$P_f = \Pr(Z < 0)$$

S. Peyghami, Z. Wang and F. Blaabjerg *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 10958-10968, Oct. 2020

► Reliability Modeling in PE

Wear out failure rate prediction – stress-strength analysis

Structural reliability

$$Z = R - S$$

Strength (Resistance, R) load (Stress, S)

$$R = g(x_1, \dots, x_n)$$

$$Z(t) = R - tS; t = 1, 2, \dots$$

S. Peyghami, Z. Wang and F. Blaabjerg *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 10958-10968, Oct. 2020



► Reliability Modeling in PE

Wear out failure rate prediction – stress-strength analysis

Impact of mission profile

$$Z(t) = \sum_{i=1}^h (R_i - tS_i); t = 1, 2, \dots$$

Damage

$$D = \sum_{i=1}^h \frac{S_i}{R_i}$$

Equivalent (total) stress

$$S_T = \sum_{i=1}^h S_i$$

Equivalent variables

$$\forall_{\substack{i=1:h \\ i \neq k}} x_{i,eq} \triangleq \frac{1}{h} \sum_{j=1}^h x_{i,h} \quad x_{k,eq} \triangleq g^{-1}(R_T) \Big|_{x_{i,eq}^{(h)}, h \neq k}$$

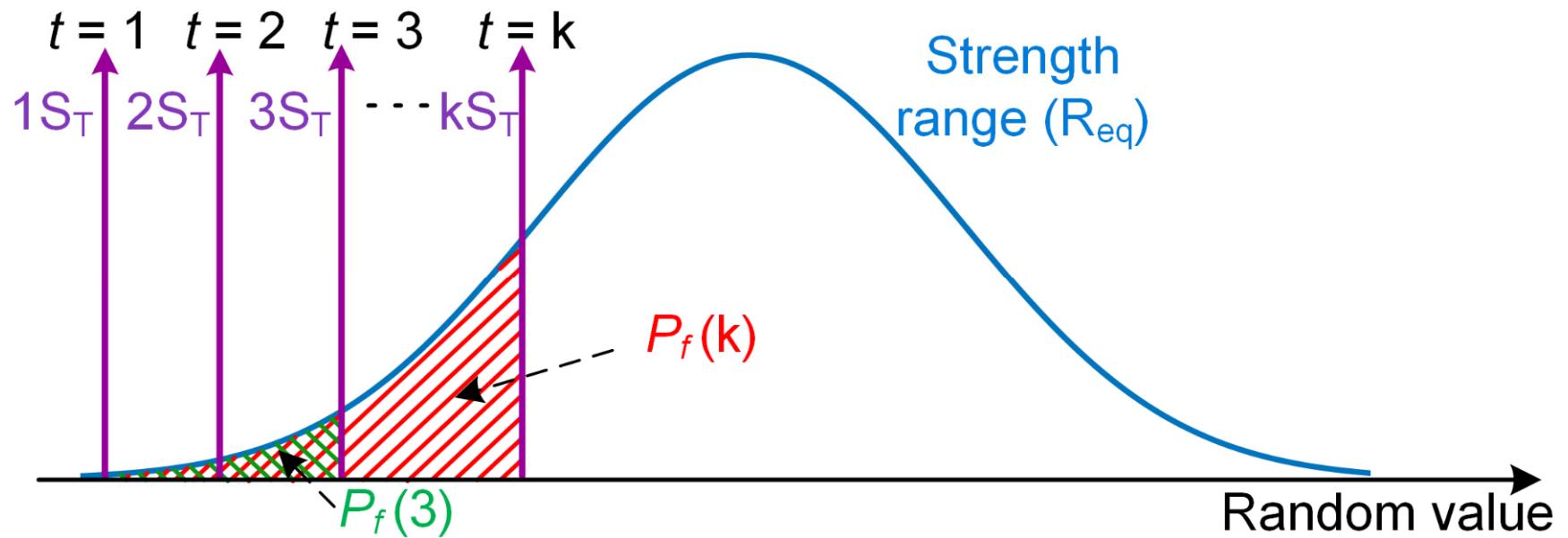
S. Peyghami, Z. Wang and F. Blaabjerg *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 10958-10968, Oct. 2020



► Reliability Modeling in PE

Wear out failure rate prediction – stress-strength analysis

$$Z(t) = R_{eq} - tS_T = g(x_{1,eq}, \dots, x_{n,eq}) - tS_T$$



S. Peyghami, Z. Wang and F. Blaabjerg *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 10958-10968, Oct. 2020

► Reliability Modeling in PE

Wear out failure rate prediction – stress-strength analysis

First Order Reliability Method (FORM)

$$P_f(t) \approx \Phi\left(-\frac{\mu_z}{\sigma_z}\right)$$

$$\mu_z \approx g(\mu_{x_{1,eq}}, \dots, \mu_{x_{n,eq}}) - tS_T$$

$$\sigma_z^2 \approx \sum_{i=1}^n \left(\frac{\partial g(x_{1,eq}, \dots, x_{n,eq})}{\partial x_{i,eq}} \right)^2 \sigma_{x_{i,eq}}^2$$

Φ : standard normal distribution function

S. Peyghami, Z. Wang and F. Blaabjerg *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 10958-10968, Oct. 2020



► Reliability Modeling in PE

Wear out failure rate prediction – stress-strength analysis

- Capacitor damage

$$L_w = L_r \cdot 2^{\frac{T_r - T_w}{n_1}} \left(\frac{V_w}{V_r} \right)^{-n_2}$$

- Semiconductor damage

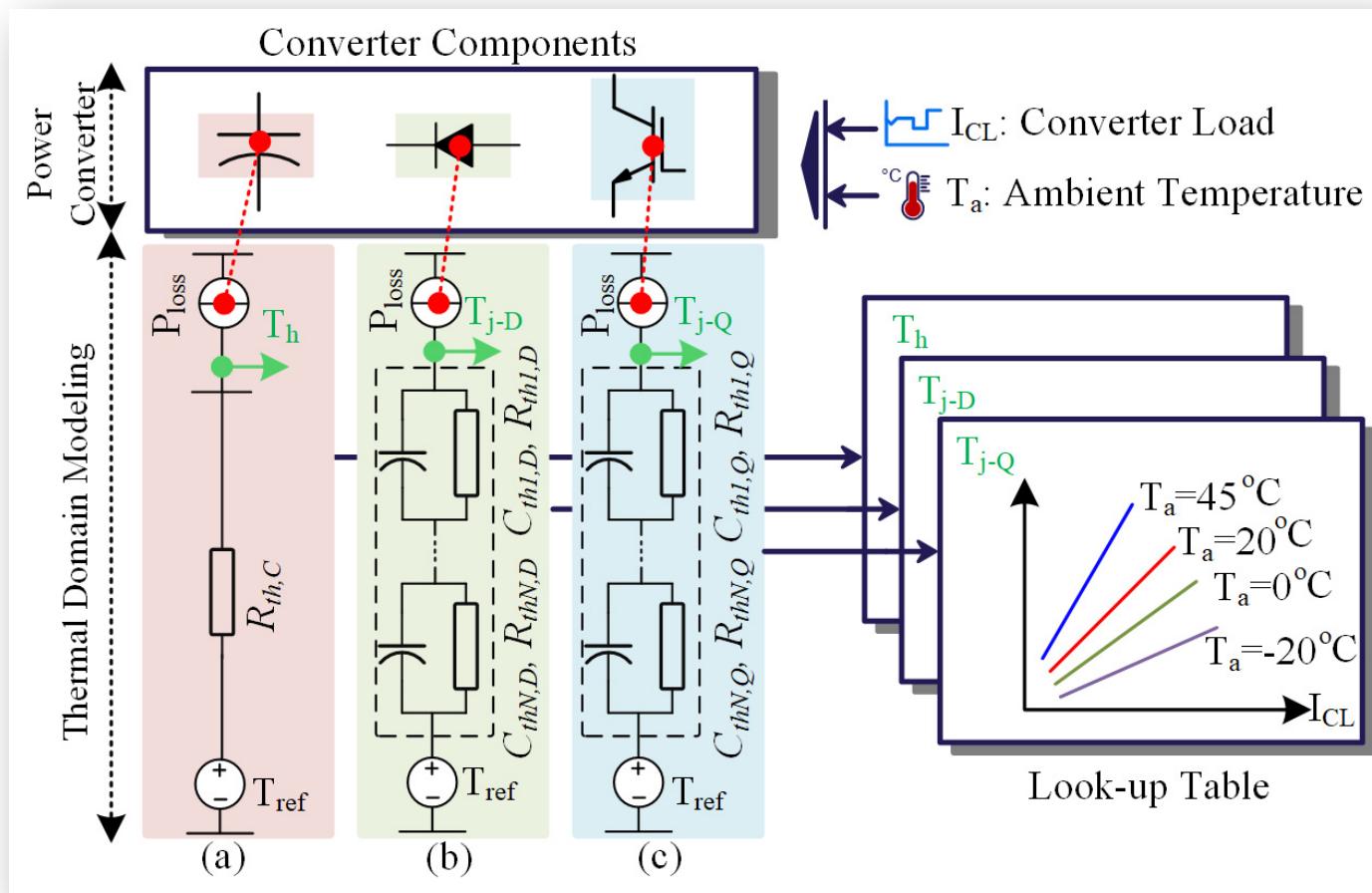
$$N = A \cdot \Delta T_j^\alpha \cdot \exp\left(\frac{\beta}{T_{jm} + 273.15}\right) t_{on}^\gamma$$

S. Peyghami, Z. Wang and F. Blaabjerg *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 10958-10968, Oct. 2020



► Reliability Modeling in PE

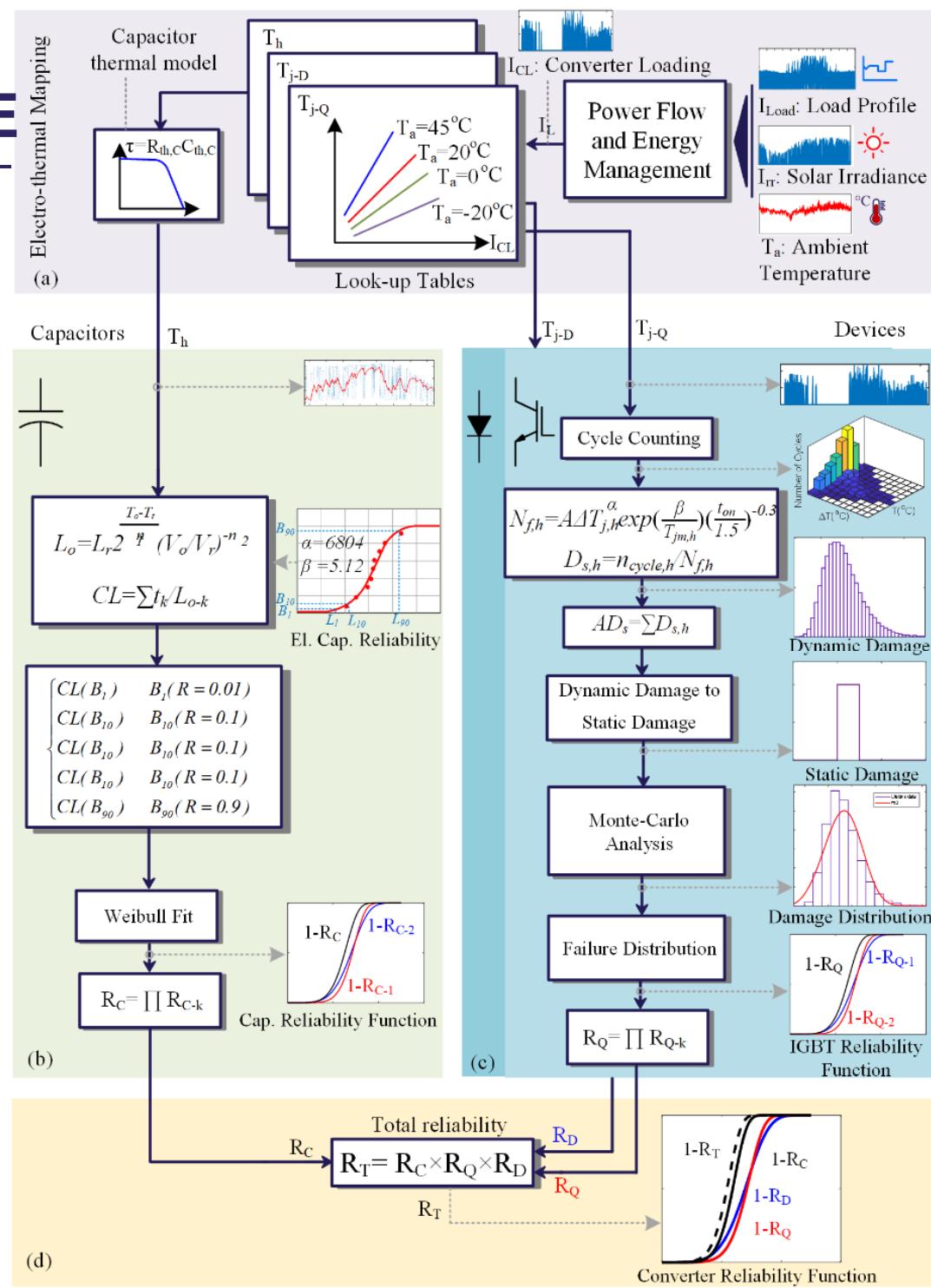
Electro-thermal mapping



Source: S. Peyghami, P. Davari and F. Blaabjerg, *IEEE Trans. Ind. App.*, doi: 10.1109/TIA.2019.2918049

► Reliability Modeling in PE

Wear out prediction



Source: S. Peyghami, P. Davari and F. Blaabjerg, *IEEE Trans. Ind. App.*, doi: 10.1109/TIA.2019.2918049

► Reliability Modeling in PE – A case study

Converter topology

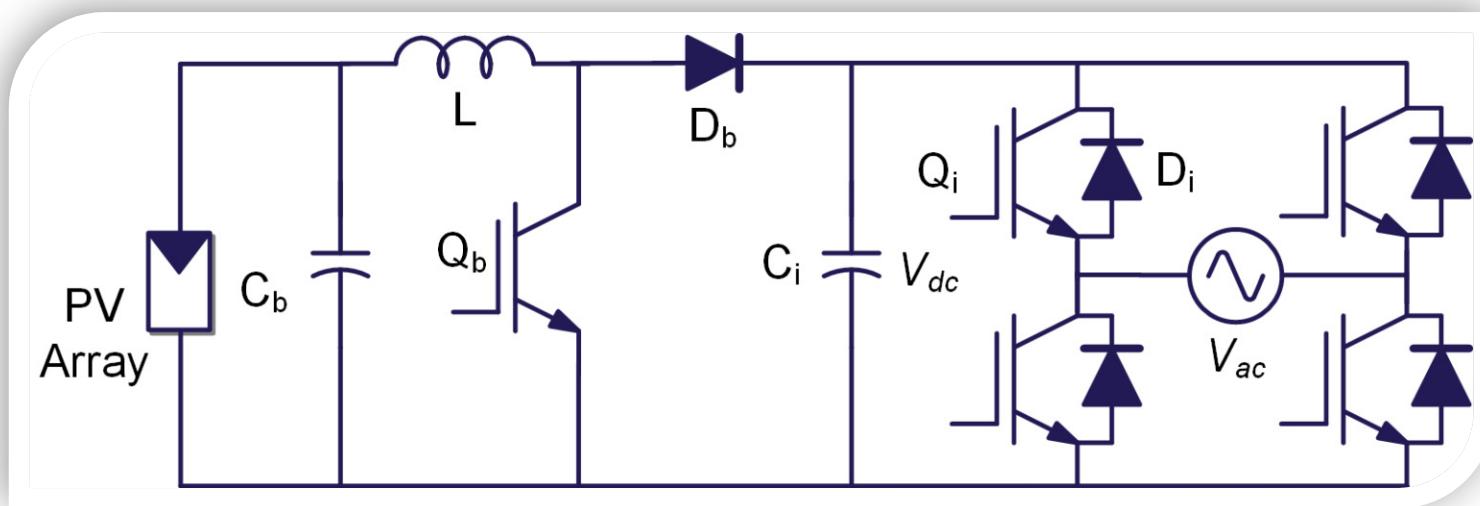


TABLE I. INVERTER COMPONENTS PARAMETERS AND LIFETIME MODEL.

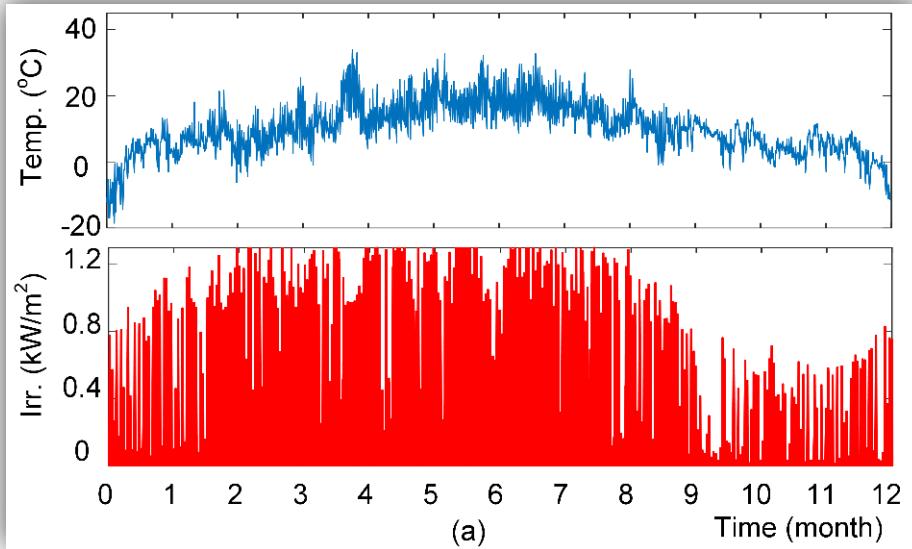
Parameter	Value	Parameter	Value
L	2 mH	A	$9.34\text{E}14 \pm 5\%$
C_b	$120 \mu\text{F}$	α	$-4.416 \pm 5\%$
C_i	$3 \times 390 \mu\text{F}$	β	$1285 \pm 5\%$
Q_b	IGB10N60T	γ	$0.3 \pm 5\%$
Q_i	GB15N60T	n_1	$10 \pm 5\%$
D_b	IDV20E65D1	n_2	$3 \pm 5\%$
D_i	IDV20E65D1	T_n	105°C
f_{sw}	20 kHz	V_n	450 V
V_{dc}	400 V	V_{ac}	$230 \text{ V}, 50 \text{ Hz}$

S. Peyghami, Z. Wang and F. Blaabjerg *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 10958-10968, Oct. 2020

► Reliability Modeling in PE – A case study

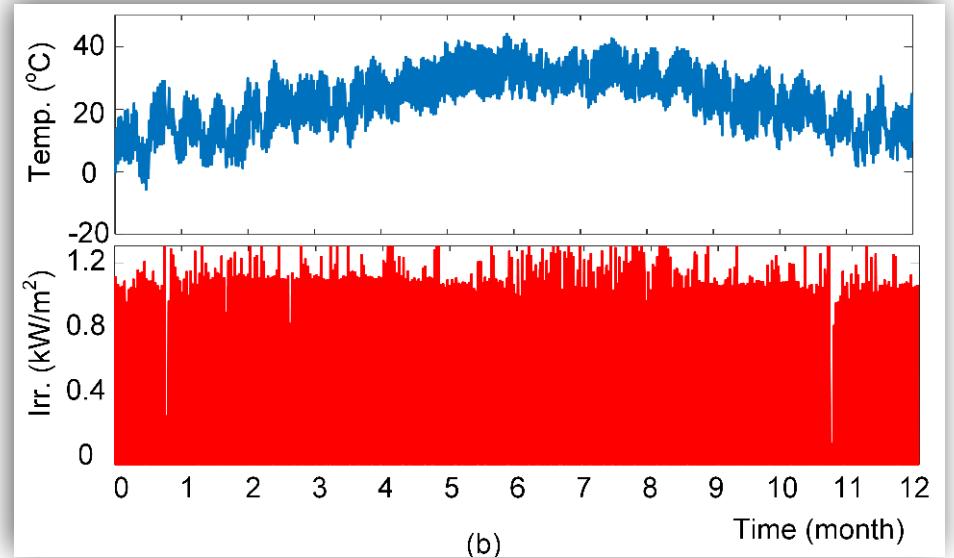
Mission profiles

Location A (Denmark)



(a)

Location B (Arizona)



