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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Capacitors: Content (1)

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Capacitors: Content (2)

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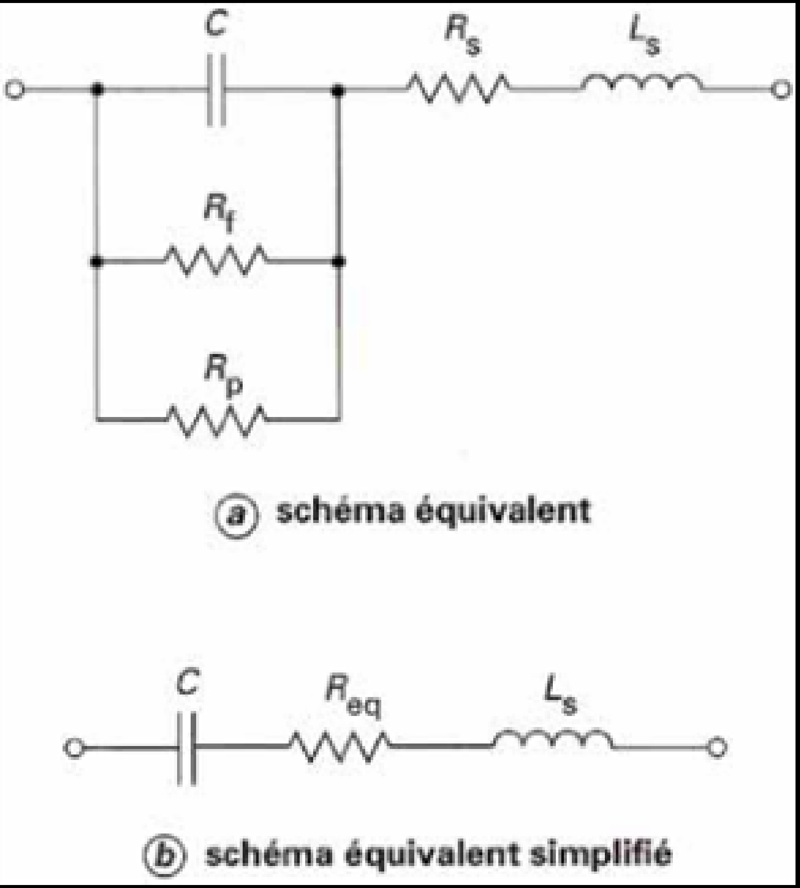
Distinctive Features

- **Capacitors used in *electrotechnics* (increase power factor, start single-phase asynchronous motors, etc.)**
  - **almost sinusoidal waveforms at industrial frequencies (50 or 60 Hz)**
  - **absence of a notable constant voltage**
- **Capacitors used in *power-electronic* circuits**
  - **currents not sinusoidal**
    - **harmonics can easily exceed 60 %**
    - **often pulse-like with d*i*/d*t* easily exceeding 10 A/µs**
    - **often fundamental frequencies of 1 to 50 kHz**
  - **high permanent constant voltage superimposed to the alternating or pulse-like component**
  - **parasitic series inductance and resistance must be as small as possible.**

Equivalent Circuit

- C ideal capacitor
- L_s series inductance
- R_s series resistance
- R_p equivalent parallel resistance (dielectric losses)
- R_{eq} equivalent series resistance (total capacitor losses)
- R_f leakage resistance (R_fC often bigger than 1000 s => influence can be neglected)



Constraints (electrical)

- **Dielectric ageing problem**
  - voltage waveform (continuous, alternating, or both superimposed)
  - frequency
  - harmonics
  - temperature
  - over-voltage stress
- **Problems linked to pulse-like currents**
  - high currents => high forces => rupture or breakdown of terminals and internal connections
  - metallised electrodes are sensible
  - maximum values for dv/dt or I^2t

Constraints (thermal)

- **Thermal problem**
  - **determines component reliability**
  - **heating calculations are delicate and require a lot of experience**
  - **capacitors dielectrics are quite limited in temperature (85°C vs. 150 to 200°C for transformers or motors)**
  - **life time exponential function of temperature (for example, life time divided by 10 between 70 and 85 C)**

Limitations (general)

- **Ohmic losses**
  - connections and the electrodes (R_s)
  - depend on frequency (skin effect)
- **Dielectric losses**
  - dielectric (R_p)
  - product of reactive power (✪ $E^2\omega$) and tangent of the loss angle ($\tan\delta = C\omega/R_p = f(U,\omega,\theta)$)
- **Electromagnetic losses**
  - induced currents in the metal case
  - often imposes the use of amagnetic metals (such as aluminium)

