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Film Capacitors

Robustness & Fail-Safe

Topics:

- **Most common failure-modes and their root-causes.**
- **Fail-Safe.**
- **Suitable Qualification-test - respecting the most common failure-modes and assuring a Fail-Safe behaviour in the application.**
- **Considerations for selecting the most suitable types.**
- **Lifetime-Expectancy – how to calculate by formula.**

Metallized Film Capacitors

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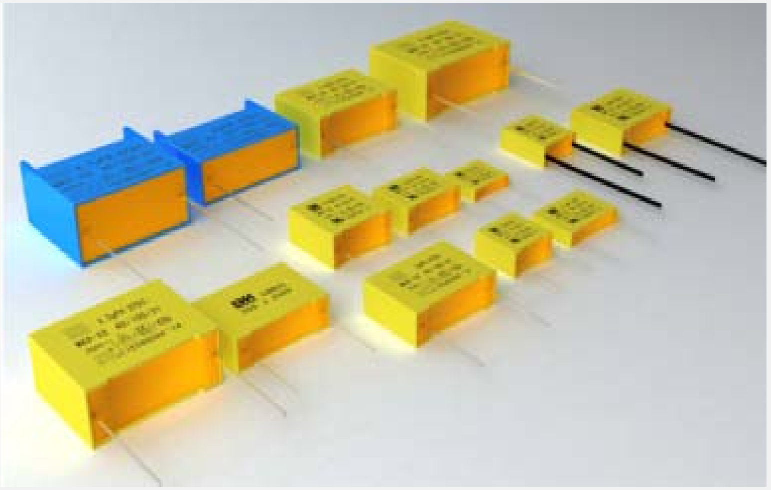
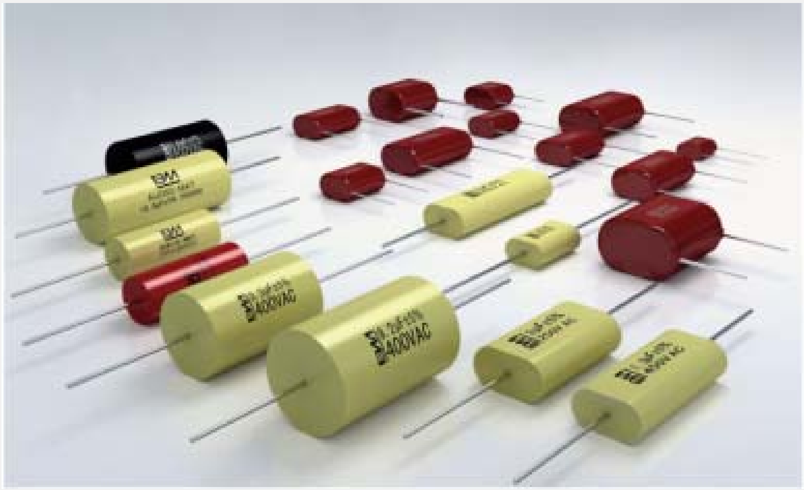


