Capacitors 101

Capacitor Basics and Technologies

Presenters:

Frank Puhane, Wurth Elektronik and Stephan Menzel, CapXon

Tuesday February 21, 2023

10 AM CDT, 4 PM GMT

https://zoom.us/join

Webinar ID: 811 3974 3171

CAPXON

Capacitor 101

Cap Basics and Cap Technologies

2023-02-21

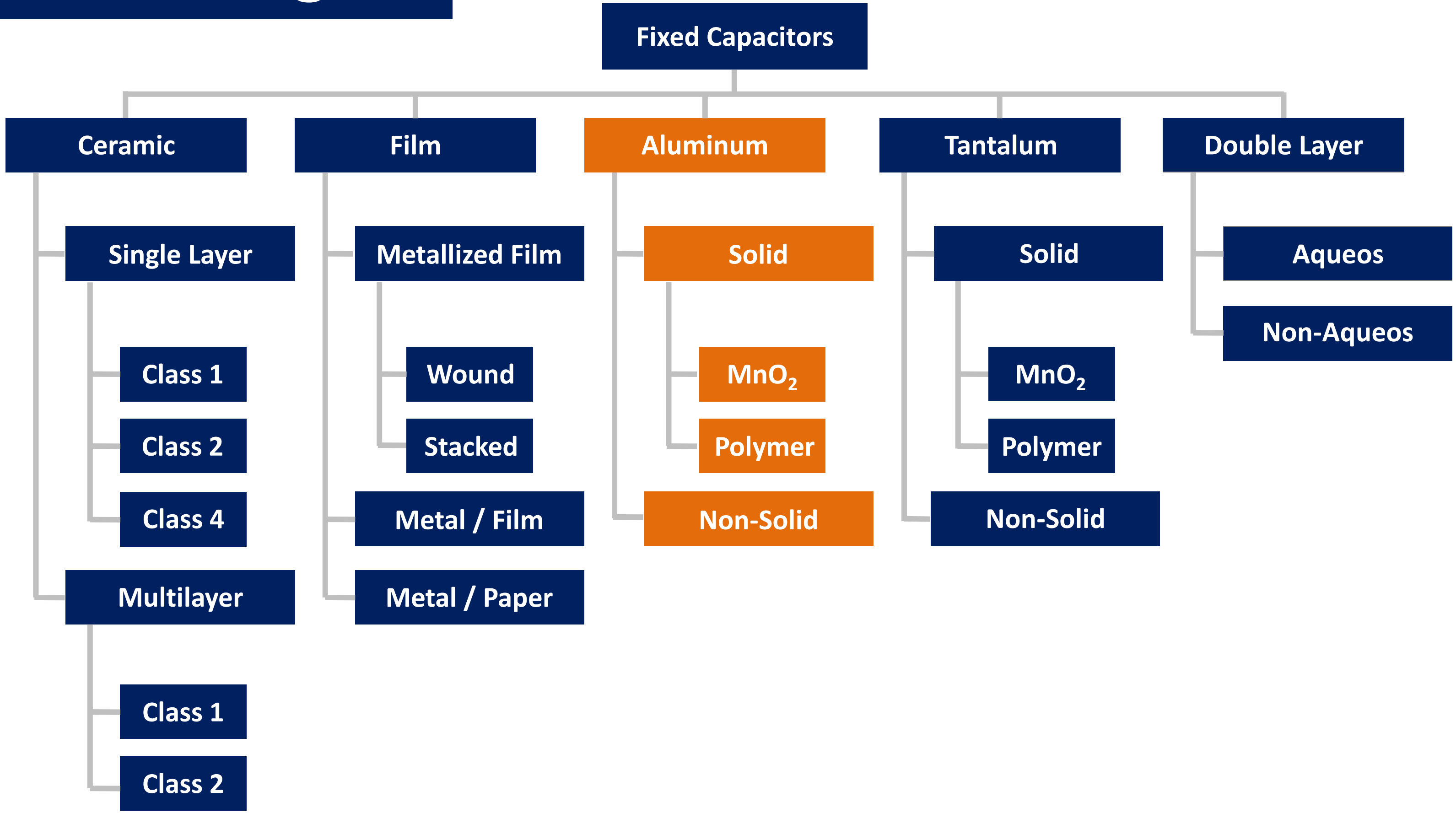
CapXon - Manufacturer for professional
aluminum electrolytic, conductive polymer and hybrid electrolytic capacitors as well etched and formed aluminum foil

Capacitor Basics

CapXon - Manufacturer for professional

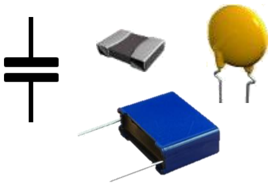
aluminum electrolytic, conductive polymer and hybrid electrolytic capacitors as well etched and formed aluminum foil

Cap Technologies

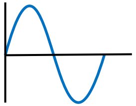


Basic Applications

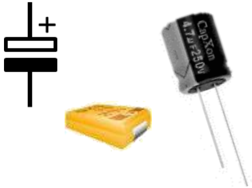
- **Capacitors**
  - **Fixed**
    - **Unpolarized**

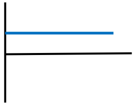
      - **AC**

        - Coupling
        - Filtering
        - Oscillation
        - Leakaging
    - **Polarized (E-Cap)**

      - **DC**

        - Smoothing
        - Buffering
        - Energy Storage
        - Timing Element
  - **Adjustable**
    - **Potentiometer**

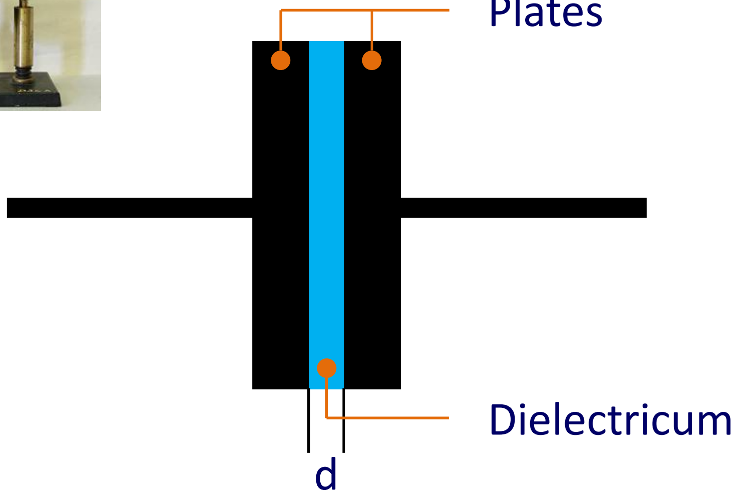
      Adjustment during operation
    - **Trimmer**

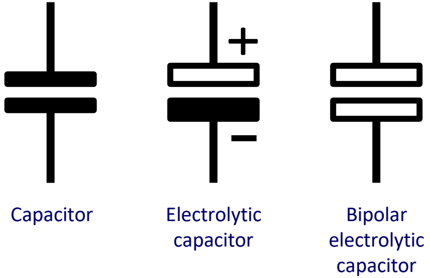
      Setting for adjustment purposes

Basics

Physics



Model of a simple capacitor



Definition of the capacity:

$$C = \varepsilon \cdot \frac{A}{d}$$

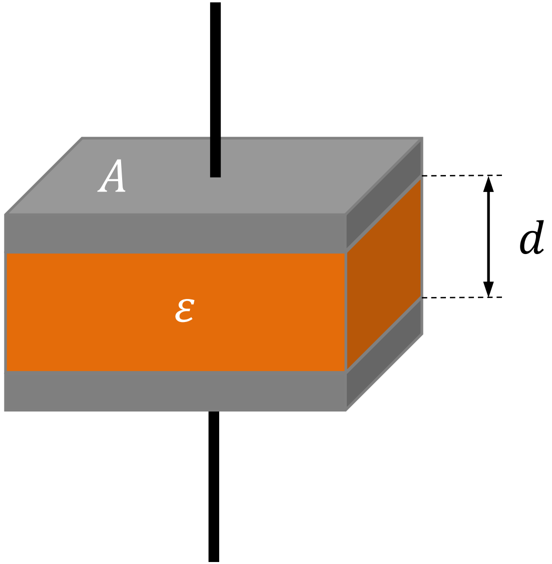
A : Surface area
d : Distance between plates
ε : Material function

CAPXON

Basics

Capacitance C of a capacitor:

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



C = Capacitance
ε_0 = Dielectric constant of insulator (vacuum)
ε_r = Dielectric constant of matter
A = Surface area of plates
d = Distance between plates

$$E = \frac{1}{2} \cdot C \cdot V^2$$

Energy

$$Z = \frac{1}{j \cdot \omega \cdot C}$$

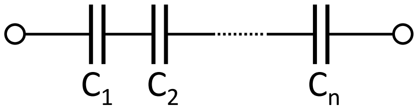
Reactance

$$Q = C \cdot V = \int_{-\infty}^{+\infty} I \cdot \delta t$$

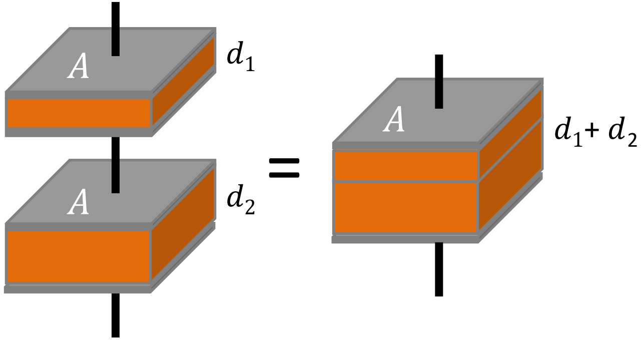
Electrical charge

Basics

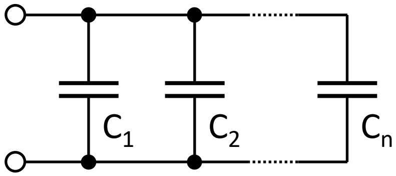
Series and parallel arrangement



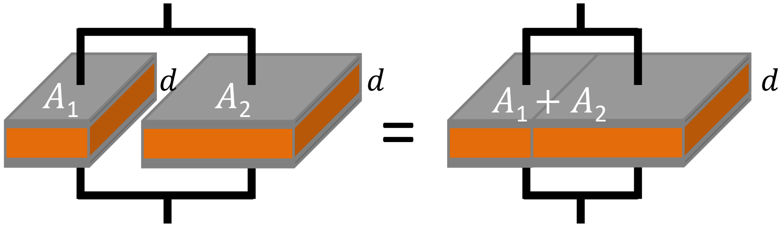
$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots + \frac{1}{C_n}$$