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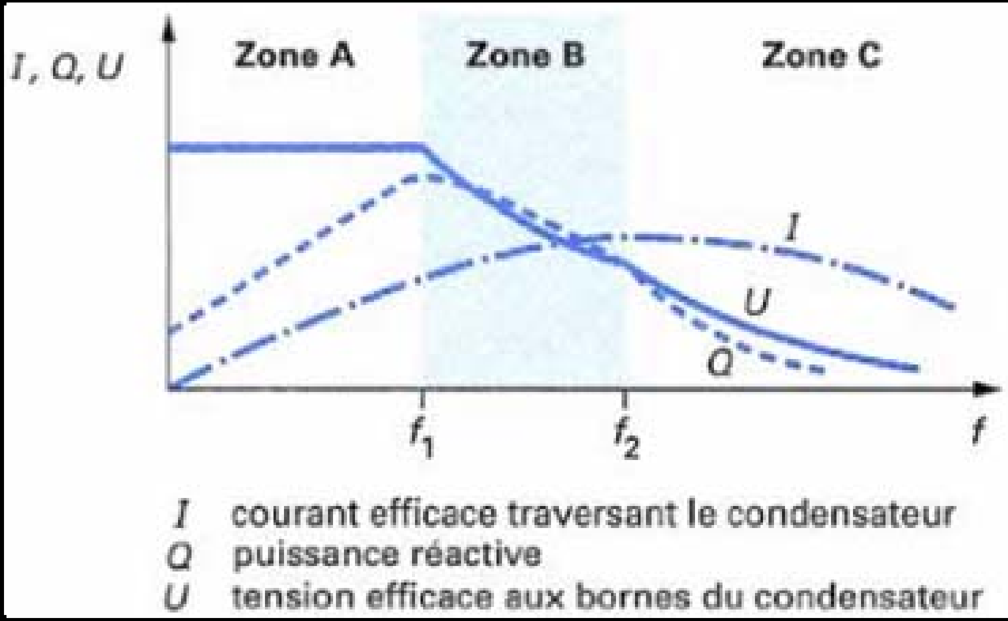
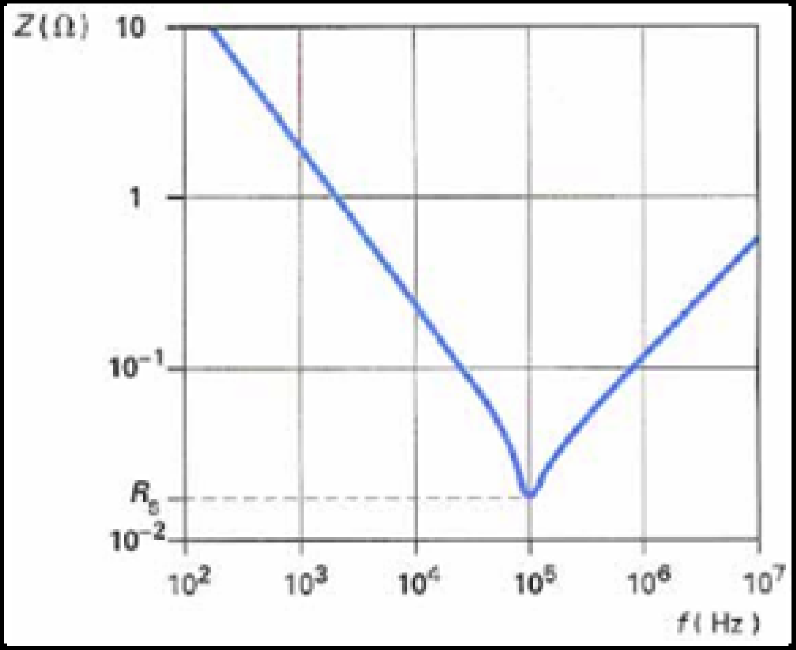
Limitations (sinusoidal operation)

- **Zone A**
  - **limitation by voltage**
  - $Q = U^2 C\omega$
  - **maximum power @ f_1**
- **Zone B**
  - **limitation by losses**
- **Zone C**
  - **limitation by current**
  - **maximum current @ f_2**
  - **reduces with frequency due to skin effect**



Series Inductance

- Series inductance L_s produces important transient voltage drop ($L_s$di/dt)
- Impedance function of frequency
- Minimum corresponds to series resonance ($L_s C\omega^2 = 1$)
- Difficulties if resonance frequency close to some higher-rank harmonics
  - occurs particularly in high-frequency resonant converters (above 5 to 10 kHz)
- **In practice:** do not use capacitor above 1/5th of resonance frequency



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Conclusion

- **Constraints met in power electronics require capacitor technologies adapted to each application**
- **Big currents of high frequency and temperature limits of actual dielectrics impose components of very low losses and low thermal impedance**
- **General orders of magnitude:**
  - R_s **0.1 to 10 mΩ**
  - L_s **5 to 400 nH**
  - **tan δ** **2e-4 to 100e-4**
  - Z_{th} **0.5 to 20 K/W**

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Used Technologies

- **Three large families for power electronics**
  - electrolytic aluminium capacitors
    - filtering of continuous voltages
    - $P > 10$ kW, $U < 1000$ V
    - $P > 100$ kW, $U < 3500$ V
  - ceramic capacitors
    - high frequencies: $f > 1$ MHz
    - high cost
  - film capacitors (papers, plastics, dry or impregnated)
    - winding of metallic electrodes and dielectric (paper or plastic film)
    - general technology

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Dielectrics

	rel. perm.	tan δ	strength	vol. mass	temp. coeff.
		(10^{-4})	(kV/mm)	(kg/m^3)	$(10^{-6}/K)$
paper	6.6			1200	
polypropylene	2.2	2	600	900	-200
polyester	3.2	50	500	1400	+1200
mineral oil	2.3	10	60	860	-1400
silicone	2.8	2	60	900	-3300

