Seminar in delavnica

Načrtovanje elektronike za EMC

Elektromagnetna združljivost (EMC)

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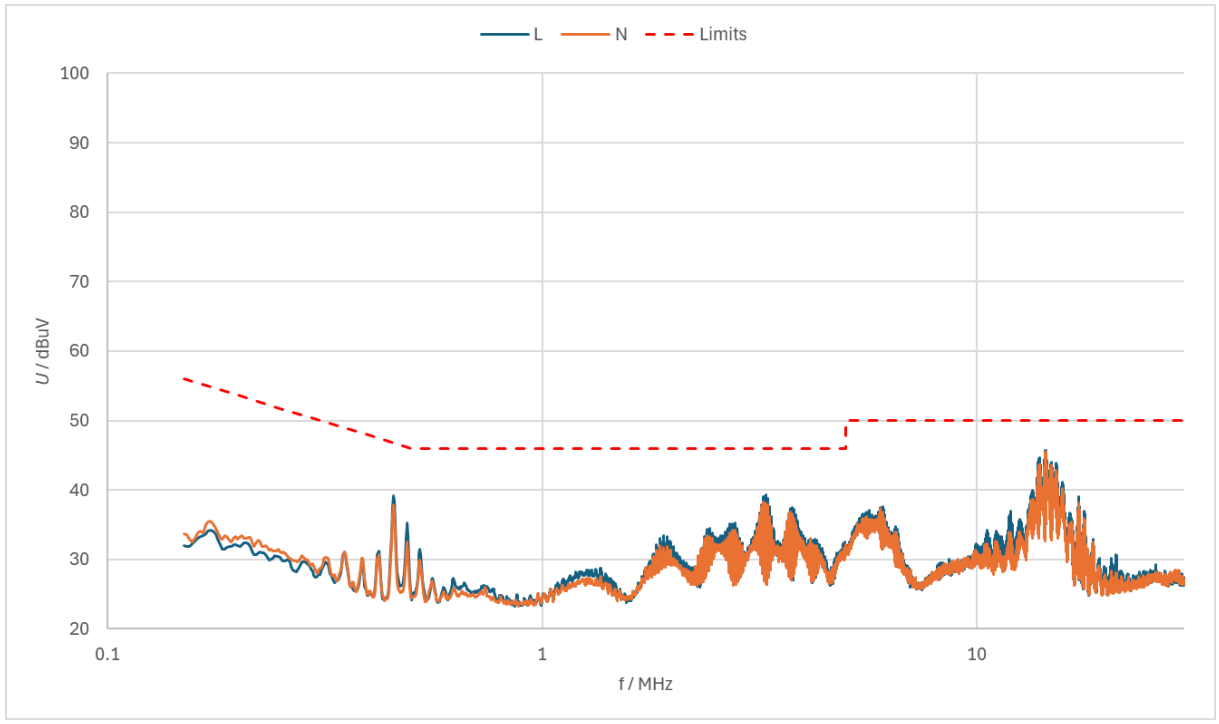
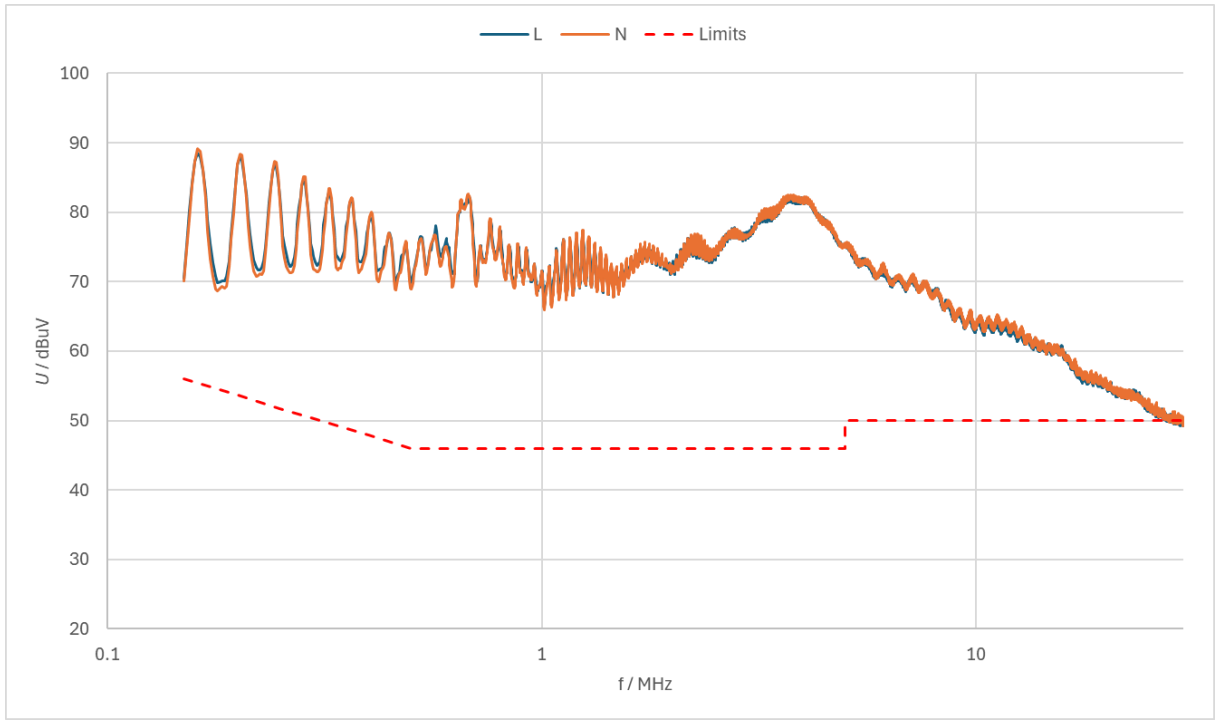
Namesto uvoda

