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Wir schaffen Wissen – heute für morgen

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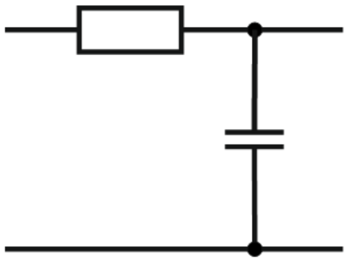
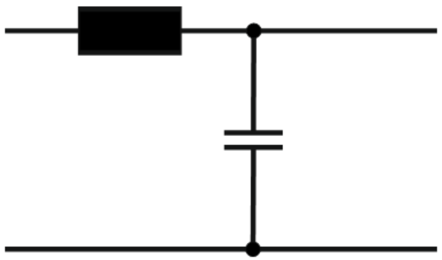
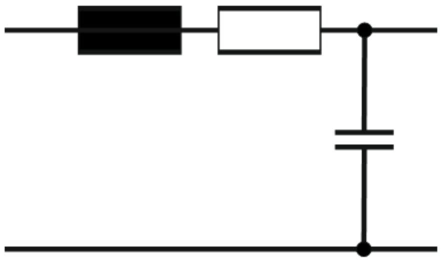
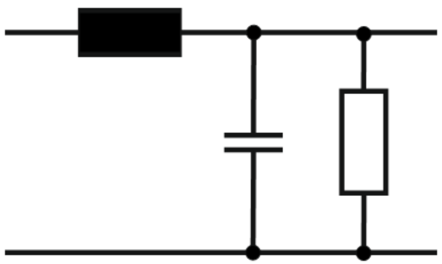
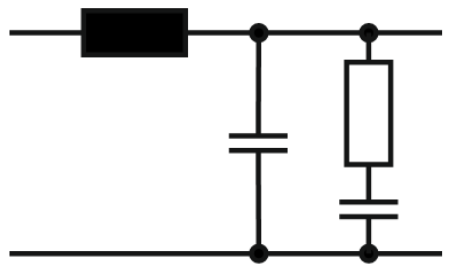
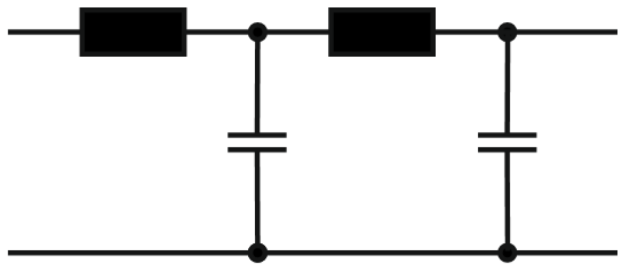
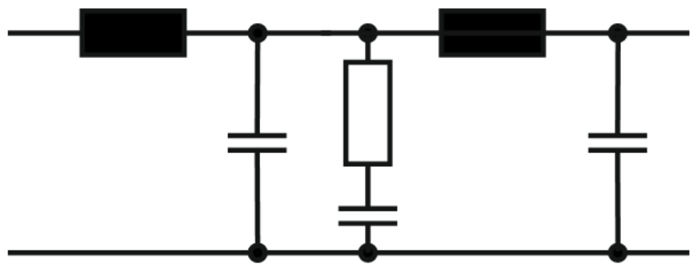
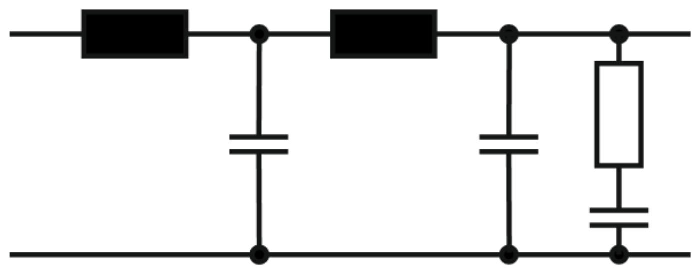
Filter Design - Passive Power Filters

CERN Accelerator School 2014, Baden, Switzerland

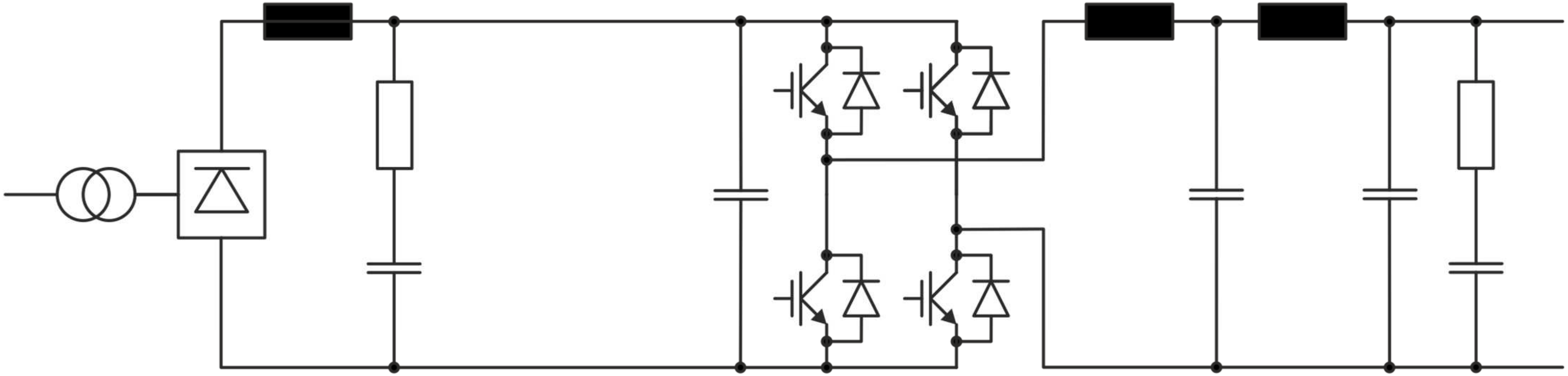
Suitable Filter Structures

		For signal filters simple RC are commonly used Attenuation only 20dB/decade Full current through R → Losses !
		With a LC structure we get 40dB/decade There is a high resonance
		Series damping in order to overcome the resonance problem Full current through R → Losses!
		Parallel damping in order to overcome the resonance problem Full voltage across R → Losses!

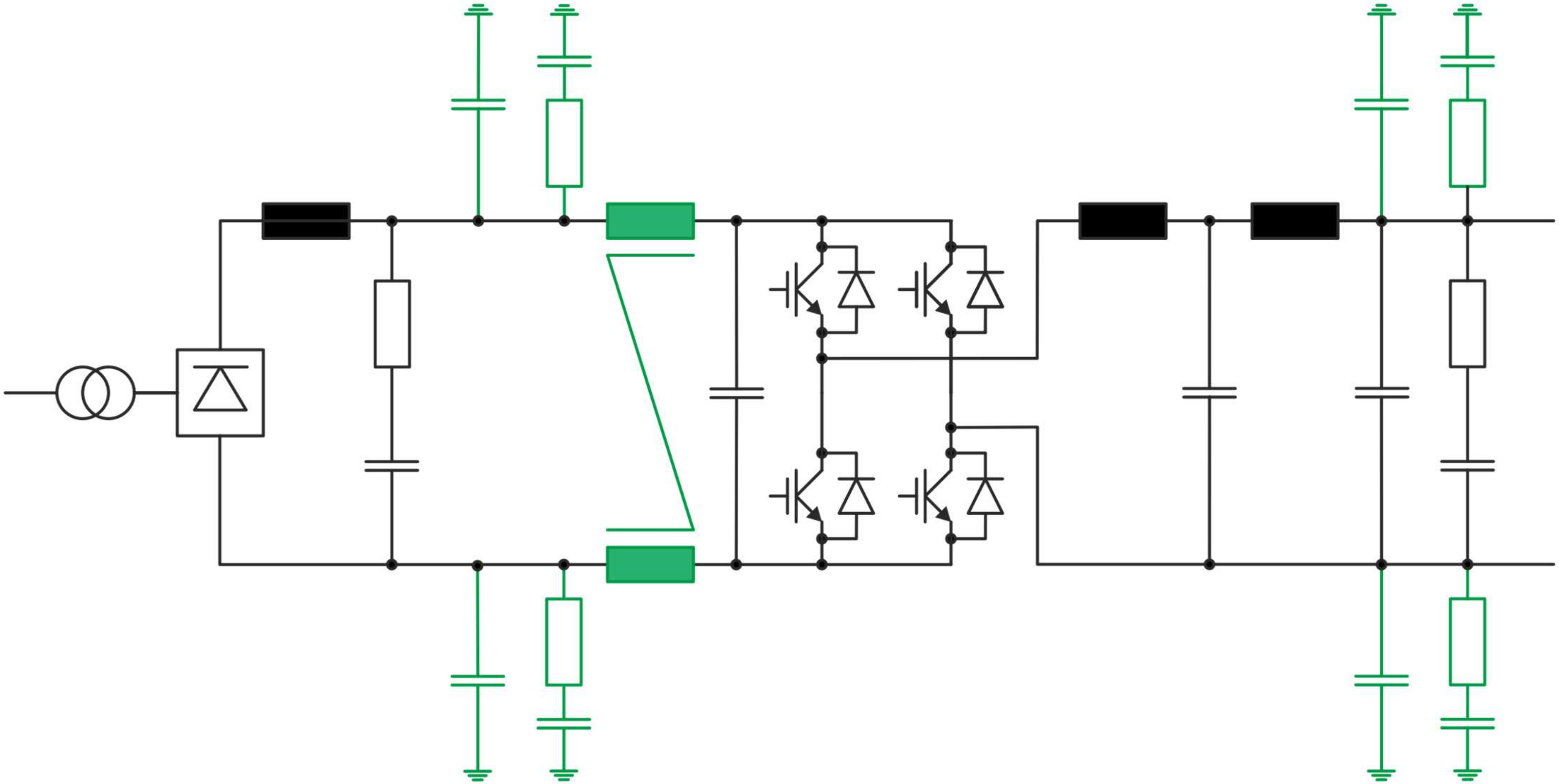
Suitable Filter Structures

		2nd order lowpass filter with parallel RC-damping Resonance can be damped Reasonable losses
		For better attenuation 2 LC stages are necessary Again high resonance
		RC damping after first stage Resonance ok High losses in RC damping due to high ripple currents
		4th order lowpass filter with parallel RC-damping after second stage Resonance can be damped Reasonable losses