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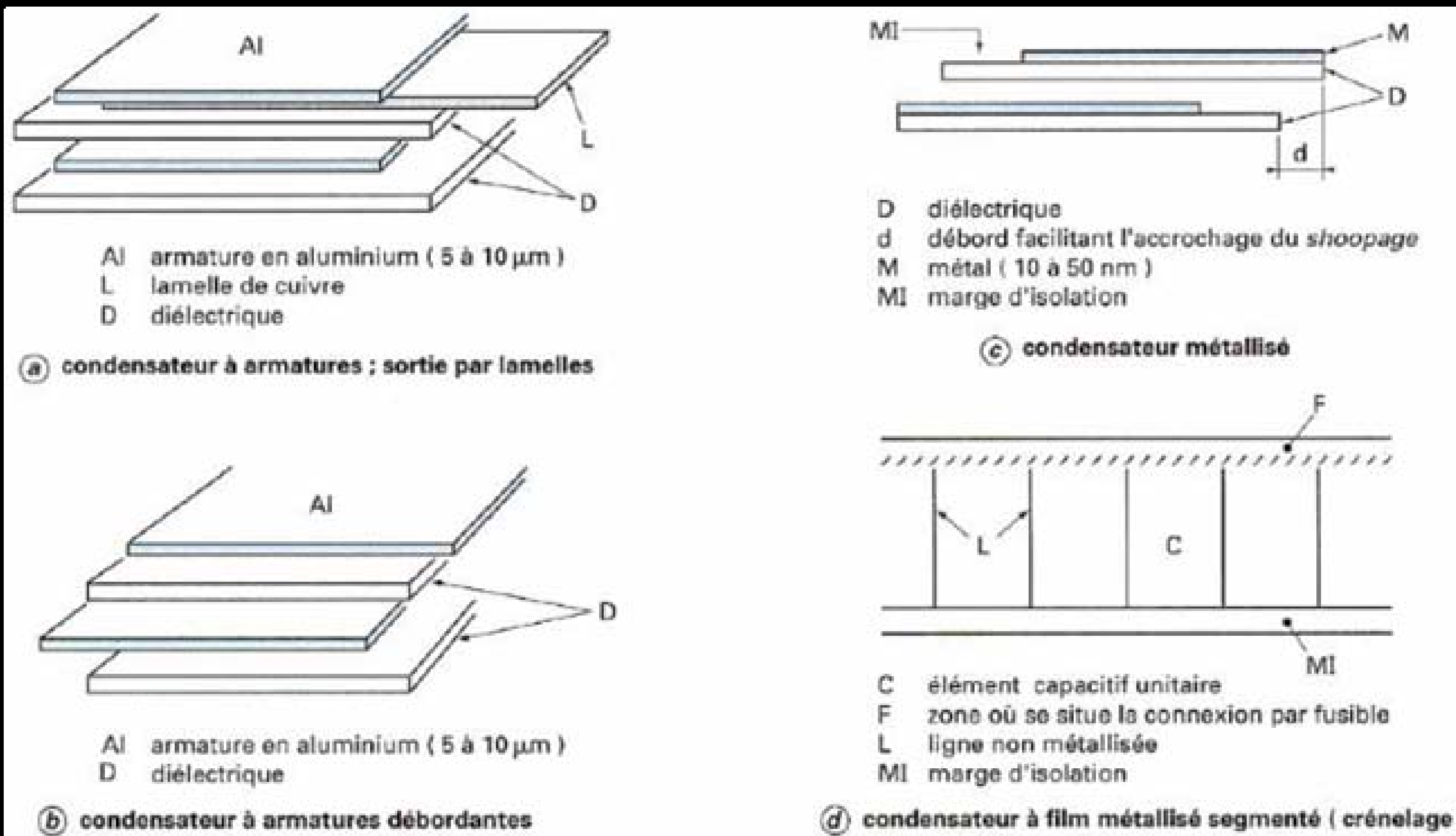
Capacitor Realisation



(a) condensateur à armatures ; sortie par lamelles

(b) condensateur à armatures débordantes

(c) condensateur métallisé

(d) condensateur à film métallisé segmenté (crénelage)