The charge on each capacitor is the same -> less capacitance and less charge storage than with either alone but the total voltage is divided between the numbers of capacitors



$$C_{eq} = C_1 + C_2 + \cdots + C_n$$

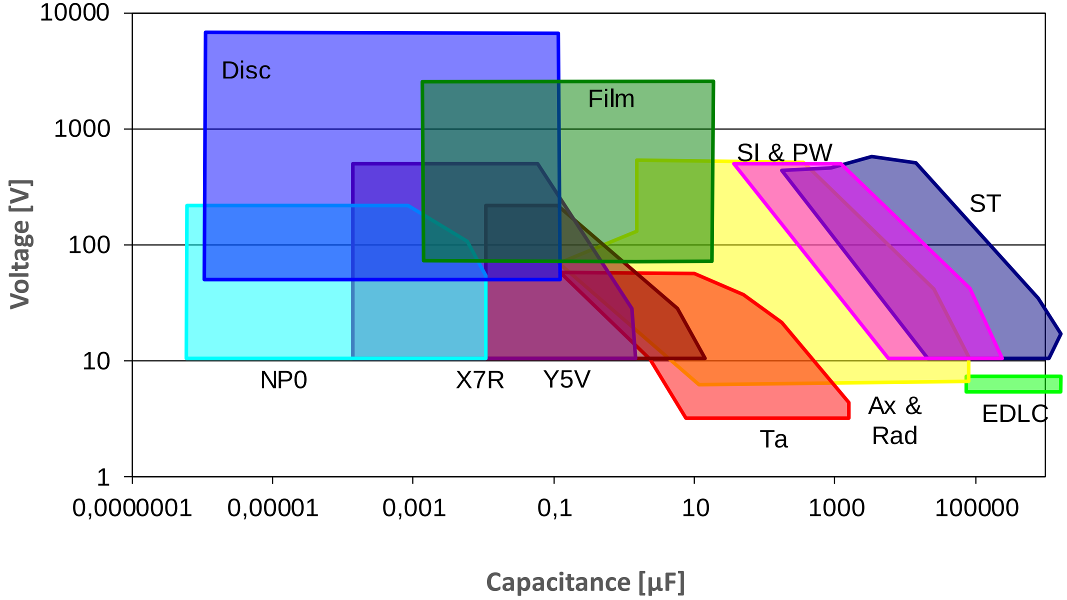


The total charge stored is the sum of the charge in each capacitor -> more capacitance and more charge storage than with either alone but the same voltage on each capacitors

Basics

Comparison dielectrics

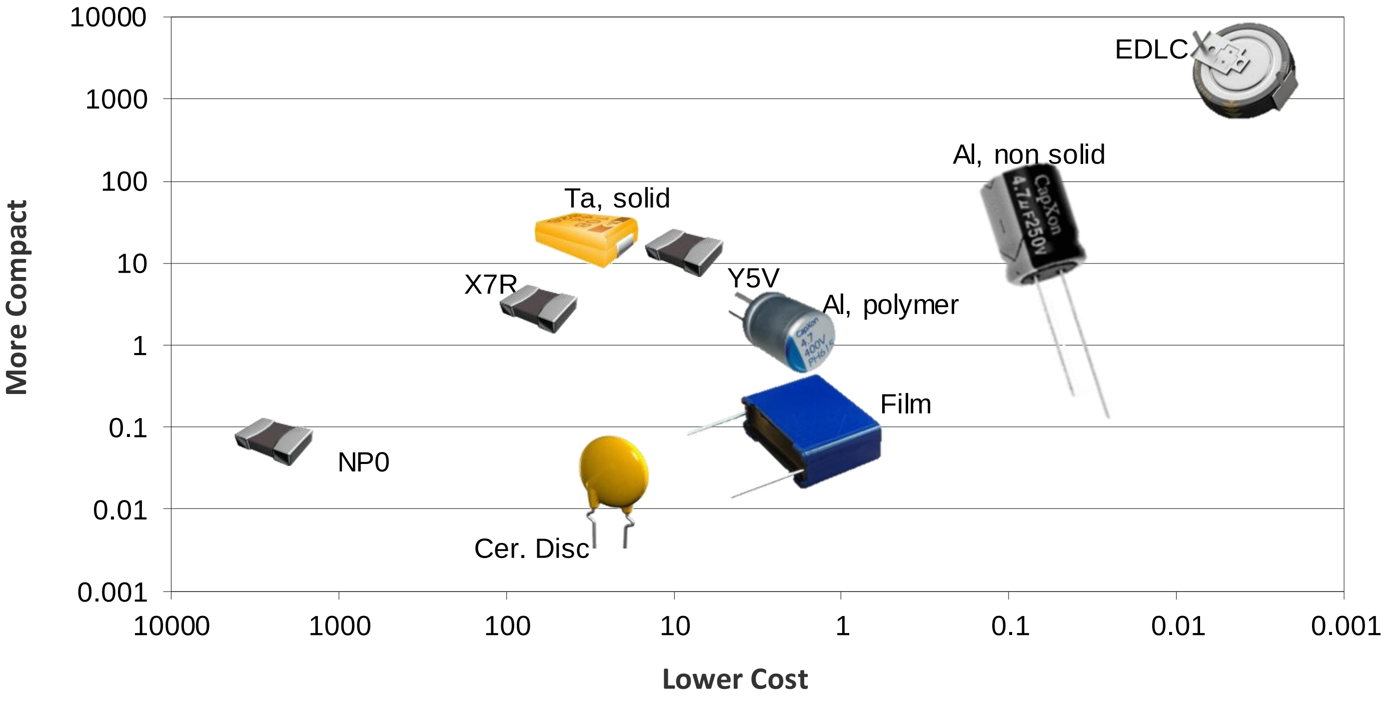
Dielectric	Characteristics
Aluminum	Losses, limited life Rugged
Ceramic	Brittle Small & low cost
Double Layer	≤ 3 V High density
Film	dV/dt limit Low losses
Tantalum	Unstable oxide High ε matrial



CAPXON

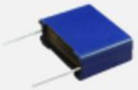
Basics

Compactness vs. cost



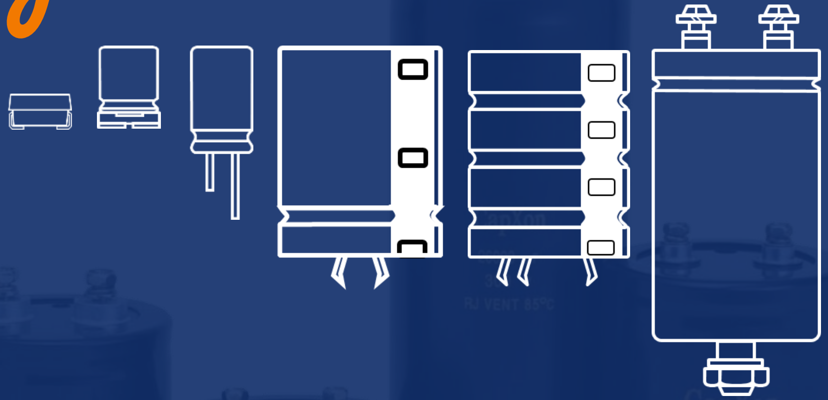
Basics

Technology comparison

Technology	Illustration	Capacitance	Voltage	Current load capacity	Temperature	Main applications
Aluminum e-cap		+ + >100 000µF	− Up to 650 VDC	− Up to 0.05 A/µF	+ + Up to 150°C	DC-Link, Storage, Smoothing
Film cap		+ Some 1000 µF	+ + Up to 10 kVDC	+ Up to 3A/µF	− ≈ 110°C	Filtering, DC-Link, Compensation
Ceramic cap		− Up to 100 µF	+ + Up to 50 kVDC	+ + Up to 10 A/µF	+ + Up to 150°C	Filtering, DC-Link, Coupling,

CAPXON

Aluminum Electrolytic Capacitors

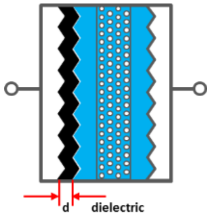


CapXon - Manufacturer for professional

aluminum electrolytic, conductive polymer and hybrid electrolytic capacitors as well etched and formed aluminum foil

Aluminum E-Caps

How to build / increase capacitance?



