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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 \( \frac{di}{dt} \) easily exceeding 10 A/\( \mu \)s
    - 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
  \((R_fC \text{ often bigger than } 1000 \text{ s } \Rightarrow \text{influence can be neglected})\)
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 $\Rightarrow$ high forces $\Rightarrow$ rupture or breakdown of terminals and internal connections
  - metallised electrodes are sensible
  - maximum values for $\frac{dv}{dt}$ 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)
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 ($L_s\frac{di}{dt}$)
- Impedance function of frequency
- Minimum corresponds to series resonance ($L_sC\omega^2 = 1$)
- 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 $1/5^{th}$ of resonance frequency
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 m\(\Omega\)
  – \( L_s \) 5 to 400 nH
  – \( \tan \delta \) 2e-4 to 100e-4
  – \( Z_{th} \) 0.5 to 20 K/W
Used Technologies

- Three large families for power electronics
  - electrolytic aluminium capacitors
    - filtering of continuous voltages
    - $P > 10 \text{ kW}, U < 1000 \text{ V}$
    - $P > 100 \text{ kW}, U < 3500 \text{ V}$
  - ceramic capacitors
    - high frequencies: $f > 1 \text{ MHz}$
    - 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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<th>rel. perm.</th>
<th>tan δ (10^{-4})</th>
<th>strength (kV/mm)</th>
<th>vol. mass (kg/m³)</th>
<th>temp. coeff. (10^{-6}/K)</th>
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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)
Electrolytic Capacitors
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
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
AC Voltage

- Dielectric and ohmic losses important
Current, Reactive and Loss Power Calculation

\[ i = \frac{\pi}{2} C \left( \frac{U_1 + U_2}{l} \right) \]
\[ I_{\text{rms}} = \frac{\pi}{2} C (U_1 + U_2) \sqrt{\frac{I_1}{l}} \]
\[ Q = \frac{\pi}{4} C (U_1 + U_2)^2 f_r \]
\[ f = \frac{1}{2t} \]
\[ P = Q (2 + kf) 10^{-4} \]

\[ \tan \delta = \tan \delta \text{ dielectric} + CR_e \cdot 2\pi f \]
\[ \tan \delta \text{ dielectric} = 2 \cdot 10^{-4} \text{ for polypropylene} \]
\[ CR_e \cdot 2\pi = k \cdot 10^{-4} \text{ galvanic component} \]
\[ \tan \delta = (2 + kf) 10^{-4} \]
Current, Reactive and Loss Power Calculation

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

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

\[ I_{rms} = \frac{\pi}{2} C (U_1 + U_2) \sqrt{\frac{f_r}{2t_1} + \frac{f_r}{2t_2}} \]

\[ Q = \frac{\pi}{4} C (U_1 + U_2)^2 f_r \]

\[ f_1 = \frac{1}{2t_1} \]

\[ f_2 = \frac{1}{2t_2} \]

\[ P = \frac{Q}{2} [(2 + k_f_1) 10^{-4} + (2 + k_f_2) 10^{-4}] \]

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

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

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

\[ Q = \frac{\pi}{4} C (U_1 + U_2)^2 f_r \]

\[ f_1 = \frac{1}{2t_1} \]

\[ f_2 = \frac{1}{2t_2} \]

\[ P = \frac{Q}{2} [(2 + k_f_1) 10^{-4} + (2 + k_f_2) 10^{-4}] \]
Current, Reactive and Loss Power Calculation

Forme n° 4

\[ \hat{i}_1 = \frac{\pi}{2} C \frac{\Delta U_1}{i_1} \]
\[ \hat{i}_2 = \frac{\pi}{2} C \frac{\Delta U_2}{i_2} \]
\[ i_{\text{rms}} = \frac{\pi}{2} C \sqrt{\left( \frac{\Delta U_1^2}{t_1} + \frac{\Delta U_2^2}{t_2} \right) f_r} \]
\[ Q = \frac{\pi}{4} C (\Delta U_1 + \Delta U_2)^2 f_r \]
\[ f_1 = \frac{1}{2t_1} \]
\[ f_2 = \frac{1}{2t_2} \]
\[ P = \frac{\pi}{4} C f_r \left[ \Delta U_1^2 \left( 2 + k f_1 \right) 10^{-4} + \Delta U_2^2 \left( 2 + k f_2 \right) 10^{-4} + 2\Delta U_1 \Delta U_2 \left( 2 \right) 10^{-4} \right] \]

Forme n° 5

\[ i = C \frac{2U}{t} \]
\[ i_{\text{rms}} = CU \sqrt{\frac{6f_r}{t}} \]
\[ Q = \frac{3\pi}{4} CU^2 f_r \]
\[ f = \frac{1}{2t} \]
\[ P = Q \left( 2 + k f \right) 10^{-4} \]
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 $U_~$
  - for given current, $fU_~$ not constant, $U_~$ 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 (125×340×787 mm³, 49 kg) to segmented metallised rape-oil-impregnated polypropylene film, 4th generation (125×340×430 mm³, 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, 690×140×185 mm³).
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 $\delta$)
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 $\frac{dv}{dt}$
- Capacitor absorbs load current at switch opening: big pulsed currents $\Rightarrow$ series inductance $L_s$ must be minimum
- GTO: parasitic inductance of RCD-circuit very critical ($< 100$ nH) $\Rightarrow$ 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