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Capacitor Failure Modes and Lifetime Models – from an Application Perspective

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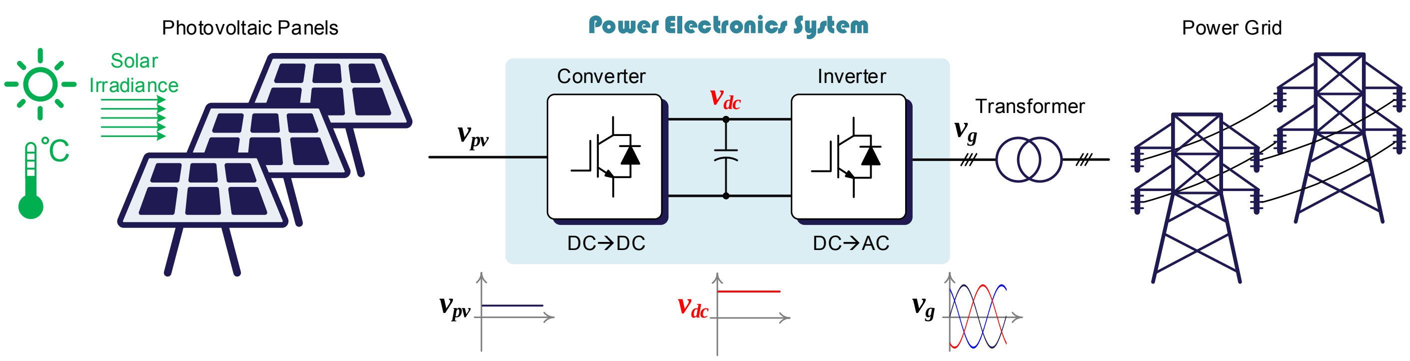
▶ Case I

Film capacitors are widely assumed to be more reliable than Aluminum electrolytic capacitors. Company A replaced the DC-link electrolytic capacitors of ten 6 kW three-phase inverter products by film capacitors, which expected to extend the lifetime of the inverters. The ten inverters were put in field operation among other inverters with electrolytic capacitors in 2012.

The field testing result in 2012 and 2013 is a big surprise for Company A! Those DC-link film capacitors degrade faster than the aluminum electrolytic capacitors.

Is our assumption wrong?
What are the root causes of the "unexpected" degradation of the film capacitors?



▶ Case II

Assume that you are asked to predict the lifetime of a kind of electrolytic capacitor for a power electronic converter product with expected sale of 10,000 units (each use 4 such capacitor). The useful lifetime from the datasheet is 5,000 hours with rated voltage of 450 V and rated ripple current of 3 A at upper category temperature 105°C. You were given the lifetime model below with n = 4.4 and obtained the results shown in the table below.

$$L_x = L_0 \times \left(\frac{V_x}{V_0}\right)^{-n} \times 2^{\frac{T_0 - T_x}{10}}$$

Voltage stress V_x (V)	Temperature T_x (°C)	Predicted lifetime Lx (in Hrs.)	Predicted lifetime Lx (in Yrs.)
420	65	1.08E+05	12
420	55	2.17E+05	25
420	35	8.67E+05	99

You are then asked by your product manager:

How many capacitors expect to fail after 12 years operating at 420 V and 65°C?

Is it realistic that the capacitors can survive 99 years operating at 420 V and 35°C?

► Failure Modes, Mechanisms, and Stressors

Aluminum Electrolytic Capacitors (Al-Caps)

	Failure modes	Critical failure mechanisms	Critical stressors
Al-Caps	Open circuit	Electrolyte loss	V_C, T_a, i_C
		Poor connection of terminals	Vibration
	Short circuit	Dielectric breakdown of oxide layer	V_C, T_a, i_C
	Wearout: electrical parameter drift (C, ESR, tanδ, I_{LC}, R_p)	Electrolyte loss	T_a, i_C
		Electrochemical reaction (e.g. degradation of oxide layer, anode foil capacitance drop)	V_C, T_a, i_C
	Open vent	Internal pressure increase	V_C, T_a, i_C

Which failure mechanism(s) are dominant in field operation?

