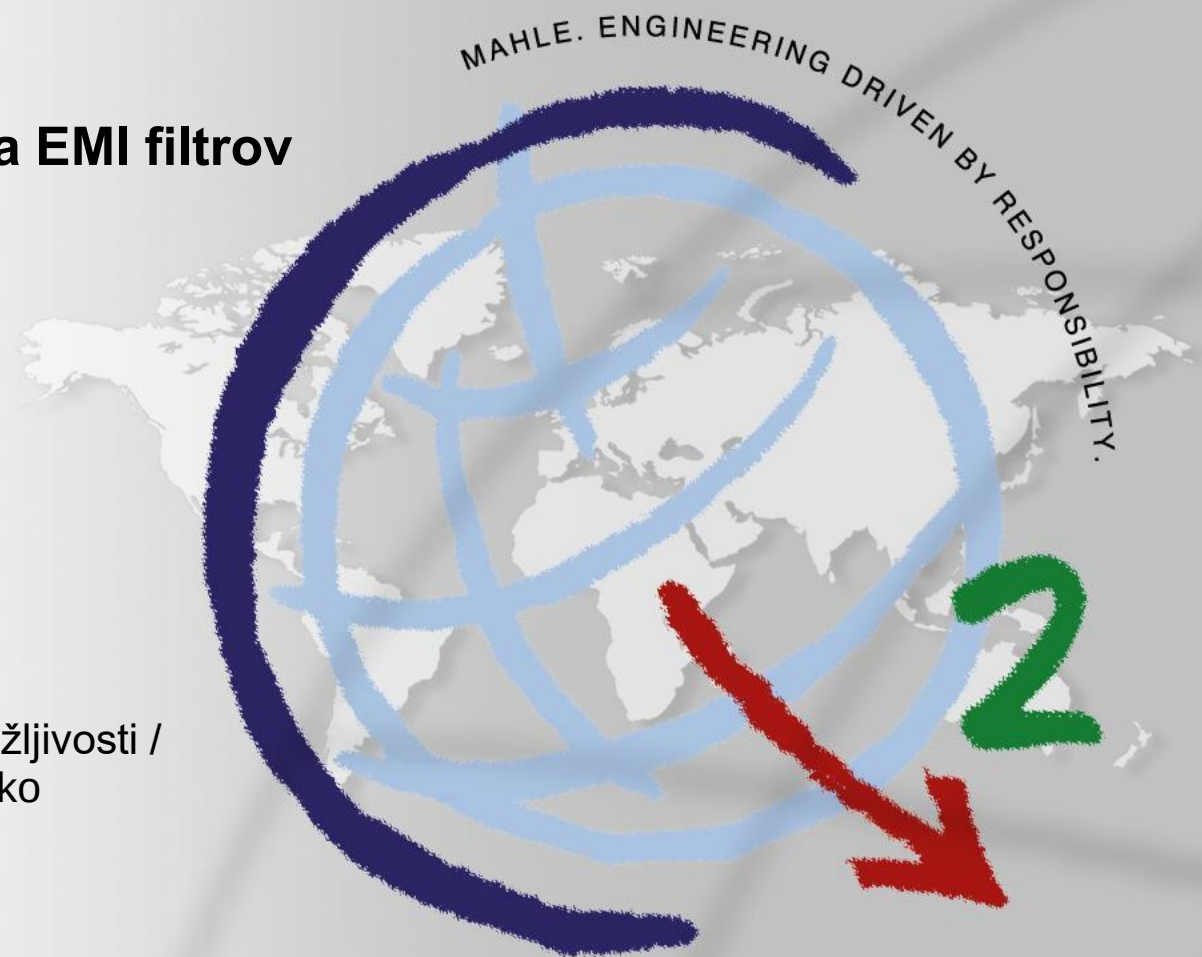


Praktična delavnica načrtovanja EMI filtrov

dr. Gregor Ergaver (MAHLE, RR EMC),
izr. prof. dr. Marko Jankovec (FE, LPVO)
Raziskave in razvoj elektromagnetne združljivosti /
Laboratorij za fotovoltaiiko in optoelektroniko
RR EMC/LPVO



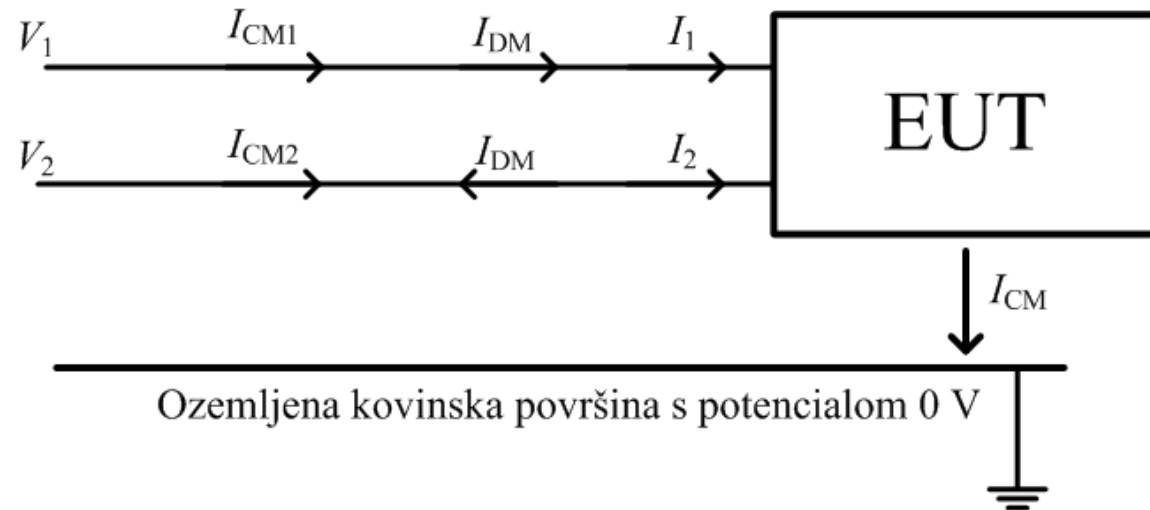
Teorija pasivnih filtrov

$$I_1 = I_{DM} + I_{CM1}$$

$$I_2 = I_{CM2} - I_{DM}$$

$$I_{CM} = I_1 + I_2$$

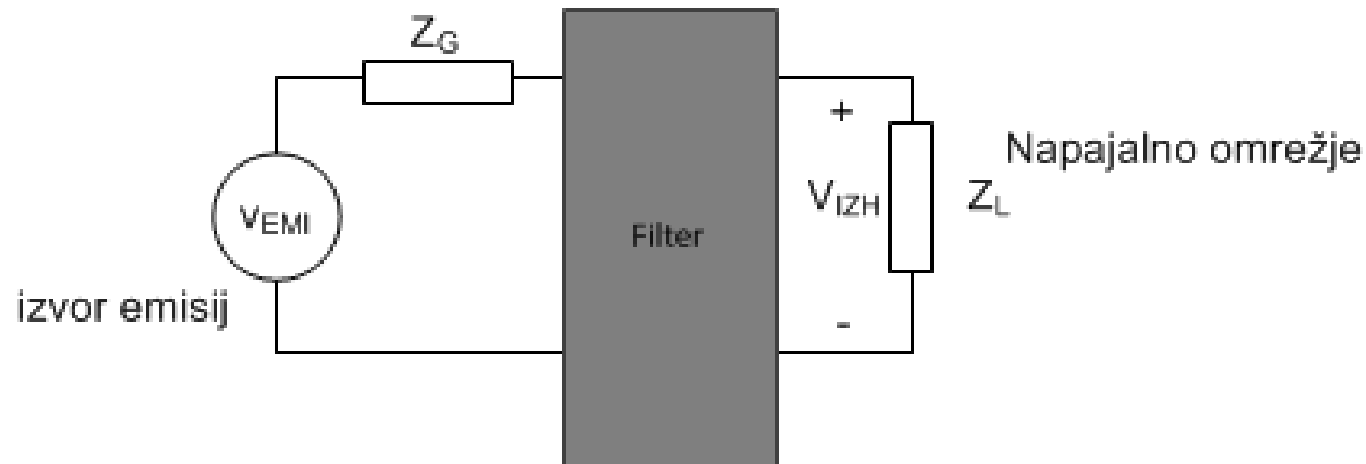
$$I_{DM} = \frac{I_1 - I_2}{2}$$



- Definicija tipa emisij glede na pot
 - **Protifazne (DM):** prenosna pot le med napajalnima vodnikoma (B+/B-, L/N, itd.)
 - **Sofazne (CM):** prenosna pot vključuje kovinsko površino, ki je ozemljena (ozemljitveni vodnik)

Teorija filtrov – vstavitveno dušenje

- Gradniki pasivnih filtrov: R, L, C -> Kako vemo katerega izbrati?



- Definicija dušenja filtra:

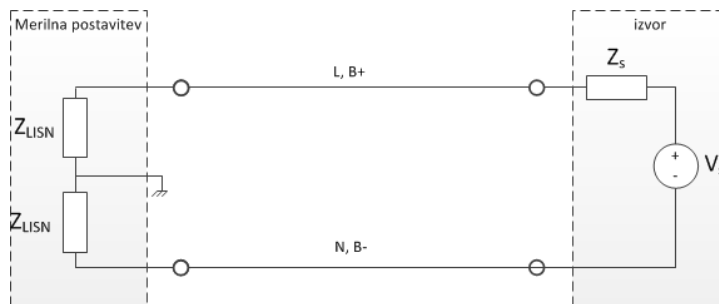
- $$A = 20 \log_{10} \left| \frac{v_{izh, brez filtra}}{v_{izh, s filtrom}} \right|$$

- Cilj je A -> preko vseh meja (čim več dB)

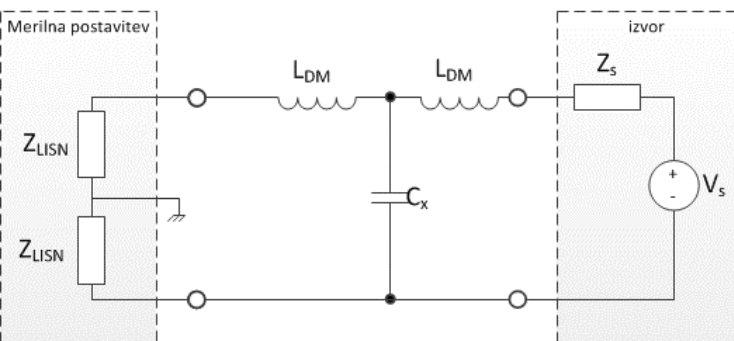
Teorija pasivnih filtrov

■ Protifazne emisije – gradnja filtra

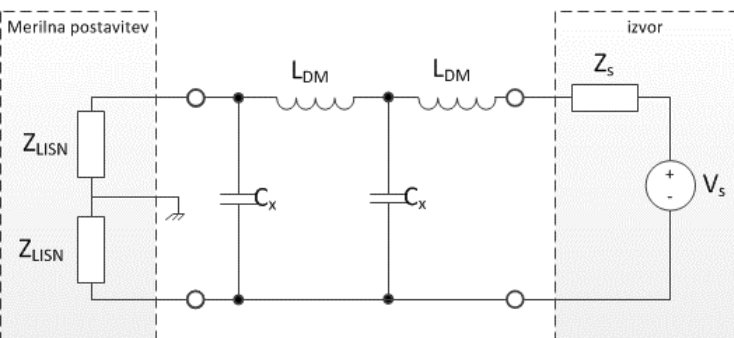
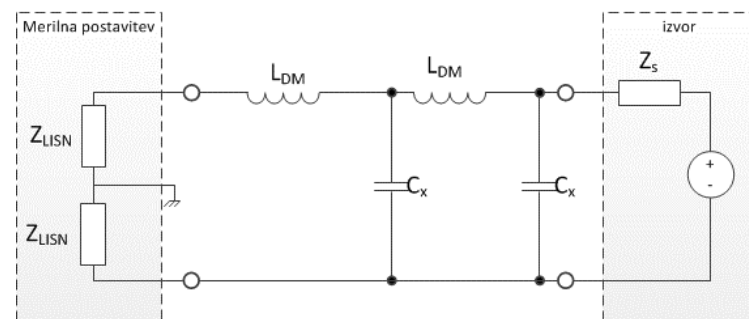
$$Z_S < Z_{LDM}$$