Namesto uvoda



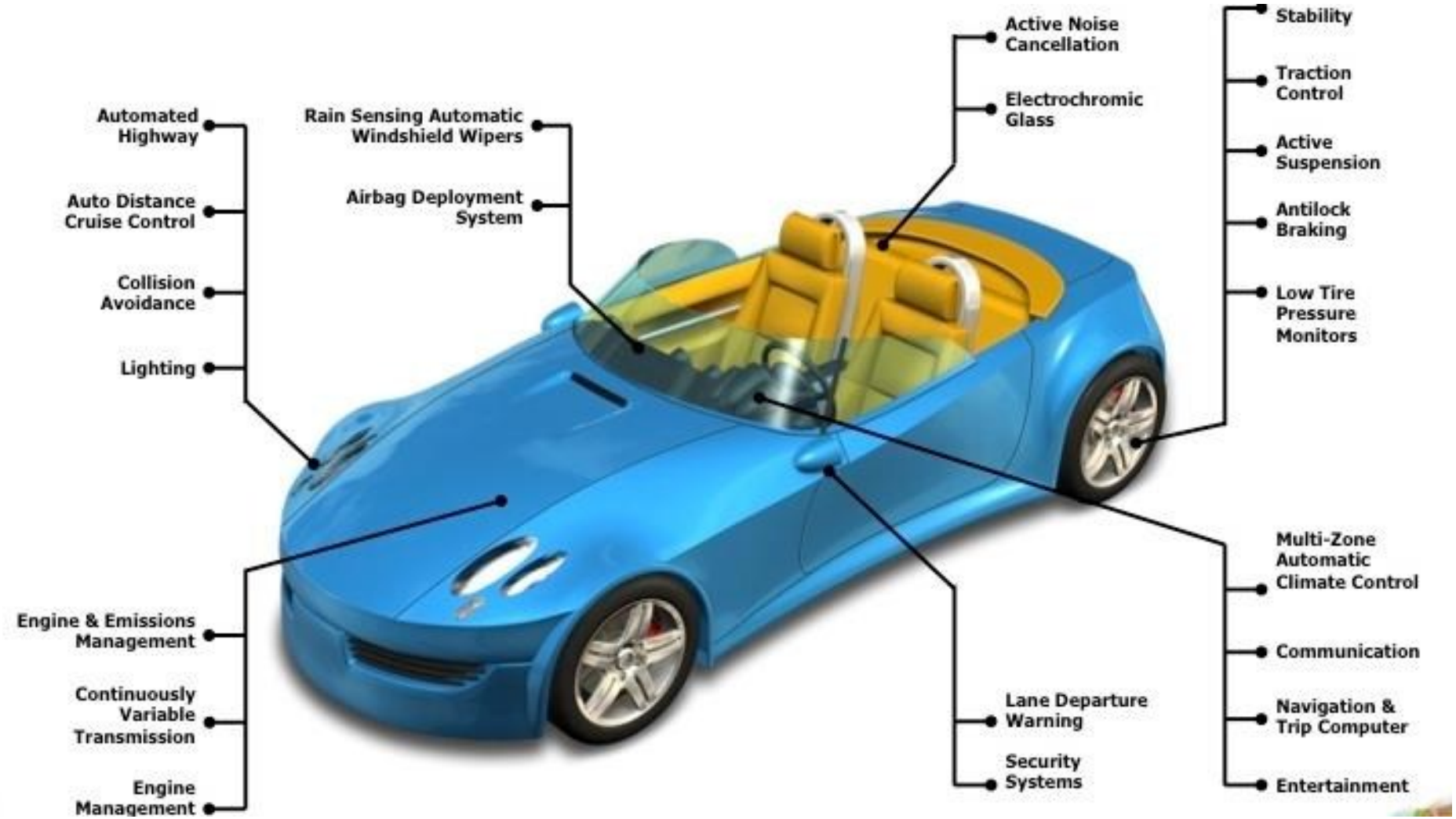


Namesto uvoda

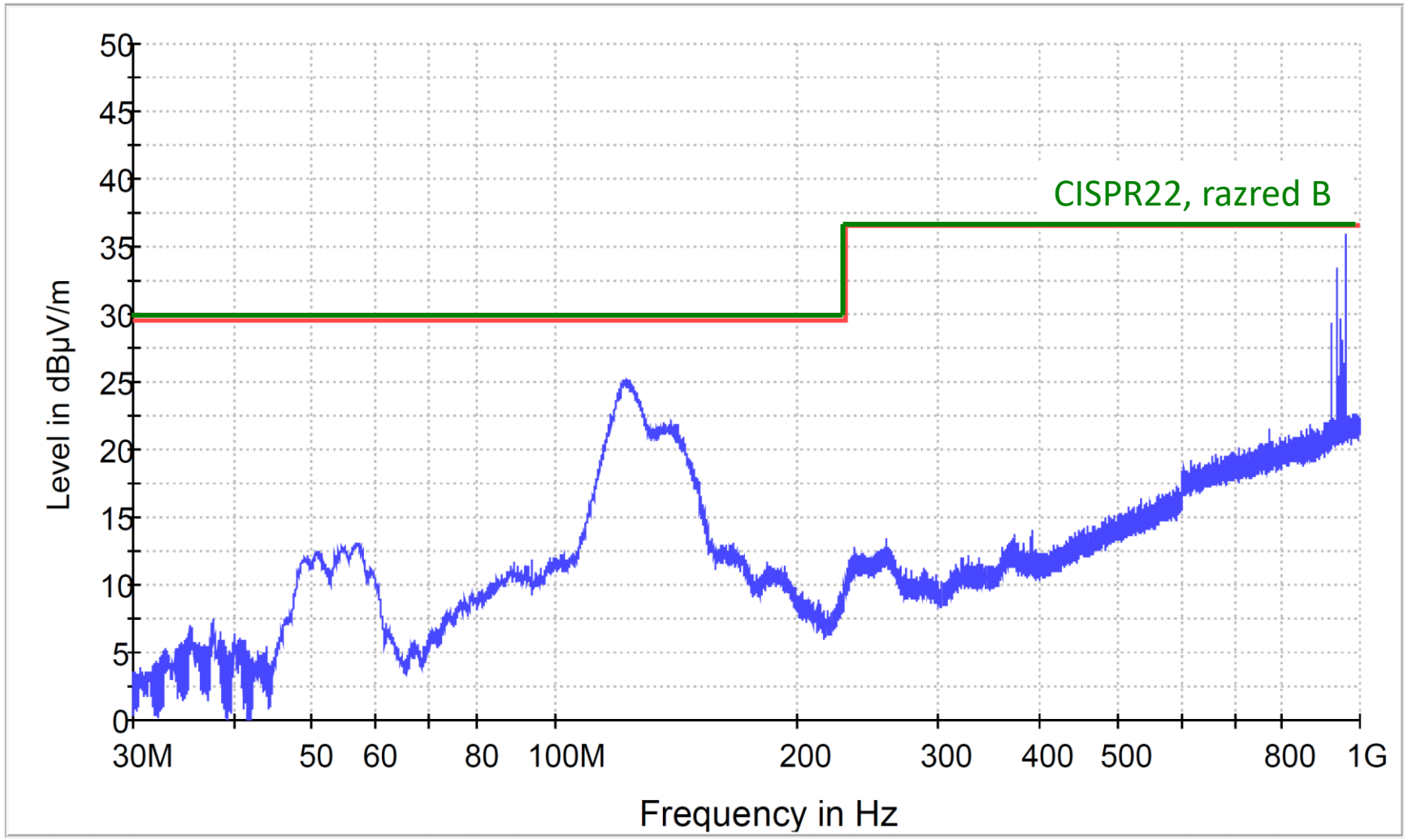
Namesto uvoda

Smrtno nevaren EMC problem

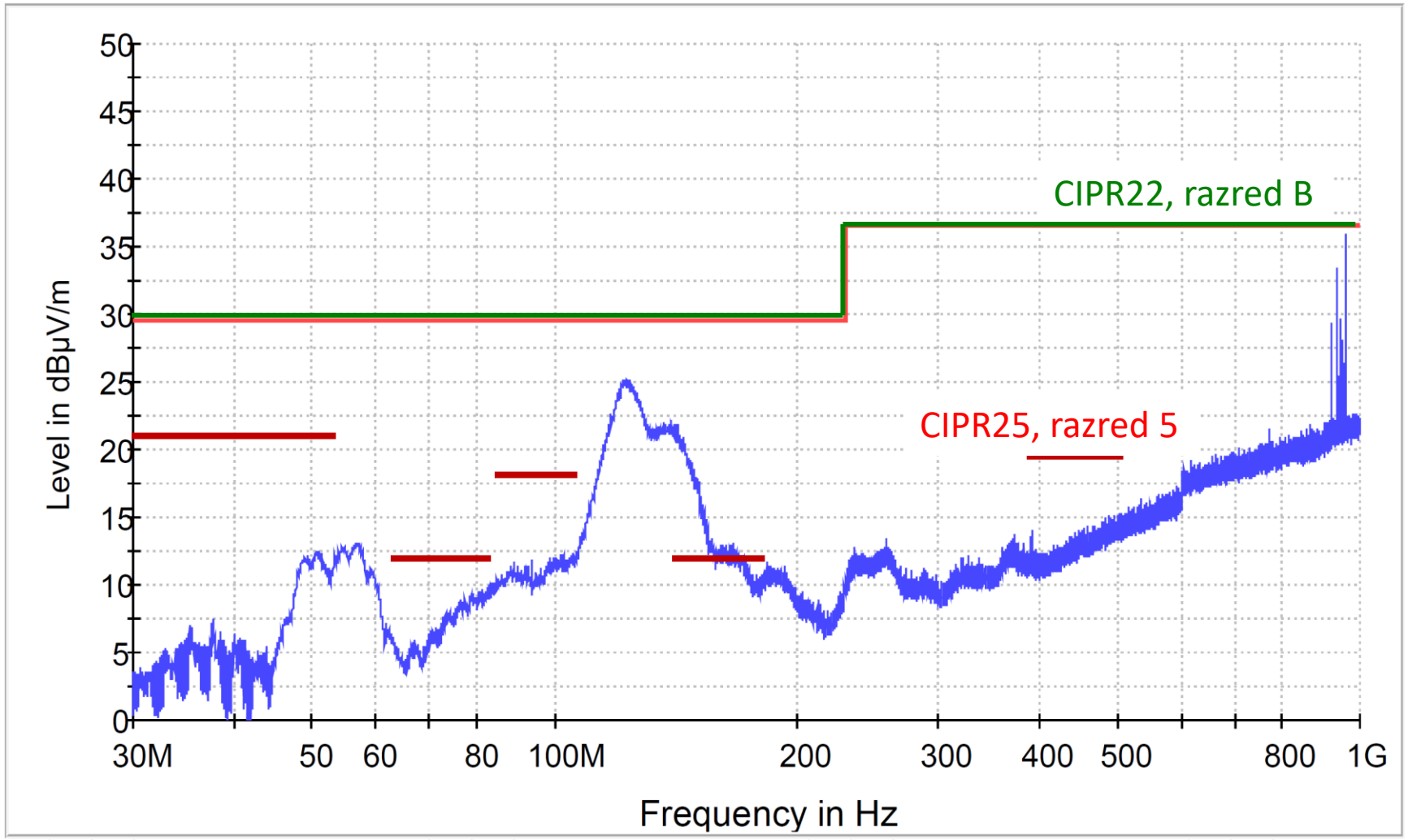
EMC v avtomobilski industriji