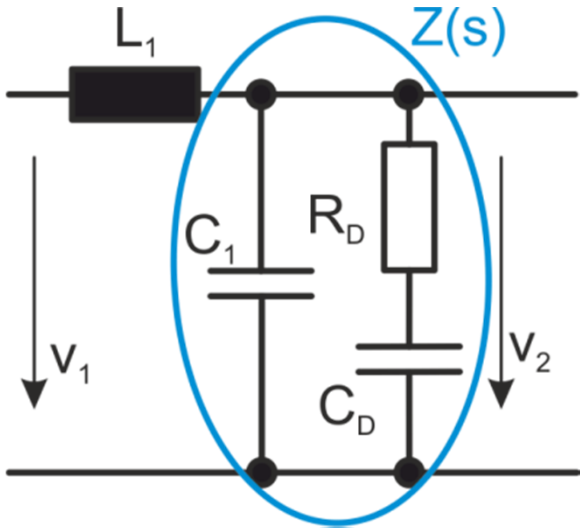
H-Bridge



H-Bridge with CM filter



2nd order filter - Transferfunction



$$Z(s) = \frac{1}{C_1 s + \frac{1}{R_D + \frac{1}{C_D s}}} = \frac{R_D C_D s + 1}{C_1 R_D C_D s^2 + (C_1 + C_D) s}$$

$$G(s) = \frac{v_2(s)}{v_1(s)} = \frac{Z(s)}{L_1 s + Z(s)} = \frac{\mathrm{R_D C_D s} + 1}{\mathrm{L_1 C_1 R_D C_D}\, \mathrm{s}^3 + \mathrm{L_1 (C_1 + C_D) s^2} + \mathrm{R_D C_D s} + 1} \qquad (1)$$

$$G(s) = \frac{k_1 s + 1}{k_3 s^3 + k_2 s^2 + k_1 s + 1}$$

1st order PD

3rd order PT

with

$$k_1 = R_D C_D$$

$$k_2 = L_1 (C_1 + C_D)$$

$$k_3 = L_1 C_1 R_D C_D$$

2^{nd} order filter - Transferfunction

3^{rd} order PT in its normalized form:

$$G_{PT}(s) = \frac{1}{(1 + a_1 \frac{s}{\omega_0}) \cdot (1 + a_2 \frac{s}{\omega_0} + b_2 \frac{s^2}{{\omega_0}^2})} \quad (2)$$

Method	a_1	a_2	b_2
Butterworth	1.0000	1.0000	1.0000
Bessel	0.7560	0.9996	0.4772
Critical damping	0.5098	1.0197	0.2599

2^{nd} order filter - Transferfunction

By expanding (2) and comparing the coefficients with (1) we get:

$$G_{PT}(s) = \frac{1}{\frac{a_1 b_2}{{\omega_0}^3} s^3 + \frac{(a_1 a_2 + b_2)}{{\omega_0}^2} s^2 + \frac{(a_1 + a_2)}{\omega_0} s + 1}$$

$$k_1 = R_D C_D = \frac{a_1 + a_2}{\omega_0} \qquad (3a)$$

$$k_2 = L_1 (C_1 + C_D) = \frac{a_1 a_2 + b_2}{{\omega_0}^2} \qquad (3b)$$

$$k_3 = L_1 C_1 R_D C_D = \frac{a_1 b_2}{{\omega_0}^3} \qquad (3c)$$

The 3 independent equations (3a….3c) contain 5 unknowns (L_1, C_1, R_D, C_D and ω_0). Therefore we have the choice to select 2 of them and the remaining 3 depend on that selection.

2nd order filter - Selection of ω_0

For a given frequency ω_B well in the blocking area ($\omega_B >> \omega_0$) we can define the desired attenuation G_B. In the blocking area the highest order terms of both the numerator and denominator in equation (1) dominate, therefore (1) can be simplified to:

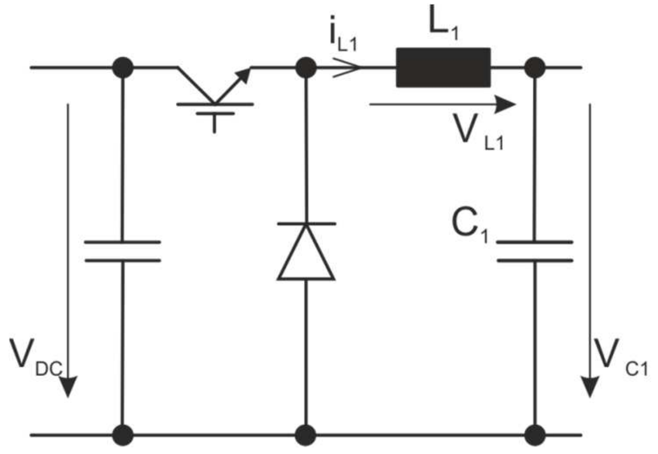
$$G_B = \frac{R_D C_D s}{L_1 C_1 R_D C_D s^3} = \frac{\frac{a_1 + a_2}{\omega_0} s}{\frac{a_1 b_2}{\omega_0{}^3} s^3} = \frac{a_1 + a_2}{a_1 b_2} \cdot \frac{\omega_0{}^2}{s^2} = -\frac{a_1 + a_2}{a_1 b_2} \cdot \frac{\omega_0{}^2}{\omega_B{}^2}$$

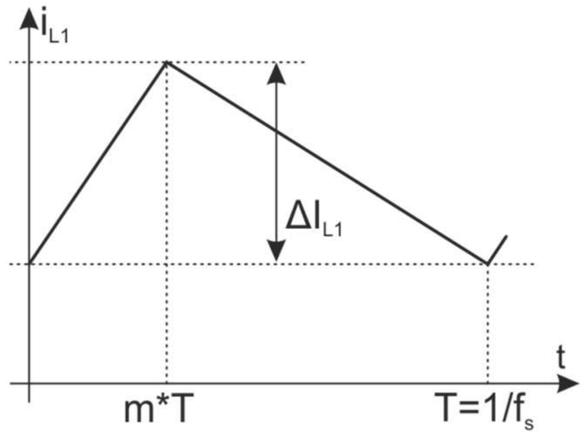
$$(j)^2 = -1$$

$$\omega_0 = \omega_B \cdot \sqrt{\frac{|G_B| \cdot a_1 b_2}{a_1 + a_2}} \qquad (4)$$

2^{nd} order filter - Definition of L_1

For cost reasons L_1 should be as small as possible, but a too small inductance will result in an excessive ripple current!





The DC-voltage across C_1 is m*V_{DC}. When the IGBT is on, the current in L_1 increases and the peak-peak ripple current ΔI_{L1} can be calculated:

$$V_{L1} = L_1 \cdot \frac{di_{L1}}{dt} = V_{DC} - V_{C1} = V_{DC} \cdot (1-m)$$

$$\Delta I_{L1} = m \cdot T \cdot \frac{di_{L1}}{dt} = m \cdot \frac{1}{f_s} \cdot \frac{V_{DC} \cdot (1-m)}{L_1} = \frac{V_{DC} \cdot (1-m) \cdot m}{f_s \cdot L_1}$$

Maximum 0.25 for m = 0.5

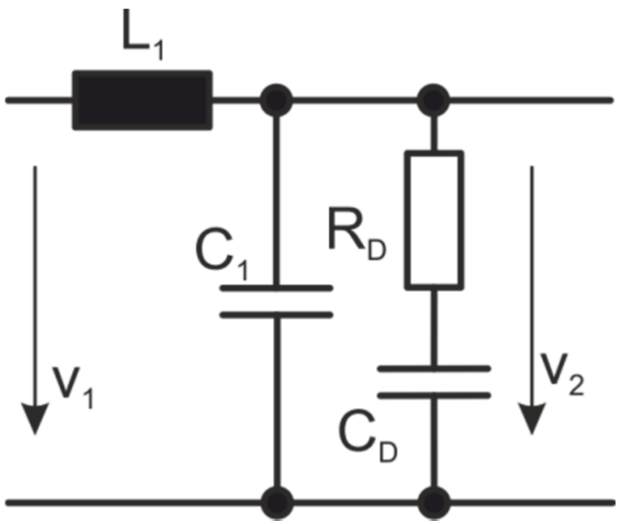
$$L_1 = \frac{V_{DC} \cdot 0.25}{f_s \cdot \Delta I_{L1}} \qquad (5)$$