$$C = \varepsilon \cdot \frac{A}{d}$$

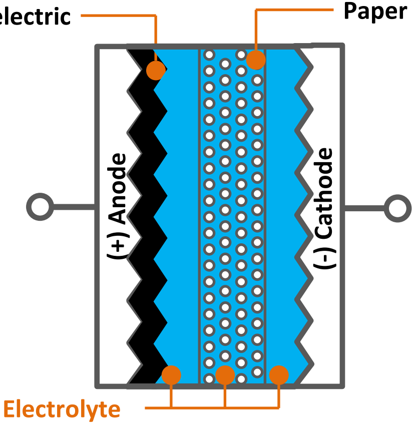
Anode foil of the capacitor

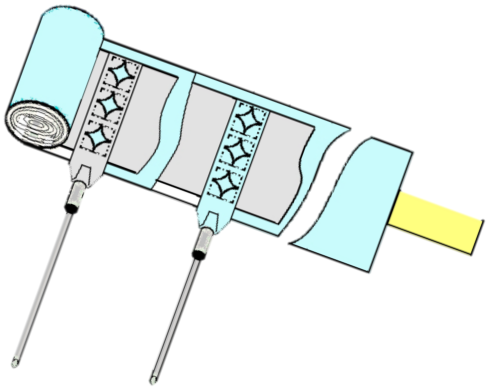
Increase the surface etching anode foil

Very thin layer of dielectric forming Al_2O_3 layer

Fill the rough surface by impregnating with electrolyte

Contact cathode foil

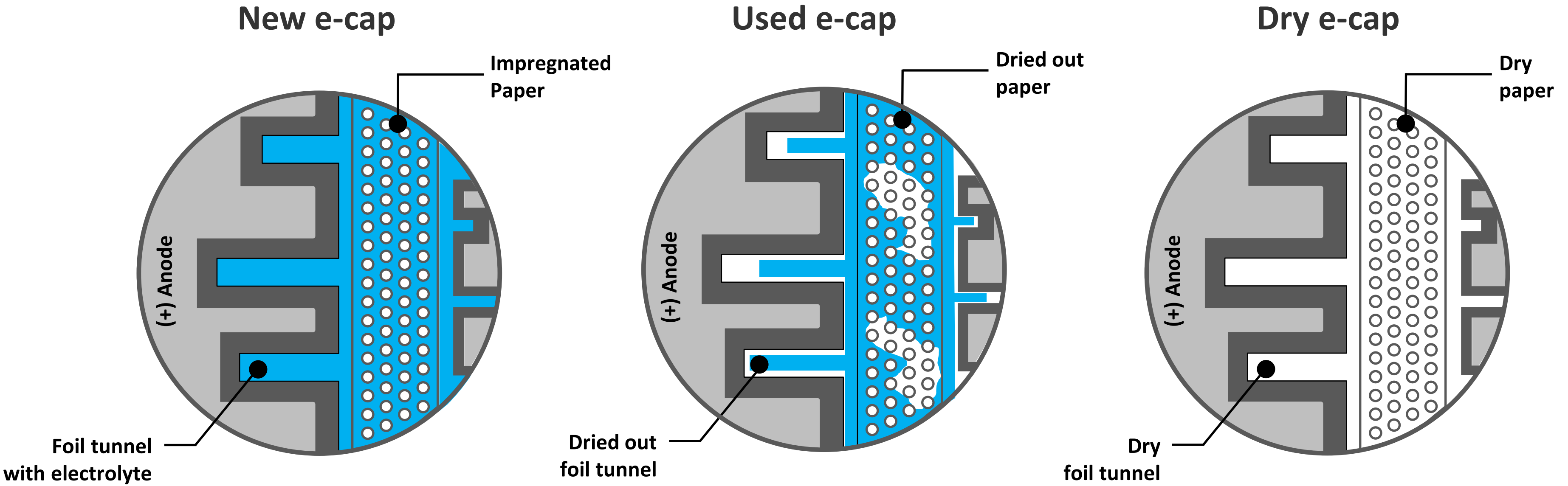




Model of a simple aluminum electrolytic capacitor

CAPXON

Lifetime estimation



- Capacitance
- ESR/Impedance
- Leakage current

- Capacitance
- ESR/Impedance
- Leakage current

- Capacitance
- ESR/Impedance
- Leakage current

END OF LIFETIME

CAPXON

Aluminum E-Caps

Applicable standards

Applicable standards for Aluminum electrolytic capacitors

- IEC60384-1 and JIS C5101-1 - Fixed capacitors for use in electronic equipment
- IEC60384-4 and JIS C5101-4 - Aluminum electrolytic capacitors with solid and non-solid electrolyte

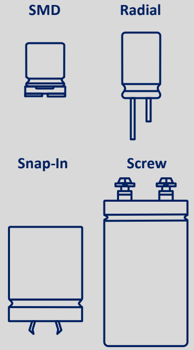
Useful life, load life, endurance, shelf life etc…is a difference in the specified drift and manufacturer dependent…so check the data sheet details exactly

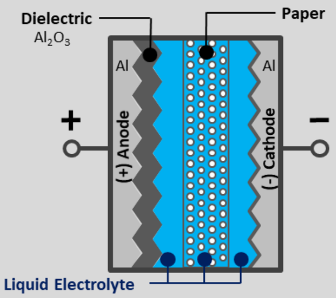
Test conditions	Useful life / Load life	Endurance	Shelf life
Duration	e.g. 10000h @T_{0_Max}	e.g. 5000h @T_{0_Max}	1000h @ T_{0_Max}
Applied values	V_R and I_R	V_R **or** (V_R and I_R)	None
After test requirements			
Capacitance change	≤ ±30% of initial measured value	≤ ±10% of initial measured value	≤ ±10% of initial measured value
Dissipation factor change	≤ ±300% of initial measured value	≤ ±130% of initial measured value	≤ ±130% of initial measured value
Leakage current change	≤ the initial specified value		

Example for different test conditions

Al E-Cap Technologies

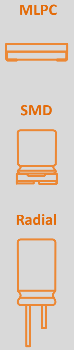
Aluminum Electrolytic

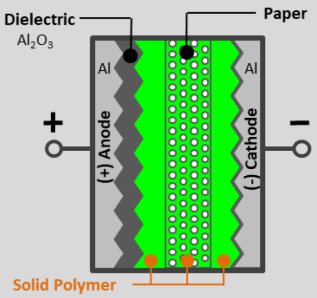




Rated Voltage ▪ V_R	4 VDC to 650 VDC
Cathode Material	Liquid Electrolyte
Self-healing of Dielectric	Yes
Package	Widest range in all sizes
Stability	Reduced performance at low temperature
Lifetime	Limited life at high temperature
Reliability	AEC-Q200 qualified

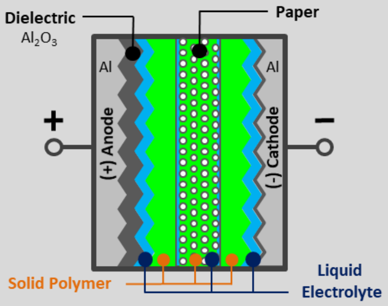
Solid Conductive Polymer





Rated Voltage ▪ V_R	2.5 VDC to 100 VDC
Cathode Material	Solid Conductive Polymer
Self-healing of Dielectric	No
ESR	Ultra-low ESR at high frequency
Stability	Stable for low and high temperature
Lifetime	Very stable and long life – no dry out
Reliability	Only internal standard qualification

Hybrid Conductive Polymer



Rated Voltage ▪ V_R	16 VDC to 400 VDC
Cathode Material	Solid Conductive Polymer & Liquid Electrolyte
Self-healing of Dielectric	Yes
ESR	Very low ESR at high frequency
Stability	Even more stable than liquid type
Leakage current. ▪ I_{LEAK}	Lower leakage current than Solid Conductive Polymer Type
Reliability	AEC-Q200 qualified

Conductive Polymer

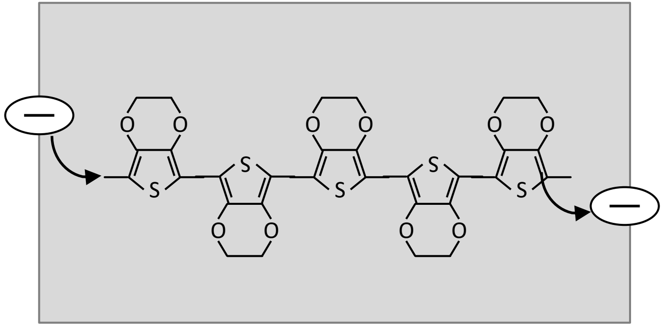
Polymer vs. liquid electrolyte

What is the difference between Conductive Polymer and Liquid Electrolyte?

Conductive Polymer

Electron moves on molecules *FAST*

(low resistance)

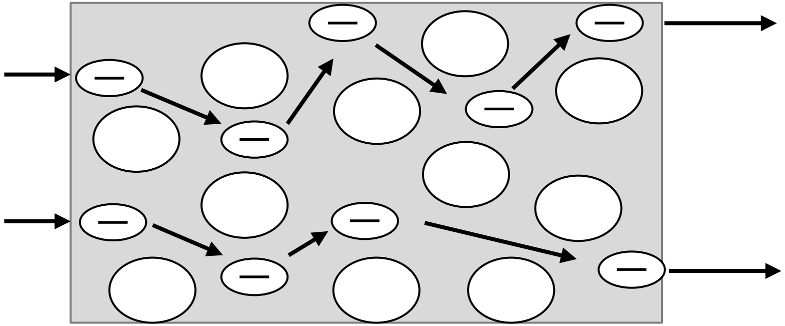


Conductivity index: 1,000 to 10,000 !!!!

Liquid Electrolyte

Electron moves in solution S L O W

(high resistance)



Conductivity index: 1

ADVANTAGES WHAT MAKES HYBRID POLYMER SO INTERESTING?

As a mix of the two worlds, the hybrid polymer technology offers the best performance of high-capacity storage components

Liquid Electrolyte

- High voltage capabilities
- High temperature performance
- Low leakage current

+

Solid Conductive Polymer

- High ripple current
- High lifetime perfomance
- Low ESR

=

Hybrid Polymer

- Best performance of both worlds

CAPXON

Conductive Polymer vs. other dielectrics

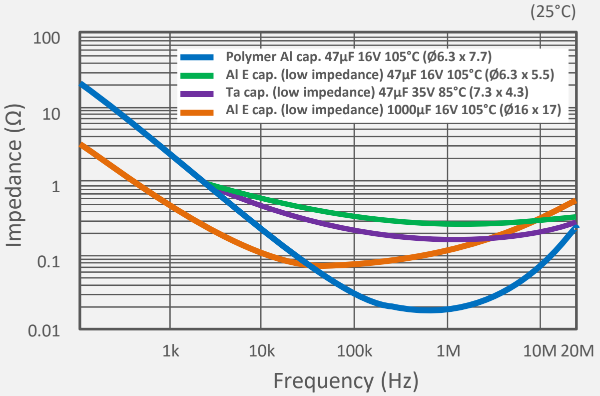
Solid Conductive Polymer Cap.

Al E Cap.

Tantalum Cap.