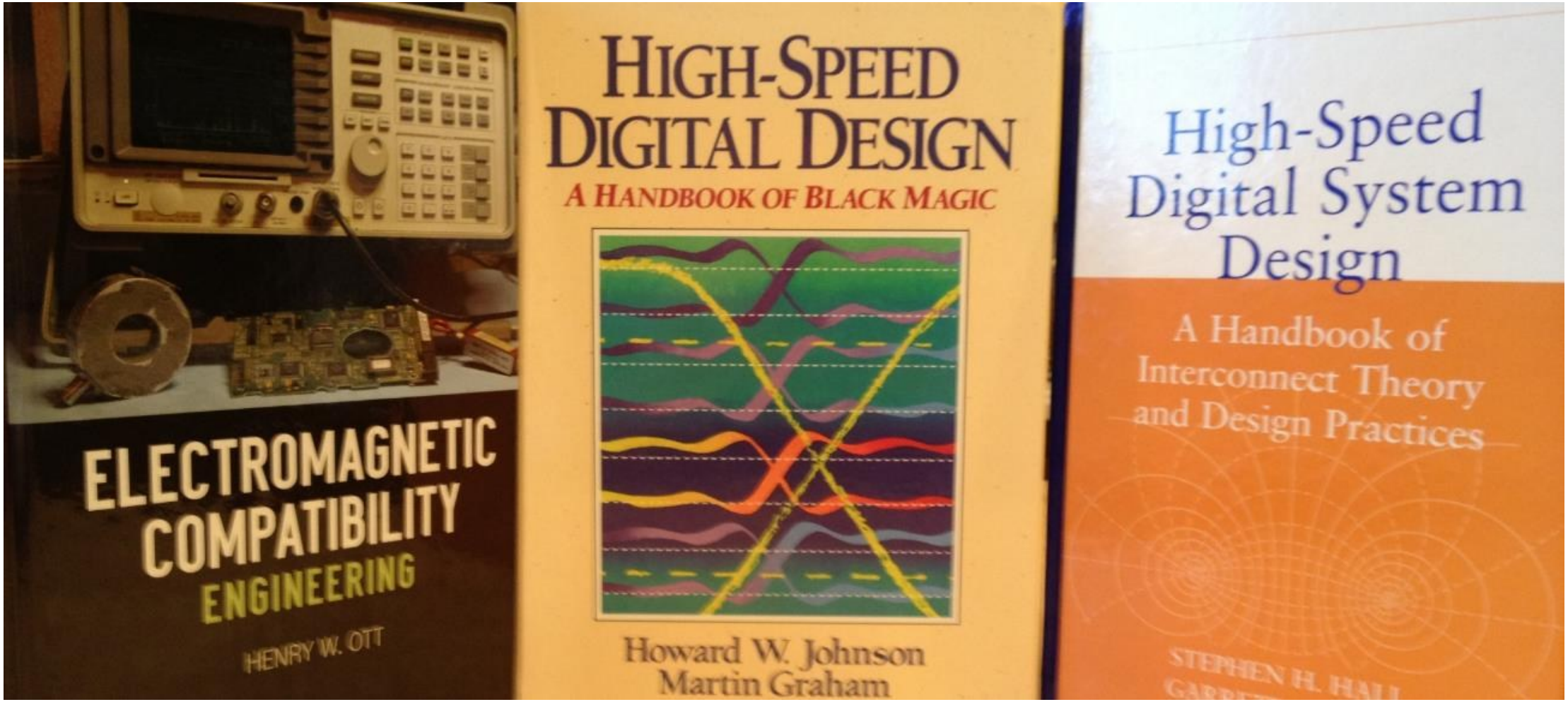
Splošne emisijske meje



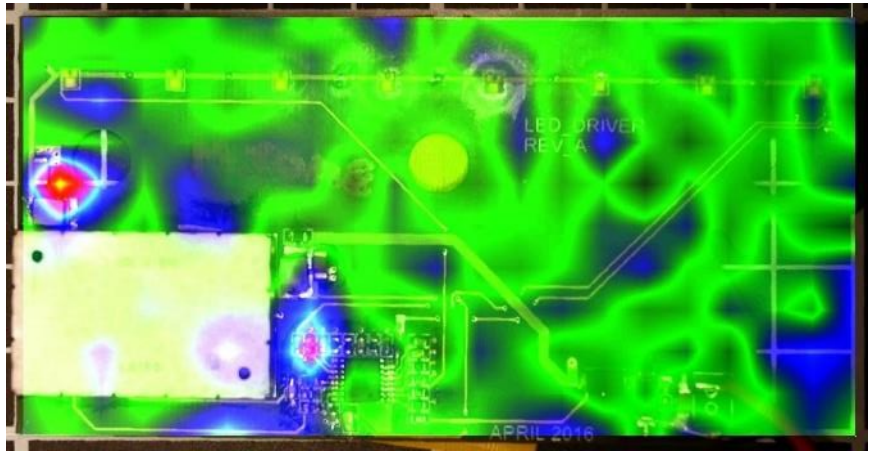
Emisijske meje v avtomobilski industriji

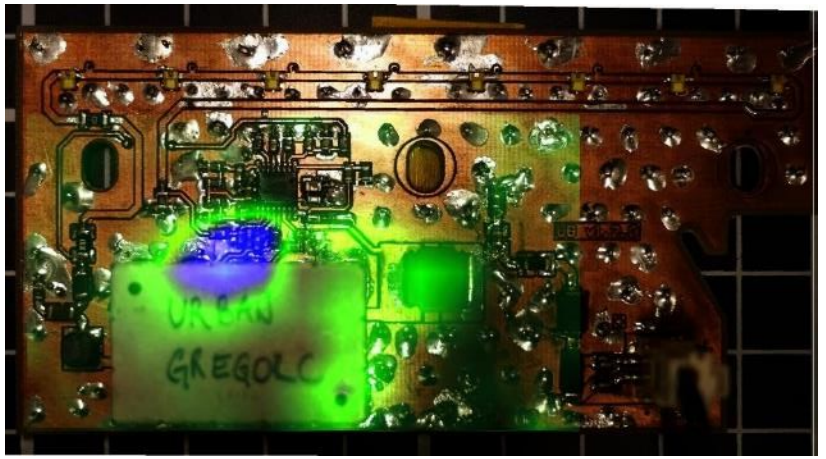


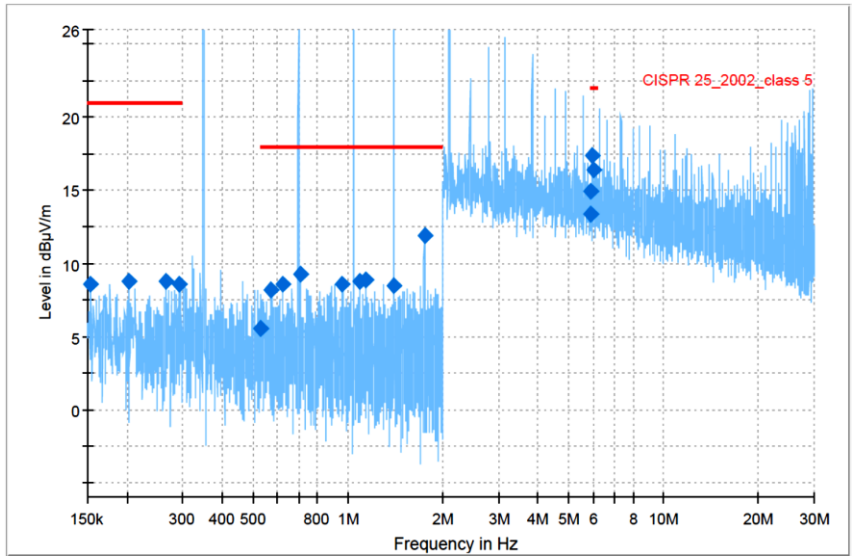
Teorija!