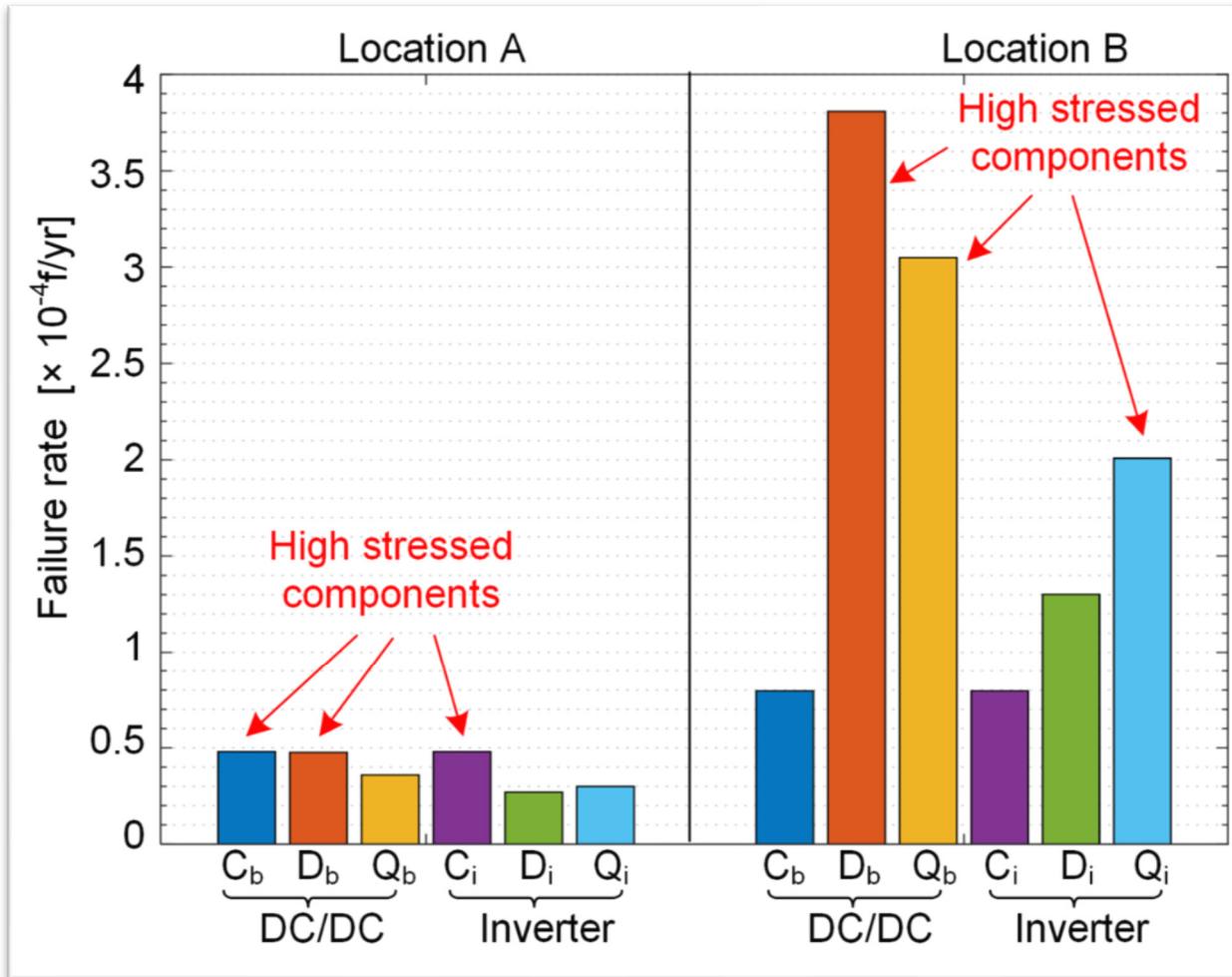
(b)

S. Peyghami, Z. Wang and F. Blaabjerg *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 10958-10968, Oct. 2020



► Reliability Modeling in PE – A case study

Constant failure rate of converter components – 2 mission profile

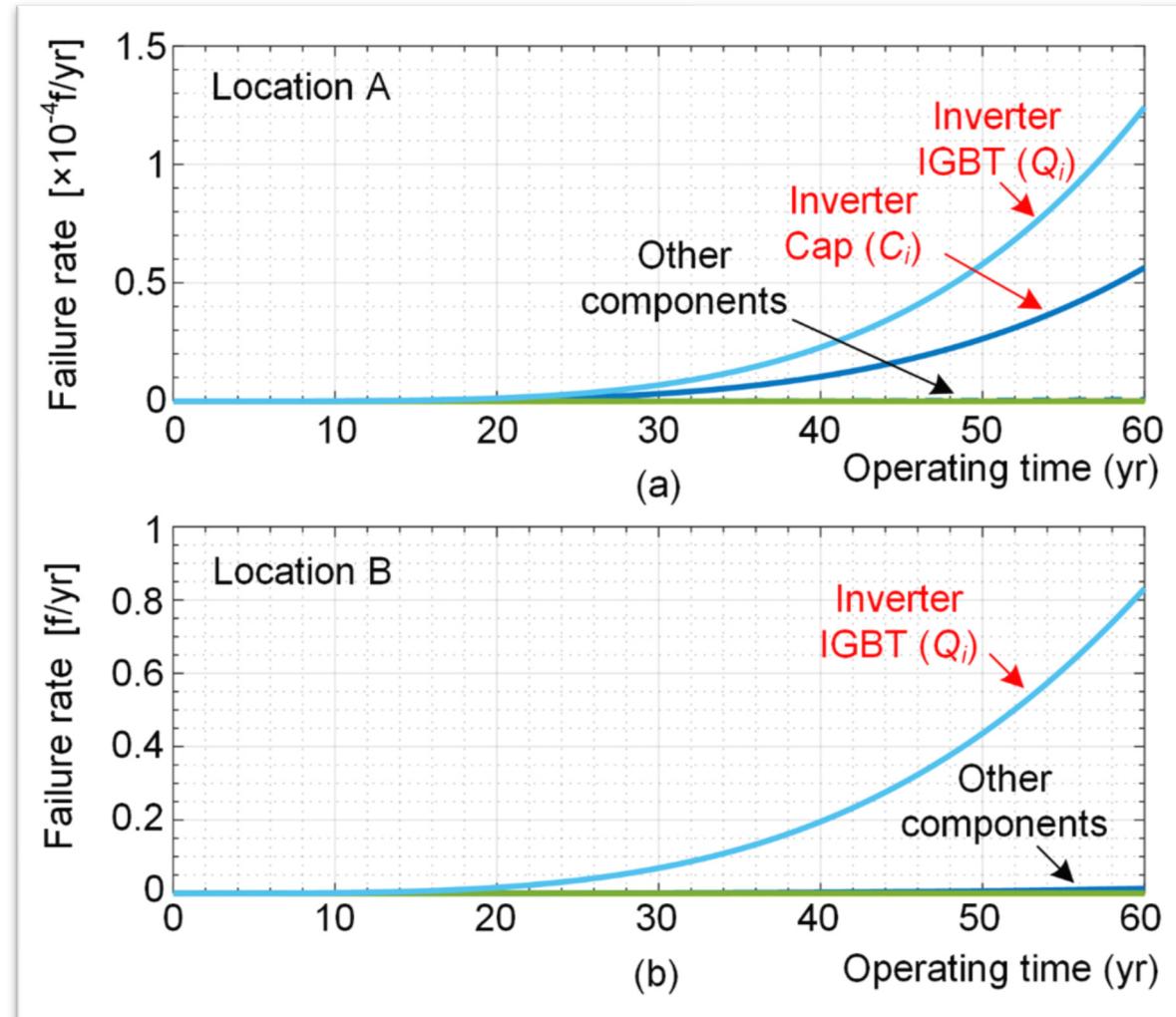


S. Peyghami, Z. Wang and F. Blaabjerg *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 10958-10968, Oct. 2020



► Reliability Modeling in PE – A case study

Wear-out failure rate of converter components – 2 mission profile

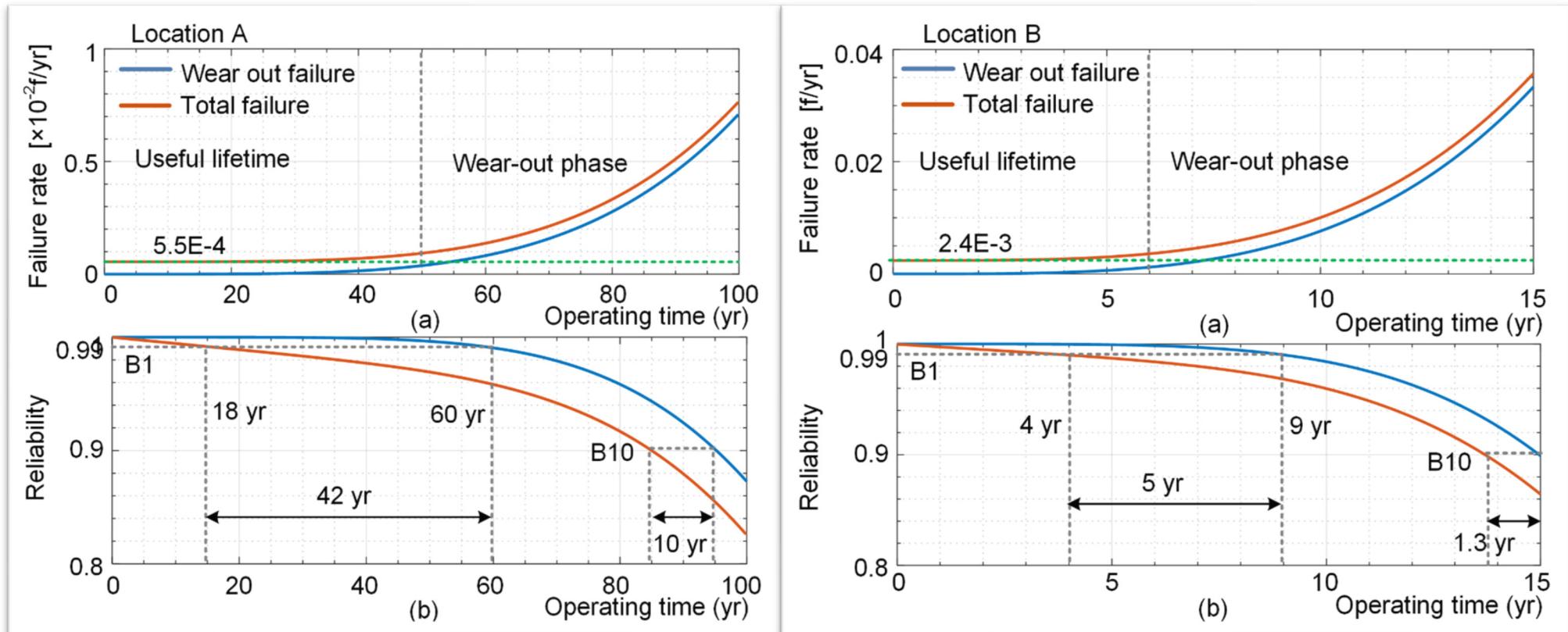


S. Peyghami, Z. Wang and F. Blaabjerg *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 10958-10968, Oct. 2020

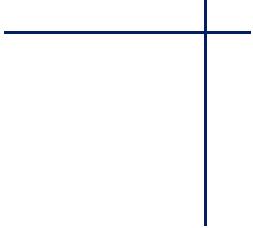


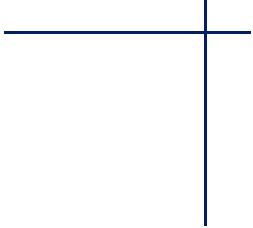
► Reliability Modeling in PE – A case study

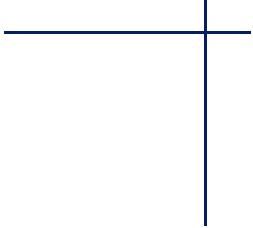
Converter reliability of converter under two mission profile



S. Peyghami, Z. Wang and F. Blaabjerg *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 10958-10968, Oct. 2020

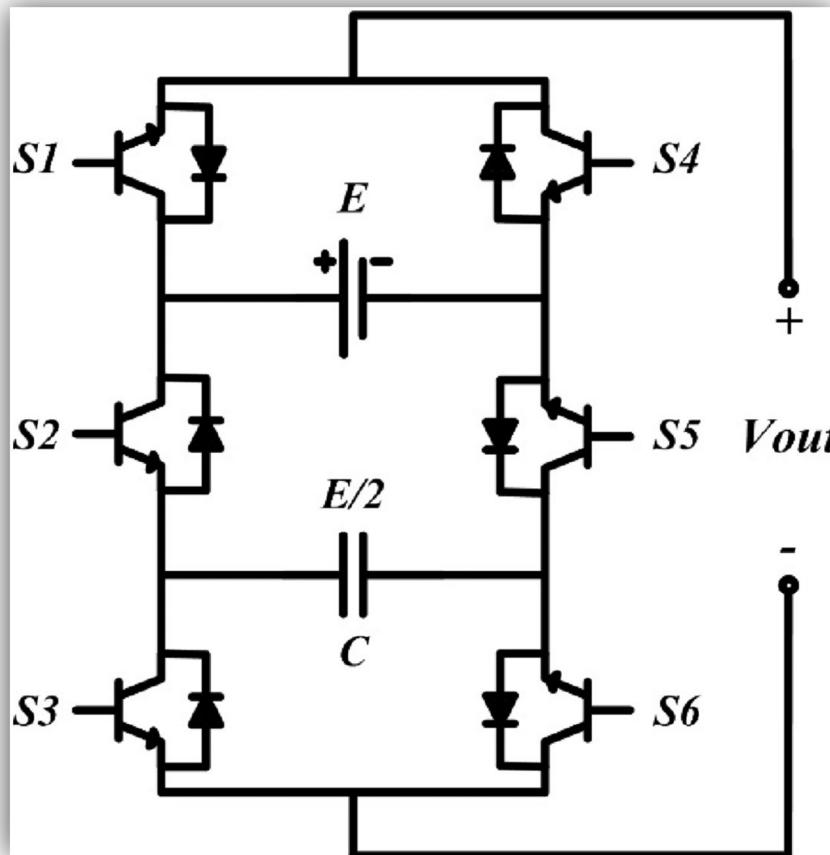
- 
- **Introduction**
 - **Reliability Definition in PEPS**
 - **Reliability Modeling in PE**
 - **Reliability Analysis**
 - **Reliability Enhancement**
 - **Summary**

- 
- **Reliability Analysis**
 - **Impact of Modulation Scheme**
 - **Impact of Mission Profile**
 - **Impact of Converter Topology**

- 
- **Reliability Analysis**
 - Impact of Modulation Scheme
 - Impact of Mission Profile
 - Impact of Converter Topology

► Reliability Analysis – Impact of Modulation Scheme

Converter topology



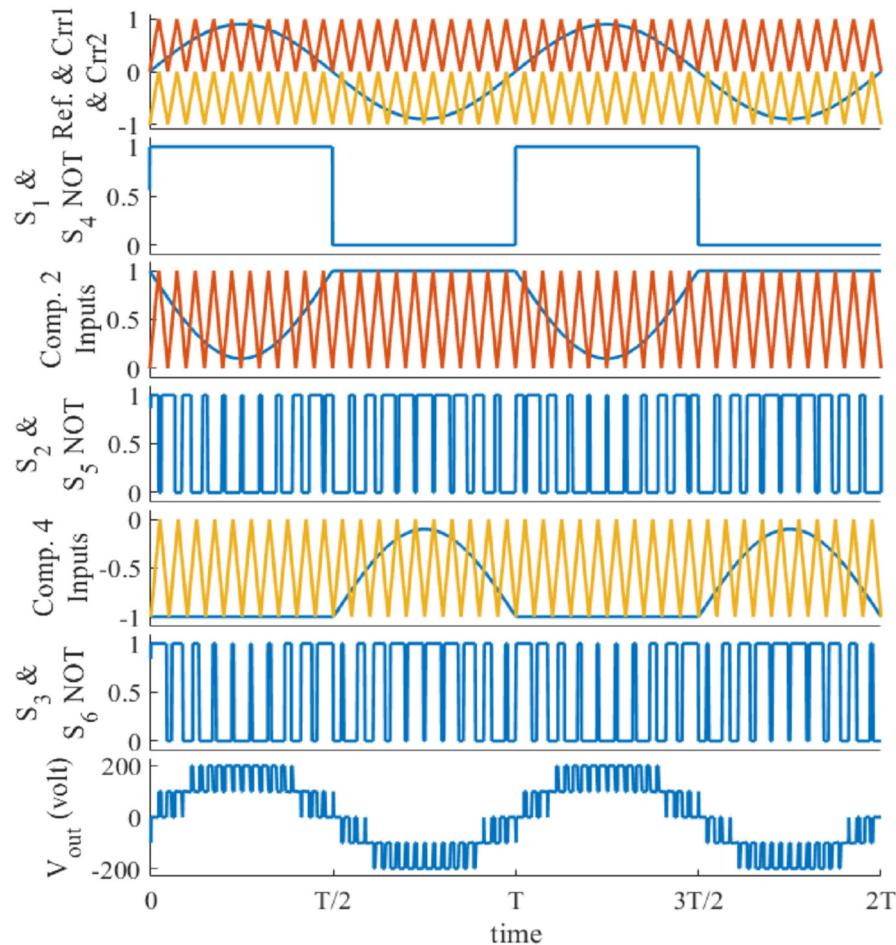
PUC 5 Converter Topology

Source: M. Abarzadeh, S. Peyghami, K. Al-Haddad, N. Weise, L. Chang and F. Blaabjerg, "Reliability and Performance Improvement of PUC Converter Using A New Single-Carrier Sensor-Less PWM Method with Pseudo Reference Functions," in *IEEE Transactions on Power Electronics*, doi: 10.1109/TPEL.2020.3030698.

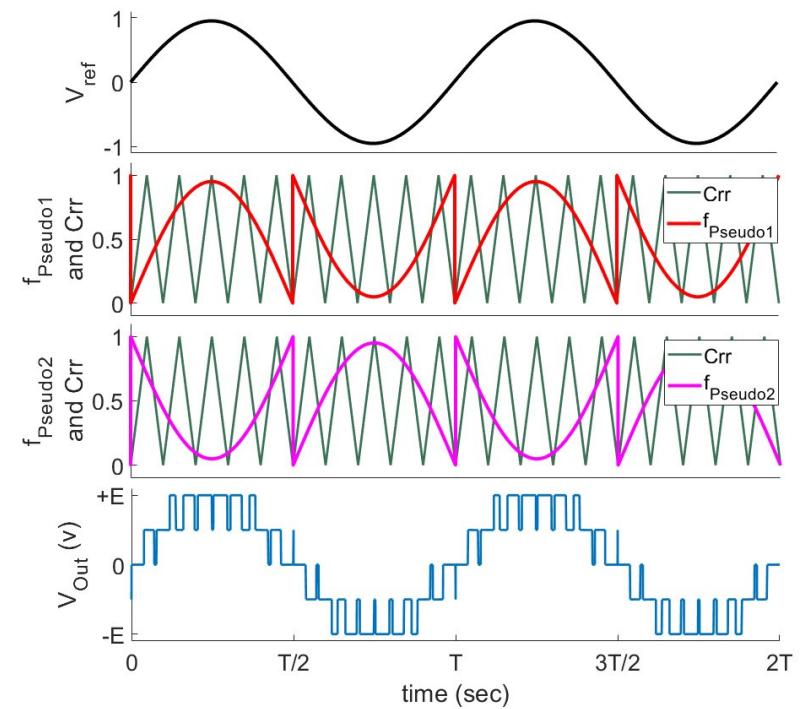


► Reliability Analysis – Impact of Modulation Scheme

Modulation schemes



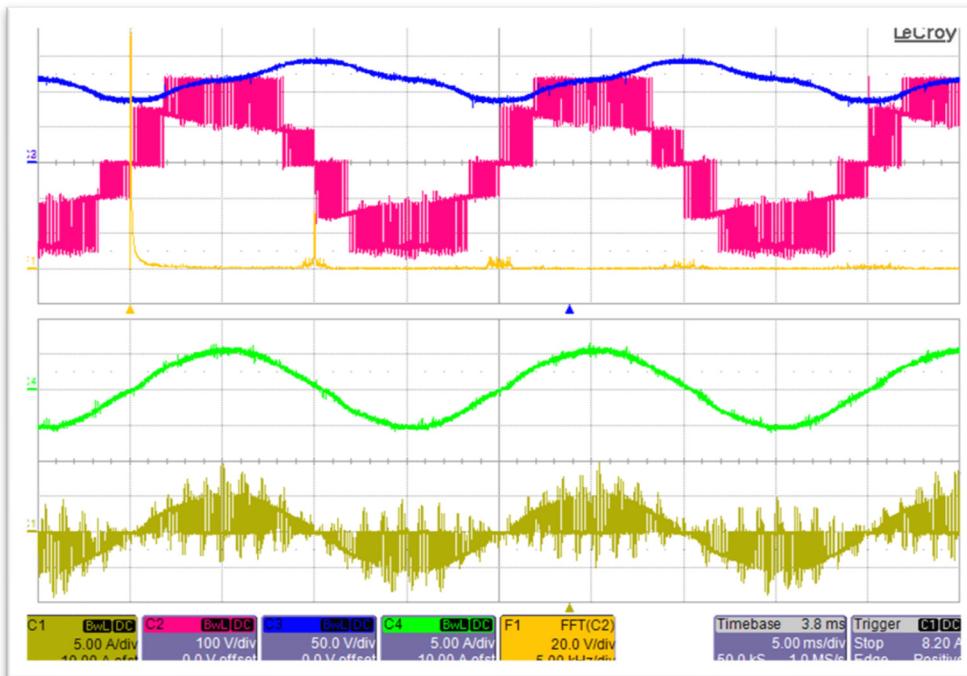
Traditional switching scheme



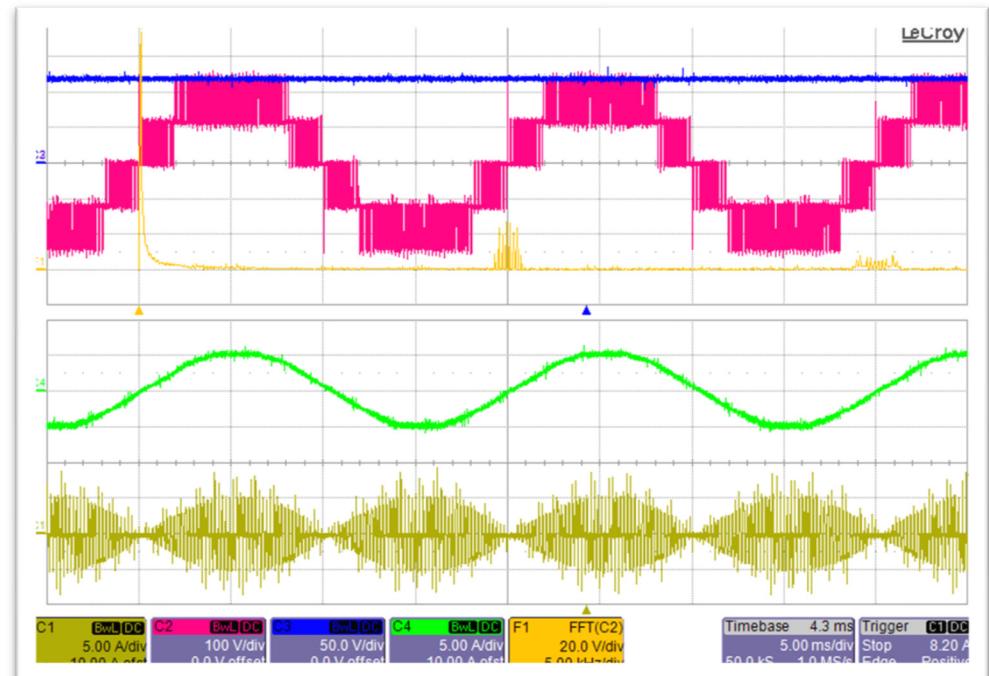
Proposed switching scheme

► Reliability Analysis – Impact of Modulation Scheme

Output waveforms



Traditional switching scheme



Proposed switching scheme

► Reliability Analysis – Impact of Modulation Scheme

What happens?