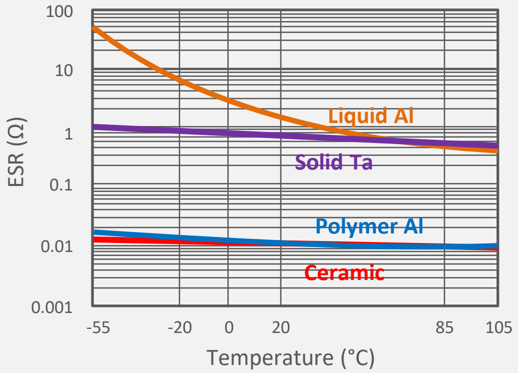
MLCC

Impedance vs. Frequency



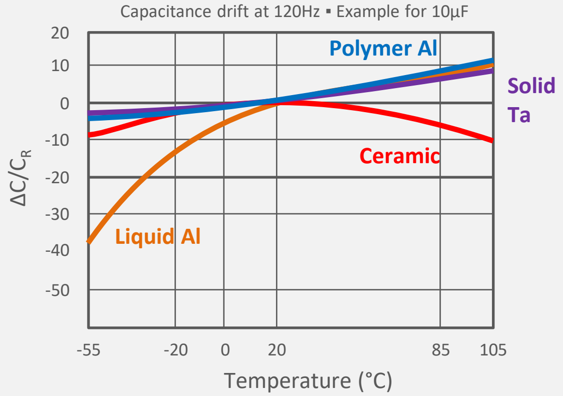
Low impedance at high frequency
Allows large ripple current
Discharges quickly
Coupling to remove the ripple in the circuit, pulse, electrostatic and other various kinds of noise

ESR vs. Temperature



ESR hardly changes with temperature

$\Delta C/C_R$ vs. Temperature



Stable capacitance in a wide temp. range
Positive temp. coefficient
Extremely stable at low temp.

CAPXON

Technology Comparison

++ ... best performance

\+ ... well performance

● ... basic performance

Characteristics	Aluminum Electrolytic Capacitor	Solid Conductive Polymer Capacitor	Hybrid Conductive Polymer Capacitor
ESR at High Frequency	● (120 ~ 1000 mΩ)	++ (7 ~ 15 mΩ)	+ (20 ~ 30 mΩ)
Leakage Current ▪ I_{LEAK}	++ (0.01*C_R*V_R)	● (0.2*C_R*VR)	++ (0.01*C_R*V_R)
Ripple Current ▪ I_R	● (~ 600 mA)	++ (2000 ~ 7000 mA)	+ (2000 ~ 3000 mA)
Rated Voltage ▪ V_R	++ (~ 700 V)	● (~ 100 V)	+ (~ 400 V)
Operating Temperature Characteristics	+ (-40 ~ + 125 °C)	+ (-55 ~ + 125 °C)	++ (-55 ~ + 150 °C)
Low Temperature Characteristics	● (-40 ~ + 125 °C)	++ (-55 ~ + 125 °C)	+ (-55 ~ + 150 °C)
Lifetime	● (105 °C / 3000h)	++ (105 °C / 5000h)	++ (105 °C / 10000h)
Failure Mode	+ Open	● Open / Short	+ Open

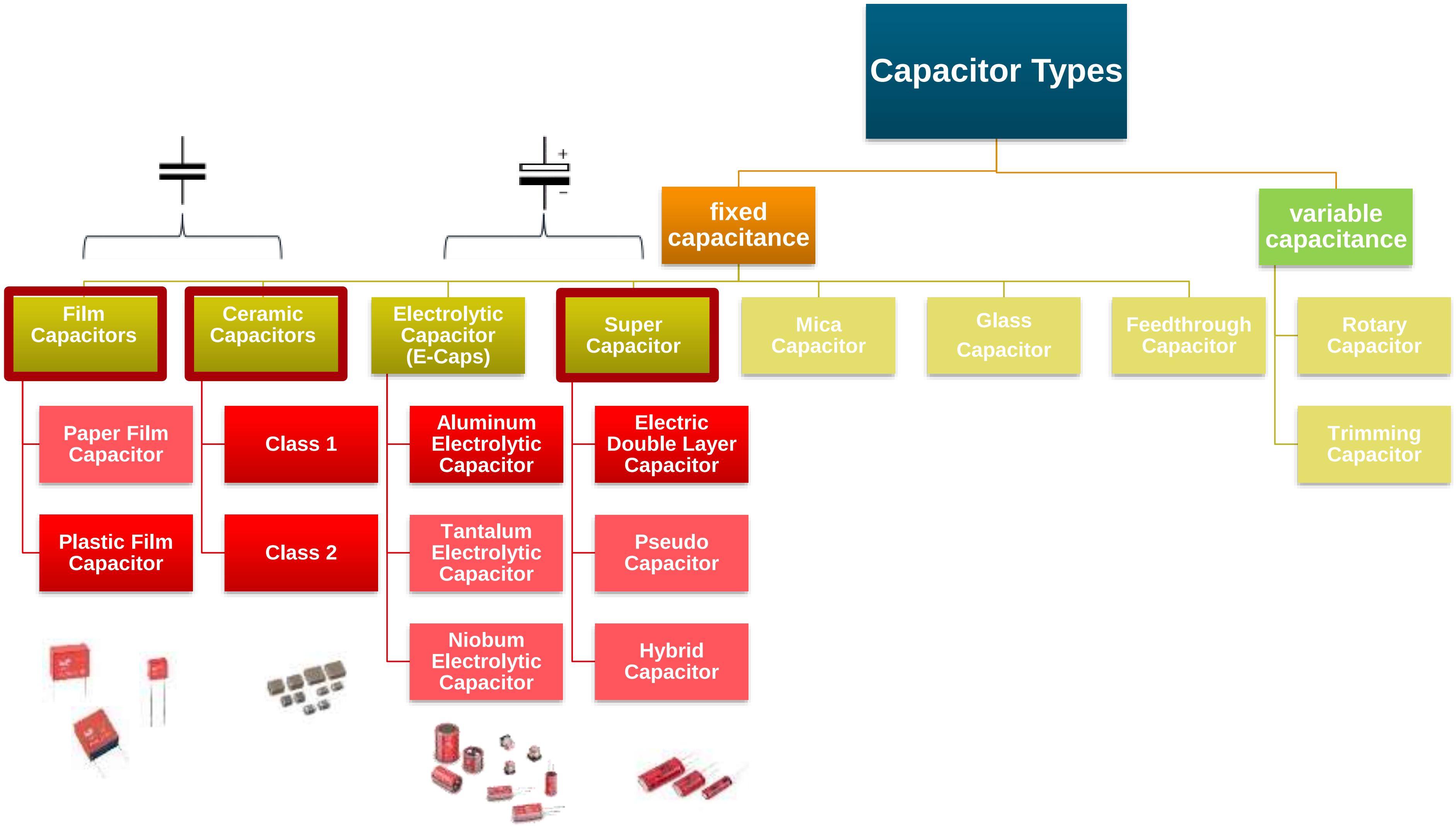
CAPXON

CAPACITOR 101
CAP BASICS AND CAP TECHNOLOGIES

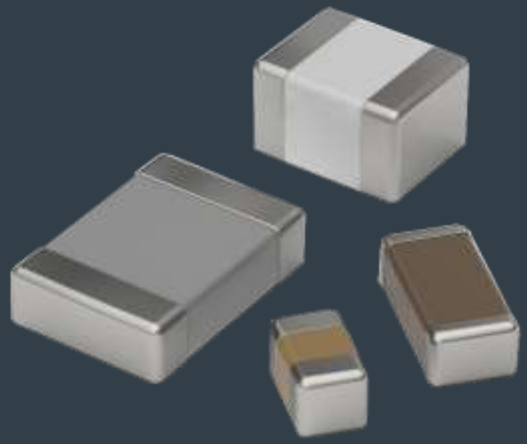
Frank Puhane
Head of Product Management - Capacitors & Resistors

WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

CAPACITOR TYPES

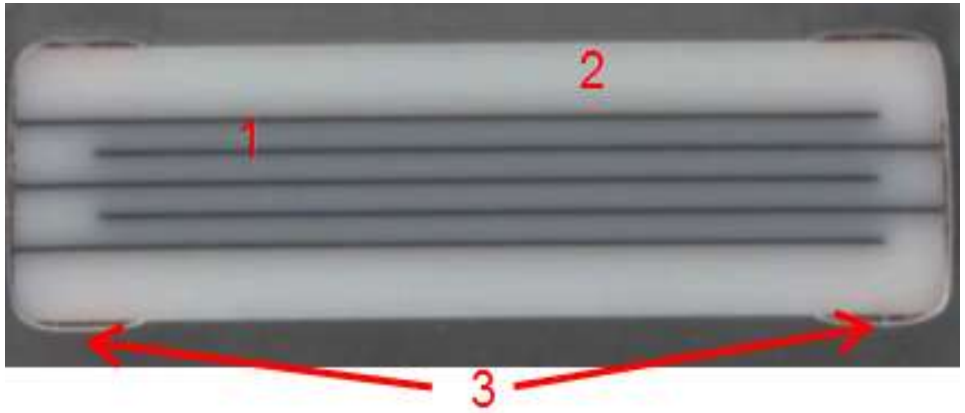


MLCC

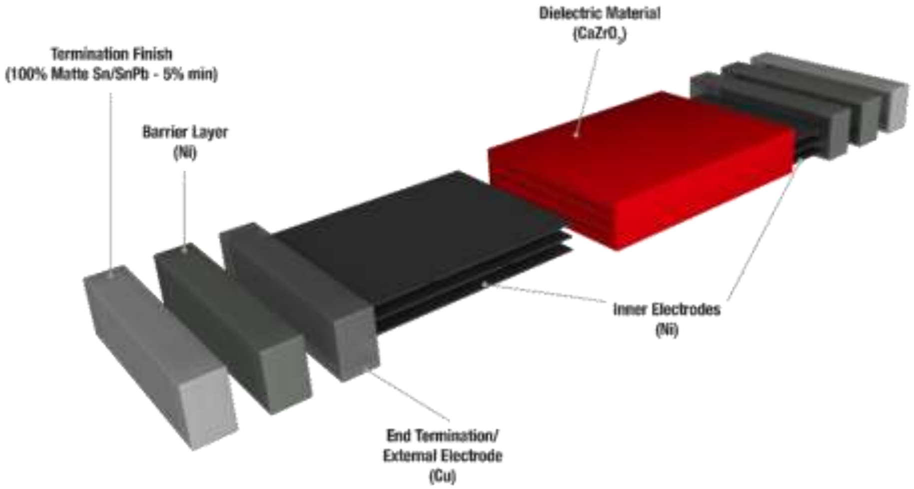


PROPERTIES OF CERAMIC CAPACITORS

- Naming by the used dielectrics
- Distinction of the capacitors by the used dielectric
- Monolithic ceramic body



- Construction by multi-layer method
- Multi-Layer Ceramic Capacitor (MLCC)



WHAT NEED TO BE CONSIDERED?

