Power Capacitors for Power Converters. Analysis of Losses, Design and Technologies.

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I. Introduction

The following deals with losses in capacitors for power electronic components. Initially, some hints on capacitor technology are going to be discussed. Later, the losses will be estimated, and finally, a hint on how to design a DC link is going to be discussed (it should be made clear, however, at which operation point must this condition be fulfilled).

The following parameters define capacitors [2][3]:

- 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

The capacitance is given by:

$$C = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{d} \tag{1}$$

where ε_0 is the dielectric constant of vacuum, ε_r is the relative dielectric constant of the material, and A and d are the area and thickness of the dielectric layer.

Another key parameter is the **ripple current** rating, I_r, defined as the RMS AC component of the capacitor current.

$$P_d = I_r^2 \cdot ESR \tag{2}$$

$$I_r = \sqrt{\frac{P_d}{ESR}} = \sqrt{\frac{h \cdot A \cdot \Delta T}{ESR}} \tag{3}$$

where P_d is the maximum power dissipation, h the heat transfer coefficient, A is the area, ΔT is the temperature difference between capacitor and ambient, and ESR is the equivalent series resistor of the capacitor.

For non sinusoidal curves, the expression can be defined as:

$$I_r = \sqrt{I_1^2 + I_2^2 + I_3^2 + \cdots + I_n^2} \tag{4}$$

Also, the volumetric efficiency is used to compare different devices, as defined per:

$$\eta_v = \frac{C \cdot V}{Vol} \tag{5}$$

where C is the voltage rating and Vol is the volume of the device.

II. Capacitors technologies.

In order to select the optimal power capacitors for a given application, an analysis of the possible dielectric materials must be carried out.

The basic technologies are summarized in the following picture:

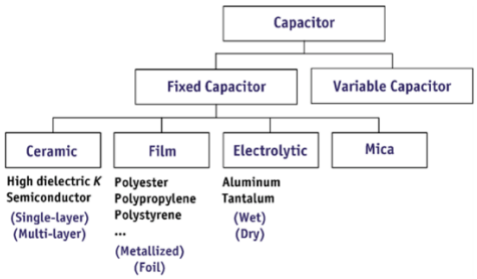


Figure 1 Types of Capacitors [2]

The following paragraphs discuss on the different technologies.

a) Ceramic Capacitors

The main properties of ceramic capacitors are:

- The dielectric is a ceramic material
- Non-polarized
- The most commonly used type of capacitor, cheap and reliable.
- Multiple layers, as to increase the capacitance level.
- Well suited for high frequencies and high pulsed currents.
- Can also be manufactured for very high voltages (single layer, less capacitance…)
- There are 2 basic classes: Class 1 ceramic capacitors are highly thermally stable, and present low losses. Class 2 have large capacitance.
- The capacitance also changes with voltage, specially for class 2 ceramic capacitors, causing a non-linear behavior:

b) Film Capacitors, Plastic Capacitors or Polymer Capacitors

- The dielectric is a very thin film, typically smaller than 1μm.
- Usually wounded to increase the area of the plates, as to increase the capacitance level
- Non-polarized
- Also widely used.
- Well suited for high frequencies and high pulsed currents.

There are two basic types: Film/foil capacitors present 2 layers of dielectric with a metal foil are stacked, that allow for large currents. Metallized film capacitors (deposition of aluminum on a plastic film) large capacitance, but smaller current ratings, also allowing for

self-healing (automatically open circuit close to the defect after arcing).

There are DC and AC voltage derating curves.

The following table summarizes main characteristics of film capacitors as a function of the dielectric material.

Dielectric	Abbr.	DC voltage range	Cap. Range	tanδ (·10⁻⁴)			
				1 kHz	10 kHz	100 kHz	1 MHz
Polypropylene	PP	40-2000	100pF-10uF	0.5-5	2-8	2-25	4-40
Polyester	PET	50-1000	100pF-22uF	50-200	110-150	170-300	200-350
Polyethylene naphthalate	PEN	16-250	100pF-1uF	42-80	54-150	120-300	-
Polyphenylene sulfide	PPS	16-100	100pF-470nF	2-15	2.5-25	12-60	18-70

Table I. Film capacitor dielectric cm material vs. properties [9].

c) Electrolytic Capacitors.