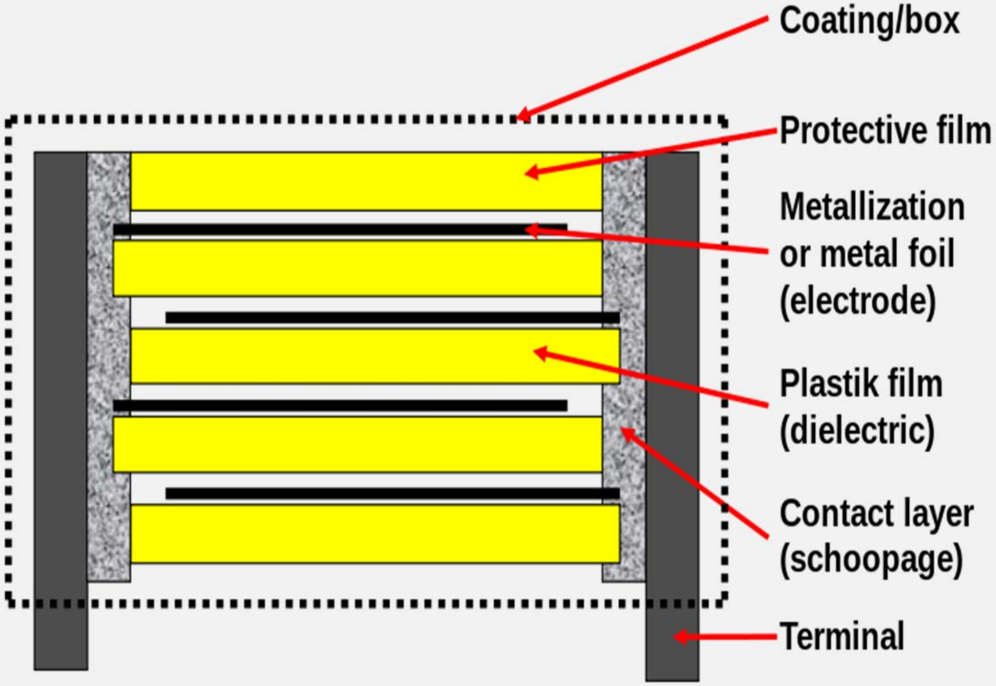


AC – Capacitors: X- and Y- Noise Suppression Capacitors

DC – Capacitors: MKT-, MKP-, Impulse-, DC-link Capacitors

Most common failure-modes

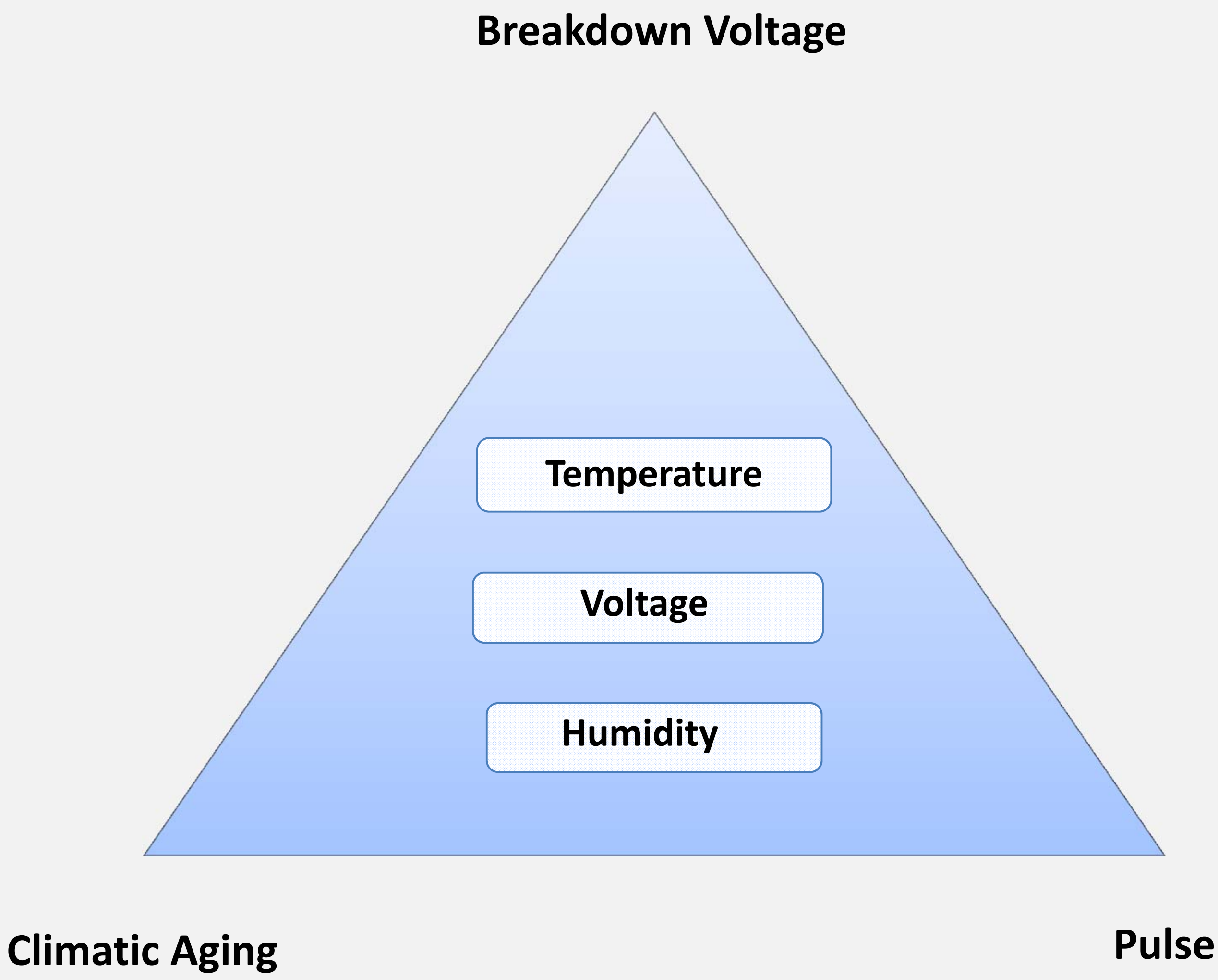
Construction of a metallized film capacitor:



Most <u>critical parts</u> for a reduction of the lifetime-expectancy:

Dielectric, Electrode and endspray-contacts

Determining stress-factors for the lifetime-expectancy



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Definition End-of-Life of a metallized film capacitor:

the *End-of-Life* descripes the moment from which on the capacitor does not fullfill its specified values anymore.

Criteria:

- **too big loss of capacitance.**
- **too high increase of tangent delta.**
- **too strong reduction of the insulation resistance.**

e.g..:

- $\Delta C/C$	$\leq$ 10%
- Δ tan δ / tan δ	$\leq$ 200%
- IR	$\geq$ 50% of initial value.

What are the reasons for a capacitance-loss?

→ **Capacitance-loss = loss of conductive electrode-surface !**

Such a loss of electrode-surface can be caused by:

- **Selfhealings**
- **Humidity-Corrosion**
- **Partial Discharge (Corona-phenomenon)**

Selfhealing

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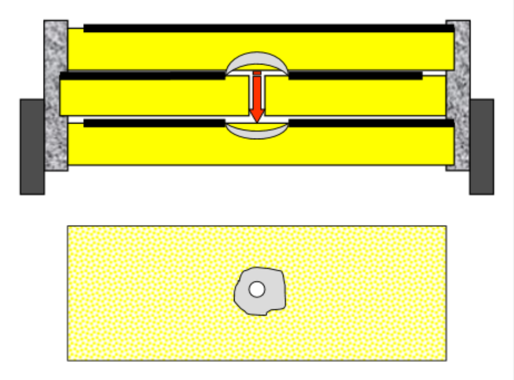
Selfhealing = ability to clear faults under the influence of a voltage.