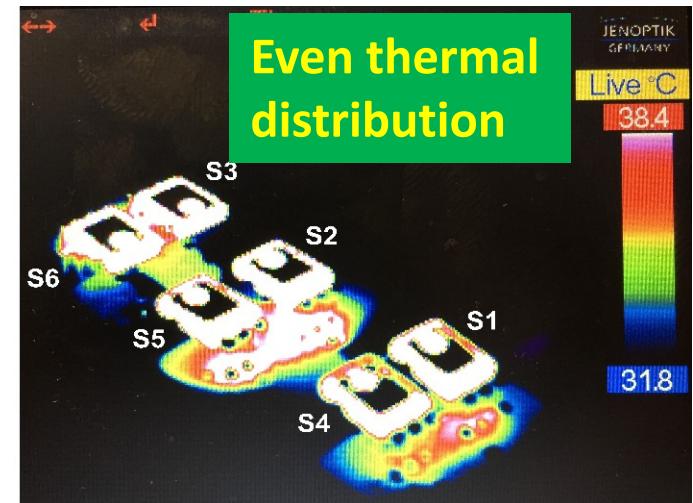
- ❖ Evenly distributing the **thermal stress** on switches

Switch Temp.

Traditional switching scheme



Proposed switching scheme

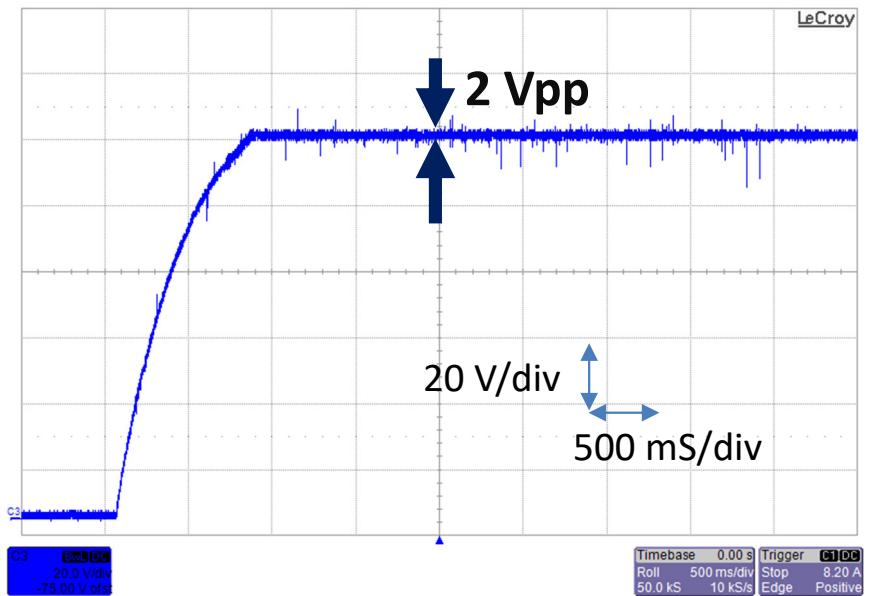
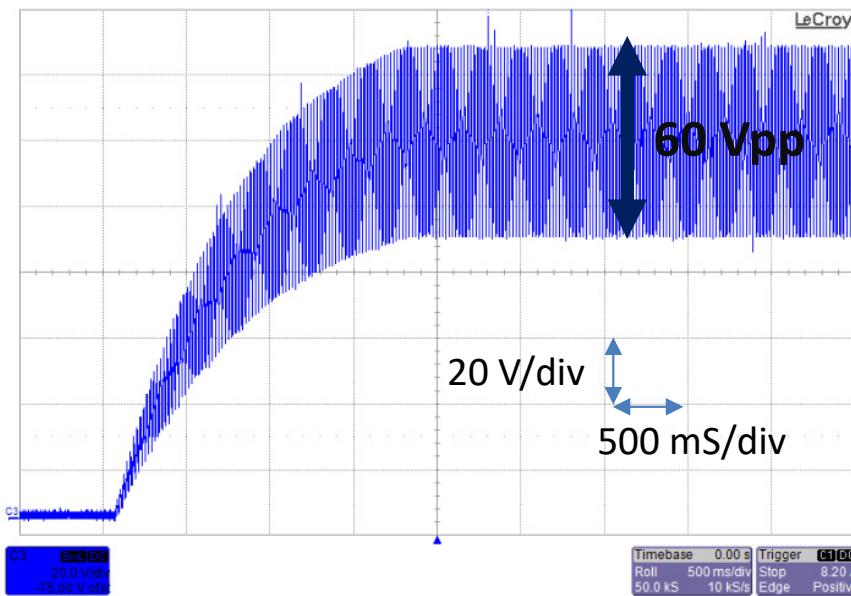


► Reliability Analysis – Impact of Modulation Scheme

What happens?

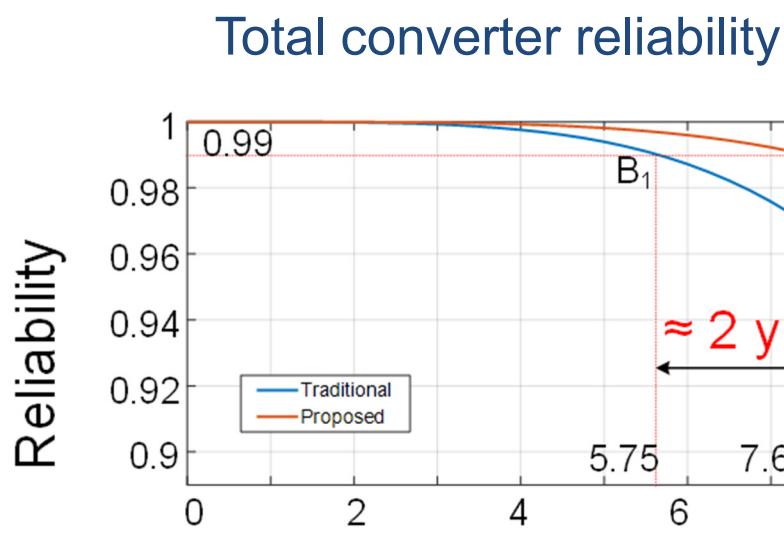
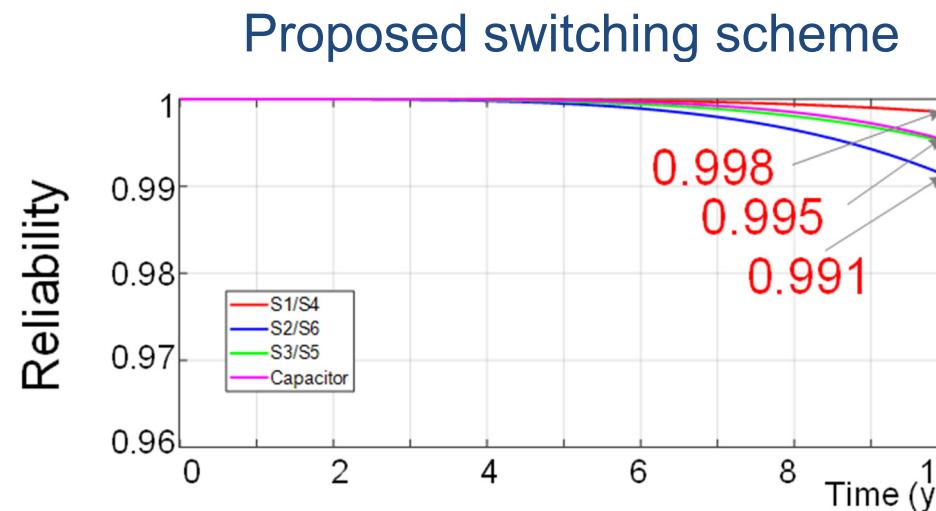
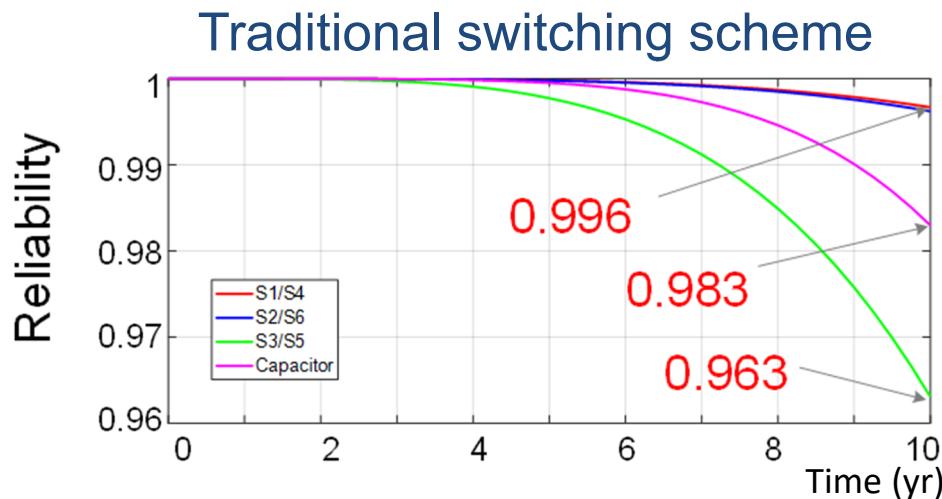
- ❖ Reducing dc link voltage ripple

Capacitor voltage ripple



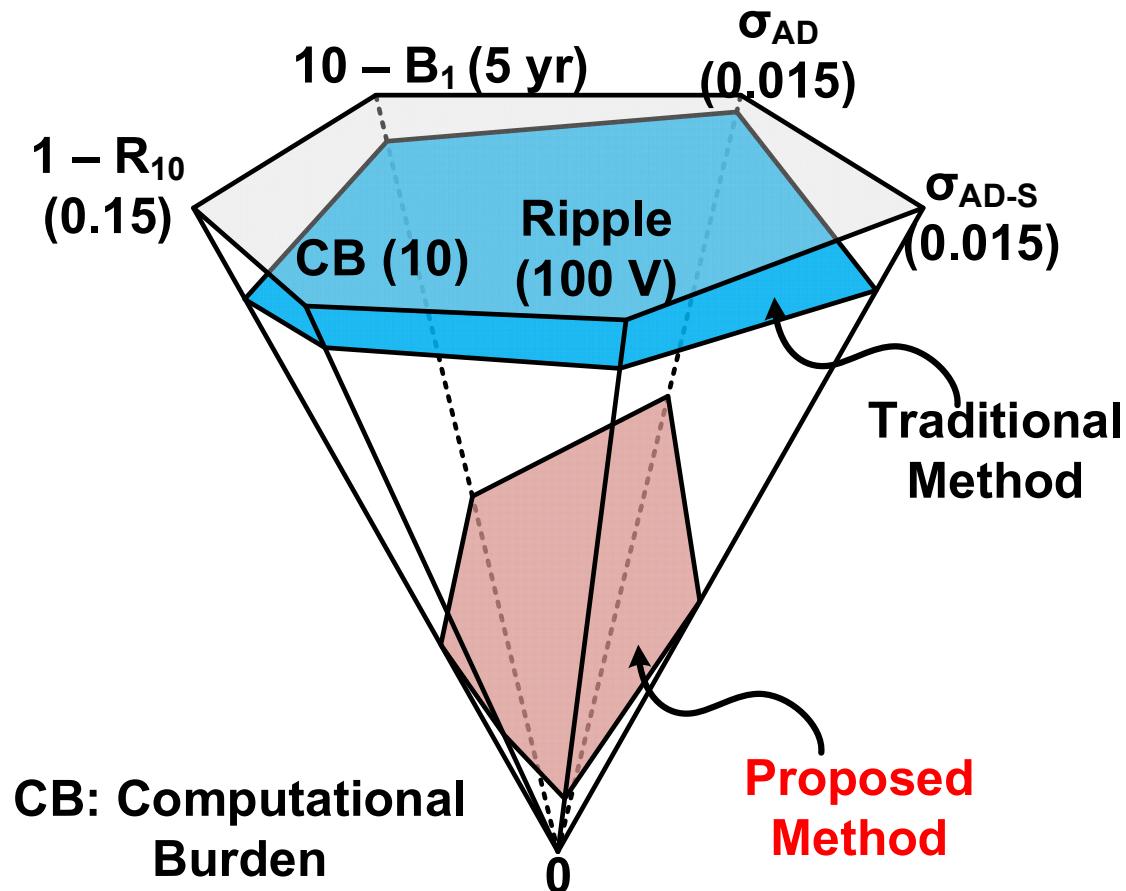
► Reliability Analysis – Impact of Modulation Scheme

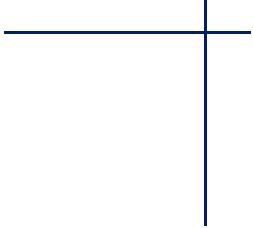
Reliability results



► Reliability Analysis – Impact of Modulation Scheme

Reliability results



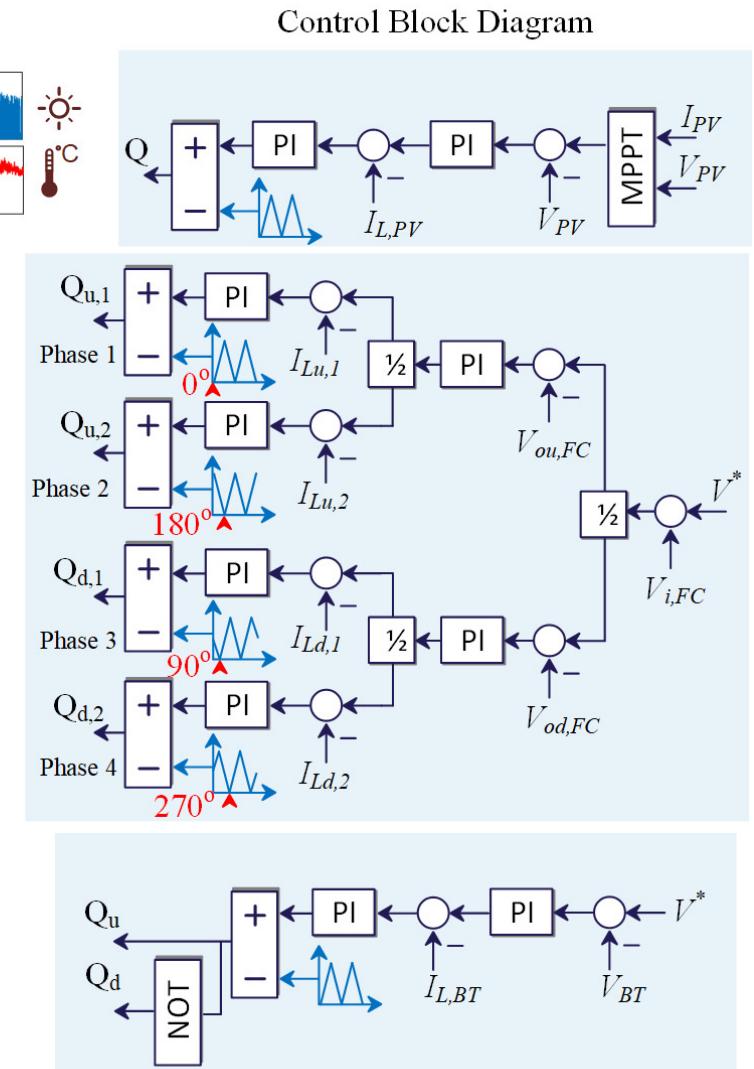
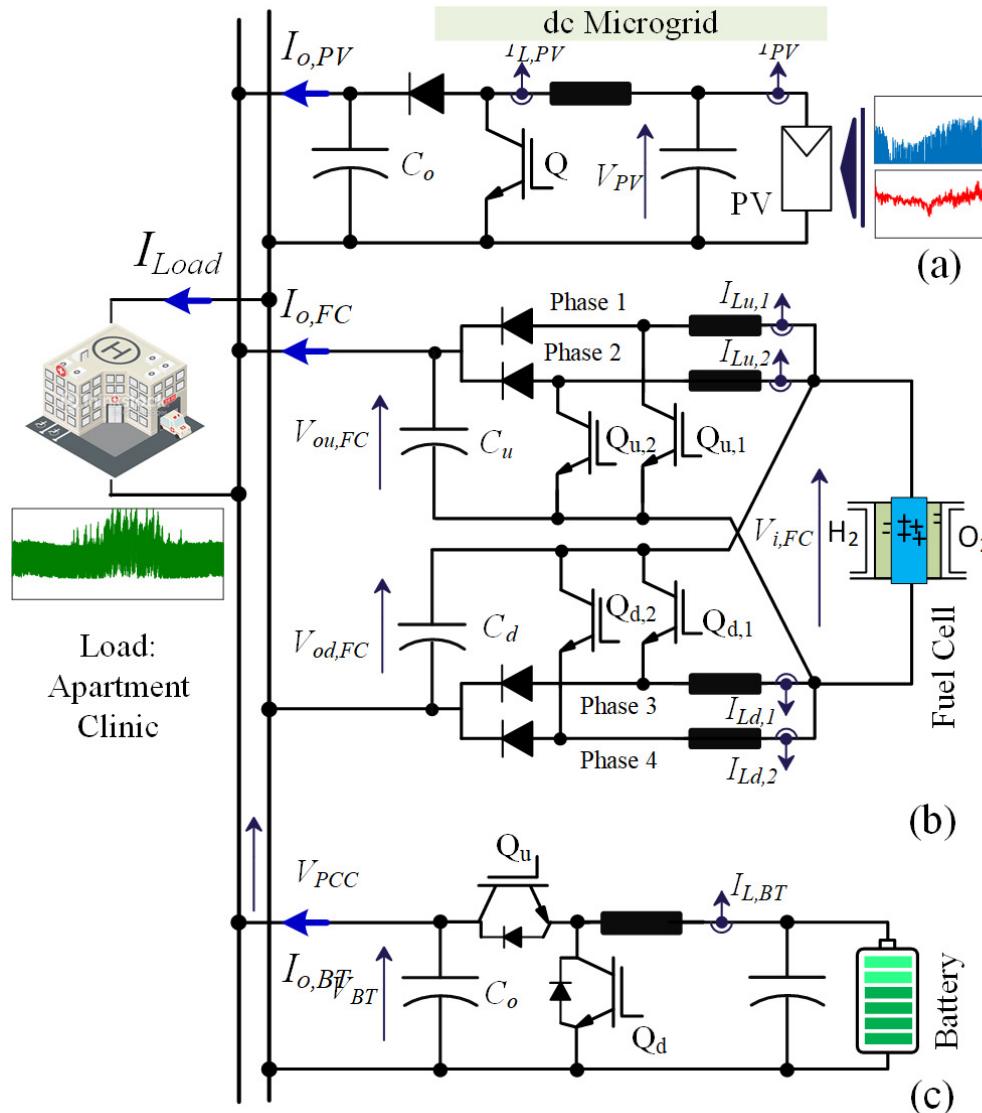


➤ Reliability Analysis

- Impact of Modulation Scheme
- Impact of Mission Profile
- Impact of Converter Topology

► Reliability Analysis – Impact of Mission Profile

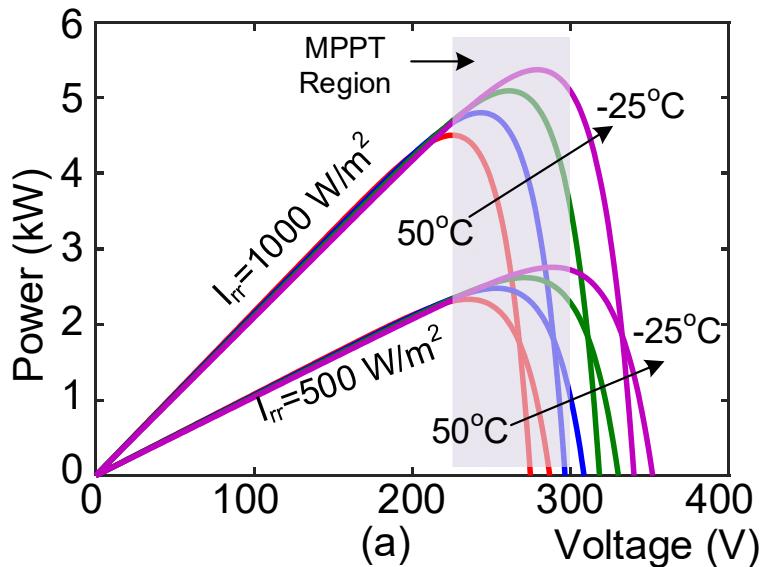
Impact of topology



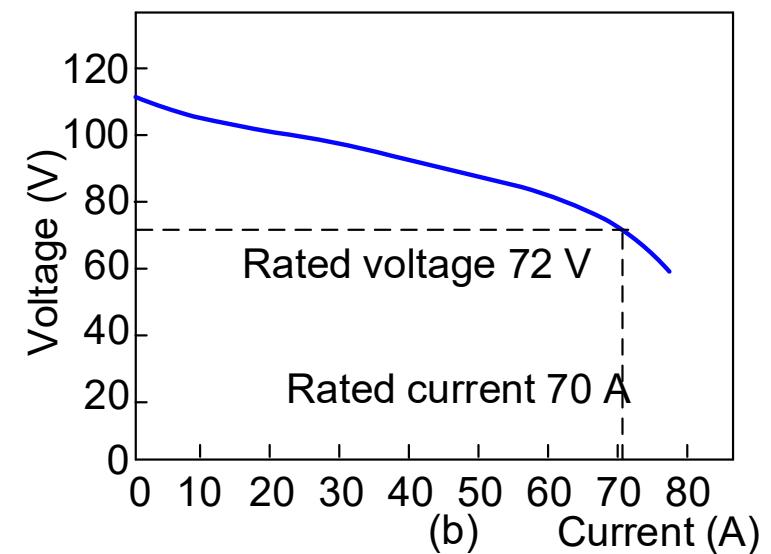
S. Peyghami, P. Davari, H. Wang and F. Blaabjerg, "The Impact of Topology and Mission Profile on the Reliability of Boost-type Converters in PV Applications," in Proc. IEEE COMPEL, Padua, 2018, pp. 1-8.