- The dielectric is an oxidized layer in the anode. The cathode/negative layer is an electrolyte.
- Largest capacitance per volume.
- Polarized component.
- Widely used for bulk storage (typically in DC links).
- Hazardous component, failure might be catastrophic.
- Three basic types: aluminum, tantalum and niobium capacitors.

The following table summarizes main characteristics of electrolityc capacitors as a function of the family.

Dielectric	DC voltage range	Cap. Range	ESR (100kHz, 20°C)	Max ripple current
Aluminum	25-630	0.1uF-1000mF	300-900 mΩ	200 mA
Tantalum	25-125	0.1uF – 3.3mF	30-100 mΩ	1000-5000 mA
Niobium	10-25	1uF-1500mF	40-80 mΩ	1000 mA

Table II. Electrolytic capacitor family vs. properties [9]

III. Equivalent Circuit and Losses

This section is exemplified on ceramic capacitors, but a similar behavior is found in film capacitors. The equivalent circuit can be simplified as:

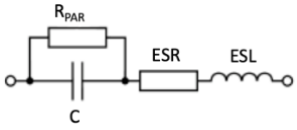
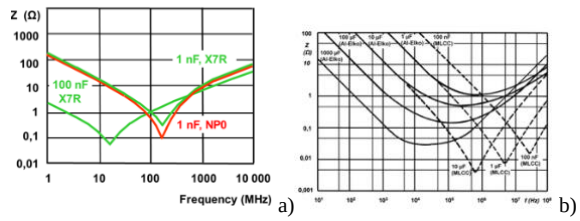


Figure 2 Equivalent Circuit of Capacitors [6]



a) b)

Figure 3 a) Typical frequency behavior of ceramic and film capacitors [7]. b) comparison in the case of electrolytic capacitors [11].

Usually, R_{PAR} can be neglected. The losses are given by the equivalent series resistor, ESR; by the dissipation factor, DF or tanδ; or as quality factor, Q.

For low frequencies (disregarding ESL), then:

$$tan\delta = ESR \cdot \omega \cdot C = \frac{1}{Q} = \frac{B}{f_0} \qquad (6)$$

The Q factor represents the effect of electrical resistance, and characterizes a resonator's bandwidth B relative to its center or resonant frequency, f_0. A high Q value is a mark of the quality of the resonance for resonant circuits.

For high frequencies, ESL, and the electrical resonance, must be considered. There is a resonance at frequency f_0:

$$f_0 = \frac{1}{2 \cdot \pi \cdot \sqrt{ESL \cdot C}} \qquad (7)$$

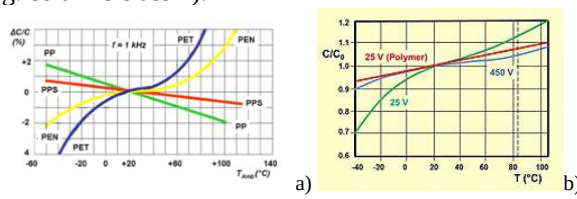
The self-resonant frequency is the lowest frequency at which impedance passes through a minimum. For any AC application the self-resonant frequency is the highest frequency at which a capacitor can be used as a capacitive component. At frequencies above the resonance, the impedance increases again due to ESL: the capacitor becomes an inductor with inductance equal to capacitor's ESL, and resistance equal to ESR at the given frequency [6].

In the case of electrolytic capacitors, if the ripple current is exceeded, the result tends to be explosive (in any case, it will imply life shortening).

IV. Stability of Capacitor Parameters

a) Stability of Capacitance vs. temperature

For Ceramic and Film capacitors, there is different behavior vs. increasing temperature. The temperature dependence is expressed as ppm per degree Celsius (e.g. ceramic class 1) or in % over the total temperature range (e.g. ceramic class 2).