- Class 1:
  - Mainly the C-tolerance need to be taken into account
  - Depended on specific type no temperature dependency (e.g. C0G / NP0) or linear temperature dependency
  - No further derating
    - So this types provide stable and precis C-values
    - For applications with fixed and stable c-values (e.g. clock) the proper choice

- Class 2:
  - There are multiple effects with influence on given C-value:
    - C-tolerance (according to datasheet)
    - Non linear temperature dependency (manufacturer specific, related to material mix / construction)
    - DC-bias (manufacturer specific, related to material mix / construction)
    - Aging behavior

The capacitance value of datasheet will be different with in an running application

- **Check the manufacturer data to be able to assume occurring effects**

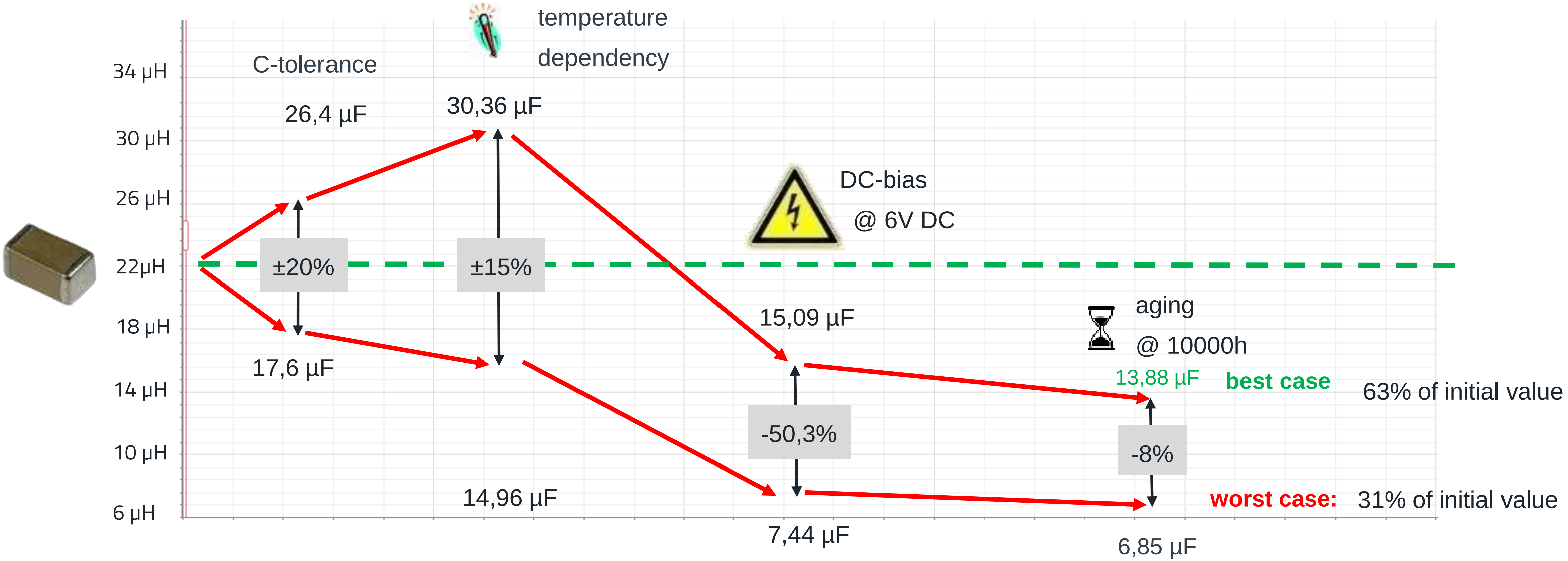
DIFFERENT CODING

IEC 60384-21 coding for class 1 ceramics			
Coding			
Identifier	Temperature coefficient TC [ppm/°C]	Tolerance of the temperature coefficient TC [ppm/°C]	Equivalent EIA-RS-198 coding
P100	100	±30	M7G
NP0	0	±30	C0G
N33	–33	±30	S2G
N75	–75	±30	U1G
N150	–150	±60	P2H
N220	–220	±60	R2H
N330	–330	±60	S2H
N470	–470	±60	T2H
N750	–750	±120	U2J
N1000	–1000	±250	M3K
N1500	–1500	±250	P3K

EIA-RS-198 coding for class 2 ceramic capacitors					
1st character		2nd character		3rd character	
Letter	Lower temperature limit	Number	Upper temperature limit	Letter	Capacitance change over the permissible temperature range
X	–55 °C	**2**	+45 °C	**A**	±1.0%
Y	–30 °C	**4**	+65 °C	**B**	±1.5%
Z	+10 °C	**5**	+85 °C	**C**	±2.2%
		6	+105 °C	**D**	±3.3%
		7	+125 °C	**E**	±4.7%
		8	+150 °C	**F**	±7.5%
		9	+200 °C	**P**	±10%
				R	±15%
				S	±22%
				T	+22/–33%
				U	+22/–56%
				V	+22/–82%

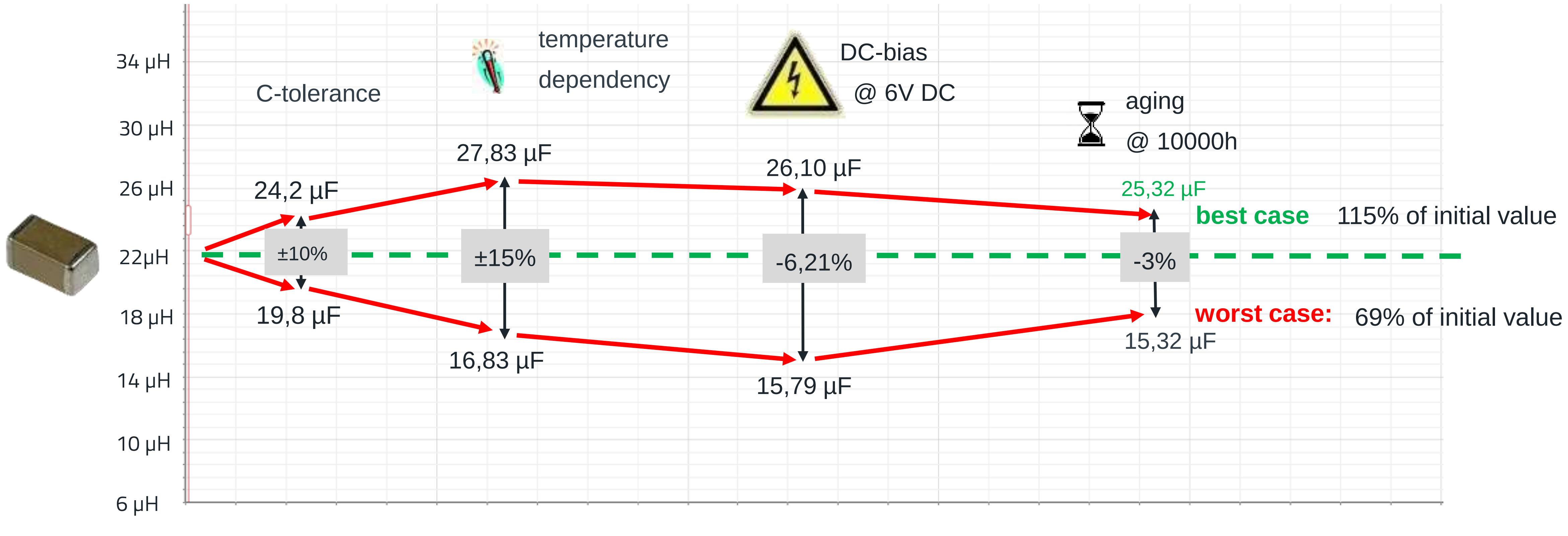
EXAMPLE 1: HOW MUCH CAPACITANCE DO YOU REALLY GET?

885012108011: 22µF / X5R / 1206 / 20% @ 6V DC

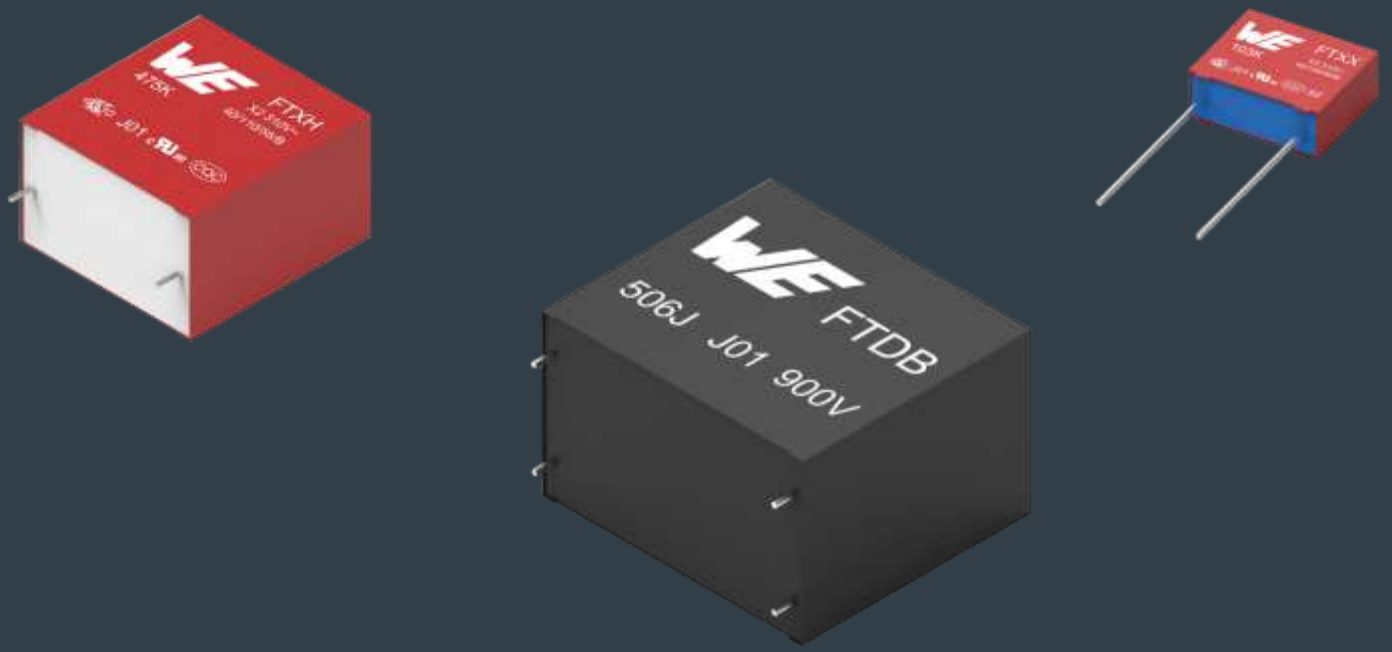


EXAMPLE 2: HOW MUCH CAPACITANCE DO YOU REALLY GET?