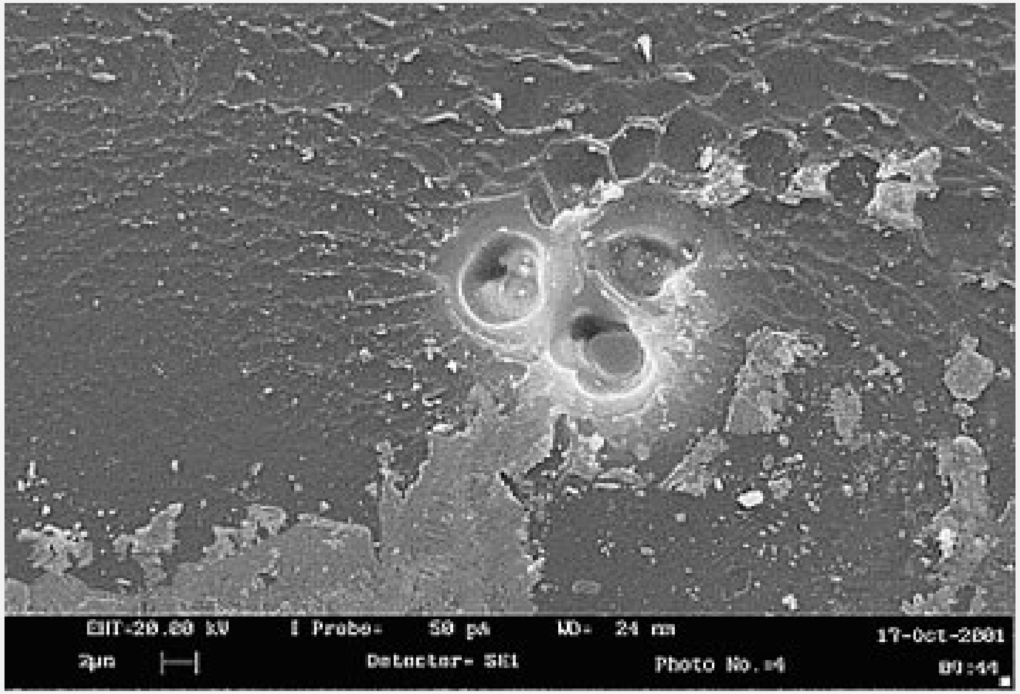
- **The metal coating on the plastic film is very thin (about 20…50 nm).**
- **When the dielectric breakdown field strength is exceeded locally at a weak point → dielectric breakdown!**
- **Very high temperatures in the breakdown channel (up to 6000K) → transformation of the dielectric into a highly compressed plasma → force its way out.**
- **The metal coating next to the channel evaporates together with the plasma.**
- **The rapid expansion of plasma leads to a quick cooling-down of this material. Therefore the discharge will be stopped.**

  → This process (within microseconds) leads to an insulated area which deactivates the defective point.

Selfhealing

→ **Selfhealings corresponds to loss of electrode surface.**

→ **Capacitance losses due a self-healing processes are relatively small.**



Magnification of self-healing points in a polypropylene film

Humidity-Corrosion

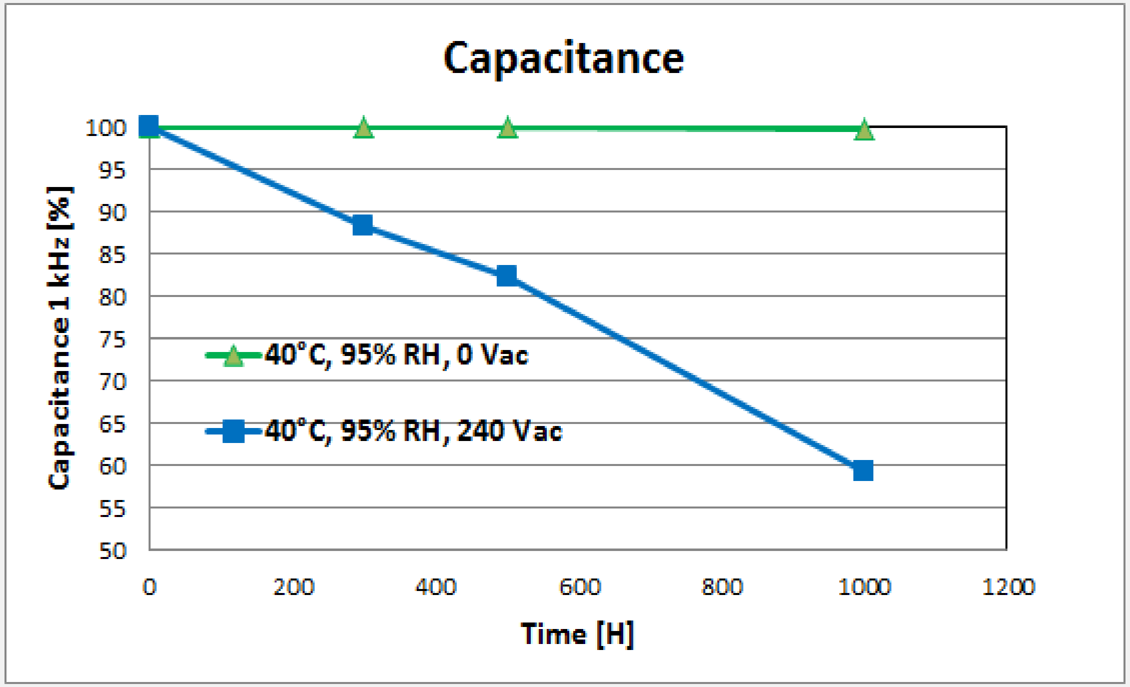
- Usually the very thin metal coating of the plastic film is either Zinc or Aluminium, or a mixture of both.
- The combination of humidity (water -> dipol) and applied voltage reacts with both materials (Zinc ++, Aluminium+) and leads to a corrosion-process.