► Failure Modes, Mechanisms, and Stressors

Metallized Polypropylene Film Capacitors (MPPF-Caps)

	Failure modes	Critical failure mechanisms	Critical stressors
MPPF-Caps	Open circuit (typical)	Self-healing dielectric breakdown	V_C, T_a, dV_C/dt
		Connection instability by heat contraction of a dielectric film	T_a, i_C
		Reduction in electrode area caused by oxidation of evaporated metal due to moisture absorption	Humidity
	Short circuit (with resistance)	Dielectric film breakdown	V_C, dV_C/dt
		Self-healing due to overcurrent	T_a, i_C
		Moisture absorption by film	Humidity
	Wearout: electrical parameter drift (C, ESR, tanδ, I_{LC}, R_p)	Dielectric loss	V_C, T_a, i_C, humidity

Which failure mechanism(s) are dominant in field operation?

▶ Existing Capacitor Lifetime Models

$$L = L_0 \times \left(\frac{V}{V_0}\right)^{-n} \times exp\left[\left(\frac{E_a}{K_B}\right)\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

$$L = L_0 \times \left(\frac{V}{V_0}\right)^{-n_1} \times 2^{\frac{T_0 - T}{n_2}}$$

$$L = L_0 \times \left(\frac{RH}{RH_0}\right)^{-n_3} \times \left(\frac{V}{V_0}\right)^{-n_1} \times 2^{\frac{T_0 - T}{n_2}}$$

- **What is the definition of the lifetime?**
- **What are the exact failure mechanisms and failure modes for the lifetime models?**
- **Are those failure mechanisms and failure modes relevant to field operation conditions?**
- **What are the applicable ranges of L, V, T, and RH?**