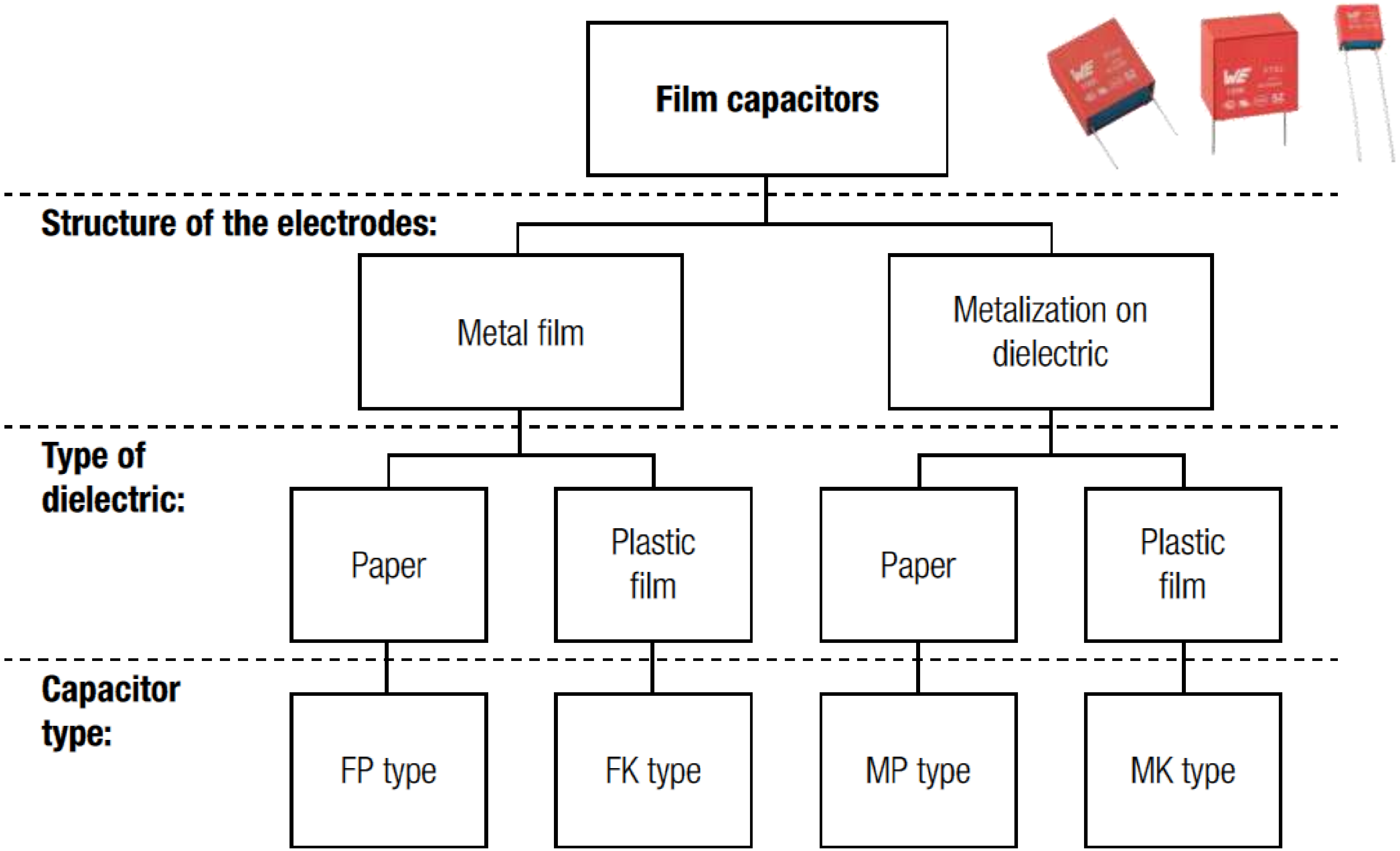
885012109006: 22µF / X7R / 1210 / 10% @ 6V DC



FILM CAPACITOR



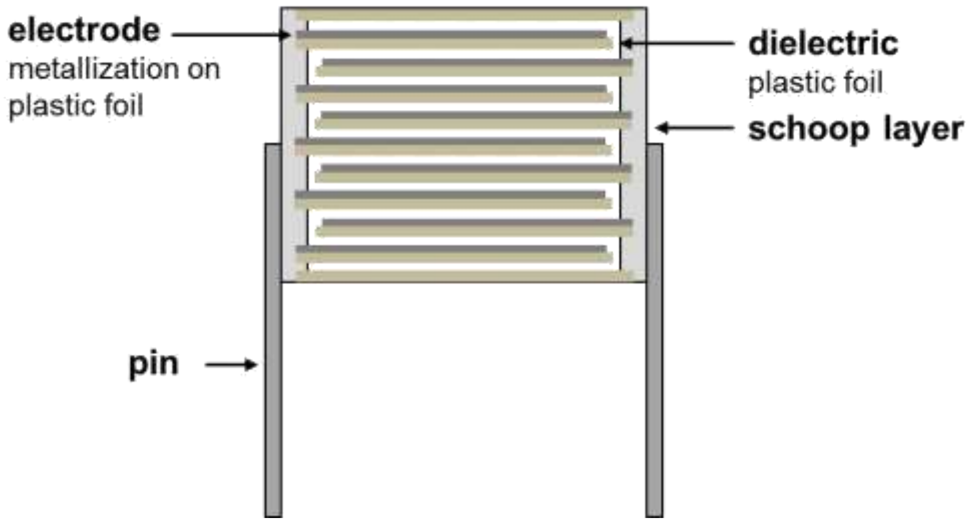
TYPES OF FILM CAPACITORS

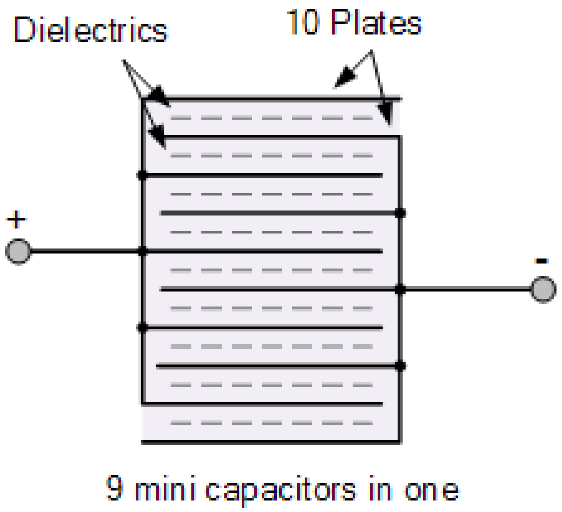


(M = metalized; F = film; K = plastic; P = paper)

CONSTRUCTION FILM CAPACITORS

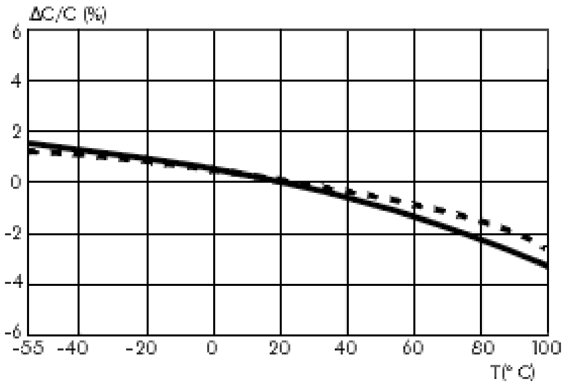
Dielectric	Code for the FK capacitor	Code for the MK capacitor
Polyester (PETP)	KT	MKT
Polycarbonate (PC)	KC	MKC
Polypropylene (PP)	KP	MKP
Polystyrene (PS)	KS	MKS