Film metallization displaying significant corrosion

When humidity-corrosion occurs in the film metallization, the metallization coating breaks down.

This results in a thinning of the metal layer and ultimately loss of conductive electrode surface area, with a corresponding loss of capacitance.

Humidity-Corrosion



Mean values of the capacitance-loss over the time

<u>Green curve:</u>
Regular X2-capacitors in accordance with the latest issue of IEC 60384-14, testet with the conditions of point 4.12 of the IEC-norm (40°C/95% RH, 0V).

<u>Blue curve</u>:
Regular X2-capacitors in accordance with the latest issue of IEC 60384-14, testet with the conditions of point 4.12 of the IEC-Norm <u>plus</u> voltage (40°C/95% RH, 240Vac).

Partial Discharge (PD) – Corona

- Because of a bad winding-process and an insufficient hot press-process, air-bubbles between the film-layers may occur.

- When the electrical field in the capacitor is higher than the breakdown-strength of the air → a local breakdown is occuring which is leading to the ionization of this air. (= Partial Discharge/C orona). Small light-arc occurs with this discharge, which evaporates the metallization locally.
  Discharge → high current and selfhealings → evaporation of the metallization.

- Under a given voltage , the electrical field in a thin film is higher than in a thick film 230Vac/5µm = 46V/µm; 230V/7µm = 33V/µm → 40% difference !
  This is like an accelerating factor corresponding to 1.4 Urated.

- With a higher electrical field, breadowns occurs much faster and more breakdowns can be observed in shorter time

- The breakdown-strength from humid air is lower than from dry air → ***<u>Humidity</u>*** accelerates partial discharges.
  Humidity reduces the dielectric rigidity of the gas, or in other words the capability of the gas to withstand ionization.

→ ***Miniaturization and Humidity provoke PD/Corona***

Partial Discharge (PD) – Corona

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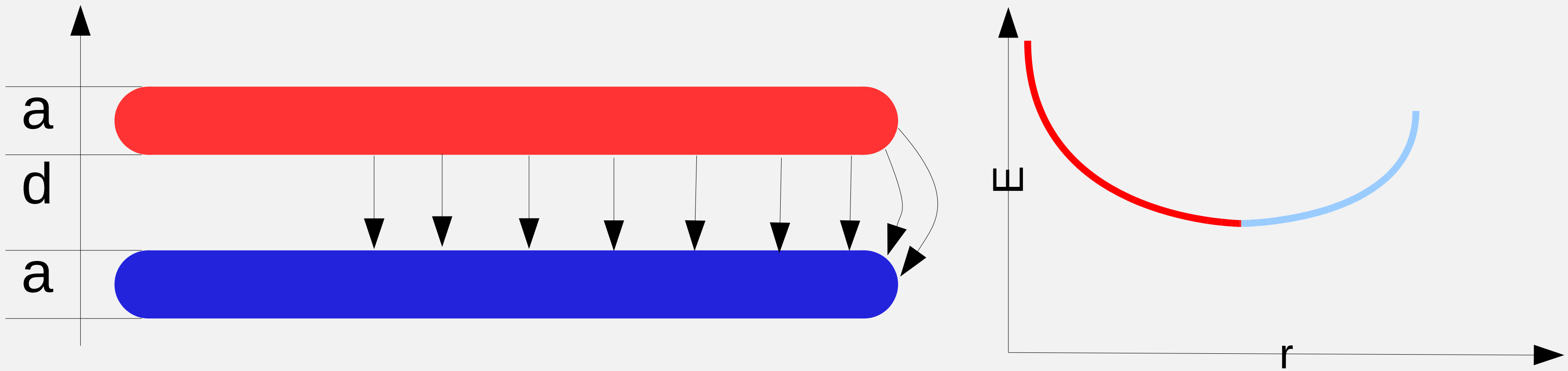
- The highest concentration of the electrical field in a capacitor is at the metallization edges (major disturbance of the electrical field homogenity).

$$U = \int \vec{E}\, d\vec{r}$$

The field intensity is maximum close to the edges



a= electrode thickness; d = dielectric film thickness

- **Therefore PD/Corona starts in the air-gaps at the metallization-edges and evaporates the metallization from the outside to the inside.**

- **A PD/Corona-process is comparable to a glow discharge. Under voltage-load this process might kept alive until there is no capacitance (= no electrical field) left →**

evaporation of both electrodes from the free margin to about the half of the width.