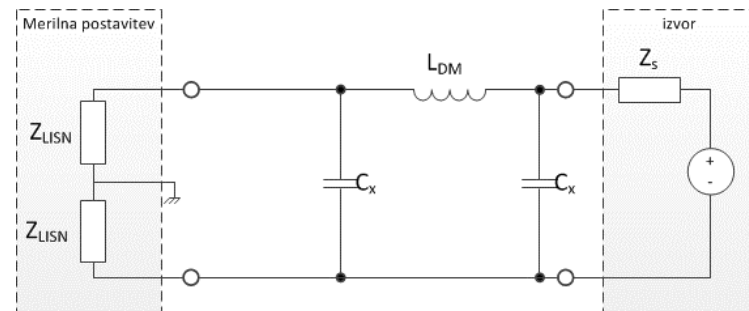
$$Z_S > Z_{LDM}$$



$$2Z_{LISN} < Z_{LDM}$$



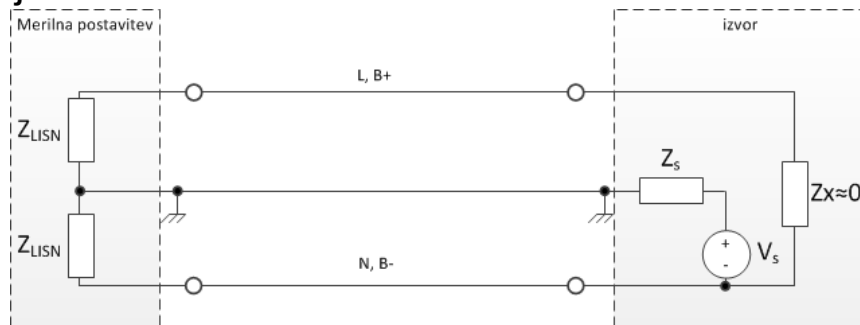
$$2Z_{LISN} > Z_{LDM}$$



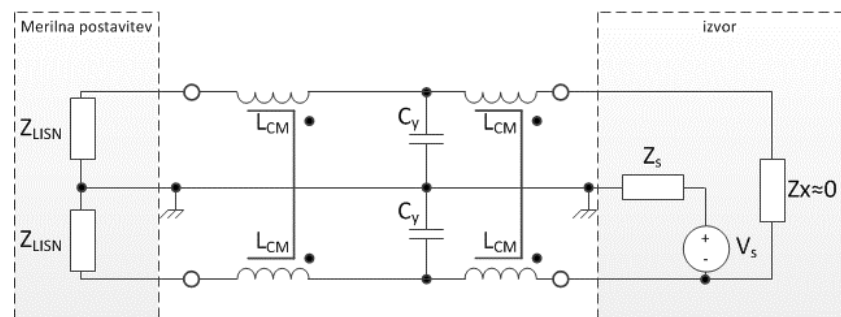
Teorija pasivnih filtrov

■ Sofazne emisije – gradnja filtra

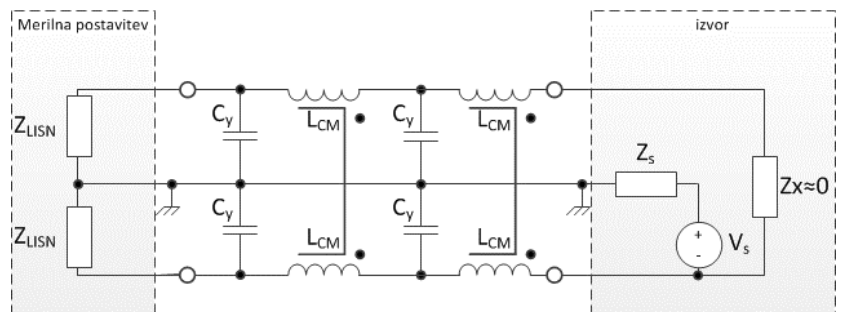
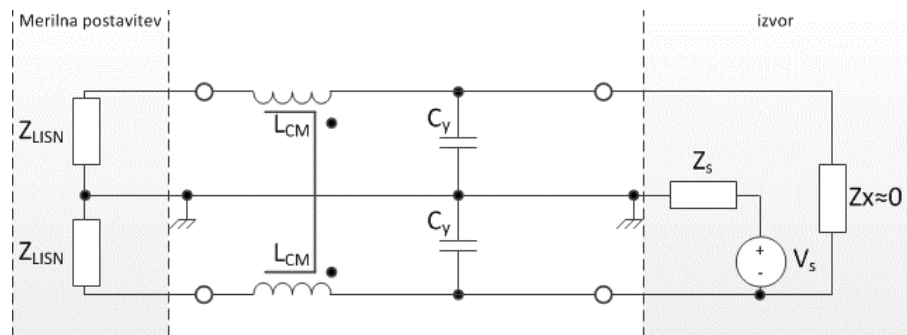
$$Z_S < Z_{LCM}$$



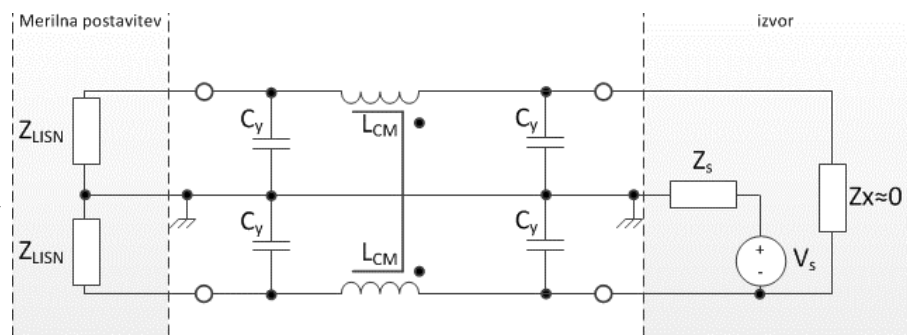
$$Z_S > Z_{LCM}$$



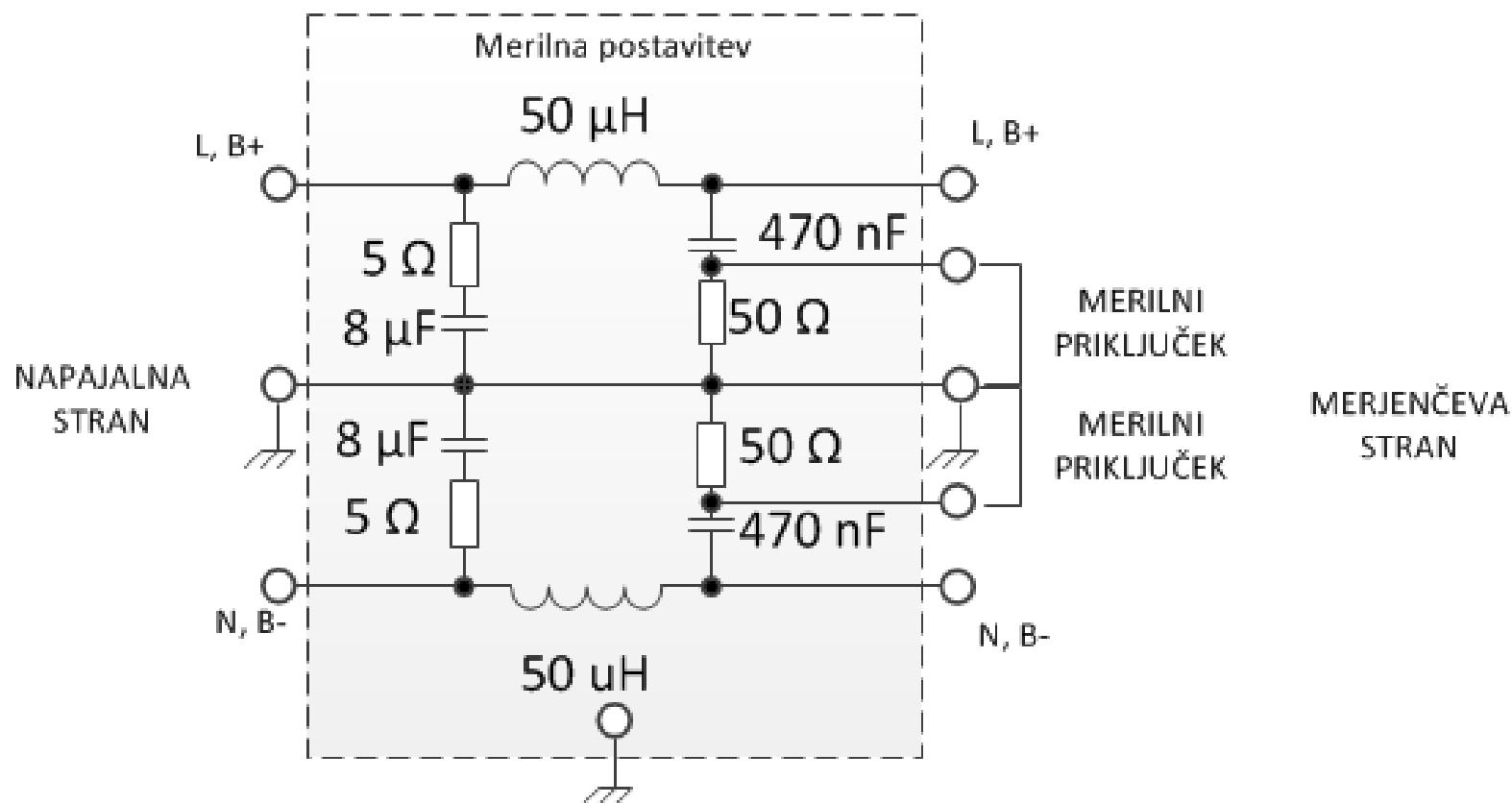
$$\frac{Z_{LISN}}{2} < Z_{LCM}$$



$$\frac{Z_{LISN}}{2} > Z_{LCM}$$

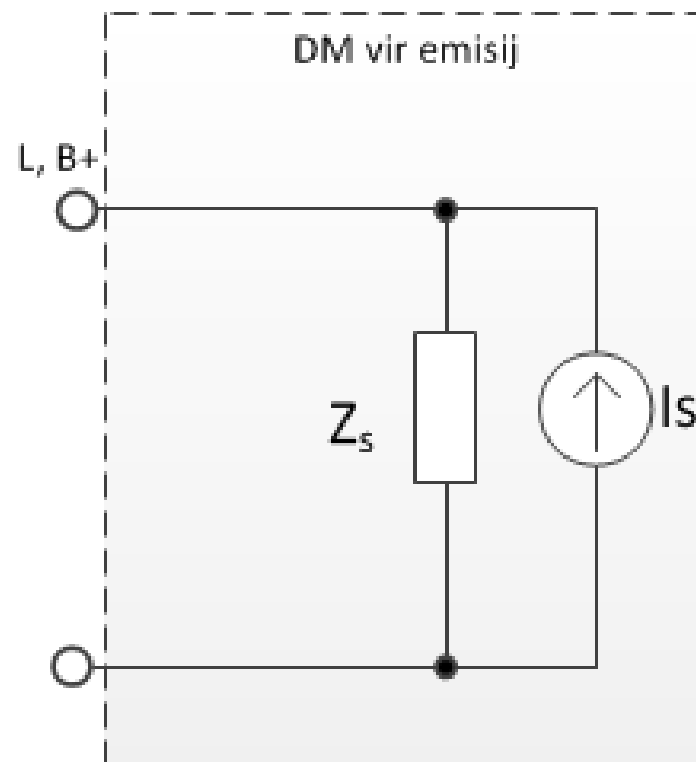
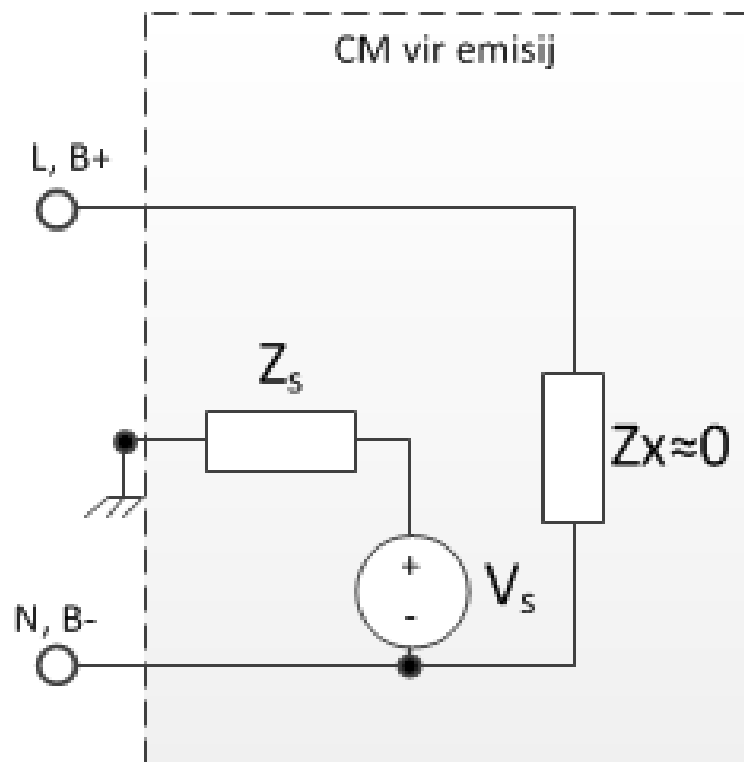