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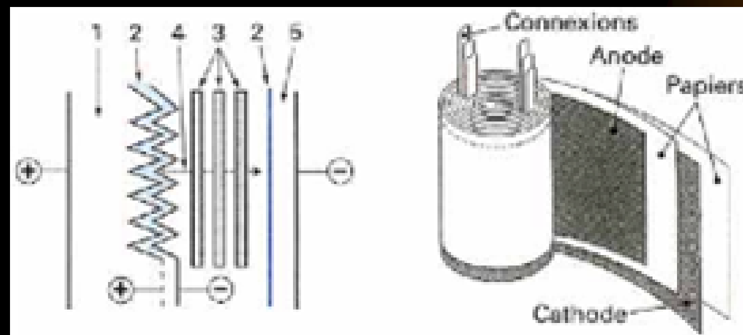
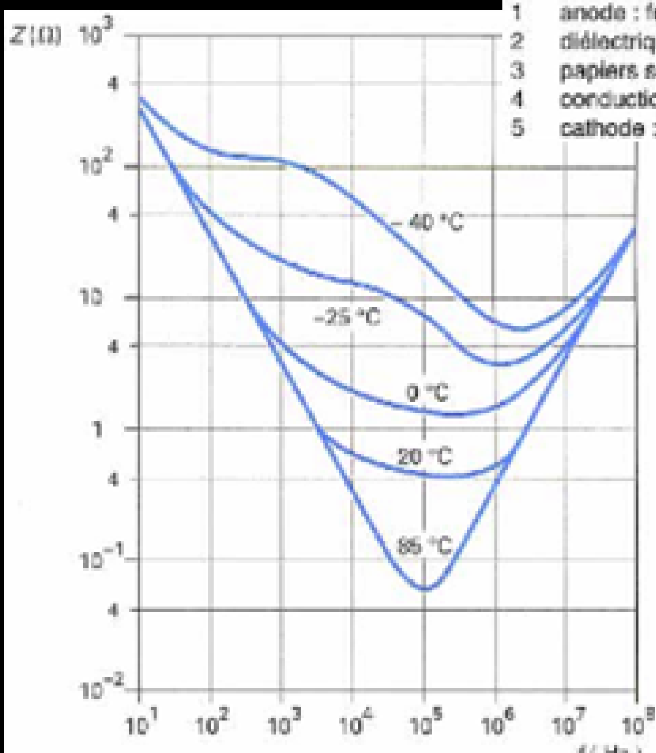
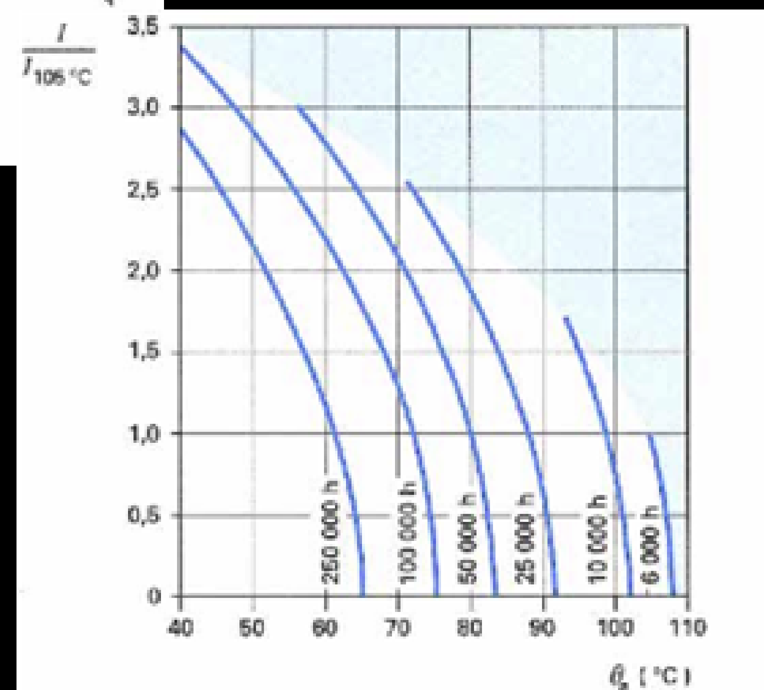
Electrolytic Capacitors



1 anode : feuille d'aluminium
2 diélectrique : alumine
3 papiers séparateurs imprégnés d'électrolyte
4 conduction ionique assurée par l'électrolyte
5 cathode : feuille d'aluminium





ⓐ durée de vie en fonction de la température ambiante θ_a et du courant efficace admissible

Applications and Specifications

- **Difficult and expensive to manufacture capacitors satisfying all specifications for power-electronic capacitors => Components adapted to each application**
- **Two large families of capacitors:**
  - **operating voltage continuous and unipolar**
    - **filtering**
    - **de-coupling**
    - **energy storage**
  - **operating voltage alternating**
    - **harmonic filtering**
    - **commutation**
    - **resonance**
    - **commutation aid**
    - **semiconductor protection**

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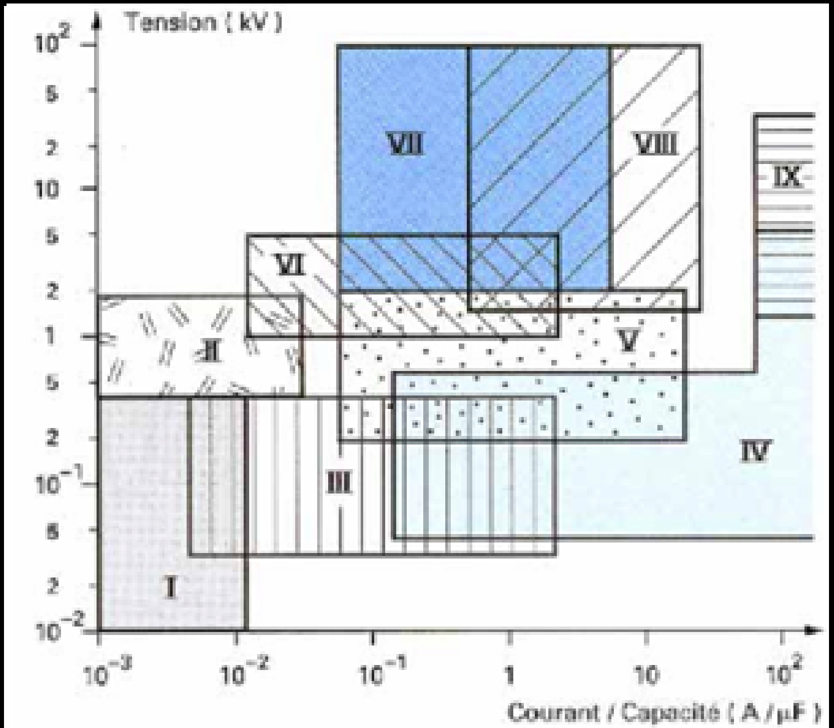
DC Voltage