Partial Discharge (PD) – Corona

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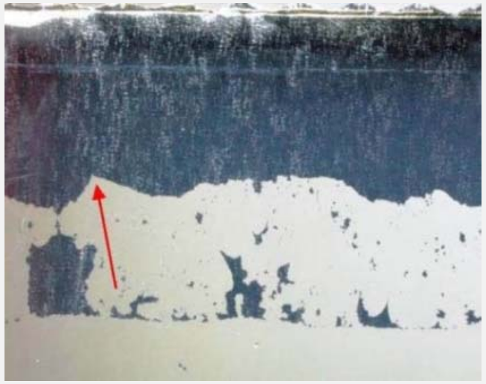
Red arrow: Position X, both metallized films of capacitor



Position X, upper film

Position X, below film

Each electrode is eaten until the middle on each side. When they "join", the phenomenon stop because there is no more electrode to apply an electric field.
PD/Corona is mostly just present in AC-applications.

Humidity – Enemy No.1 !

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Humidity can destabilize the whole capacitor-sytem

Acceleration of loss of capacitance:

- by humidity-corrosion of the electrodes.
- by PD/Corona-discharges (Humidity promotes it to areas with lower electrical field).
- by Selfhealings around dielectric breakdown:
  Humidity has the effect to reduce the breakdown strength of the system and consequently increase the number of selfhealings.

Acceleration of increase of loss-factor tan δ:

- by (climatic) aging of the dielectric (U,T).
- by humidity-corrosion in the metallization.
- by humidity-corrosion in the endspray-contacts.
- by complete break-off of the endspray-contacts (humidity accelerates it).

Acceleration of drop of Insulation Resistanc IR:

- humidty in the dielectric cause a drop of IR →increased current through the dielectric.

→ Humidity is the film capacitor‘s enemy no.1 !

Determining stress-factors for the lifetime-expectancy

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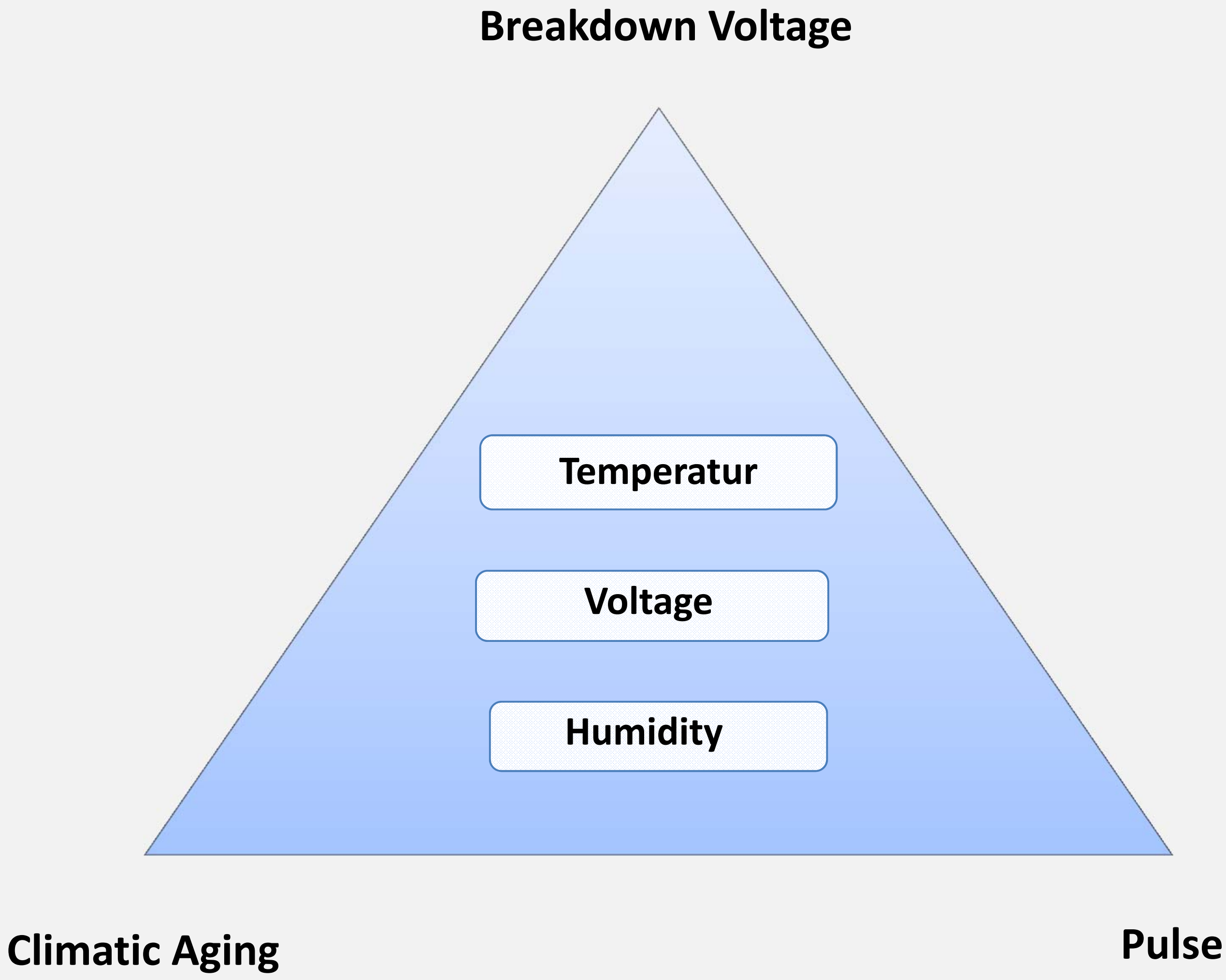

Pulses

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Surge-Pulses e.g. from lightening strokes.
Continously repeated low amplitude pulse loads – steadily increasing by more converters and PFC‘s in the power net.

