IECON 2016 Tutorial
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Capacitors in Power Electronics Applications – Reliability and Circuit Design

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► Biography of Speaker

Huai Wang is currently an Associate Professor and a research trust leader with the Center of Reliable Power Electronics (CORPE), Aalborg University, Denmark. His research addresses the fundamental challenges in modelling and validation of the failure mechanisms of power electronic components, 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 is the principal investigator of a project on Reliability of Capacitors in Power Electronic Systems. Dr. Wang is the co-lecturer of a PhD course on Reliability of Power Electronic Systems at Aalborg University since 2013, an invited speaker at the European Center for Power Electronics (ECPE) workshops, and a tutorial lecturer at leading power electronics conferences (ECCE, APEC, EPE, PCIM, etc.). He has co-edited a book on *Reliability of Power Electronic Converter Systems* in 2015, filed four patents in capacitive DC-link inventions, and contributed a few concept papers in the area of power electronics reliability.

Dr. Wang received his PhD degree from the City University of Hong Kong, Hong Kong, China, and Bachelor degree from Huazhong University of Science and Technology, Wuhan, China. He was a visiting scientist with the ETH Zurich, Switzerland, from August to September, 2014 and with the Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, from September to November, 2013. He was with the ABB Corporate Research Center, Baden, Switzerland, in 2009. Dr. Wang received the IEEE PELS Richard M. Bass Outstanding Young Power Electronics Engineer Award, in 2016, for the contribution to the reliability of power electronic conversion systems. He serves as an Associate Editor of IEEE Journal of Emerging and Selected Topics in Power Electronics and IEEE Transactions on Power Electronics.

▶ Tutorial Schedule

- **Introduction to Capacitors in Power Electronics Applications**
  - Functions of capacitors in power electronic systems
  - Dielectric materials and types of capacitors
- **Reliability of Capacitors**
  - Failure modes, failure mechanisms, and critical stressors of capacitors
  - Mission profile based electro-thermal stress analysis
  - Degradation testing of capacitors
  - Condition monitoring of capacitors
- **Design of Capacitive DC-links**
  - Considerations in capacitor bank configuration and design
  - DC-link capacitor sizing criteria in power electronics
  - Active capacitive DC-links

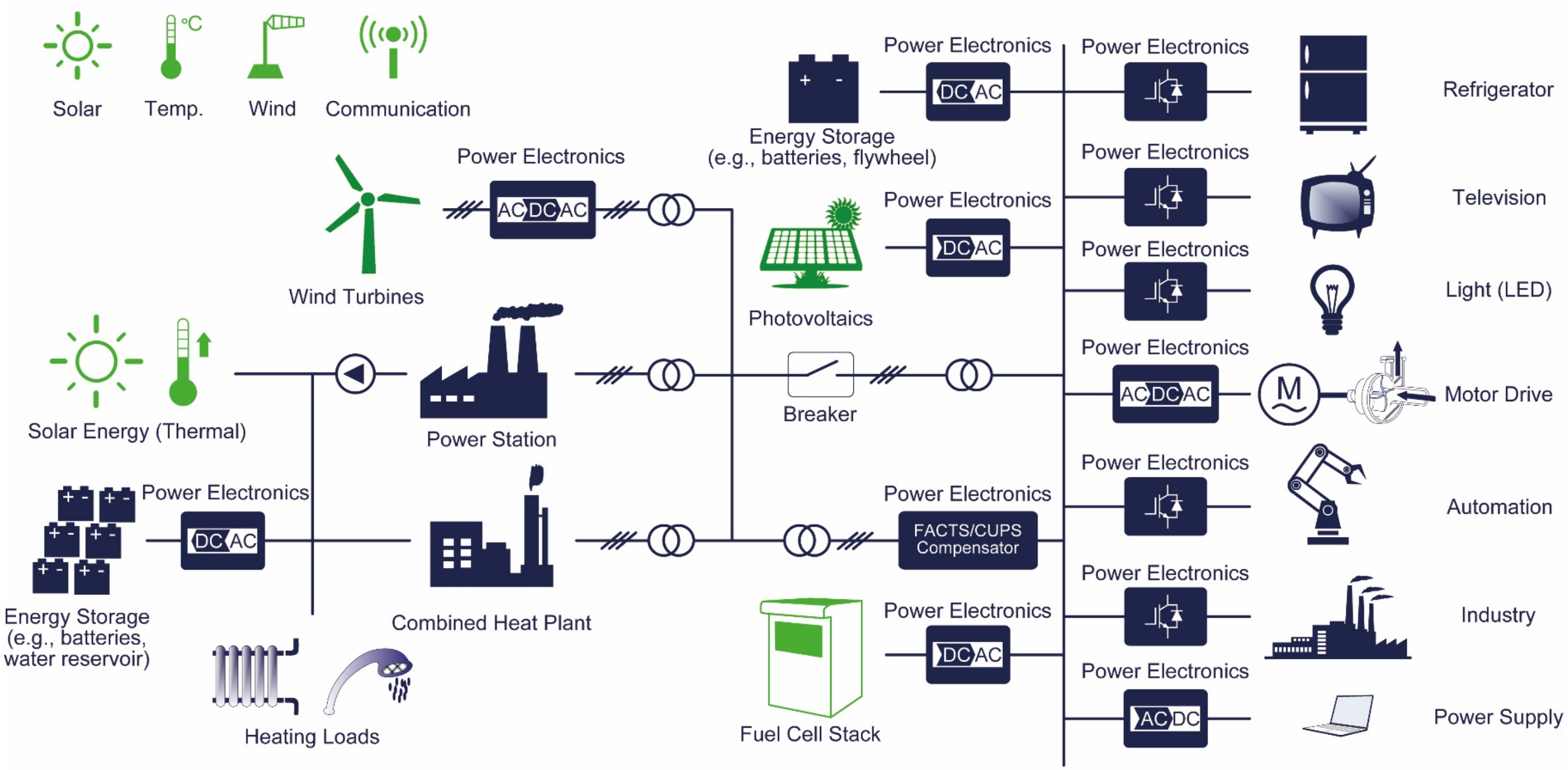
▶ Aalborg University, Denmark

Inaugurated in 1974
22,000+ students
2,000+ faculty

PBL-Aalborg Model
Project-organized and problem-based

► Department of Energy Technology

40+ Faculty, **100+** PhDs, **30+** RAs & Postdocs, **20+** Technical staff



Energy production - distribution - consumption - control

▶ Department of Energy Technology

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

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

Multi-disciplinary Research Programs

Core power electronics research program
- Efficient and Reliable Power Electronics

Programs of power electronics intensive applications
- Wind Power Systems
- Photovoltaic Systems
- E-Mobility and Industrial Drives
- Micrograds

Programs of power electronics related applications
- Fuel Cell and Battery Systems
- Intelligent EnergySystems and Active Networks
- Modern Power Transmission Systems
- Offshore Energy Systems
- Green Buildings
- Thermoelectrics

- Fluid Power in Wind and Wave Energy
- Biomass

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

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

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

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

► Center of Reliable Power Electronics (CORPE)

CORPE

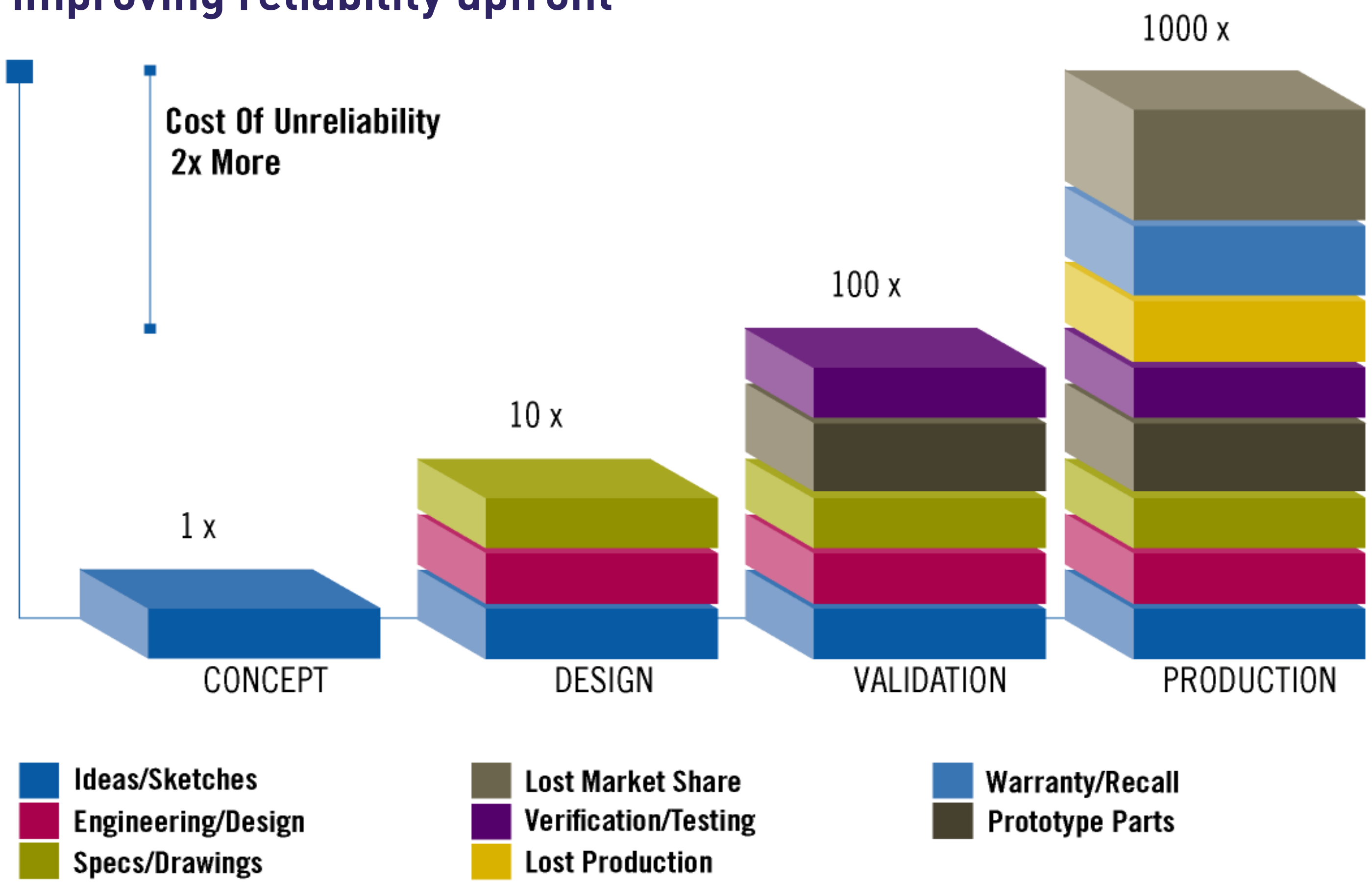
An Industrial Initiated Strategic Research Center

Design for Reliability

By obtaining high-reliability power electronic systems for use in all fields of electrical applications used both in design and operation where the main drivers are lower development cost, manufacturing cost, efficiency, reliability, predictability, lower operational and maintenance costs during the lifetime.

▶ Motivation for More Reliable Product Design

Reduce costs by improving reliability upfront



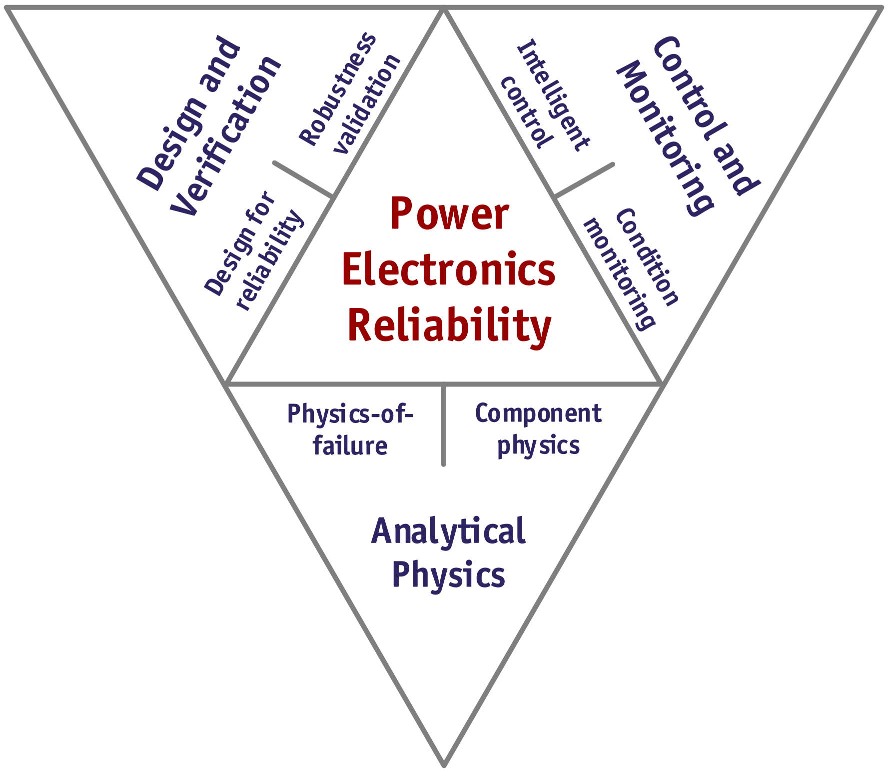
Source: DfR Solutions, Designing reliability in electronics, CORPE Workshop, 2012.

► Typical Lifetime Targets of Industry Applications

Applications	Typical design target of Lifetime
Aircraft	24 years (100,000 hours flight operation)
Automotive	15 years (10,000 operating hours, 300, 000 km)
Industry motor drives	5-20 years (40,000 hours in at full load)
Railway	20-30 years (73,000 – 110,000 hours)
Wind turbines	20 years (120,000 hours)
Photovoltaic plants	30 years (90,000 to 130,000 hours)

► The Scope of Reliability of Power Electronics

H. Wang (2012, 2014 IEEE)



Paradigm Shift

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

1 Introduction to Capacitors in Power Electronics

- Functions of capacitors in power electronic systems
- Dielectric materials and types of capacitors

▶ Power Electronics

Reinvent the way electrical energy processed



Electricity generation

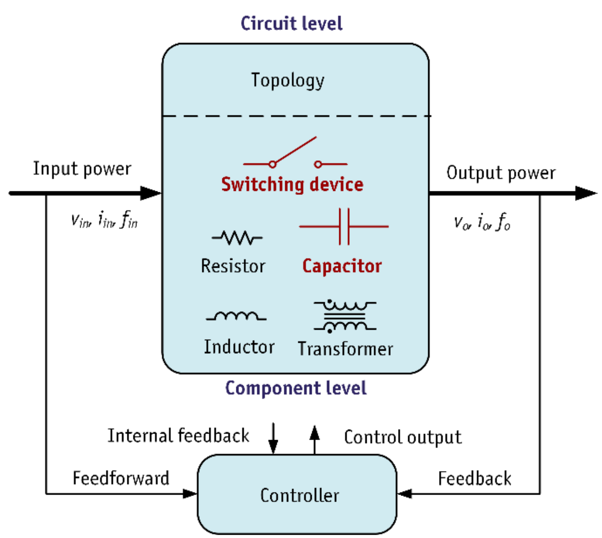
...

Interfaces

Integration to electric grid
Power transmission
Power distribution
Power conversion
Power control

Power Electronics

enable efficient conversion
and flexible control of electrical energy





Electricity consumption

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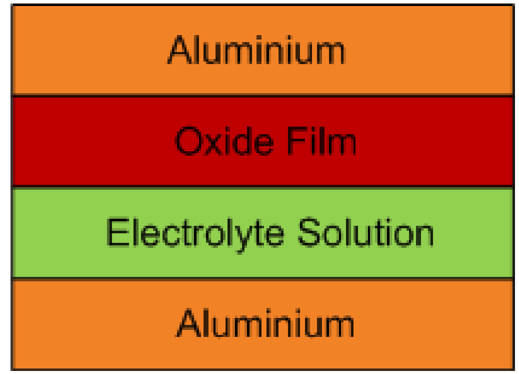
▶ Capacitors

Sandwich
(Source: http://www.jhdeli.com/Templates/Cold_Sandwich.html)



Aluminum Electrolytic Capacitor

Capacitance

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

Ripple current rating

$$I_r = \sqrt{\frac{P_d}{R_s}} = \sqrt{\frac{hA\Delta T}{R_s}}$$

Volumetric efficiency

$$\eta_{\mathrm{v}} = \frac{CV}{\mathrm{volume}}$$

where $\boldsymbol{\varepsilon}_0$ is the dielectric constant, $\boldsymbol{\varepsilon}_r$ is the relative dielectric constant for different materials, A is the surface area and d is the thickness of the dielectric layer; C is the capacitance and V is the voltage rating; P_d is the maximum power dissipation, h is the heat transfer coefficient, ΔT is the temperature difference between capacitor surface and ambient and R_s is the equivalent series resistance (ESR).

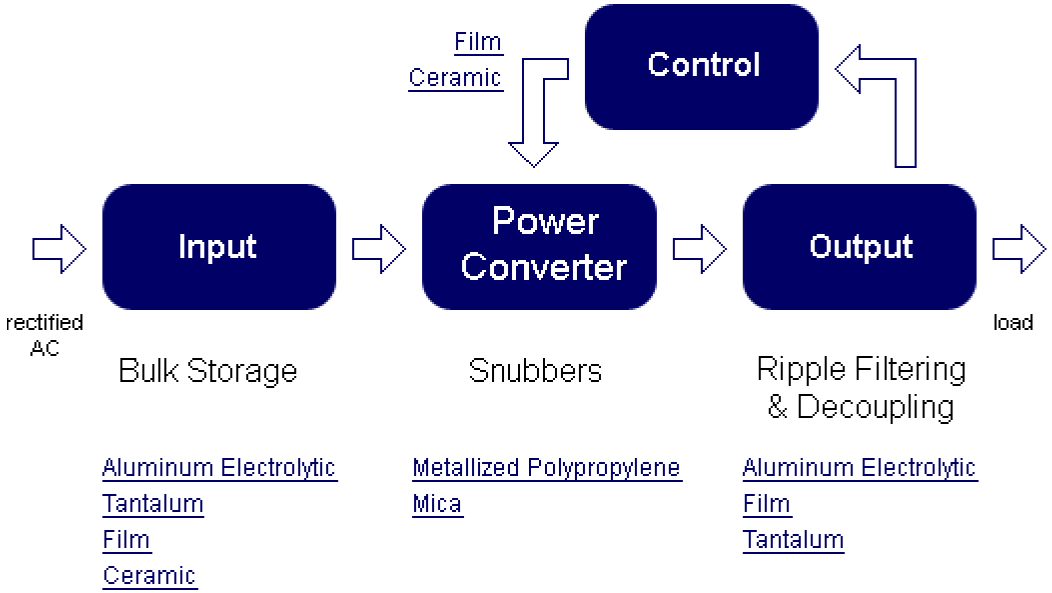
► Capacitors in Power Electronics

Various types of capacitors (Picture courtesy of CDE).

Important factors

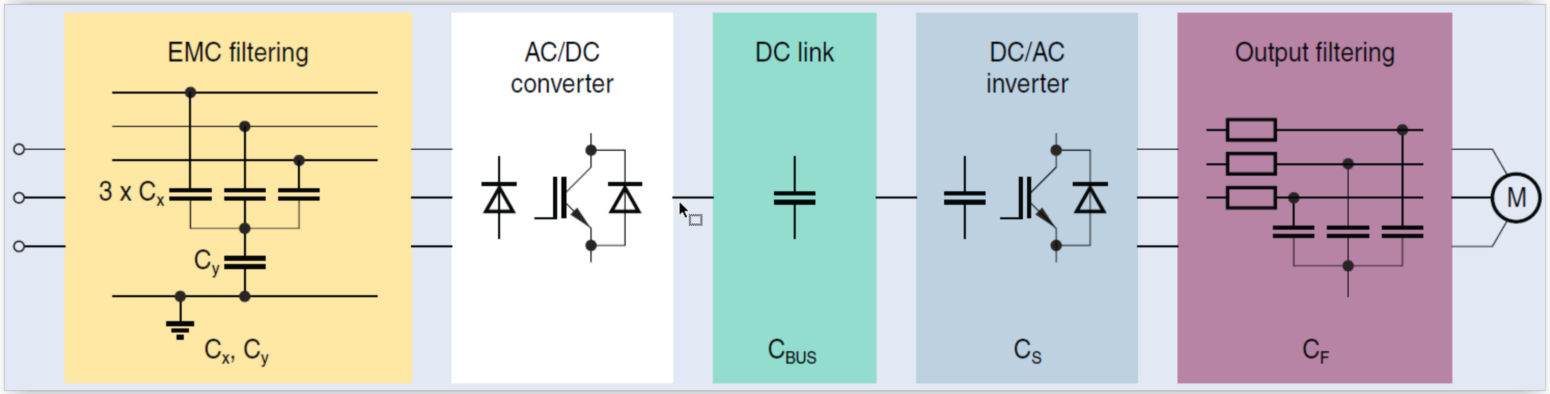
Voltage rating
Capacitance
Capacitance stability
Ripple current rating
Leakage current
Temperature range
Resonant frequency
Equivalent series resistance (ESR)
Equivalent series inductance (ESL)
Volumetric efficiency
Lifetime
Cost
...

► Functions of Capacitors in Power Electronic Systems



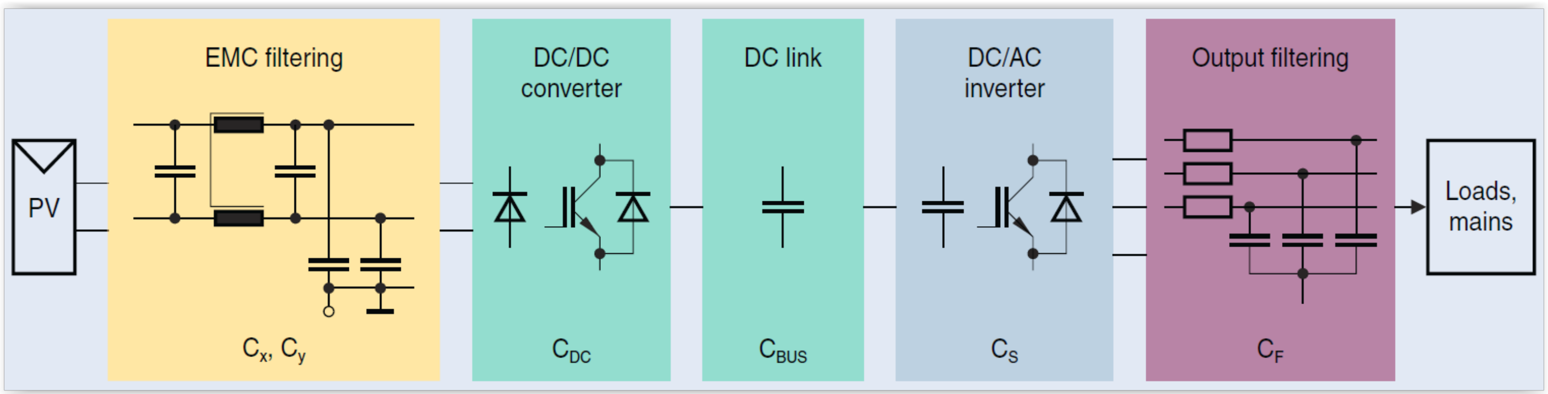
Capacitors in typical power Converters
(Source: http://www.cde.com/catalog/switch/power/)

▶ Functions of Capacitors in Power Electronic Systems



Typical applications of capacitors in motor drives

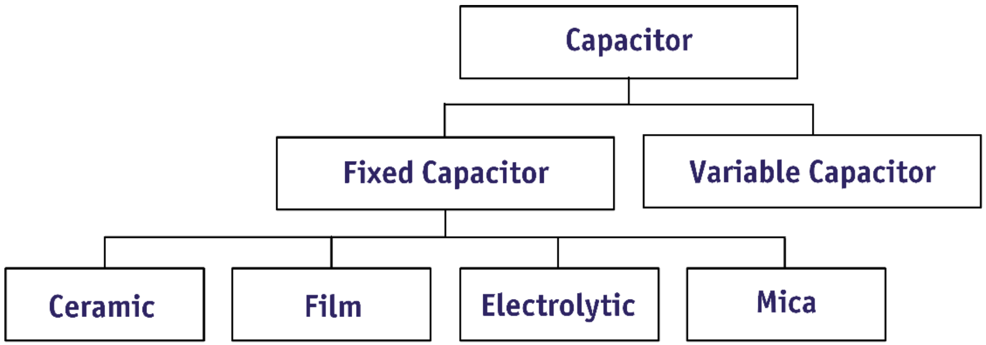
(Figure source: TDK EPCOS product profile: Film Capacitors for Industrial Applications)



Typical applications of capacitors in Photovoltaic (PV) inverters

(Figure source: TDK EPCOS product profile: Film Capacitors for Industrial Applications)

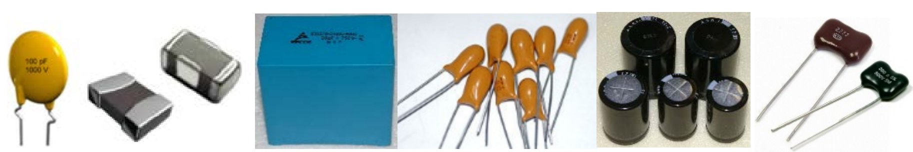
► Capacitor Types According to Dielectric Materials



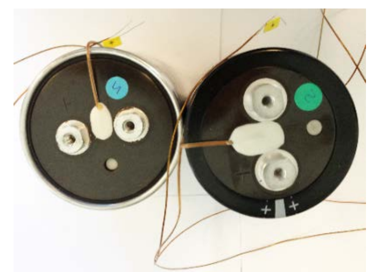
Ceramic: High dielectric *K*, Semiconductor (Single-layer) (Multi-layer)