► Capacitor Wear Out Testing System at Aalborg University

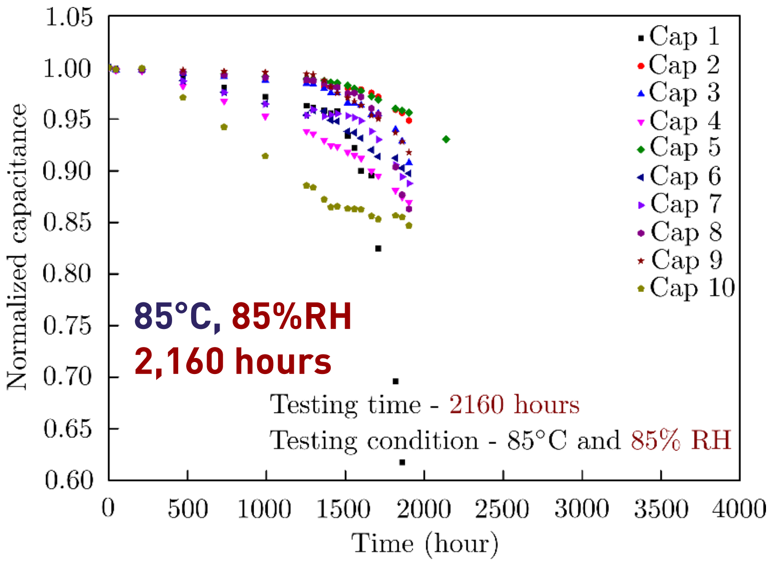
System configuration

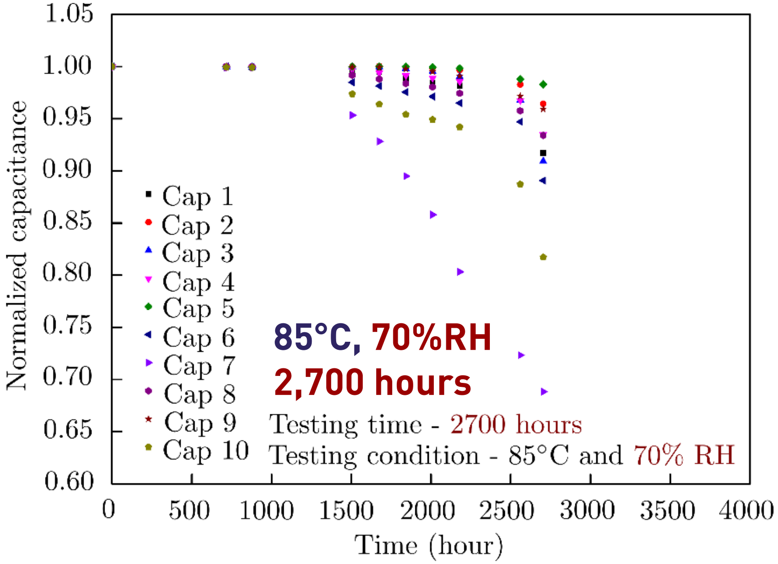
- Climatic chamber
- 2000 V (DC) / 100 A (AC) / 50 Hz to 1 kHz ripple current tester
- 2000 V (DC) / 50 A (AC) / 20 kHz to 100 kHz (discrete) ripple current tester
- 500 V (DC) / 30A (AC) / 100 Hz to 1 kHz (discrete) ripple current tester
- LCR meter
- IR / leakage current meter
- Computer

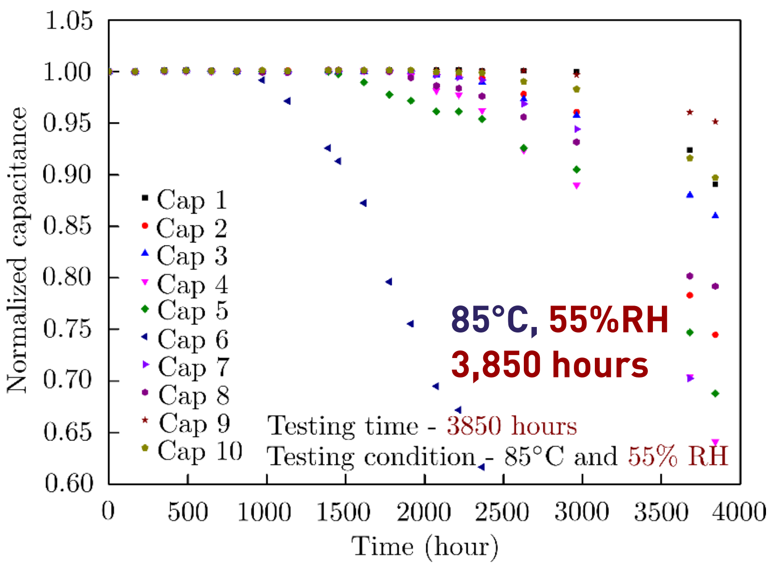
System capability

- Temp. range -70 °C to +180 °C
- Humidity range (for a certain range of temp.): 10 % RH to 95 % RH
- DC voltage stress up to 2000 V and ripple current stress up to 100 A and 100 kHz
- Measurement of capacitance, ESR, inductance, insulation resistance, leakage current and hotspot temperature

▶ Testing Results MPPF-Caps Capacitance (Normalized)