■ MERILNA POSTAVITEV - CISPR 16 LISN – ENO FAZNI



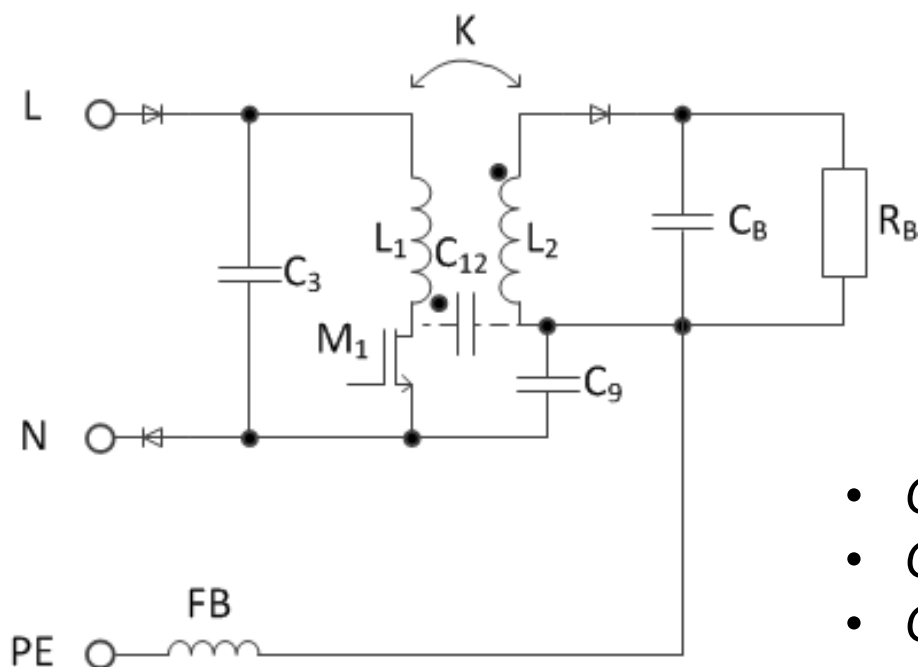
Model emisij

MODEL VIROV EMISIJ



Praktični primer – Wuerthov izvor emisij

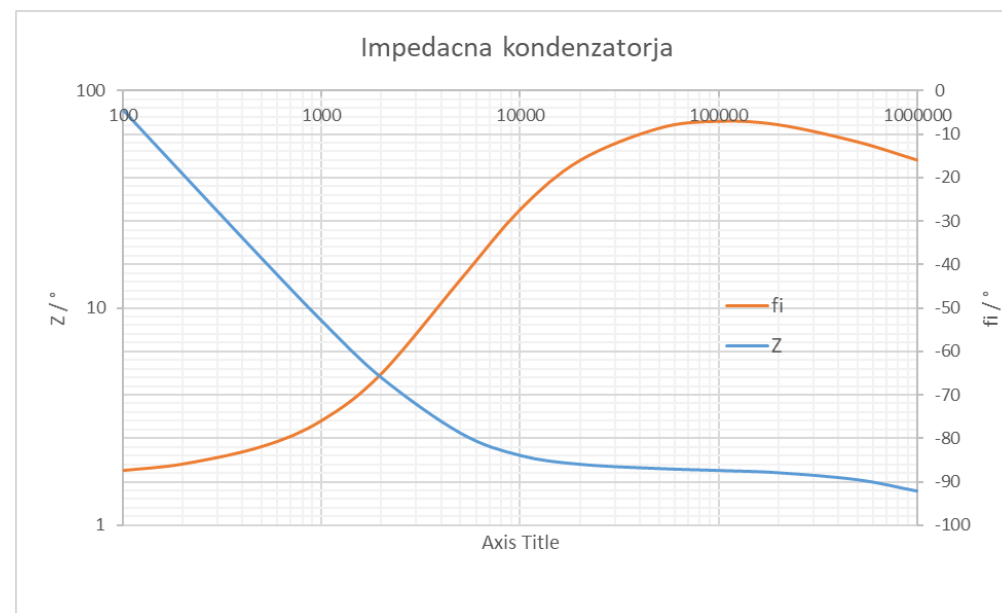
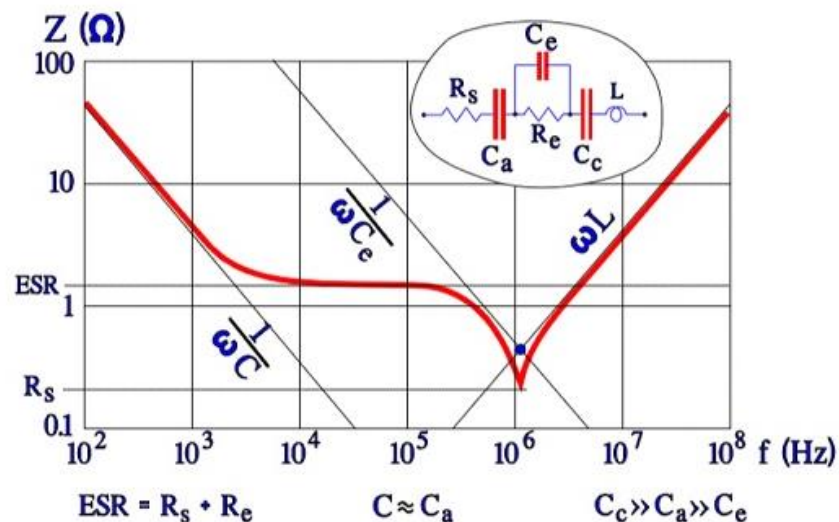
■ AC/DC stikalni napajalnik



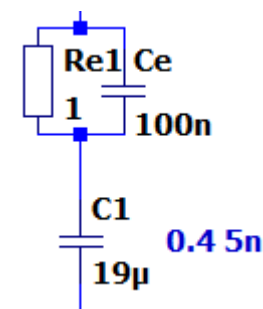
- C_3 : $C = 19 \mu\text{F}$, $ESR = 430 \text{ m}\Omega$, $ESL = 5 \text{ nH}$
- C_9 : $C = 2,2 \text{ nF}$, $ESR = 410 \text{ m}\Omega$, $ESL = 5 \text{ nH}$
- C_{12} : $C = 10 \text{ pF}$
- FB: $L = 1,85 \mu\text{H}$, $ESR = 10 \text{ m}\Omega$, $R_p = 150 \Omega$
- cca. 2 metra kabla do LISN vezja

Praktični primer – Wuerthov izvor emisij

Model elektrolitskega kondenzatorja C3:

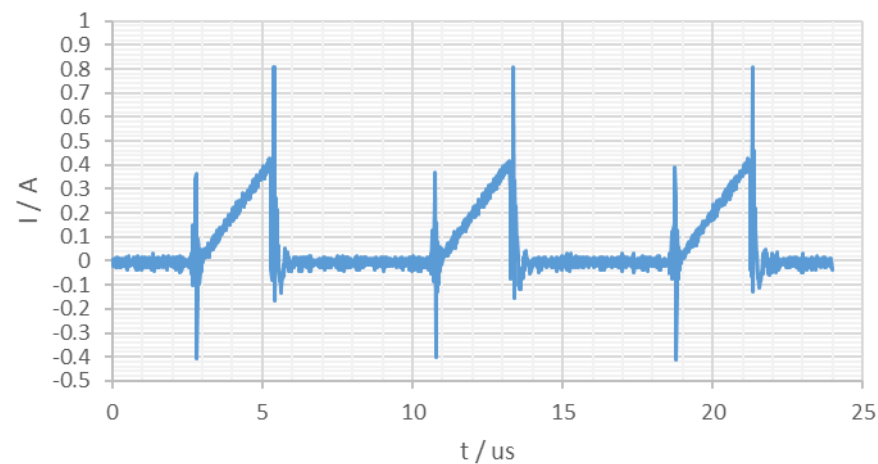
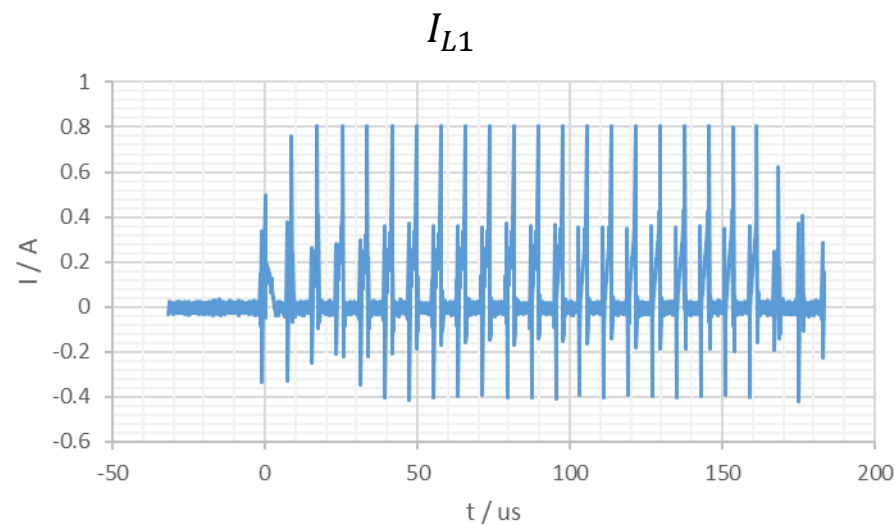
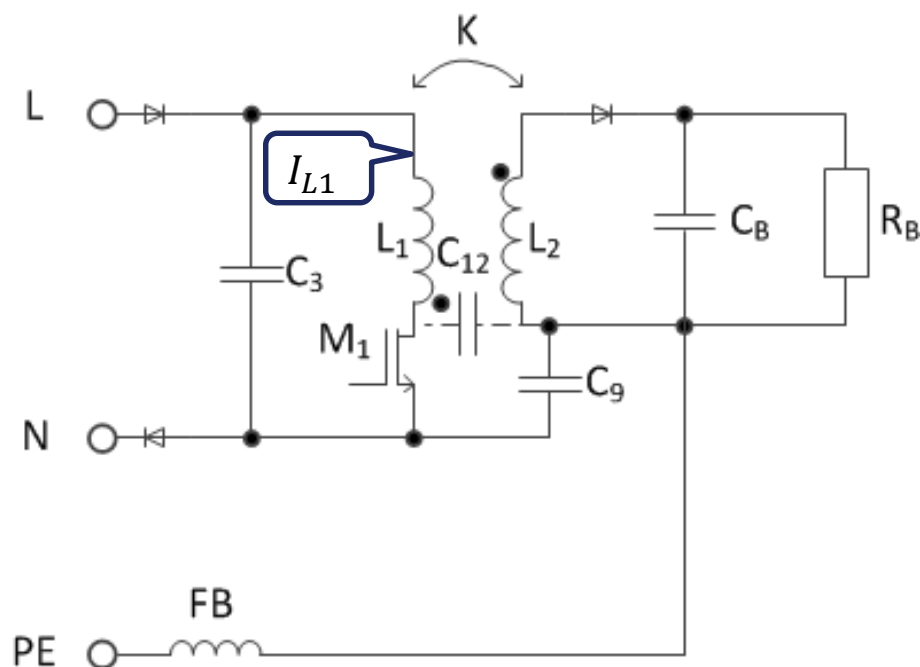


<https://passive-components.eu/capacitors-electrolytic-capacitors/>



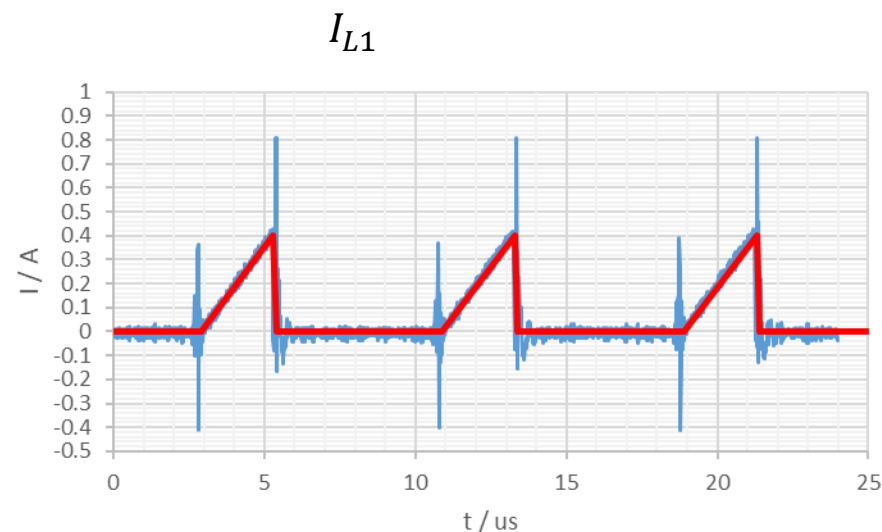
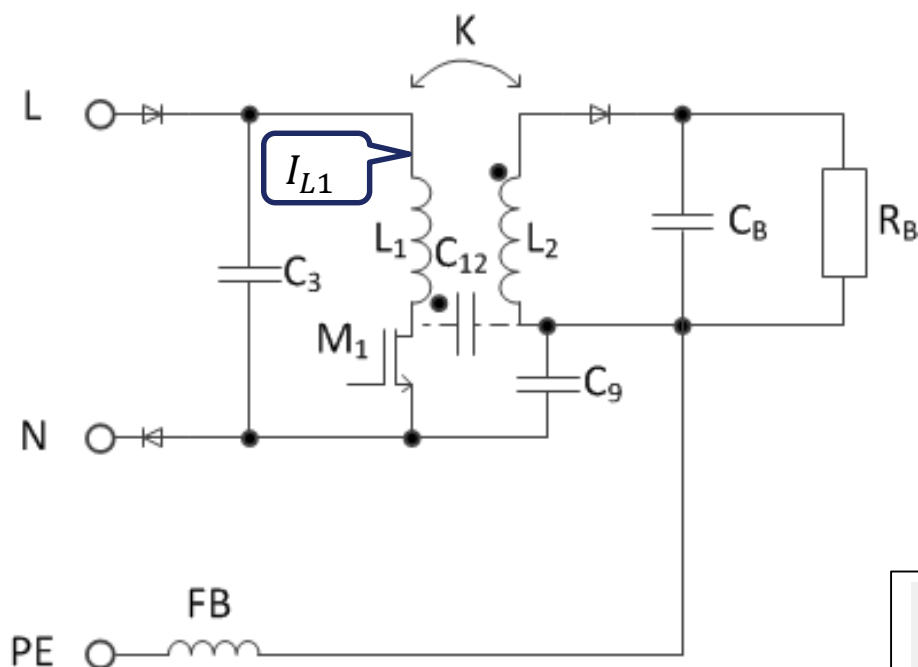
Praktični primer – Wuerthov izvor emisij

■ Časovni signal toka skozi L1



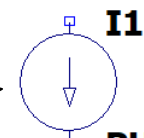
Praktični primer – Wuerthov izvor emisij