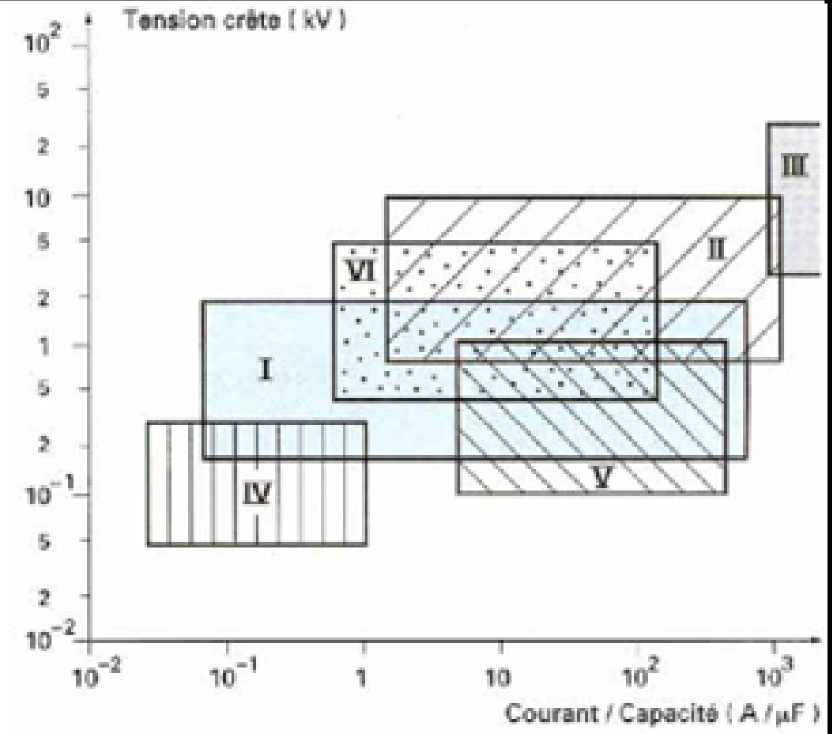
- Capacitors for continuous voltage
- Capacitors for energy storage with low discharge recurrence (few Hz)
- Low reactive powers
- Dielectric losses not dominant
- Series resistance and rms-current are the essential heating factors



I condensateur électrolytique (§ 2.6)
II condensateur électrolytique par montage série-parallèle (§ 2.6)
III condensateur film polyester, métallisé sec (§ 2.52)
IV condensateur céramique multicouche,sec (§ 2.1)
V condensateur au polypropylène, métallisé sec (§ 2.512)
VI condensateur au polypropylène, métallisé imprégné (§ 2.612) et condensateur au papier métallisé imprégné (§ 2.42)
VII condensateur au papier avec armature, imprégné (§ 2.41)
VIII condensateur mixte (papier et film), imprégné (§ 2.51)
IX condensateur céramique HT , sec (§ 2.1)

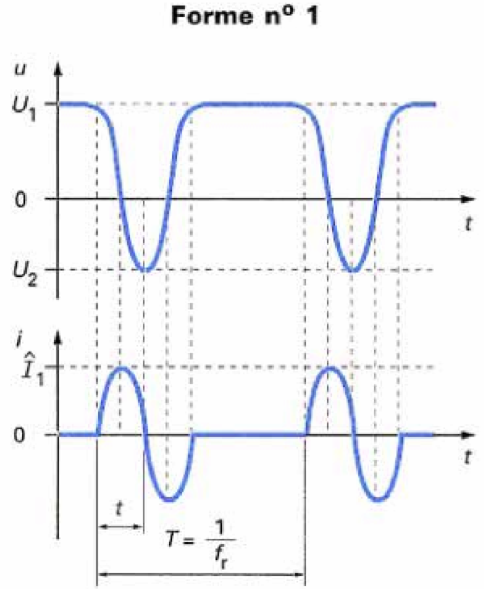
AC Voltage

- Dielectric and ohmic losses important



I condensateur au polypropylène, métallisé sec (§ 2.512)
II condensateur au polypropylène, *tout film* imprégné (§ 2.511)
III condensateur céramique HT, HF (§ 2.1)
IV condensateur au polyester, métallisé sec (§ 2.52)
V condensateur au polypropylène avec armatures, sec (§ 2.511)
VI condensateur type MKV (§ 2.511)