Film: Polyester, Polypropylene, Polystyrene … (Metallized) (Foil)

Electrolytic: Aluminum, Tantalum (Wet) (Dry)

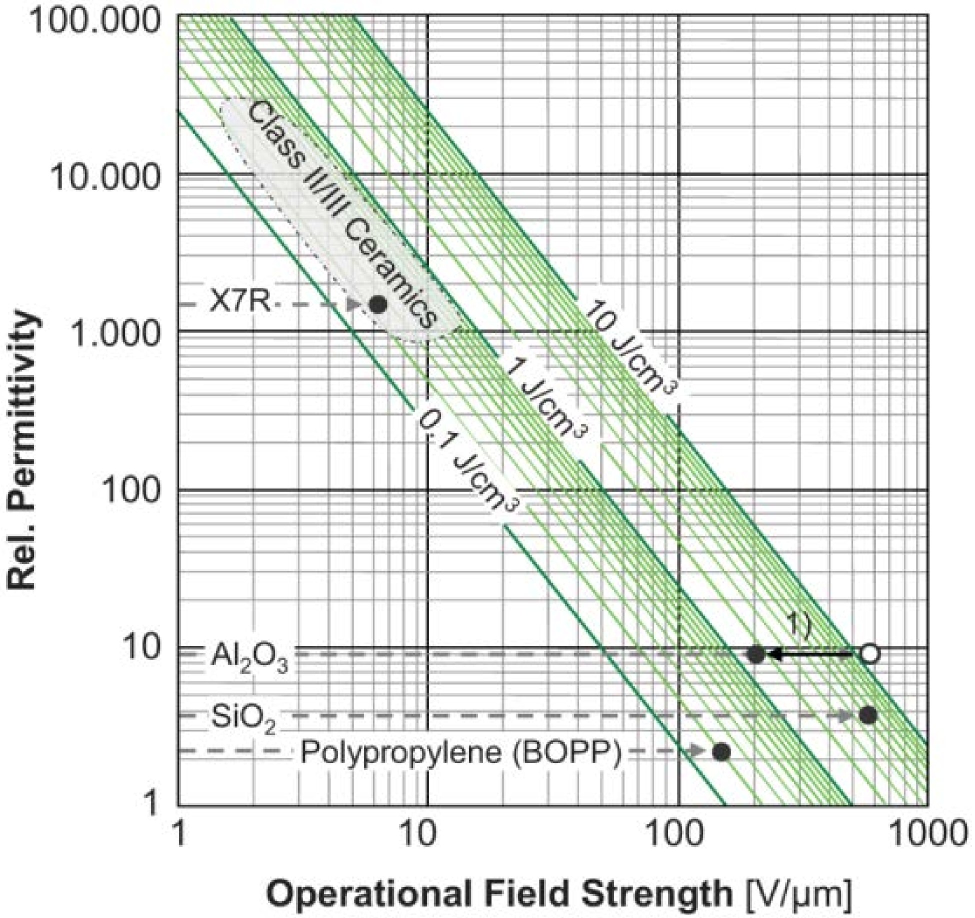


1100 V film capacitors
470 μF and 1100 μF



450 V Al-Electrolytic
capacitors 5600 μF

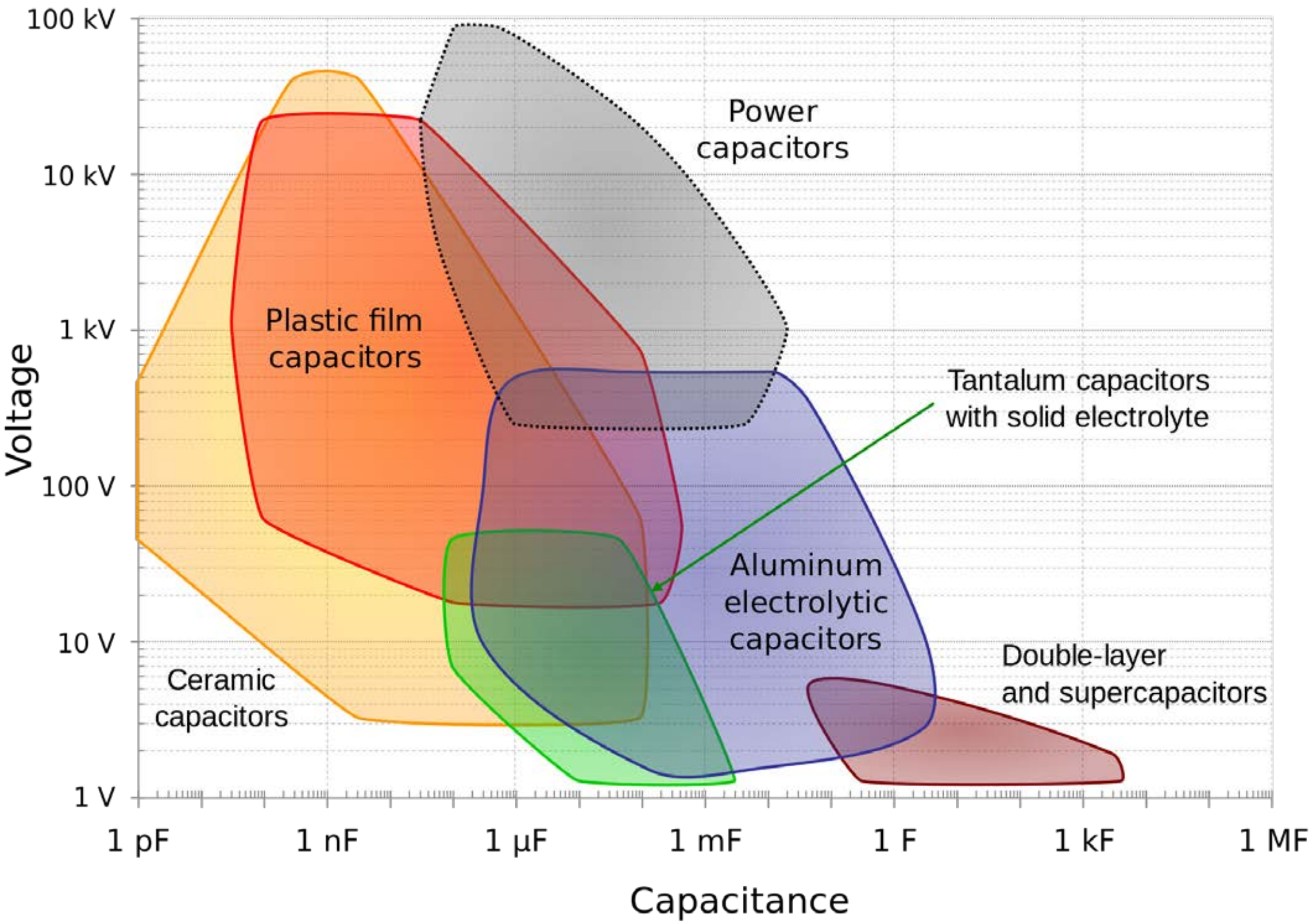
► Capacitor Dielectrics



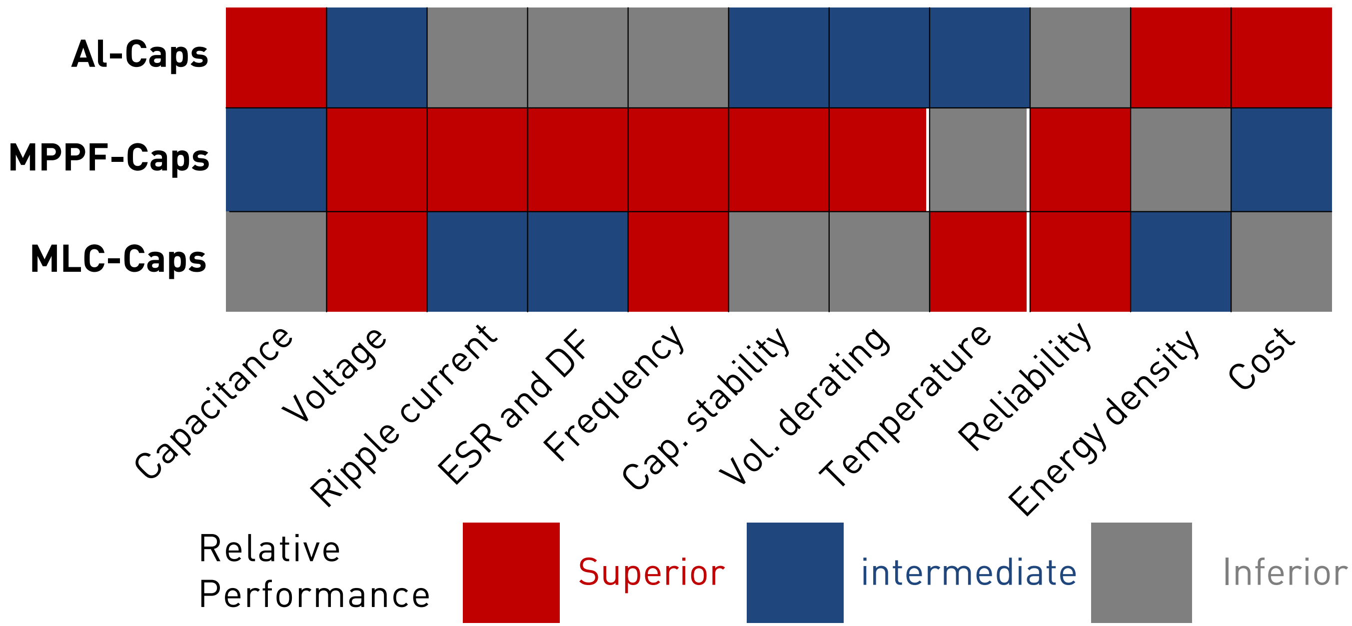
Energy storage density for various dielectrics (M. Marz, CIPS 2010).

[1)] Al electrolytic capacitors lose about one order of magnitude in energy storage density in the winding construction, due to the overhead necessary to achieve the self-healing property.

▶ Typical Capacitor Voltage and Capacitance



► Comparison of 3 Types of Capacitors (Typical)

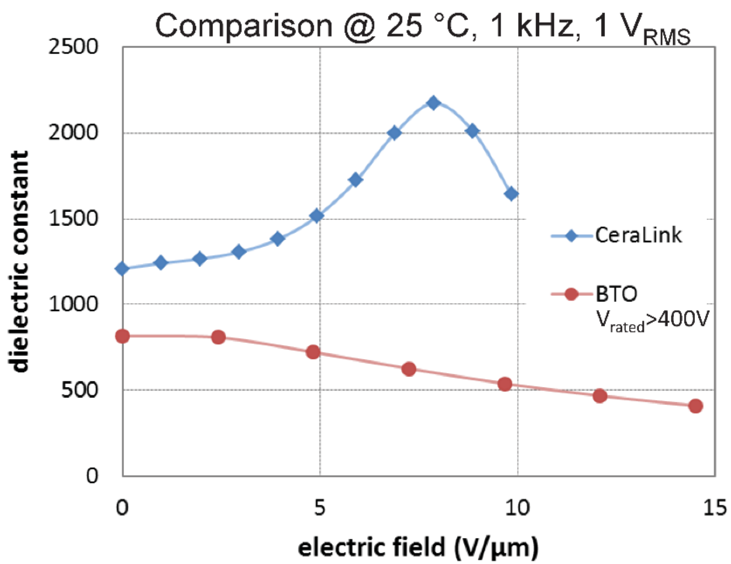


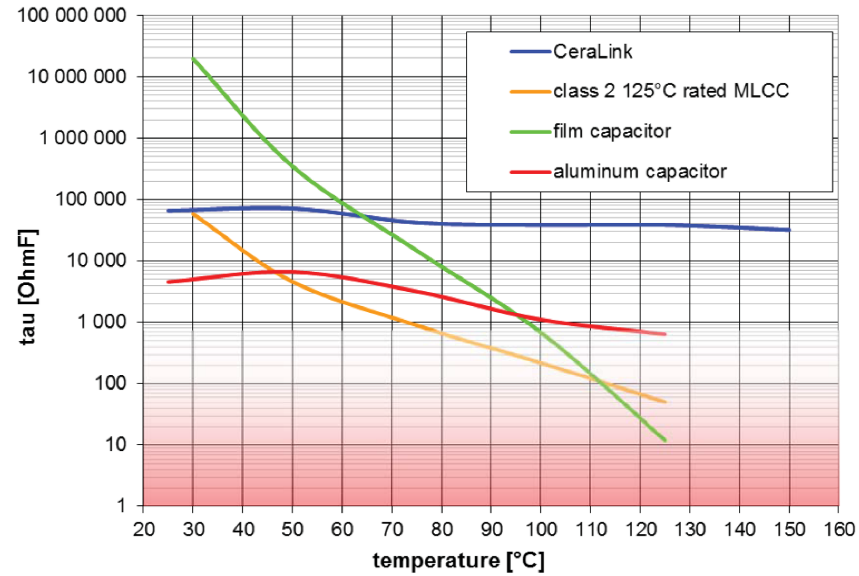
Al-Caps Aluminum Electrolytic Capacitors
MPPF-Caps Metallized Polypropylene Film Capacitors
MLC-Caps Multilayer Ceramic Capacitors

Performance comparisons of the 3 types of capacitors

► CeraLink Ceramic Capacitors

(Source: Juergen Konrad, TDK-EPCOS)

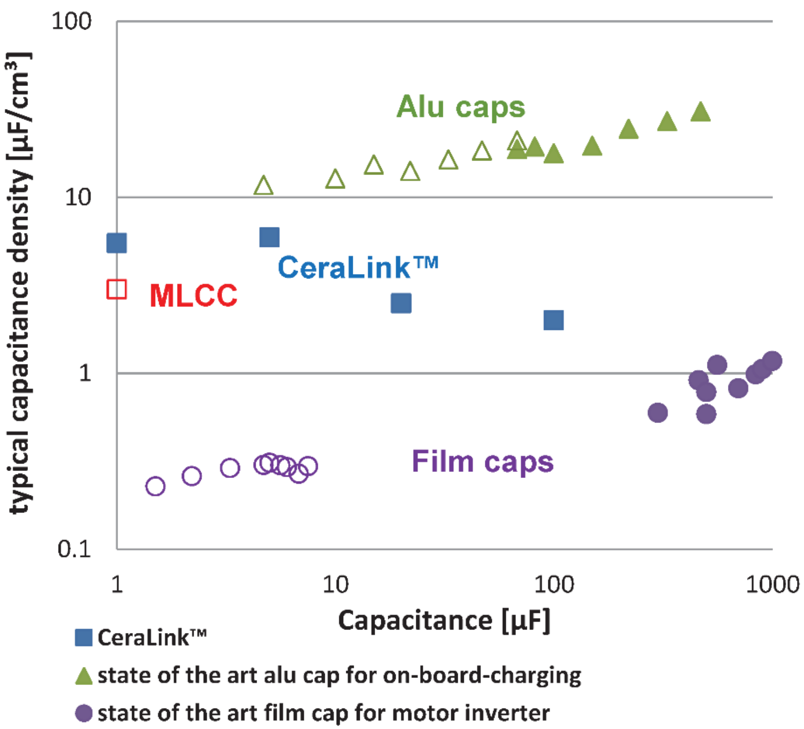




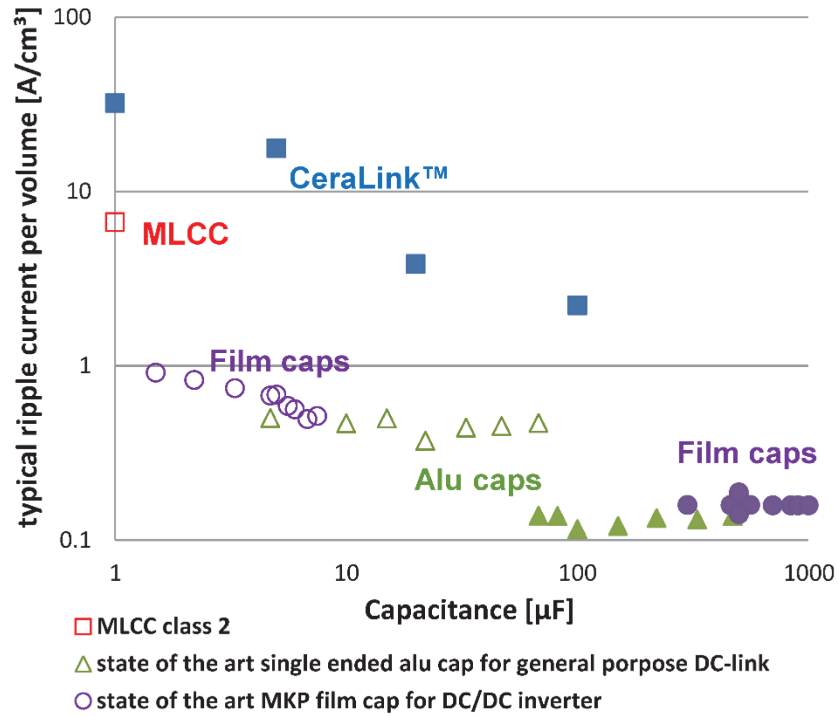
- **Anti-ferroelectric ceramics** of modified Pb La (Zr, Ti) O3
- Copper inner electrodes
- **High-temperature stable** ceramic-metal interconnects based on sintered silver to realize capacitance values up to 100 µF

▶ CeraLink Ceramic Capacitors

(Source: Juergen Konrad, TDK-EPCOS)



µF/cm³

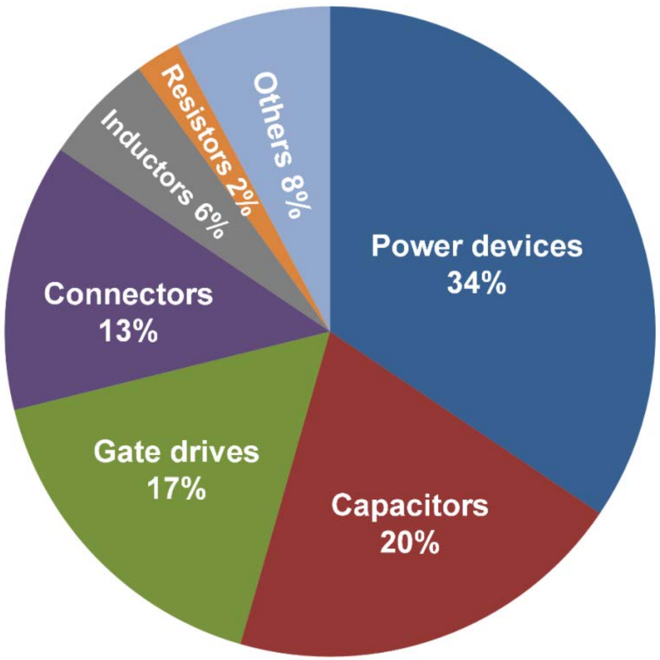


A/cm³

2 Reliability of Capacitors

- Failure modes, failure mechanisms, and critical stressors of capacitors
- Mission profile based electro-thermal stress analysis
- Degradation testing of capacitors
- Condition monitoring of capacitors

► Reliability Critical Components



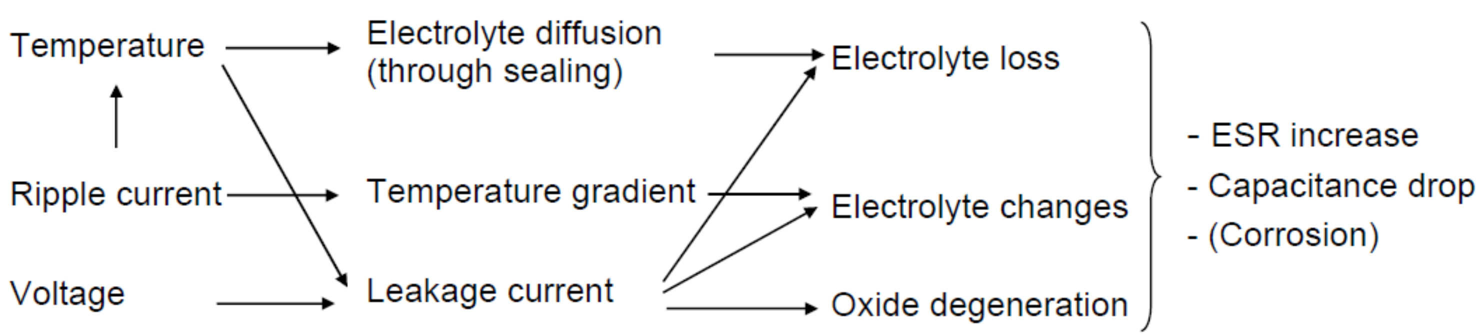
Percentage of the response to the most frangible components in power electronic systems from an industry survey (% may vary for different applications and designs)

Data sources: S. Yang, A. Bryant, P. Mawby, D. Xiang, R. Li, and P. Tavner, "An Industry-Based Survey of Reliability in Power Electronic Converters," IEEE Transactions on Industry Applications, vol. 47, pp. 1441-1451, 2011.

▶ 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 /shock
	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



► Failure Modes, Mechanisms, and Stressors

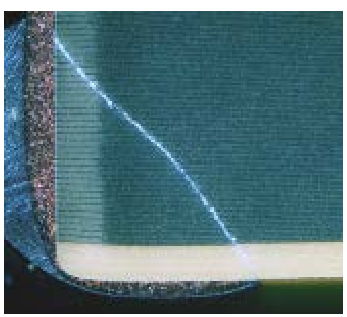
Metallized Polypropylene Film Capacitors (MPPF-Caps)

	Failure modes	Critical failure mechanisms	Critical stressors
MPPF-Caps	Open circuit (typical)	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

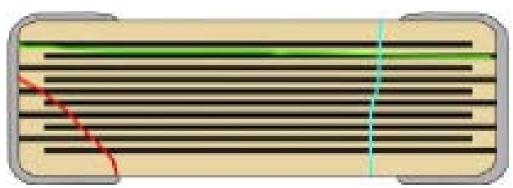
► Failure Modes, Mechanisms, and Stressors

Multilayer Ceramic Capacitors (MLC-Caps)

	Failure modes	Critical failure mechanisms	Critical stressors
MLC-Caps	Short circuit (typical)	Dielectric breakdown	V_C, T_a, i_C
		Cracking; damage to capacitor body	Vibration /shock
	Wearout: electrical parameter drift (C, ESR, tanδ, I_{LC}, R_p)	Oxide vacancy migration; dielectric puncture; insulation degradation; micro-crack within ceramic	V_C, T_a, i_C, vibration /shock



Typical flex crack of MLC-Caps (Source: Kemet)



Red crack represents flex crack; green crack represents typical thermal shock crack; blue crack represents mechanical damage. (Source: Kemet)

▶ Failure Modes, Mechanisms, and Stressors

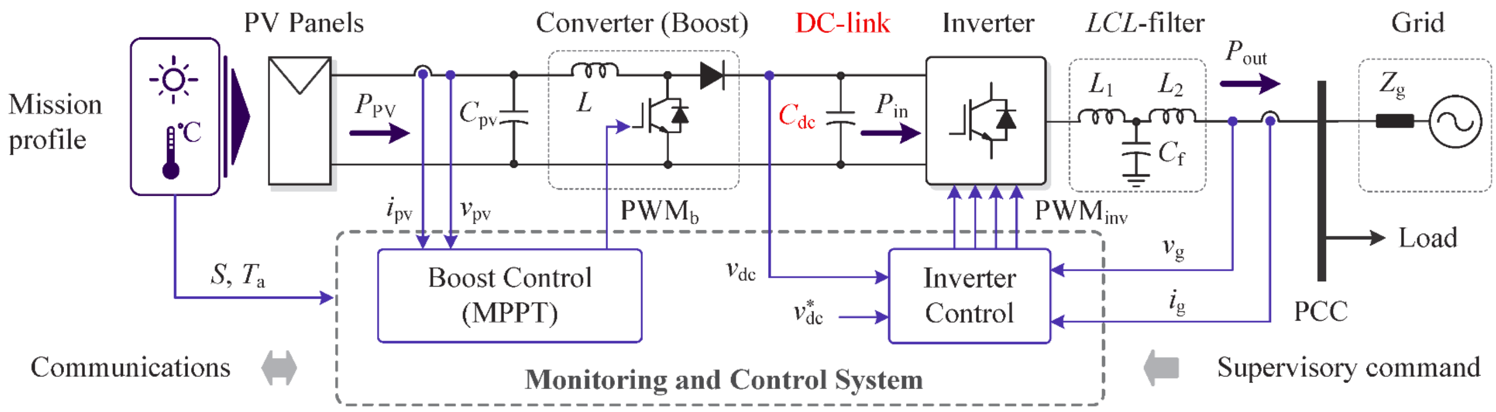
Summary

	Al-Caps	MPPF-Caps	MLCC-Caps
Dominant failure modes	wear out		
	open circuit	open circuit	short circuit
Most critical stressors	T_a, V_C, i_C	T_a, V_C, humidity	T_a, V_C, vibration/shock
Self-healing capability	moderate	good	no

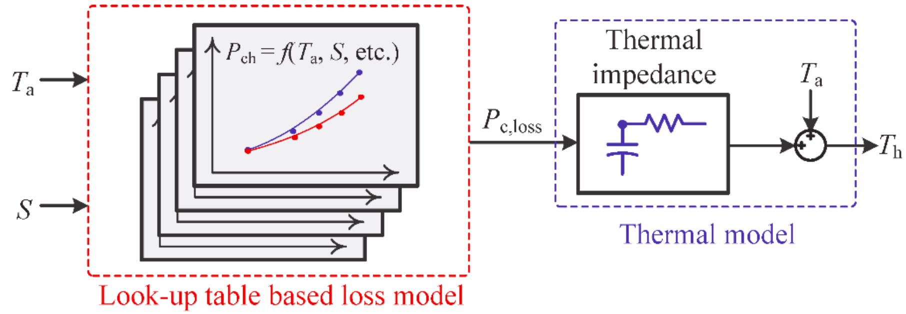
Al-Caps Aluminium Electrolytic Capacitors
MPPF-Caps Metallized Polypropylene Film Capacitors
MLC-Caps Multilayer Ceramic Capacitors