→ Pulses are stressing the endspray-contacts by high pulse-currents:

Current $i(t) = C \cdot dV/dt$.

For example, a voltage impulse in the mains with 100V/µsec leads in a 1µF X2- capacitor to a pulse-current of approx. 100A/µsec.

→ Surge-Pulses are stressing the insulation of the dielectric.

→ Pulses or/and humidity can accelerate the breakdown of the dielectric.

Voltage

Today‘s power-quality:

Temporarily Overvoltages in the power network are occuring.

Reference from a customer‘s experience:
- Highest nominal input voltage +30% for 30mi à e.g. 250Vrms x 1,3 = 325Vrms for 30min
- Highest nominal input voltage +50% for 5sec à e.g. 250Vrms x 1,5 = 375Vrms for 5sec
- Highest nominal input voltage +80% for 200msec à e.g. 250Vrms x 1,8 = 450Vrms for 200msec

Temporarily Overvoltages are especially occuring during regular changing between mains operation and generator operation, like it is common in newly industrialized countries.

→ Temporarily higher voltages and currents in the AC-line must be considered into the design.

If the temporarily overvoltges are above the Urated of the capacitor:

the breakdown voltage ability of the dielectric might be reduced → increased selfhealings.

The reduction of the breakdown voltage is associated with a higher current which can flow through the dielectric (lower IR).

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Trend: **Continouse increase of Converters and PFC's – what are the consequences?**

- Very quick dV/dt's (dV/dt decreases with lower line impedances)

- Unconsidered resonant-circuits may occur when several switched-mode sources/sinks are starting to resonant against each other.
- The wire-length is building with the individual power entry-filters a resonant frequency.
- If this resonant frequency is located in the range of the switching-frequency → → a **large current** is created by such resonances between the individual filter-capacitors .

If the filter-capacitors are loosing capacitance, a resonance is even more likely $\omega_0 = \frac{1}{\sqrt{LC}}$

- The residual ripple of the converter's output-ripple within the non-covered EMI-range (9kHz – 150 kHz) may lead to large currents.
In a soft network the current-ripple of the converter-output may lead to a voltage-ripple. Then each capacitor on the mains will be faced with this voltage-ripple, additionally to the 50 Hz.
→ capacitors on the mains are faced to **larger currents** than assumed.
The residual ripple depends on the capacitance (aging).

→ **The sufficiently strong robustness of all filter-components for the coming 20 years must be taken into account !**

Insufficient IEC-standards

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When designing power-electronics with long lifetime-expectation, each stress-factor – today and its possible change during the whole expected life – must be taken into consideration !

The stress on Film Capacitors in the field will continously increase. This is not sufficently respected in the current IEC- standards, e.g. IEC 60384-14, IEC 61071:

- **Only 24 pulses of 2.5 kV (1.2/50µs).**
- **Endurance-test and damp-heat test <u>don‘t combine</u> Temperature, Humidity and Voltage at the same time.**

  IEC 61071 Capacitors for power electronics – 5.15 (Endurance Test):
  “The purpose of the endurance test is to demonstrate the performance of the capacitor under the conditions which will actually occur in service.”
- **Selfhealing-test (e.g. Voltage-proof test IEC 60384.14 4.2.1 (4,3 Urdc, 60 sec.) is just effected under room-temperature.**

<u>Matter of fact:</u> **<u>Film Capacitors have a proven history for the End-of-Life > 20 years !</u>**
Are Aluminium-Electrolytic Capacitors able to provide such records ?

BUT: **Quality-problems in the field are showing that a homolagation-process following the IEC-standards may not be sufficient!**

Recommended additional qualification-tests

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Target: **<u>assuring Robustness and Fail-safe</u>**

- **robust against Humidity-Corrosion**
- **robust against Partial Discharge**
- **strong endspray-contacts**
- **Fail-safe under all application-conditions**

Test for the humidity-robustness

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Current IEC norms regarding humidity resistance:

<u>X- and Y- capacitors:</u>
IEC 60384-14 4.12 (Damp heat)
40°C, 90-95% humidity, 21 or 56 days (without voltage!)

<u>DC capacitors:</u>
IEC 60068-2-78 (Damp heat)
40°C, 90- 95% air humidity, 21 or 56 days (without voltage!)

These damp heat tests are only suitable for

- verifing the maximum <u>storage-perio</u>d of the capacitors in a warm and humid environment,

- for capacitors which are used in <u>intermittend applications</u> (e.g. electrical shaver, hair-dryer).

PROPOSED TESTS DURING HOMOLOGATION

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Accelerated lifetime-test under the impact of temperature, humidity and voltage:

85°C, 85% air humidity, rated voltage U_r

Duration:
either 168 hours, 504 hours or 1000 hours
(refering to IEC 60384-1 Ed. 5, clause 4.37 (damp heat test, steady state, accelerated)

This test is called THB-test (Temperature, Humidity, Bias), 85/85-test or humidity load test.

The nominal voltage is either AC or DC, depending on the type of film capacitor.

Whereby the following criteria apply:

- $\Delta C/C$	$\leq 10\%$	
- $\Delta \tan \delta / \tan \delta$	$\leq 200\%$	at 1 kHz, and at 10 kHz or 100 kHz. the loss factor may increase by a maximum factor of 3
- Insulation-resistance	$\geq 50\%$ if initial value	

PROPOSED TESTS DURING HOMOLOGATION

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The result of the THB test is the combination of a corrosion of the metallization, of the corrosion of the end spraying and of the aging of the dielectric.