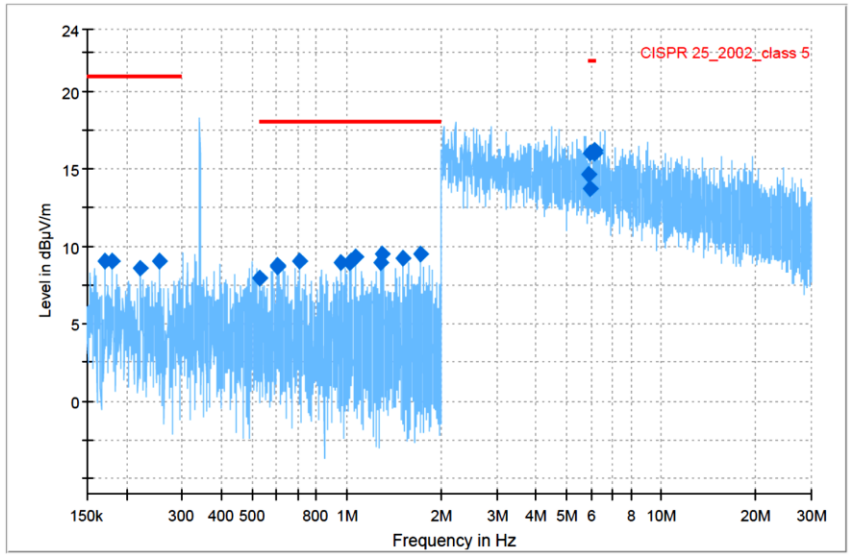

ELECTROMAGNETIC
COMPATIBILITY
ENGINEERING
HENRY W. OTT
HIGH-SPEED
DIGITAL DESIGN
A HANDBOOK OF BLACK MAGIC
Howard W. Johnson
Martin Graham
High-Speed
Digital System
Design
A Handbook of
Interconnect Theory
and Design Practices

Praksa!


APRIL 2016

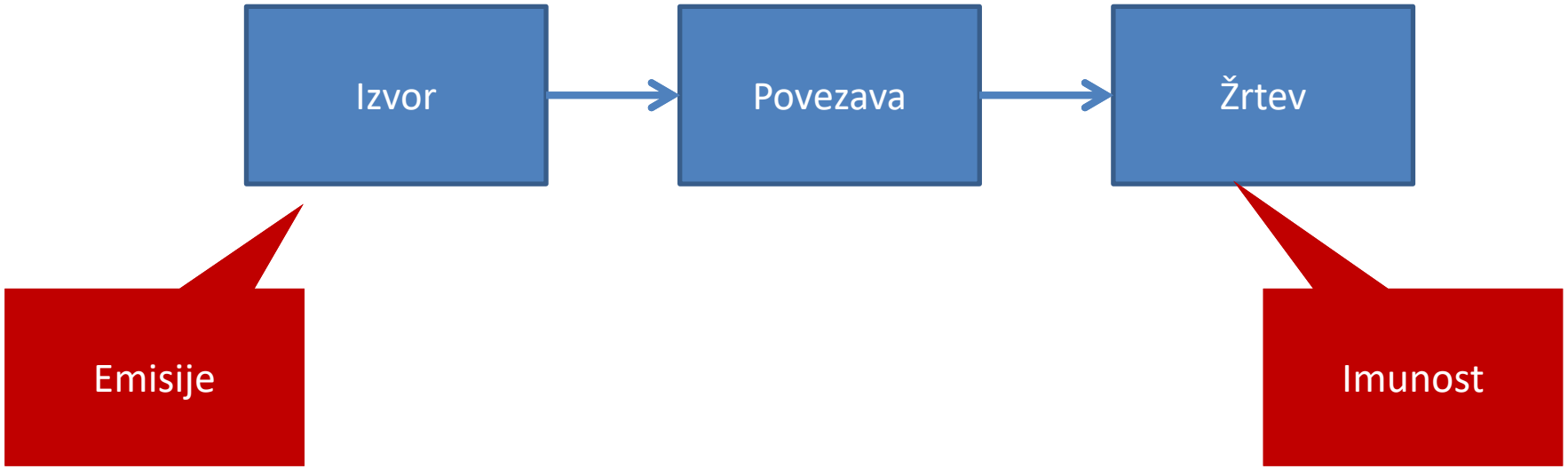

GREGOLC


CISPR 25_2002_class 5
Level in dBµV/m
Frequency in Hz
150k
300
400 500
800 1M
2M
3M
4M
5M
6
8
10M
20M
30M

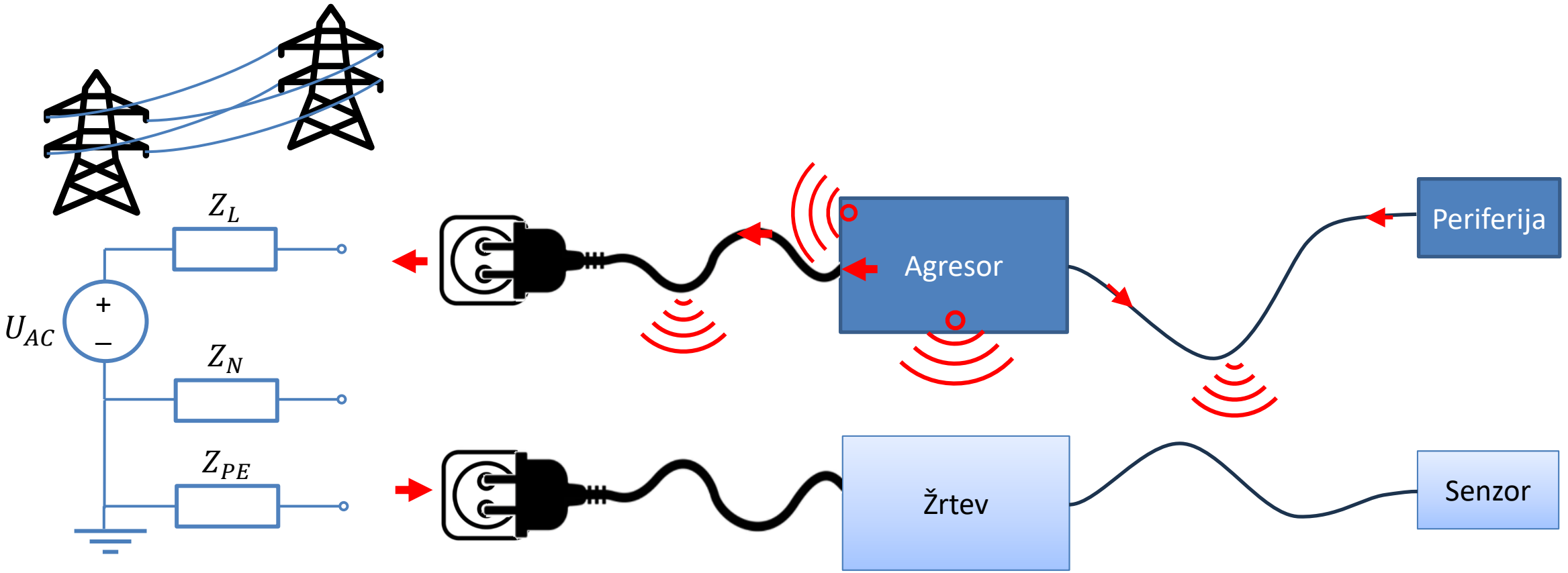

CISPR 25_2002_class 5
Level in dBµV/m
Frequency in Hz
150k
300
400 500
800 1M
2M
3M
4M
5M
6
8
10M
20M
30M

Model EMC

- **izvor** sevanja (motenj),
- **Sprejemnik**
- **povezava** med izvorom in sprejemnikom.