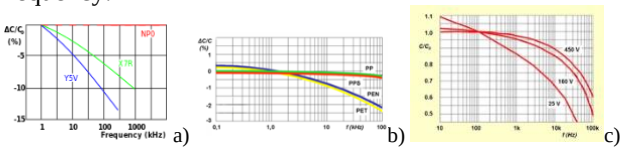


a) b)

Figure 4 a) temperature behavior of film capacitors [9]. b) idem for electrolytic capacitors [10]

b) Effect of frequency on the capacitance

The frequency dependence is due dielectric relaxation. As a result, the capacitance decreases with frequency.



a) b) c)

Figure 5 a) Ceramic Capacitance value vs frequency (NP0 is class 1, X7R and Y5V are class 2) [6]. b) Film capacitance vs. freq [9]. c) electrolytic capacitor [10].

c) Effect of the frequency on the ESR

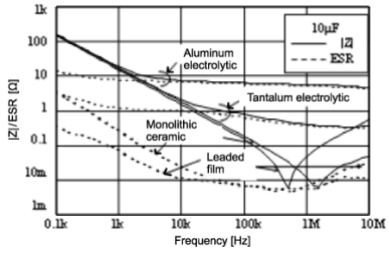


Figure 6 Variation of ESR for several technologies[15]

For a wide range of frequencies, the ESR is more or less constant. The ESR typ. at 10kHz can be used.

d) Ageing

Ageing makes the capacitance smaller with time, specially ceramic class 2 capacitors. Film capacitors have smaller variations (but mensurable).

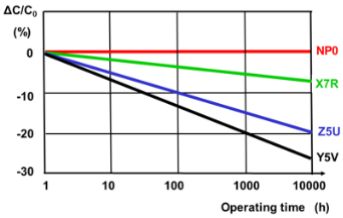


Figure 7 Typical ceramic capacitance vs. ageing [8]

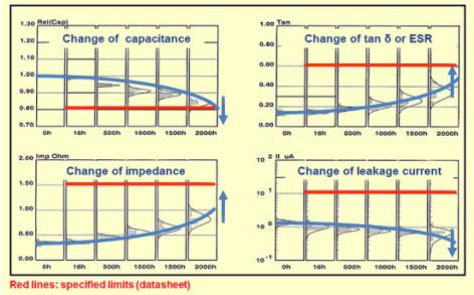


Figure 8 Life of electrolytic capacitors [10]

e) Stability vs. operating voltage

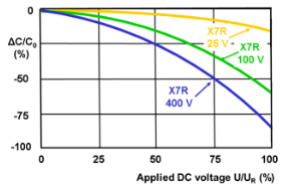
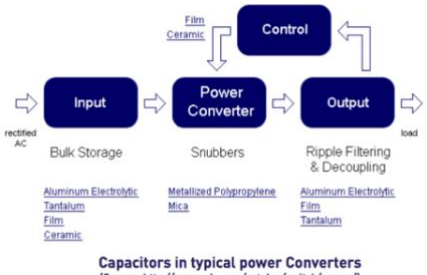


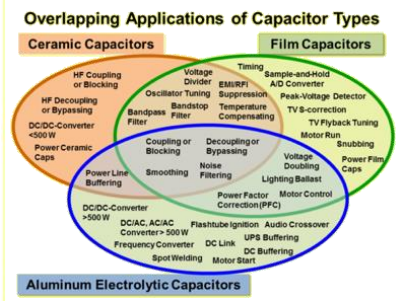
Figure 9 Ceramic Capacitance vs. Voltage [6]

V. Applications of Capacitors

Per applications, the following tables apply:



a)



b)

Figure 10 Applications. a) [1]. b) [9]