2^{nd} order filter - Definition of L_1

Alternative approach to determine L_1:

$$I_{L1\_ripple\_pp} = \frac{v_{1\_ripple\_pp}}{2 \cdot \pi \cdot f_{ripple} \cdot L_1}$$

$$L_1 = \frac{v_{1\_ripple\_pp}}{2 \cdot \pi \cdot f_{ripple} \cdot I_{L1\_ripple\_pp}} \quad (6)$$



2nd order filter – Calcualting filter elements

Substitute (3a) in (3c) and we receive:

Selection: L_1 and ω_0

$$C_1 = \frac{a_1 b_2}{L_1 {\omega_0}^2 (a_1 + a_2)} \quad (7a)$$

Selection: C_1 and ω_0

$$L_1 = \frac{a_1 b_2}{C_1 {\omega_0}^2 (a_1 + a_2)} \quad (7b)$$

Selection: L_1 and C_1

$$\omega_0 = \sqrt{\frac{a_1 b_2}{L_1 C_1 (a_1 + a_2)}} \quad (7c)$$

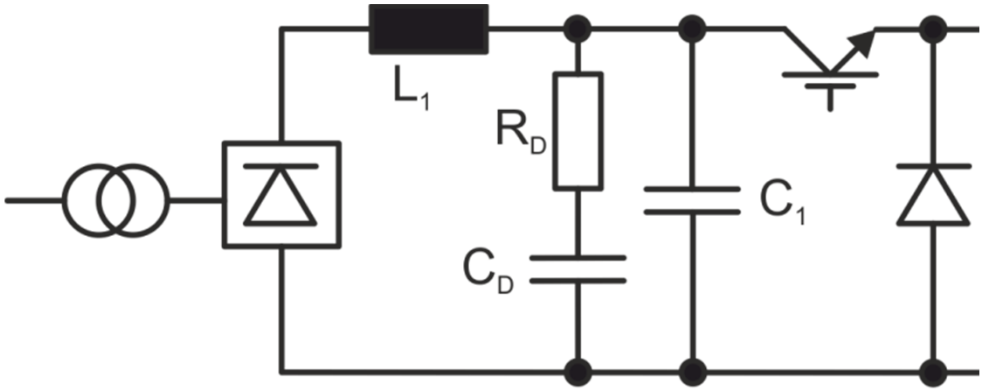
Solve (3b) for C_D:

$$C_D = \frac{a_1 a_2 + b_2}{L_1 {\omega_0}^2} - C_1 \quad (8)$$

Solve (3a) for R_D:

$$R_D = \frac{a_1 + a_2}{C_D \omega_0} \quad (9)$$

2^{nd} order filter – Example 1



- DC-link voltage: 200V
- DC-link current: 500A
- $\Delta I_{L1} \leq$ 50App.
- C_1 must be ≥ 22mF (because of high ripple current)

Design a 2^{nd} order filter for all three given optimization methods and compare the results.

2^{nd} order filter – Example 1

Select L_1 to meet the ripple current requirement:

$$L_1 = \frac{v_{1\_ripple\_pp}}{2 \cdot \pi \cdot f_{ripple} \cdot I_{L1\_ripple\_pp}} \quad (6)$$

$$L_1 = \frac{(200 \cdot 0.13)Vpp}{2 \cdot \pi \cdot 300s^{-1} \cdot 50App} = 300\mu H$$

Select C1:

$$C_1 = 22mF$$

Calculate the remaining filter elements (7c, 8, 9)

2^{nd} order filter – Example 1

Results:

	Butterworth	Bessel	Critical damping
	a_1 = 1.0000 a_2 = 1.0000 b_2 = 1.0000	a_1 = 0.7560 a_2 = 0.9996 b_2 = 0.4772	a_1 = 0.5098 a_2 = 1.0197 b_2 = 0.2599
ω_0 (f_0)	275 s^{-1} (44 Hz)	177 s^{-1} (28 Hz)	115 s^{-1} (18 Hz)
L_1 C_1 C_D R_D	300 µH 22 mF 66 mF x3 0.11 Ω	300 µH 22 mF 110 mF x5 0.09 Ω	300 µH 22 mF 176 mF x8 0.08 Ω

2nd order filter – Example 1

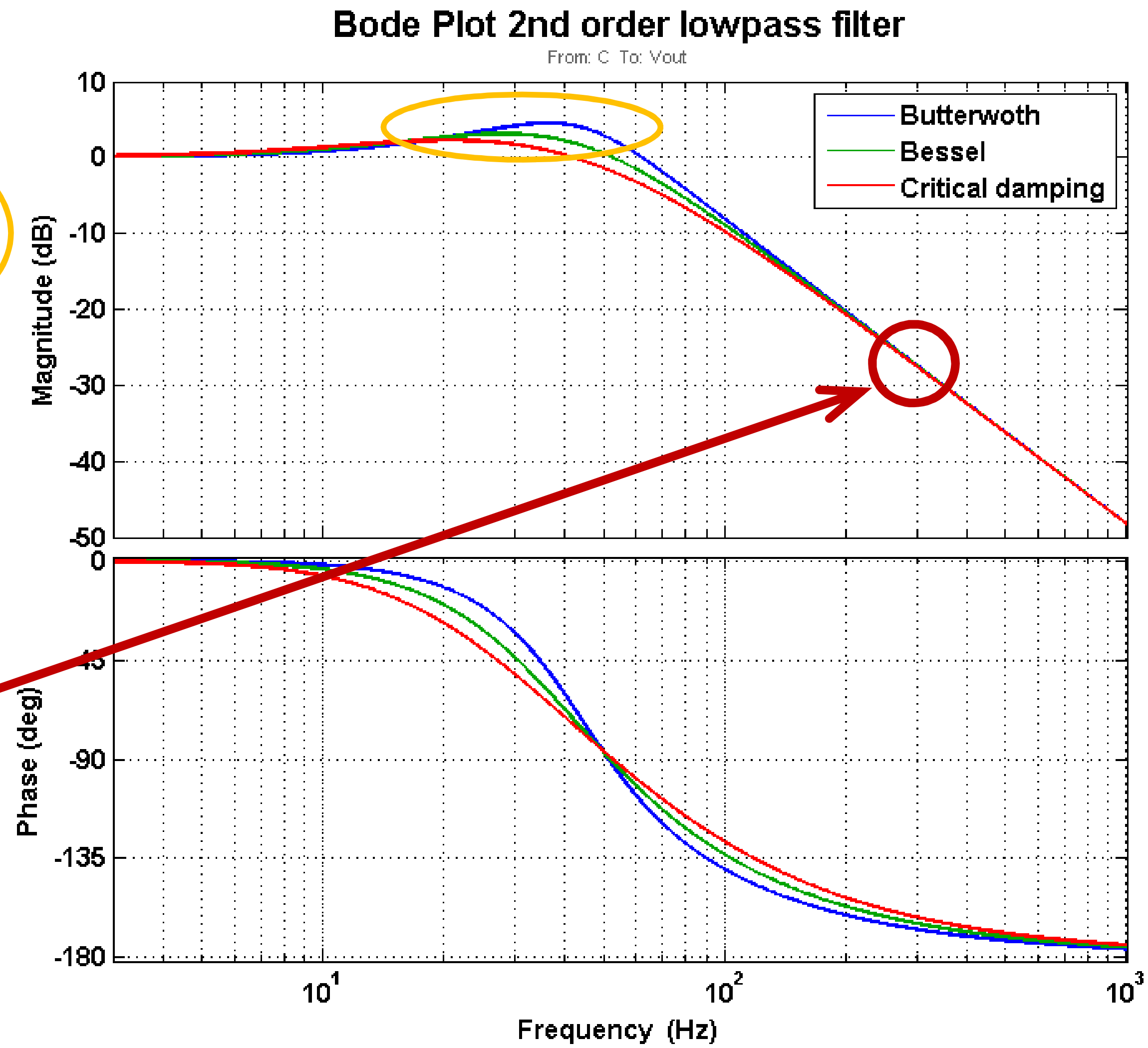
Maximum amplitude of resonance:

Butterworth	4.5 dB
Bessel	3.1 dB
Critical damping	2.3 dB

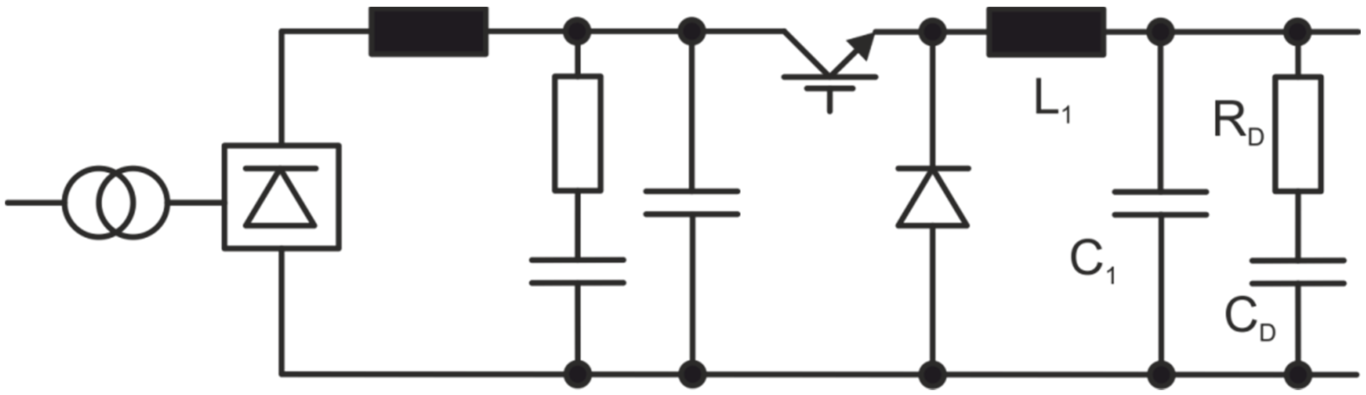
Frequency, for -3 dB attenuation:

Butterworth	74 Hz
Bessel	67 Hz
Critical damping	59 Hz

Attenuation: -28dB @ 300Hz



2^{nd} order filter – Example 2



- DC-link voltage: 120V
- f_s = 20kHz
- I_{Out_max} = 500A
- $\Delta I_{L1} \leq$ 50App.
- Attentuation: G_B = 250 @ $\omega_B = 2*\pi*$20kHz

Same premises as for example 3

Design a 2^{nd} order filter for all three given optimization methods and compare the results.

2^{nd} order filter – Example 2

Select L_1 to meet the ripple current requirement:

$$L_1 = \frac{V_{DC} \cdot 0.25}{f_s \cdot \Delta I_{L1}} = \frac{120V \cdot 0.25}{20kHz \cdot 50A} = 30\mu H \qquad (5)$$

Select ω_0 to meet the attenuation requirement:

$$\omega_0 = \omega_B \cdot \sqrt{\frac{|G_B| \cdot a_1 b_2}{a_1 + a_2}} \qquad (4)$$

Calculate the remaining filter elements (7a, 8, 9)

2^{nd} order filter – Example 2

Results:

	Butterworth	Bessel	Critical damping
	a_1 = 1.0000 a_2 = 1.0000 b_2 = 1.0000	a_1 = 0.7560 a_2 = 0.9996 b_2 = 0.4772	a_1 = 0.5098 a_2 = 1.0197 b_2 = 0.2599
ω_B	$1.26 \cdot 10^5\ s^{-1}$ (20kHz)		
G_B	0.004 (-48dB)		
ω_0	$5.62 \cdot 10^3\ s^{-1}$ (894 Hz)	$3.60 \cdot 10^3\ s^{-1}$ (573 Hz)	$2.34 \cdot 10^3\ s^{-1}$ (372 Hz)
L_1 C_1 C_D R_D	30 µH 528 µF 1'580 µF (x3) 0.22 Ω	30 µH 528 µF 2'640 µF (x5) 0.18 Ω	30 µH 528 µF 4'220 µF (x8) 0.15 Ω

2^{nd} order filter – Example 2

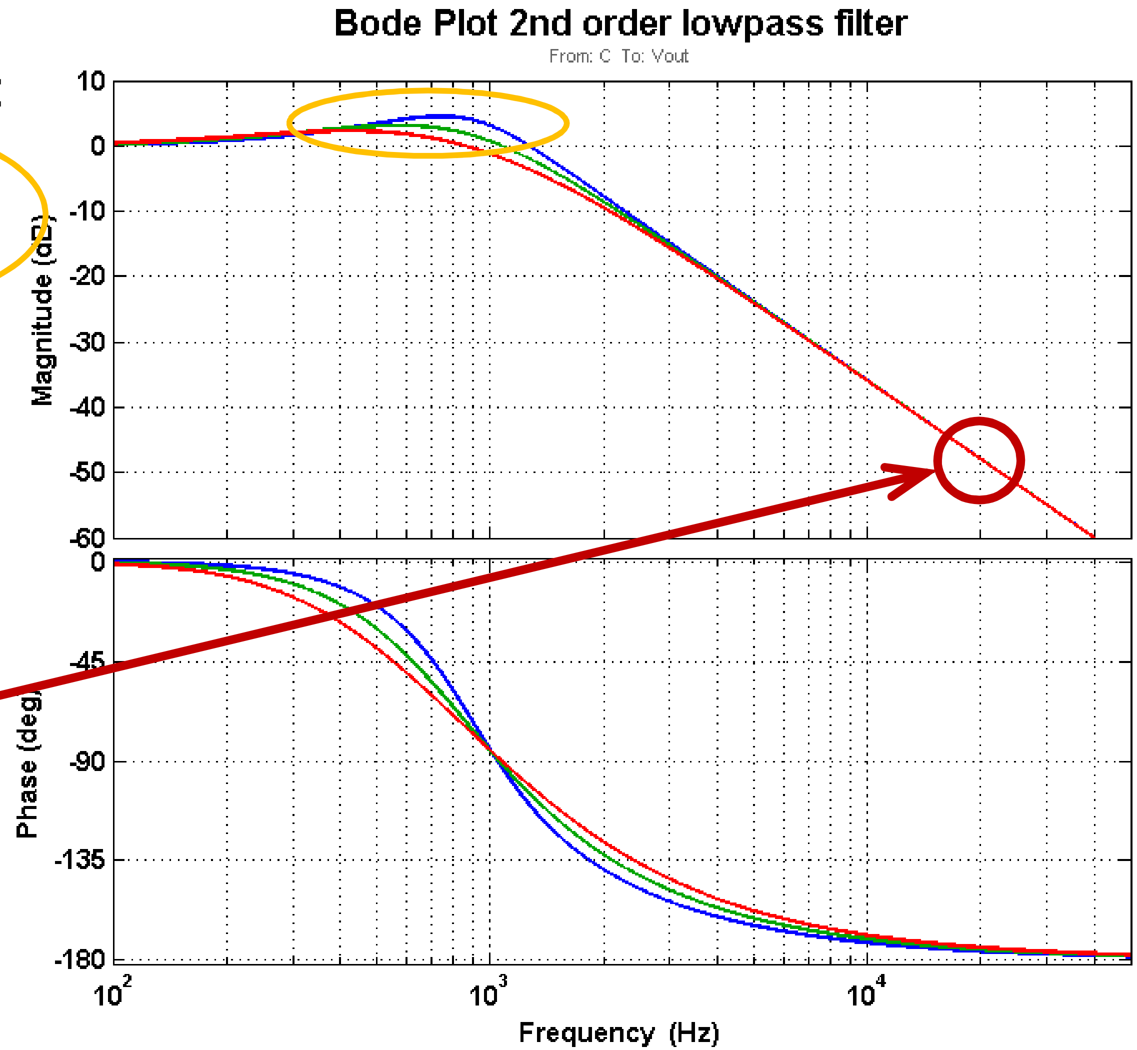
Maximum amplitude of resonance:

Butterworth	4.5 dB
Bessel	3.1 dB
Critical damping	2.3 dB

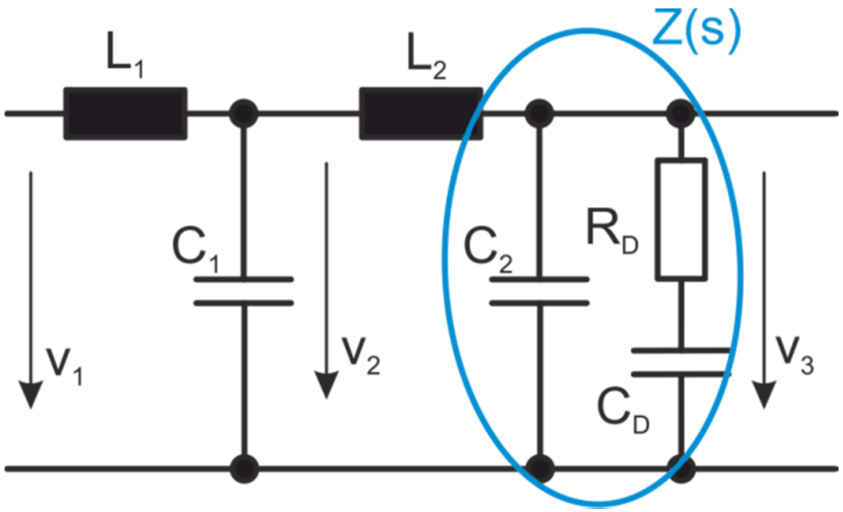
Frequency, for -3 dB attenuation:

Butterworth	1.5 kHz
Bessel	1.4 kHz
Critical damping	1.2 kHz

Attenuation: -48dB @ 20kHz



4th order filter - Transferfunction



$$Z(s) = \frac{1}{C_2 s + \frac{1}{R_D + \frac{1}{C_D s}}} = \frac{R_D C_D s + 1}{C_2 R_D C_D s^2 + (C_2 + C_D)s}$$

$$G(s) = \frac{v_3(s)}{v_1(s)} = \frac{\frac{1}{C_1 s + \frac{1}{L_2 s + Z(s)}}}{L_1 s + \frac{1}{C_1 s + \frac{1}{L_2 s + Z(s)}}} \cdot \frac{Z(s)}{L_2 s + Z(s)}$$

$$G_1(s) = \frac{v_2(s)}{v_1(s)}$$

$$G_2(s) = \frac{v_3(s)}{v_2(s)}$$

4^{th} order filter - Transferfunction

$$G(s) = \frac{R_D C_D s + 1}{L_1 L_2 C_1 C_2 R_D C_D s^5 + (C_2 + C_D) L_1 L_2 C_1 s^4 + [L_1 C_1 R_D C_D + (L_1 + L_2) C_2 R_D C_D] s^3 + \cdots} \cdots$$

$$\cdots \frac{}{\cdots + [L_1 C_1 + (L_1 + L_2)(C_2 + C_D)] s^2 + R_D C_D s + 1} \qquad (10)$$

1st order PD

$$G(s) = \frac{k_1 s + 1}{k_5 s^5 + k_4 s^4 + k_3 s^3 + k_2 s^2 + k_1 s + 1}$$

5th order PT

with

$$k_1 = R_D C_D$$

$$k_2 = L_1 (C_1 + C_2 + C_D) + L_2 (C_2 + C_D)$$

$$k_3 = R_D C_D (L_1 C_1 + L_2 C_2 + L_1 C_2)$$

$$k_4 = L_1 L_2 C_1 (C_2 + C_D)$$

$$k_5 = L_1 L_2 C_1 C_2 C_D R_D$$

4^{th} order filter - Transferfunction

5^{th} order PT in its normalized form:

$$G_{PT}(s) = \frac{1}{(1 + a_1 \frac{s}{\omega_0}) \cdot (1 + a_2 \frac{s}{\omega_0} + b_2 \frac{s^2}{{\omega_0}^2}) \cdot (1 + a_3 \frac{s}{\omega_0} + b_3 \frac{s^2}{{\omega_0}^2})} \qquad (11)$$

Optimisation methods:

	a_1	a_2	b_2	a_3	b_3
Butterworth	1.0000	1.6180	1.0000	0.6180	1.0000
Bessel	0.6656	1.1402	0.4128	0.6216	0.3245
Critical damping	0.3856	0.7712	0.1487	0.7712	0.1487

4^{th} order filter - Transferfunction

By expanding (11) and comparing the coefficients with (10) we get:

$$G_{PT}(s) = \frac{1}{\frac{a_1 b_2 b_3}{{\omega_0}^5} s^5 + \frac{(b_2 b_3 + a_1 a_2 b_3 + a_1 a_3 b_2)}{{\omega_0}^4} s^4 + \frac{(a_2 b_3 + a_3 b_2 + a_1 b_3 + a_1 a_2 a_3 + a_1 b_2)}{{\omega_0}^3} s^3 \cdots} \cdots$$

$$\cdots \frac{\cdots}{\cdots + \frac{(b_3 + a_2 a_3 + b_2 + a_1 a_3 + a_1 a_2)}{{\omega_0}^2} s^2 + \frac{(a_1 + a_2 + a_3)}{\omega_0} s + 1}$$

$$k_1 = R_D C_D = \frac{a_1 + a_2 + a_3}{\omega_0} \qquad \text{(12a)}$$

$$k_2 = L_1(C_1 + C_2 + C_D) + L_2(C_2 + C_D) = \frac{b_3 + a_2 a_3 + b_2 + a_1 a_3 + a_1 a_2}{{\omega_0}^2} \qquad \text{(12b)}$$

$$k_3 = R_D C_D (L_1 C_1 + L_2 C_2 + L_1 C_2) = \frac{a_2 b_3 + a_3 b_2 + a_1 b_3 + a_1 a_2 a_3 + a_1 b_2}{{\omega_0}^3} \qquad \text{(12c)}$$

$$k_4 = L_1 L_2 C_1 (C_2 + C_D) = \frac{b_2 b_3 + a_1 a_2 b_3 + a_1 a_3 b_2}{{\omega_0}^4} \qquad \text{(12d)}$$

$$k_5 = L_1 L_2 C_1 C_2 C_D R_D = \frac{a_1 b_2 b_3}{{\omega_0}^5} \qquad \text{(12e)}$$

4^{th} order filter – selection of ω_0 and L_1

The 5 independent equations (12a….12e) contain 7 unknowns (L_1, C_1, L_2, C_2, R_D, C_D and ω_0). Therefore we have the choice to select 2 of them (ω_0 and L_1) the remaining 5 depend on that selection.

For a given frequency ω_B well in the blocking area ($\omega_B >> \omega_0$) we can define the desired attenuation G_B. In the blocking area the highest order terms of both the numerator and denominator in equation (10) dominate, therefore (10) can be simplified to:

$$G_B = \frac{R_D C_D s}{L_1 L_2 C_1 C_2 R_D C_D s^5} = \frac{\frac{a_1 + a_2 + a_3}{\omega_0} s}{\frac{a_1 b_2 b_3}{\omega_0{}^5} s^5} = \frac{a_1 + a_2 + a_3}{a_1 b_2 b_3} \cdot \frac{\omega_0{}^4}{s^4} = \frac{a_1 + a_2 + a_3}{a_1 b_2 b_3} \cdot \frac{\omega_0{}^4}{\omega_B{}^4}$$

$$(j)^4 = +1$$

$$\omega_0 = \omega_B \cdot \sqrt[4]{\frac{G_B \cdot a_1 b_2 b_3}{a_1 + a_2 + a_3}} \qquad (13)$$

Select L_1 according to ripple current requirements with (5) or (6)

4^{th} order filter – Calculating filter elements

By solving the equation system (12a……12e) we get:

$$L_2 = \frac{L_1}{\frac{(k_3k_4 - k_2k_5)(k_1k_2 - k_3)}{(k_1k_4 - k_5)^2} - 1} \quad (14a)$$

$$C_2 = \frac{k_5(k_1k_2 - k_3)}{k_1(k_1k_4 - k_5)(L_1 + L_2)} \quad (14b)$$

$$C_1 = \frac{k_5}{k_1L_1L_2C_2} \quad (14c)$$

$$R_D = \frac{k_1k_5}{C_2(k_1k_4 - k_5)} \quad (14d)$$

$$C_D = \frac{k_1}{R_D} \quad (14e)$$

with

$$k_1 = \frac{a_1 + a_2 + a_3}{\omega_0}$$

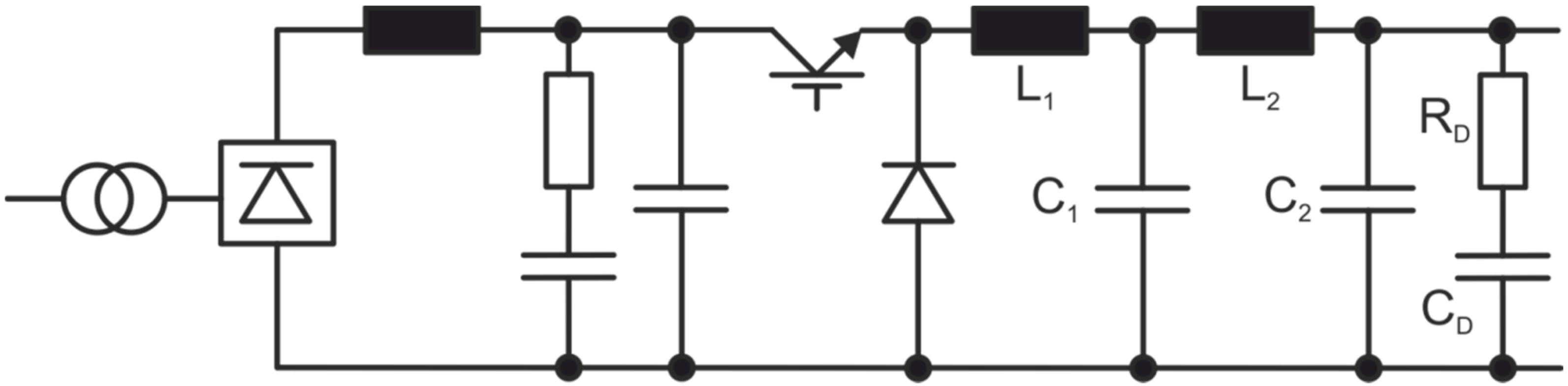
$$k_2 = \frac{b_3 + a_2a_3 + b_2 + a_1a_3 + a_1a_2}{{\omega_0}^2}$$

$$k_3 = \frac{a_2b_3 + a_3b_2 + a_1b_3 + a_1a_2a_3 + a_1b_2}{{\omega_0}^3}$$

$$k_4 = \frac{b_2b_3 + a_1a_2b_3 + a_1a_3b_2}{{\omega_0}^4}$$

$$k_5 = \frac{a_1b_2b_3}{{\omega_0}^5}$$

4^{th} order filter – Example 3



- DC-link voltage: 120V
- f_s = 20kHz
- I_{Out_max} = 500A
- $\Delta I_{L1} \leq$ 50App.
- Attentuation: G_B = 250 @ $\omega_B = 2*\pi*20kHz$

Same premises as for example 2

Design a 4^{th} order filter for all three given optimization methods and compare the results.