The criteria are set in order that none of these process may take place.

- If the metallization is too thin → no change of C, increase of tan δ

- If the contact isn't good → no change of C, increase of tan δ.

- If the metallization is too thick → big loss of C, the capacitor will show fast C-loss, decrease of IR, ev. chimney or even explosion.

- If the dielectric becomes humid → increase of tan δ and decrease of IR.

IR is a measurement for the quality of the dielectric.

The Insulation Resistance IR is reduced if:

- the film contain humidity.

- the film thickness has been reduced (compression due to the electrostatic field).

- selfhealing with defect which are not well insulated, like carbonized polypropylene (during the short, the arc burns the PP surface of the arc channel).
Selfhealed zone may correspond to a decrease of the IR because of the carrbonization of the surface of the breakdown perforation

- aging of the polymer.

The reduction of IR can be seen as conducting path through the dielectric for the electrons. (a higher current can flow through the dielectric).

IR can confirm suspicion on the dielectric breakdown voltage performance.
Lower IR => humidity or conductive points in the dielectric => easier breakdown.

PROPOSED TESTS DURING HOMOLOGATION

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The lowest increase of the tan δ during the time in operation is essential for a good quality of a metallized film capacitor!

The change of the tan δ in an accelerated lifetime-test gives information about:

- the protection of the dielectric against humidity (at low frequency, e.g. at 50 Hz).

- the robustness of the construction against Partial Discharge/Corona and Humidity Corrosion (at higher frequencies, e.g. at 10kHz or 100kHz).

- The robustness of the endspray-contacts against humidity corrosion.

In an accelerated lifetime-test, the increase of the tan δ indicates a potential problem sooner than the capacitance loss !

PROPOSED TESTS DURING HOMOLOGATION

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Effects of the increase of the tan δ:

Rationale:

Assuming a constant frequency f and capacitance C, the increase of the tan δ is caused by an increase of the ESR (equivalent series resistance):

$$\tan \delta = ESR \times 2\pi f \times C$$

Temperature increase of the capacitor (ΔT):

$$\Delta T = P_V / G$$

$$\Delta T = T_{housing} - T_{ambient}$$

Increase in the housing temperature of the capacitor (°C), maximum 15°C above rated temperature

$P_V = I_{rms}^2 \times ESR$ **(Power loss of the film capacitor (mW))**

$G =$ **Thermal conductivity (mW/°C)**

The max. permissible values for I_{rms} (dep. on the max. permissible surrounding temp.) and G must be specified by the manufacturer of the capacitor.

PROPOSED TESTS DURING HOMOLOGATION

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→ The increase of the ESR is directly proportional to an increase of the power loss P_V and to the increase of the housing temperature of the film capacitor !

→ Knowing the the max.permissible increase of the ESR (tan δ) →
the operational leakage current I_{rms} of the circuit must be limited so that,
by limiting the power loss P_V,
the max. temperature (= temperature of the hotspot) must not be exceeded.
The temperature elevation due to the losses must be considered when determining the maximal environmental temperature.

If the increase of the ESR during the lifetime is allowed to increase by times 2 →
the operational Irms must be reduced by $\sqrt{2}$ to keep the original P_V .

If the increase of the ESR during the lifetime is allowed to increase by times 5 →
the operational Irms must be reduced by $\sqrt{5}$ to keep the original P_V .

Without knowing the maximum possible increase of the ESR during the lifetime, it is impossible to design a safe and reliable design of the electronic circuit !

Test to verify the robustness against Partial Discharges / Corona:

→ THB-Test (85/85-test) with a more strict criteria for the permissible change of C, e.g.:

- **- $\Delta C/C \leq 2\%$**

Partial Discharge/Corona causes a loss of capacitance.

If during the accelerated lifetime-test during 1000 hours only a very little capacitance-loss occurs, the design proves it robustness against PD/Corona under applied voltage-load and the impact of humidity and temperature.

PROPOSED TESTS DURING HOMOLOGATION

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PD/Corona Test - if the impact of humidity can be excluded:

-1.4 Un at 85°C for or 1000hrs

Criteria:
- acceptable temperature-increase.
- acceptable capacitance-loss.

Approach:

1.4Un instead of Un accelerates the aging by a factor 100 at a given temperature
An increase of 20°C accelerates the aging by a factor 10.
1.4 Un, 85°C and 1000 hours corresponds to 100'000 hours at Un and 70°C.

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Test to verify the strength of the endspray-contacts:

For AC-Capacitors:

- Impulse-Voltage Test, according to IEC 60384-14 4.13 (e.g. 24 pulses of 2.5kV (1.2/50µs) shall be performed after the THB-test (85/85-test).

- **24 pulses for consumer-applications,**
  „x“ pulses for industrial applications with longer lifetime-expectations.

For AC- and DC-Capacitors:

- Charge/Discharge test:

100 times the Urated, charging-time 0.5 seconds, discharging-time 0.5 seconds

Criteria: no abnormal change in ΔC/C and Δ tan δ / tan δ at 1kH and at 10kHz or 100kHz.

Efficient short test to verify the contact of the metalized film with the spraying.

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The Fail-safe characteristics of a film capacitor depends on its self-healing performance !