Current, Reactive and Loss Power Calculation



$$\hat{I} = \frac{\pi}{2} C \left(\frac{U_1 + U_2}{t} \right)$$

$$I_{rms} = \frac{\pi}{2} C \left(U_1 + U_2 \right) \sqrt{\frac{f_r}{t}}$$

$$Q = \frac{\pi}{4} C \left(U_1 + U_2 \right)^2 f_r$$

$$f = \frac{1}{2t}$$

$$P = Q \left(2 + kf \right) 10^{-4}$$

$\tan\delta = \tan\delta$ dielectric $+ CR_s \cdot 2\pi f$

$\tan\delta$ dielectric $= 2 \cdot 10^{-4}$ for polypropylene

$CR_s \cdot 2\pi \quad = k \cdot 10^{-4}$ galvanic component

$\tan\delta = (2 + kf)\, 10^{-4}$

f sinusoidal frequency

f_r recurrent waveform frequency

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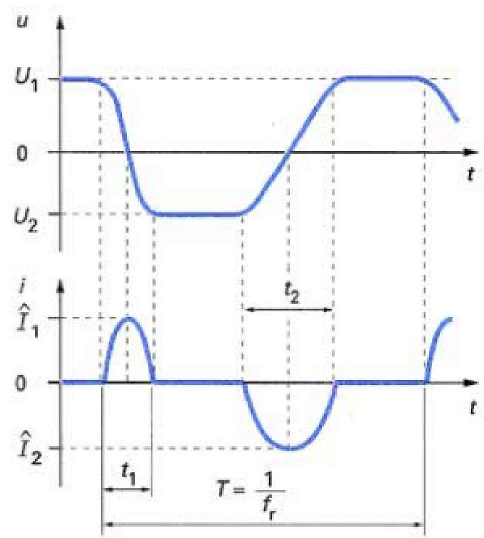
Current, Reactive and Loss Power Calculation

Forme n° 2



$$\hat{I}_1 = \frac{\pi}{2} C \left(\frac{U_1 + U_2}{t_1} \right)$$

$$\hat{I}_2 = \frac{\pi}{2} C \left(\frac{U_1 + U_2}{t_2} \right)$$

$$I_{rms} = \frac{\pi}{2} C \left(U_1 + U_2 \right) \sqrt{\frac{f_r}{2t_1} + \frac{f_r}{2t_2}}$$

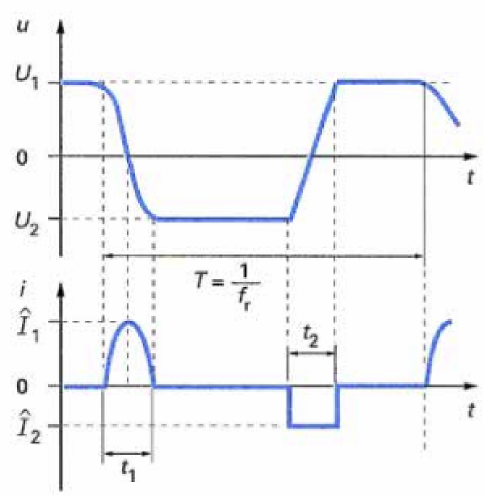
$$Q = \frac{\pi}{4} C \left(U_1 + U_2 \right)^2 f_r$$

$$f_1 = \frac{1}{2t_1}$$

$$f_2 = \frac{1}{2t_2}$$

$$P = \frac{Q}{2} \left[(2 + k f_1)\, 10^{-4} + (2 + k f_2)\, 10^{-4} \right]$$

Forme n° 3



$$\hat{I}_1 = \frac{\pi}{2} C \left(\frac{U_1 + U_2}{t_1} \right)$$

$$\hat{I}_2 = C \left(\frac{U_1 + U_2}{t_2} \right)$$

$$I_{rms} = C \left(U_1 + U_2 \right) \sqrt{\frac{\pi^2 f_r}{8t_1} + \frac{f_r}{t_2}}$$

$$Q = \frac{\pi}{4} C \left(U_1 + U_2 \right)^2 f_r$$

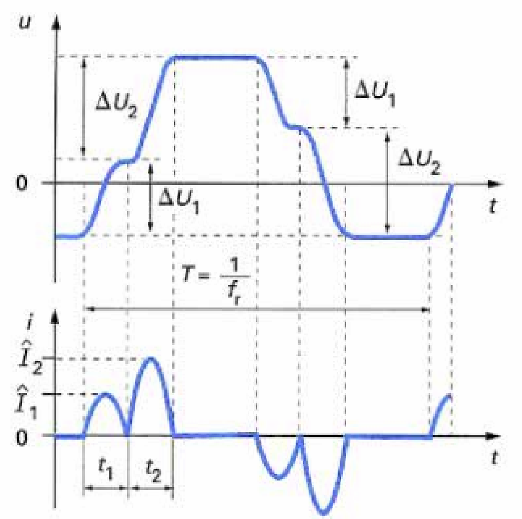
$$f_1 = \frac{1}{2t_1}$$

$$f_2 = \frac{1}{2t_2}$$

$$P = \frac{Q}{2} \left[(2 + k f_1)\, 10^{-4} + (2 + k f_2)\, 10^{-4} \right]$$

Current, Reactive and Loss Power Calculation

Forme n° 4



$$\hat{I}_1 = \frac{\pi}{2} C \frac{\Delta U_1}{t_1}$$

$$\hat{I}_2 = \frac{\pi}{2} C \frac{\Delta U_2}{t_2}$$

$$I_{rms} = \frac{\pi}{2} C \sqrt{\left(\frac{\Delta U_1^2}{t_1} + \frac{\Delta U_2^2}{t_2} \right) f_r}$$