■ Časovni signal toka skozi L1



$$I_m = 0,4 \text{ A } f = 125 \text{ kHz}$$

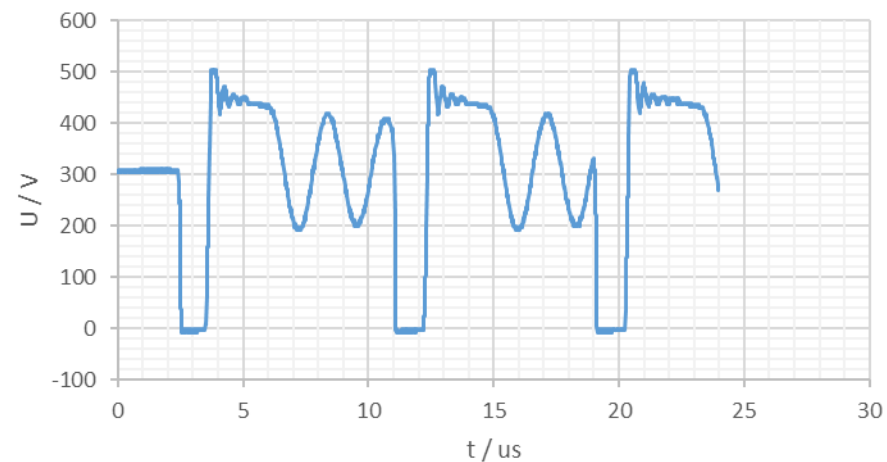
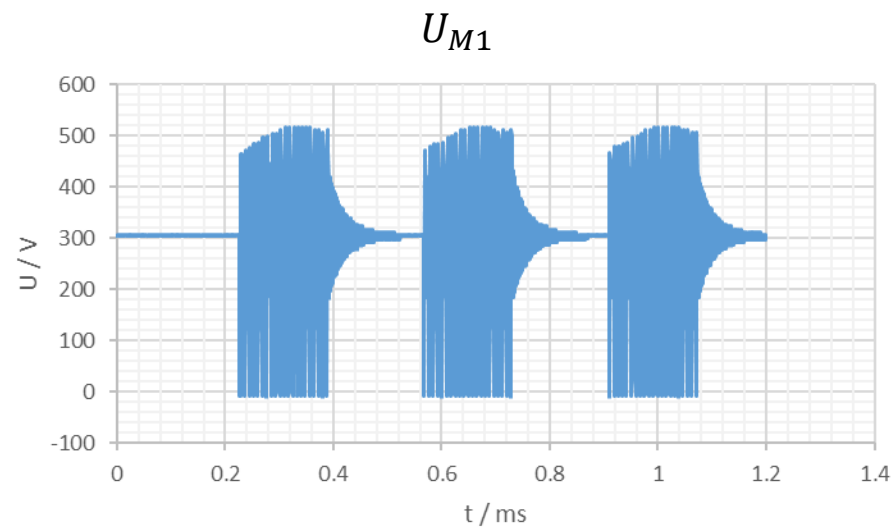
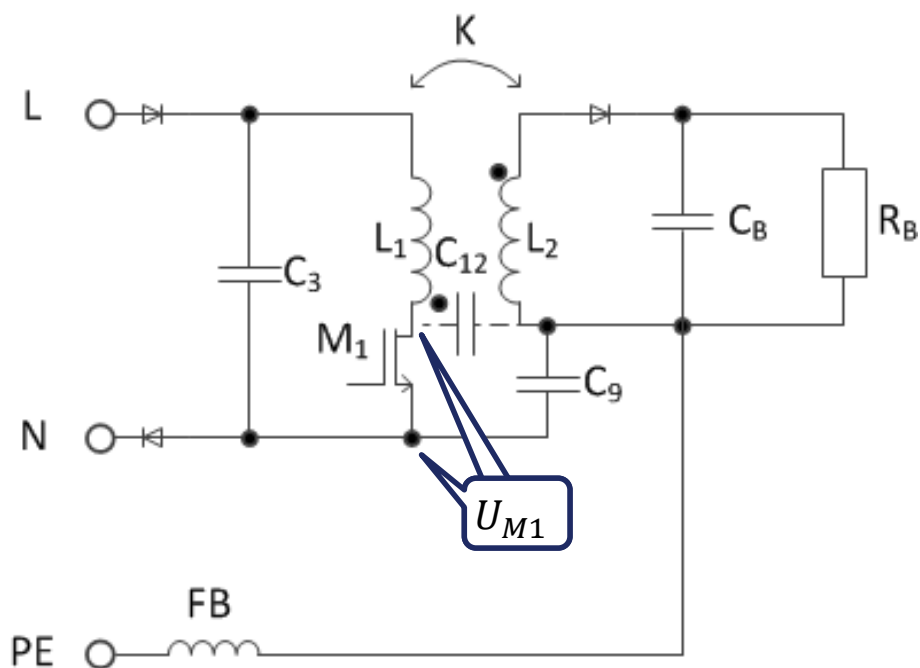
I1[A]:	0
I2[A]:	0.4
Tdelay[s]:	0
Trise[s]:	2.45u
Tfall[s]:	100n
Ton[s]:	0
Tperiod[s]:	8u
Ncycles:	



PULSE(0 0.4 0 2.45u 100n 0 8u)

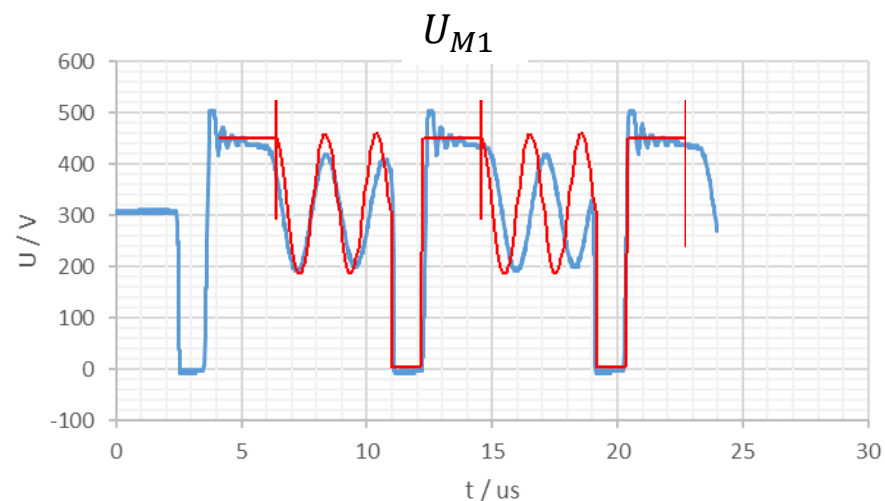
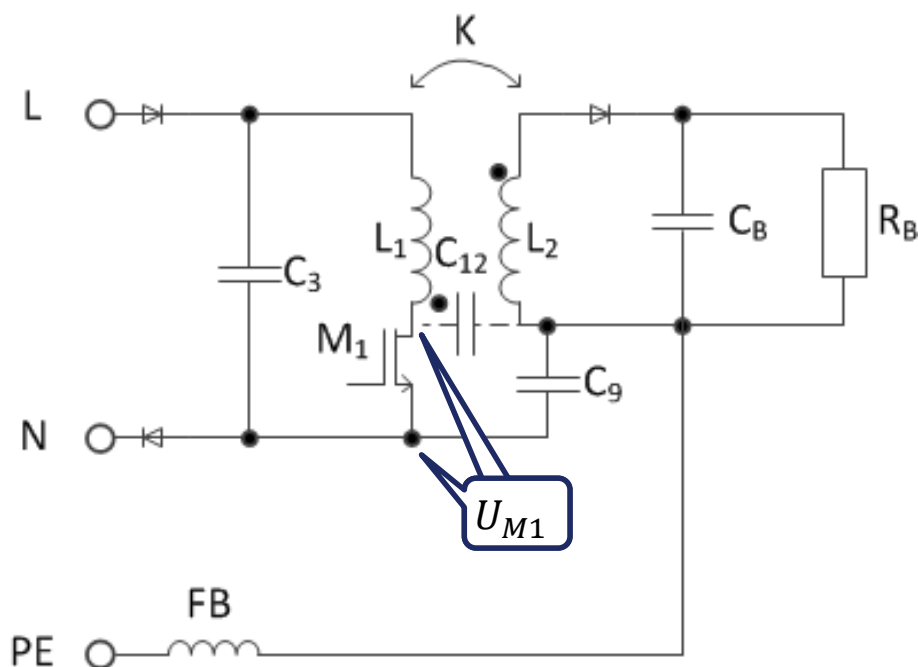
Praktični primer – Wuerthov izvor emisij

■ Časovni signal napetosti na tranzistorju M1

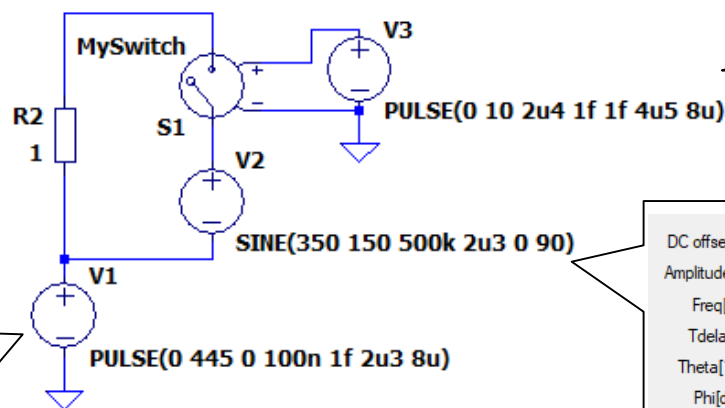


Praktični primer – Wuerthov izvor emisij

■ Časovni signal napetosti na tranzistorju M1



.model MySwitch SW(Ron=.1 Roff=1Meg Vt=5 Vh=-.5 Lser=0n Vser=0)



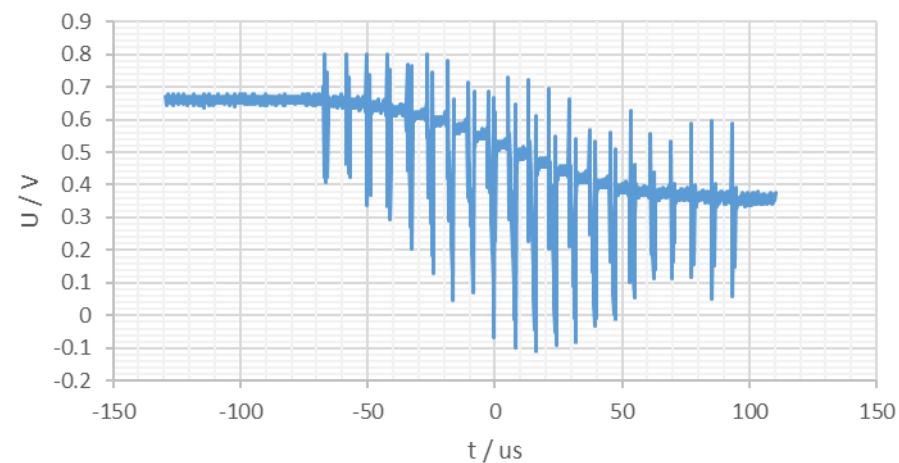
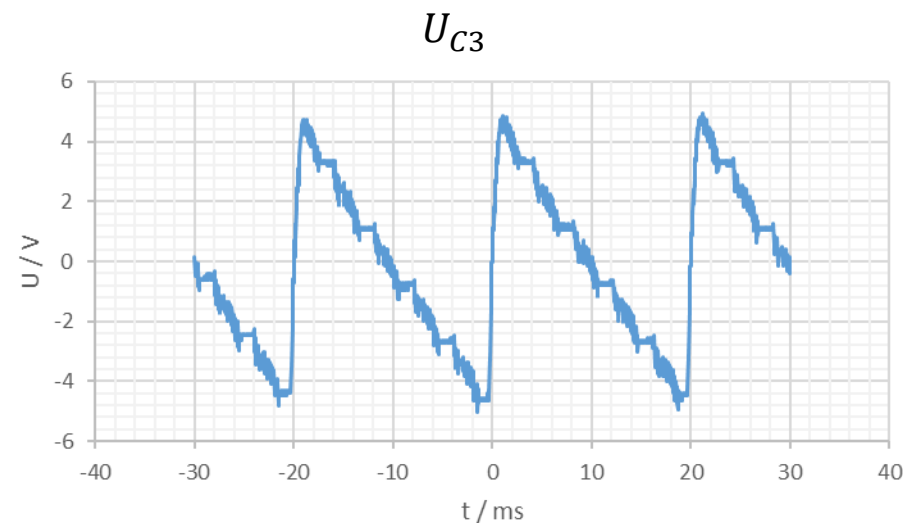
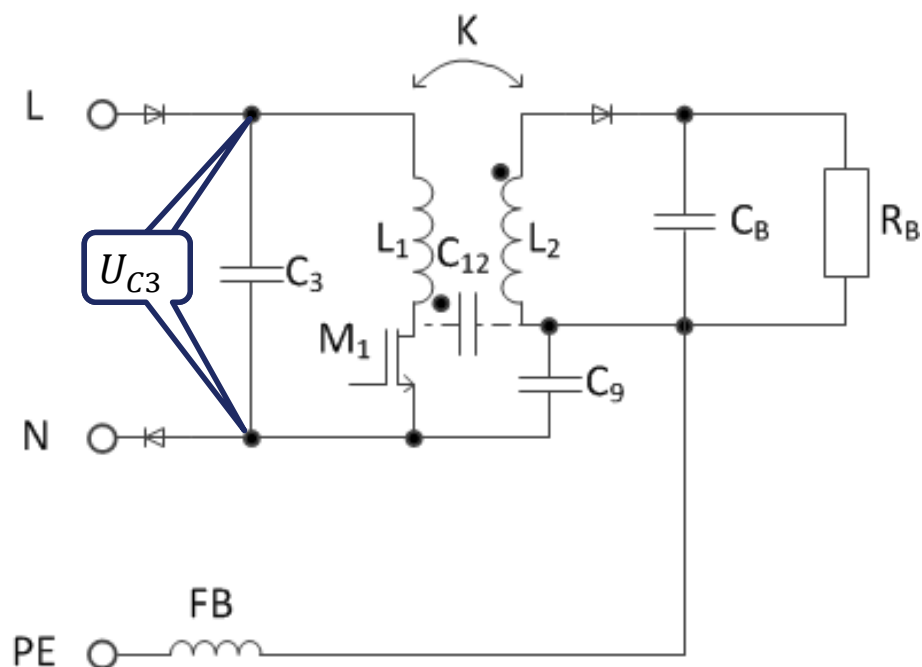
Vinitial[V]:	0
Von[V]:	445
Tdelay[s]:	0
Trise[s]:	100n
Tfall[s]:	1f
Ton[s]:	2u3
Tperiod[s]:	8u
Ncycles:	

DC offset[V]:	350
Amplitude[V]:	150
Freq[Hz]:	500k
Tdelay[s]:	2u3
Theta[1/s]:	0
Phi[deg]:	90
Ncycles:	

Vinitial[V]:	0
Von[V]:	10
Tdelay[s]:	2u4
Trise[s]:	1f
Tfall[s]:	1f
Ton[s]:	4u5
Tperiod[s]:	8u
Ncycles:	