4^{th} order filter – Example 3

Select L_1 to meet the ripple current requirement:

$$L_1 = \frac{V_{DC} \cdot 0.25}{f_s \cdot \Delta I_{L1}} = \frac{120V \cdot 0.25}{20kHz \cdot 50A} = 30\mu H \qquad (5)$$

Select ω_0 to meet the attenuation requirement:

$$\omega_0 = \omega_B \cdot \sqrt[4]{\frac{G_B \cdot a_1 b_2 b_3}{a_1 + a_2 + a_3}} \qquad (13)$$

Calculate the remaining filter elements (14a….e)

4^{th} order filter – Example 3

Results:

	Butterworth	Bessel	Critical damping
	$a_1 = 1.0000$ $a_2 = 1.6180$ $b_2 = 1.0000$ $a_3 = 0.6180$ $b_3 = 1.0000$	$a_1 = 0.6656$ $a_2 = 1.1402$ $b_2 = 0.4128$ $a_3 = 0.6216$ $b_3 = 0.3245$	$a_1 = 0.3856$ $a_2 = 0.7712$ $b_2 = 0.1487$ $a_3 = 0.7712$ $b_3 = 0.1487$
ω_B	$1.26 \cdot 10^5\ s^{-1}$ (20kHz)		
G_B	0.004 (-48dB)		
ω_0	$2.36 \cdot 10^4\ s^{-1}$ (3.8 kHz)	$1.38 \cdot 10^4\ s^{-1}$ (2.2 kHz)	$8.15 \cdot 10^3\ s^{-1}$ (1.3 kHz)
L_1	30 µH	30 µH	30 µH
L_2	57 µH	31 µH	17 µH
C_1	74 µF	90 µF	124 µF
C_2	7.9 µF	12 µF	16 µF
C_D	75 µF	168 µF	382 µF
R_D	1.83 Ω	1.04 Ω	0.62 Ω

4th order filter – Example 3

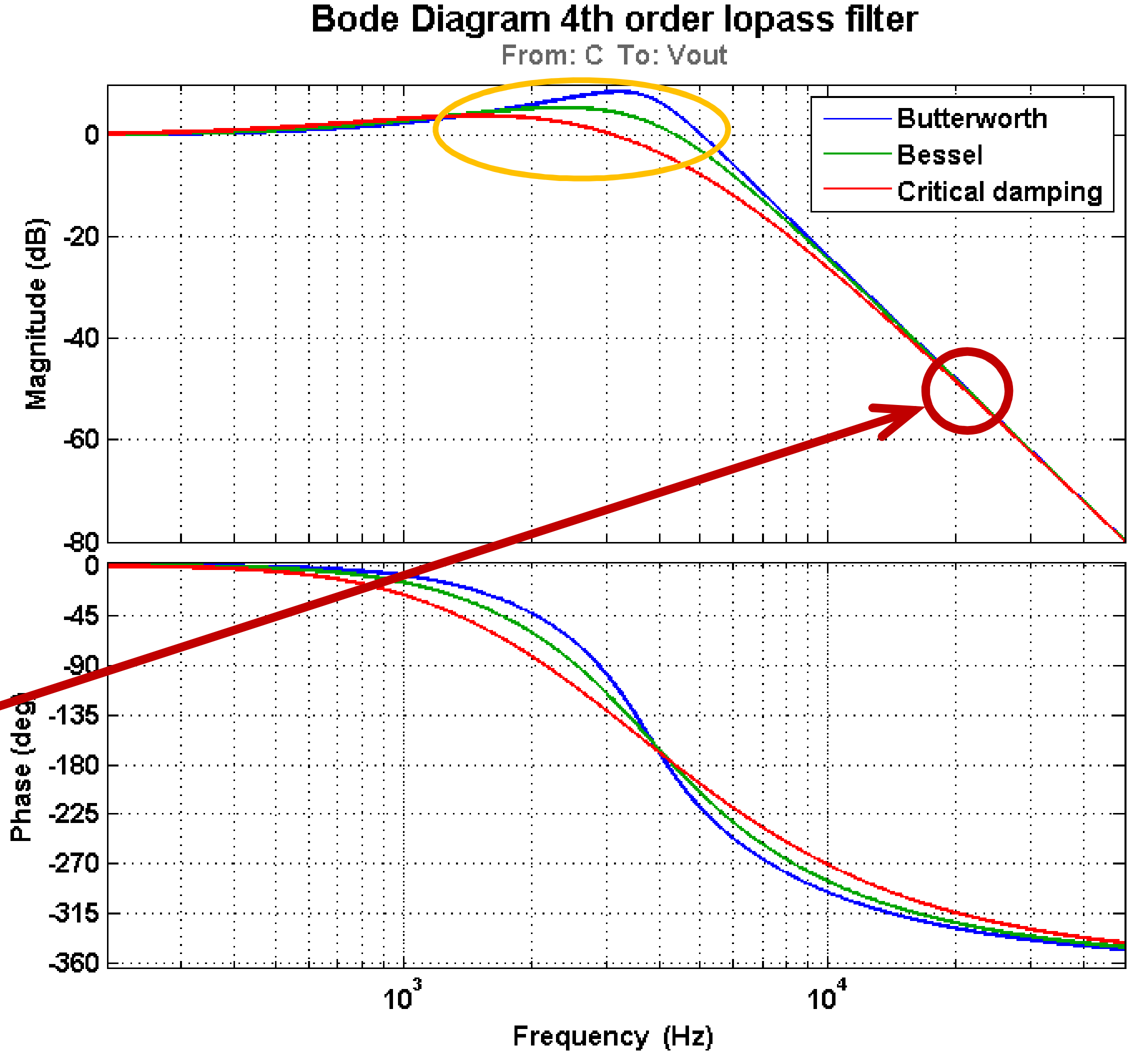
Maximum amplitude of resonance:

Butterworth	8.6 dB
Bessel	5.4 dB
Critical damping	3.8 dB

Frequency, for -3 dB attenuation:

Butterworth	5.5 kHz
Bessel	5.0 kHz
Critical damping	3.9 kHz

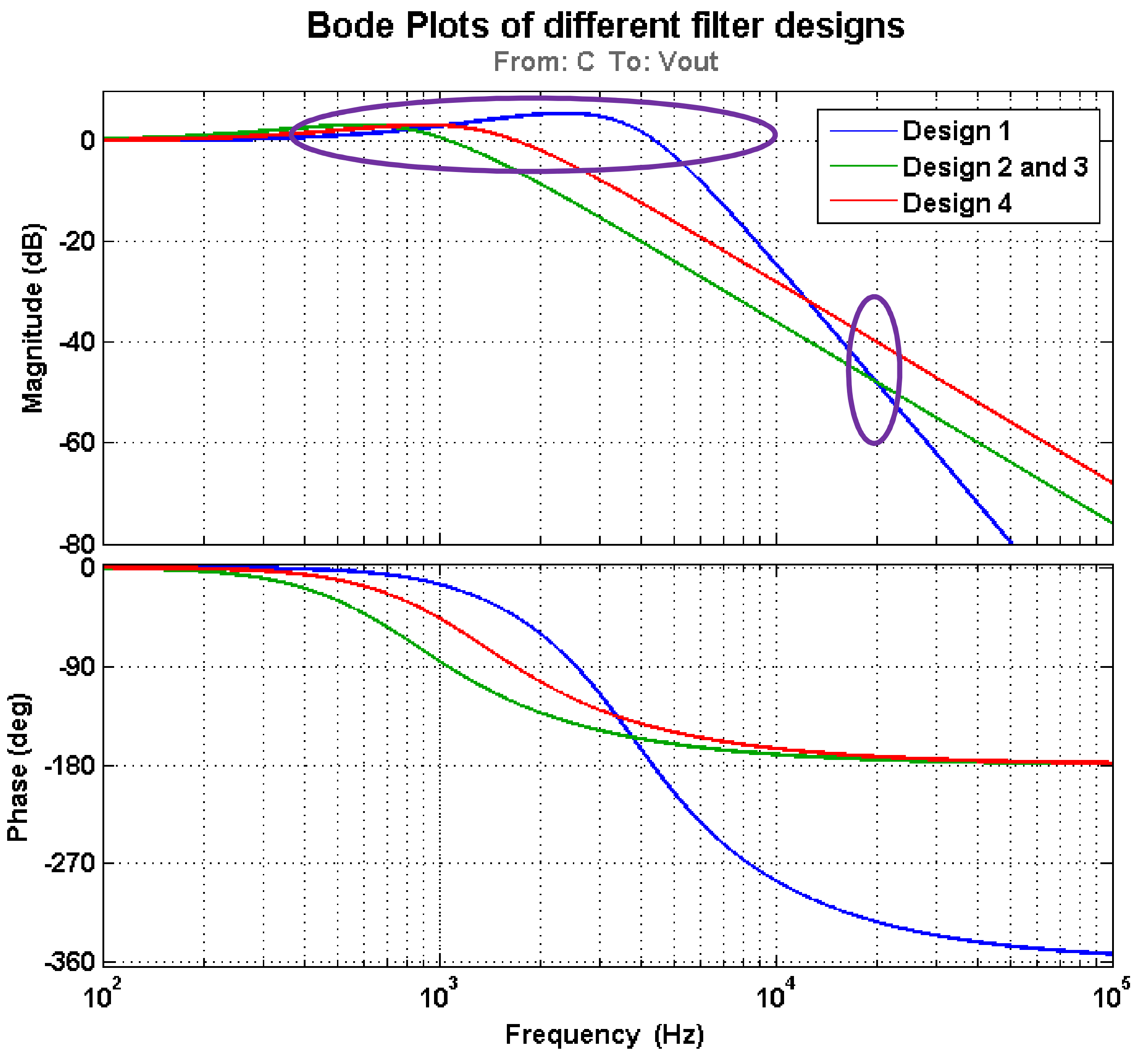
Attenuation: -48dB @ 20kHz



Comparison of different filter designs

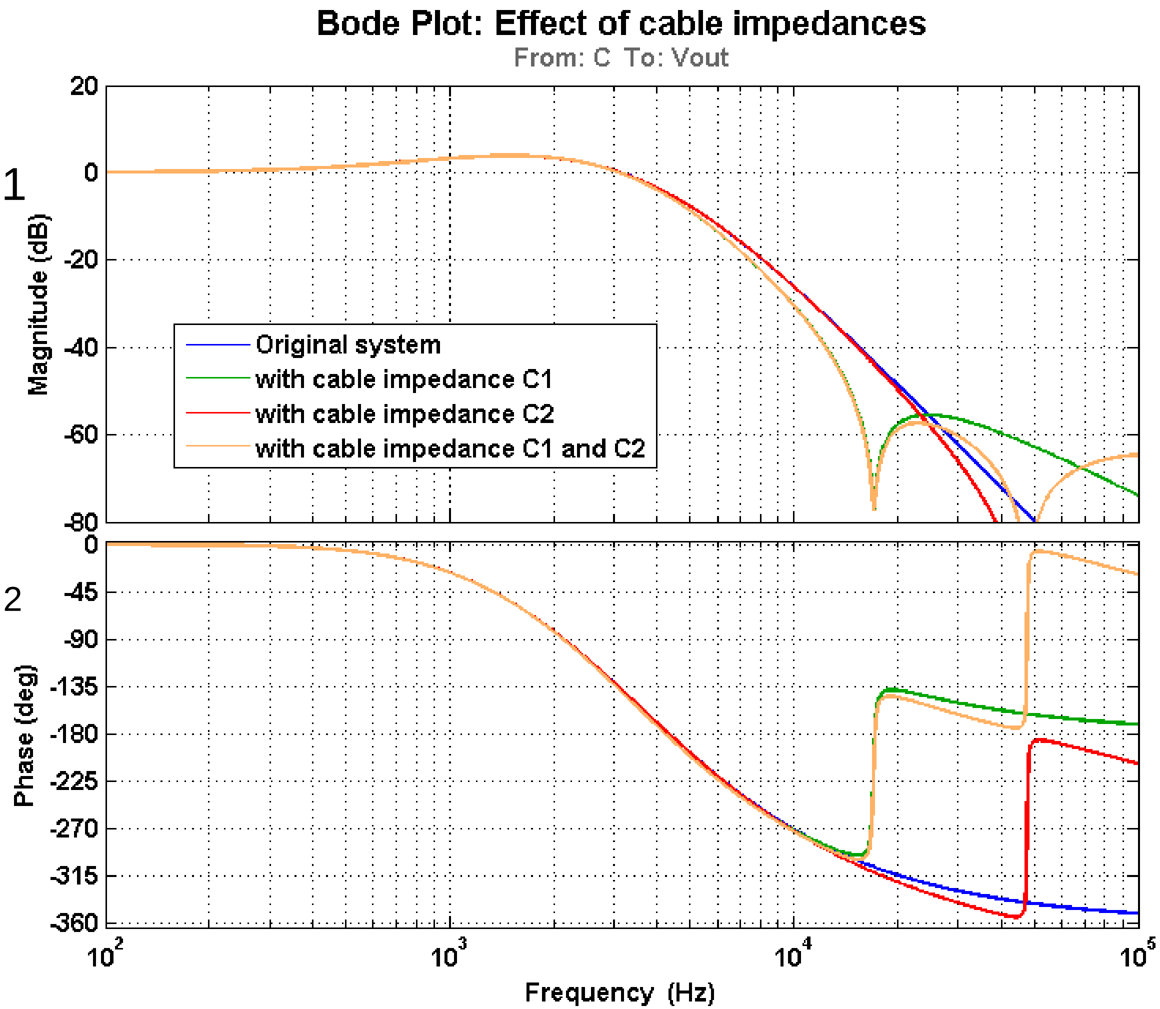
Design 1	Design 2	Design 3	Design 4
4^{th} order	2^{nd} order	2^{nd} order	2^{nd} order
Acc. to example 3	Acc. to example 2	Acc. to example 2 but L_1 = 100µH	Acc. to example 2 but L_1 = 100µH and G_B = 0.01
Optimisation: Bessel	Optimisation: Bessel	Optimisation: Bessel	Optimisation: Bessel
L_1 = 30 µH L_2 = 31 µH	L_1 = 30 µH	L_1 = 100 µH	L_1 = 100 µH +64%
C_1 = 90 µF C_2 = 12 µF	C_1 = 528 µF	C_1 = 158 µF	C_1 = 63 µF +42%
C_D = 168 µF	C_D = 2'600 µF	C_D = 790 µF	C_D = 320 µF
R_D = 1.04 Ω	R_D = 0.18 Ω	R_D = 0.62 Ω	R_D = 0.98 Ω
f_0 = 2'200 Hz	f_0 = 573 Hz	f_0 = 573 Hz	f_0 = 907 Hz

Comparison of different filter designs



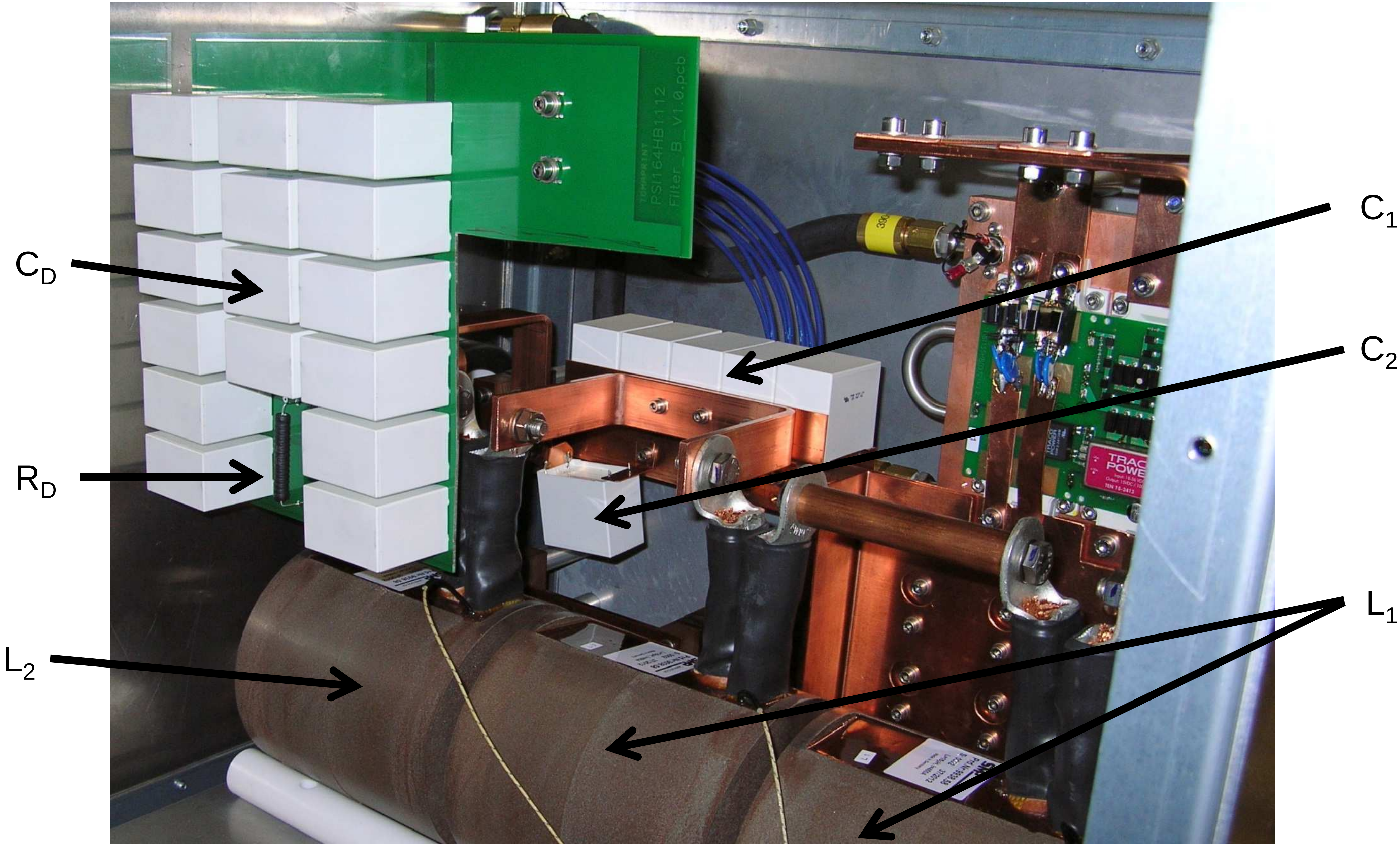
Practical Aspects - Wiring

- Effect of a 0.5m long wire 16mm² (wiring of C_1 and C_2)
  - Skin Effect
    - Skin depth in Cu @ 20kHz: 0.5mm
    - Reduces the effective cross section to 6.3 mm²
    - Wire resistance @ 20kHz: 1.4mΩ
  - Wire inductance is approx. 0.5µH



To be avoided !