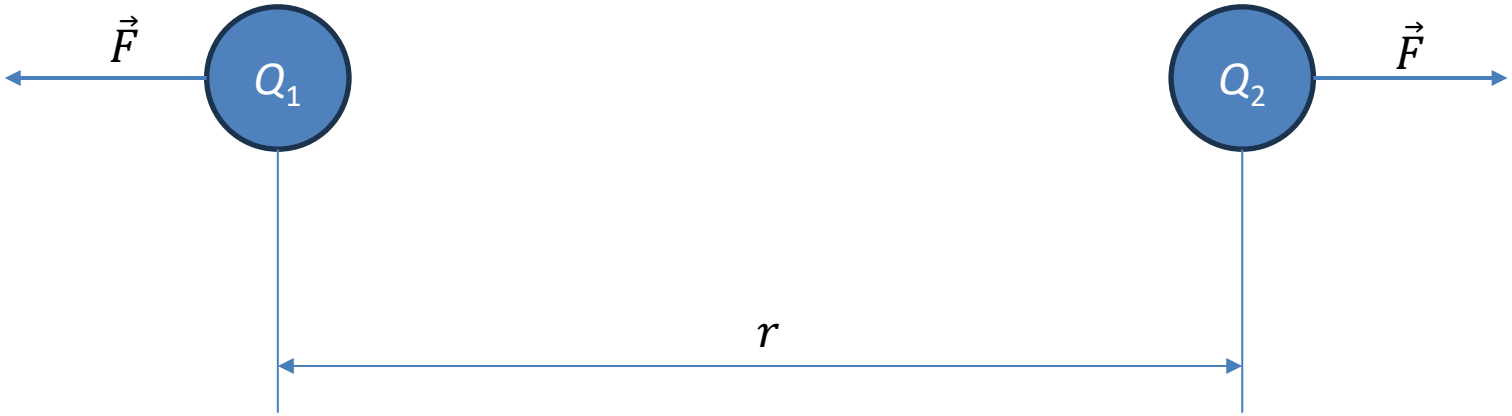


Mehanizmi sklapljanja EM motenj



Model EMC

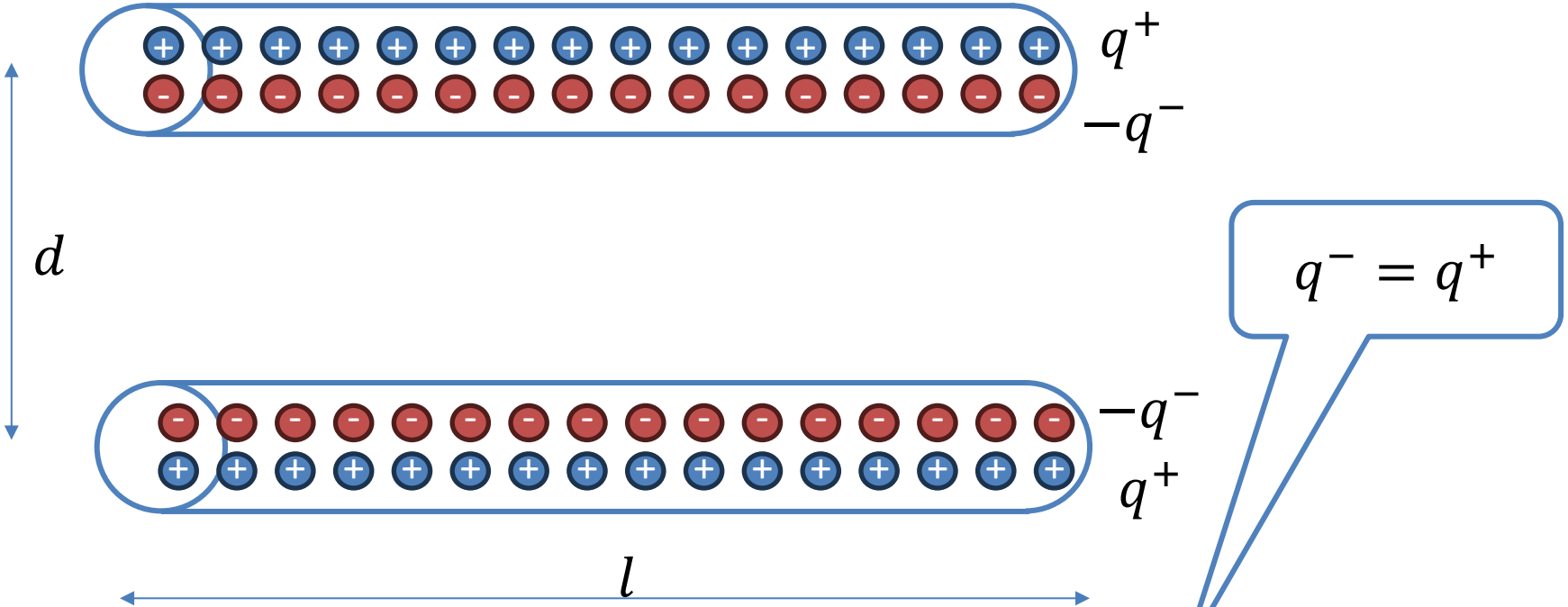
Sila med dvema nabojema



$$\vec{F} = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2}$$

$$\epsilon_0 = 8.85 \cdot 10^{-12}\,\frac{\mathrm{As}}{\mathrm{Vm}}$$

Sila med dvema vodnikoma

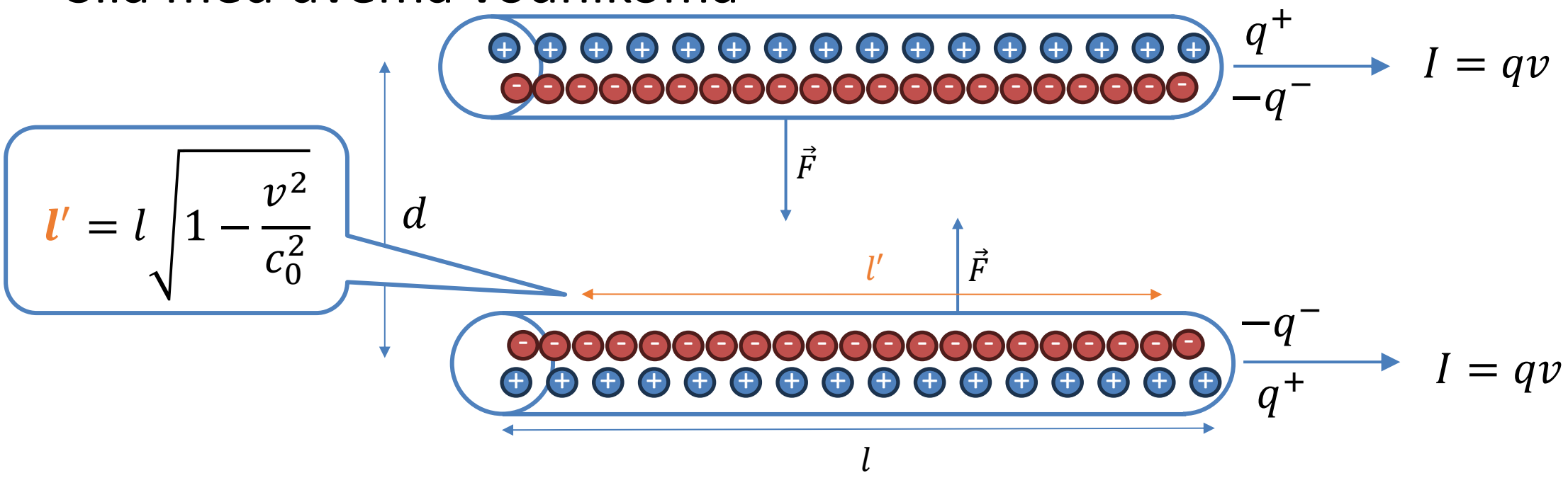


$$q = \frac{Q}{l} \longrightarrow \vec{F} = \frac{-l}{2\pi\epsilon_0 d}[q^- \cdot q^- - q^- \cdot q^+ - q^+ \cdot q^- + q^+ \cdot q^+]$$