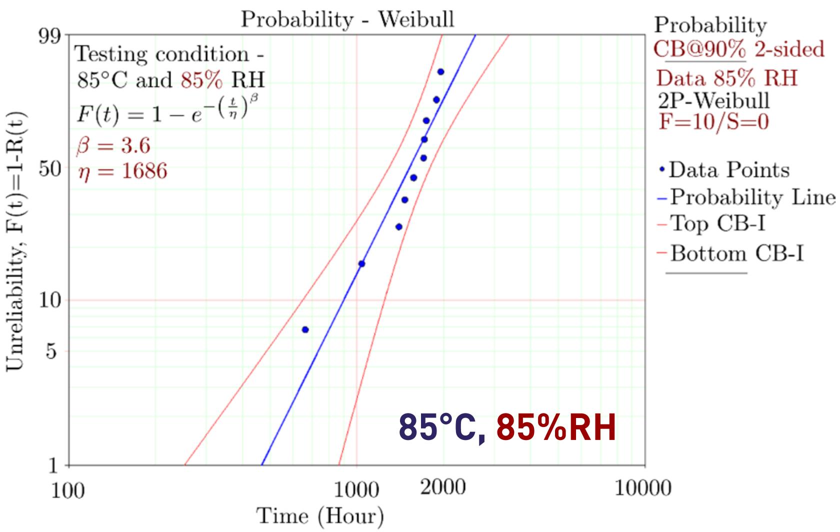


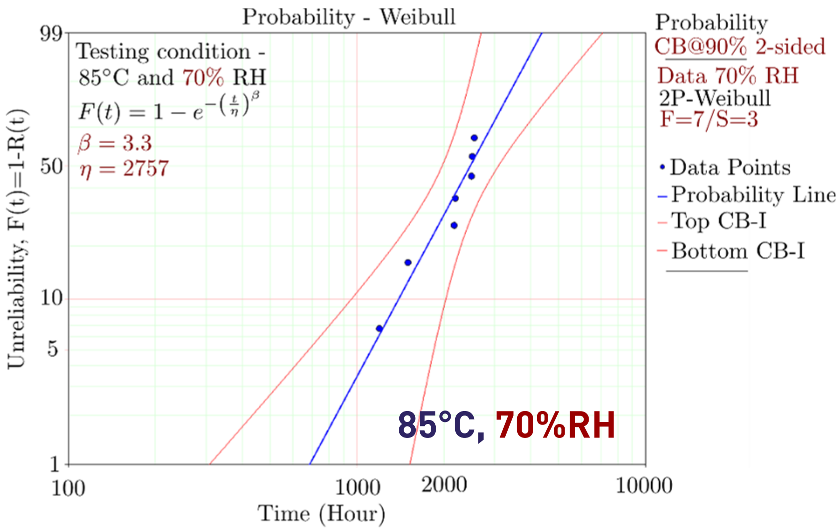
Testing of 1100 V/40 μF MPPF-Caps

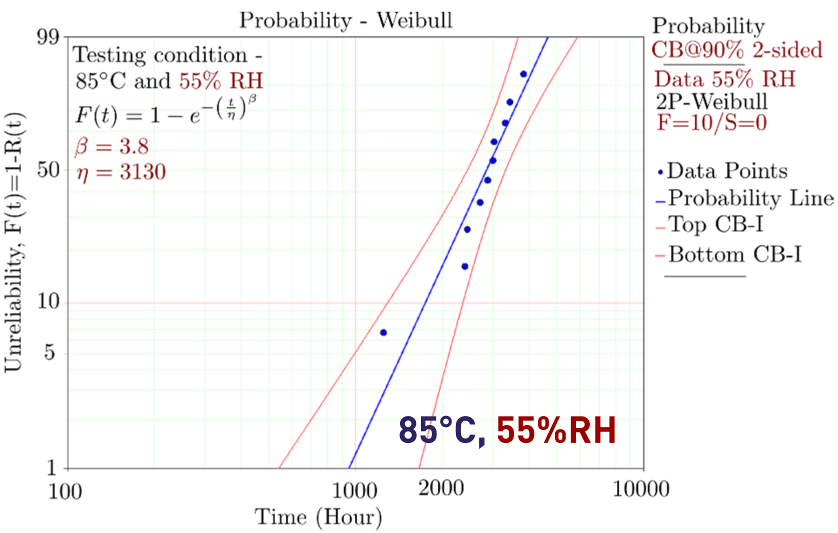
(Metalized Polypropylene Film)