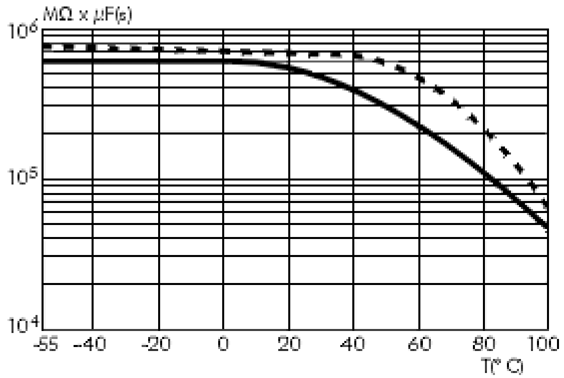


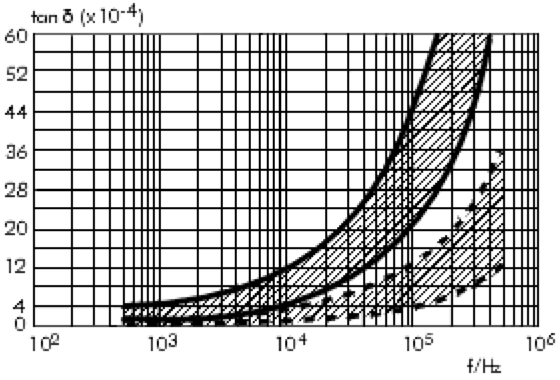


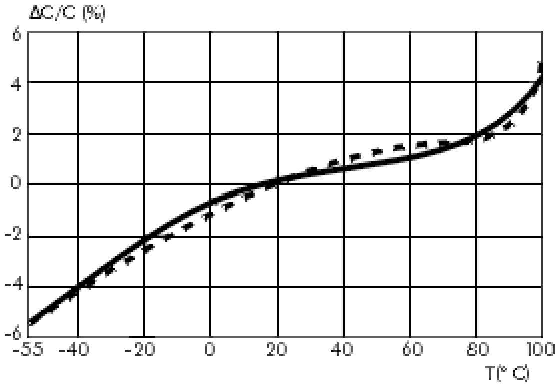
DIFFERENT BEHAVIOR OF THE DIELECTRIC MATERIAL

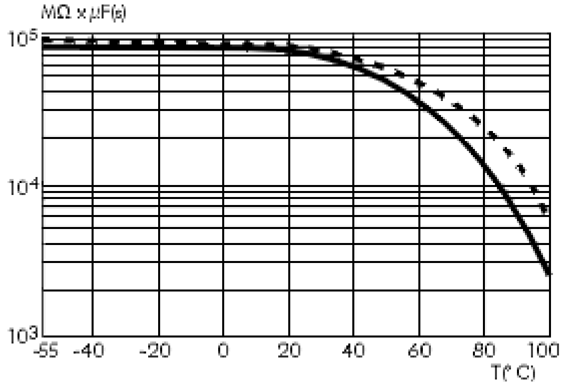
Polypropylen vs. Polyester

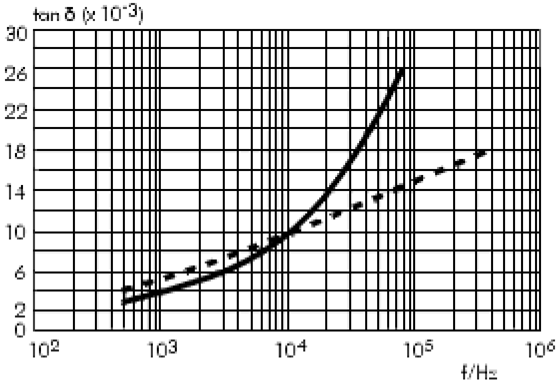




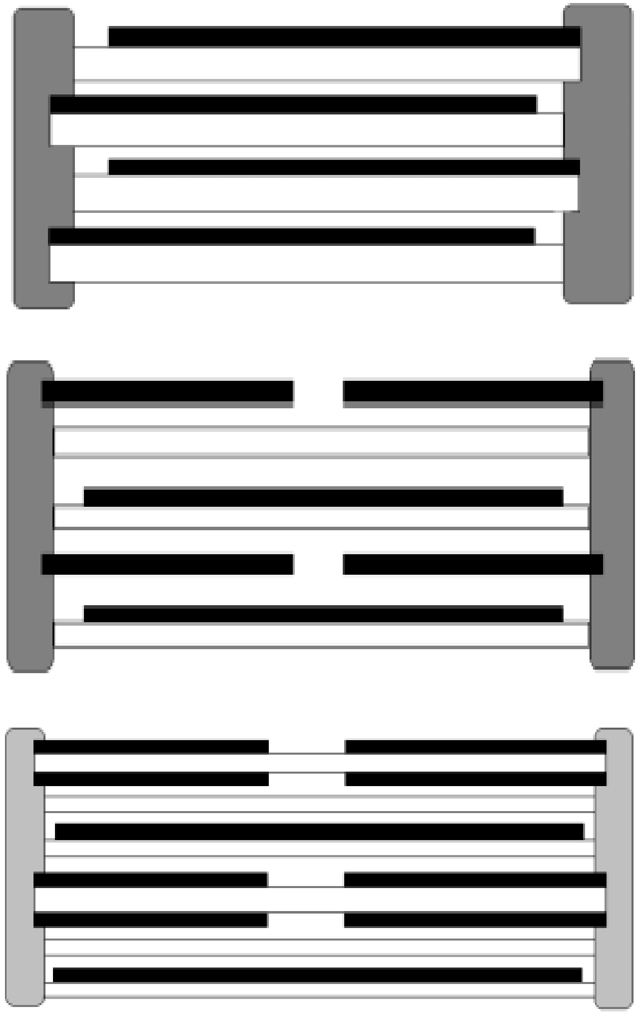






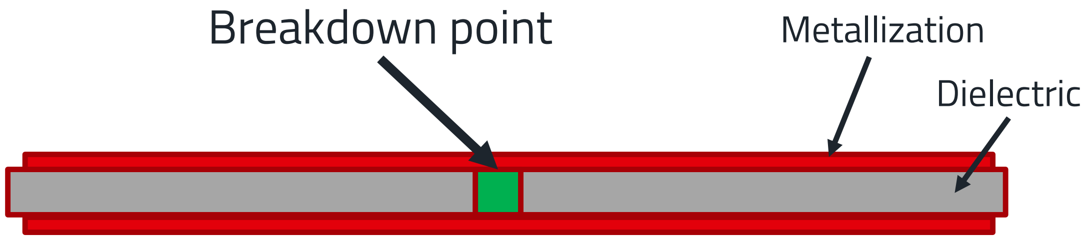


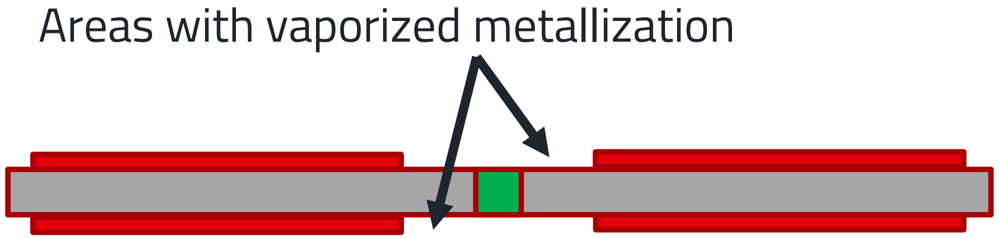
CONSTRUCTION OF FILM CAPACITORS



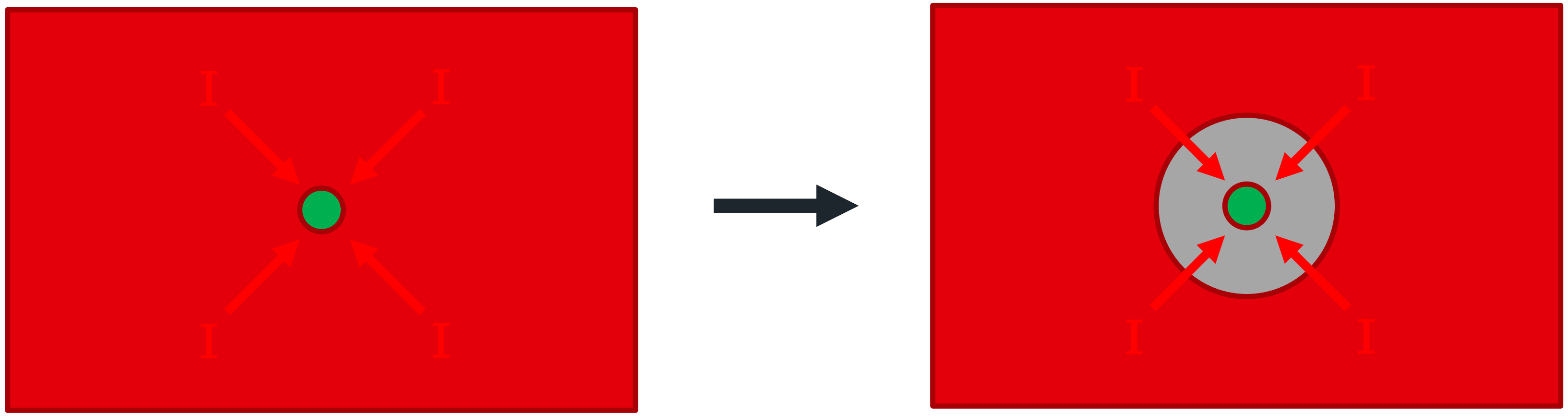
- Metallization on plastic foil
- Metallization Al and Zn (single or double sided)
- Thickness of metallization: 0.01 - 0.05µm
- Total film thickness: ≤ 1µm
- Internal wiring to increase the voltage level / pulse resistance

SELF HEALING OF FILM CAPACITORS



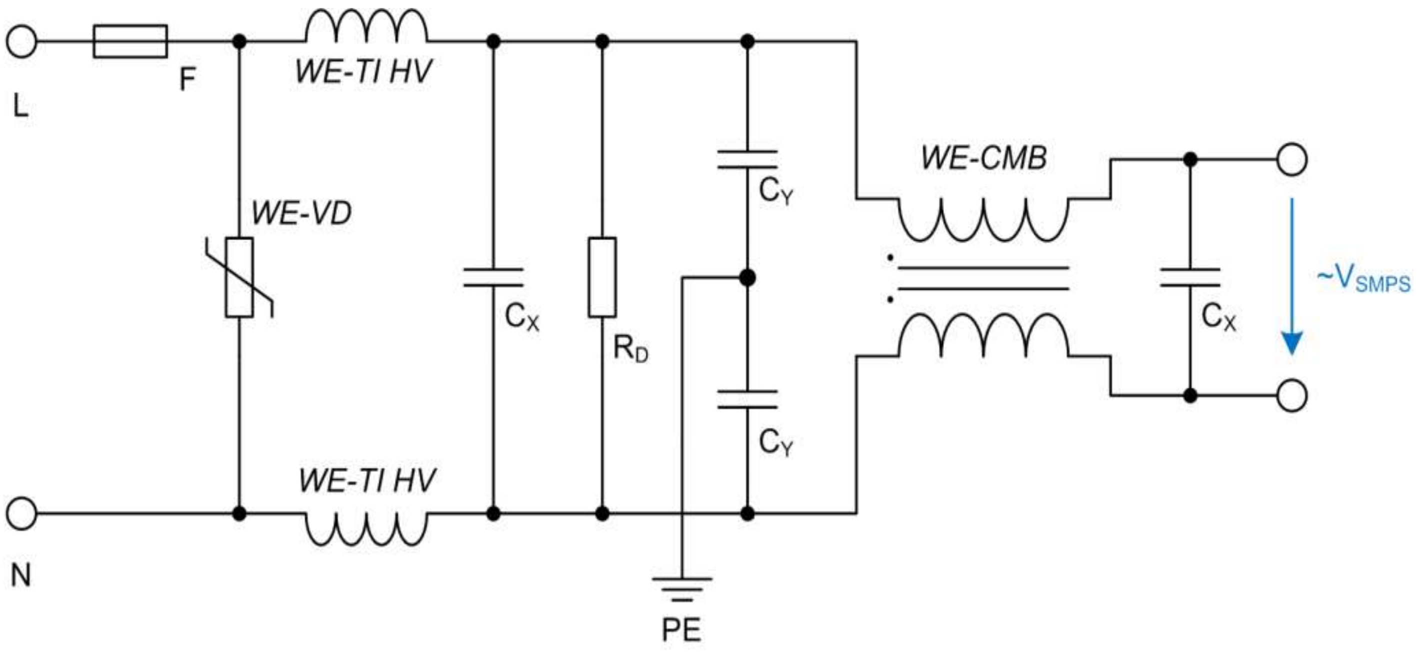


Short circuit → high current density → „evaporation zone"