$l \gg d$

$\vec{F} = 0$

Sila med dvema vodnikoma



$$l' = l\sqrt{1 - \frac{v^2}{c_0^2}}$$

$$q^{-\prime} = \frac{Q}{l'} \longrightarrow q^{-\prime} = \frac{q^-}{\sqrt{1 - \frac{v^2}{c_0^2}}} \approx \frac{I}{v}\left(1 + \frac{v^2}{2c_0^2}\right) \longrightarrow \vec{F} = \frac{l}{2\pi\epsilon_0 d}\left[\frac{I^2}{c_0^2}\right] \longrightarrow \boxed{\vec{F} = \frac{\mu_0 I^2 l}{2\pi d}}$$

$q^- \neq q^+$

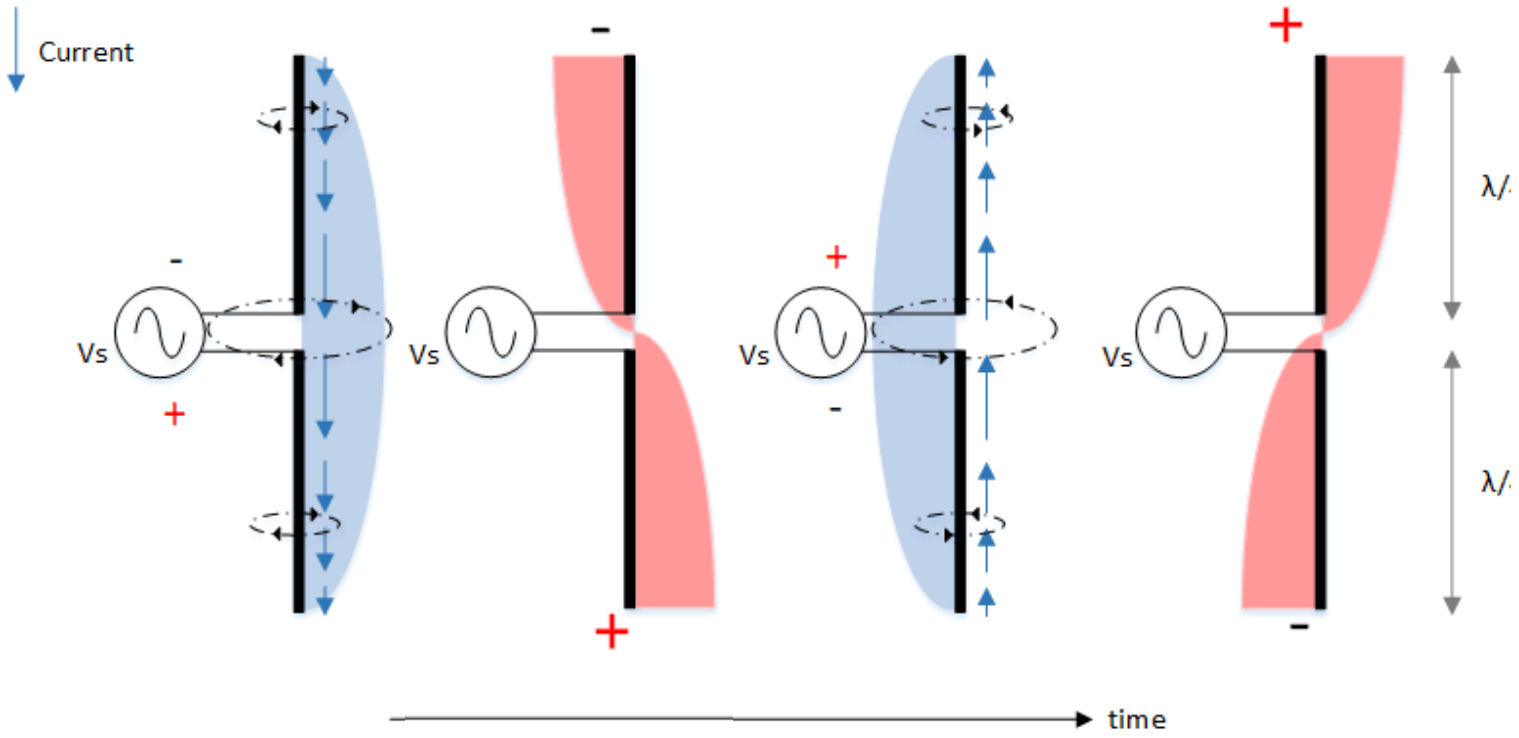
$$c_0^2 = \frac{1}{\mu_0 \epsilon_0}$$

EM valovanje

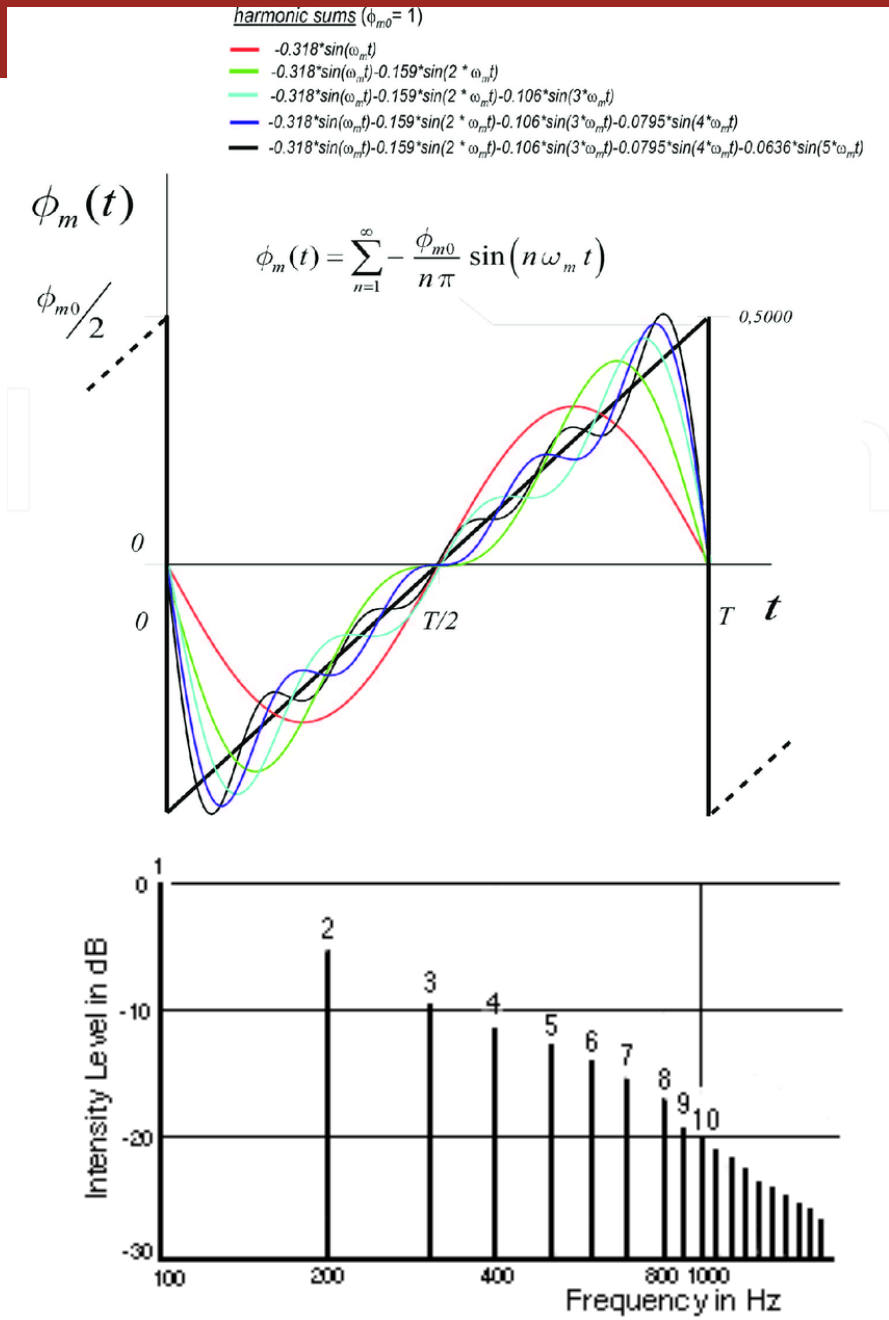
$$\nabla \times \vec{H} = \vec{J} + j\omega\vec{D}$$
$$\nabla \times \vec{E} = -j\omega\vec{B}$$
$$\nabla \cdot \vec{D} = \rho$$
$$\nabla \cdot \vec{B} = 0$$