Sample size: 10 pcs for each group of testing

▶ Weibull Plots of the Testing Data







5% capacitance drop is used as the end-of-life criteria of the testing samples

Testing of 1100 V/40 μF MPPF-Caps
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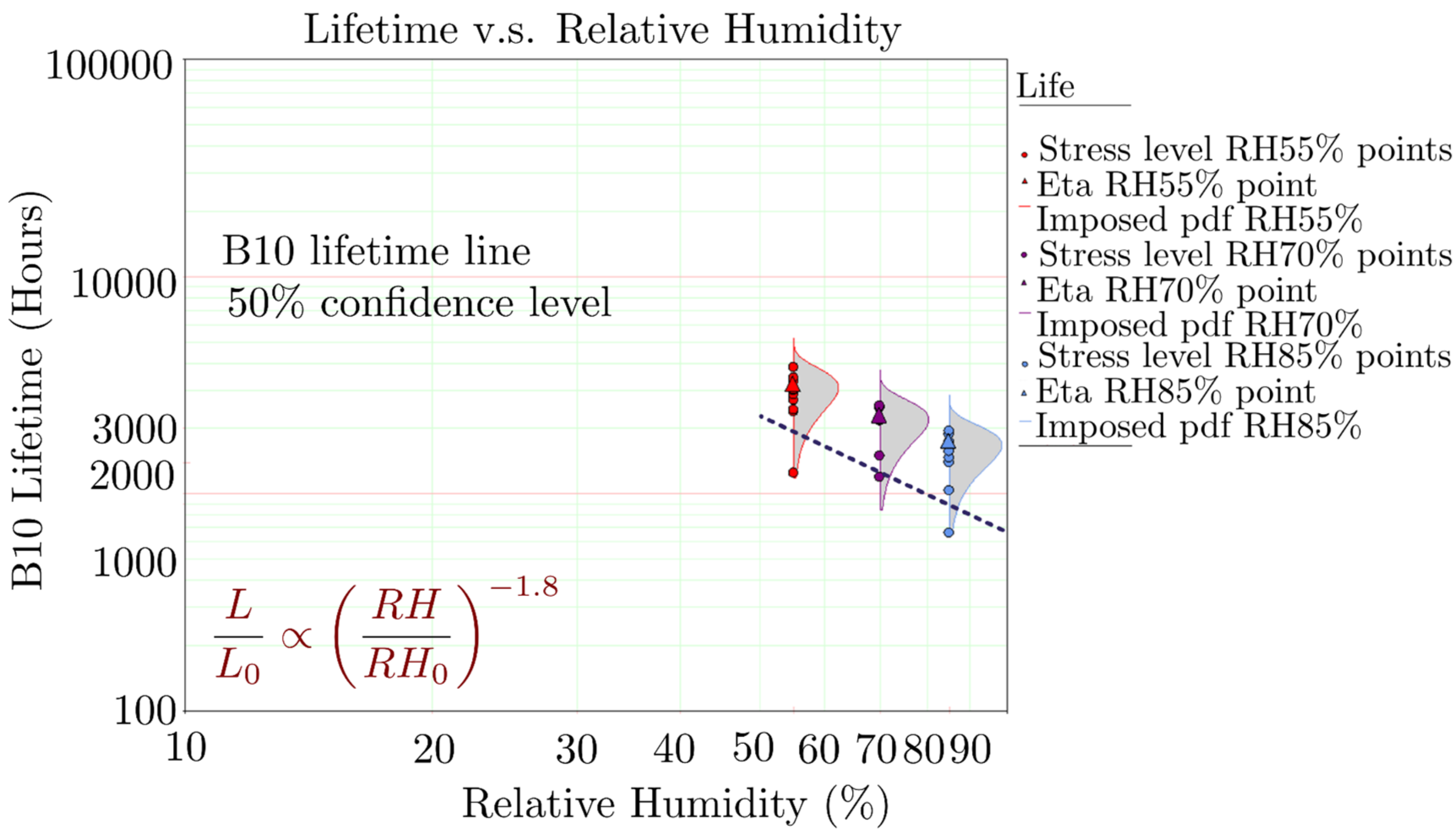
► Humidity-Dependent Lifetime of the MPPF-Caps