▶ Mission Profile based Electro-Thermal Modeling

An example of 3 kW single-phase PV inverter application



A grid-connected PV system with a 3 kW single-phase PV inverter



A method for long-term electro-thermal stress modeling

► Mission Profile based Electro-Thermal Modeling

An example of 3 kW single-phase PV inverter application - Specifications

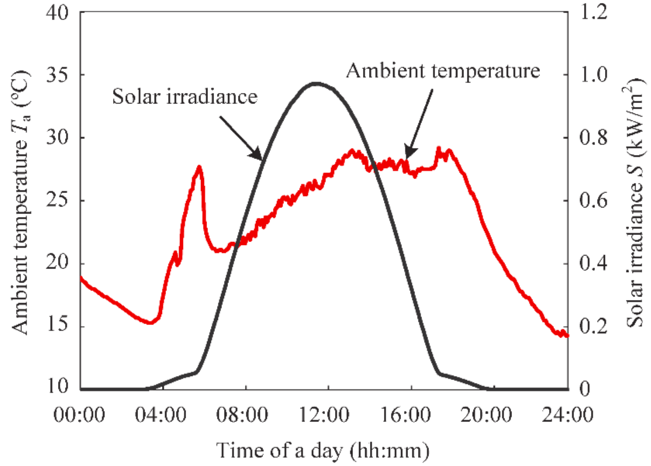
PV inverter specifications

Parameter	Value
Power rating*	$P_n = 3$ kW
Boost converter inductor	$L = 1$ mH
PV side capacitor	$C_{pv} = 220\ \mu$F
	$L_1 = 2$ mH
LCL-filter	$L_2 = 3$ mH
	$C_f = 4.7\ \mu$F
Damping resistor of *LCL*-filter	$R_d = 10\ \Omega$
Switching frequencies	$f_b = f_{inv} = 10$ kHz
Sampling frequency	$f_s = 10$ kHz
MPPT sampling frequency	$f_{mpp} = 400$ Hz
Grid voltage amplitude	$V_{gm} = 230 \times \sqrt{2}$ V
Grid frequency	$\omega_0 = 2\pi \times 50$ rad/s

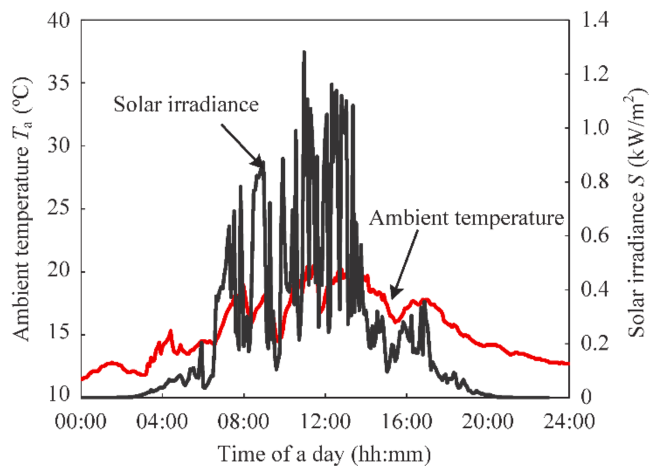
*Installed PV capacity at 1000 W/m^2, 25 °C

DC-link capacitor parameters

Parameter	Value
Rated capacitance	2200 μF
Rated voltage	385 V
Maximum ESR at 20 °C, 100 Hz	38 mΩ
Thermal resistance	2.3 °C/W



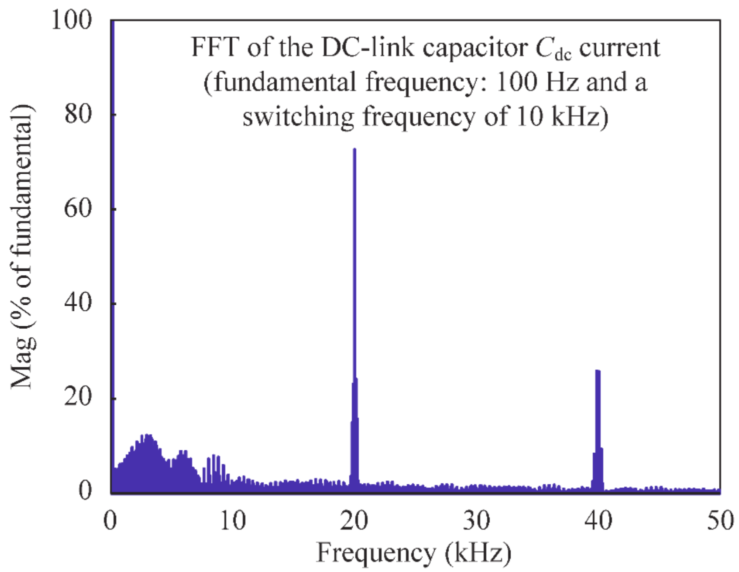
A clear day



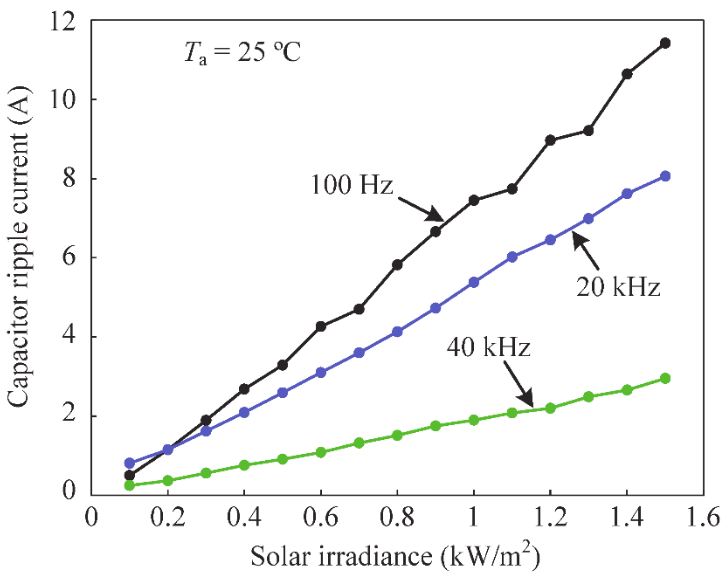
A cloudy day

► Mission Profile based Electro-Thermal Modeling

An example of 3 kW single-phase PV inverter application – Ripple Current



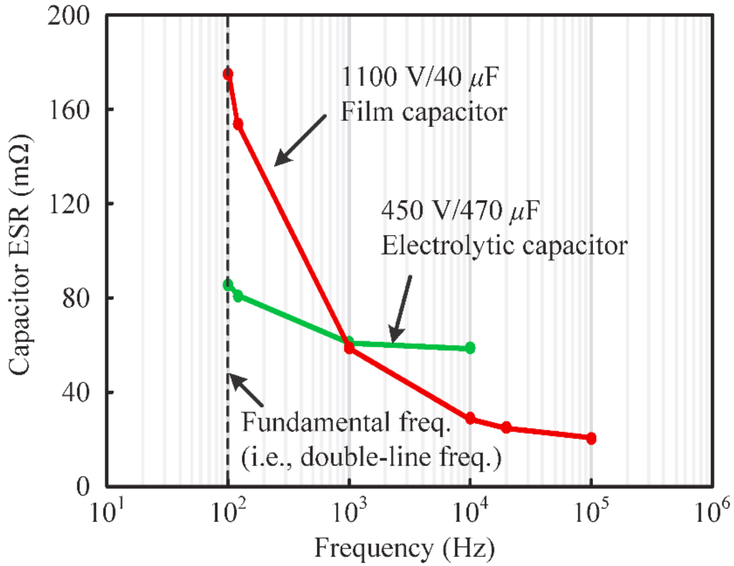
An example of ripple current harmonic spectrum at rated power and 25°C (FFT - Fast Fourier Transform)



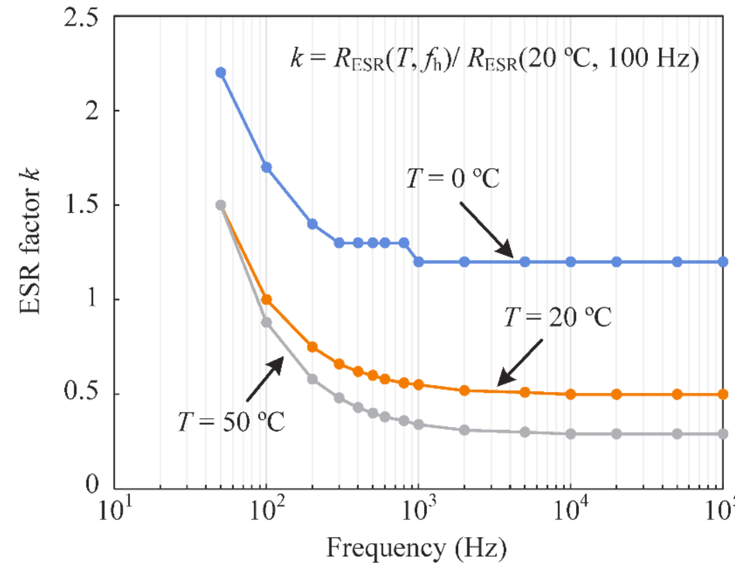
Capacitor ripple currents under different solar irradiance levels, at 25°C

▶ Mission Profile based Electro-Thermal Modeling

An example of 3 kW single-phase PV inverter application – ESR



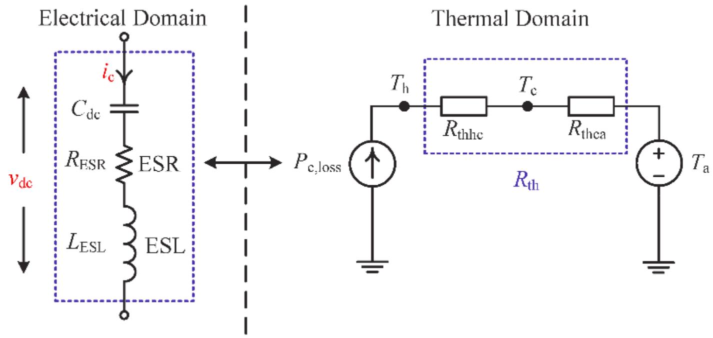
Frequency dependency of the DC-link capacitor equivalent series resistor (ESR), where Ta = 25°C.



Equivalent series resistance (ESR) frequency-dependency under different testing temperatures.

▶ Mission Profile based Electro-Thermal Modeling

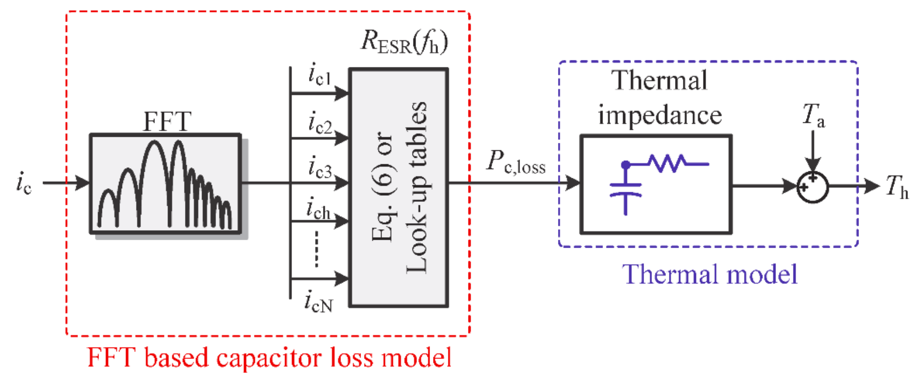
An example of 3 kW single-phase PV inverter application – electro-thermal



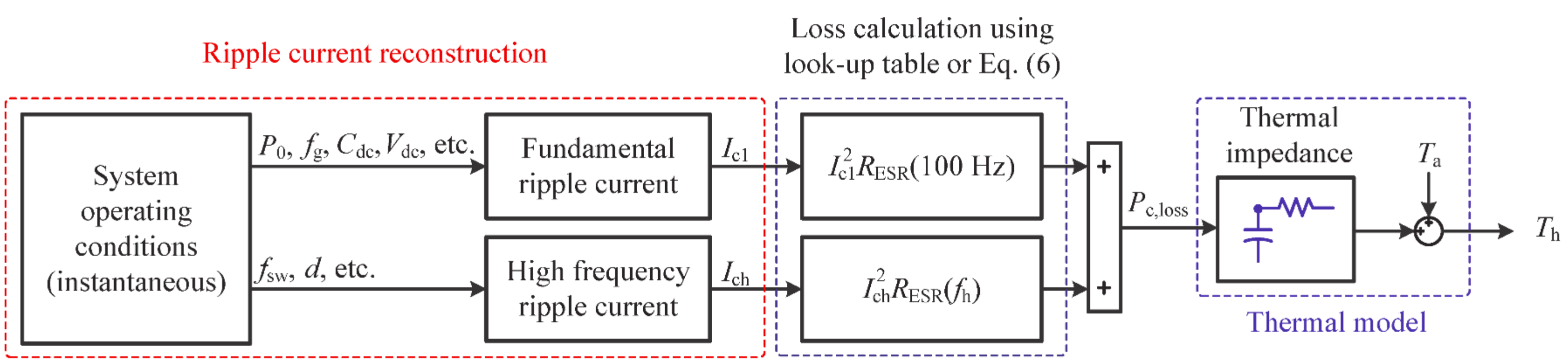
Notes: R_{thhc} – thermal resistance from hot-spot to case
R_{thca} – thermal resistance from case to ambient
T_h – hot-spot temperature
T_c – case temperature
T_a – ambient temperature

Simplified thermal model of a capacitor

Eq.(6) $R_{ESR}(f_h) = R_{ESR}(100\ \text{Hz})\left\{1 - A \cdot e^{\left(-\frac{\beta}{f_h - 100}\right)}\right\}$



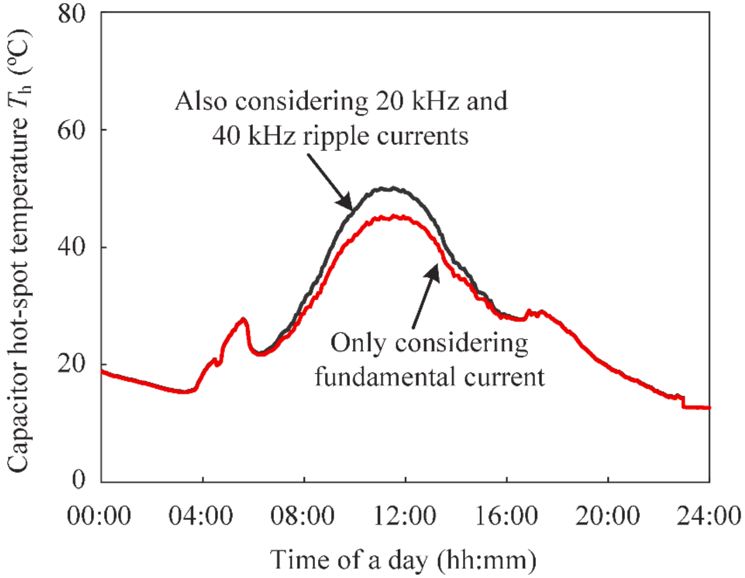
Fast Fourier transform (FFT) based instantaneous thermal modelling of the DC-link capacitor



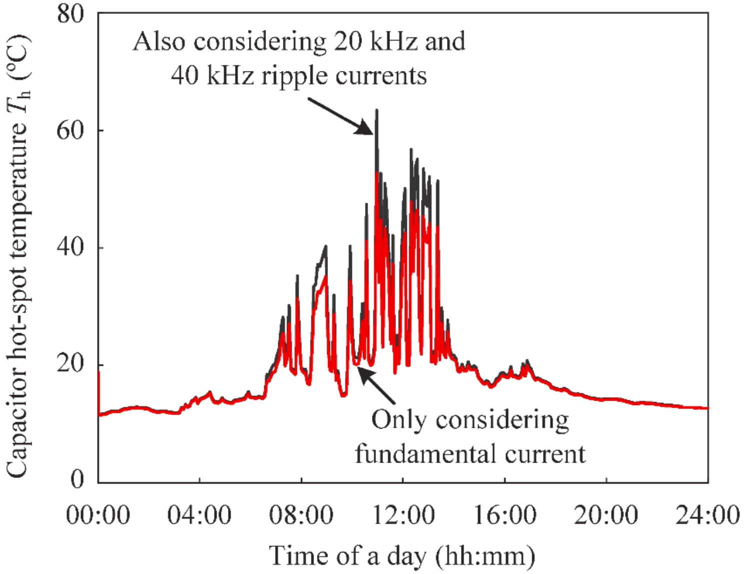
Thermal modelling for the DC-link capacitors based on the ripple current reconstruction method

► Mission Profile based Electro-Thermal Modeling

An example of 3 kW single-phase PV inverter application – thermal stresses



DC-link capacitor hot-spot thermal stress in a clear day



DC-link capacitor hot-spot thermal stress in a cloudy day

► A Widely Used Lifetime Model for Capacitors

$$L_x = L_0 \times \left(\frac{V_x}{V_0}\right)^{-n} \times exp\left[\left(\frac{E_a}{K_B}\right)\left(\frac{1}{T_x} - \frac{1}{T_0}\right)\right]$$

MLC-Caps

Typically E_a = 1.3 to 1.5, and n = 1.5 to 7 (the large discrepancies are attributed to the ceramic materials, dielectric layer thickness, etc.)

Al-Caps and MPPF-Caps

A simplified model derived from the above equation (with special case of E_a = 0.94 eV)

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

a simplified model derived from the above equation (E_a = 0.94 eV)

Typically n = 1 to 5 for Al-Caps and n = 3.5 to 9.4 for MPPF-Caps

L_x – expected operating lifetime; L_0 – expected lifetime for full rated voltage and temperature; V_x – actual applied voltage; V_o – rated voltage; T_0 – maximum rated ambient temperature; T_x – actual ambient temperature; E_a is the activation energy, K_B is Boltzmann's constant (8.62×10–5 eV/K)

▶ Lifetime Models from Manufacturers

Manufacturer 1

$$L_x = L_0 \times \left(4.3 - 3.3\frac{V_x}{V_0}\right) \times 2^{\frac{T_m - T_x}{10}}$$

Manufacturer 2

$$L_x = L_0 \times \left(\frac{V_x}{V_0}\right)^{-4.4} \times 2^{\frac{T_0 - T_x}{10}} \times 2^{\frac{\Delta T_0 - \Delta T_x}{K}}$$

$\Delta T_x \leqslant 25°\mathrm{C}, K = 10;\ 25°\mathrm{C} < \Delta T_x < 45°\mathrm{C}, K = 10\ (\geq 300\mathrm{Hz}), K = 5\ (\geqslant 120\mathrm{Hz}, < 300\mathrm{Hz})$

$\Delta T_x > 45°\mathrm{C}, K = 10\ (> 1000\mathrm{Hz}),\ K = 7\ (\geq 300\mathrm{Hz}, < 1000\mathrm{Hz}), K = 5\ (\geq 120\mathrm{Hz}, < 300\mathrm{Hz})$

Manufacturer 3

$$L_x = L_0 \times 2^{\frac{T_0 - T_x}{10}} \times 2^{\frac{\Delta T_0 - \Delta T_x}{K}}$$

$K = 10$ (below rated ripple current); $K = 5$ (above rated ripple current)

...

Manufacturer N

Observations

- **Limited to electrical and thermal stresses**
- **Other critical stressors, like humidity and mechanical stress are missed**

L_x – expected operating lifetime; L_0 – expected lifetime for full rated voltage and temperature; V_x – actual applied voltage; V_o – rated voltage; T_m – Maximum permitted internal operating temperature; T_0 – maximum rated ambient temperature; ΔT_0 – rated ripple heat generation at T_0; T_x – actual ambient temperature; ΔT_x – actual ripple heat generation from application.

► Capacitor Wear Out Testing System

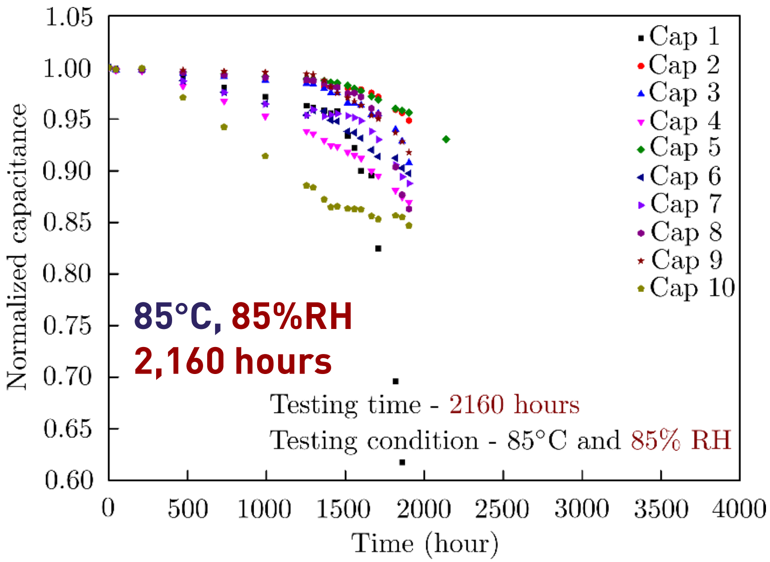
System configuration

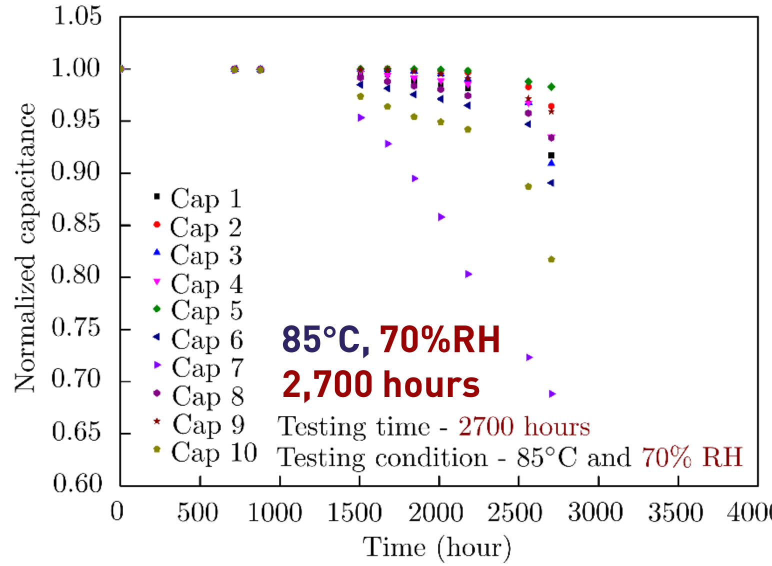
- Climatic chamber
- 2000 V (DC) / 100 A (AC) / 50 Hz to 1 kHz ripple current tester
- 2000 V (DC) / 50 A (AC) / 20 kHz to 100 kHz (discrete) ripple current tester
- 500 V (DC) / 30A (AC) / 100 Hz to 1 kHz (discrete) ripple current tester
- LCR meter
- IR / leakage current meter
- Computer

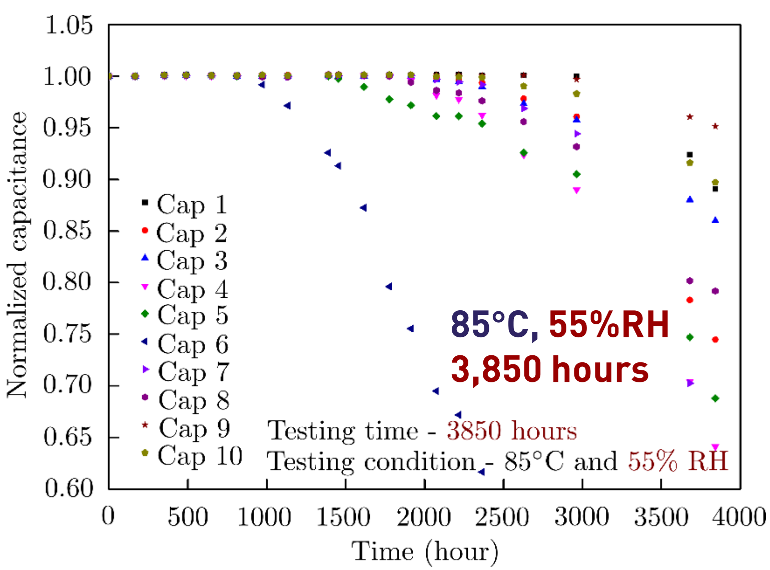
System capability

- 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

▶ Analysis Method of the Testing Data

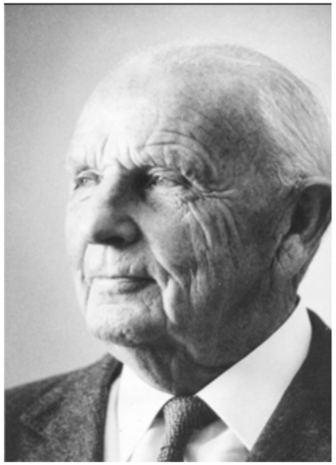
Weibull Distribution

$$f(t) = \begin{cases} \frac{\beta}{\eta^{\beta}} t^{\beta-1} \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] & (t \geq 0) \\ 0 & (t < 0) \end{cases}$$

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$$

(Two parameters)

η - Characteristics life (the time when 63.2% of items fail)
β – Shaping factor
γ – Failure free time