$$\vec{D} = \epsilon\vec{E}$$
$$\vec{B} = \mu\vec{H}$$

$$\vec{S} = \vec{E} \times \vec{H}^*$$



Spekter


harmonic sums (ϕ_{m0}= 1)
-0.318*sin(ω_mt)
-0.318*sin(ω_mt)-0.159*sin(2 * ω_mt)
-0.318*sin(ω_mt)-0.159*sin(2 * ω_mt)-0.106*sin(3*ω_mt)
-0.318*sin(ω_mt)-0.159*sin(2 * ω_mt)-0.106*sin(3*ω_mt)-0.0795*sin(4*ω_mt)
-0.318*sin(ω_mt)-0.159*sin(2 * ω_mt)-0.106*sin(3*ω_mt)-0.0795*sin(4*ω_mt)-0.0636*sin(5*ω_mt)
$\phi_m(t)$
$\phi_m(t) = \sum_{n=1}^{\infty} -\frac{\phi_{m0}}{n\pi} \sin(n\omega_m t)$
$\phi_{m0}/2$
0,5000
0
0
T/2
T
t
Intensity Level in dB
0
-10
-20
-30
1
2
3
4
5
6
7
8
9
10
100
200
400
800
1000
Frequency in Hz

Decibeli

Bel:

$$P[\mathrm{B}] = \log\left(\frac{P}{P_{ref}}\right)$$

Resolucija človeških čutil je cca 0,1 B

Decibel:

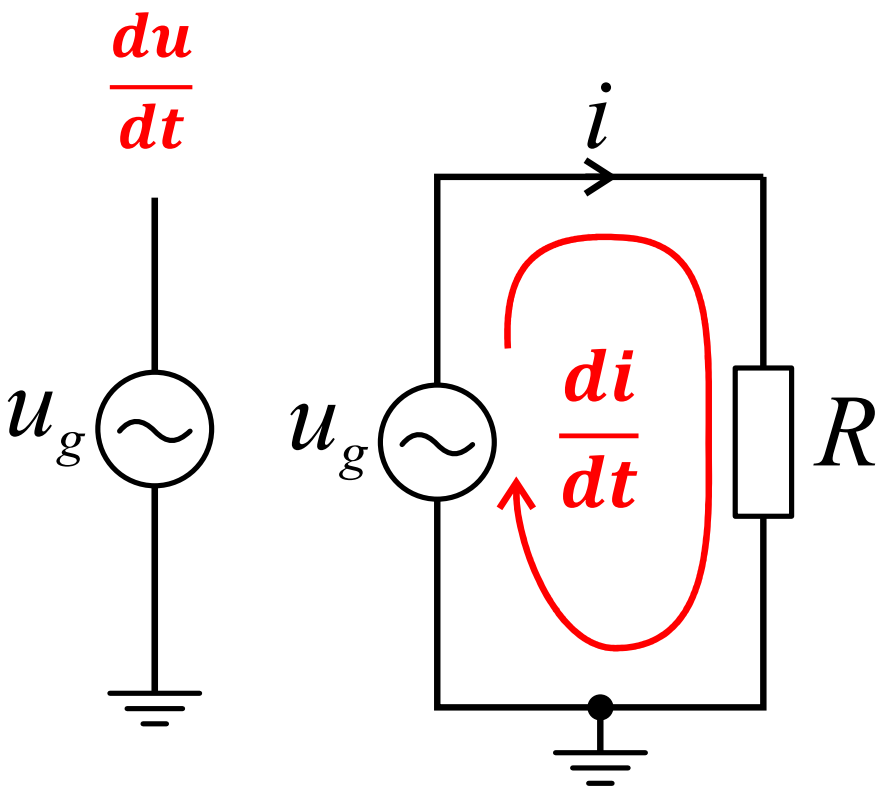
$$P[\mathrm{dB}] = 10 \cdot P[\mathrm{B}] = 10 \cdot \log\left(\frac{P}{P_{ref}}\right)$$

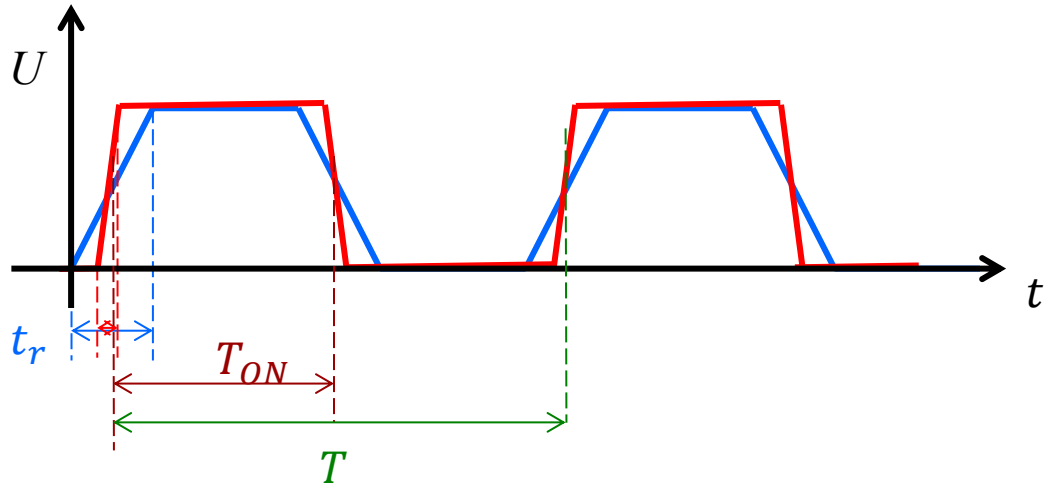
Napetost:

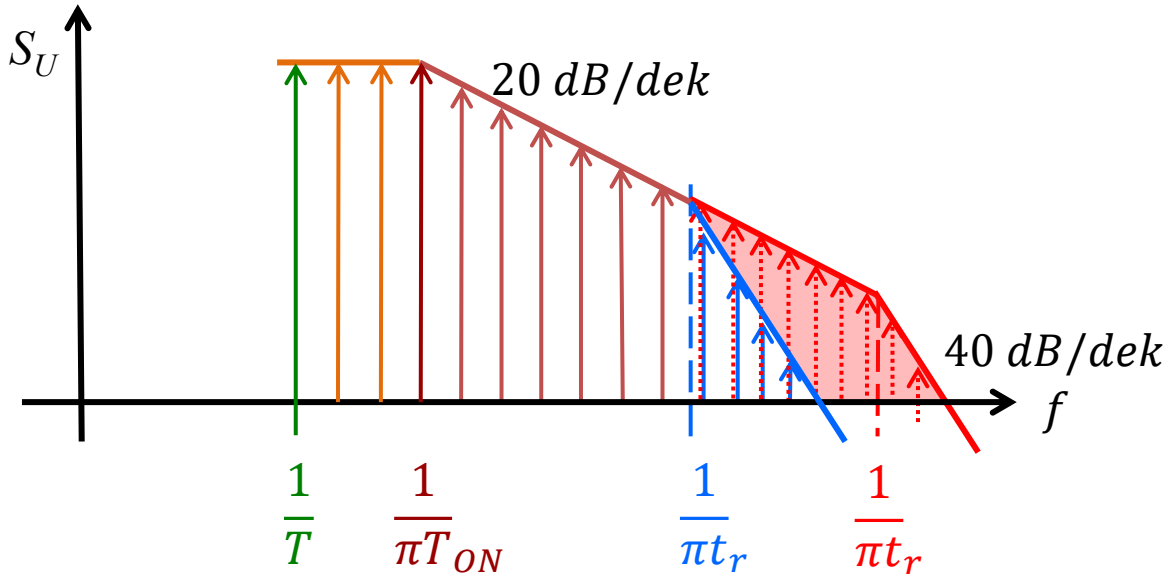
$$10 \cdot \log\left(\frac{U^2/R}{U_{ref}^2/R}\right) = 20 \cdot \log\left(\frac{U}{U_{ref}}\right)$$