► Reliability Analysis – Impact of Mission Profile

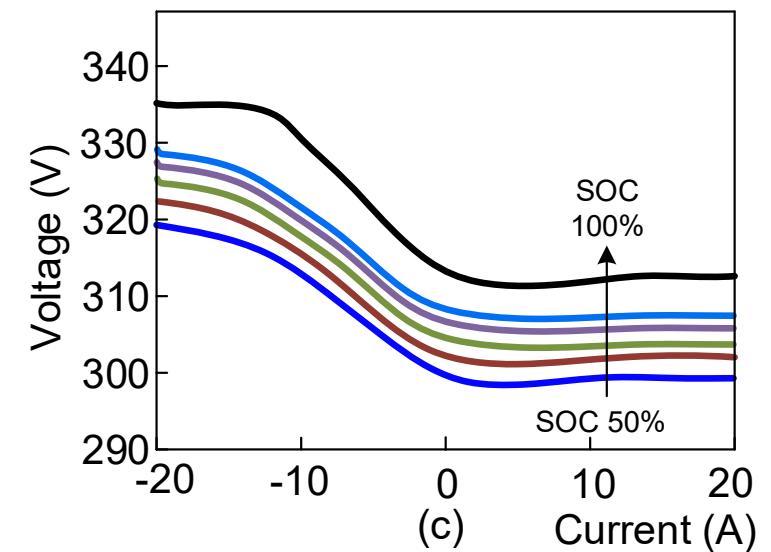
Power sources characteristics



PV model



FC model

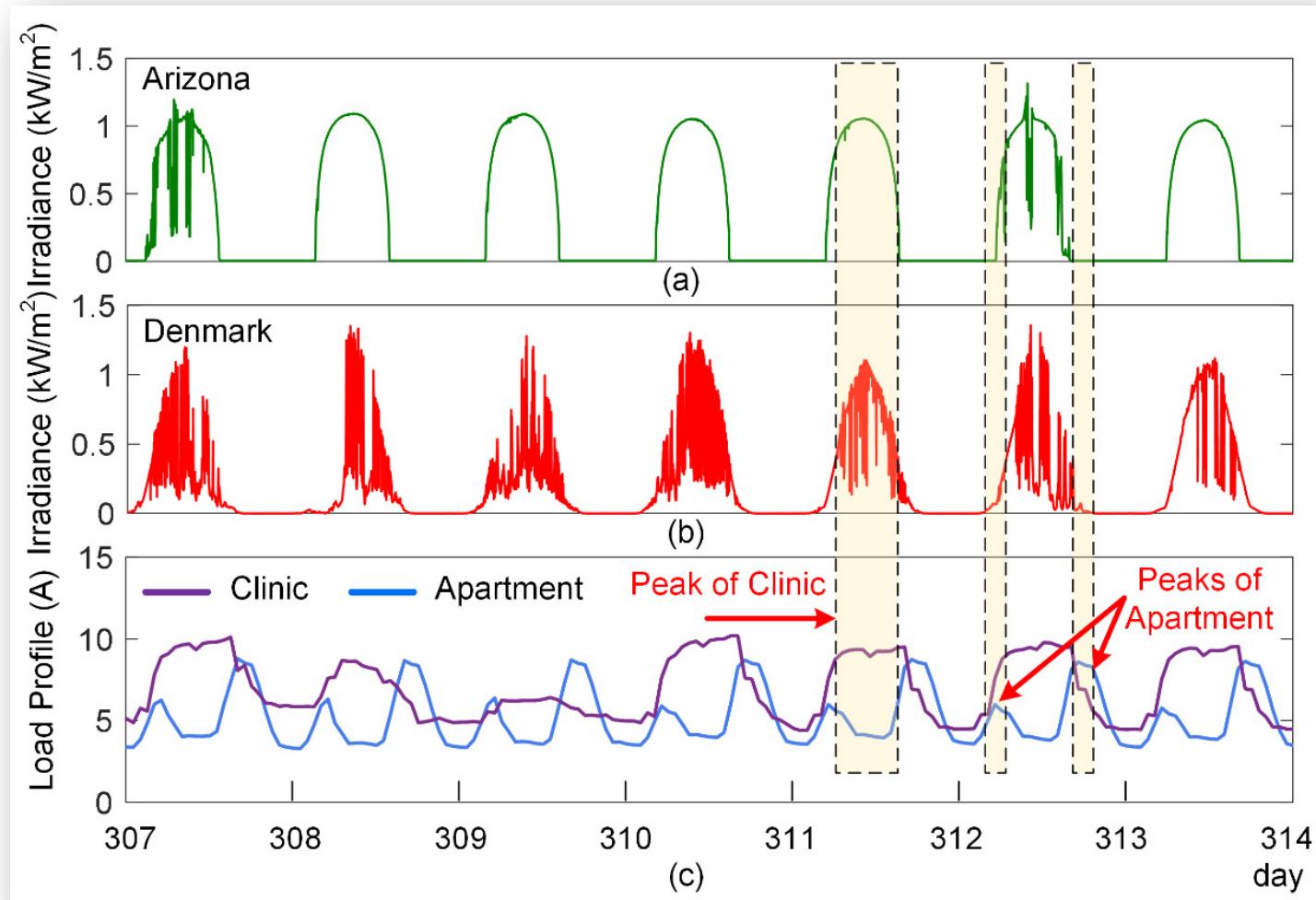


Battery model

Peyghami, S., Wang, H., Davari, P., & Blaabjerg, F., IEEE Transactions on Industry Applications, 55(5), 5055 - 5067.

► Reliability Analysis – Impact of Mission Profile

Impact of mission profile

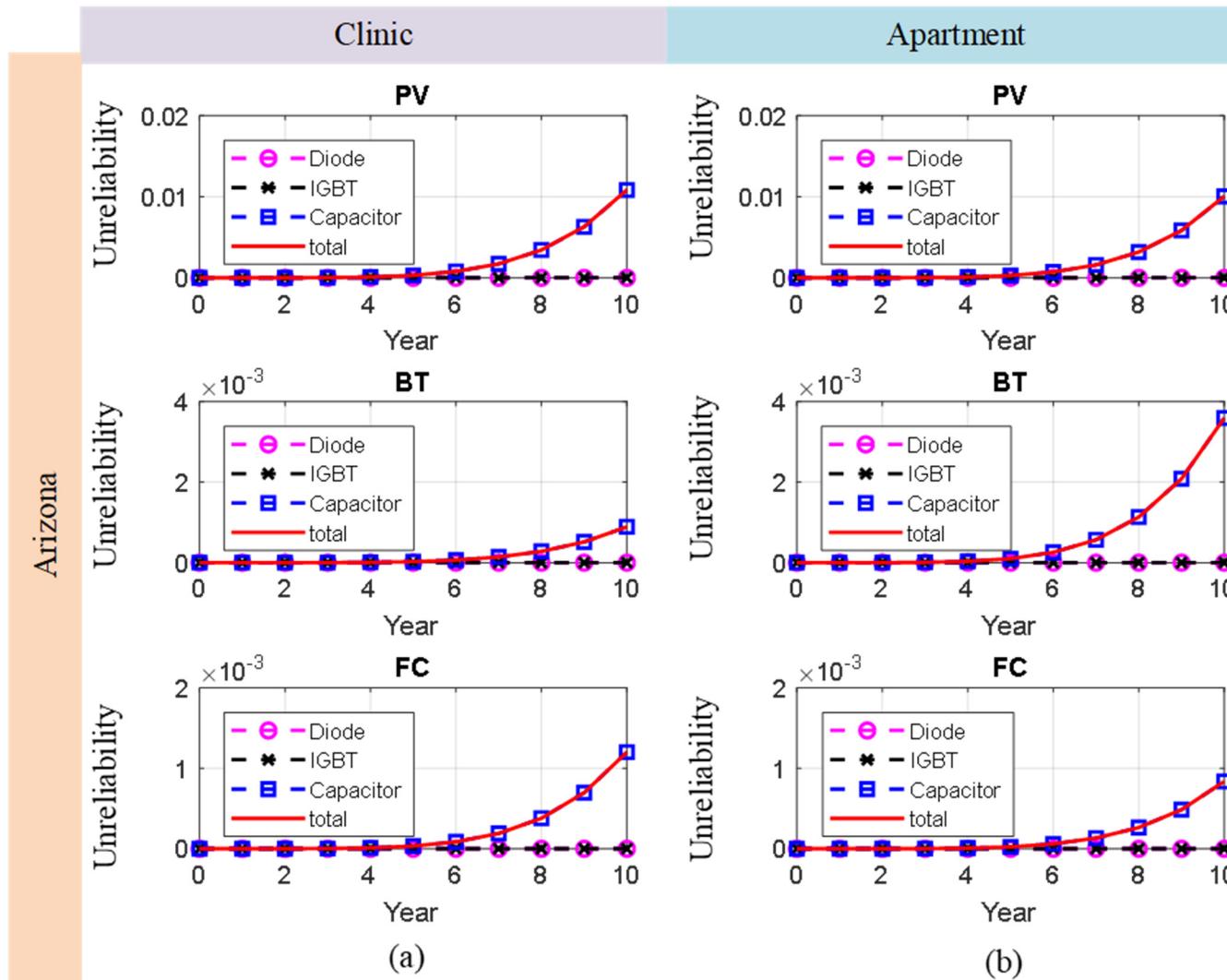


Mission Profiles

Peyghami, S., Wang, H., Davari, P., & Blaabjerg, F. (2019). IEEE Transactions on Industry Applications, 55(5), 5055 - 5067.

► Reliability Analysis – Impact of Mission Profile

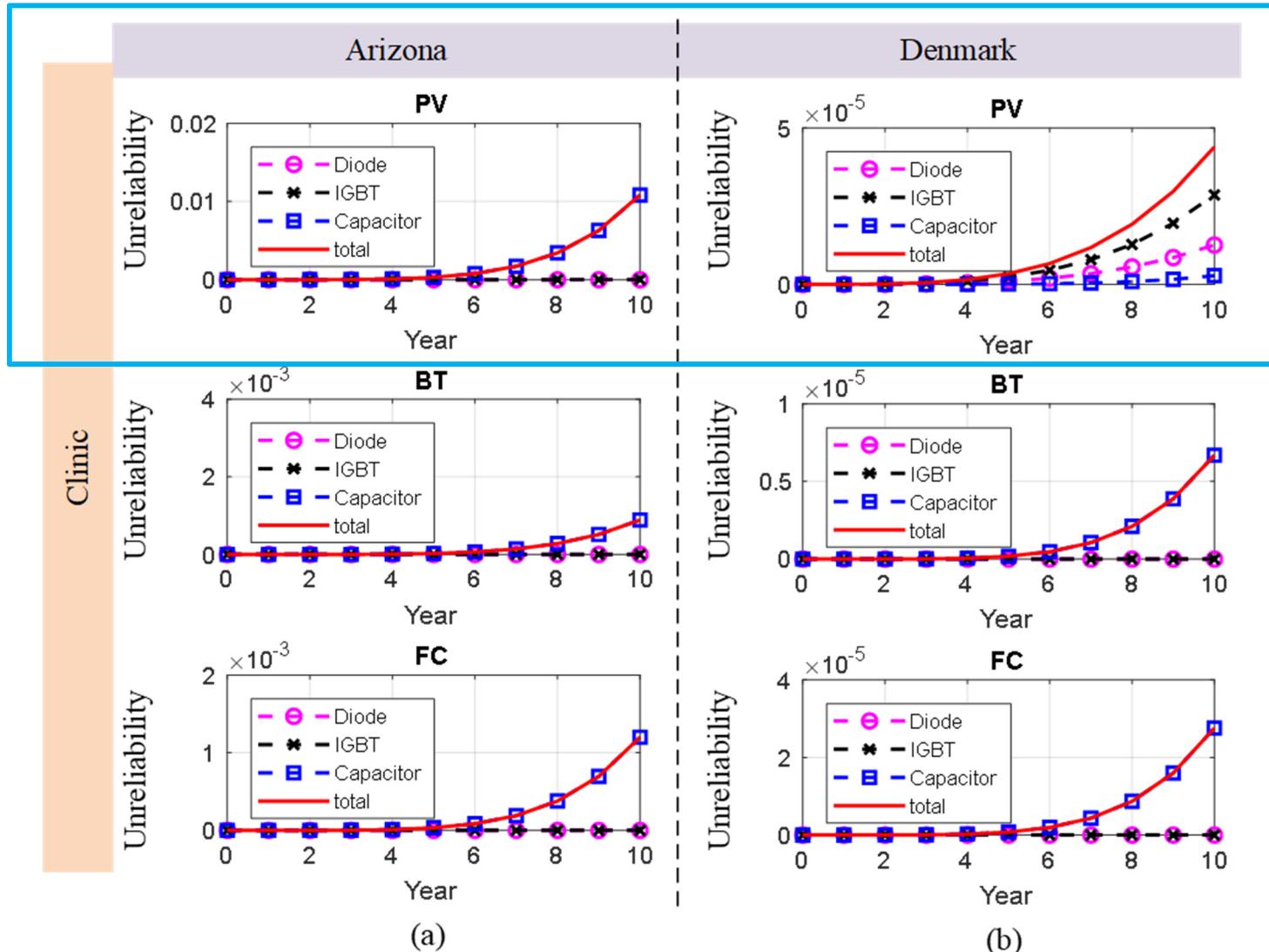
Impact of mission profile



Peyghami, S., Wang, H., Davari, P., & Blaabjerg, F. (2019). IEEE Transactions on Industry Applications, 55(5), 5055 - 5067.

► Reliability Analysis – Impact of Mission Profile

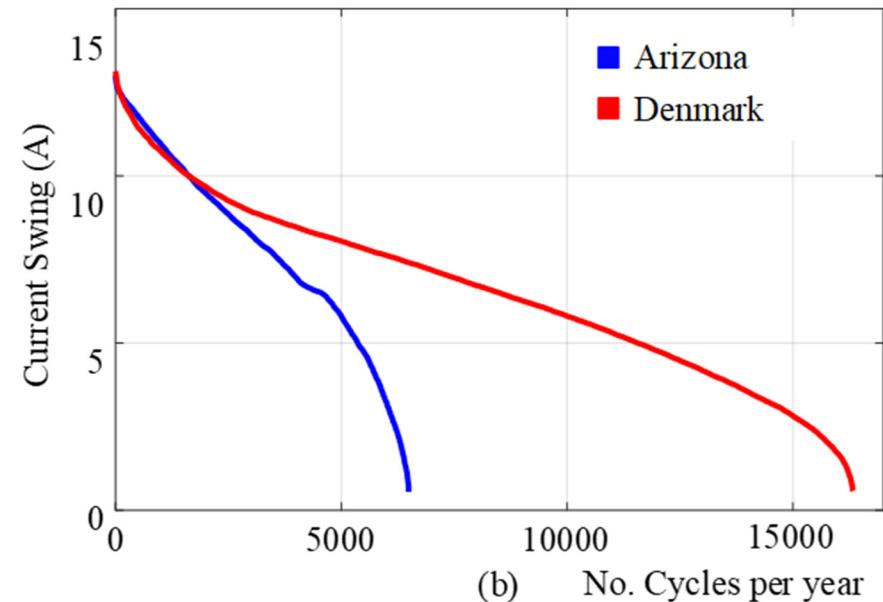
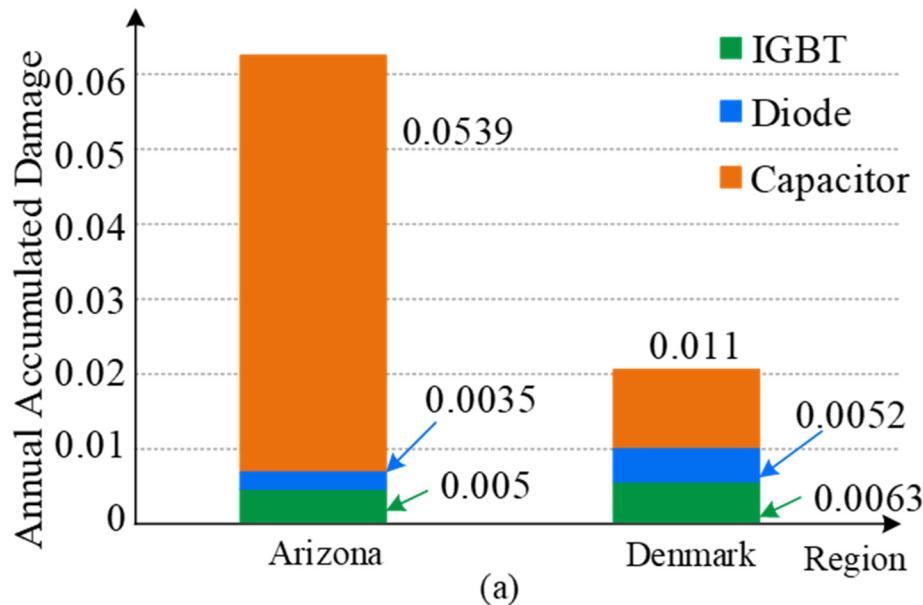
Impact of mission profile



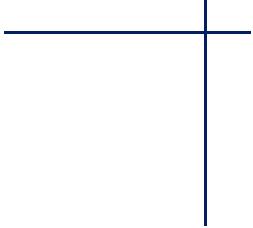
Peyghami, S., Wang, H., Davari, P., & Blaabjerg, F. (2019). IEEE Transactions on Industry Applications, 55(5), 5055 - 5067.

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Impact of mission profile



Peyghami, S., Wang, H., Davari, P., & Blaabjerg, F. (2019). IEEE Transactions on Industry Applications, 55(5), 5055 - 5067.

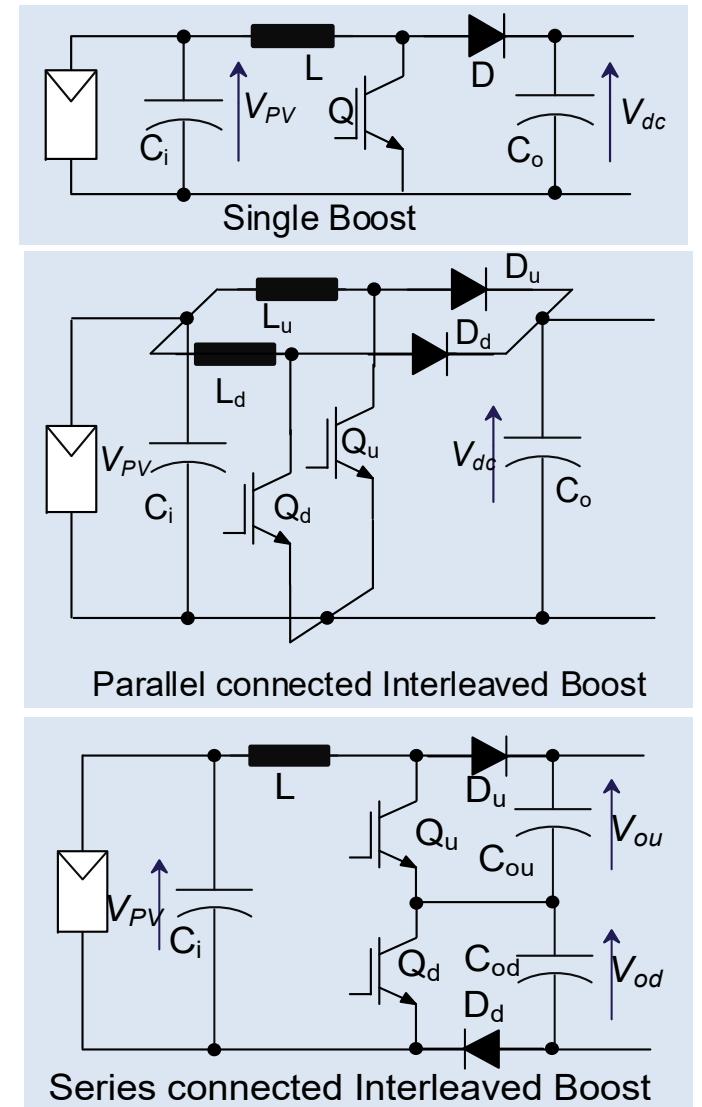
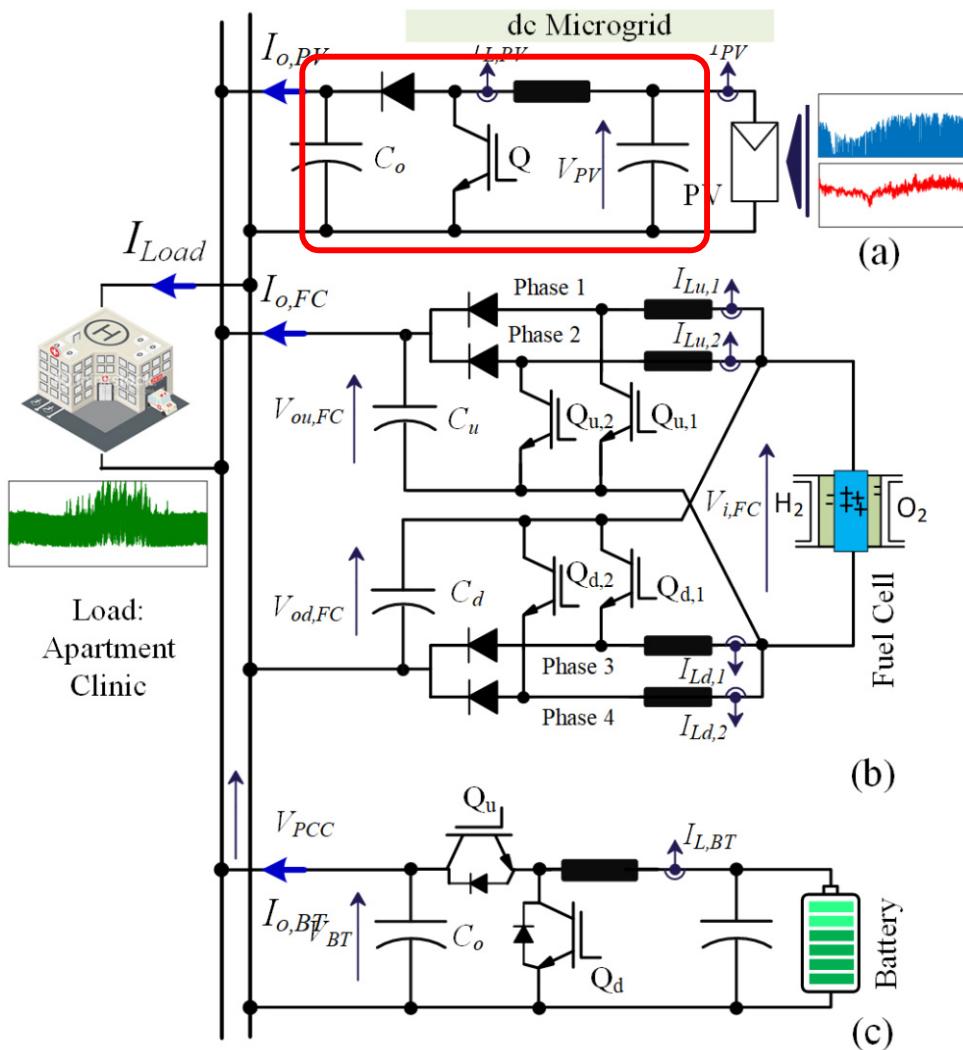