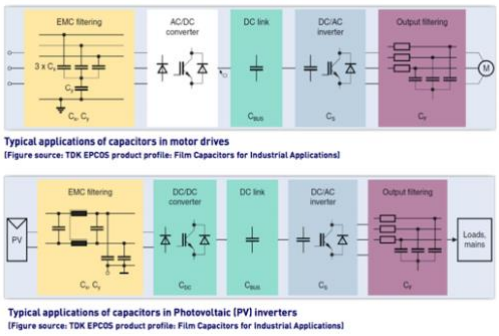
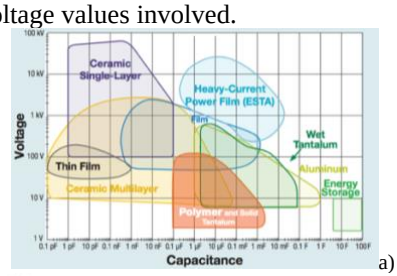
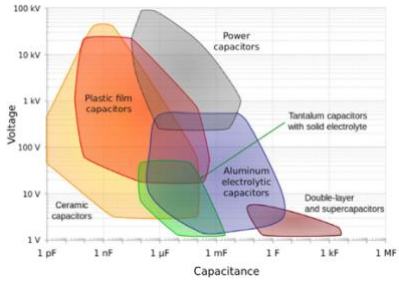


Figure 11 Applications [1]

Figure 4 shows the basic technologies of a reference manufacturer [1], as a function of the capacitance values and the voltage values involved.



a)



b)

Figure 12 a) Vishay Cap Map [1]. B) Plot in [2]

So, the following typical comparison, can be obtained [2]:

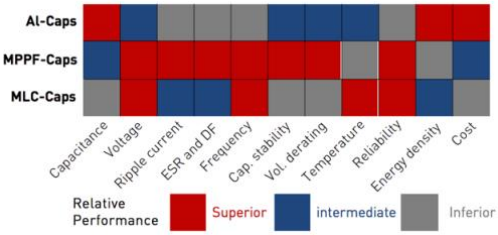


Figure 13 Performance Comparison [2][3].

VI. Design of Capacitors

To select the optimal capacitor for a certain application, the following conditions must be checked:

- The continuous peak voltage must not exceed the rated DC voltage rating of the device, at the operating temperature. If available, ageing characteristics in the datasheet must be considered.
- The capacitance must be selected to guarantee simultaneously *four* conditions:

a) Hold-up time

The capacitance must ensure a given output voltage during the required hold-up time, $t_{hold\text{-}up}$. It is assumed that the converter is off, and the only load current comes from the capacitor:

$$I_C = C \cdot \frac{dU_C}{dt} \Rightarrow I_C \cdot U_C = U_C \cdot C \cdot \frac{\Delta U_C}{t_{hold-up}} \Rightarrow$$

$$\Rightarrow P_{Ohold-up} = U_{Cnom} \cdot C \cdot \frac{U_{Cnom} - U_{Cminhold-up}}{t_{hold-up}} \quad (8)$$

And, therefore:

$$C_{hold-up} \geq \frac{t_{hold-up} \cdot P_{Ohold-up}}{U_{Cnom} \cdot (U_{Cnom} - U_{Cminhold-up})} \quad (9)$$

b) The voltage ripple in steady stage.

In this case, the limiting parameter is the voltage ripple, in RMS value, denoted by U_r.

The operating point is defined. Then, the expression of the AC current through the capacitor, $I_r(t)$, is known. Thus, the RMS value of the ripple current, I_r, can be calculated.

By neglecting the ESL of the capacitor, the impedance is:

$$Z_C = \frac{1}{2 \cdot \pi \cdot f \cdot j \cdot C} + ESR \quad (10)$$

And then the voltage ripple can be estimated as:

$$\dot{U_r} = \dot{I_r} \cdot \left(\frac{1}{2 \cdot \pi \cdot f \cdot j \cdot C} + ESR \right) \Rightarrow$$

$$\Rightarrow U_r = I_r \cdot \sqrt{\frac{1}{4 \cdot \pi^2 \cdot f^2 \cdot C^2} + ESR^2} \quad (11)$$

And this ripple must be below the limit for the application. Alternatively:

$$C_{ripple} \geq \frac{1}{2 \cdot \pi \cdot f \cdot \sqrt{\frac{U_r^2}{I_r^2} - ESR^2}} \quad (12)$$