Fail safe:
The selfhealing process must be managed in all the conditions defined by the specification. It does mean that the electrode must evaporate around the defect and that this evaporation must be able to stop. At the end of the selfhealing, the short must be perfectly insulated.

Schneider Electric Recalls Inverters
By RenewableEnergyWorld.com Editors , 21. Januar 2011 | 8 Comments
The company announced that it was recalling its Xantrex GT Series Grid Tie Solar Inverters due to injury hazard.

Washington, D.C., United States – The U.S. Consumer Product Safety Commission, in cooperation with the Schneider Electric announced a voluntary recall of about 25,000 Xantrex Grid Tie Inverters.
*According to a company press release, a **capacitor** of the inverter can **degrade**, causing **outgassing** within the wiring compartment of the inverter. When arcing occurs, gasses could build and force the compartment **cover to be blown off**.*

PROPOSED TESTS DURING HOMOLOGATION

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The self-healing performance of a metallized film capacitor is decreasing with increasing temperatures.

- at higher temperature the film mechanical properties are much weaker. A selfhealing-process may damage the weaker film much easier.

- at higher temperature the dielectric strength of the film is much weaker → higher probability of breakdown which must be healed by selfhealing. If there are more selfhealings, there will be too much energy dissipate in the same time - the extinction of the breakdown won't be effective.

- at higher temperature the local Delta T brought by the selfhealing will heat the film to a point which is above the maximum temperature the capacitor can stand without breakdown.

PROPOSED TESTS DURING HOMOLOGATION

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As temperature has a big impact on the selfhealing-performace, the Fail-Safe Test must be effected under the maximum temperature of the hot spot inside the capacitor during the full time in service.

Hot spot temperature:

The hot spot temperature at the warmest spot on the interior of the film capacitor must not exceed the specified maximum operating temperature.

The difference in the temperature between the environment and the hotspot (ΔT_{HS}) is approximately 2x the temperature difference Δ T between the environment and the housing.

$\Delta T_{HS} \sim 2 \times \Delta T$

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Proposed tests during homologation:

→ **THB-test (85/85-test, U_R , 1000hrs) & Step Test**

= Combination of an accelerated lifetime-test & Fail-safe test

The purpose of the accelerated lifetime-test is to demonstrate the performance of the capacitor under the conditions which will actually occur in service.

The purpose of the Fail-safe test is to verify the selfhealing-performance of the capacitor under the conditions which will actually occur in service.

It is important to effect both tests, in order to verify that the selfhealing -performance of
the capacitor was not sacrified by strengthen the humidity-robustness of the electrodes
simply by using a very thick metallization.
The metallization is too thick when an initiated selfhealing-process (with the occuring very high arc temperature) don‘t stops → no Fail-safe!

FAIL-SAFE TEST – Step-Test

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Step Test (at a fixed temperature):

0.) a) Initial measurement (at RT) of C and tan δ at 50 Hz, 1 kHz and 10 kHz.
b) Preparation of the pieces 24 hours at Tmax.
c) Initial measurement (at Tmax) of C and tan δ at 50 Hz, 1 kHz and 10 kHz.

1.) a) 36 hours at U_R and $T_{max.}$
b) 12 hours shorted (= without voltage) at $T_{max.}$
c) Measurement (at $T_{max.}$) of C and tan δ at 50 Hz, 1 kHz and 10 kHz.

2.) a) 36 hours at 1.2 U_R and $T_{max.}$
b) 12 hours shorted (= without voltage) at $T_{max.}$
c) Measurement (at $T_{max.}$) of C and tan δ at 50 Hz, 1 kHz and 10 kHz.

3.) a) 36 hours at 1.4 U_R and $T_{max.}$
b) 12 hours shorted (= without voltage) at $T_{max.}$
c) Measurement (at $T_{max.}$) of C and tan δ at 50 Hz, 1 kHz and 10 kHz.

.....

x) a) 36 hours at x U_R and $T_{max.}$
b) 12 hours shorted (= without voltage) at $T_{max.}$
c) Measurement (at $T_{max.}$) of C and tan δ at 50 Hz, 1 kHz and 10 kHz.

FAIL-SAFE TEST – Step-Test

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Remarks:

RT: Room-temperature.

U_R : rated a.c. voltage for AC-applications, rated d.c. voltage for DC-applications.

$T_{max.}$: the max. temperature of the hot spot inside the capacitor during the complete tim in operation.

The oven temperature shall be set to get a hot spot at $T_{max.}$.

If possible, the pieces shall be left in the oven to do the measurement.

If it's not possible, the RLC meter should be just before the door of the oven to do an immediate measurement, especially if the pieces are small.

FAIL-SAFE TEST – Step-Test

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It has to be considered that the aging of the capacitors increases its ESR and power-loss during the time in service, respectively the temperature of the capacitor's hot spot.

A Fail-Safe peformance is mandatory when the capacitor in service keeps on exceeding its End-of-Life . Therefore the Step-Test must be performed at the $T_{max.}$.

The steps are only stopped when the capacitance-drop is bigger than 50% .
(capacitance-loss during this test = selfhealing is working).

A Fail-safe performance of a metallized film capacitor is assured by its ability to clear faults by selfhealings.

The Step-Test is intended to show that the selfhealing-performance of the capacitor is not only under control at room-temperature, but also during the full time in service.

Target to reach: 50% of capacitance-loss without sign of chimney or burning or explosion.