➤ Reliability Analysis

- Impact of Modulation Scheme
- Impact of Mission Profile
- Impact of Converter Topology

► Reliability Analysis – Impact of Converter Topology

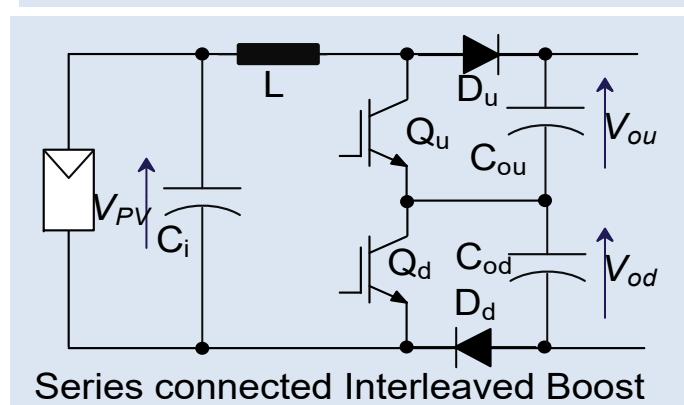
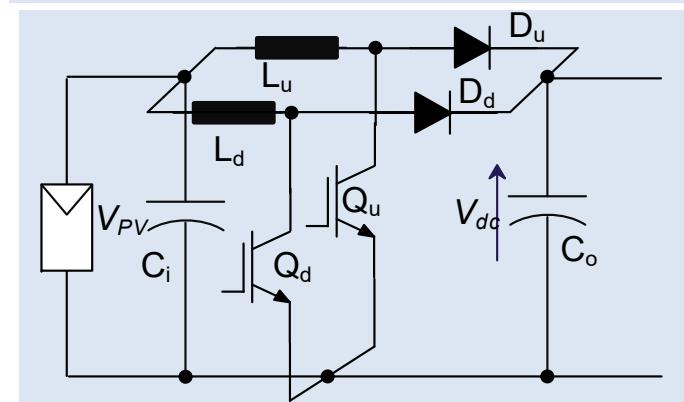
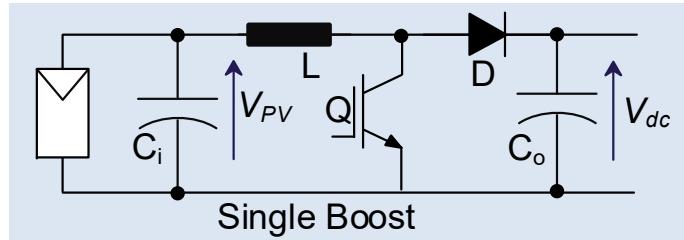
Impact of topology



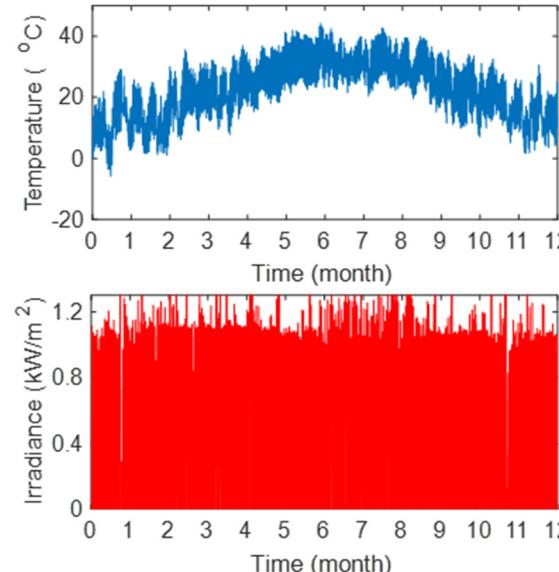
S. Peyghami, P. Davari, H. Wang and F. Blaabjerg, "The Impact of Topology and Mission Profile on the Reliability of Boost-type Converters in PV Applications," in Proc. IEEE COMPEL, Padua, 2018, pp. 1-8.

► Reliability Analysis – Impact of Converter Topology

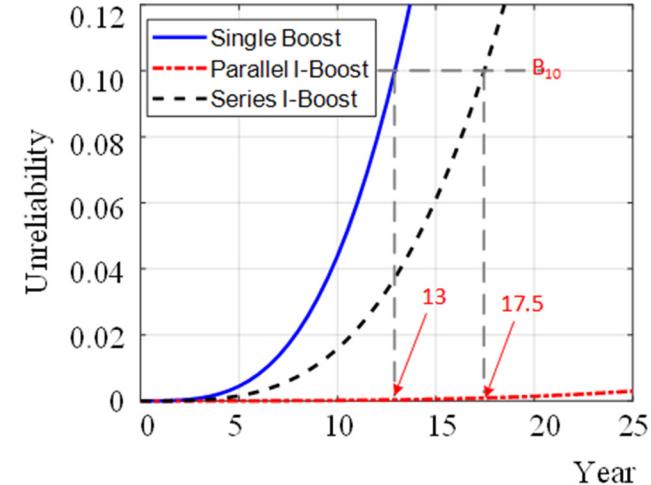
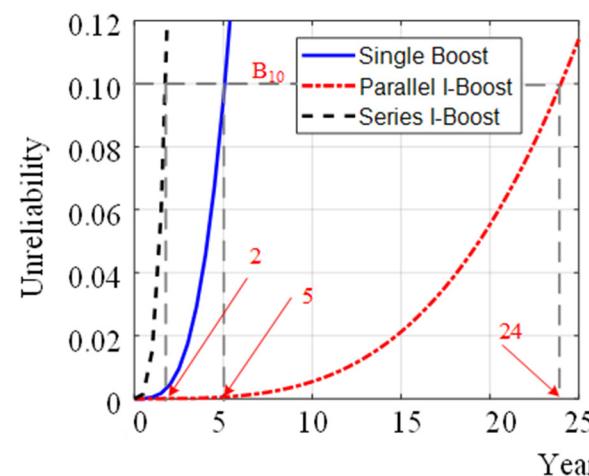
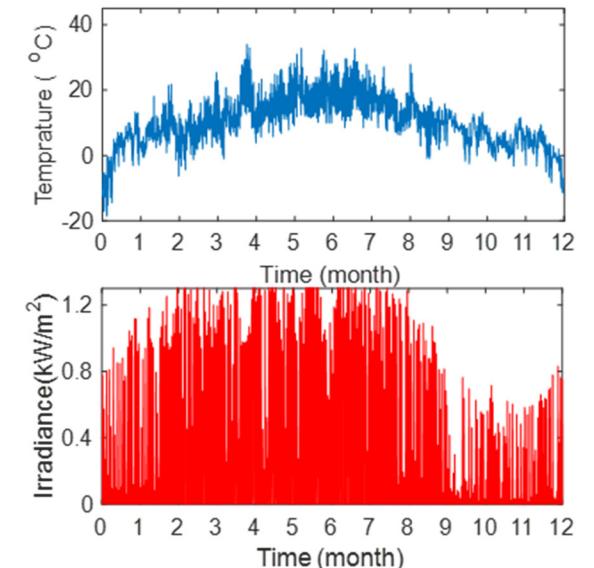
Impact of topology



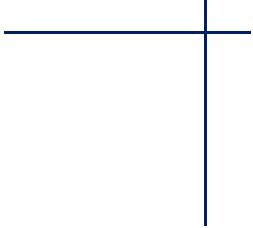
Arizona

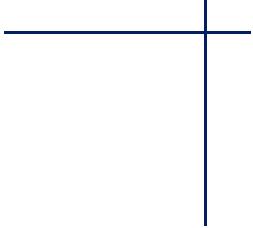


Denmark



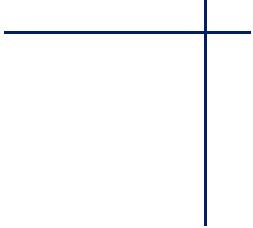
S. Peyghami, P. Davari, H. Wang and F. Blaabjerg, "The Impact of Topology and Mission Profile on the Reliability of Boost-type Converters in PV Applications," in Proc. IEEE COMPEL, Padua, 2018, pp. 1-8.

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➤ Reliability Enhancement

- Impact of Integrated Design
- Design for Reliability (DfR)
- Control for Reliability
- Impact of Replacement

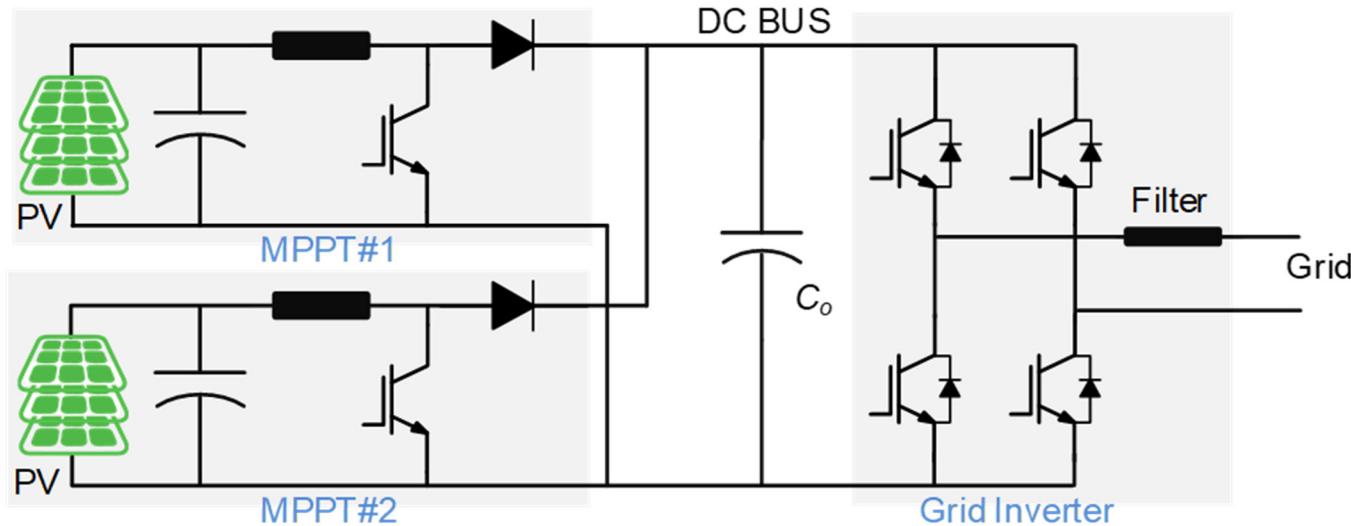


➤ Reliability Enhancement

- Impact of Integrated Design
- Design for Reliability (DfR)
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- Impact of Replacement

► Reliability Enhancement – Impact of Integrated Design

Single phase PV system

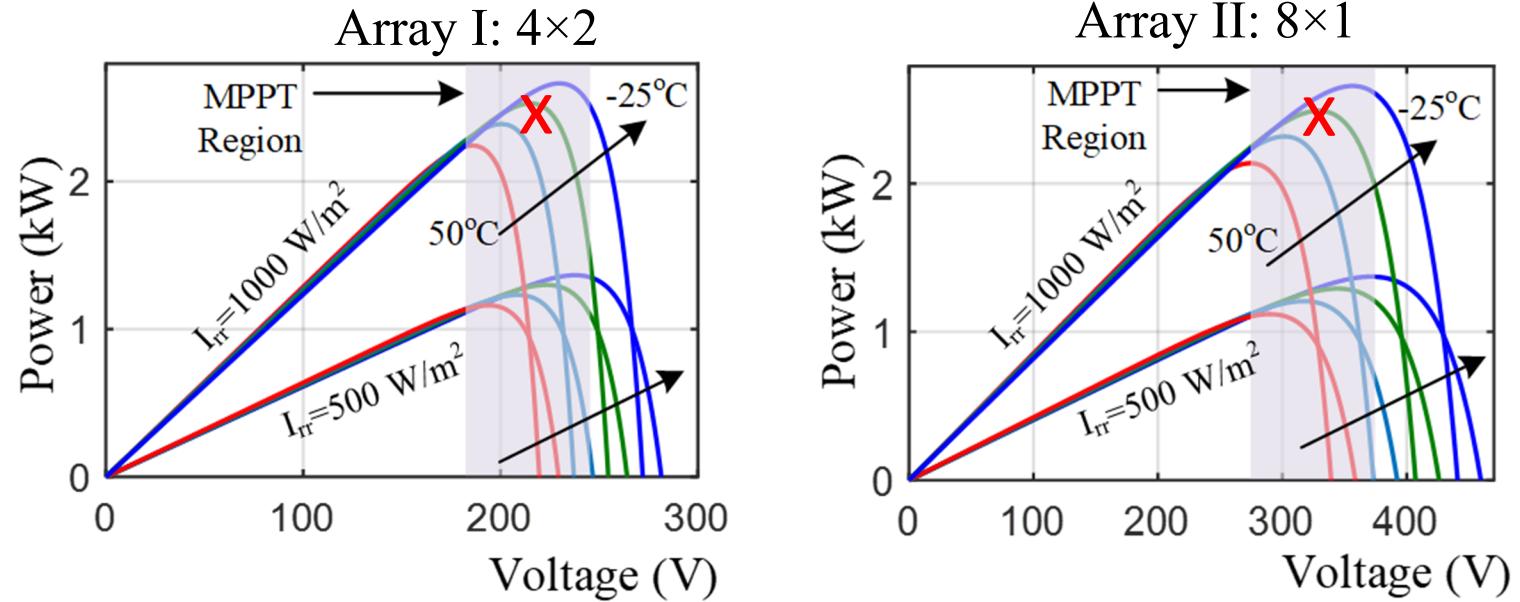


Parameter	Symbol	Array I	Array II
Panel Rated Power	P_r (W)	320	320
Open Circuit Voltage	V_{oc} (V)	64.8	45.98
Short Circuit Current	I_{sc} (A)	6.24	8.89
MPPT Voltage	V_m (V)	54.7	36.73
MPPT Current	I_m (A)	5.86	8.58
Number of Series panels	N_s	4	8
Number of Parallel panels	N_p	2	1

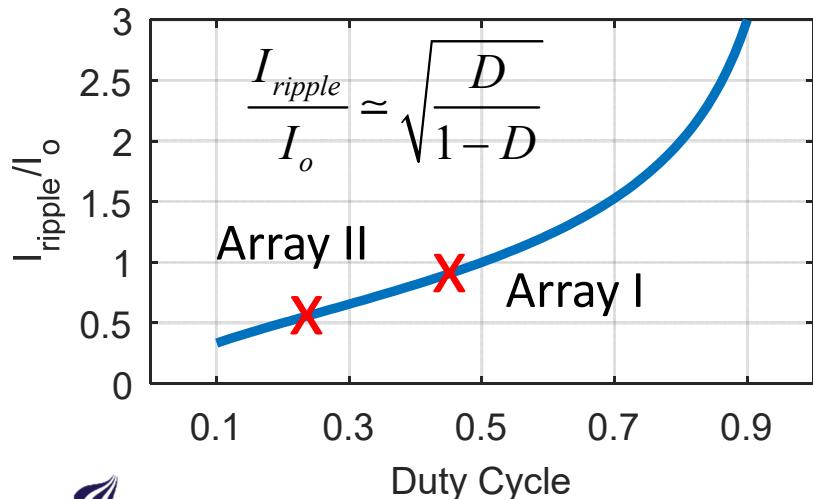
Source: Saeed Peyghami, Pooya Davari, Huai Wang, Frede Blaabjerg, System-level reliability enhancement of DC/DC stage in a single-phase PV inverter, Microelectronics Reliability, Volumes 88–90, 2018, Pages 1030-1035, ISSN 0026-2714.

► Reliability Enhancement – Impact of Integrated Design

PV Array configuration



Capacitor ripple

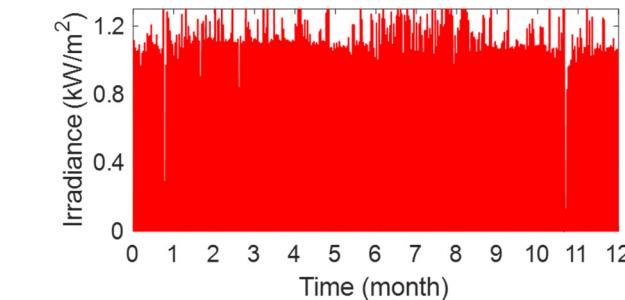


	V_{MPPT}	D	I_{ripple}	Temp
Array I	Red triangle	Blue triangle	Blue triangle	Blue triangle
Array II	Blue triangle	Red triangle	Red triangle	Red triangle

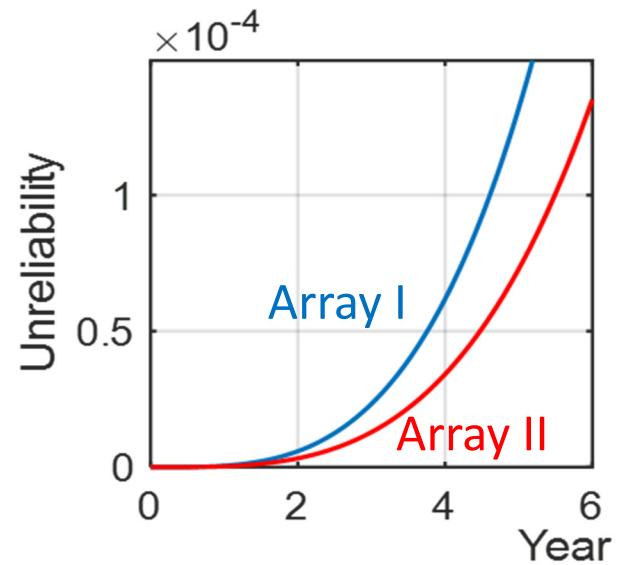
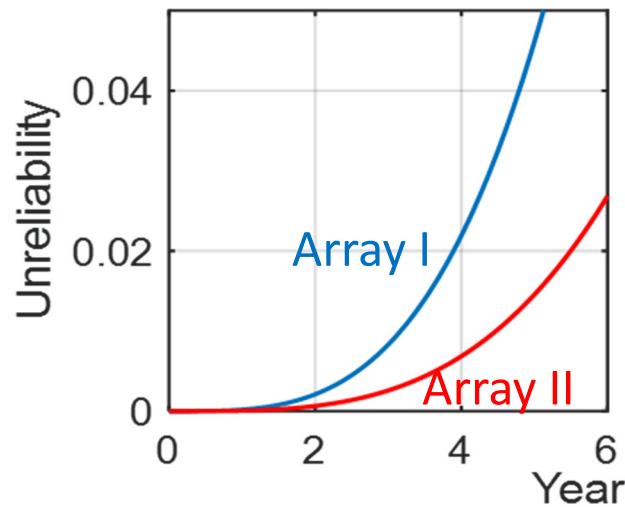
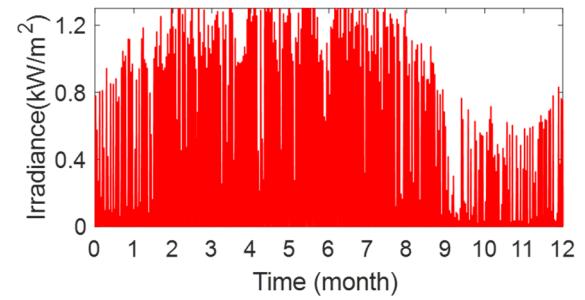
► Reliability Enhancement – Impact of Integrated Design

PV converter reliability

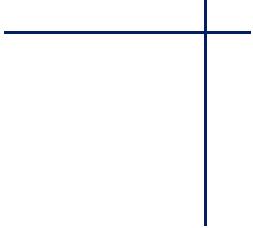
Arizona



Aalborg



- ❖ The **Array II** yields better reliability in both locations
- ❖ The mission profile (**location**) has dominant impact on the reliability
- ❖ The PV system should be **designed integrated** (PV array + converter) to have optimal performance (reliability, ...) for a **specific site**.