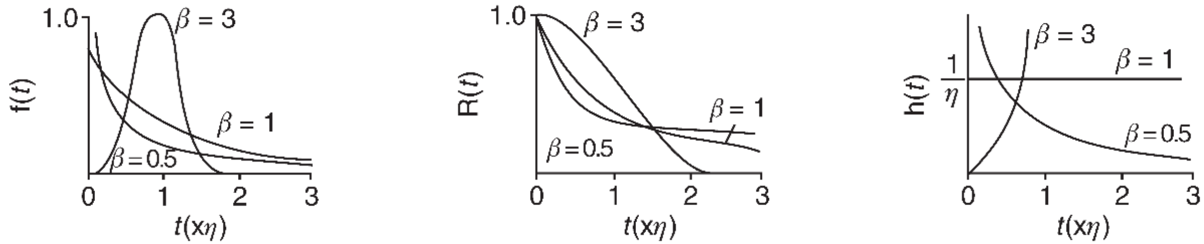
Wallodi Weibull
1887-1979
Wallodi Shown at Age 88 in 1975
Photo by Sam C. Saunders

▶ Testing Data Analysis Method

Weibull Distribution

Shape, β Scale (characteristic life), η

Location (minimum life), γ
Curves shown for $\gamma = 0$



$$f(t) = \frac{\beta}{\eta^\beta}(t-\gamma)^{\beta-1}\exp\left[\left(\frac{t-\gamma}{\eta}\right)^\beta\right]$$

$$R(t) = \exp\left[-\left(\frac{t-\gamma}{\eta}\right)^\beta\right]$$

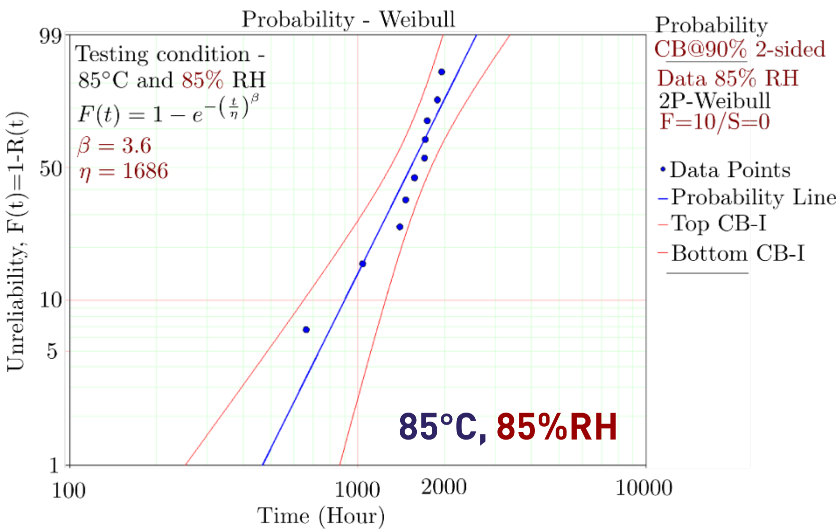
$$h(t) = \frac{\beta(t-\gamma)^{\beta-1}}{\eta^\beta}$$

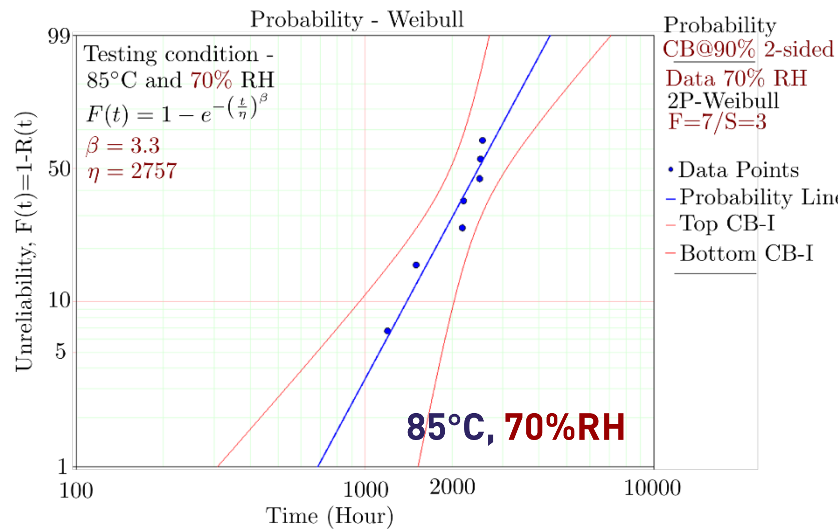
When β = 1, Weibull distribution is the exponential distribution

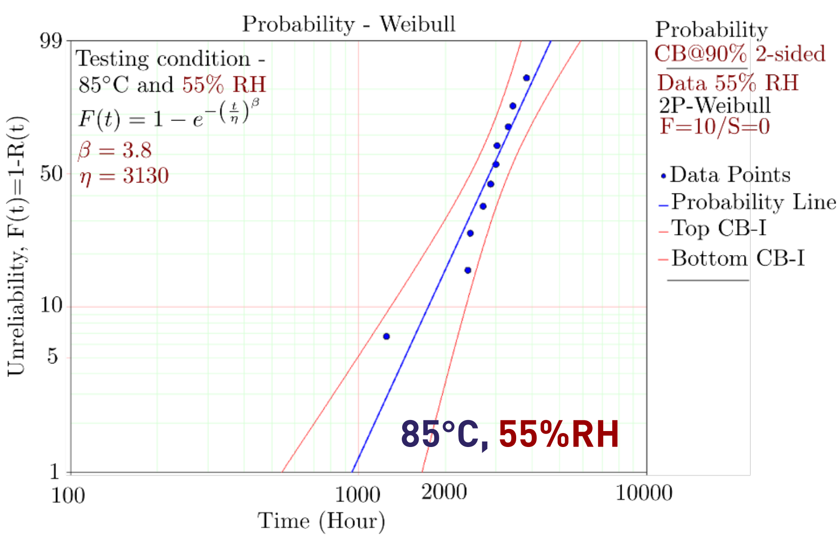
When β = 3.5, Weibull distribution approximates to normal distribution

Weibull distribution can be used to model a wide range of life distributions characteristic of engineered products

▶ Weibull Plots of the Testing Data





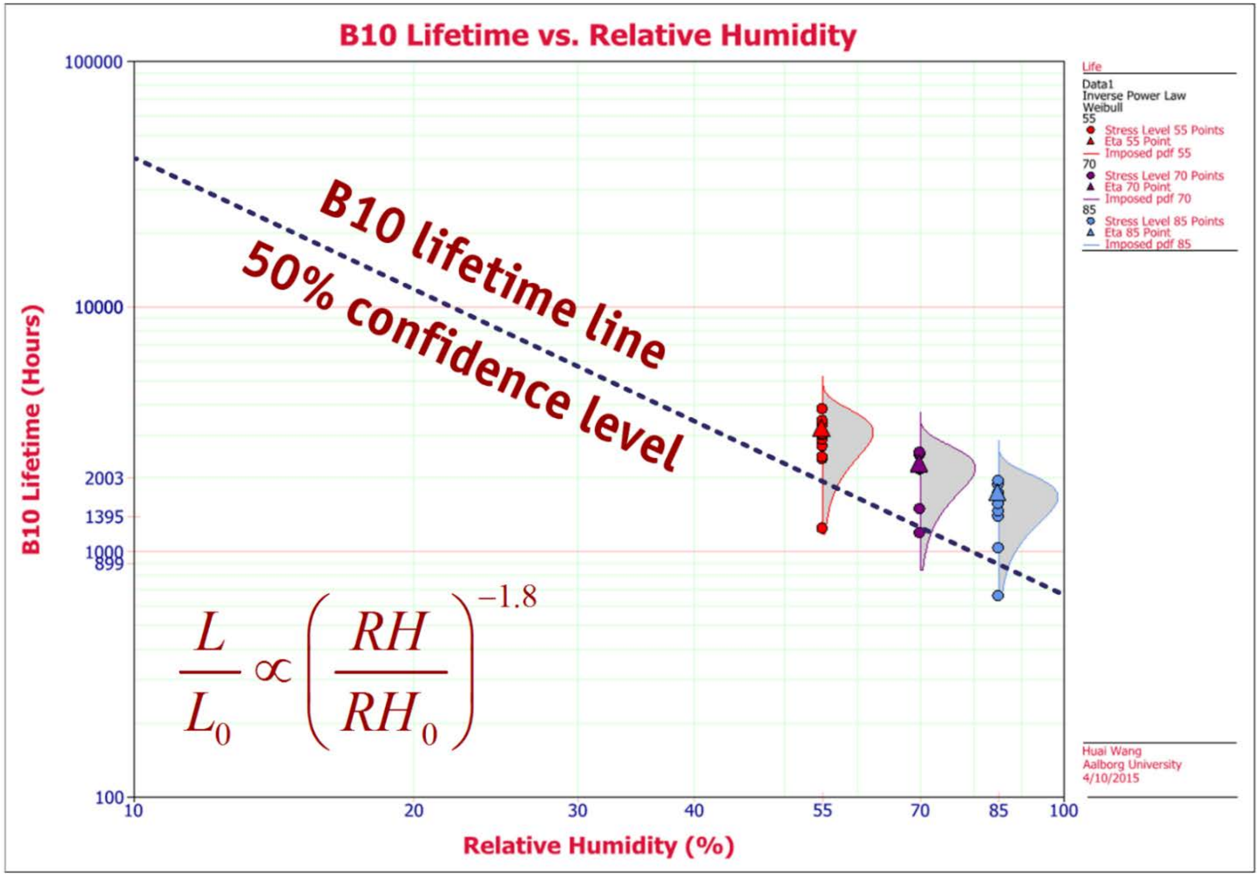


5% capacitance drop is used as the end-of-life criteria of the testing samples

Testing of 1100 V/40 μF MPPF-Caps
(Metalized Polypropylene Film)

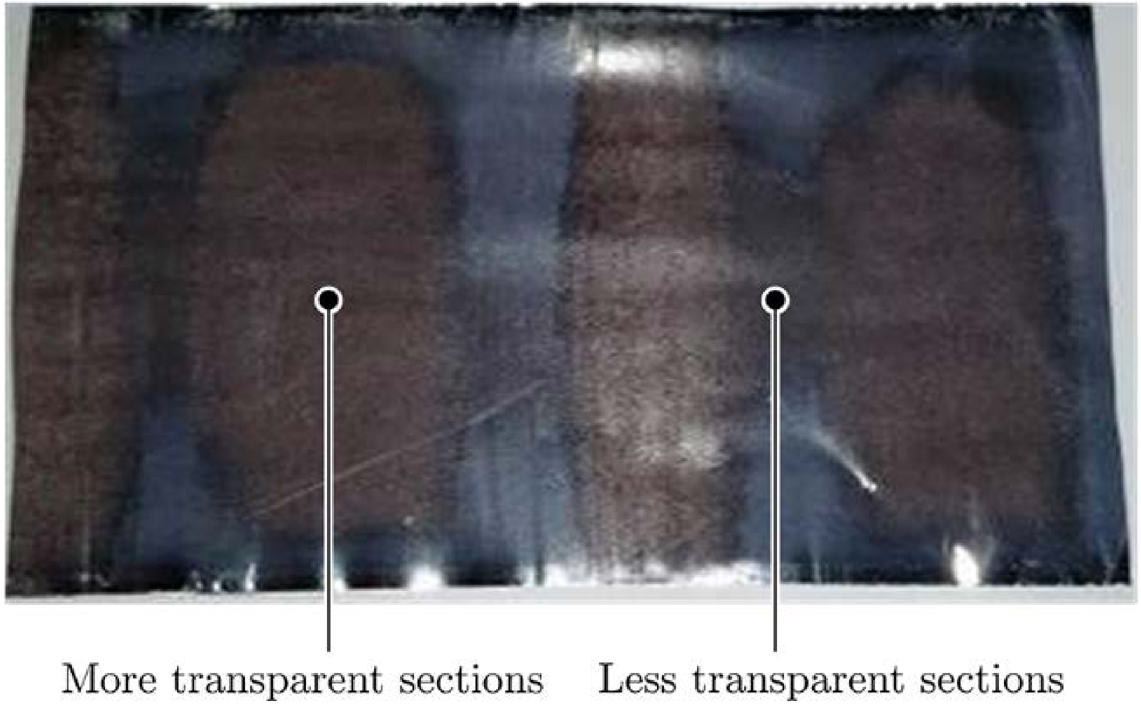
Sample size: 10 pcs for each group of testing

► Humidity-Dependent Lifetime of the MPPF-Caps



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

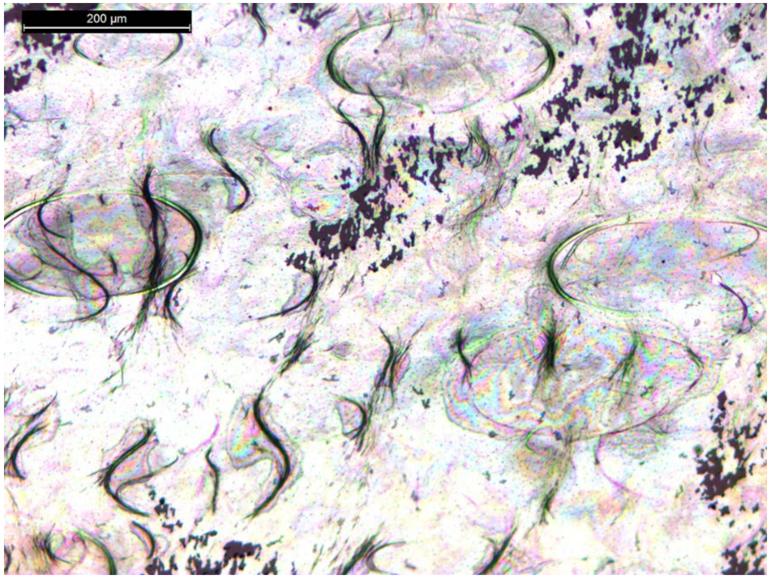
▶ Failure Analysis – Visual Inspection



Photography of the capacitor film at 25m into the capacitor roll of Cap 10 in the test Group 1.

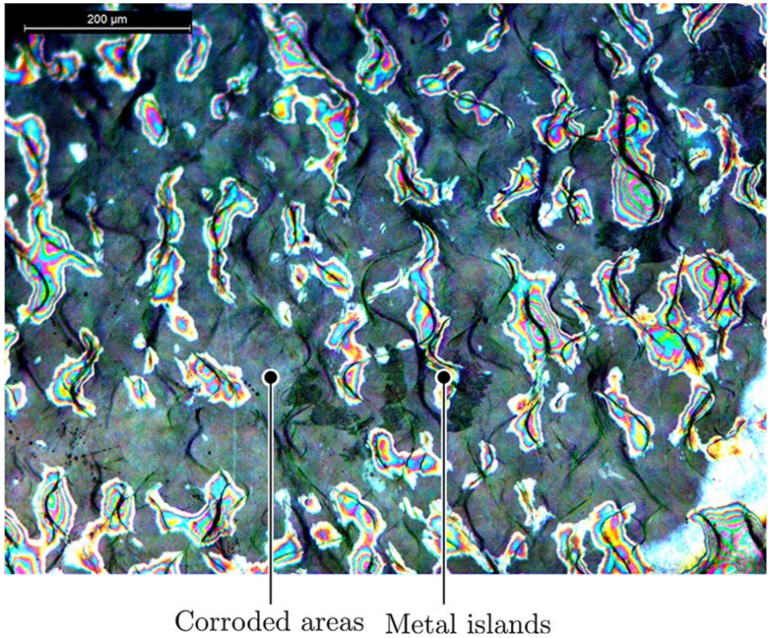
The more transparent sections indicate corrosion of the metallization layer

► Failure Analysis – Optical Microscopy Investigation



A new capacitor sample (at 1 m into the roll)

The metallization layer is fairly intact



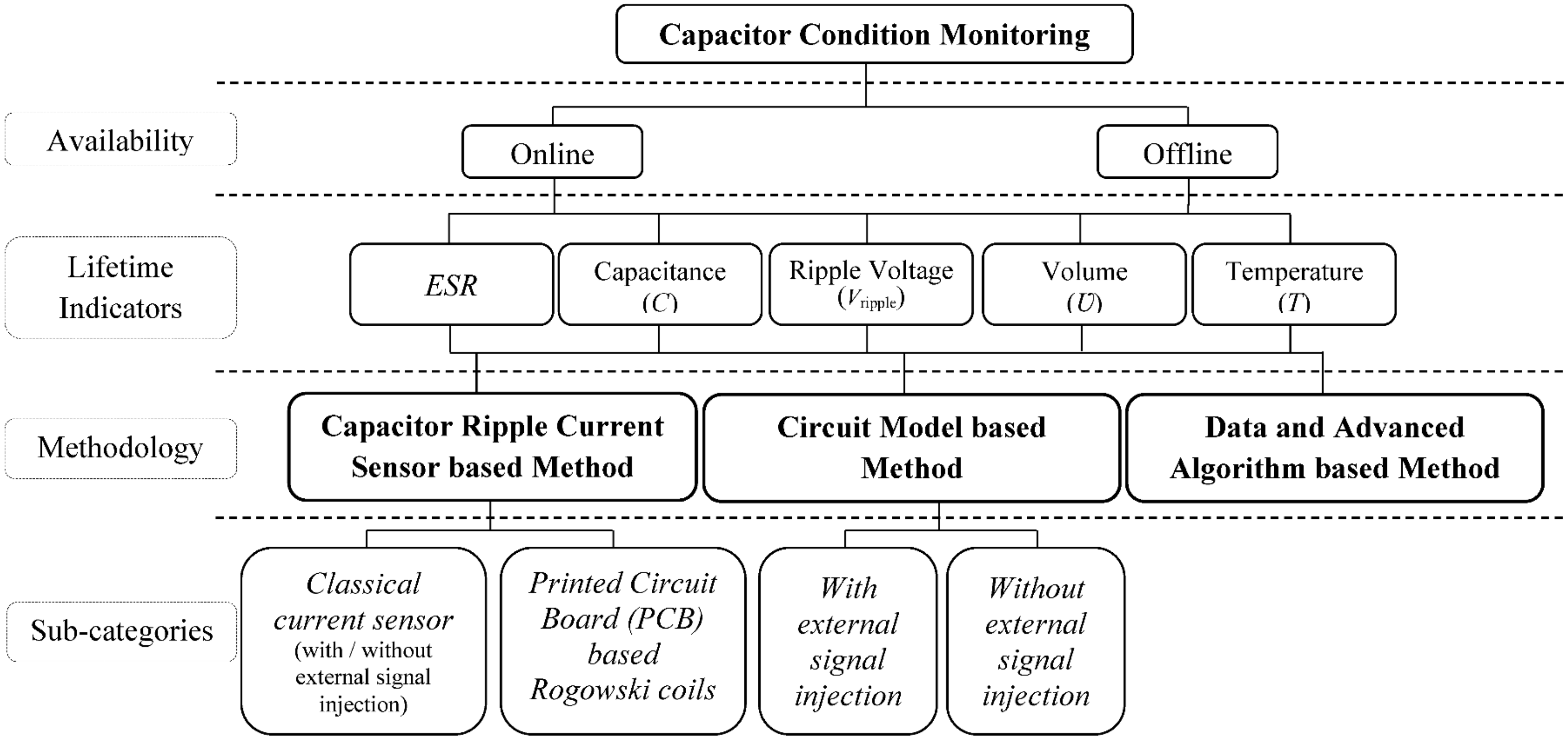
Cap 10 in Group 1 after the degradation testing (at 1 m into the roll)

Small metal islands left, the rest of the metallization layer has corroded

Microscopy images of the metallization film from a new capacitor and from a tested capacitor (the scale bars represent a distance of 200 μm).

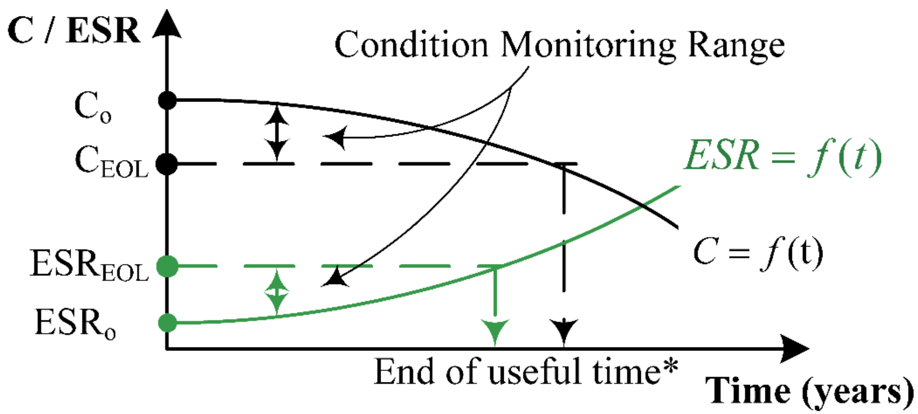
▶ Classification of Capacitor Condition Monitoring Methods

H. Soliman, H. Wang (IEEE, 2016)

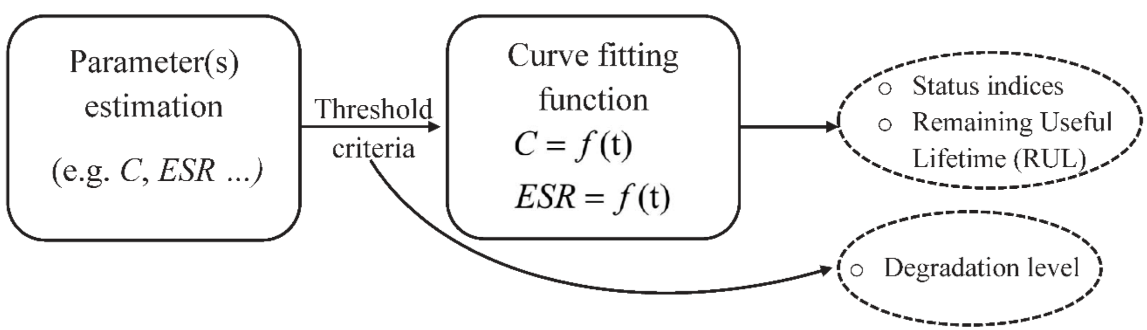


► Key Indicators for Condition Monitoring

H. Soliman, H. Wang (IEEE, 2016)

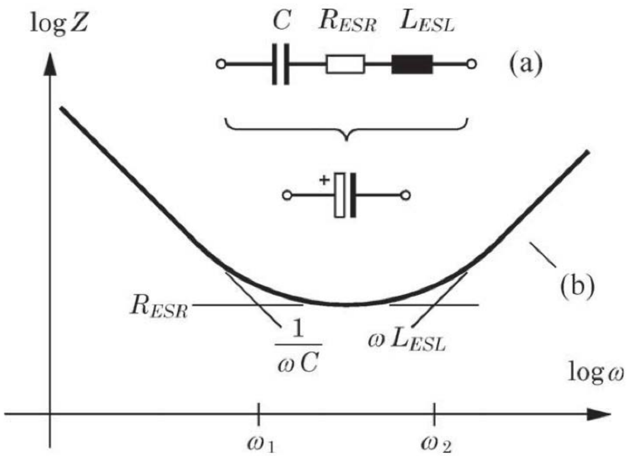


C_o = Initial capacitance. C_{EOL} = Capacitance at End-Of-Life.
ESR_o = Initial equivalent series resistance. ESR_{EOL} = equivalent series resistance at End-Of-Life.
*C_{EOL} could be larger or smaller than ESR_{EOL}, it depends on the application and the capacitor type.

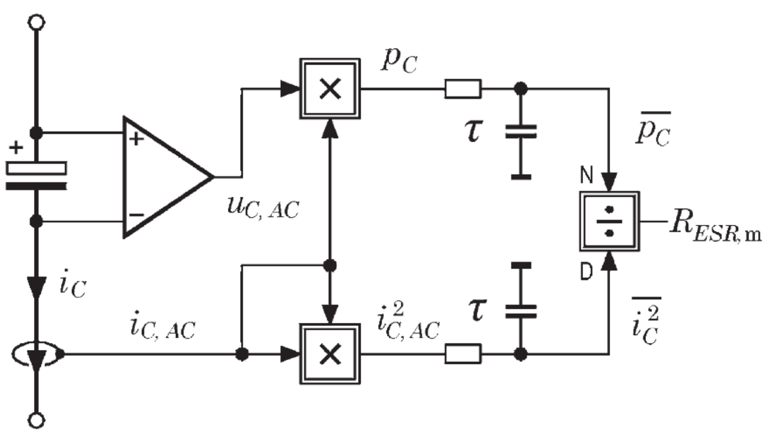


▶ Condition Monitoring of DC-Link Capacitors (Example)

M. A. Vogelsberger (IEEE, 2011)



Model and impedance characteristics of capacitors.



The principle of ESR estimation.