Practical Aspects – low inductive setup



Life time of electrolytic capacitors

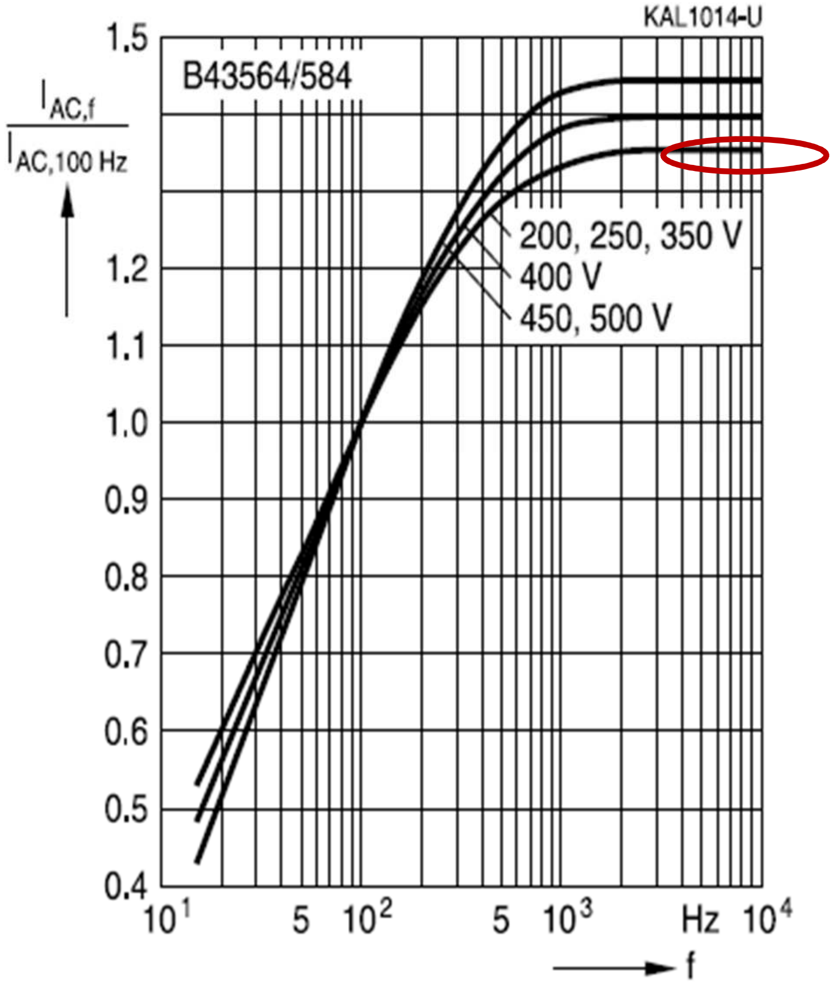
The useful life time of an electrolytic capacitor depends very much on the ripple current and the ambient temperature.

C_R 100 Hz 20 °C µF	Case dimensions d × l mm	ESR_{typ} 100 Hz 20 °C mΩ	Z_{max} 10 kHz 20 °C mΩ	$I_{AC,max}$ 100 Hz 40 °C A	$I_{AC,R}$ 100 Hz 85 °C A	$I_{AC,R}(B)$ 100 Hz 85 °C A	Ordering code (composition see below)
V_R = 200 V DC							
3300	51.6 × 80.7	40	48	21	7.9	15.3	B435*4E2338M0##
4700	51.6 × 105.7	29	35	27	10.1	17.6	B435*4E2478M0##
4700	64.3 × 80.7	29	35	27	10.0	18.6	B435*4F2478M0##
6800	64.3 × 105.7	21	25	34	12.6	22.0	B435*4E2688M0##
8200	76.9 × 105.7	17	20	41	15.2	26.8	B435*4E2828M0##
10000	76.9 × 105.7	14	17	47	17.4	32.8	B435*4E2109M0##
15000	76.9 × 143.2	8	10	57	25.6	43.6	B435*4E2159M0##
22000	91.0 × 144.5	5	6	80	35.9	63.6	B435*4E2229M0##

- Nominal ripple current at
  - nominal frequency (100Hz) and
  - nominal capacitor temperature (85ºC).
  - *17.4A in our example*

Life time of electrolytic capacitors

Frequency factor of permissible ripple current I_{AC} versus frequency f



Apply frequency factor:

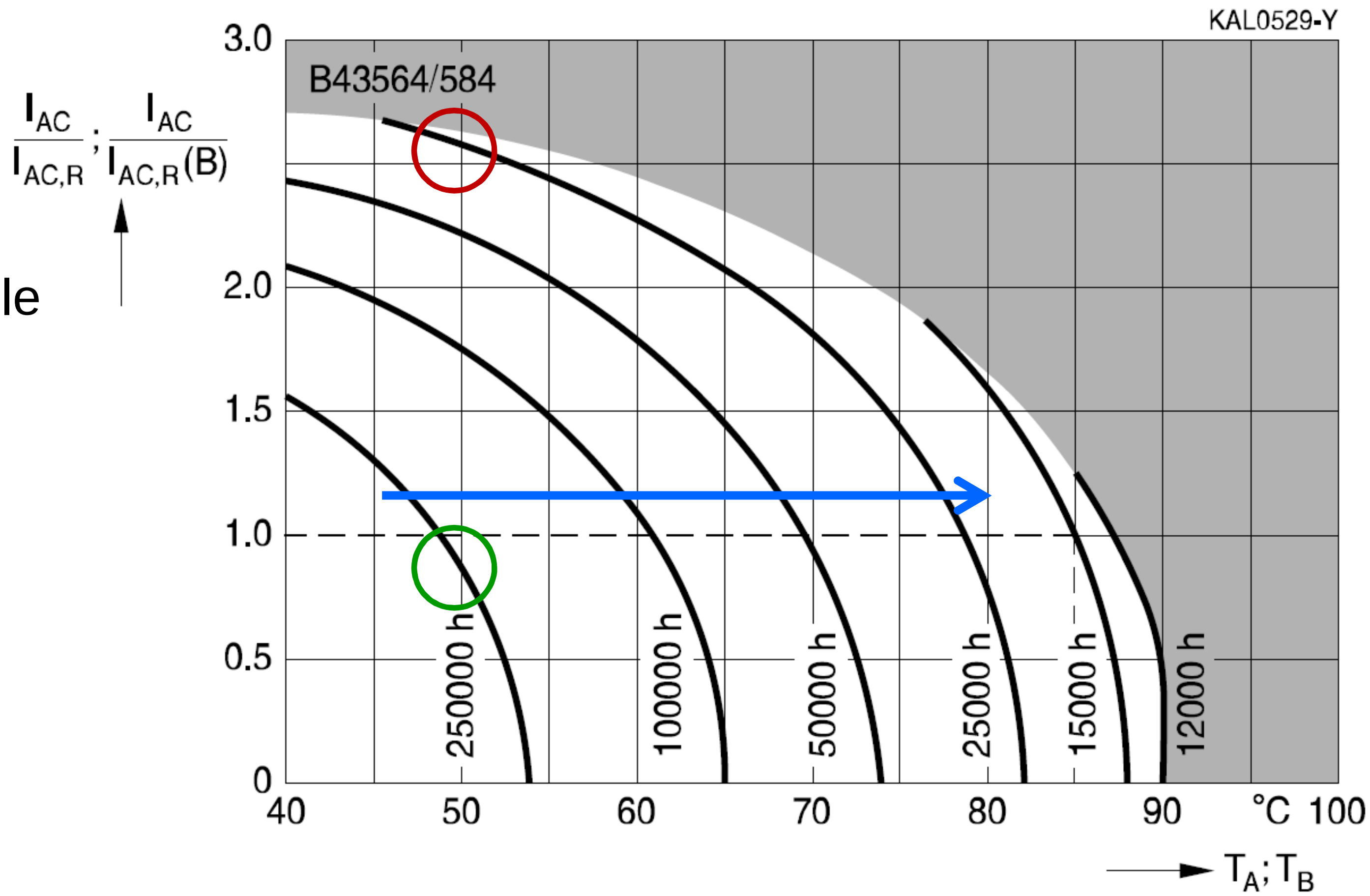
For 10kHz a current factor of 1.35 is applicable
→ 23.5A @ 10kHz

Life time of electrolytic capacitors

Determine the allowed ripple current for a desired useful life and Ta:

For 25'000h (3 years) and Ta = 50ºC,
*→ 2.6 * 23.5A = 61A*

For 250'000h (30years) and Ta = 50ºC
*→ 0.85 * 23.5A = 20A*



The useful life time dramatically decreases at higher ambient temperatures!

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Thank you for your attention

Questions?

References

- U. Tietze, Ch. Schenk; Halbleiter-Schaltungs-Technik, 12. Auflage, Pages 815ff
- Epcos, Datasheet, Capacitors with screw terminals Type B43564, B43584, November 2012