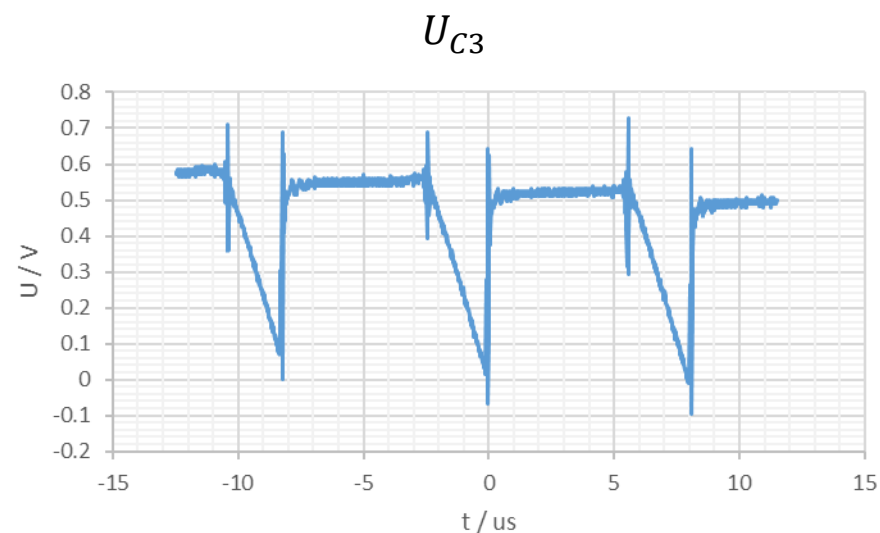
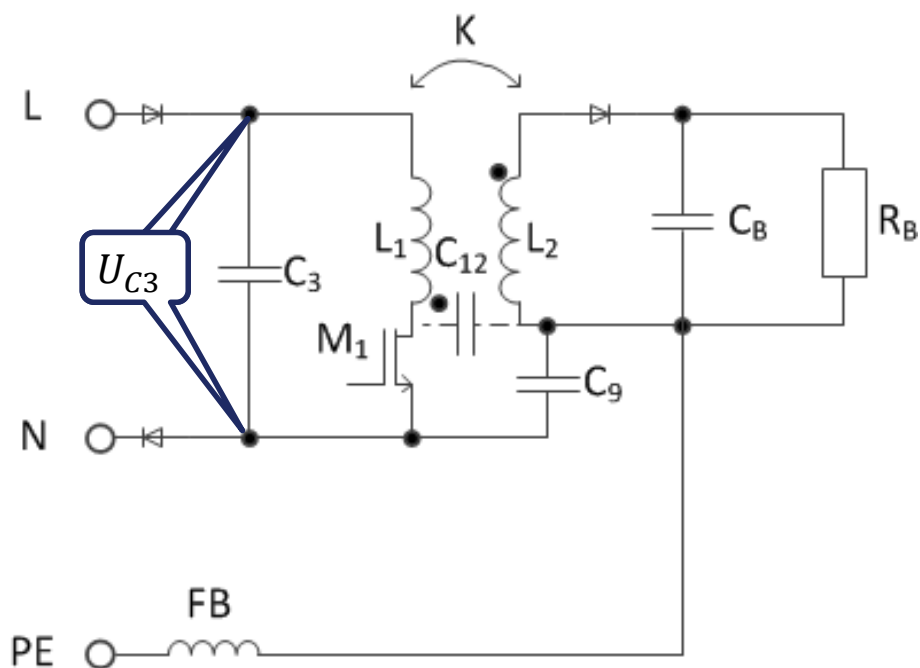
Praktični primer – Wuerthov izvor emisij

■ Časovni signal napetosti na kondenzatorju C3



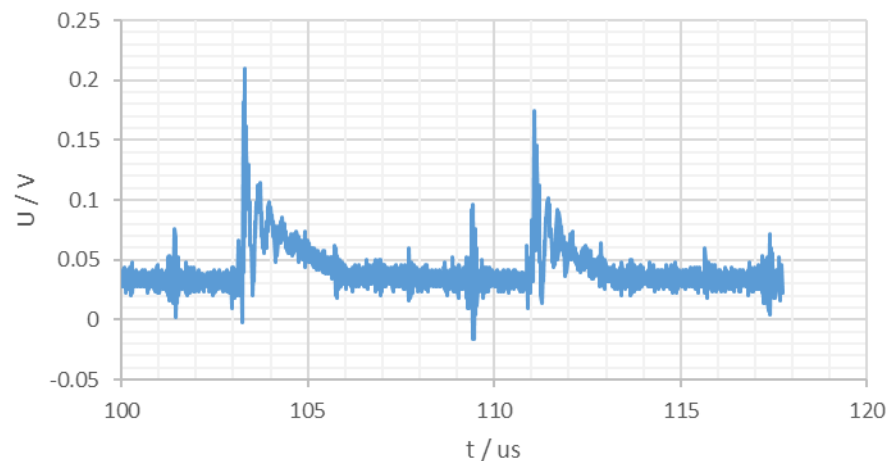
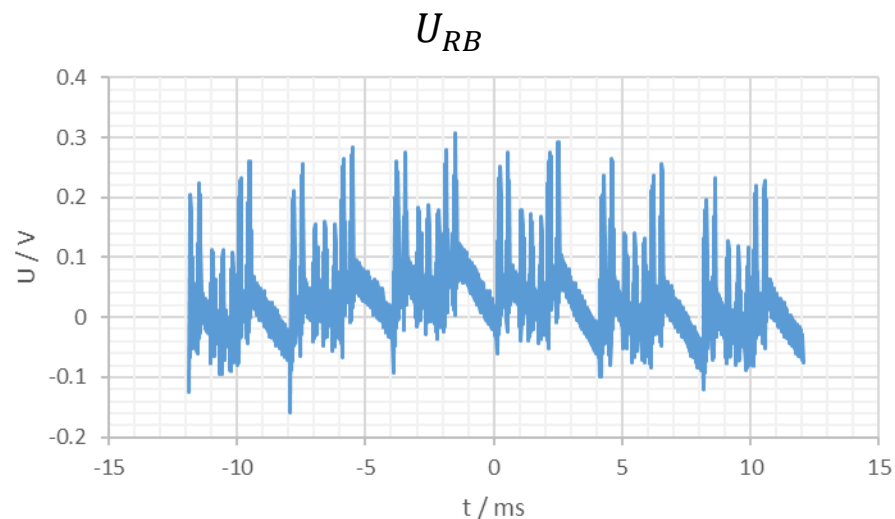
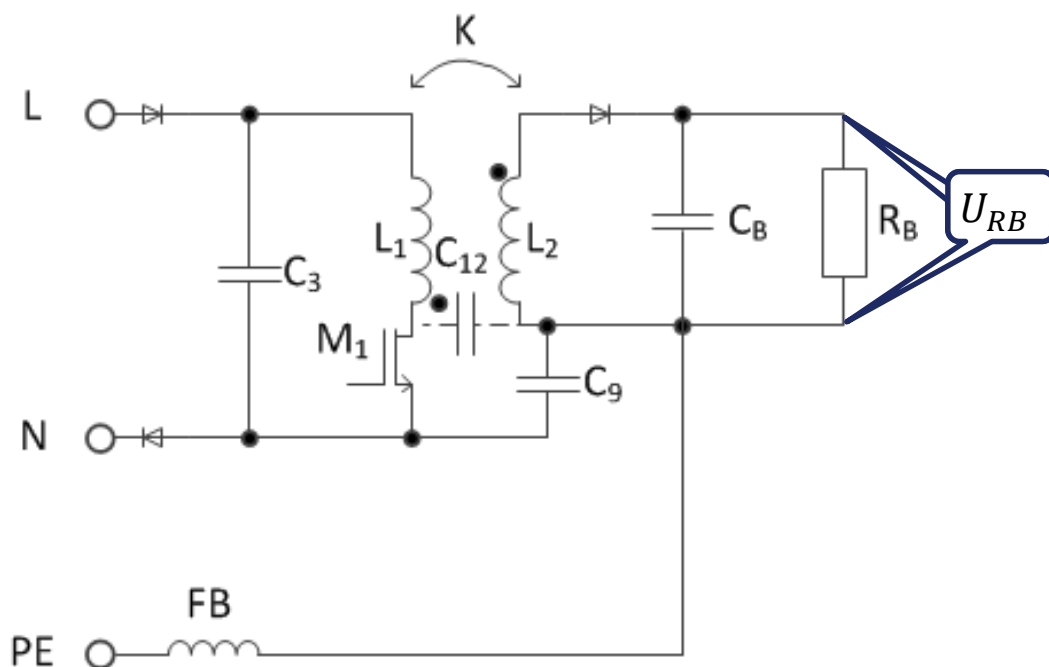
Praktični primer – Wuerthov izvor emisij

■ Časovni signal napetosti na kondenzatorju C3



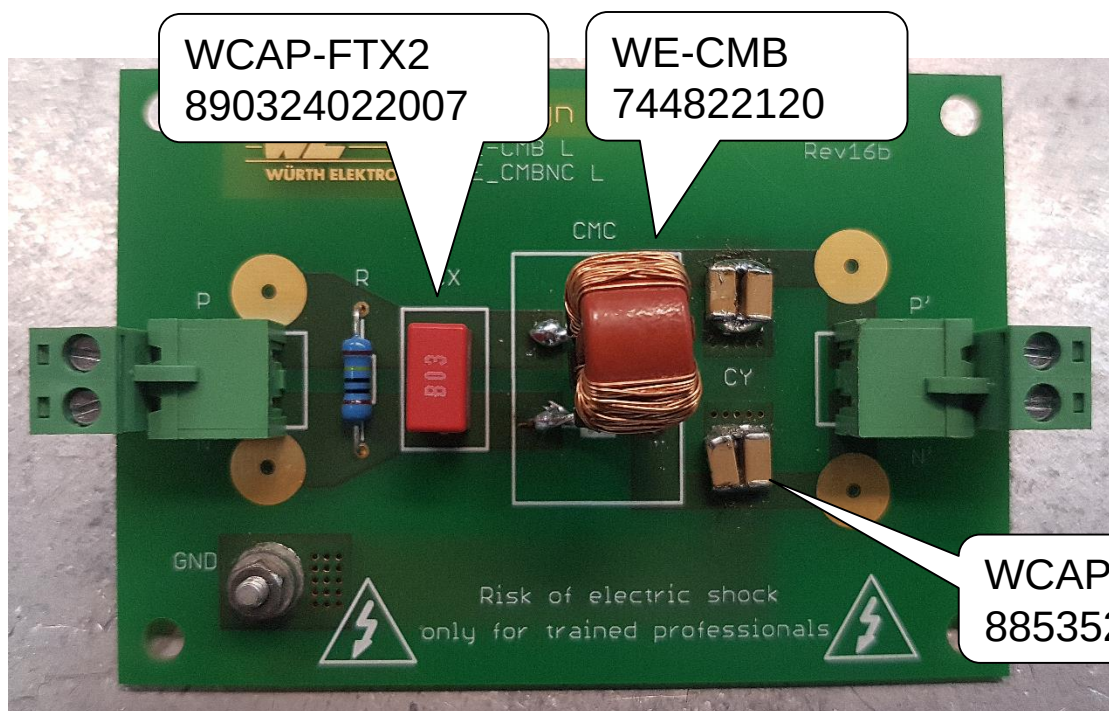
Praktični primer – Wuerthov izvor emisij

- Časovni signal napetosti na izhodu R_B

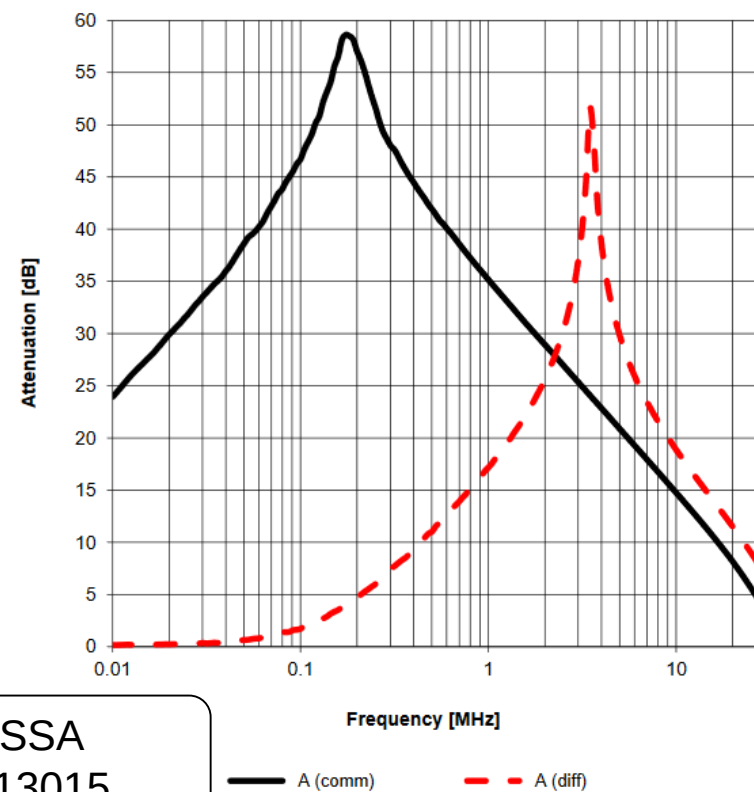


Praktični primer – Wuerthov izvor emisij

■ Wuerthov dodatni filter



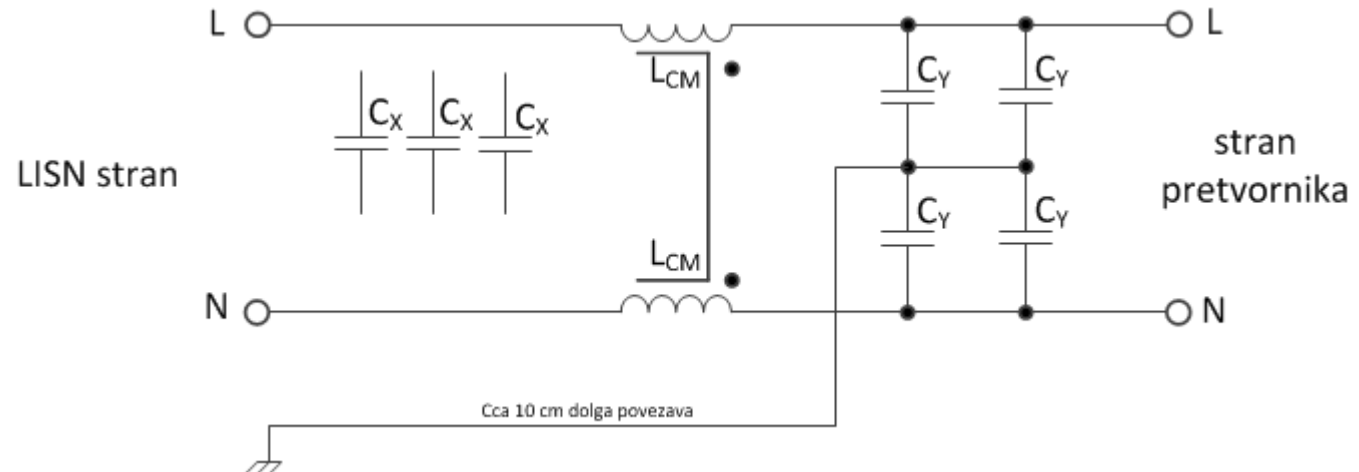
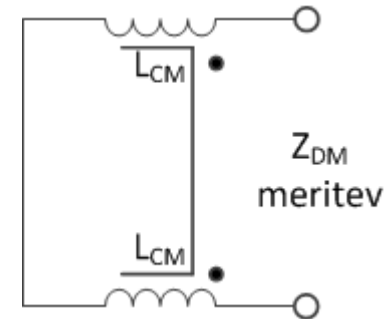
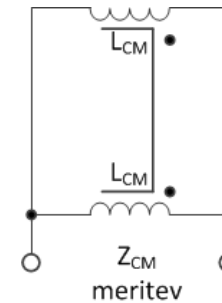
Typical Insertion Loss: WE-CMB 744822120