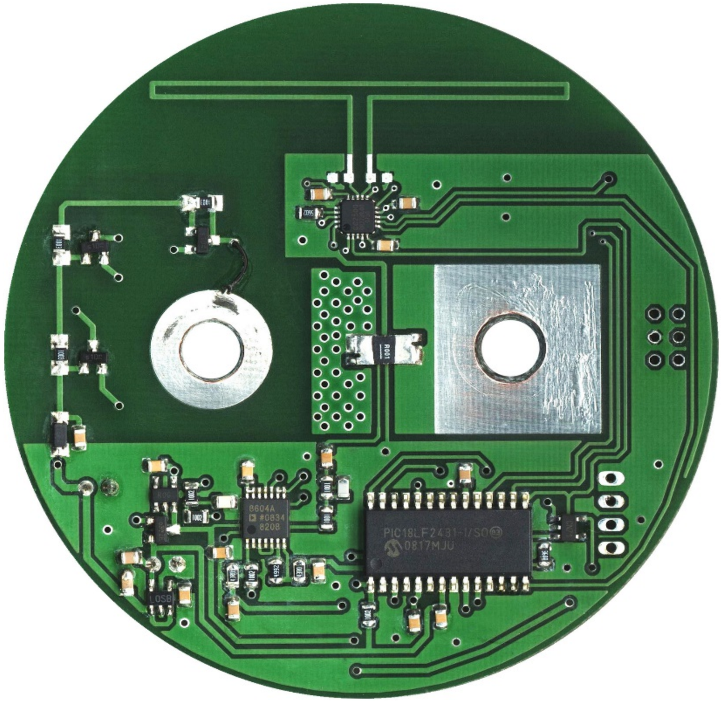
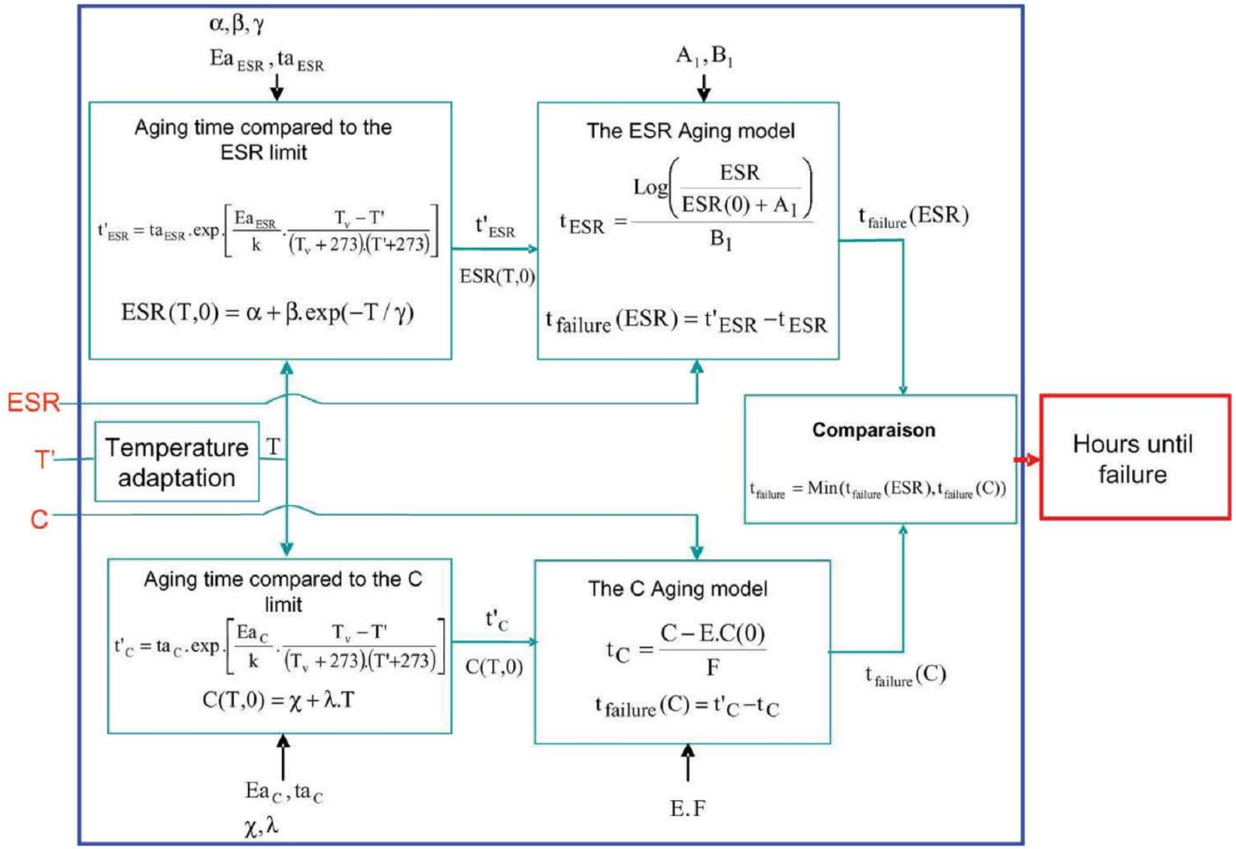


Photo of prototype for online ESR estimation of DC-link capacitors.

Based on capacitor's power loss
Temperature effect compensation
Criterion: ESR increases to double

► Remaining Lifetime Prediction of Capacitors (Example)

K. Abdennadher (IEEE, 2010)

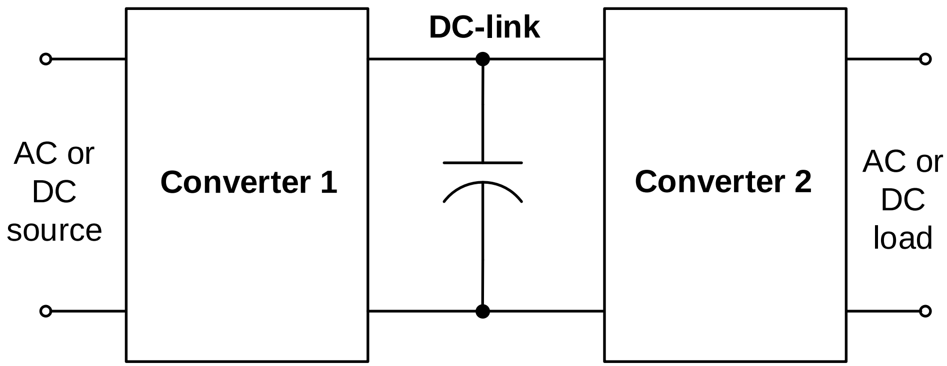


Algorithm for online remaining lifetime prediction of DC-link capacitors.

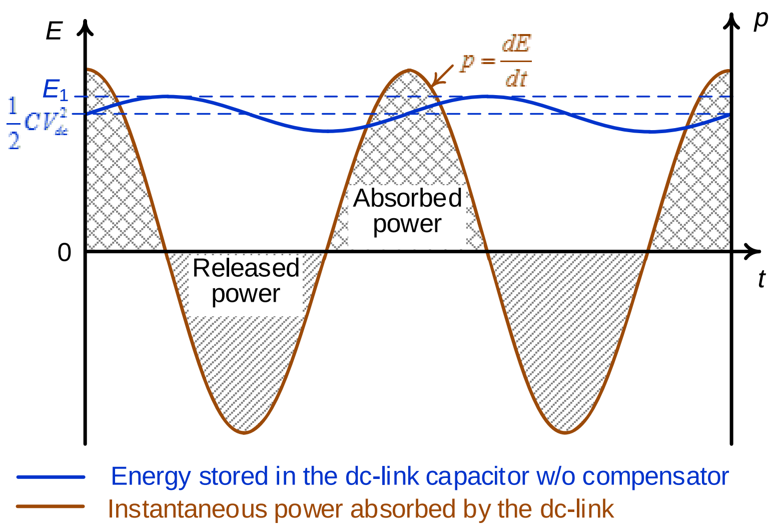
3 Design of Capacitive DC-links

- Considerations in capacitor bank configuration and design
- DC-link capacitor sizing criteria in power electronics
- Active capacitive DC-links

▶ Function of DC-Link Capacitors



Typical power electronics conversion system.



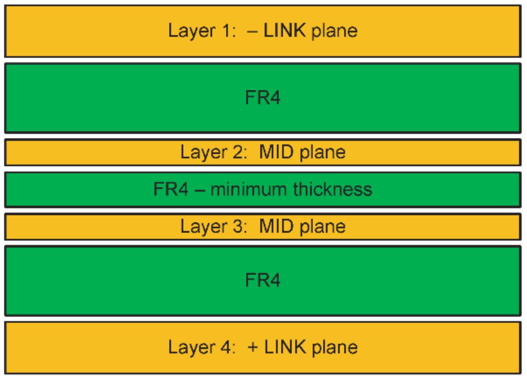
Energy storage and instantaneous power of a capacitive dc-link in a single-phase AC-DC or DC-AC system (typical).

Capacitive DC-link function

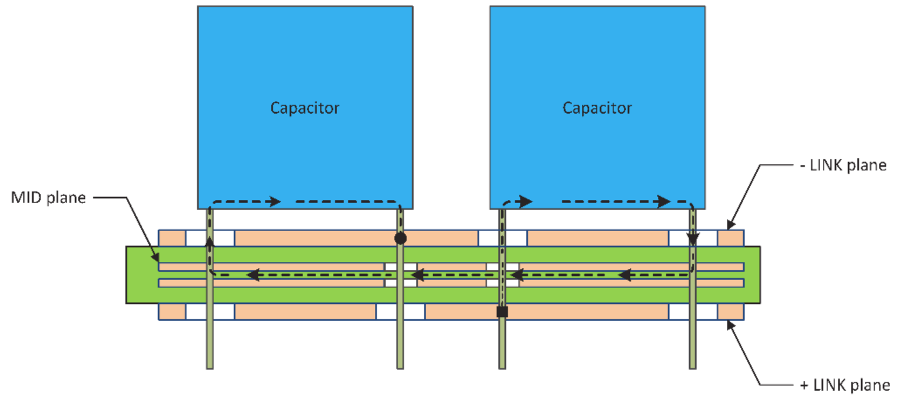
- balance power
- limit voltage ripple (both for steady-state and transient)
- energy storage

▶ Low-Inductance Capacitor Bank Design

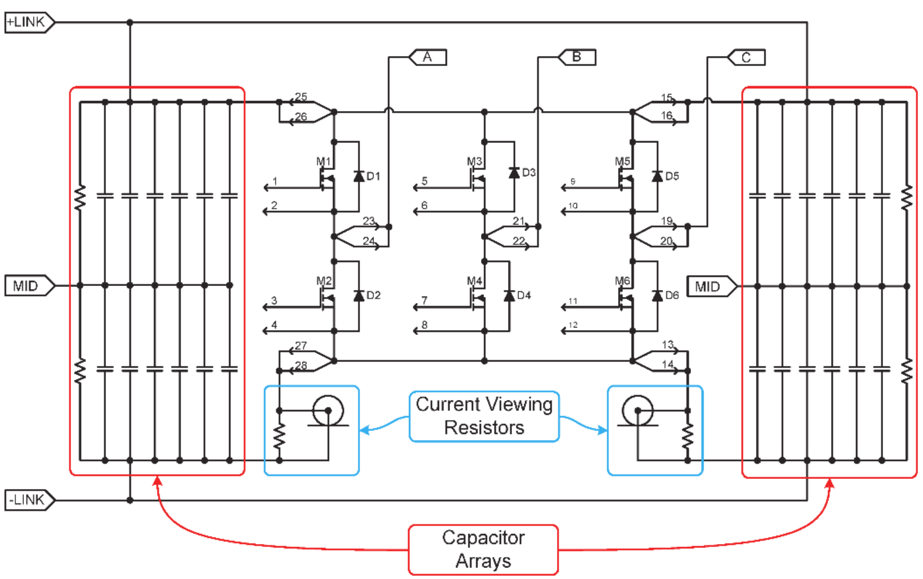
(Source: CREE application note)



Printed circuit board layers

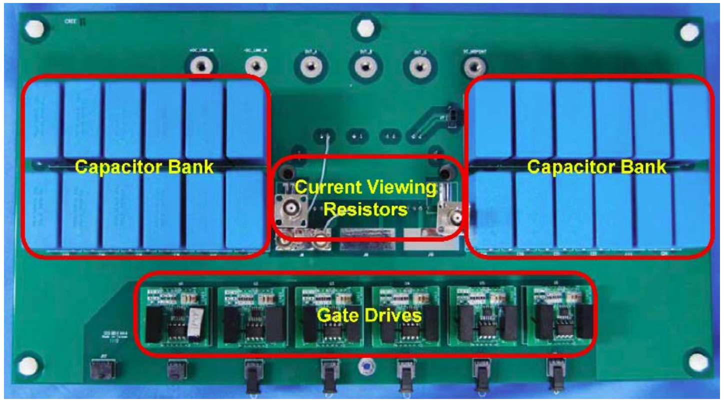


Capacitor series connection magnetic field cancellation scheme

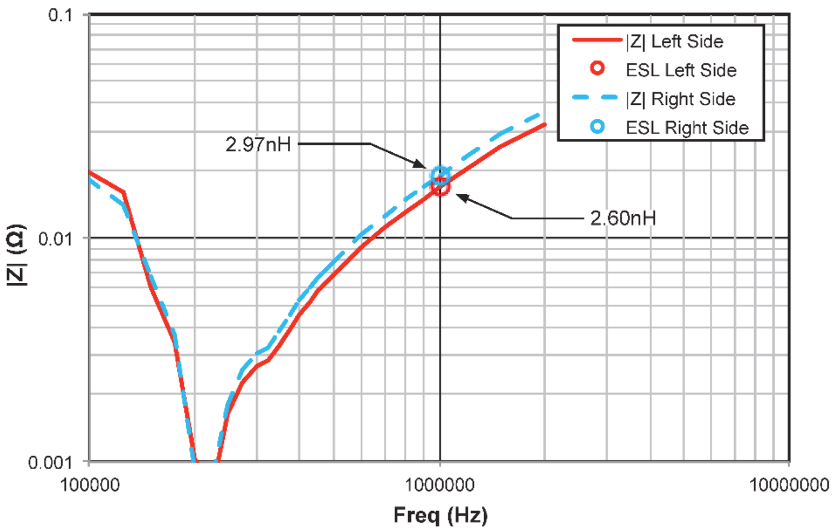


Schematic of a 3-phase inverter with a DC-link bank

▶ Low-Inductance Capacitor Bank Design
(Source: CREE application note)



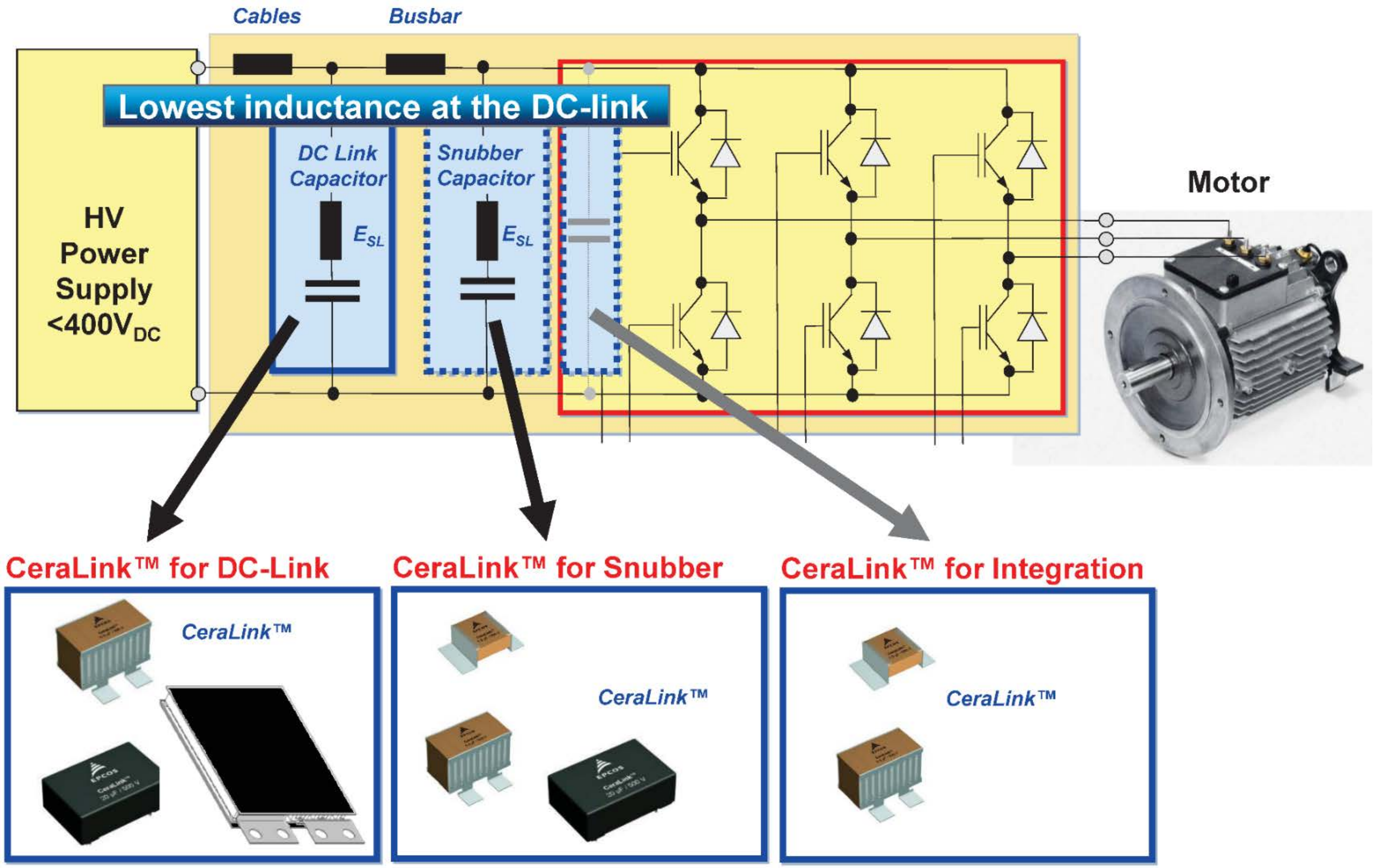
Prototype photo of a 3-phase inverter with a DC-link bank



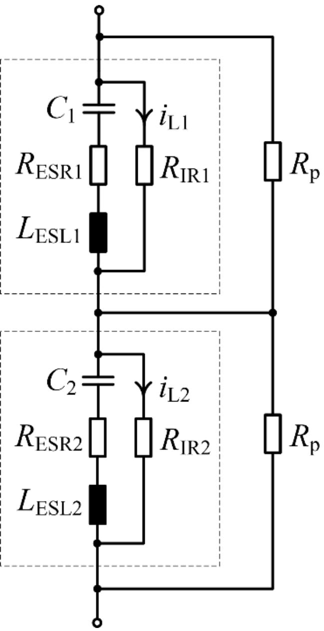
Impedance vs. frequency for each set of DC link connections and ESL differences

► Low-Inductance Capacitor Bank Design

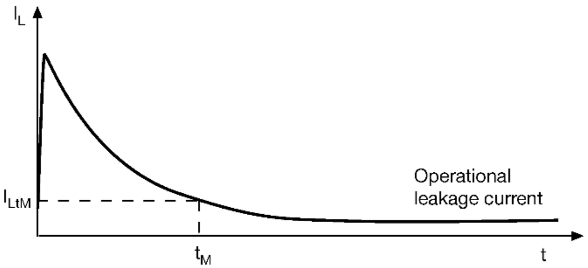
(Source: Juergen Konrad, TDK-EPCOS)



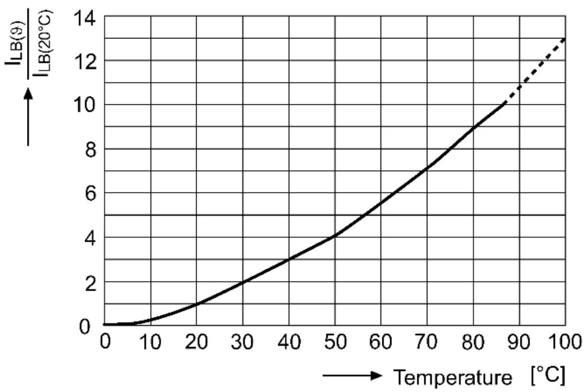
► Voltage Balancing of Series-Connected Capacitors



Simplified circuit model of two series connected capacitors
(R_p is the voltage balance resistor, R_{IR1} and R_{IR2} are insulation resistances, I_{L1} and I_{L2} are leakage currents)



Typical variation of leakage current with time (Source: Vishay)



Typical variation of leakage current with temperature (Source: Vishay)

- The R_p should be selected for the lowest insulation resistances
- Trade-off between the power losses of R_p and voltage balancing
- Active voltage balancing solutions are available, but with increased complexity.

► DC-link Capacitor Sizing Criteria

Criteria (Application-Specific)

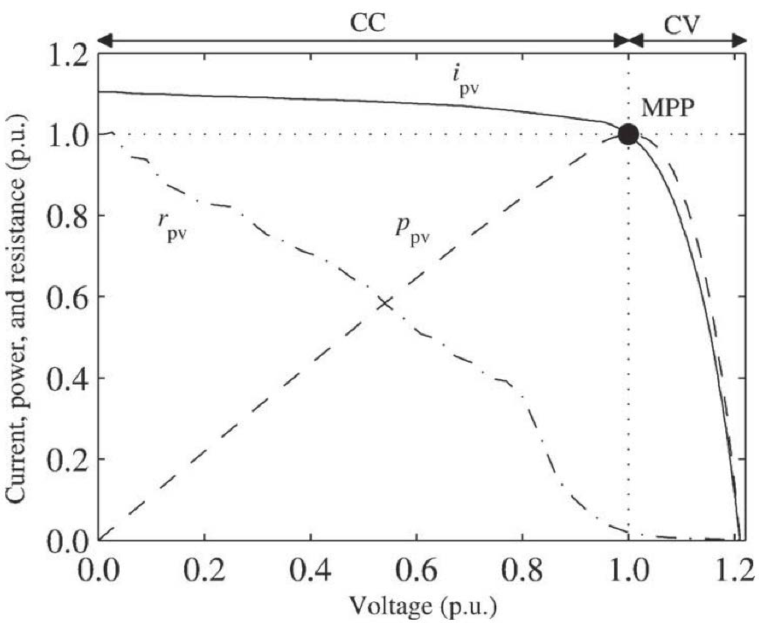
- Voltage ripple (steady-state)
- Voltage ripple (transients and abnormal operation)
- Energy storage requirement (e.g., hold-up time)
- Stability (related to control performance)
- ...

Considerations

- Temperature range
- Capacitance stability
- Frequency characteristics
- Lifetime
- End-of-life parameters and tolerances
- ...

▶ Sizing Criteria - Stability

An example of three-phase inverters in PV applications (Source: T. Messo, IEEE TPEL, 2014)

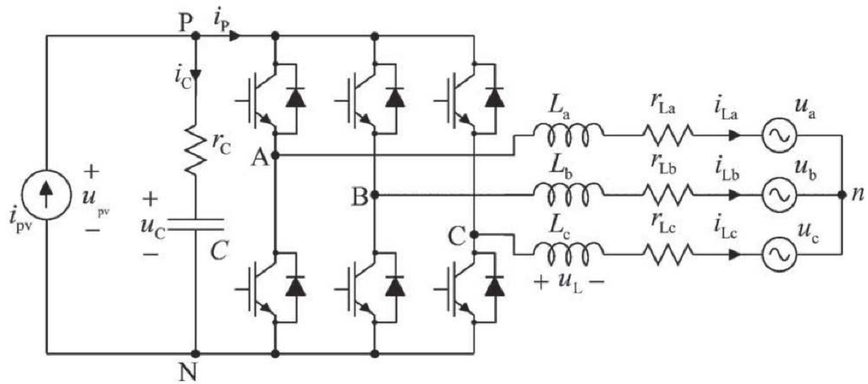


Characteristics of a PV generator

CC- Constant current region, when the dynamic resistance is higher than the static resistance
CV – Constant voltage region, when the dynamic resistance is higher than the static resistance

► Sizing Criteria - Stability

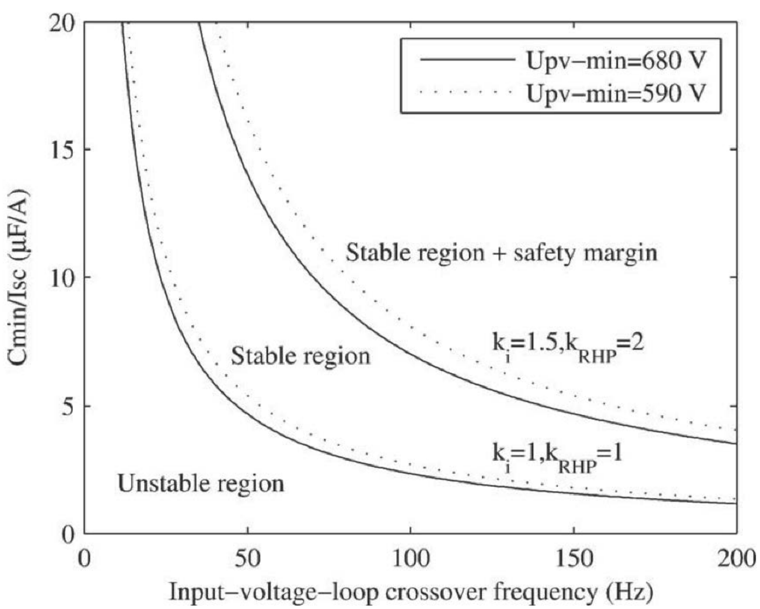
Single-stage three-phase PV inverter (Source: T. Messo, IEEE TPEL, 2014)



RHP pole in the dc-link voltage control loop

$$\omega_{RHP} = \frac{1}{C_{dc}}\left(\frac{I_{\mathrm{pv}}}{U_{\mathrm{pv}}} - \frac{1}{r_{\mathrm{pv}}}\right)$$

When in the constant current (CC) region: dynamic resistance is higher than the static resistance
RHP – Right half-plane



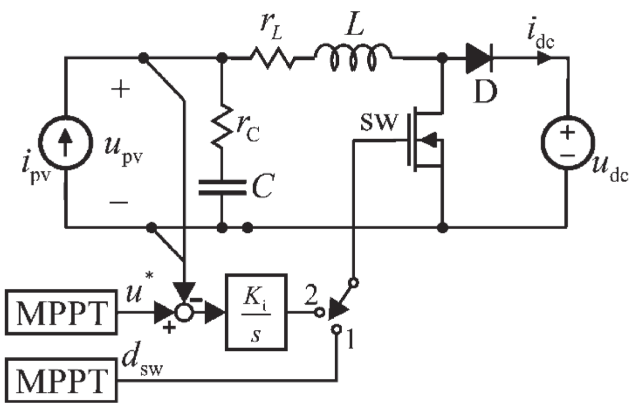
Minimum required capacitance to ensure stability:

$$C_{\min} = k_{\mathrm{RHP}}\, k_i \frac{I_{\mathrm{sc}}}{U_{\mathrm{pv\text{-}min}}\,\omega_c}$$

I_{SC} – short-circuit current of the PV generator
k_{RHP} – ratio between the crossover frequency of the dc-link voltage control loop and the RHP.
k_i – a constant to take into account the cloud enhancement