TYPICAL APPLICATION

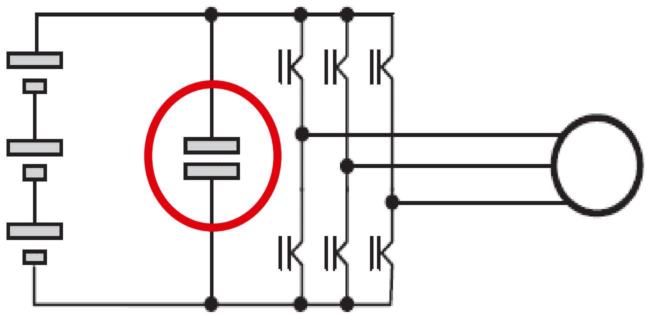
Mains filter



TYPICAL APPLICATION

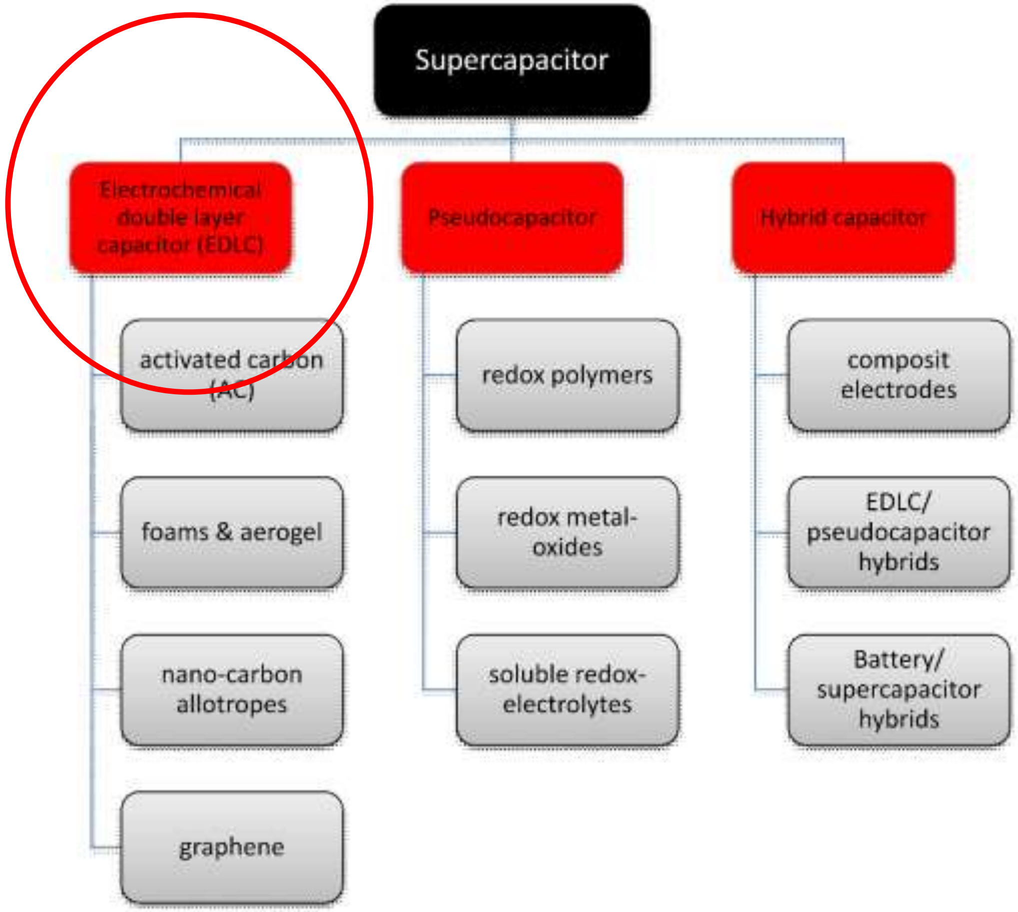
DC-link

- Power converters



SUPERCAPACITOR

CLASSIFICATION OF CAPACITORS



Types of Supercapacitors, based on design of electrodes:

- Double-layer capacitors
  - Electrodes: carbon or carbon derivatives
- Pseudocapacitors
  - Electrodes: oxides or conducting polymers (high faradaic pseudocapacitance)
- Hybrid capacitors
  - Electrodes: special electrodes with significant double-layer capacitance and pseudocapacitance, such as lithium-ion

CLASSIFICATION OF CAPACITORS

Supercapacitors vs. Batteries and Capacitors

Supercaps

- fast charging and discharging (min – sec)
- high life cycle (≈ 500,000 cycles)
- high power output
  - ≈ **10** times higher than Li-ion battery

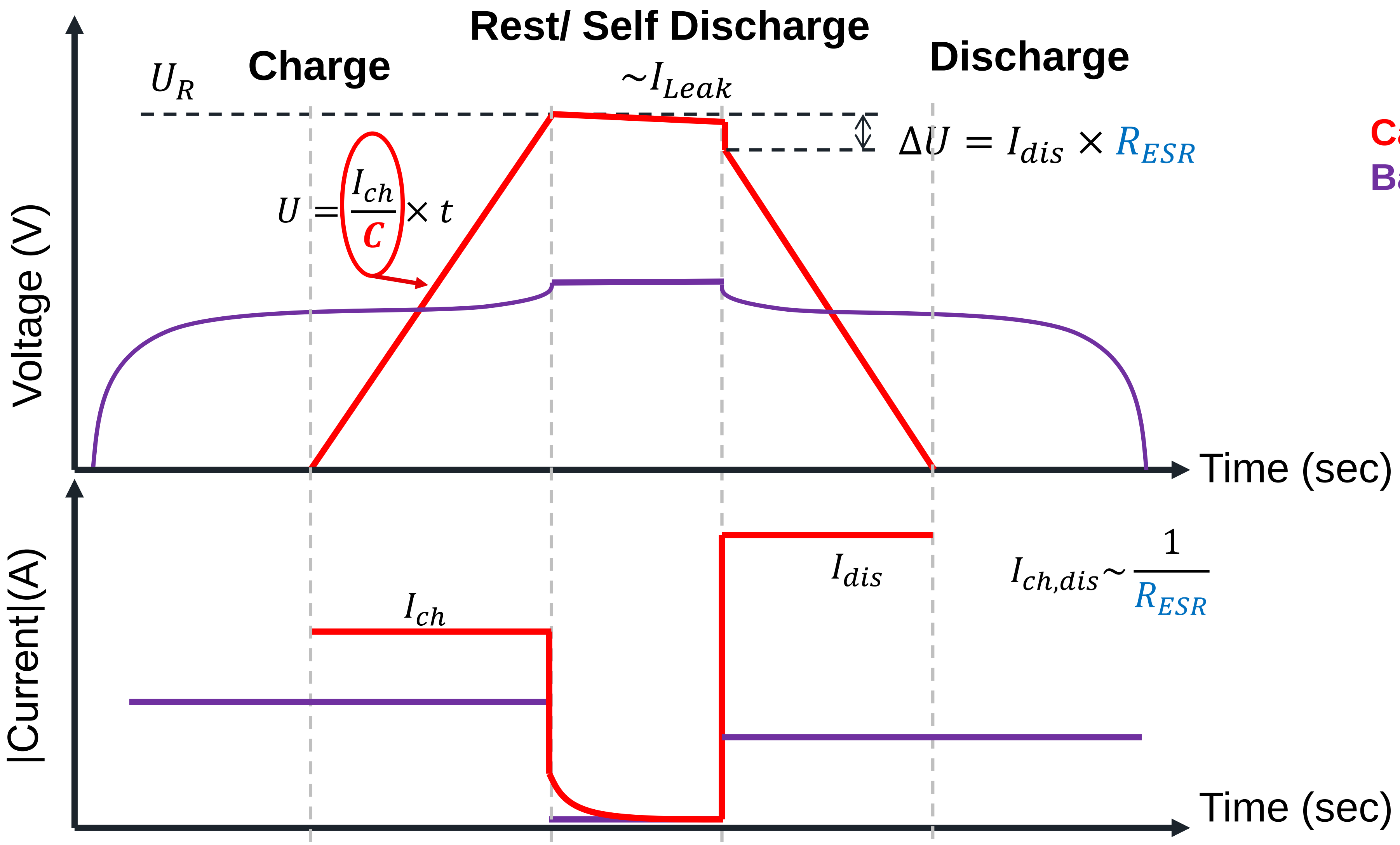
- low energy capacity
  - ≈ 30 times lower than Li-ion battery
- linear voltage dependence

Capacitors

- fast charging and discharging (≪ sec)
- high life time
- high operating voltages
- high power output

- low energy capacity

CHARGE AND DISCHARGE BEHAVIOR



TYPICAL APPLICATION

Power backup solution