Praktični primer – Wuerthov izvor emisij

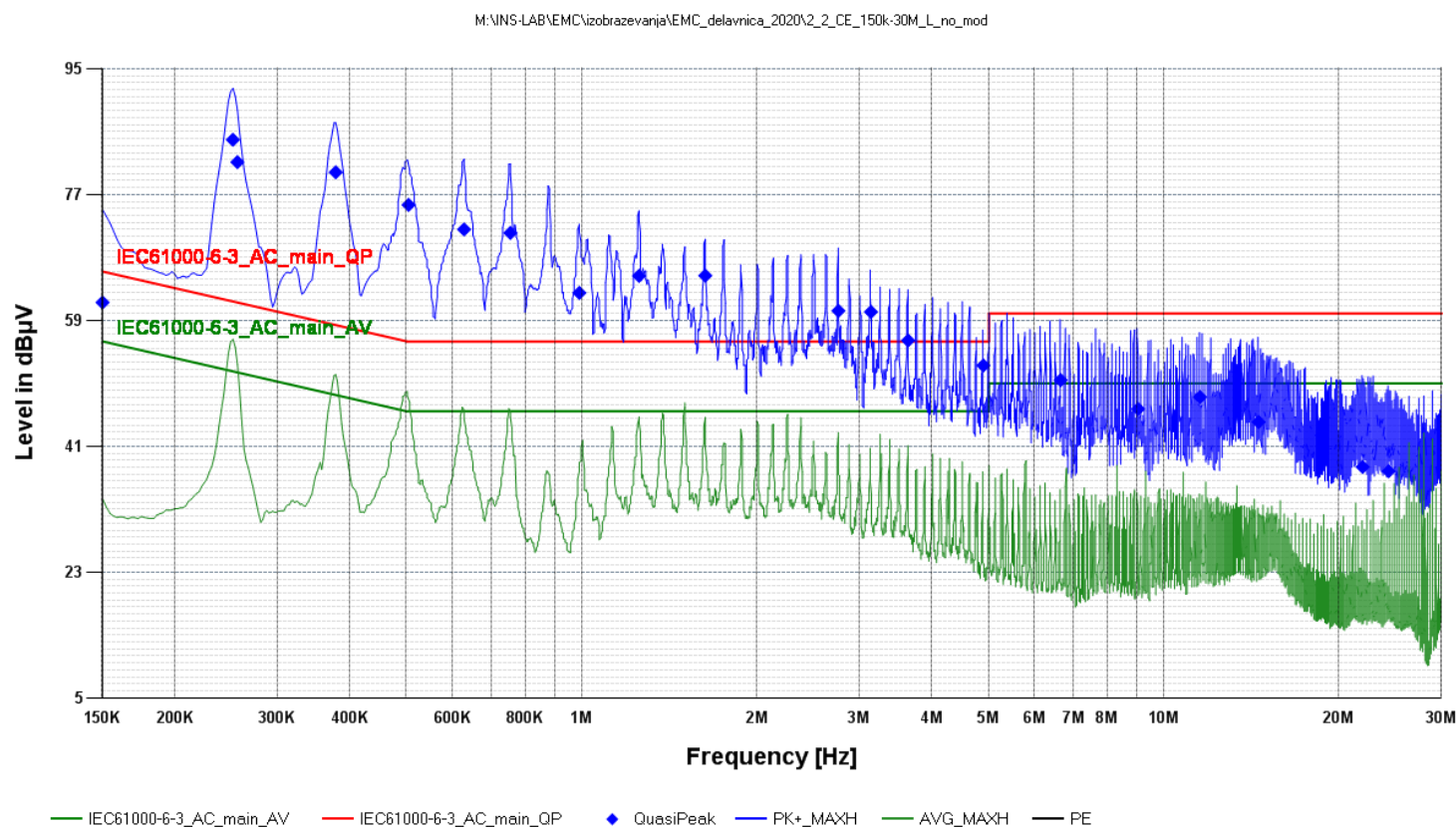
■ Wuerthov dodatni filter - gradniki

- C_x : $C = 15 \text{ nF}$, $ESR = 75 \text{ m}\Omega$, $ESL = 5 \text{ nH}$
- C_y : $C = 2,2 \text{ nF}$, $ESR = 41 \text{ m}\Omega$, $ESL = 2,4 \text{ nH}$
- CMC:
 - CM: $L_{CM} = 22 \text{ mH}$, $R_{pcm} = 79 \text{ k}\Omega$, $C_{pcm} = 24 \text{ pF}$
 - DM: $L_{DM} = 105 \text{ }\mu\text{H}$, $C_{pdm} = 7 \text{ pF}$, $R_{pdm} = 77 \text{ k}\Omega$
- 20 cm kabli do filtra
- 2m kabli od filtra do LISNa



Praktični primer – Wuerthov izvor emisij Brez filtra

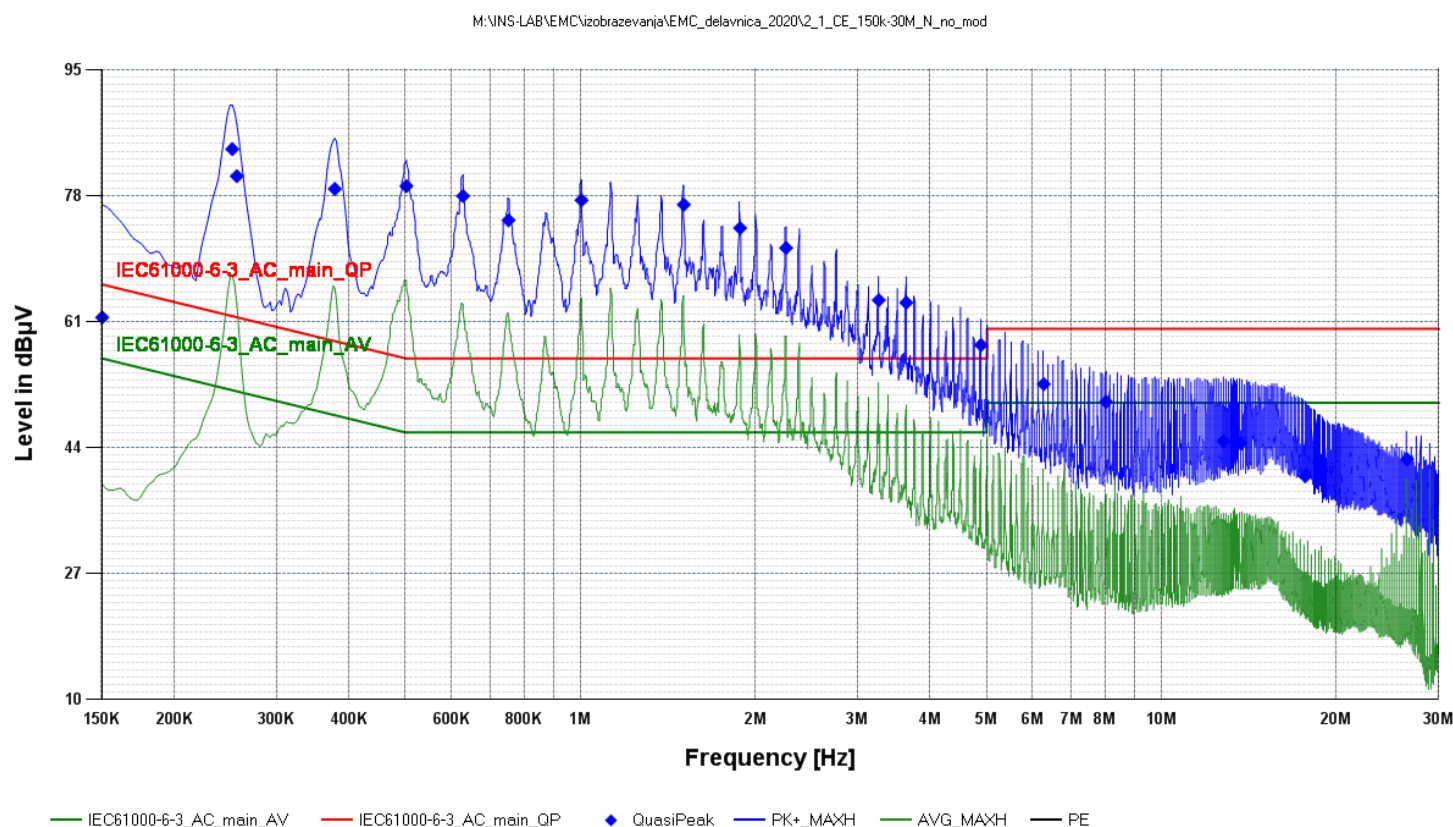
Rezultati meritev, L terminal



Frequency MHz	MaxPeak dBμV	Average dBμV
0,251	92,2	---
0,377	87,25	---
0,256	89,04	---
0,627	82,1	---
0,503	81,97	---
0,753	81,4	---
1,253	74,67	---
0,989	72,74	---
1,628	70,61	---
2,758	69,38	---
3,136	66,24	---
0,15	74,86	---
3,633	63,42	---
0,251	---	56,30
0,377	---	51,25
0,501	---	48,81
4,893	57,65	---
1,505	---	47,24
0,256	---	52,66
0,625	---	46,60
0,751	---	46,38
2,256	---	45,58
6,644	59,14	---
1,628	---	45,13
1,248	---	44,22
9,024	57,88	---
11,533	57,28	---
3,26	---	42,75
14,537	56,63	---
3,635	---	41,11
27,958	---	42,92
4,889	---	37,38
21,937	51,13	---
24,317	49,66	---
8,311	---	38,30
6,799	---	37,86
10,829	---	37,31
14,357	---	33,45
22,918	---	33,28
0,195	---	31,85