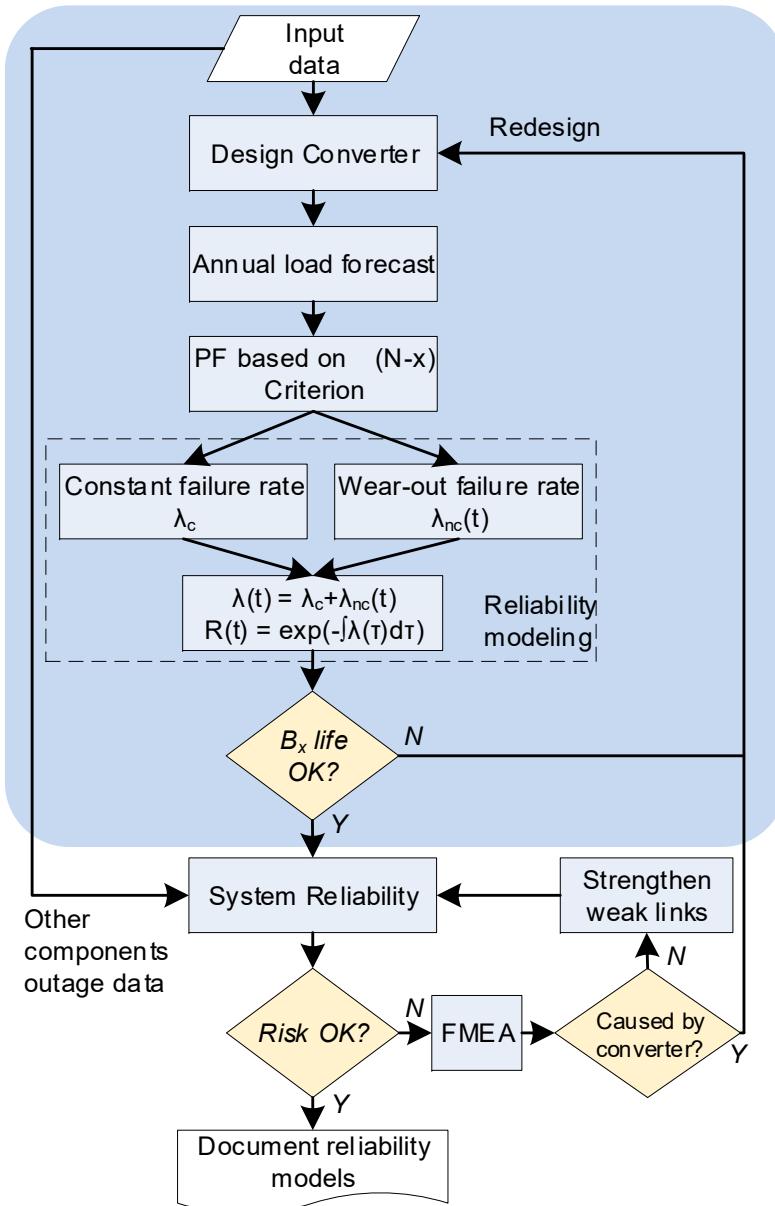
➤ Reliability Enhancement

- Impact of Integrated Design
- Design for Reliability (DfR)
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► Reliability Enhancement – Design for Reliability (DfR)

Proposed System-level DfR

Converter level DfR



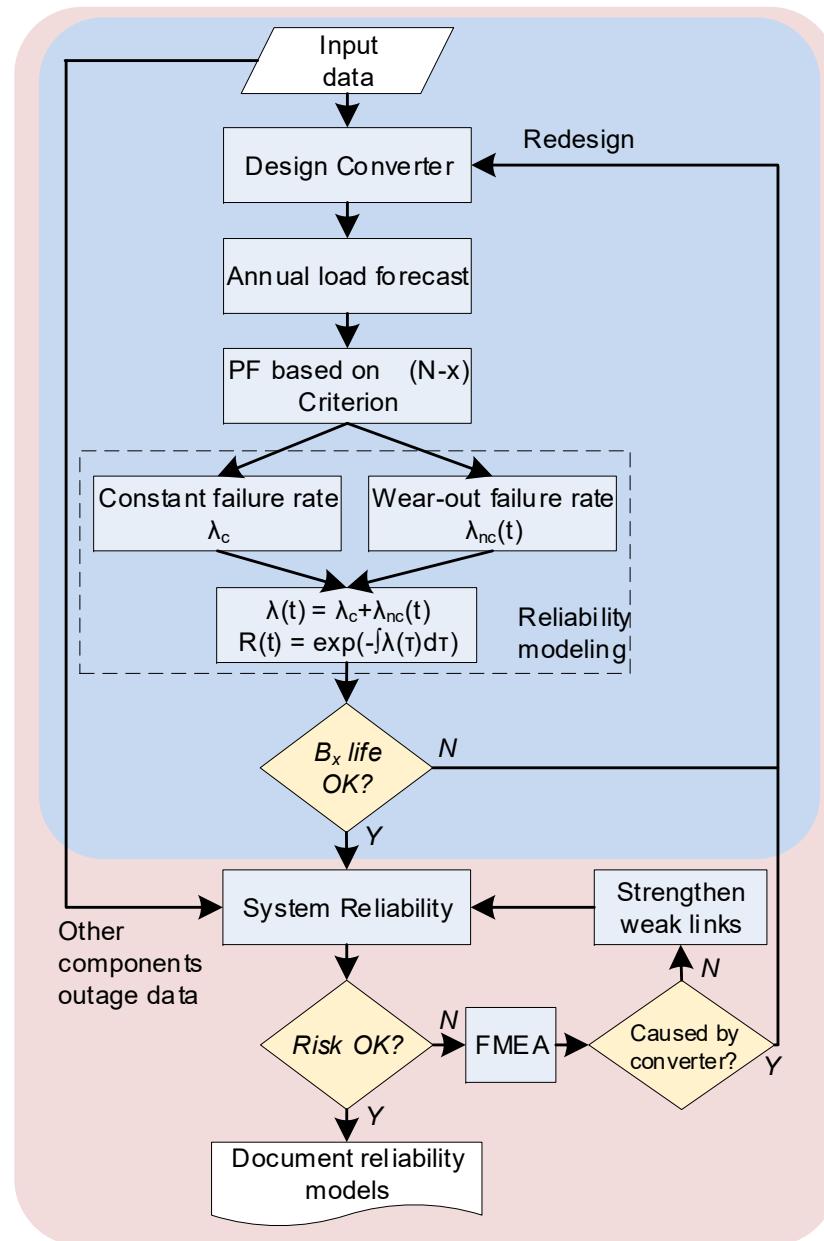
Source: S. Peyghami, P. Palensky, M. Fotuhi-Firuzabad and F. Blaabjerg IEEE Open Access Journal of Power and Energy, doi: 10.1109/OAJPE.2020.3029229.

► Reliability Enhancement – Design for Reliability (DfR)

Proposed System-level DfR

Converter level DfR

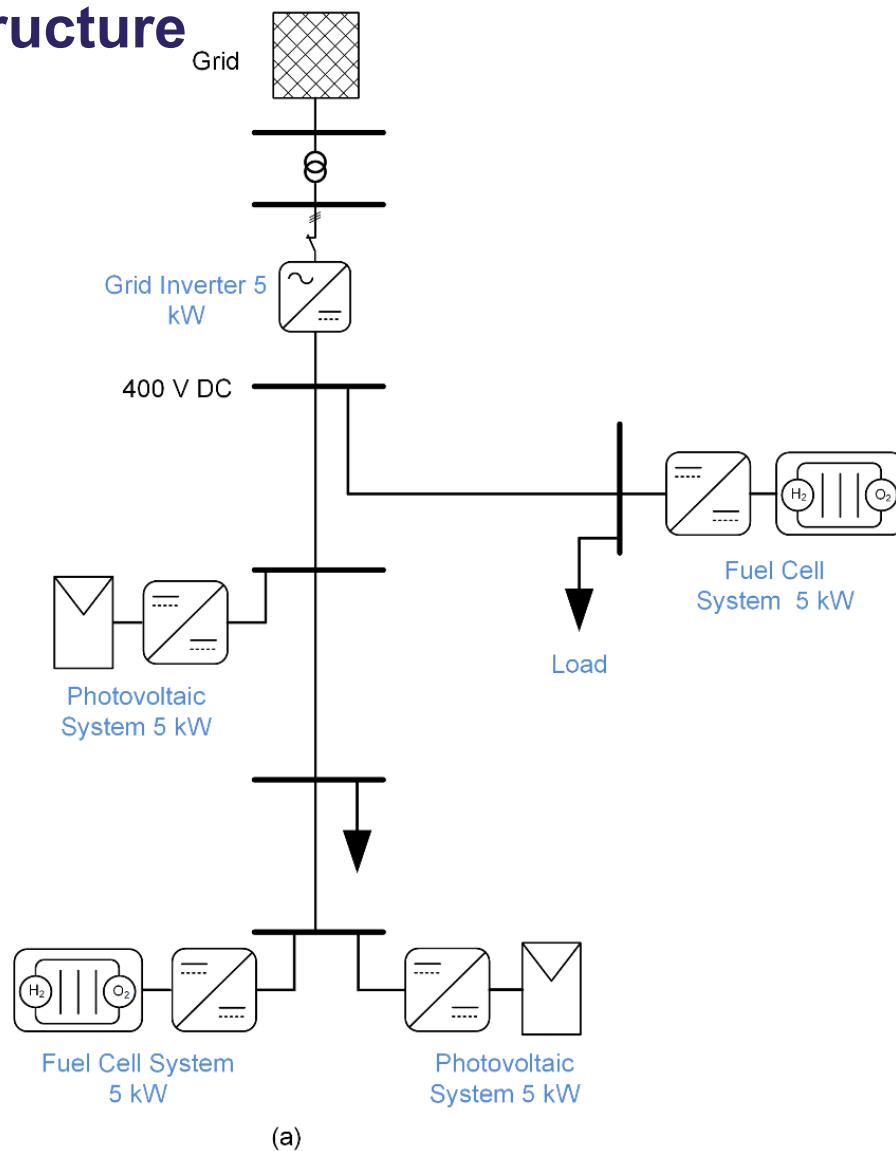
System level DfR



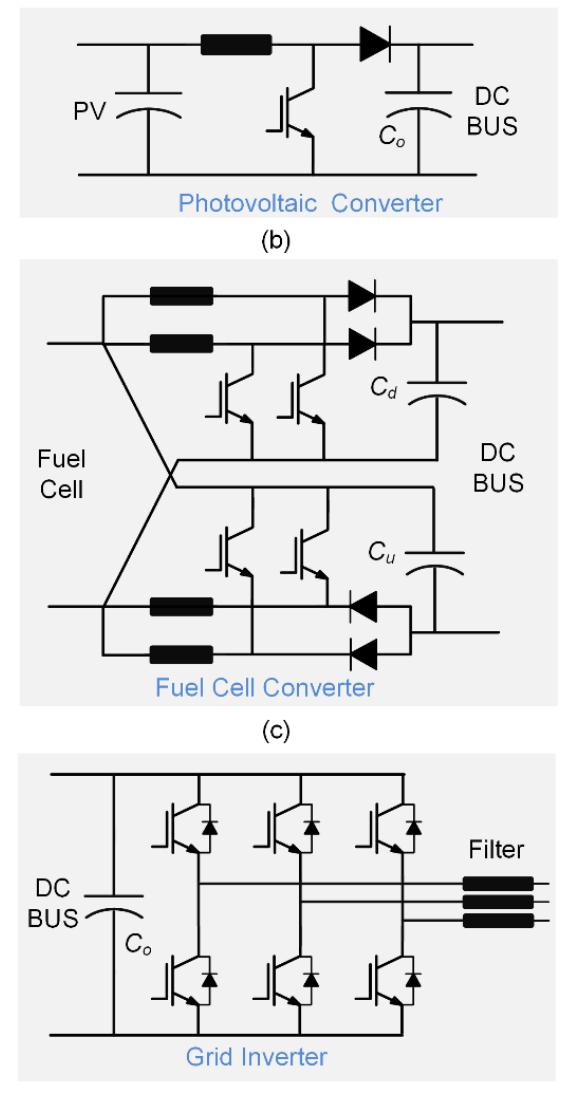
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► Reliability Enhancement – Design for Reliability (DfR)

DC PEPS Structure



(a)

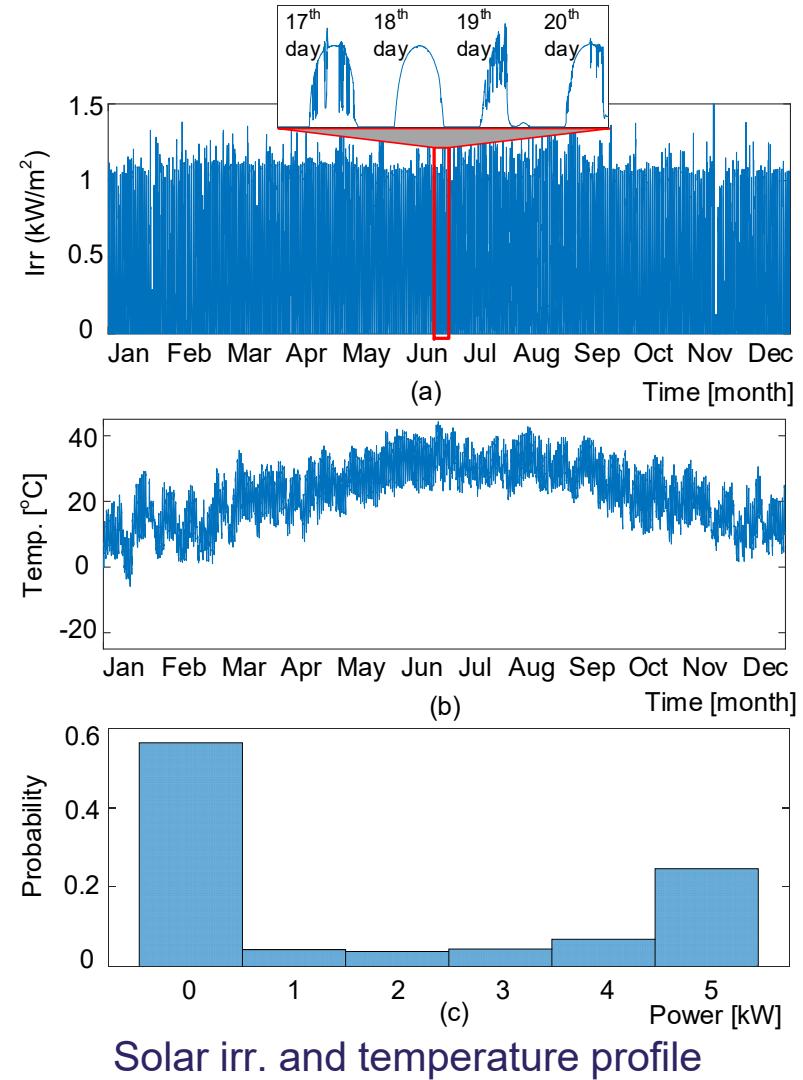
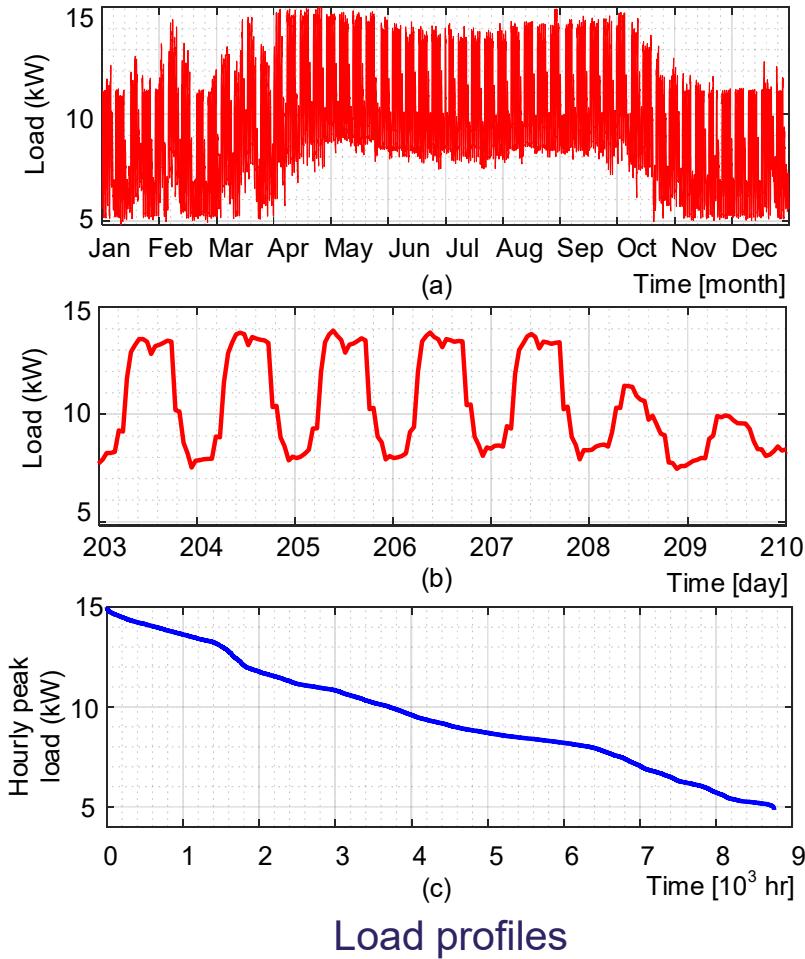


(d)

Source: S. Peyghami, P. Palensky, M. Fotuhi-Firuzabad and F. Blaabjerg IEEE Open Access Journal of Power and Energy, doi: 10.1109/OAJPE.2020.3029229.

► Reliability Enhancement – Design for Reliability (DfR)

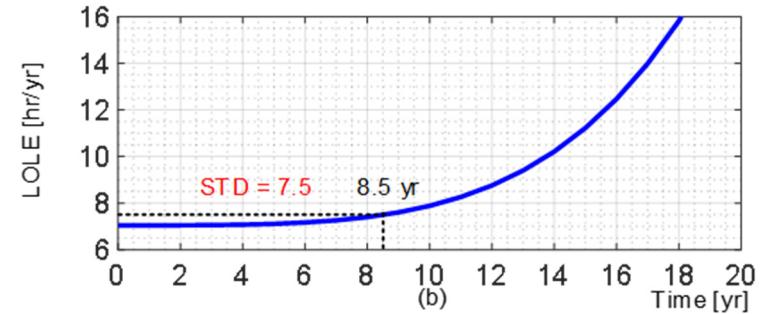
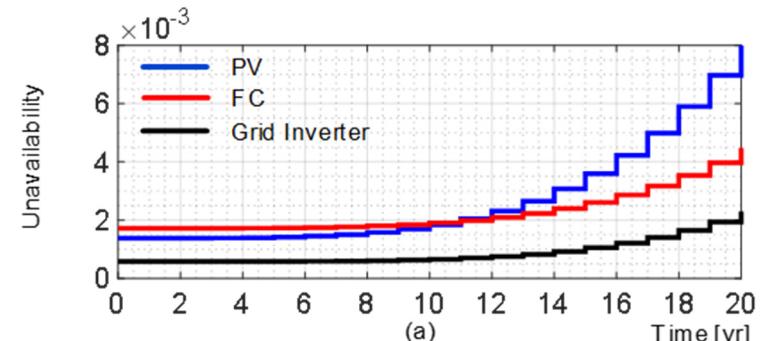
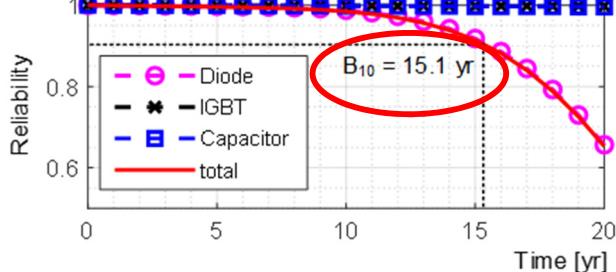
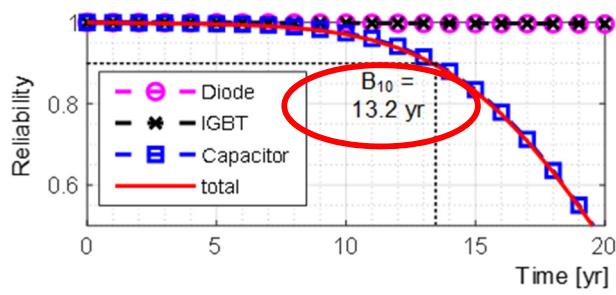
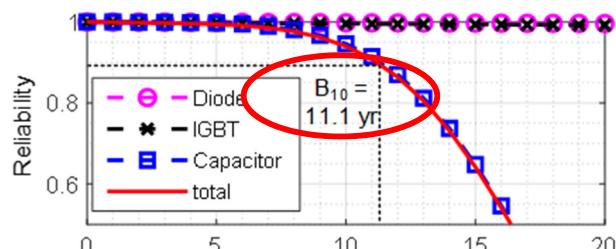
Mission profiles



Source: S. Peyghami, P. Palensky, M. Fotuhi-Firuzabad and F. Blaabjerg, "System-level Design for Reliability and Maintenance Scheduling in Modern Power Electronic-based Power Systems," in IEEE Open Access Journal of Power and Energy, doi: 10.1109/OAJPE.2020.3029229.