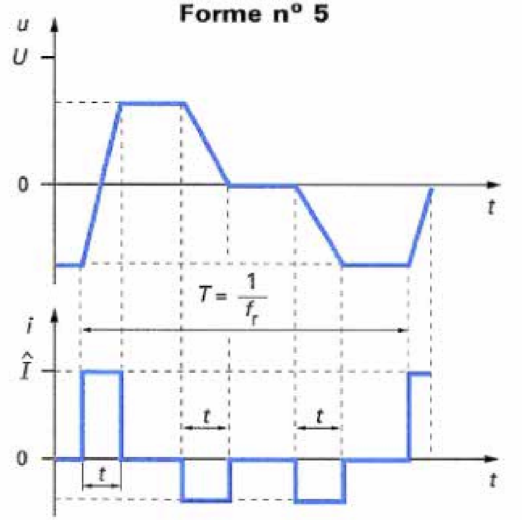
$$Q = \frac{\pi}{4} C \left(\Delta U_1 + \Delta U_2 \right)^2 f_r$$

$$f_1 = \frac{1}{2t_1}$$

$$f_2 = \frac{1}{2t_2}$$

$$P = \frac{\pi}{4} C f_r \left[\Delta U_1^2 \left(2 + k f_1 \right) 10^{-4} + \right.$$
$$+ \Delta U_2^2 \left(2 + k f_2 \right) 10^{-4} +$$
$$\left. + 2 \Delta U_1 \Delta U_2 \left(2 \right) 10^{-4} \right]$$

Forme n° 5



$$\hat{I} = C \frac{2U}{t}$$

$$I_{rms} = CU \sqrt{\frac{6 f_r}{t}}$$

$$Q = \frac{3\pi}{4} C U^2 f_r$$

$$f = \frac{1}{2t}$$

$$P = Q \left(2 + k f \right) 10^{-4}$$

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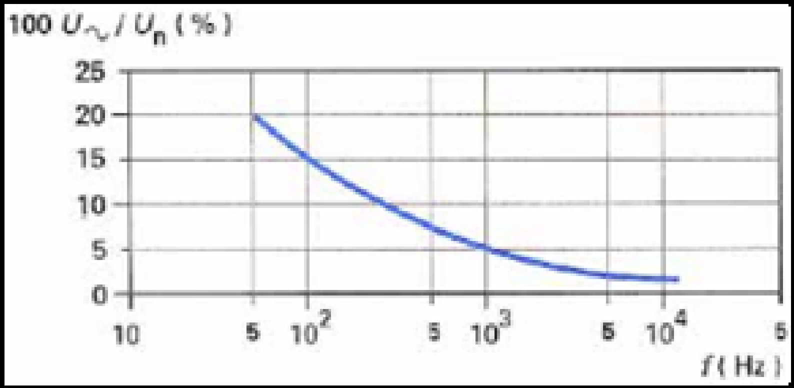
Filter Capacitors for Rectifiers at Industrial Frequencies

- **Low-pass filters**
- **Unipolar voltages**
- **Main constraint:**
  - continuous voltage (average rectified voltage)
  - peak value of oscillating voltage
  - sum of both defines nominal operating voltage U_n
- **Second constraint:**
  - rms-value of current
  - proportional to f and $U_\sim$
  - for given current, $fU_\sim$ not constant, $U_\sim$ decreases slower than f increases (skin effect, dissipating power, etc.)

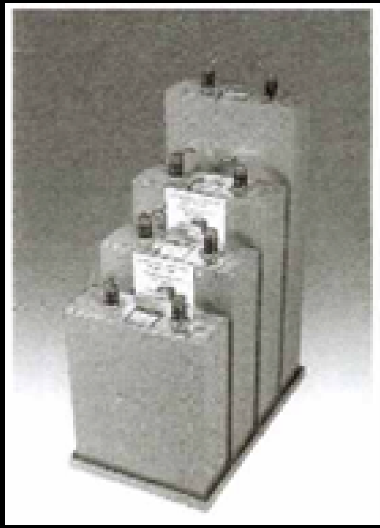


- **Series inductance negligible at power supply with $f_s \leq 400$ Hz**

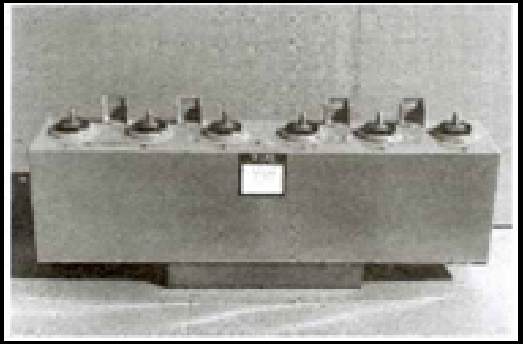
De-Coupling Capacitors

- **Resembling the preceding ones**
- **Constitute links of theoretically zero impedance in circuits with superimposed continuous and alternating components**
- **Peak value of alternating component can be *bigger* than continuous voltage => terminal voltage susceptible to inversion**
- **Principle use:**
  - **input and output filters of de-coupled power supplies**
  - **input filters of voltage-source converters**
  - **de-coupling of parasitic supply-cable inductances and batteries (autonomous supplies)**

Examples



Filter capacitor for the TGV Atlantique (2000 µF, 1800 V). Evolution from metallised wax-impregnated paper (125x340x787 mm^3, 49 kg) to segmented metallised rape-oil-impregnated polypropylene film, 4th generation (125x340x430 mm^3, 21 kg).