Praktični primer – Wuerthov izvor emisij Brez filtra

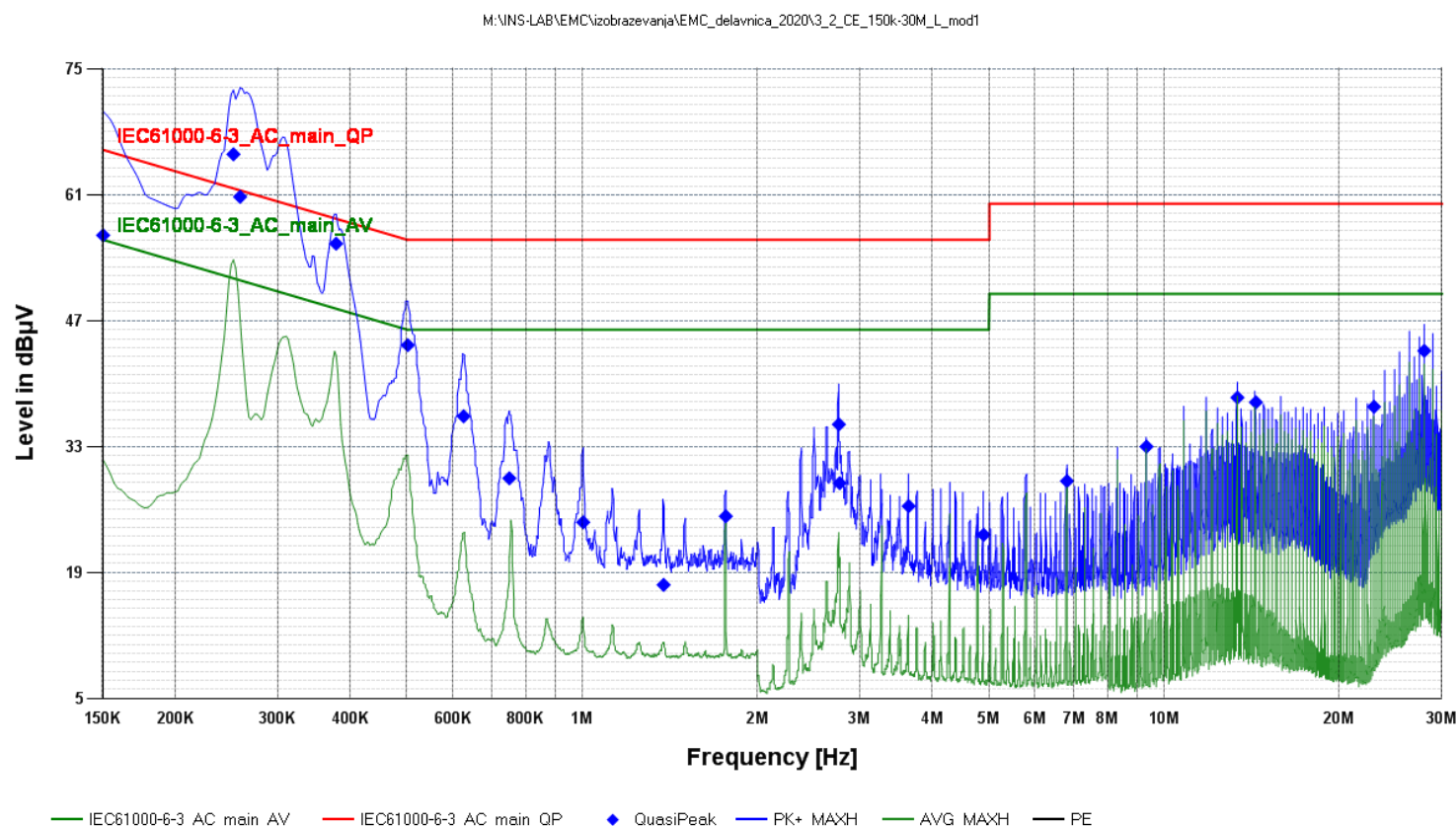
Rezultati meritev, N terminal



Frequency MHz	MaxPeak dBμV	Average dBμV
0,251	90,24	---
0,377	85,73	---
0,501	82,76	---
0,256	87,68	---
0,627	80,82	---
1,003	80,16	---
1,505	79,42	---
0,751	77,7	---
1,88	77,2	---
0,501	---	66,53
1,129	---	65,53
1,502	---	64,50
2,256	73,77	---
0,625	---	63,47
0,375	---	65,79
0,749	---	62,18
0,251	---	67,20
1,628	---	60,65
2,254	---	59,03
0,256	---	63,38
3,257	67,11	---
3,633	67,03	---
0,15	76,76	---
2,882	---	53,00
4,886	61,3	---
3,633	---	49,75
4,886	---	45,03
6,263	57,03	---
8,018	54,33	---
12,775	53,51	---
13,652	53,3	---
27,953	---	41,55
6,266	---	41,09
17,664	50,27	---
8,311	---	39,87
10,829	---	37,39
0,195	---	40,68
26,441	46,16	---
13,781	---	35,34
17,882	---	31,38

Praktični primer – Wuerthov izvor emisij S filtrom

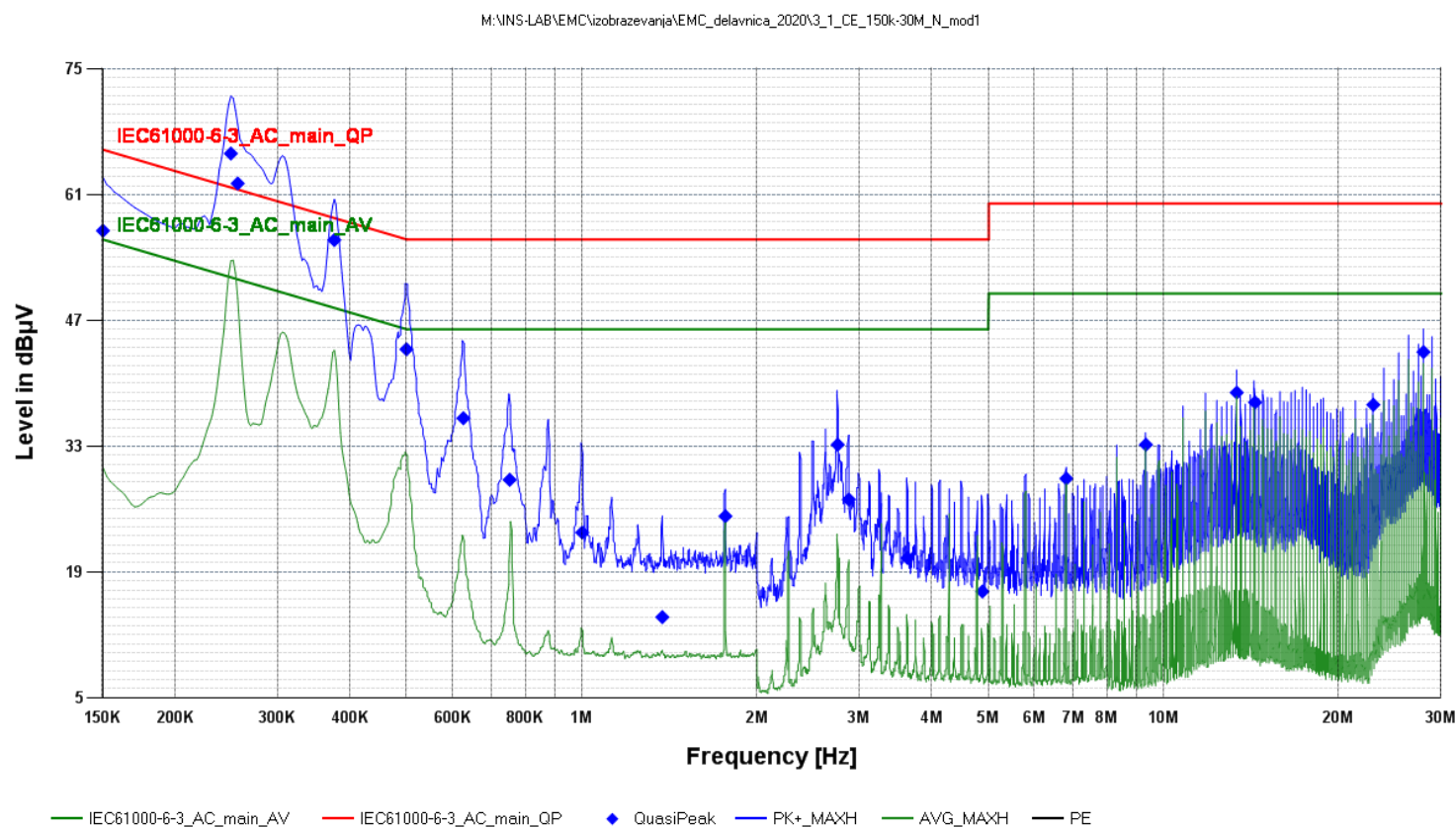
Rezultati meritev, L terminal



Frequency MHz	MaxPeak dBμV	Average dBμV
0,258	72,92	---
0,251	72,65	---
0,15	70,29	---
0,251	---	53,77
0,377	58,85	---
0,256	---	50,44
0,375	---	43,59
0,501	49,2	---
26,444	---	42,39
13,346	---	38,64
14,357	---	37,44
0,625	43,33	---
27,953	46,62	---
22,918	---	36,39
0,501	---	32,07
2,758	39,98	---
9,319	---	32,79
0,749	36,97	---
13,349	40,19	---
4,281	---	25,57
22,918	39,27	---
14,357	39,2	---
0,755	---	24,81
6,801	---	28,51
1,763	---	24,48
3,273	---	24,21
5,793	---	27,84
2,767	33,63	---
0,627	---	23,47
2,758	---	23,46
1,003	32,88	---
0,15	---	31,53
9,317	34,05	---
3,635	29,98	---
1,763	28,12	---
4,889	28,06	---
1,379	27,13	---
6,801	31	---
1,003	---	14,03
1,505	---	11,35

Praktični primer – Wuerthov izvor emisij S filtrom

Rezultati meritev, N terminal



Frequency MHz	MaxPeak dBμV	Average dBμV
0,249	71,96	---
0,256	68,83	---
0,375	60,48	---
0,251	---	53,71
0,256	---	49,44
0,15	62,92	---
0,375	---	43,68
0,499	51,11	---
26,446	---	42,66
0,625	44,75	---
13,349	---	38,56
14,357	---	37,31
22,92	---	36,47
0,499	---	32,36
27,96	46,06	---
2,751	39,22	---
0,751	38,81	---
9,319	---	32,81
13,351	41,5	---
14,357	40,29	---
4,281	---	25,50
22,92	38,9	---
6,801	---	28,87
0,755	---	24,63
1,763	---	24,49
3,275	---	24,40
2,875	34,24	---
5,793	---	27,98
1,001	33,35	---
2,751	---	23,24
0,625	---	23,10
0,15	---	30,64
9,319	34,51	---
3,626	29,49	---
1,763	28,18	---
4,877	27,53	---
6,801	30,67	---
1,374	25,22	---
1,001	---	12,77
1,376	---	10,28