► Sizing Criteria - Stability

Two-stage three-phase PV inverter (Source: T. Messo, IEEE TPEL, 2014)



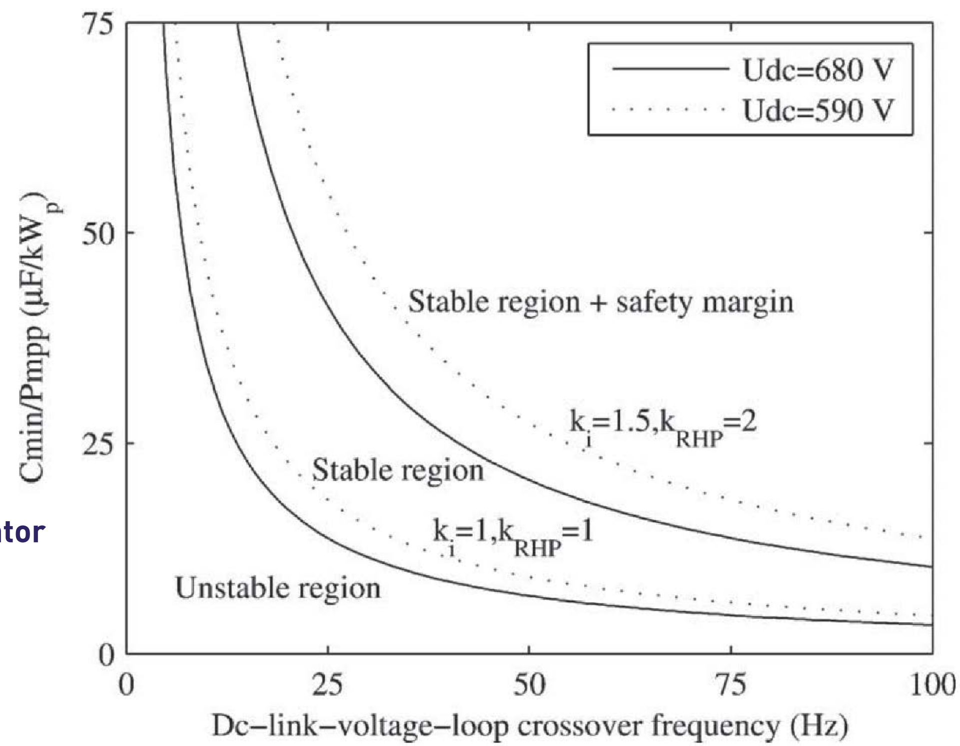
DC-DC stage for the inverter

RHP pole : $$\omega_{\mathrm{RHP}} = \frac{1}{U_{\mathrm{dc}}^2 C_{\mathrm{dc}}} \left(P_{\mathrm{pv}} - \frac{U_{\mathrm{pv}}^2}{r_{\mathrm{pv}}} \right)$$

Minimum required capacitance to ensure stability:

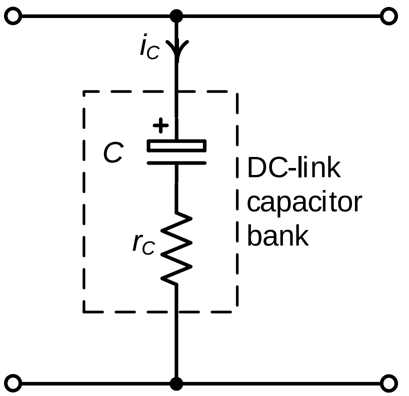
$$C_{\mathrm{dc\text{-}min}} = k_{\mathrm{RHP}} k_i \frac{P_{\mathrm{mpp}}}{U_{\mathrm{dc}}^2 \omega_c}$$

P_{mpp} – Maximum power of the PV generator

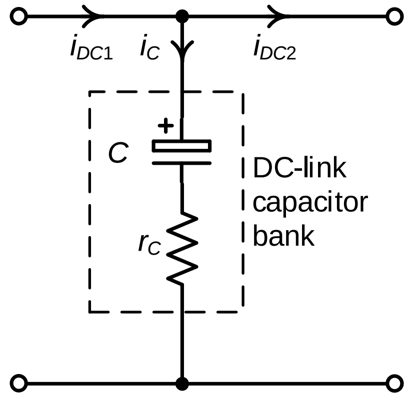


► DC-Link Design Solutions

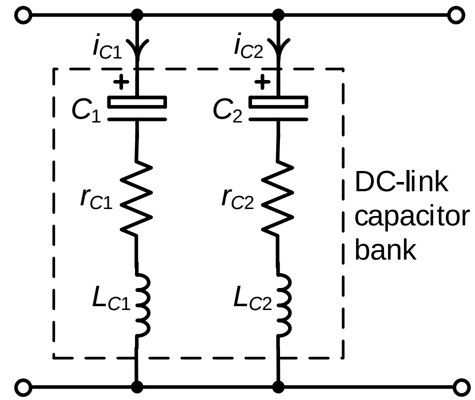
Passive capacitive DC-links



Conventional design

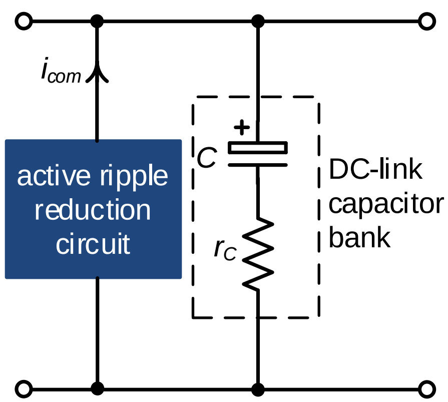


Additional control schemes

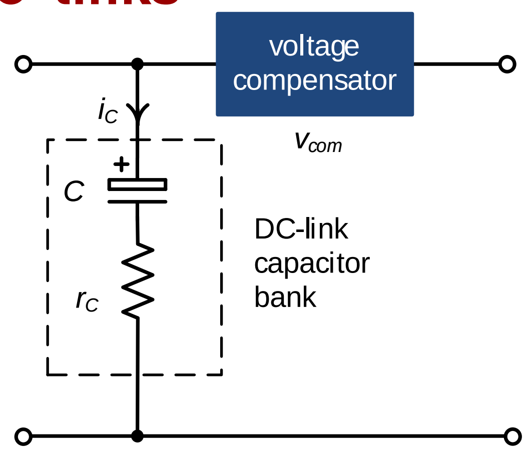


Hybrid DC-link bank design

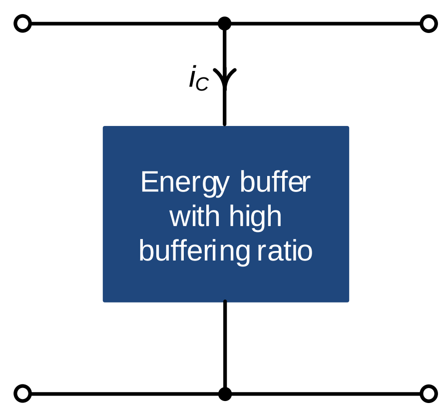
Active capacitive DC-links



Parallel-connected active circuit



Series-connected active circuit



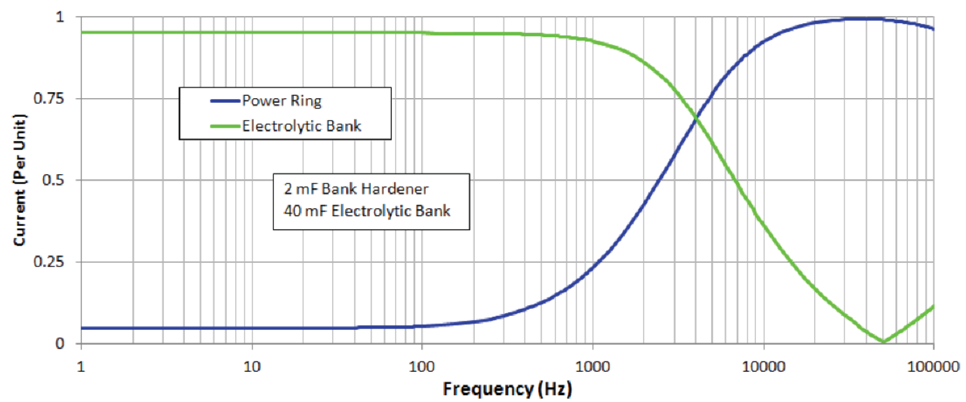
Direct replacement of active circuit

► Hybrid DC-Link Bank Design

M. A. Brubaker (SBE, PCIM 2013)

250 kW inverter
Ripple current on the order of 400 Arms
DC bus voltage of 1000 Vdc

Photo of the DC-link bank.



Low pass filter response created by parallel addition of film capacitor to electrolytic bank.

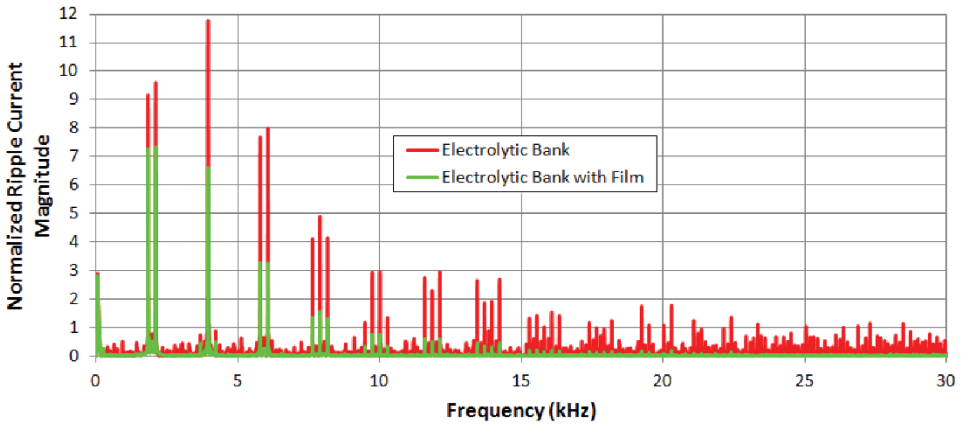
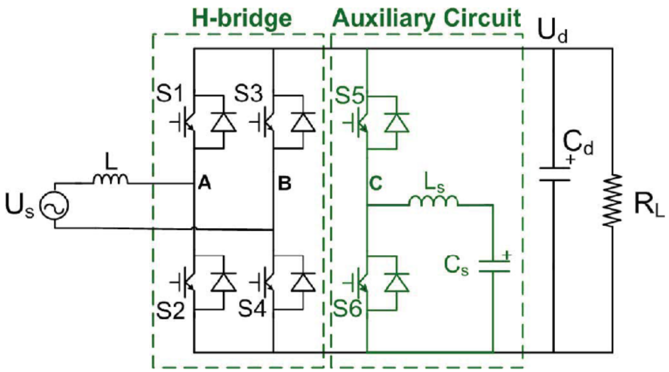


Illustration of ripple current harmonic reduction by adding a parallel 2mF Power Ring Film Capacitor to an existing 40mF electrolytic bank.

► Active DC-link Design – Parallel Circuit

R. Wang (2011, IEEE): 15kW single-phase PWM rectifier with active dc-link design



Topology

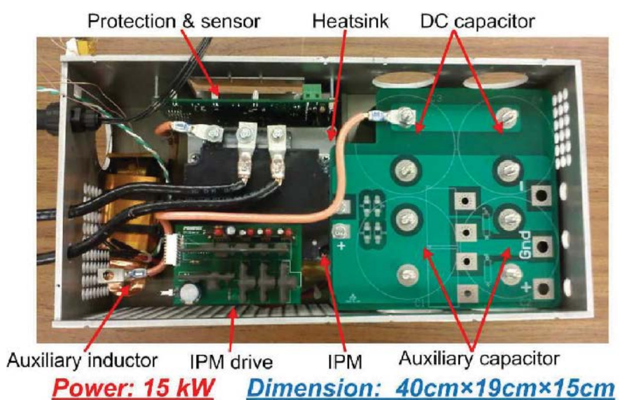
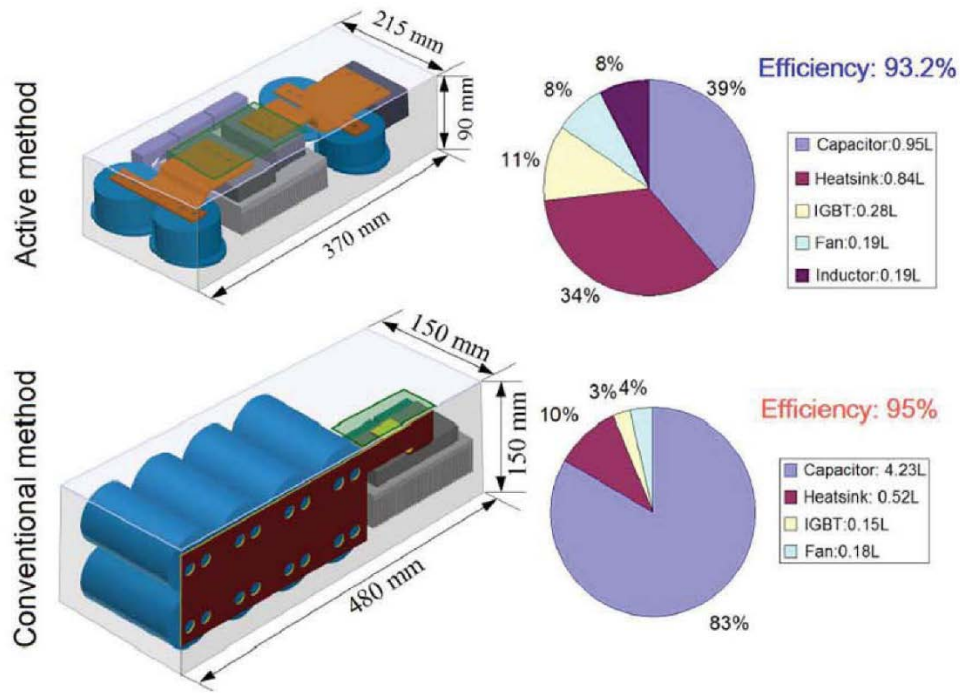


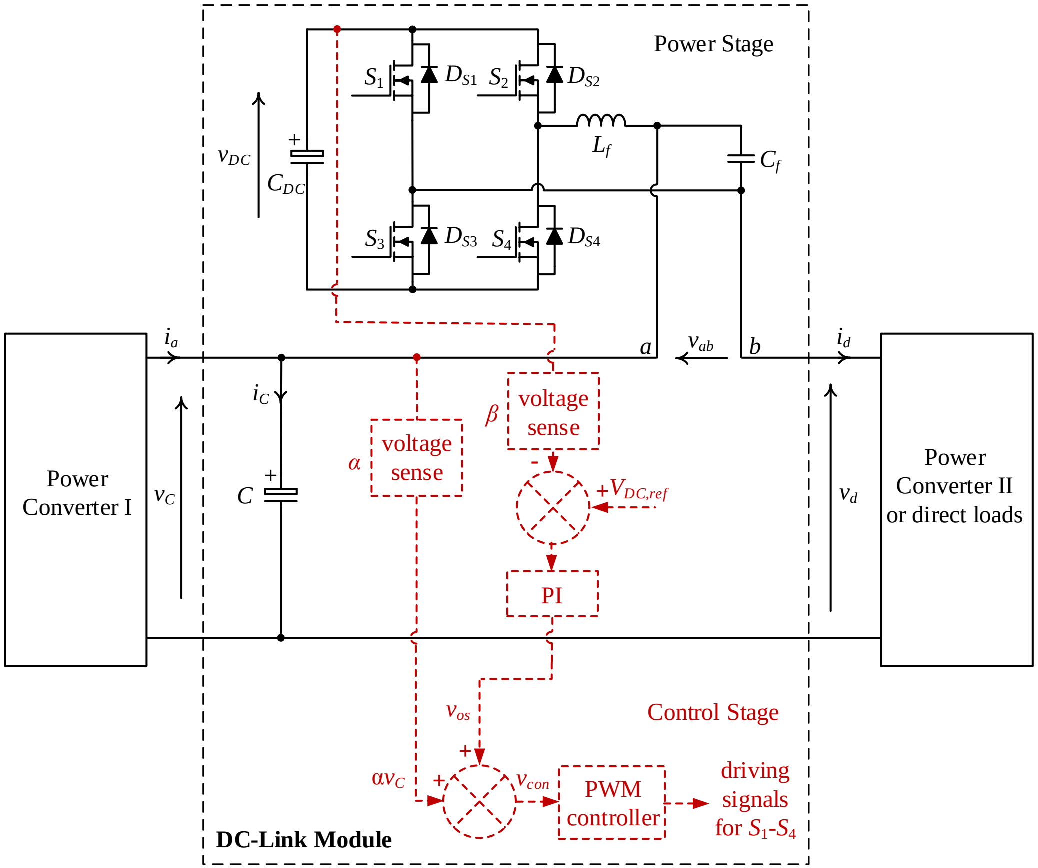
Photo of prototype



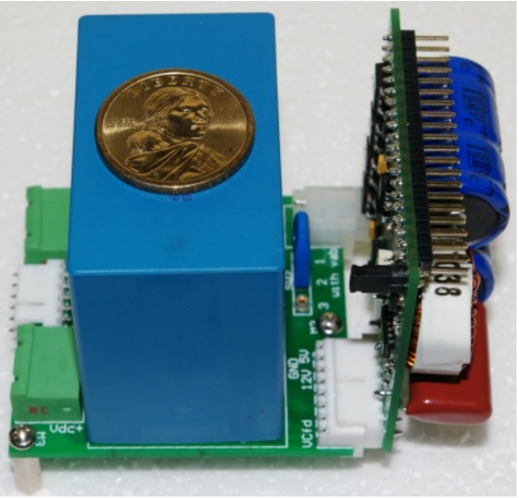
Converter level (main components) comparison of conventional passive dc-link design and active dc-link design.

▶ Active DC-link Design – Series Circuit (1/5)

H. Wang (2011, 2014 IEEE): DC-link module for capacitor-supported systems



DC-link module with DC-link capacitors and series-connected voltage compensator.



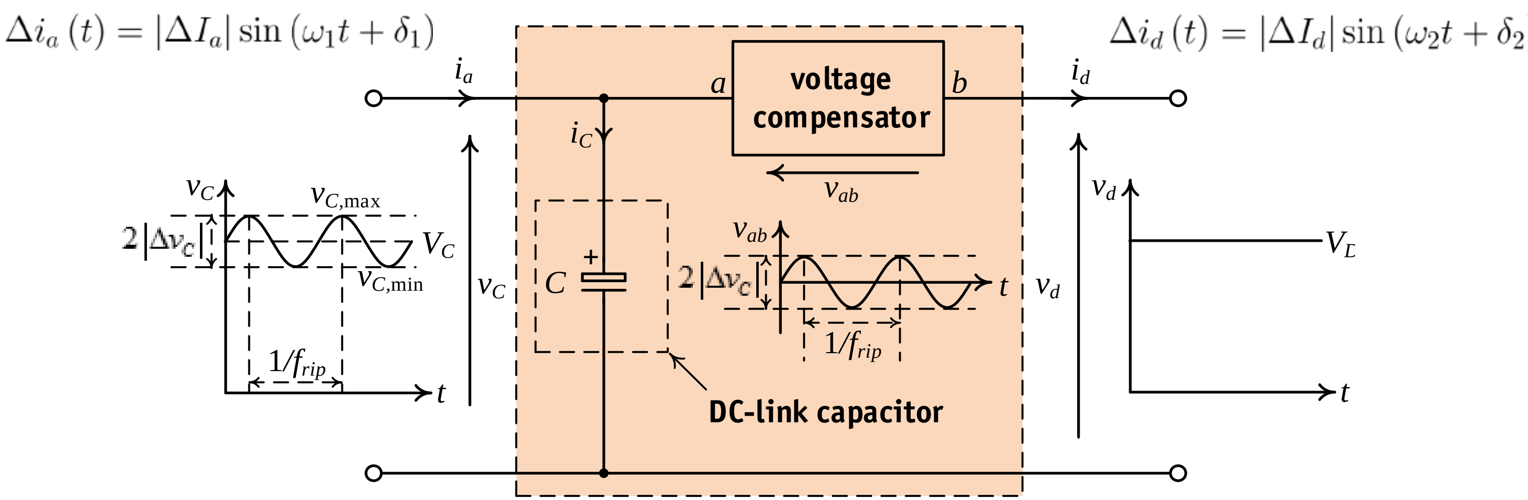
DC-link module for 1 kW AC-DC-DC application with a 110μF film capacitor (Max: 1.6kW).

Series compensator

Voltage ripple reduction
Reactive power only
Low voltage components
Simple circuit and control

► Active DC-link Design – Series Circuit (2/5)

H. Wang (2011, 2014 IEEE): DC-link module for capacitor-supported systems



$$P_{ab} = \frac{1}{T}\int_0^T v_{ab}(t)\, i_d(t)\, dt = \frac{|\Delta I_a|\,|\Delta I_d|}{2\omega_1 C T}\int_0^T \sin\left[(\omega_1 - \omega_2)t + (\delta_1 - \delta_2)\right] dt$$

P_{ab} ideally equal to 0 except for the case when $\omega_1 = \omega_2$ and $\delta_1 \neq \delta_2$

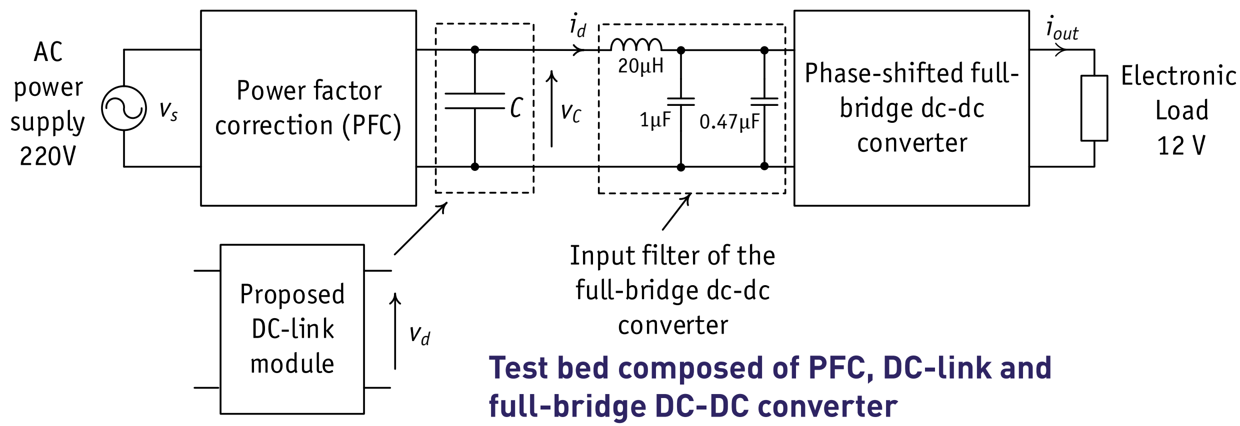
$$\frac{S_{ab}}{S_m} = \frac{\Delta V_{C,\mathrm{rms}}}{V_C}$$

S_{ab} – apparent power of the voltage compensator
S_m – apparent power of the main power conversion system
$\Delta V_{C,rms}$ – root-mean-square value of the voltage ripple across the capacitor

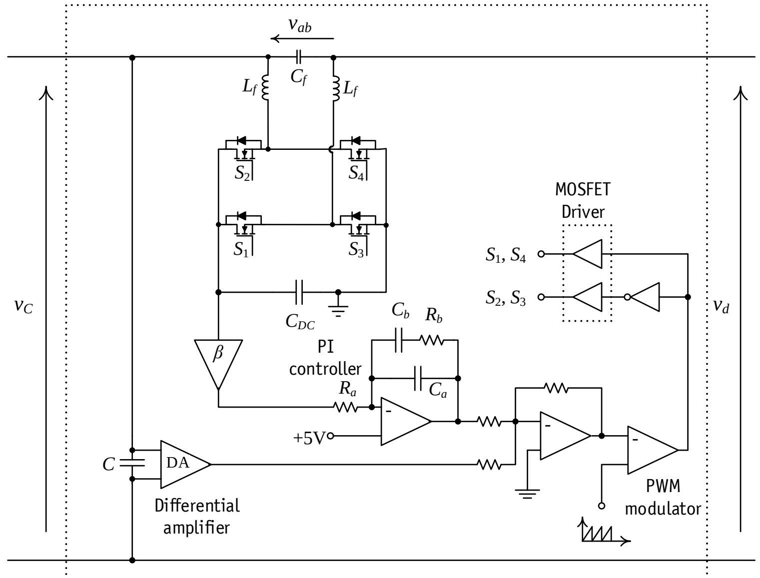
Low S_{ab} can be achieved and compromised with the capacitance value

▶ Active DC-link Design – Series Circuit (3/5)

H. Wang (2011, 2014 IEEE): DC-link module for capacitor-supported systems



Test bed composed of PFC, DC-link and full-bridge DC-DC converter



Implementation of the proposed DC-link module.

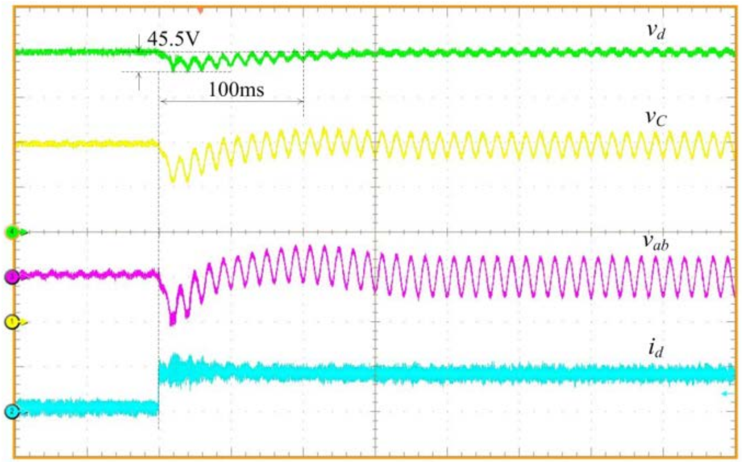
Parameter	Value / part no.	Parameter	Value / part no.
V_d	400V	P_L	600W
V_{DC}	50V	C	120μF, 450V
C_{DC}	1000μF, 63V	L_f	120μH
C_f	3.3μF, 100V	R_a	100kΩ
C_a	10μF, 35V	R_b	33kΩ
C_b	0.1μF, 50V	α	0.06
$S_1 - S_4$	FDD86102	β	0.1

20% energy storage in the DC-link module with respect to E-Cap solution.