If the ESL is known, then the full expression of the impedance, as depicted in figure 2, can be calculated as:

$$Z_C = \frac{1}{2 \cdot \pi \cdot f \cdot j \cdot C} + ESR + 2 \cdot \pi \cdot f \cdot ESL \cdot j \quad (13)$$

And thus:

$$\dot{U_r} = \dot{I_r} \cdot \left(\frac{1}{2 \cdot \pi \cdot f \cdot j \cdot C} + ESR + 2 \cdot \pi \cdot f \cdot ESL \cdot j \right) \Rightarrow$$

$$\Rightarrow U_r = I_r \cdot \sqrt{\frac{1}{4 \cdot \pi^2 \cdot f^2 \cdot C^2} + ESR^2 + 4 \cdot \pi^2 \cdot f^2 \cdot ESL^2} \quad (14)$$

And in this case:

$$C_{ripple} \geq \frac{1}{2 \cdot \pi \cdot f \cdot \sqrt{\frac{U_r^2}{I_r^2} - ESR^2 - 4 \cdot \pi^2 \cdot f^2 \cdot ESL^2}} \quad (15)$$

c) The current ripple

The current ripple must be lower than the maximum value allowed by the manufacturer.

d) The power dissipated

This is often the most restrictive constraint in the design [14]. The current ripple, implies also a power dissipation, equal to:

$$P_d = ESR \cdot {I_r}^2 \leq h \cdot A \cdot \Delta T = G \cdot \Delta T \quad (16)$$

where G (mW/ºC) is given by the manufacturer.

Alternatively, the maximum working operation temperature can be calculated for a given capacitor:

$$T_{Cmax} = \frac{ESR \cdot I_r^2}{h \cdot A} + T_{Ambmax} \quad (17)$$

Thus, the final capacitor must fulfill simultaneously the constraints of hold-up time, of current and voltage ripples, and of the maximum temperature.

VII. Parallelizing different technologies.

Typically, an electrolytic capacitor can be placed for ensuring (9) and (12) at low frequencies, while a ceramic (or film) capacitor can be placed for ensuring low dissipation (13)-(17) or filtering at high frequencies.

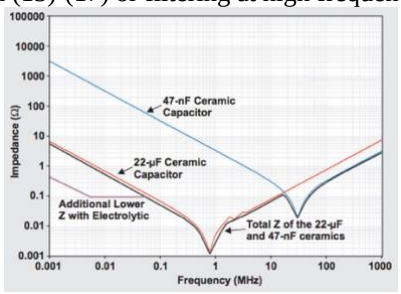


Figure 14 Impedance of Ceramic and Electrolytic capacitors [13].

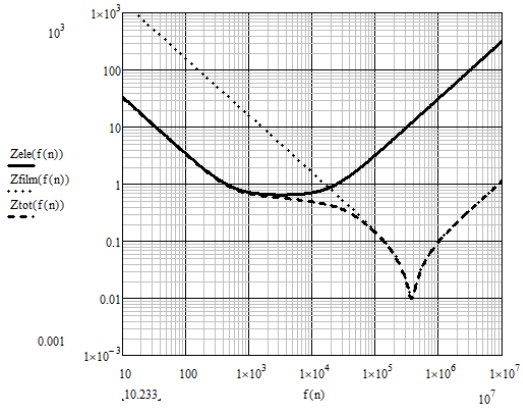


Figure 15 Impedance of parallelized 470uF/550V Electrolytic Capacitor and 10uF/500V Film Capacitor.