► Reliability Enhancement – Design for Reliability (DfR)

Converter and system reliability



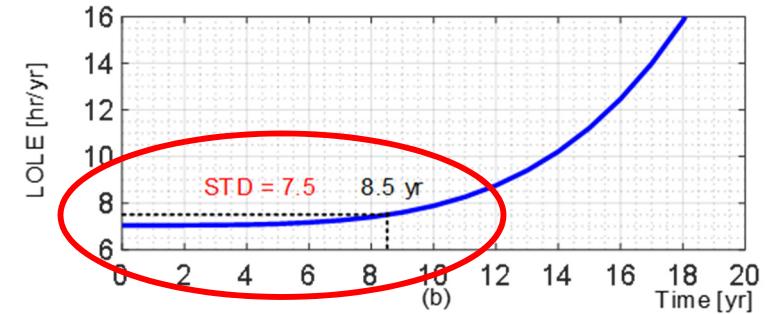
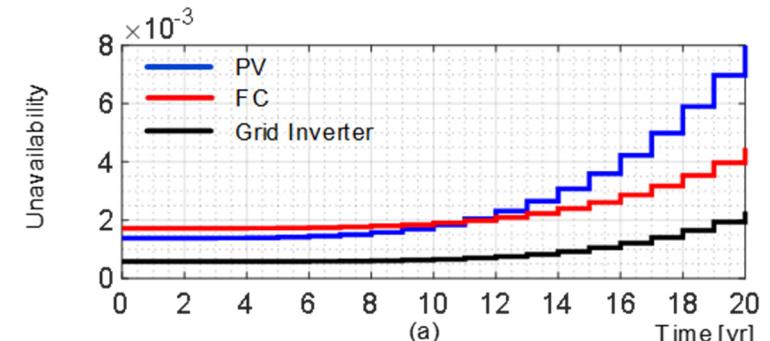
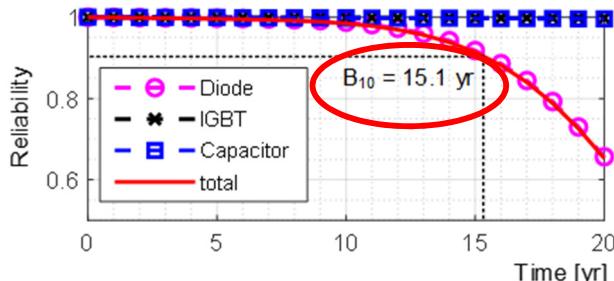
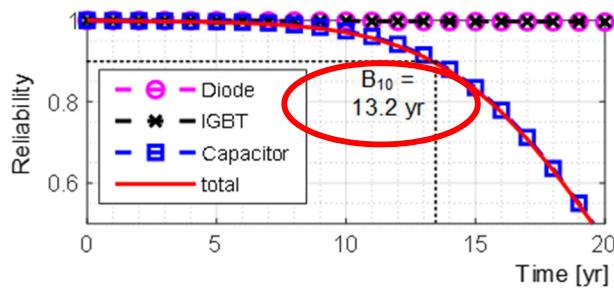
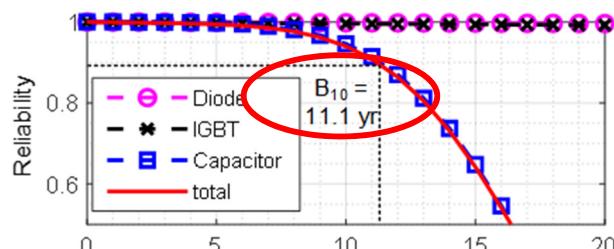
System reliability

- ❖ Based on converter level DfR, the converters B₁₀ lifetime is higher than 10 year.



► Reliability Enhancement – Design for Reliability (DfR)

Converter and system reliability



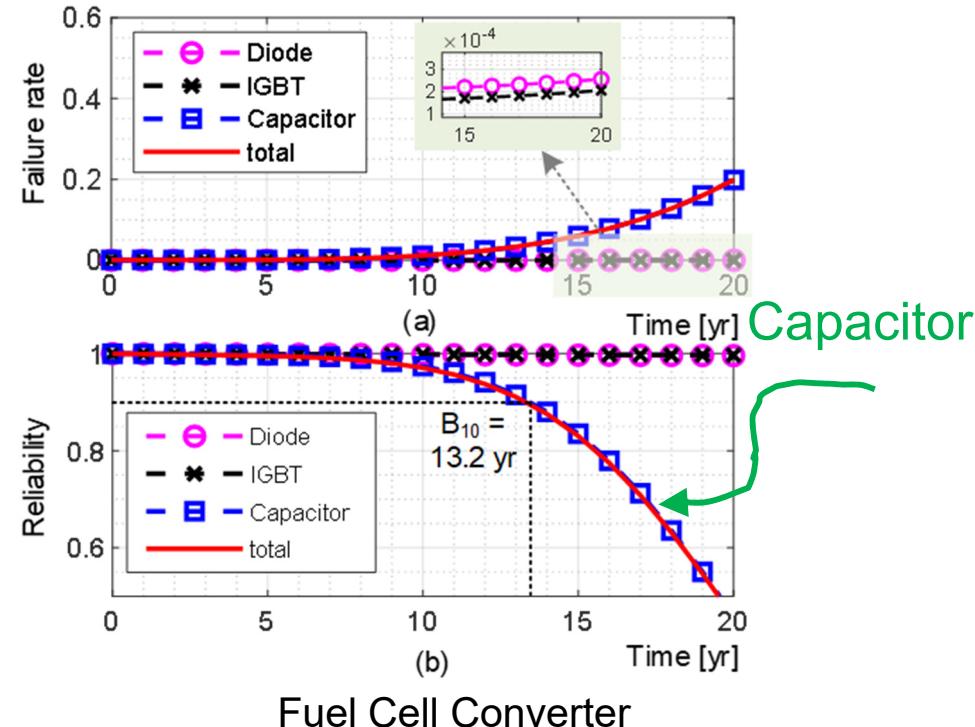
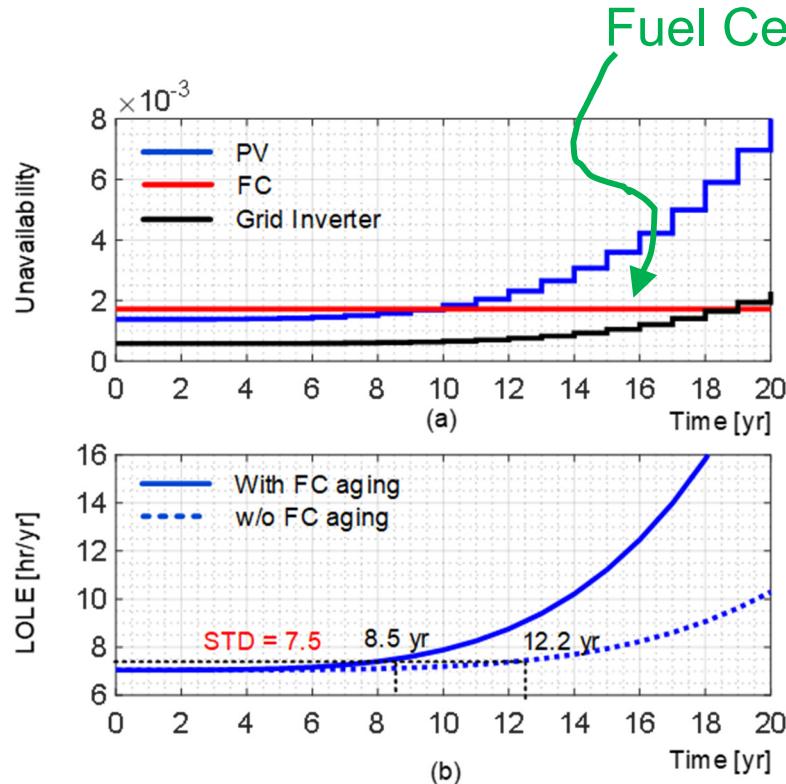
System reliability

- ❖ Based on converter level DfR, the converters B₁₀ lifetime is higher than 10 year.
- ❖ However, the system becomes unreliable after 8.5 years



► Reliability Enhancement – Design for Reliability (DfR)

System level DfR - FMEA

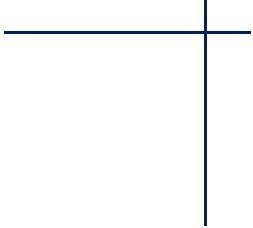


FMEA

- The Fuel Cell Converter has dominant impact on System Reliability
- Then the Grid Converter will become important.

System level DfR

- ❖ Identify the weakest converter in the system
- ❖ Design of converters based on system requirements
- ❖ Optimal decision-making in the system planning – investment on converters and their maintenance

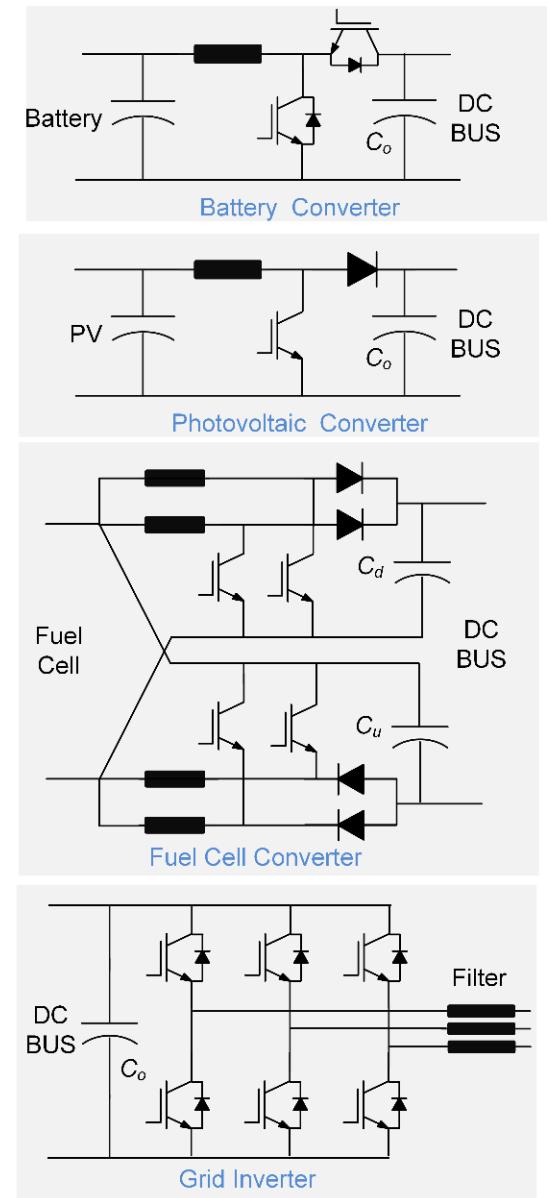
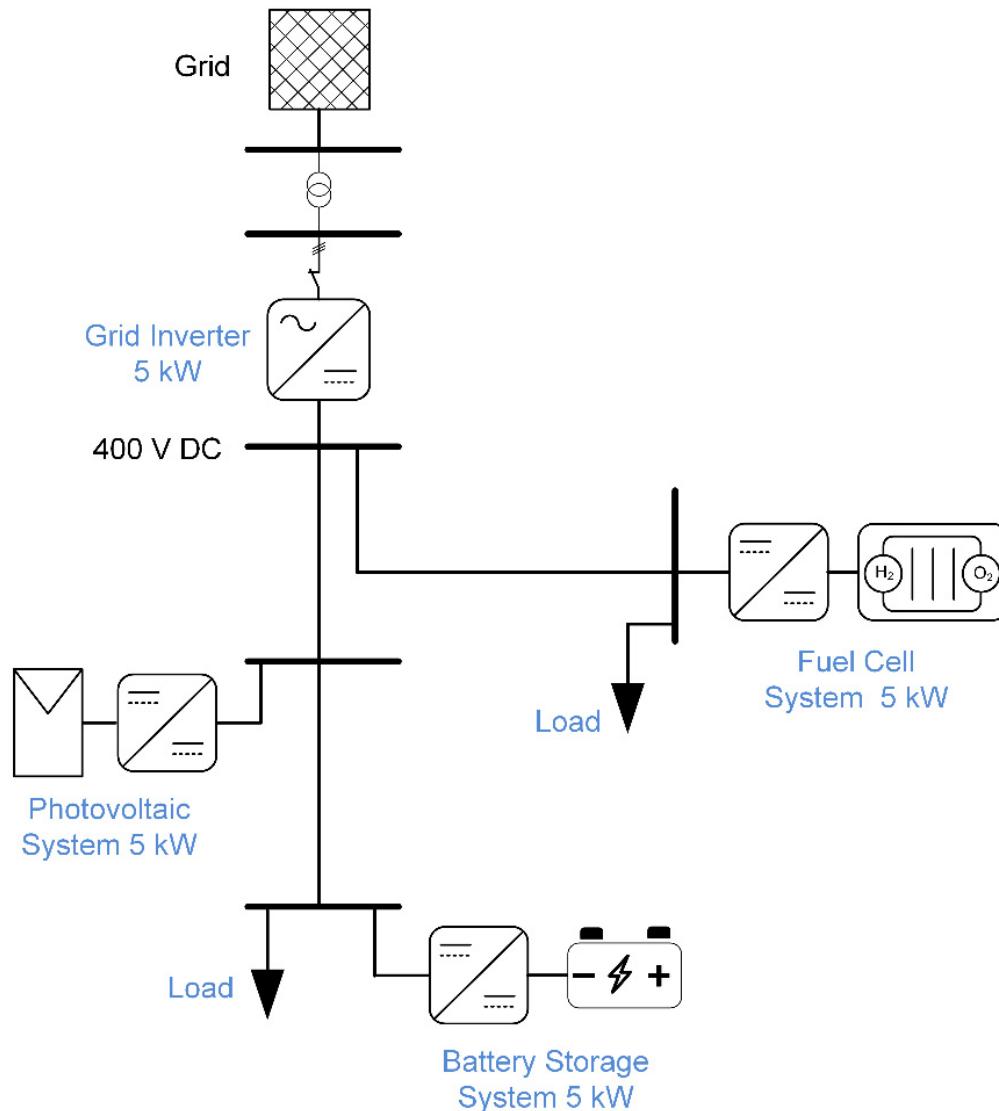


➤ Reliability Enhancement

- Impact of Integrated Design
- Design for Reliability (DfR)
- **Control for Reliability**
- Impact of Replacement

► Reliability Enhancement – Control for Reliability

DC PEPS Structure



Source: S. Peyghami, P. Davari and F. Blaabjerg, IEEE Trans. Ind. App., doi: 10.1109/TIA.2019.2918049

► Reliability Enhancement – Control for Reliability

Reliability oriented power sharing

❖ Proposed droop method

$$R^{(k)} = \alpha \cdot R_o^{(k)} + (1 - \alpha) \cdot \frac{D^{(k)}}{\text{Max}_j \{D^{(j)}\}}$$

➤ Total damage of converter

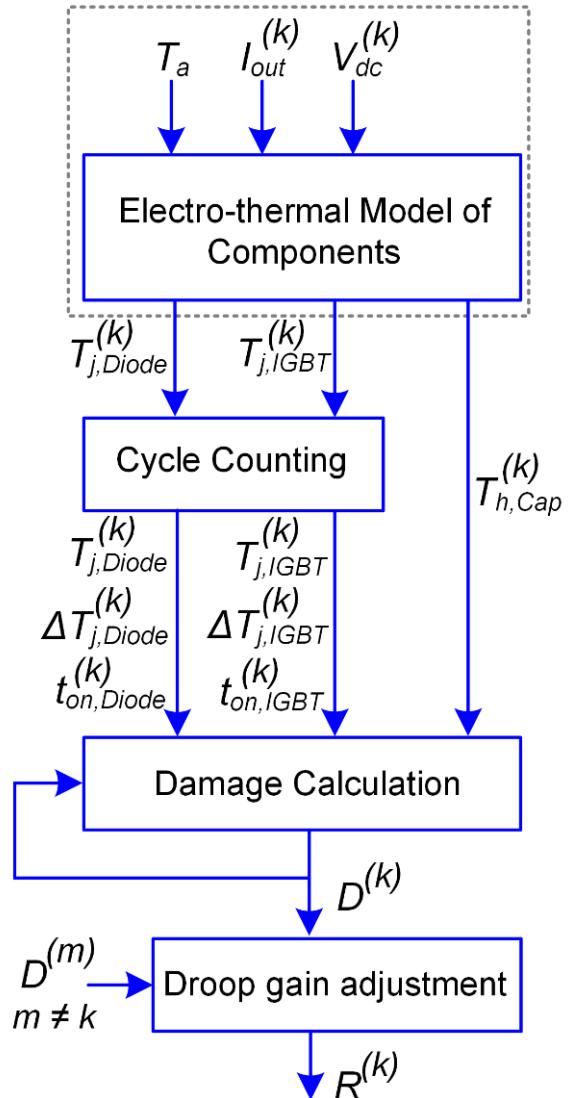
$$D = \frac{1}{M^{(sw)} + M^{(cap)}} \left(\sum_j^{M^{(sw)}} D_j^{(Cap)} + \sum_j^{M^{(cap)}} D_j^{(Switch)} \right)$$

➤ Capacitor damage

$$L_w = L_r \cdot 2^{\frac{T_r - T_w}{n_1}} \left(\frac{V_w}{V_r} \right)^{-n_2}$$

➤ Semiconductor damage

$$N = A \cdot \Delta T_j^\alpha \cdot \exp \left(\frac{\beta}{T_{jm} + 273.15} \right) t_{on}^\gamma$$

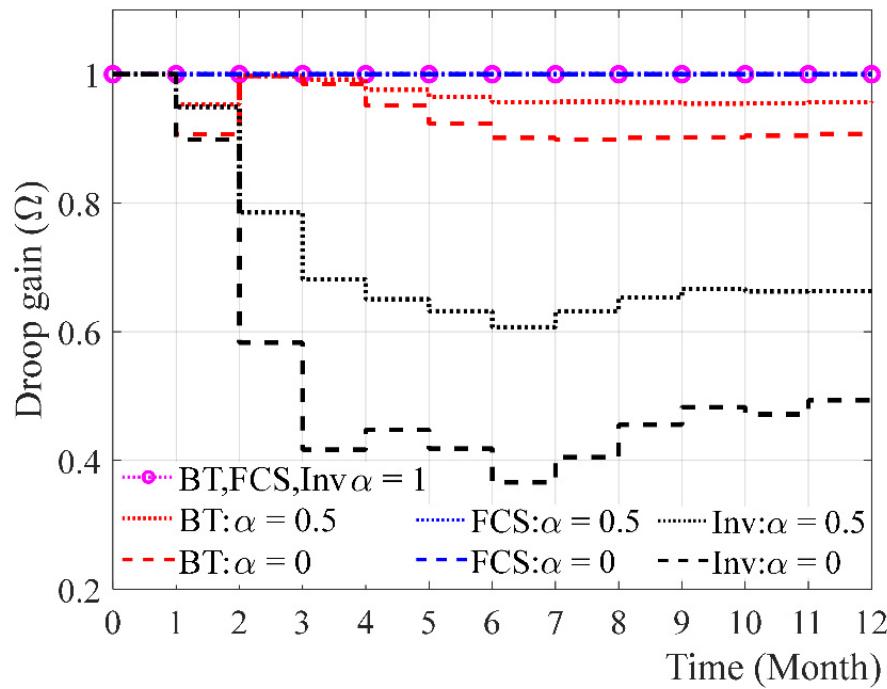


Source: S. Peyghami, P. Davari and F. Blaabjerg, "System-Level Reliability-Oriented Power Sharing Strategy for DC Power Systems," IEEE Trans. Ind. App., doi: 10.1109/TIA.2019.2918049

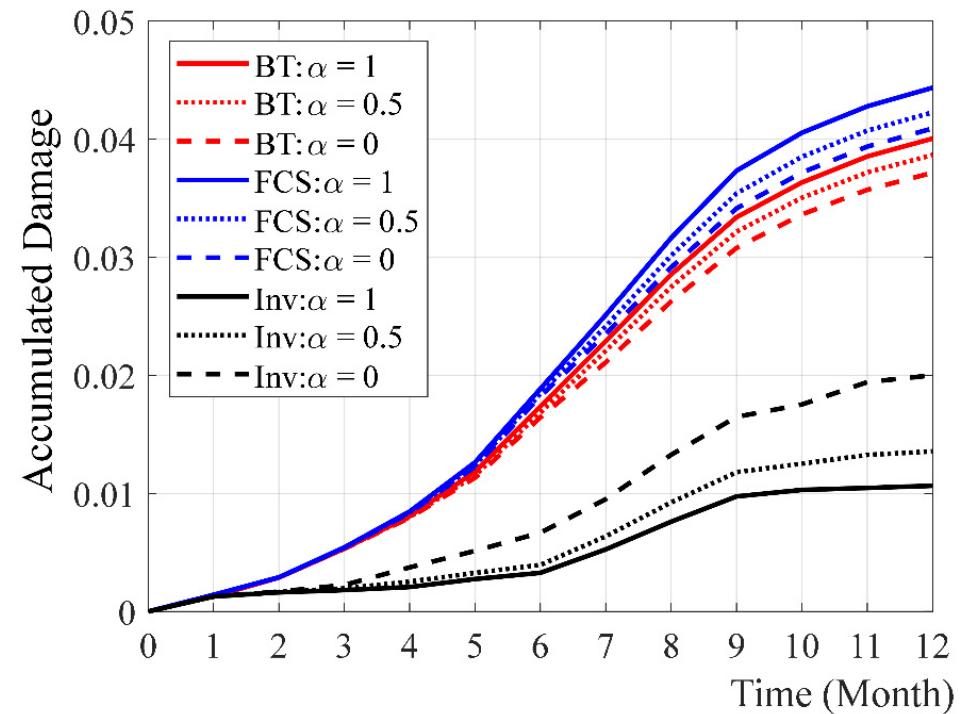
► Reliability Enhancement – Control for Reliability