B10 lifetime – the time when reliability is 0.9 (i.e., 10% failure)

▶ A Complete Lifetime Definition – 4 Boundaries

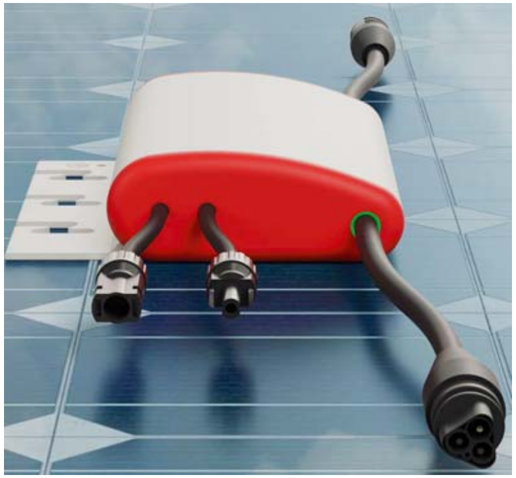
- Definition of failure - end-of-life criteria of individual capacitors
- Reliability level %
- Confidence level %
- Stress conditions

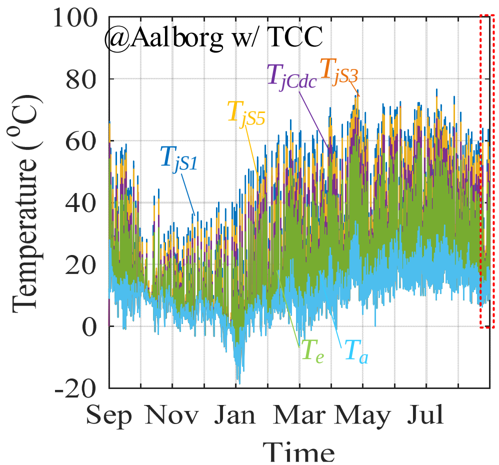
Without consistent definitions of all the above four boundary conditions, meaningful comparisons cannot be made among different capacitors.

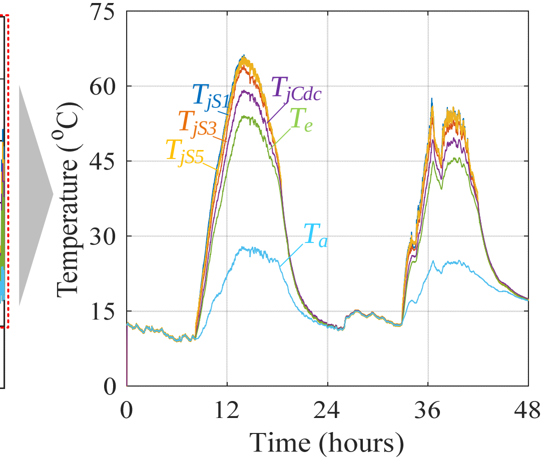
Different lifetime values with different definitions (with the previous testing case in slides 8-10)

Lifetime	Confidence Level	85°C and 85% RH (Hours)			85°C and 70% RH (Hours)			85°C and 55% RH (Hours)		
		Bottom CB	Nominal	Top CB	Bottom CB	Nominal	Top CB	Bottom CB	Nominal	Top CB
B1	99%	177	466	1226	195	685	2399	666	1277	2448
	90%	251		864	307		1525	843		1935
B10	99%	538	899	1500	774	1395	2515	1387	2003	2893
	90%	648		1246	958		2032	1584		2533
B63.2	99%	1310	1686	2169	1852	2757	4104	2619	3083	3628
	90%	1435		1980	2139		3554	2778		3421
MTTF	99%	1174	1519	1964	1740	2474	3517	2355	2838	3419
	90%	1288		1790	1975		3097	2519		3196

▶ Lifetime Models Are **NOT** Sufficient to Reliability Analysis







An example of a micro-PV inverter and its internal component temperatures under one-year operation

- **How to accumulate the degradation effect under different stress levels? Linear accumulated damage model or not?**
- **Not only lifetime model but also the entire reliability curve is needed when come to converter level lifetime or reliability analysis.**

▶ Wear Out Failure is NOT Sufficient to Reliability Analysis

Capacitor bank testing setup at Aalborg University

Capacitor bank

Abnormal operations and Single-event failure matters a lot!