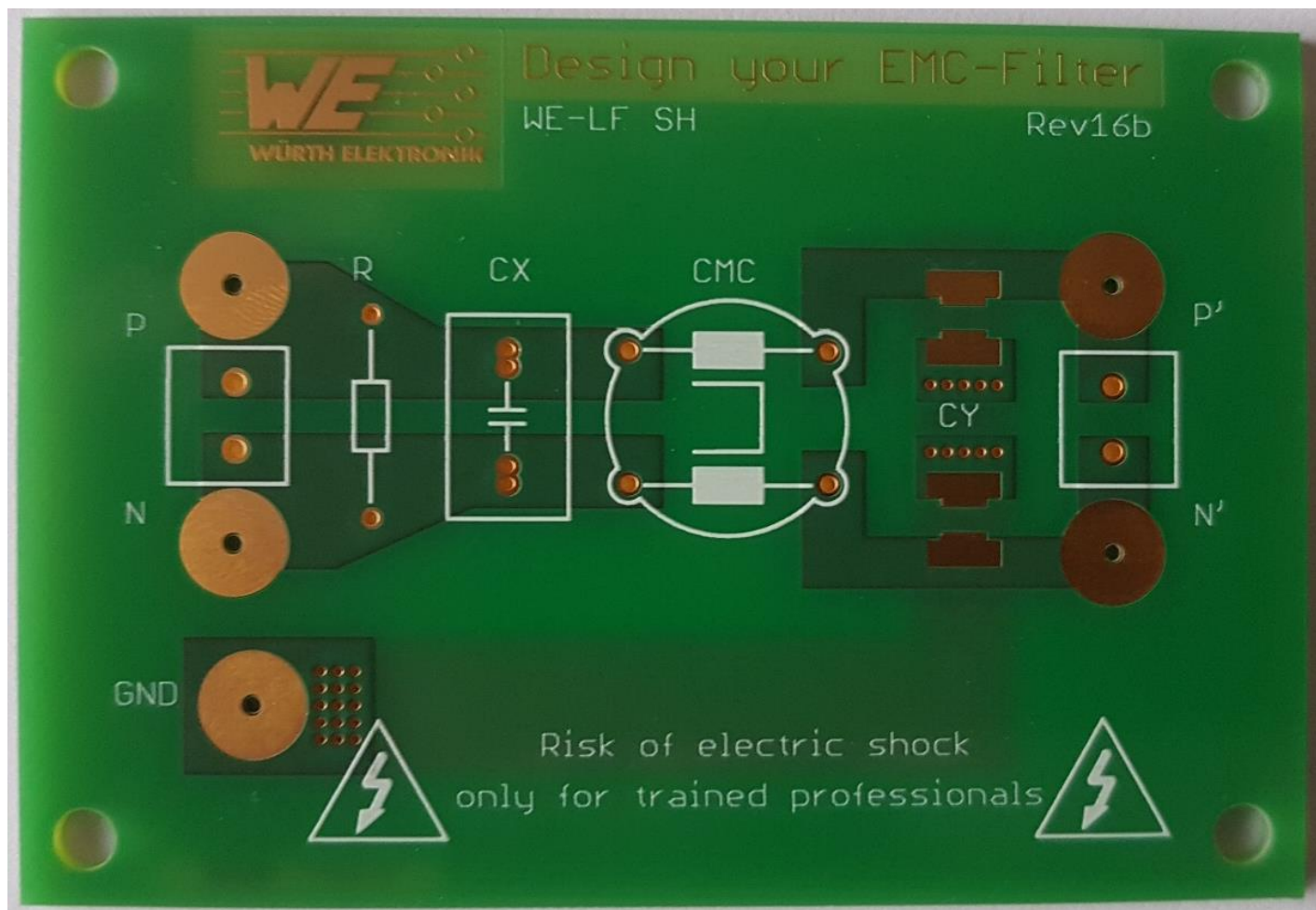
Priprava na Würth praktično delavnico



Laboratorij za fotovoltaike
in optoelektroniko

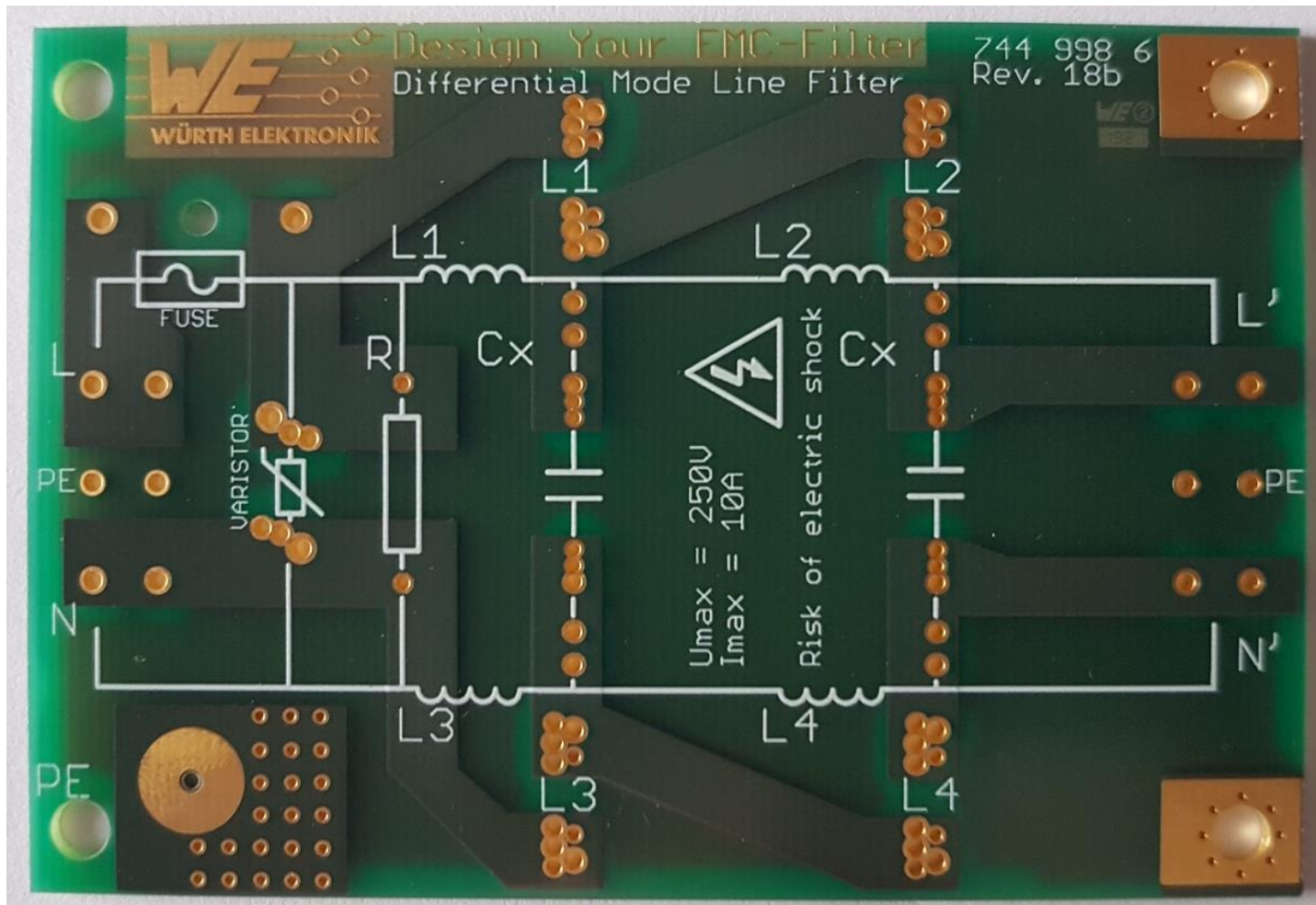


■ Design your EMC-filter



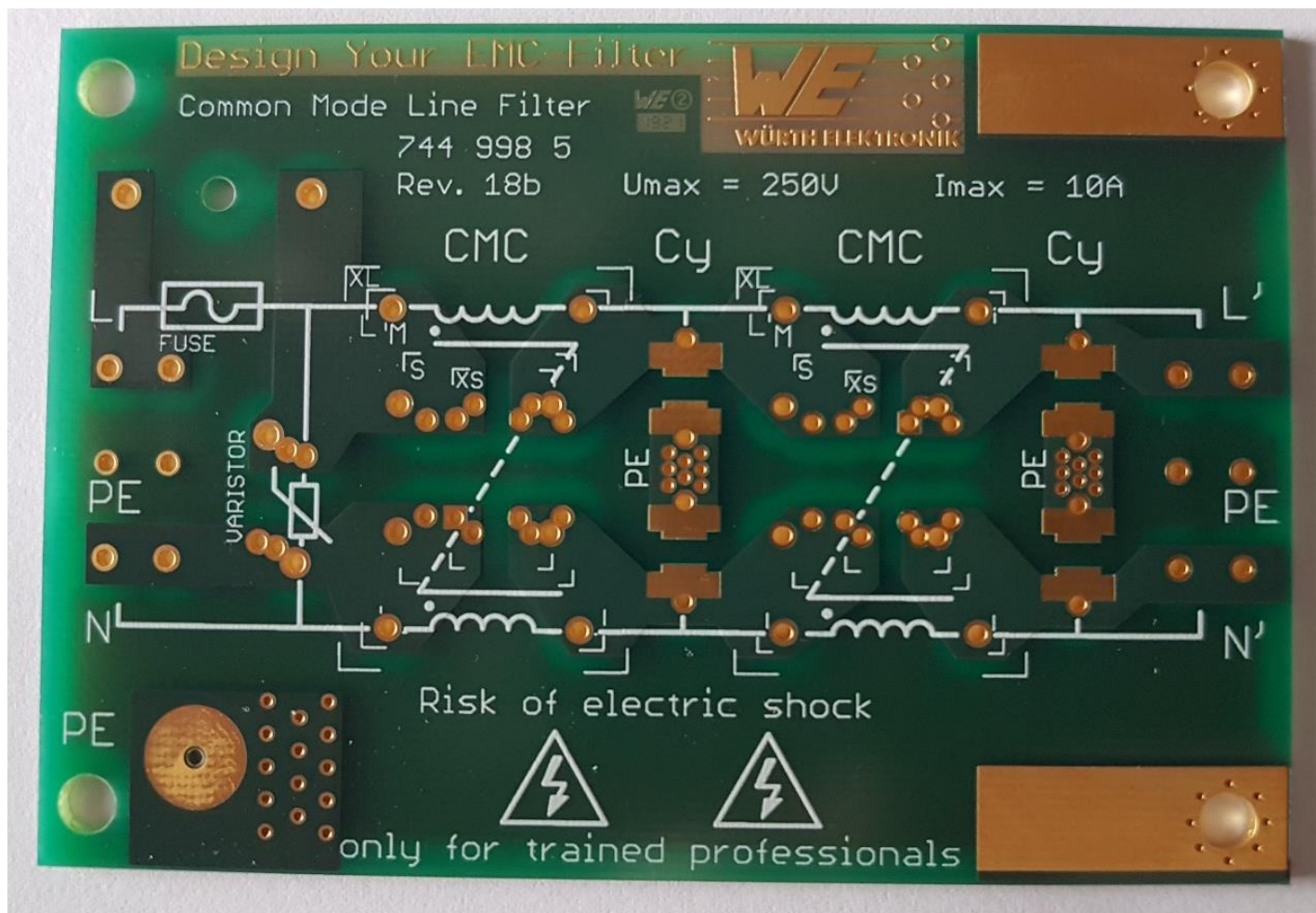
Priprava na Würth praktično delavnico

■ Differential mode line filter



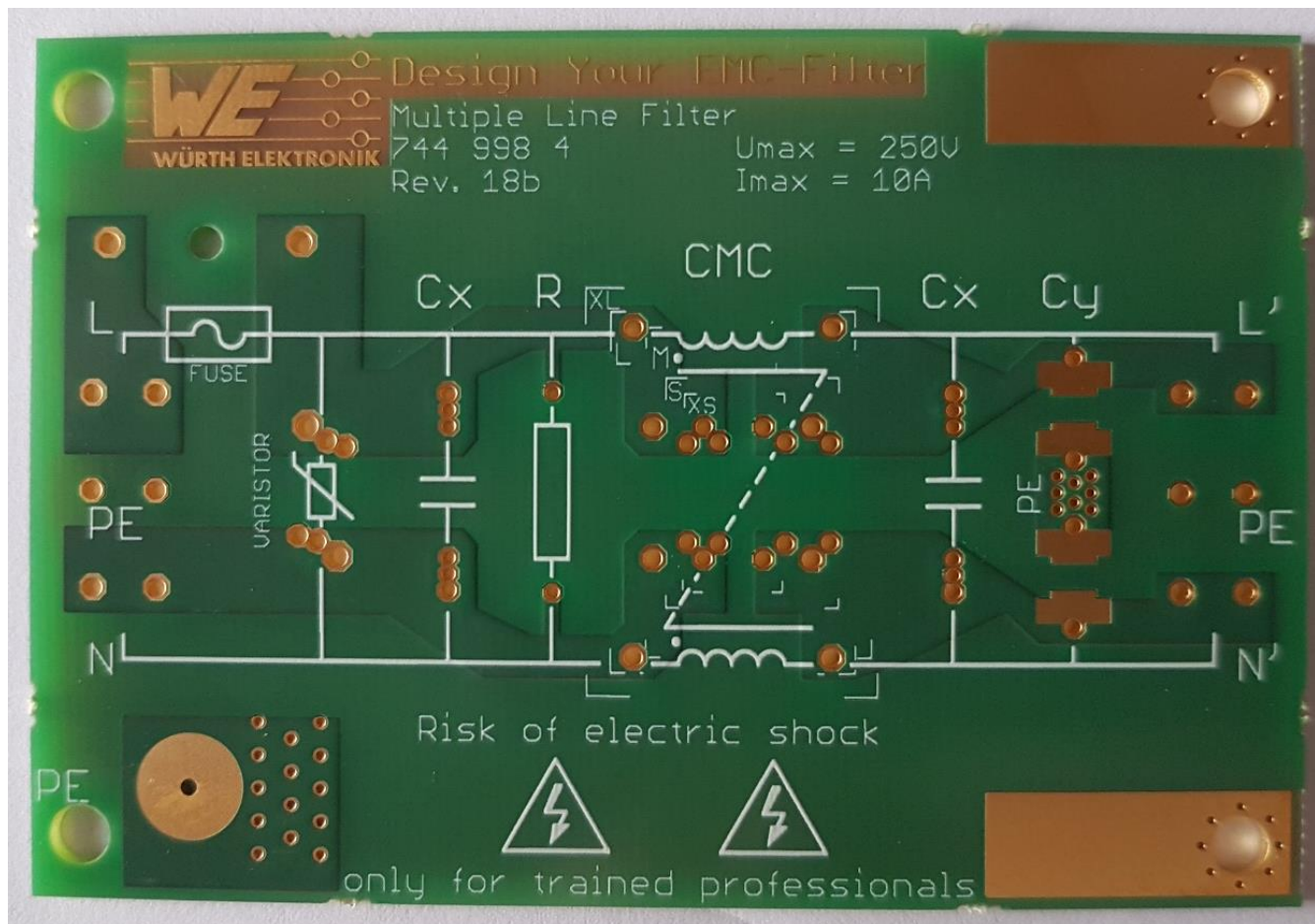
Priprava na Würth praktično delavnico

■ Common mode line filter



Priprava na Würth praktično delavnico

■ Multiple line filter



Nabor materiala

- Design kit: 744998 - https://www.we-online.com/catalog/en/DESIGNKIT_744998

Design your EMC Filter

Test Board Quantity: 10	WCAP-FTX2 890 324 023 025 Pitch: 10 mm C: 0.15 μ F U_{dc} : 275 VAC dV/dt : 300 V/ μ S	WCAP-CSSA 885 352 211 002 Quantity: 10 C: 680 pF U_{dc} : 250 VAC Safety Class: X1/Y2
Resistor Quantity: 10 R: 1M Ω	WA-SNSR 702 936 000 Quantity: 20 Length: 15.9 mm	WCAP-CSSA 885 352 211 003 Quantity: 10 C: 1000 pF U_{dc} : 250 VAC Safety Class: X1/Y2
WR-TBL 691 134 710 002 Quantity: 10 VDE: 450 VAC/24 A UL: 300 VAC/16 A R_{dc} : 20 m Ω 0.05 up to 2 mm ² Wires	WCAP-FTX2 890 324 022 007 Pitch: 7.5 mm C: 0.015 μ F U_{dc} : 275 VAC dV/dt : 500 V/ μ S	WE-CMB 744 822 301 Quantity: 2 L: 1 mH I_{dc} : 3 A R_{dc} : 35 m Ω
WR-SMSH 746 611 3 Quantity: 10 I_{dc} : 50 A Thread: M3	WCAP-FTX2 890 324 023 006 Pitch: 10 mm C: 0.01 μ F U_{dc} : 275 VAC dV/dt : 500 V/ μ S	WE-CMB 744 822 222 Quantity: 2 L: 2.2 mH I_{dc} : 2 A R_{dc} : 70 m Ω
WR-SMSH 746 611 4 Quantity: 10 I_{dc} : 50 A Thread: M4	WCAP-CSSA 885 352 213 011 Quantity: 10 C: 1000 pF U_{dc} : 250 VAC Safety Class: X1/Y2	WE-CMB 744 823 601 Quantity: 2 L: 1 mH I_{dc} : 6 A R_{dc} : 13 m Ω
WE-LF 744 662 400 07 Quantity: 1 L: 0.7 mH I_{dc} : 4 A R_{dc} : 27 m Ω	WE-CMBNG 744 803 050 9 Quantity: 1 L: 9 mH I_{dc} : 5 A R_{dc} : 28 m Ω	WE-CMB 744 824 101 Quantity: 2 L: 1 mH I_{dc} : 10 A R_{dc} : 7 m Ω
WE-LF 744 662 200 2 Quantity: 1 L: 2.2 mH I_{dc} : 2 A R_{dc} : 100 m Ω	WE-CMBNG 744 804 070 7 Quantity: 1 L: 7 mH I_{dc} : 7 A R_{dc} : 20 m Ω	WE-CMB 744 824 622 Quantity: 2 L: 2.2 mH I_{dc} : 6 A R_{dc} : 20 m Ω
WE-LF 744 662 100 7 Quantity: 1 L: 6.8 mH I_{dc} : 1 A R_{dc} : 300 m Ω	WE-CMBNG 744 823 305 Quantity: 2 L: 5 mH I_{dc} : 2.5 A R_{dc} : 95 m Ω	WE-CMB 744 824 433 Quantity: 2 L: 3.3 mH I_{dc} : 4 A R_{dc} : 35 m Ω
WE-LF 744 662 002 7 Quantity: 1 L: 27 mH I_{dc} : 0.4 A R_{dc} : 1.200 m Ω	WE-CMBNG 744 823 210 Quantity: 2 L: 10 mH I_{dc} : 2 A R_{dc} : 125 m Ω	WE-CMB 744 824 310 Quantity: 2 L: 10 mH I_{dc} : 3 A R_{dc} : 105 m Ω
	WE-CMBNG 744 822 120 Quantity: 2 L: 20 mH I_{dc} : 0.5 A R_{dc} : 540 m Ω	WE-CMB 744 824 220 Quantity: 2 L: 20 mH I_{dc} : 2 A R_{dc} : 220 m Ω