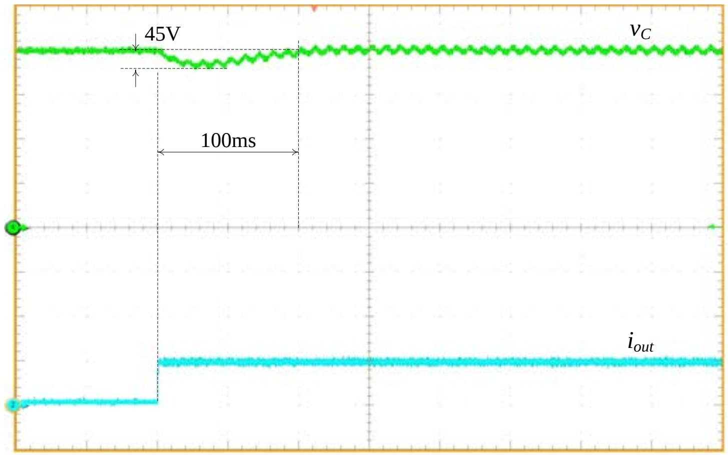
1.1W increase of power loss.

► Active DC-link Design – Series Circuit (4/5)

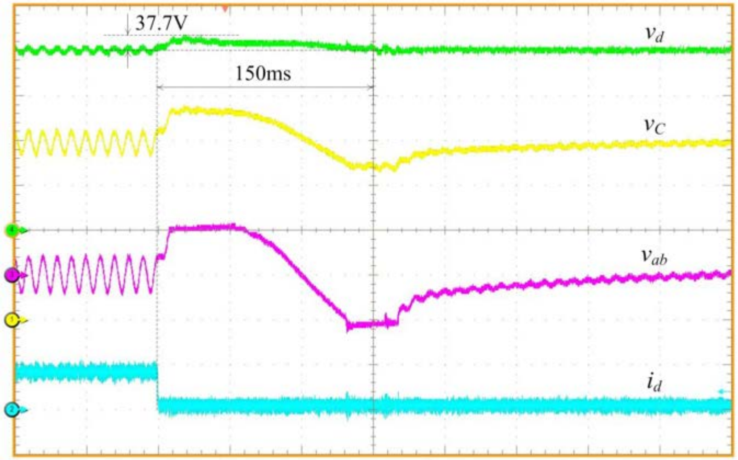
H. Wang (2011, 2014 IEEE): DC-link module for capacitor-supported systems



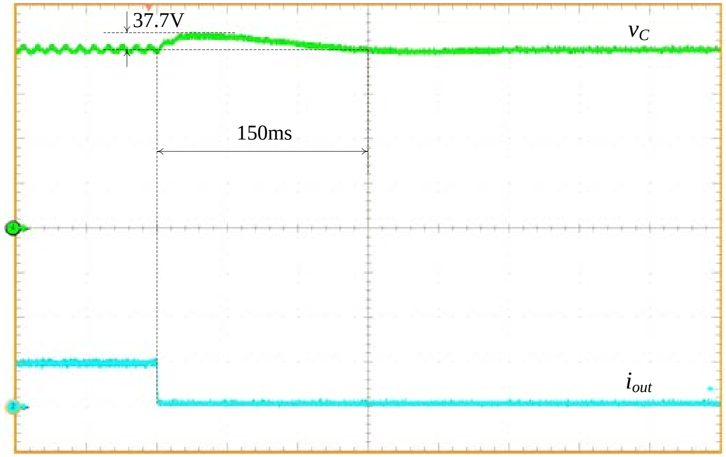
10% load to full load (with DC-link module) (v_d: 100V/div, v_C:100V/div, v_{ab}:40V/div, i_d: 2A/div, Timebase: 50ms/div).



10% load to full load (with 660μF E-Caps) (v_C:100V/div, v_{ab}:40V/div, i_{out}: 50A/div, Timebase: 50ms/div).



Full load to 10% load (with DC-link module) (v_d: 100V/div, v_C:100V/div, v_{ab}:40V/div, i_d: 2A/div, Timebase: 50ms/div).

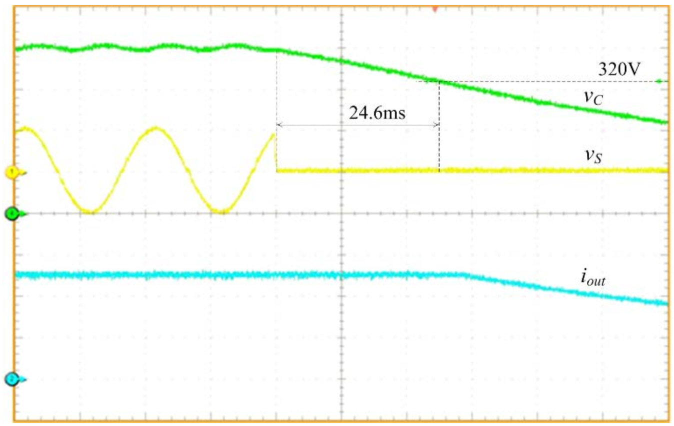


Full load to 10% load (with 660μF E-Caps) (v_C:100V/div, v_{ab}:40V/div, i_{out}: 50A/div, Timebase: 50ms/div).

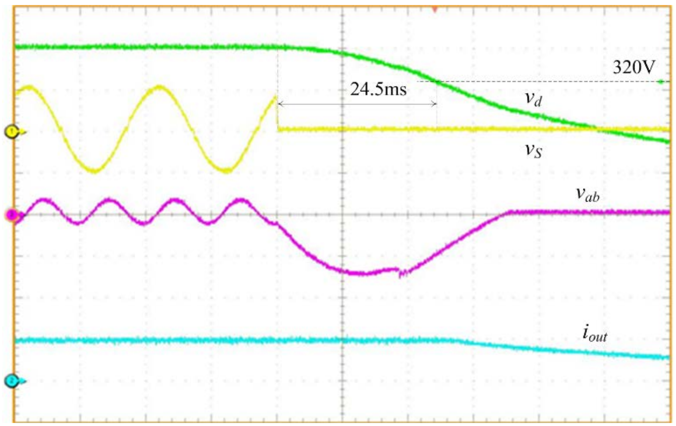
▶ Active DC-link Design – Series Circuit (5/5)

H. Wang (2011, 2014 IEEE): DC-link module for capacitor-supported systems

To fulfill the hold-up time requirement in PFC application



(v_C:100V/div, v_S: 300V/div, i_{out}: 20A/div, Timebase: 10ms/div).
(100% energy storage with capacitor only)



(v_d:100V/div, v_S: 300V/div, v_{ab}: 20V/div, i_{out}: 50A/div, Timebase: 10ms/div).
(72% energy storage with the DC-link module)

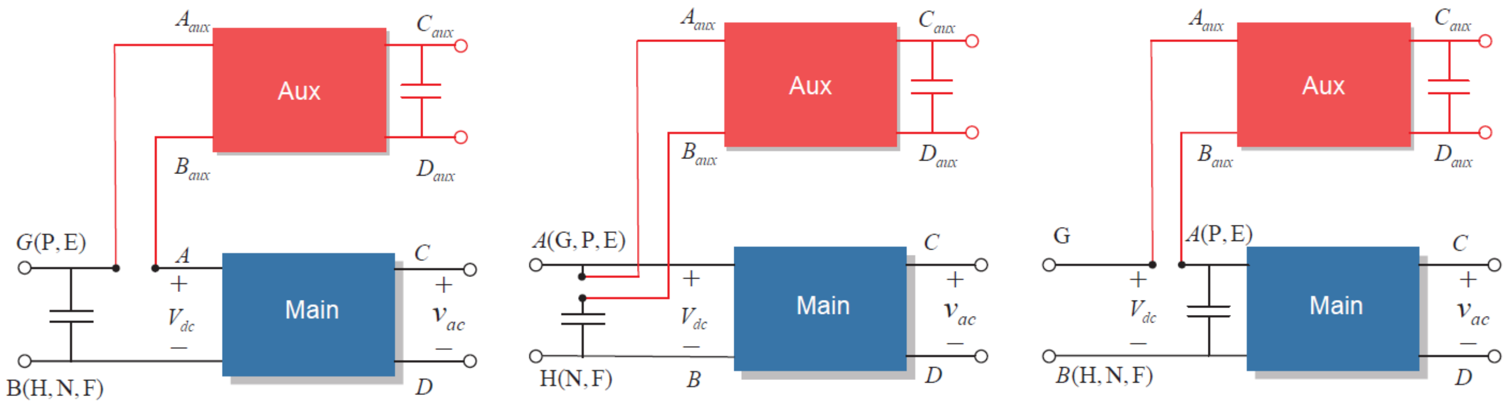
Waveforms after a sudden supply outage under 600 W loading condition.

► Active DC-link Design

There are many other active DC-link solutions in literature

Which DC-link design solution is the best? In terms of what?

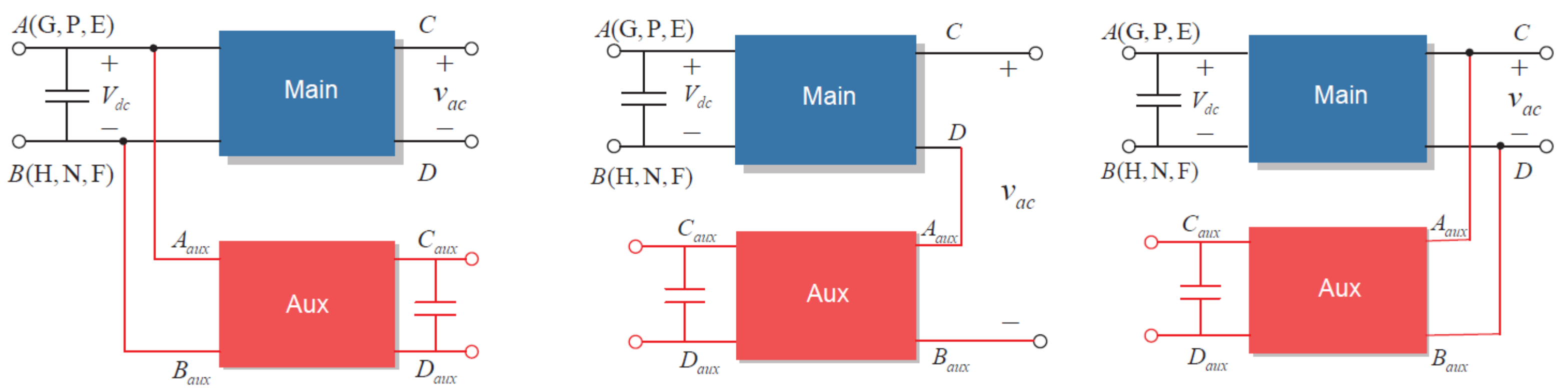
▶ General Structures of Active DC-link Circuits



(a) connected in series at DC side (Converter side)

(b) connected in series at DC side (Capacitor side)

(c) connected in series at DC side (Input side)



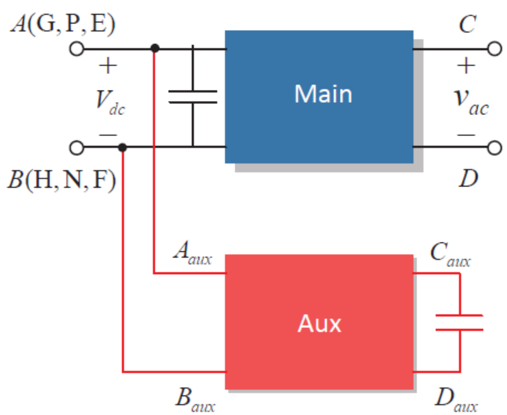
(d) connected in parallel at DC side

(e) connected in series at AC side

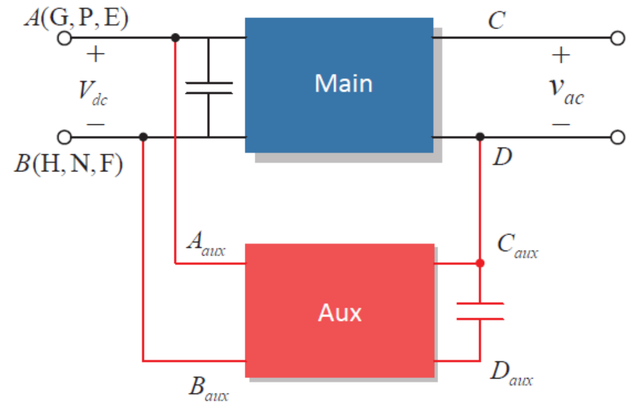
(f) connected in parallel at AC side

▶ Synthesis from the General Structures

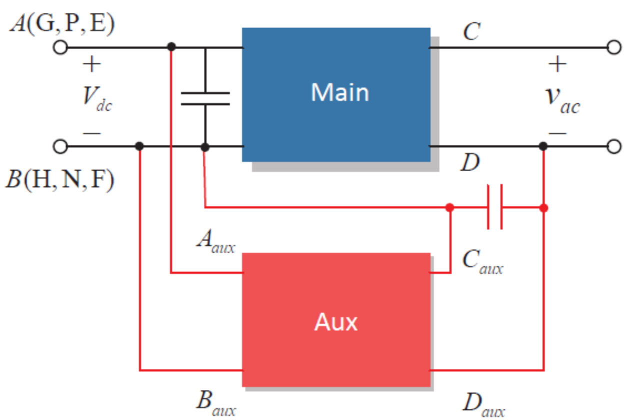
Take DC-Parallel as an example



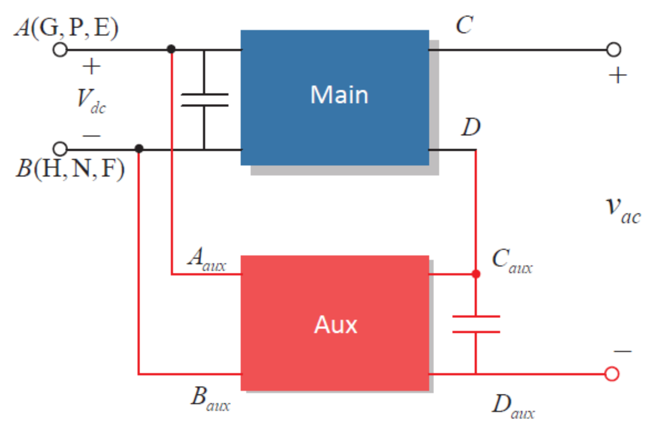
(a) Hang mode



(b) Float mode

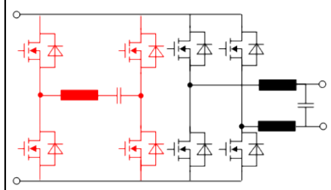
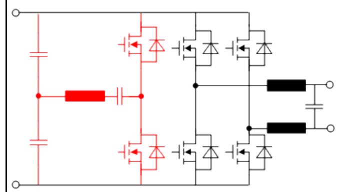
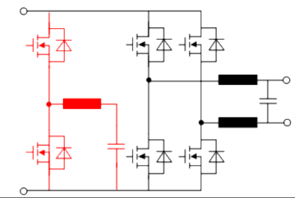
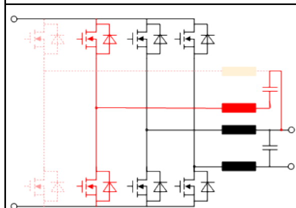
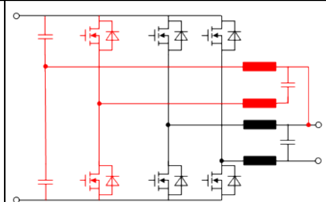
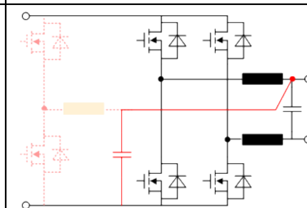
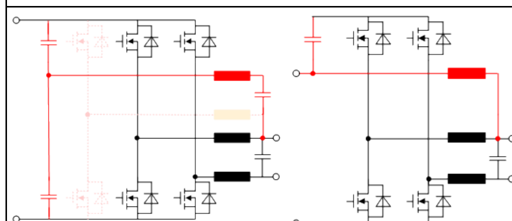


(c) Parallel mode



(d) Series mode

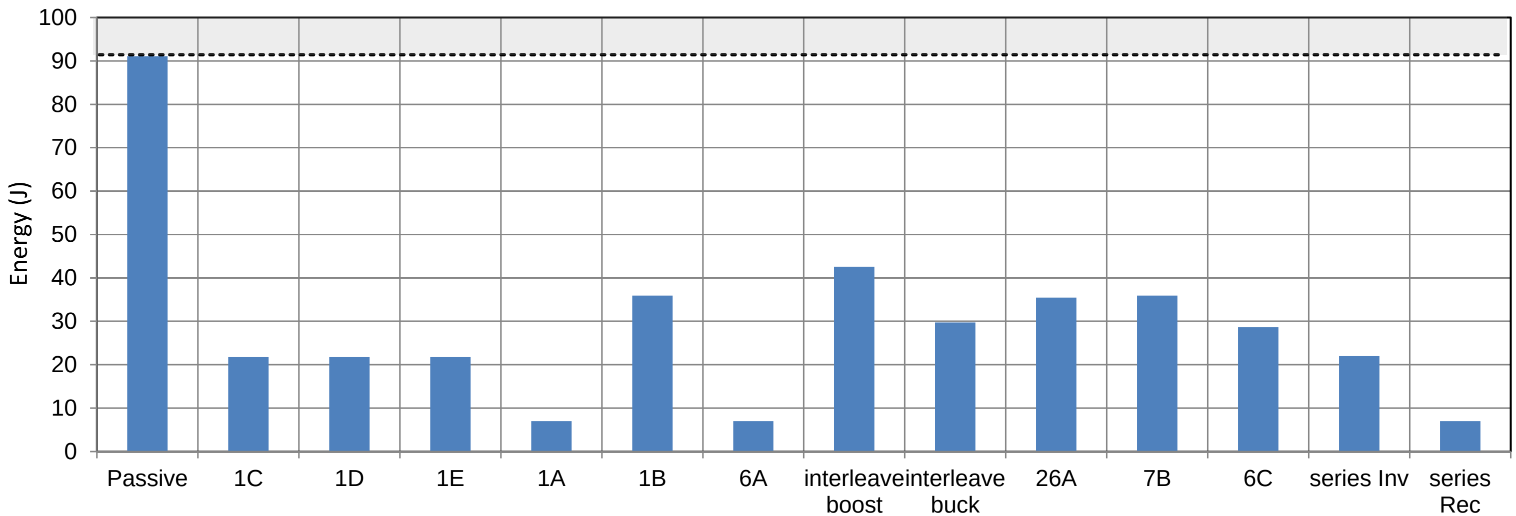
► Topology Derivation of Active DC-Links (Partly)

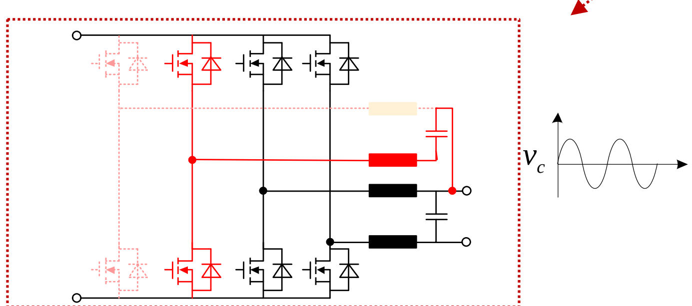
Auxiliary circuit topology (red)			Full-bridge	Half-bridge	Buck
			A	B	C
Hang mode		1	1A 	1B 	1C 
Float mode	A-C_{aux}	2	swtich short circuit	cap short circuit	swtich short circuit
	A-D_{aux}	3	swtich short circuit	swtich short circuit	1C
	B-C_{aux}	4	swtich short circuit	cap short circuit	swtich short circuit
	B-D_{aux}	5	swtich short circuit	swtich short circuit	1C
	C-C_{aux}	6	6A 	6B 	6C 
	C-D_{aux}	7	6A	7B 	1C
	D-C_{aux}	8	6A	6B	6C
	D-D_{aux}	9	6A	7B	1C

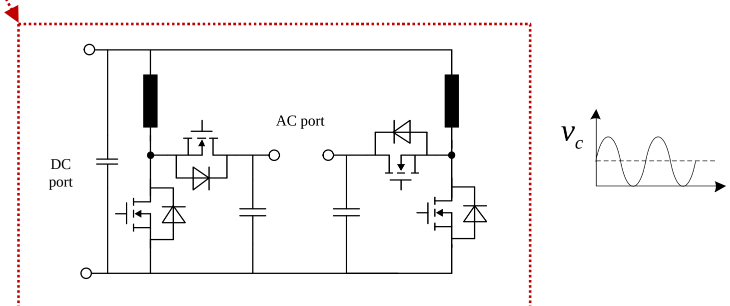
▶ Capacitor Energy Storage

Total energy storage is the sum of the energy storage in all the capacitors

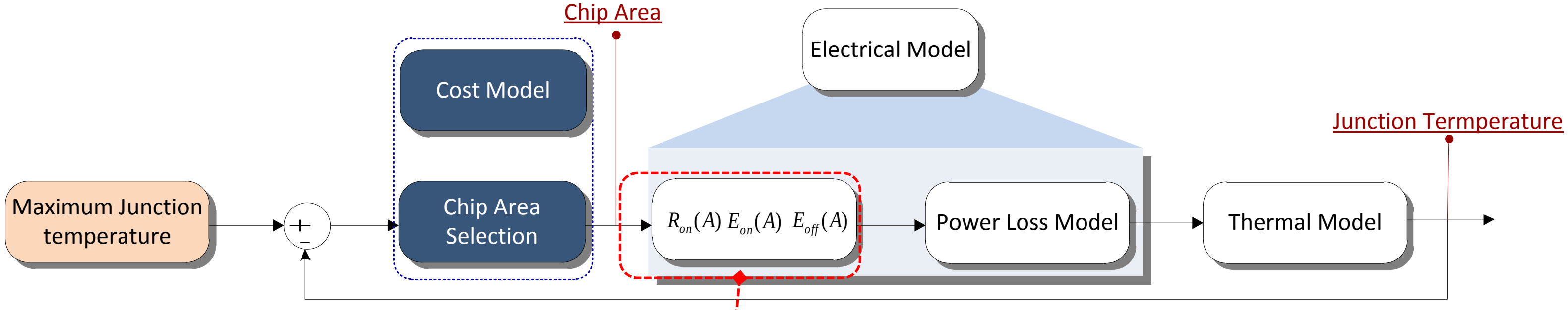
$$E_{\mathrm{c-tot}} = \frac{1}{2} C_{\mathrm{dc}} V_{\mathrm{dc-max}}^{2} + \frac{1}{2} C_{\mathrm{b}} V_{\mathrm{c-max}}^{2}$$





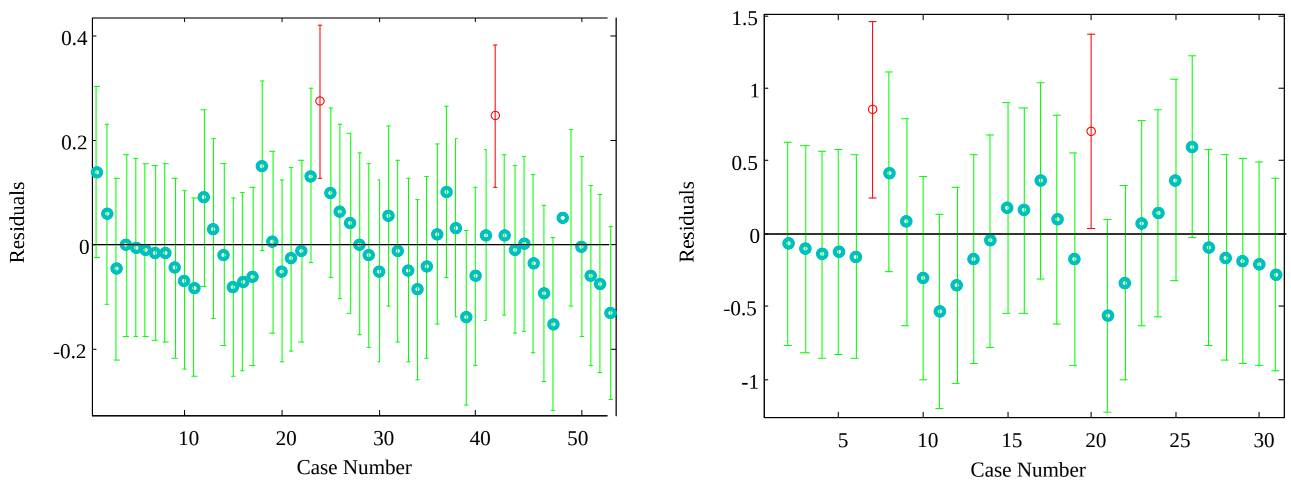


▶ Cost Evaluation of Power Semiconductor



Infineon: High-speed 3 (600 V, 1200 V)
Infineon: IGBT Bare Die (600 V, 1200 V)