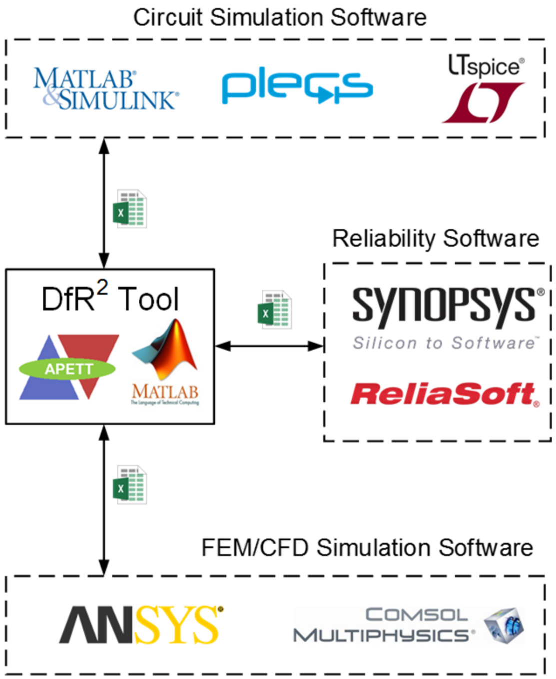
Testing Capability

Lab power sources - from 400 Vac to 11 kVac, up to 400 kVA for 400 Vac and 690 Vac up to 2 MVA 11kVac

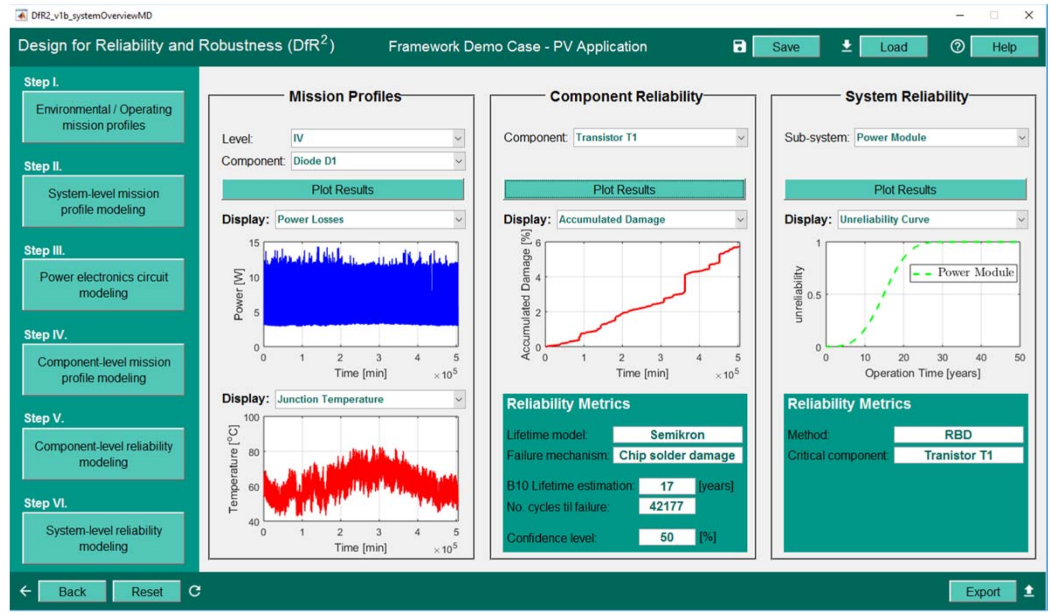
- Capacitor bank thermal characterizations
- Capacitor bank abnormal operation emulation (test at extreme conditions)
- Application-oriented capacitor bank degradation testing