VIII. Analysis of Capacitor Losses

The following deals with losses in capacitors for power electronic components. There are mainly two types of capacitors: the electrolytic and the film/ceramic capacitors. The primary advantage of an electrolytic capacitor is large capacity in a small package size at a relatively low cost, however, it has a limited life, and the Equivalent Series Resistance (ESR) is relatively large. Ceramic capacitors have very low ESR, but capacitance is reduced greatly with high bias voltage and can be expensive for large values. Ceramic capacitors are best for high frequency and large-value electrolytic capacitors are good for low frequency. Using both ceramic and electrolytic output capacitors, in parallel, minimizes capacitor impedance across frequency. The losses in these types of capacitors will be studied.

a) HF Ceramic Capacitor

The power losses in a capacitor is calculated as follows.

$$P_{cap}|_{HF} = I_c|_{RMS\_HF}{}^2 * ESR|_{HF} \quad (18)$$

where *ESR* is the equivalent series resistance of the capacitor, and $I_c|_{RMS}$ is the RMS capacitor current. The RMS capacitor current is calculated based on the converter topology, thus for a boost converter operating with duty retio D, the expression is as follows.

$$I_c|_{RMS\_HF} = i_{o\ AVG} * \sqrt{\frac{D+\frac{\Delta i_{Lpp}|_{pu}{}^2}{12}}{1-D}} \quad (19)$$

$$I_c|_{RMS\_HF} = i_{L\ AVG} * \sqrt{\left(D+\frac{\Delta i_L|_{pu}{}^2}{12}\right)(1-D)} \quad (20)$$

The *ESR*, in turn, depends on the capacitive reactance, and the dissipation factor, DF, also called the tangent of the loss angle, $tan\delta$, and is calculated as follows.

$$ESR|_{HF} = X_c|_{HF} * tan\delta \quad (21)$$

where X_c is the capacitive impedance and is expressed as:

$$X_c|_{HF} = \frac{1}{2*\pi*f*C_o} \quad (22)$$

where the capacitance, C_o, varies inversely with the output ripple voltage, ΔV_o, as well as directly with the output current, I_o, and duty cycle, D. Thus the capacitance value can be selected as follows.

$$C_o \geq \frac{I_o|_{max}*D}{f*\Delta V_o} \quad (23)$$

Based on this selected value of the capacitance, $tan\delta$ can be obtained from the datasheet, and thus the ESR can be calculated.

b) LF Electrolytic Capacitor

If there is a need for an electrolytic capacitor for energy storage/ hold-up, it should be sized to meet both of the hold-up time, t_{hold}, and the low frequency voltage ripple requirements, $\Delta V_o|_{LF}$. The capacitor value is selected to have the larger value among the two equations in below [4].

$$C_o \geq \frac{2*P_o*t_{hold}}{({V_o}^2-{V_o}|_{min})} \quad (24)$$

$$C_o \geq \frac{P_o}{2*\pi*f_{line}*\Delta V_o|_{LF}*V_o} \quad (25)$$

where f_{line} is the line frequency, 50Hz. Also V_o is the output voltage, 400V, and $V_o|_{min}$ is minimum output voltage, 340V. The hold-up time is the time at $V_o|_{min}$, thus 20ms (1/50Hz).

After selecting the capacitor value, the power losses in the electrolytic capacitor should be calculated similarly, as follows.

$$P_{cap}|_{LF} = I_c|_{RMS\_LF}{}^2 * ESR|_{LF} \quad (26)$$

where

$$I_c|_{RMS\_LF} = D * I_{rms}|_{LF} \quad (27)$$

and the total power losses in the mixed DC-Link is the summation of losses in both capacitor types.

$$P_{cap}|_{total} = P_{cap}|_{HF} + P_{cap}|_{LF} \quad (28)$$

IX. Conclusions

A general rule is to use electrolytic capacitors to guarantee enough capacitance (e.g. hold up time, LF grid frequency ripple, LF filters in inverters, etc.), and use film capacitors for HF filtering (e.g. in DC-DC converters). Electrolytic devices can be parallelized to film capacitors, in order to decrease the ESR and Z at high frequencies.

If critical temperature/frequency performance is desired, then ceramic capacitors are used (e.g. resonant converters, tuned filters, etc.).

About the design of the capacitor bank, the final assembly of devices must fulfill simultaneously the constraints of hold-up time (if existing), of HF and LF current and voltage ripples, and of the maximum temperature.

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