Droop gains and damage distribution

Droop gains of converters



Accumulated damage of converters

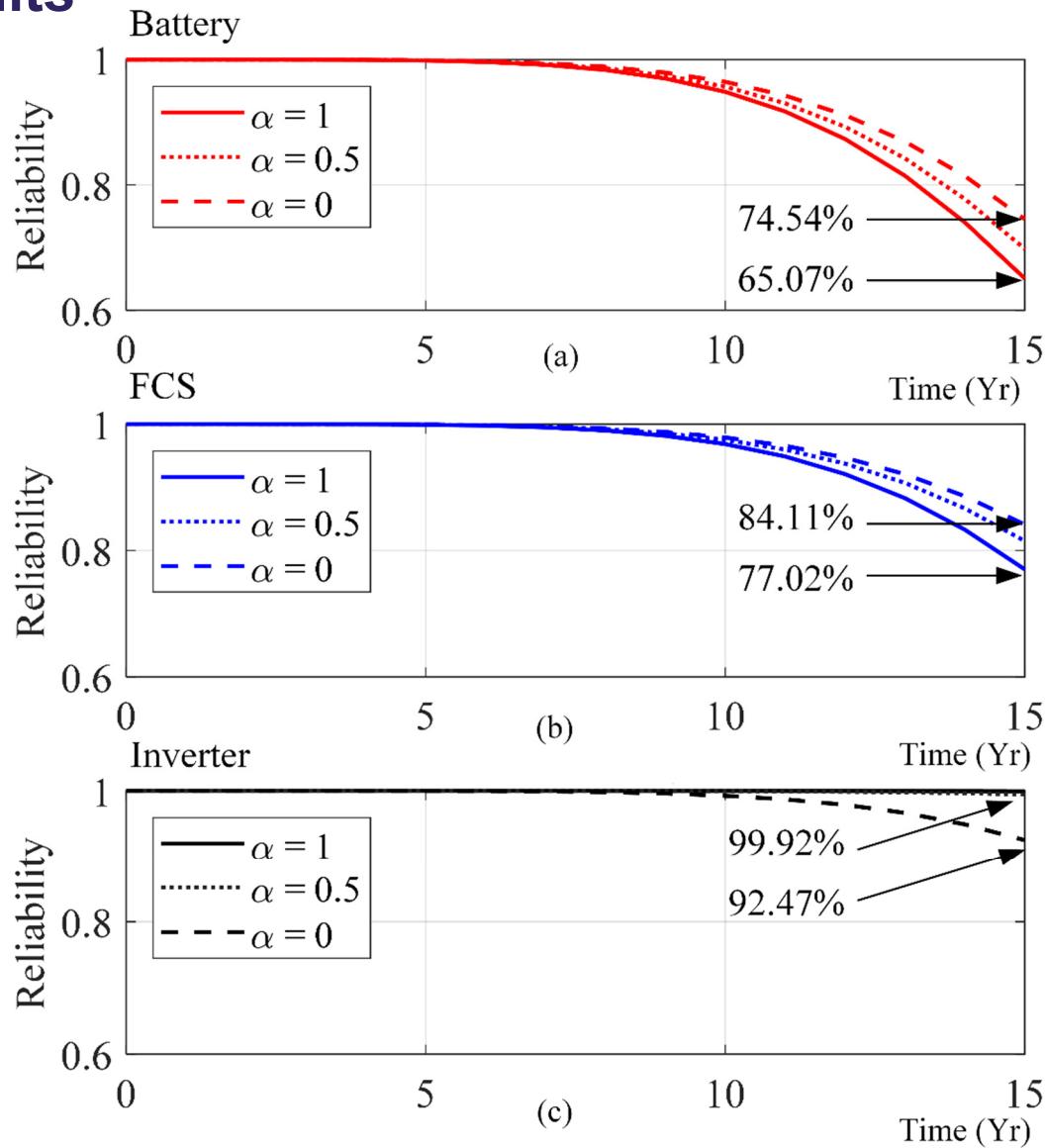


The accumulated damages of converters are approaching together.

Source: S. Peyghami, P. Davari and F. Blaabjerg, "System-Level Reliability-Oriented Power Sharing Strategy for DC Power Systems," IEEE Trans. Ind. App., doi: 10.1109/TIA.2019.2918049

► Reliability Enhancement – Control for Reliability

Reliability of Units

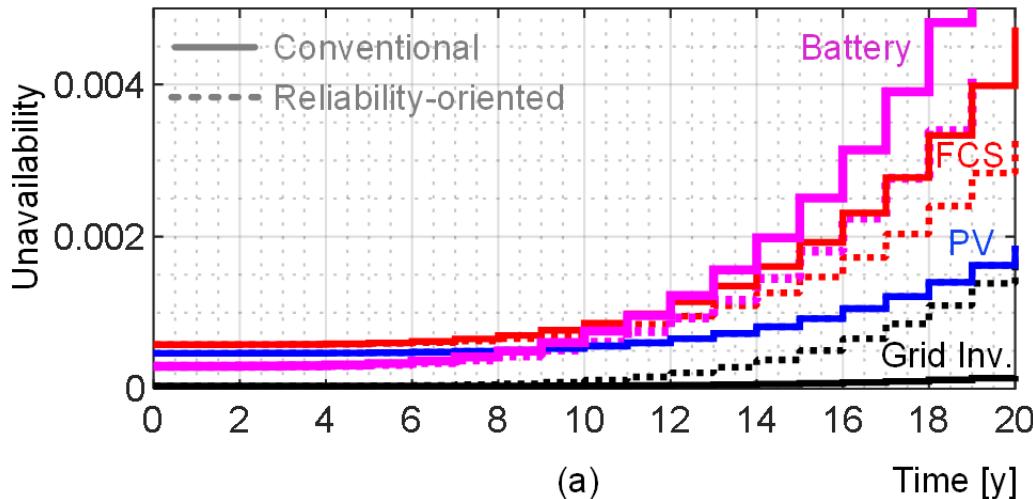


Source: S. Peyghami, P. Davari and F. Blaabjerg, "System-Level Reliability-Oriented Power Sharing Strategy for DC Power Systems," IEEE Trans. Ind. App., doi: 10.1109/TIA.2019.2918049

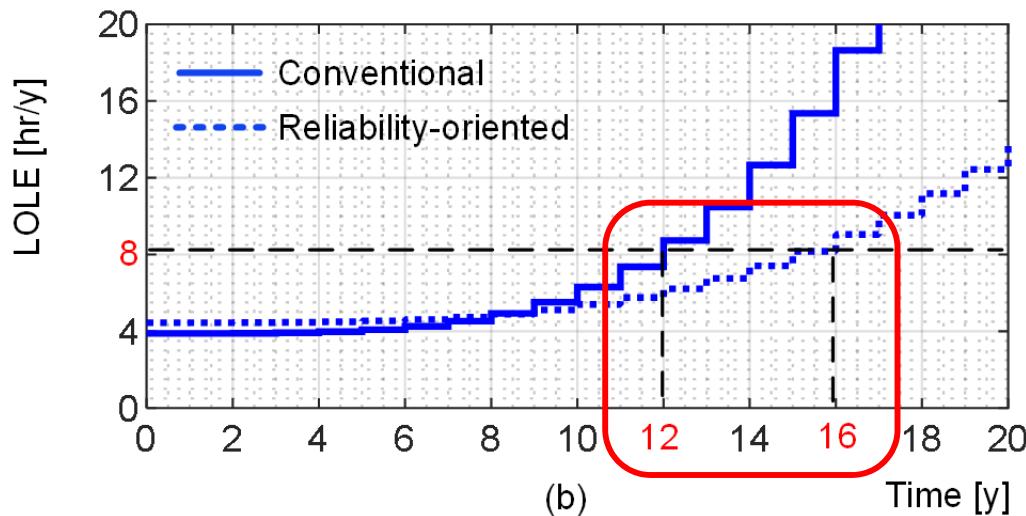
SAEED PEYGHAMI, DEPARTMENT OF ENERGY TECHNOLOGY, AALBORG UNIVERSITY, SAP@ET.AAU.DK

► Reliability Enhancement – Control for Reliability

Availability of units and reliability of DC PEPS



(a)



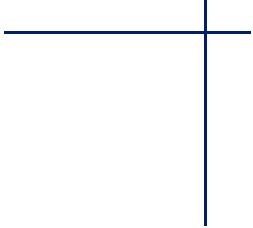
(b)

LOLE: Loss of Load Execution

FCS: Fuel Cell Stack

With reliability oriented control

- ✓ Reliability of FCS is improved
- ✓ Availability of FCS is improved
- ✓ LOLE of the system is enhanced and the system will stay **4 more years** under standard level of 8 hr/y
- ✓ Thus, FCS can be **replaced** after 16 years instead of 12 years

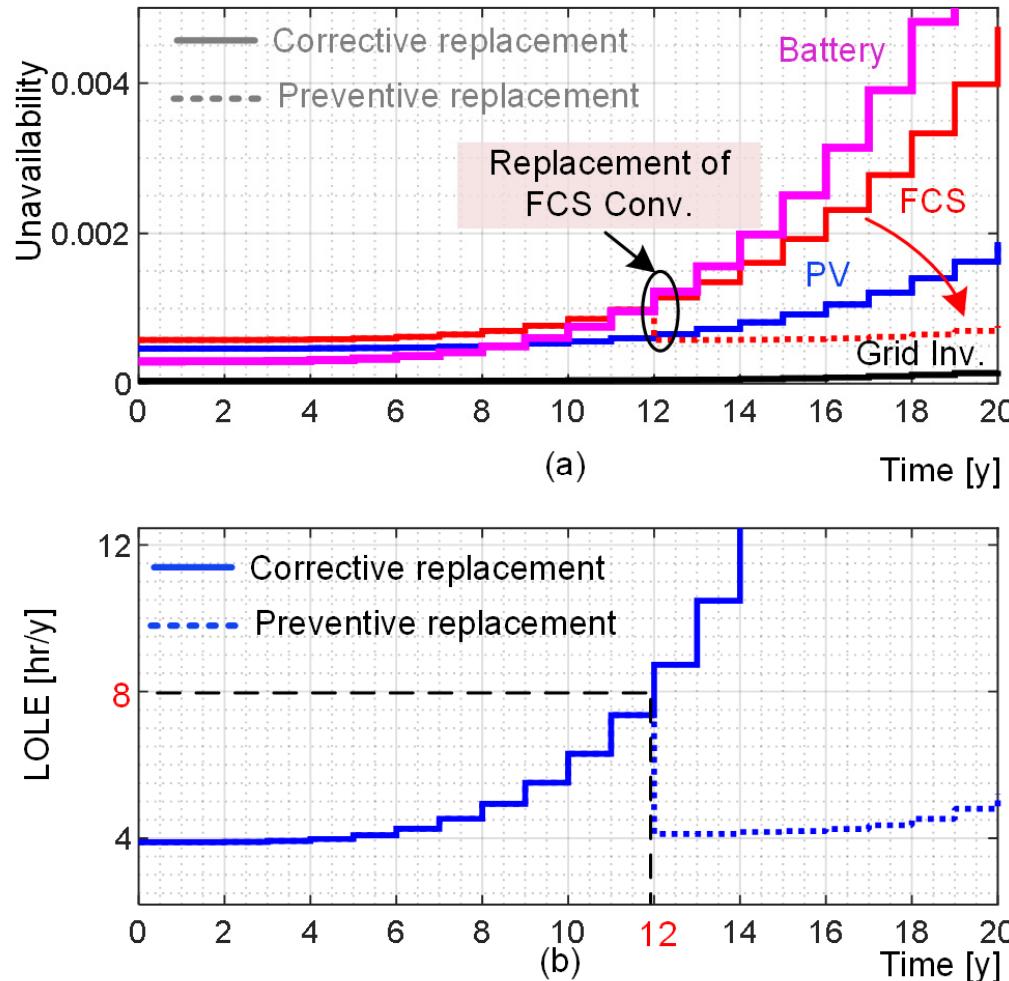


➤ Reliability Enhancement

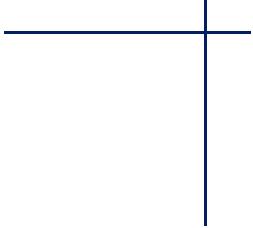
- Impact of Integrated Design
- Design for Reliability (DfR)
- Control for Reliability
- Impact of Replacement

► Reliability Enhancement – Impact of Replacement

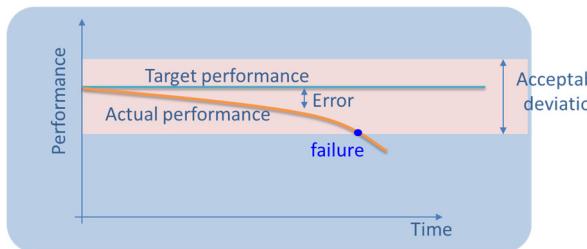
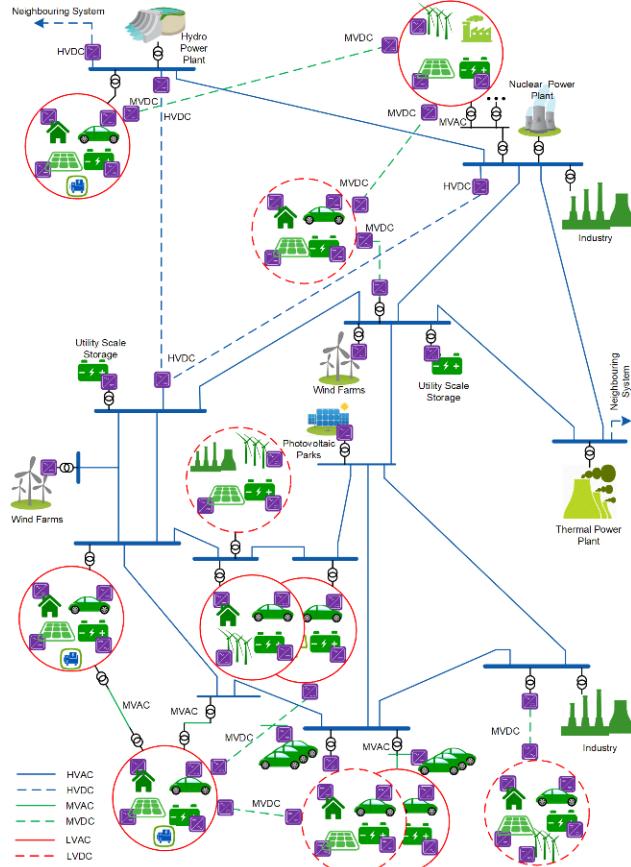
Maintenance based on system performance



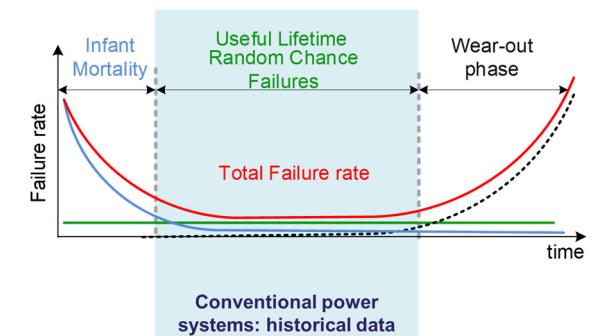
(a) Unavailability of units and (b) system performance

- 
- **Introduction**
 - **Reliability Definition in PEPS**
 - **Reliability Modeling in PE**
 - **Reliability Analysis**
 - **Reliability Enhancement**
 - **Summary**

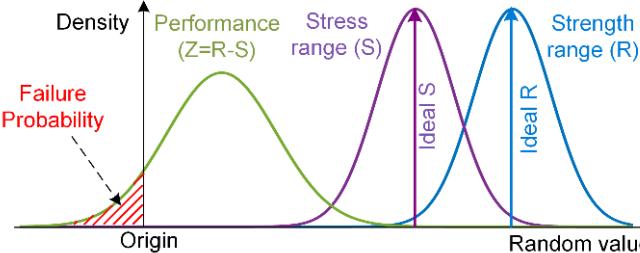
► Summary



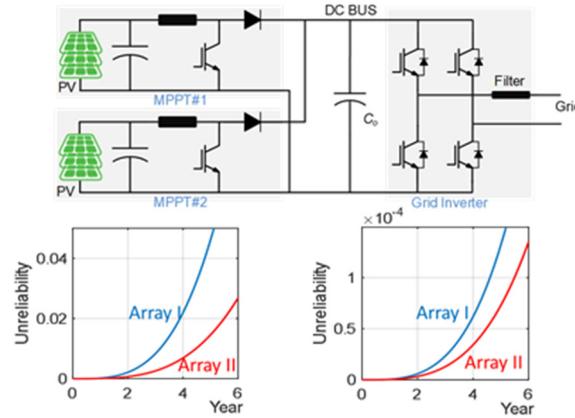
Definition of reliability



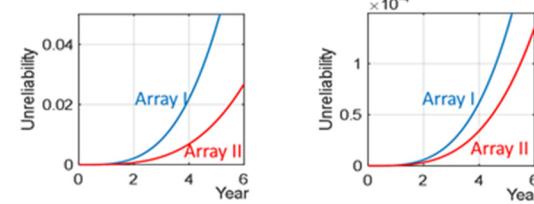
Reliability modeling



Stress-strength analysis

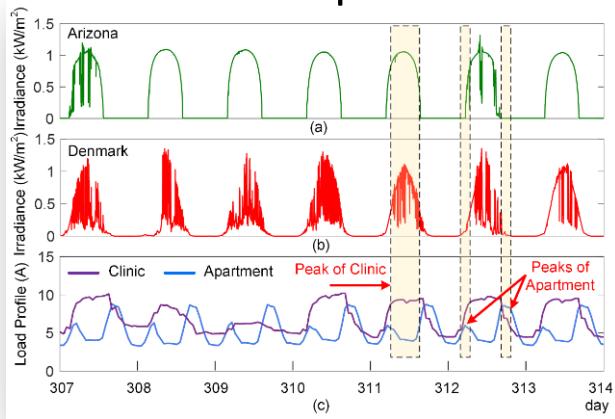


Integrated design



► Summary

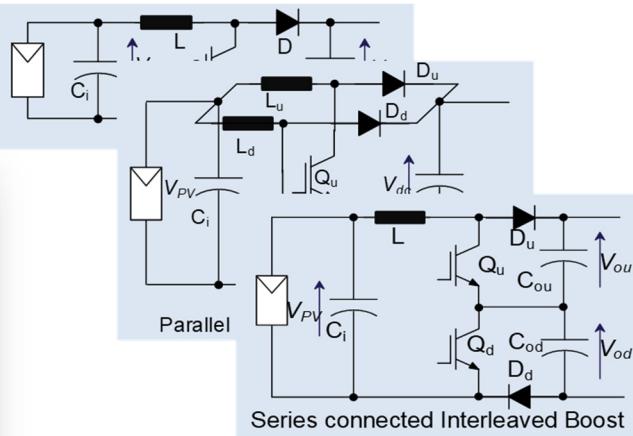
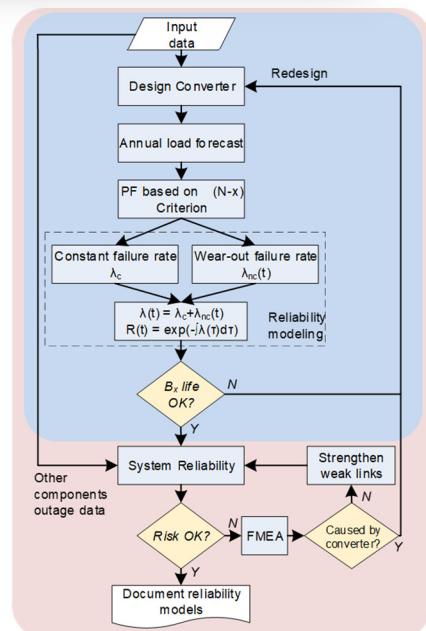
Mission profile



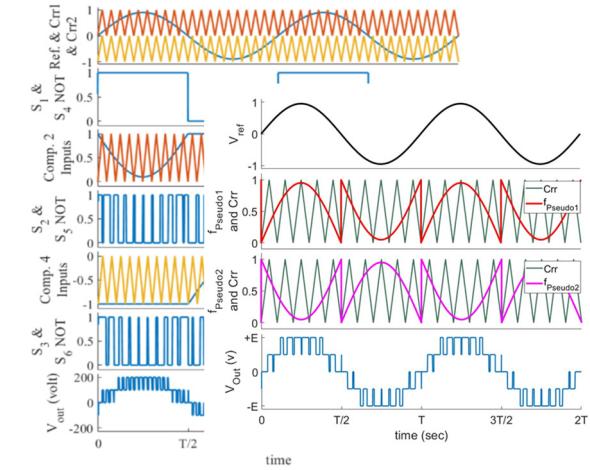
Converter level DfR

Design for reliability

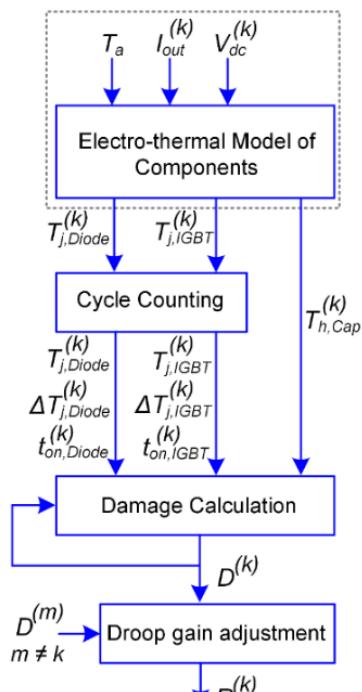
System level DfR



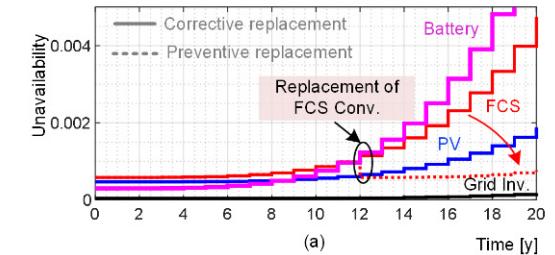
Converter topology



Switching scheme



Control for reliability



Replacement



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Thank you for your
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Questions?