▶ DfR² Tool Platform at CORPE for Industry Applications

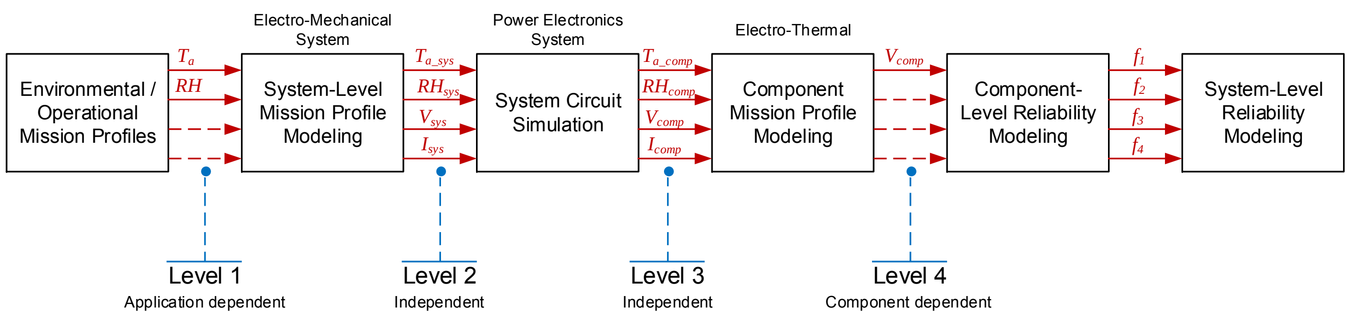
Design for Reliability and Robustness (DfR²), including the package for capacitors



Interfaces to other software



Main GUI panel



Modeling Framework

▶ Summary

- Necessary to identify the most relevant failure modes/failure mechanisms in practical applications
- Research needs to develop lifetime models specific to failure mechanisms
- Necessary to have a comprehensive lifetime definition when capacitor lifetime models are given
- The Center of Reliable Power Electronics at Aalborg University is making efforts to application-oriented testing, capacitor bank testing, capacitor abnormal operation study, reliability prediction tools, etc.), working closely with industry partners across the value chain.

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▶ References

1. H. Wang and F. Blaabjerg, "Reliability of capacitors for dc-link applications in power electronic converters-an overview," IEEE Trans. Ind. Appl., vol. 50, no. 5, pp. 3569–3578, Sept 2014.
2. H. Chung, H. Wang, Frede Blaabjerg, and Michael Pecht, *Reliability of power electronic converter systems*, IET, 2015.
3. H. Wang, D. A. Nielsen, and F. Blaabjerg, "Degradation testing and failure analysis of DC film capacitors under high humidity conditions," Microelectronics Reliability, in press, doi:10.1016/j.microrel.2015.06.011.
4. H. Wang and H. Wang, "A two-terminal active capacitor," IEEE Transactions on Power Electronics, vol. 32, no. 8, pp. 5893-5896, Aug. 2017.

► Biography of Speaker

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).

Prof. Wang received his PhD degree from the City University of Hong Kong, Hong Kong, China, and B. E. degree from the Huazhong University of Science and Technology, Wuhan, China. He was a short-term visiting scientist with the Massachusetts Institute of Technology (MIT), USA, and ETH Zurich, Switzerland. He was with the ABB Corporate Research Center, Baden, Switzerland, in 2009. Dr. Wang received the Richard M. Bass Outstanding Young Power Electronics Engineer Award from the IEEE Power Electronics Society in 2016, for the contribution to reliability of power electronic converter systems. He serves as the Award Chair of the Technical Committee of the High Performance and Emerging Technologies (TC6), IEEE Power Electronics Society, and as an Associate Editor of IET Power Electronics, IEEE Journal of Emerging and Selected Topics in Power Electronics, and IEEE Transactions on Power Electronics.