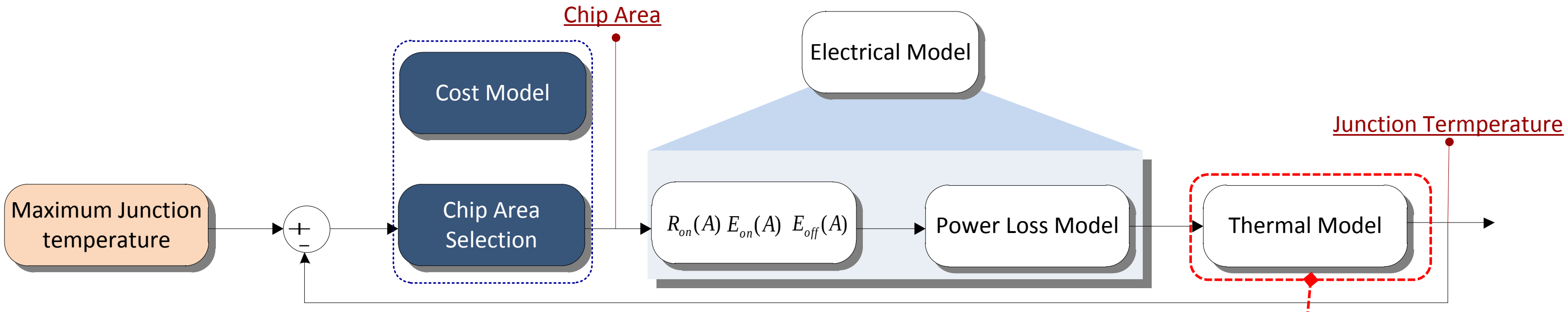
$$\begin{cases} V_{\mathrm{CE}}(A_{\mathrm{chip}}, T_{\mathrm{j}}, i_{\mathrm{sw}}) = a_0 + a_1 A_{\mathrm{chip}} + a_2 T_{\mathrm{j}} + a_3 i_{\mathrm{sw}} \\ E_{\mathrm{tot}}(A_{\mathrm{chip}}, T_{\mathrm{j}}, i_{\mathrm{sw}}, V_{\mathrm{dc}}) = V_{\mathrm{dc}} \times i_{\mathrm{sw}} \times (a_0 + a_1 A_{\mathrm{chip}} + a_2 T_{\mathrm{j}}) \end{cases}$$



(a) Etot (600 V) cases
R2=0.9847

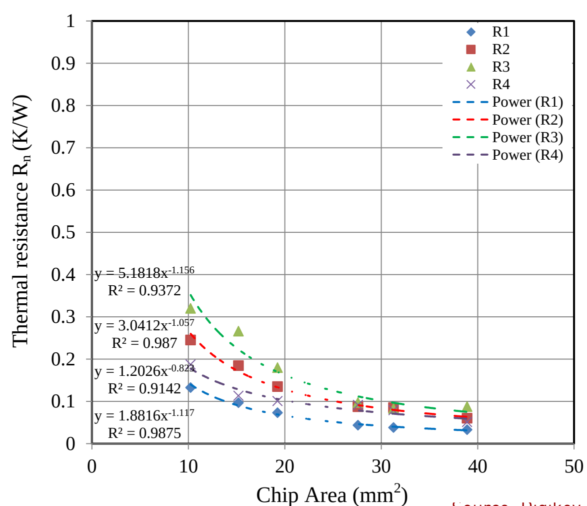
(b) Vce (600 V) cases
R2=0.9094

▶ Cost Evaluation of Power Semiconductor

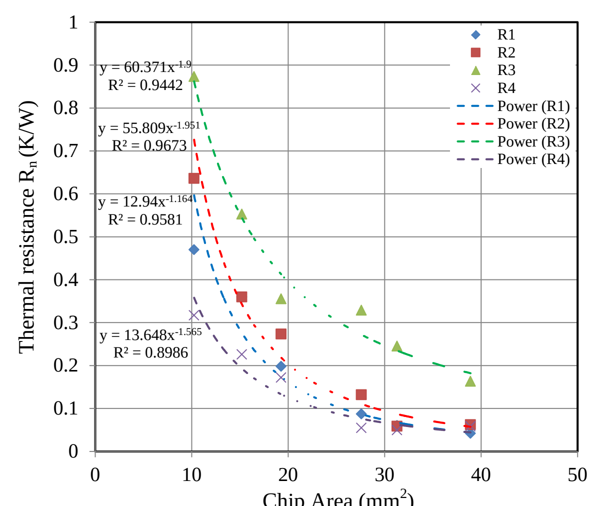


Infineon: High-speed 3 (600 V, 1200 V)
Infineon: IGBT Bare Die (600 V, 1200 V)

$$Z_{\mathrm{th}}(A_{\mathrm{chip}}) = \sum_{n=1}^{4} R_{\mathrm{n}}(A_{\mathrm{chip}})(1 - e^{-\frac{t}{\tau_{\mathrm{n}}}}) = \sum_{n=1}^{4} a_{\mathrm{n_0}} A_{\mathrm{chip}}^{a_{\mathrm{n_1}}} (1 - e^{-\frac{t}{\tau_{\mathrm{n}}}})$$



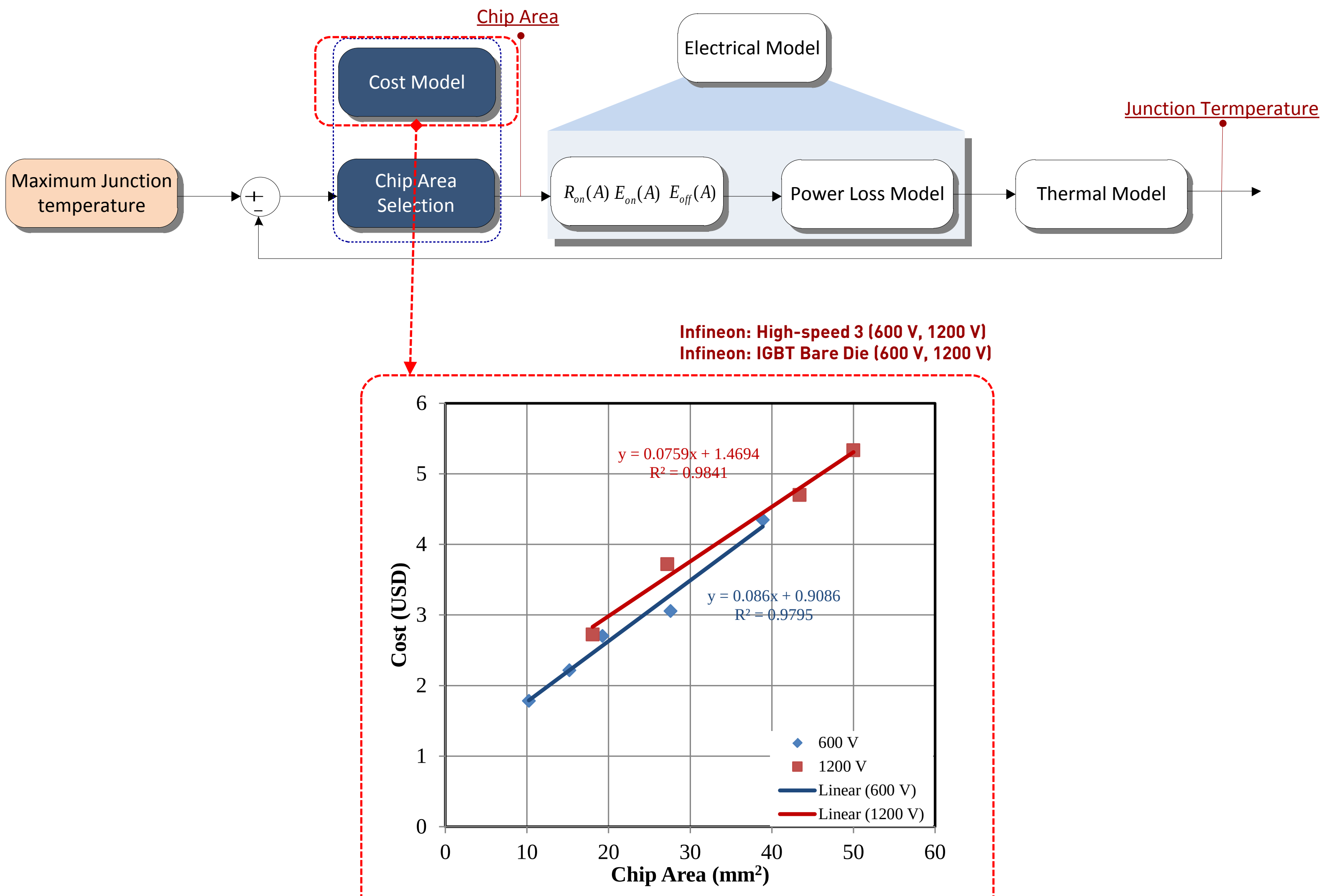
(a) 600 V transistor



(b) 600 V diode

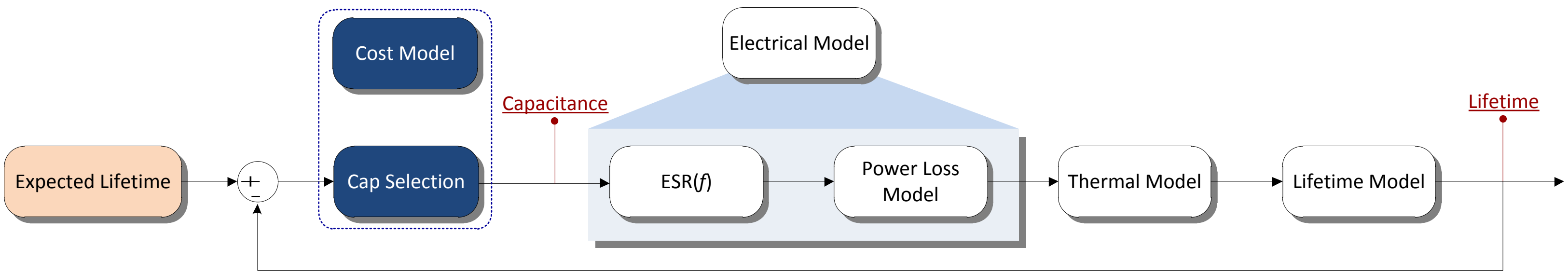
Source: Digikey→http://www.digikey.dk/
Infineon→https://www.infineon.com/

▶ Cost Evaluation of Power Semiconductor

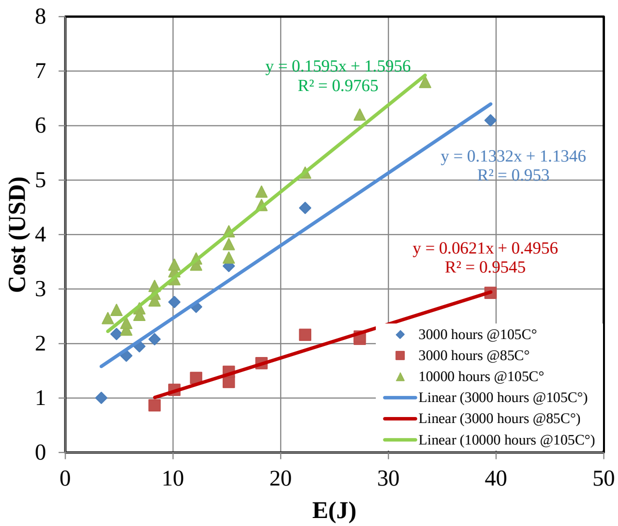


Cost model by curve fitting

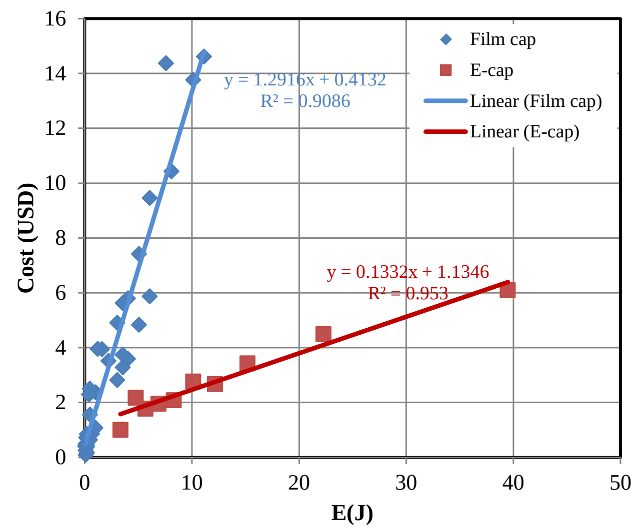
▶ Cost Evaluation of Capacitor



Voltage ratio: 450 V, +20 %, snap in

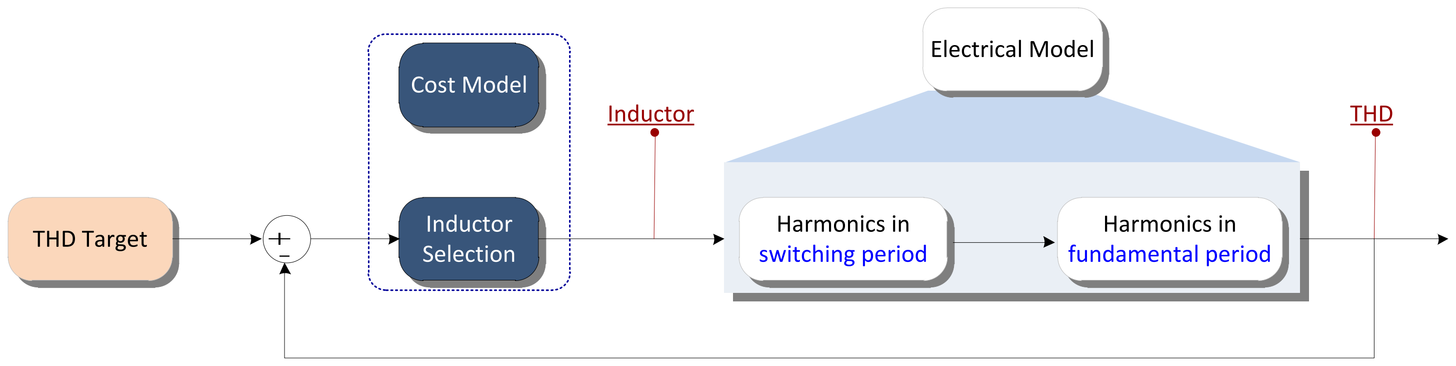


Voltage ratio: 450 V, 105 °C



Cost model by curve fitting (Source: Digikey→http://www.digikey.dk/)

▶ Cost Evaluation of Inductor

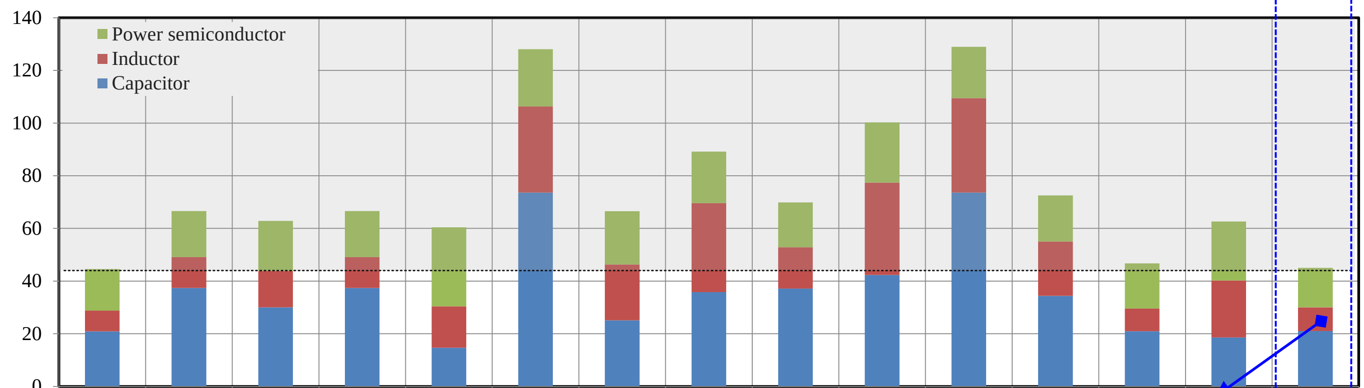


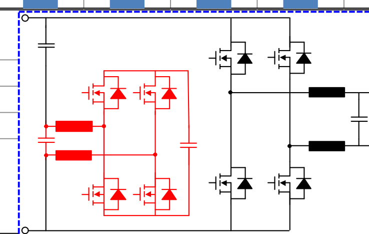
Considerations

- Current ripple ratio
- Winding factor (35-40 %)
- Core structure and material (high flux ferrite core and solid round winding)
- Data from Magnetics and Digikey

▶ Cost Comparison with Different Designed Lifetime

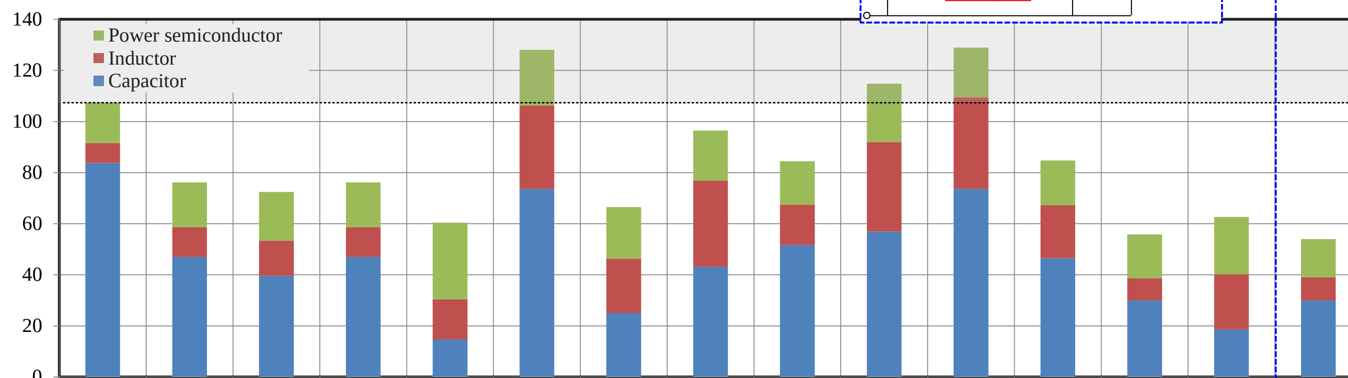
10 years





	Passive	1C	1D	1E	1A	1B	6A	interleave boost	interleave buck	8A	42F
Power semiconductor	16	18	19	18	30	22	20	20	17	22	15
Inductor	8	12	14	12	16	33	21	34	16	22	9
Capacitor	21	37	30	37	15	74	25	36	37	19	21

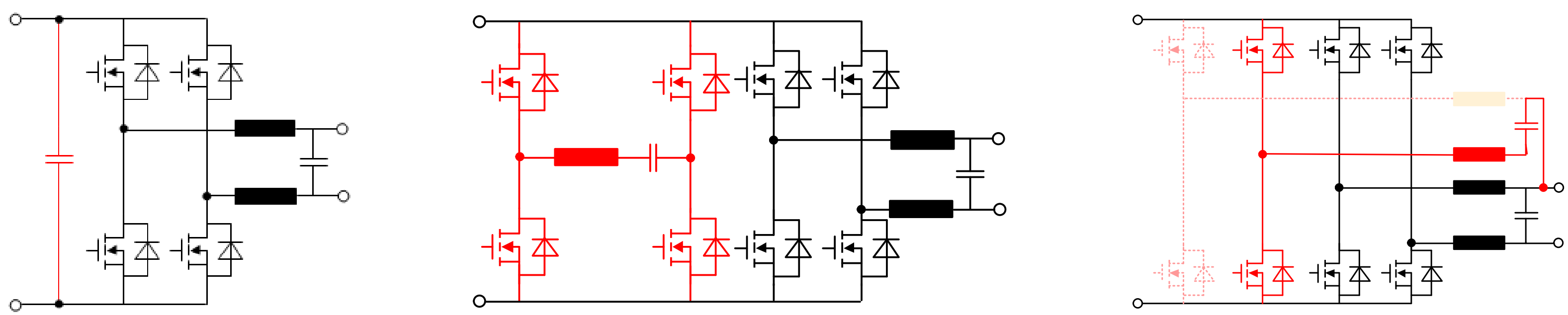
35 years



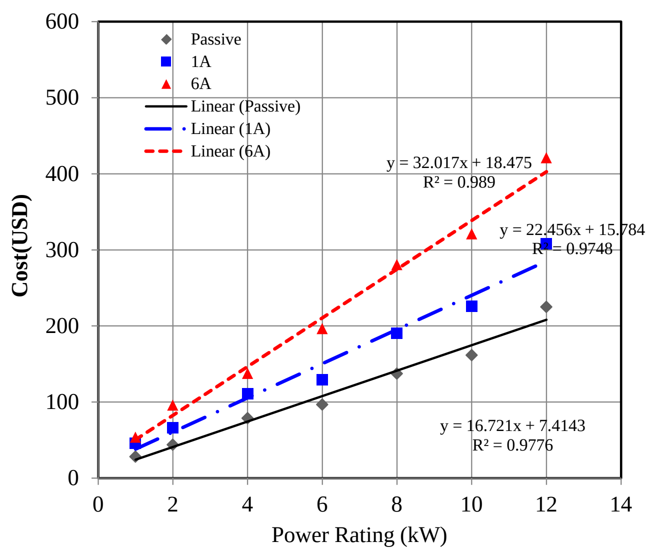
	Passive	1C	1D	1E	1A	1B	6A	interleave boost	interleave buck	34A	7B	6C	38F	38A	42F
Power semiconductor	16	18	19	18	30	22	20	20	17	23	20	18	17	22	15
Inductor	8	12	14	12	16	33	21	34	16	35	36	21	9	22	9
Capacitor	84	47	40	47	15	74	25	43	52	57	74	47	30	19	30

▶ Cost Scalability of Designed Power Ratings

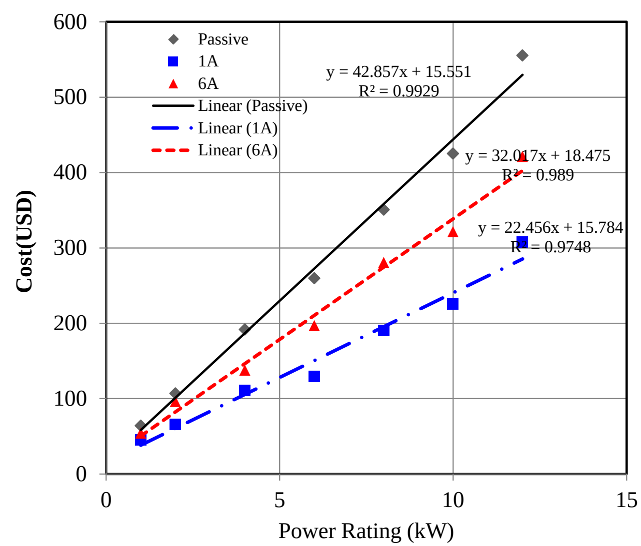
3 Study Cases



Cost v.s. Designed Power Ratings (1kW to 12kW)

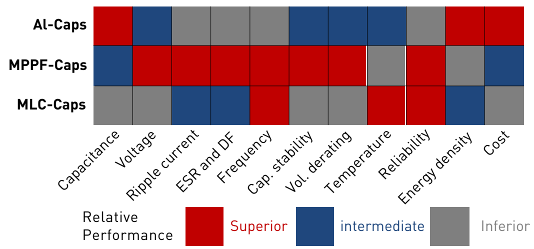


(a) with 10 years lifetime target

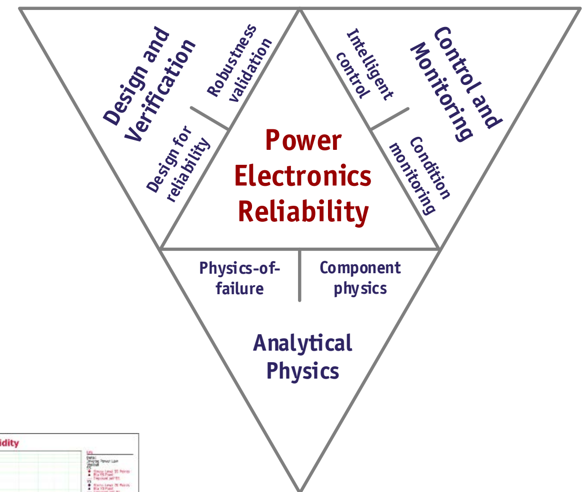


(b) with 35 years lifetime target

Summary of the Tutorial

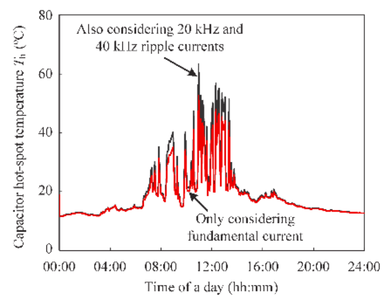


Capacitors in power electronics and sizing criteria

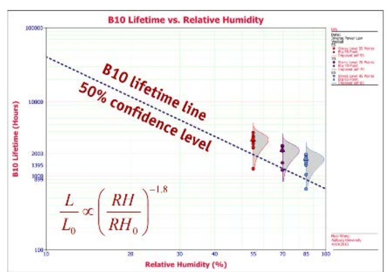


Power electronics reliability

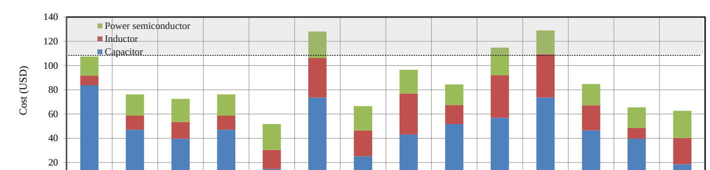
Mission profile based modeling



Wear out testing and data analysis



DC-link design solutions



	Passive	1C	1D	1E	1A	1B	6A	interleave boost	interleave buck	26A	7B	6C	30F	30A
Power semiconductor	16	18	19	18	21	22	20	20	17	23	20	18	17	22
Inductor	8	12	14	12	16	33	21	34	16	35	36	21	9	22
Capacitor	84	47	40	47	15	74	25	43	52	57	74	47	40	19

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