Filter capacitor for an IGBT traction converter (tramway). Segmented metallised rape-oil-impregnated polypropylene technology. The 3 elements with flat terminals give this capacitor a series inductance < 30 nH (3150 µF, 1000 V, 690x140x185 mm^3).

Commutation Capacitors

- **Deliver current pulses necessary to block thyristors**
- **Severe constraints, complex applied waveforms**
- **Classical thyristors disappear gradually: replaced by GTO/IGCT and IGBT**
  - **these active components do not need turn-off commutation capacitors**
- **The constraints applied to commutation capacitors remain a general type of constraints met in power electronics**
  - **dielectric constraints**
    - **voltage continuous, rms and peak value (must remain smaller than U_n)**
    - **voltage variation rate (dielectric losses increase with high dv/dt)**
  - **constraints due to ohmic losses and frequency**
    - **current rms and peak value**
    - **reactive power (estimation of loss power using tan δ)**

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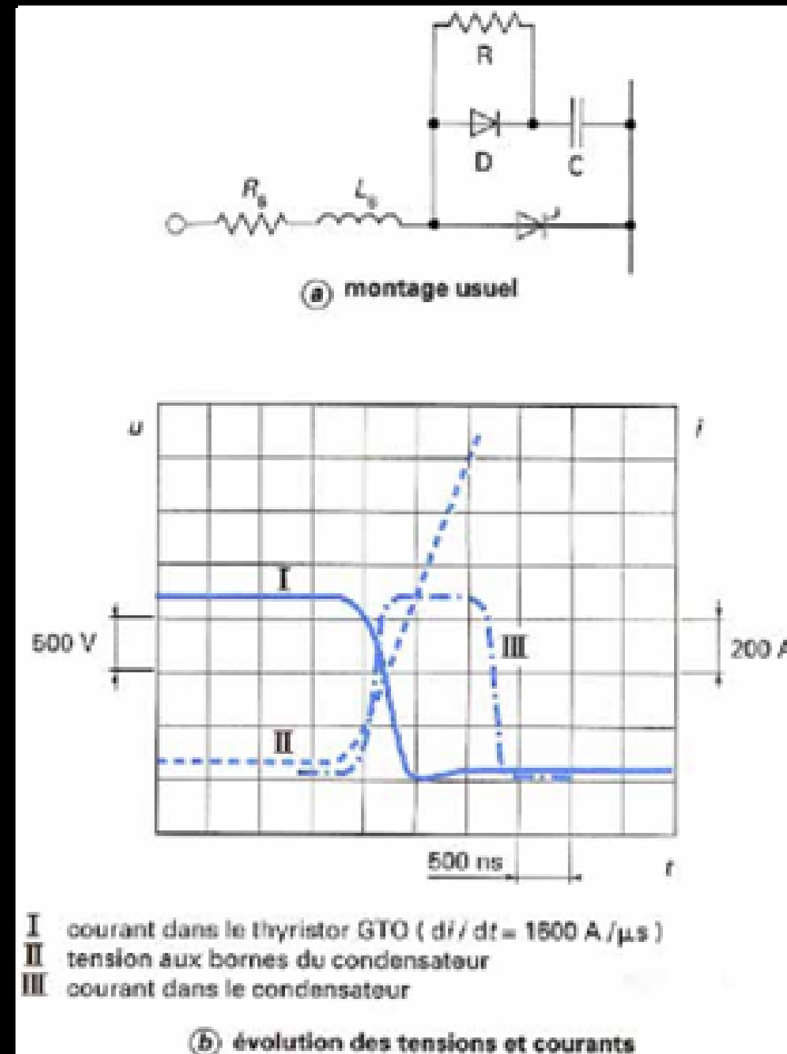
Resonance Capacitors

- Used to tune series or parallel resonant circuits used in industrial medium-frequency systems (resonant converters)
- Frequencies between several hundred Hz and several hundred kHz
- Relatively tight tolerances: often $\Delta C/C \leq 2$ %
  => exclusion of certain dielectrics
- Operate under pure alternating voltage without a superimposed continuous component
- Only constraints to take into account:
  - voltage peak value (must remain smaller than U_n)
  - current rms-value (dielectric losses, ohmic losses)

Capacitors for Semiconductor-Commutation Assistance

- Semiconductor RCD-networks
- Minimise commutation losses
- Limit d*v*/d*t*
- Capacitor absorbs load current at switch opening: big pulsed currents => series inductance *Ls* must be minimum
- GTO: parasitic inductance of RCD-circuit very critical (< 100 nH) => development of capacitors with very low specific inductance (< 10 nH)



Energy-Storage Capacitors

- Accumulate maximum energy in minimum volume
- Discharge this energy in very short times (very big currents)
- Typical applications:
  - lasers
  - lightning wave simulators
  - nuclear electromagnetic pulse simulators
- Dielectrics used at maximum strength
  => reduced life times
  - telemetric lasers: 500’000 charge-discharge cycles

50 kJ, 10 kV, peak current 60 kA,
volumetric energy 600 J/l