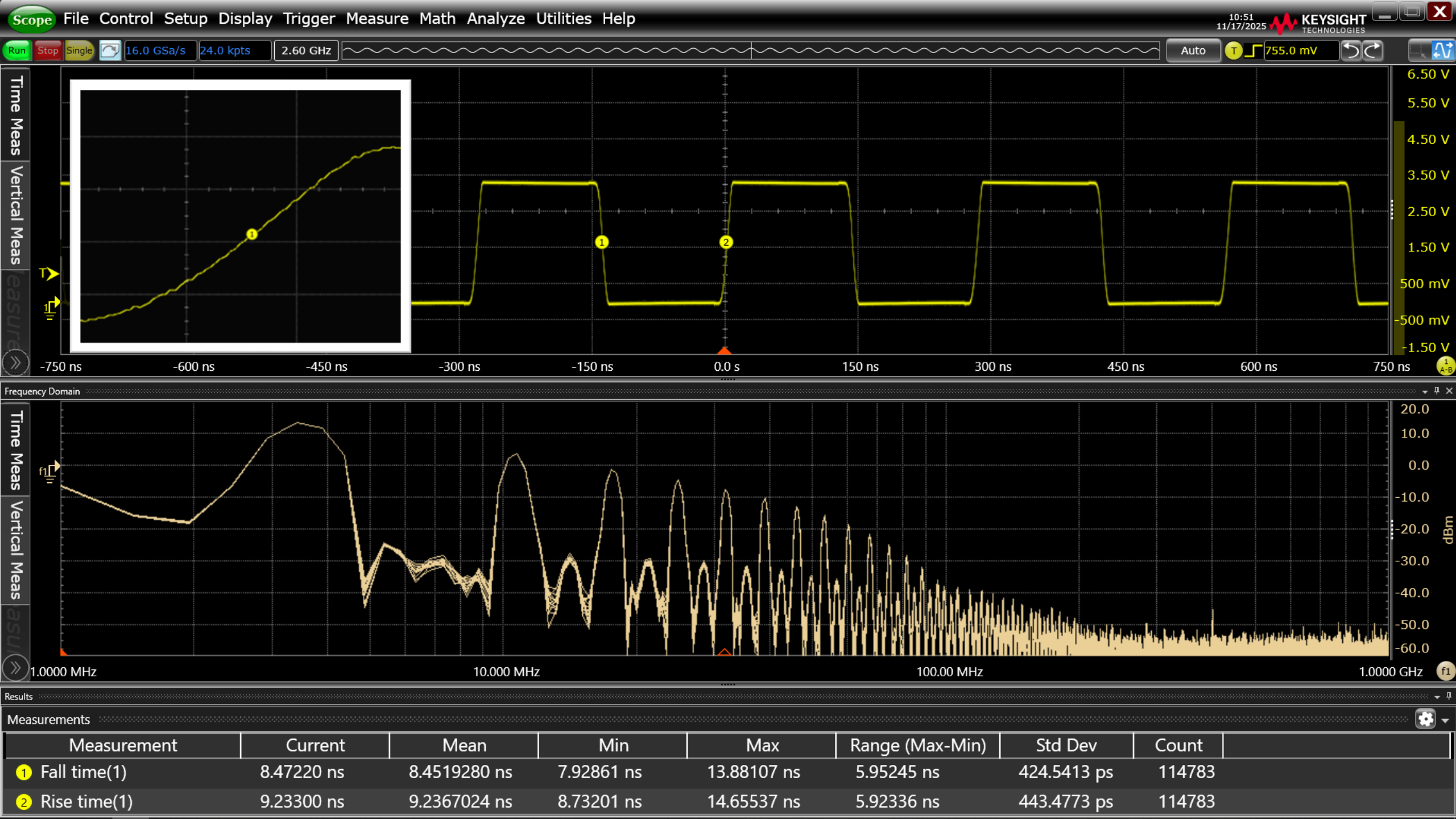
Učinek	Gostota moči		Električno polje	
Polno sončno obsevanje	1000 W/m^2		614 V_{ef}/m	+175 dBuV/m
Zaznavna toplota	100 W/m^2		194 V_{ef}/m	+165 dBuV/m
Varna meja	10 W/m^2		61 V_{ef}/m	+155 dBuV/m
Legalna meja	0.1 W/m^2		6 V_{ef}/m	+135 dBuV/m

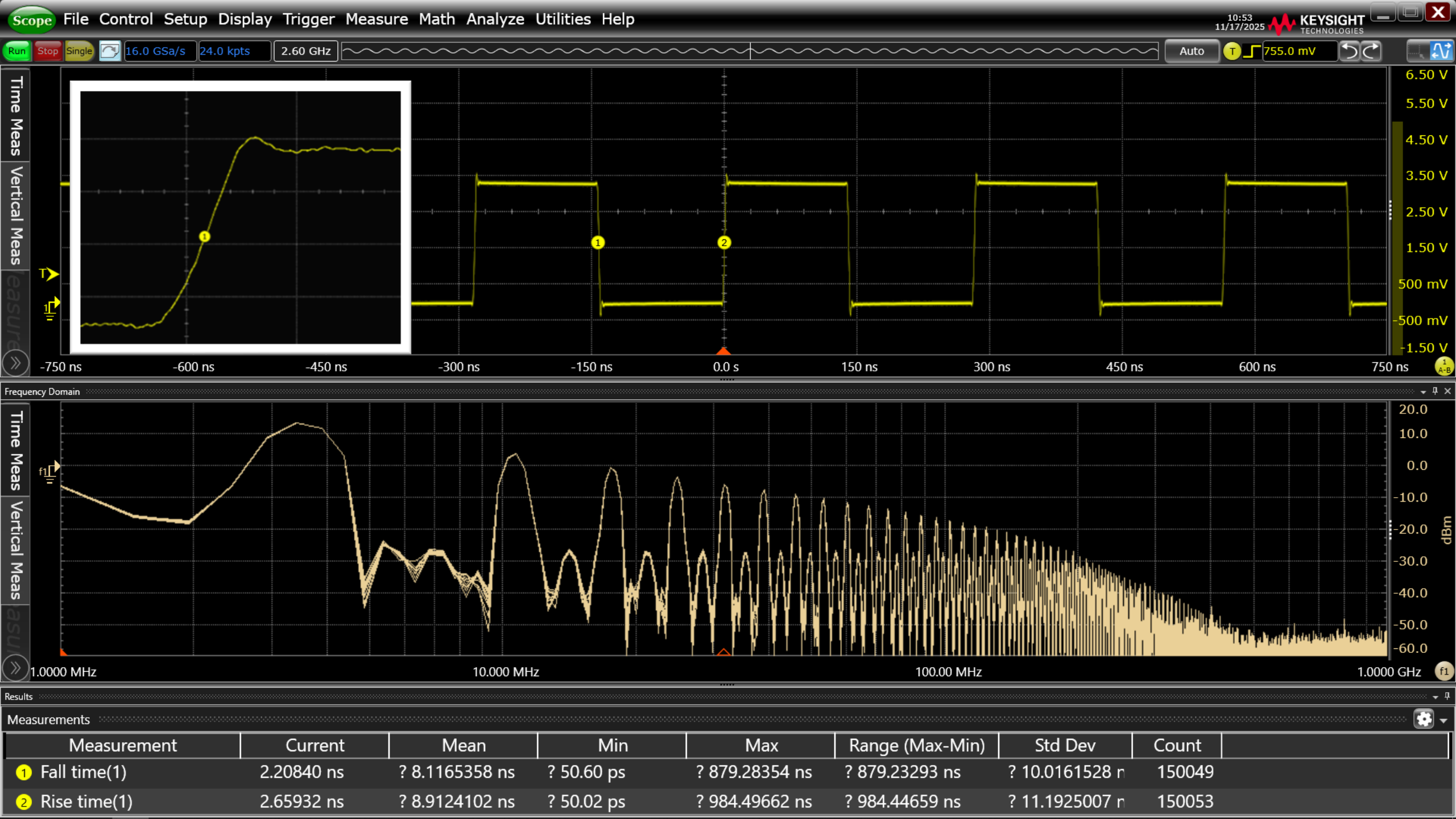
Izvori motenj

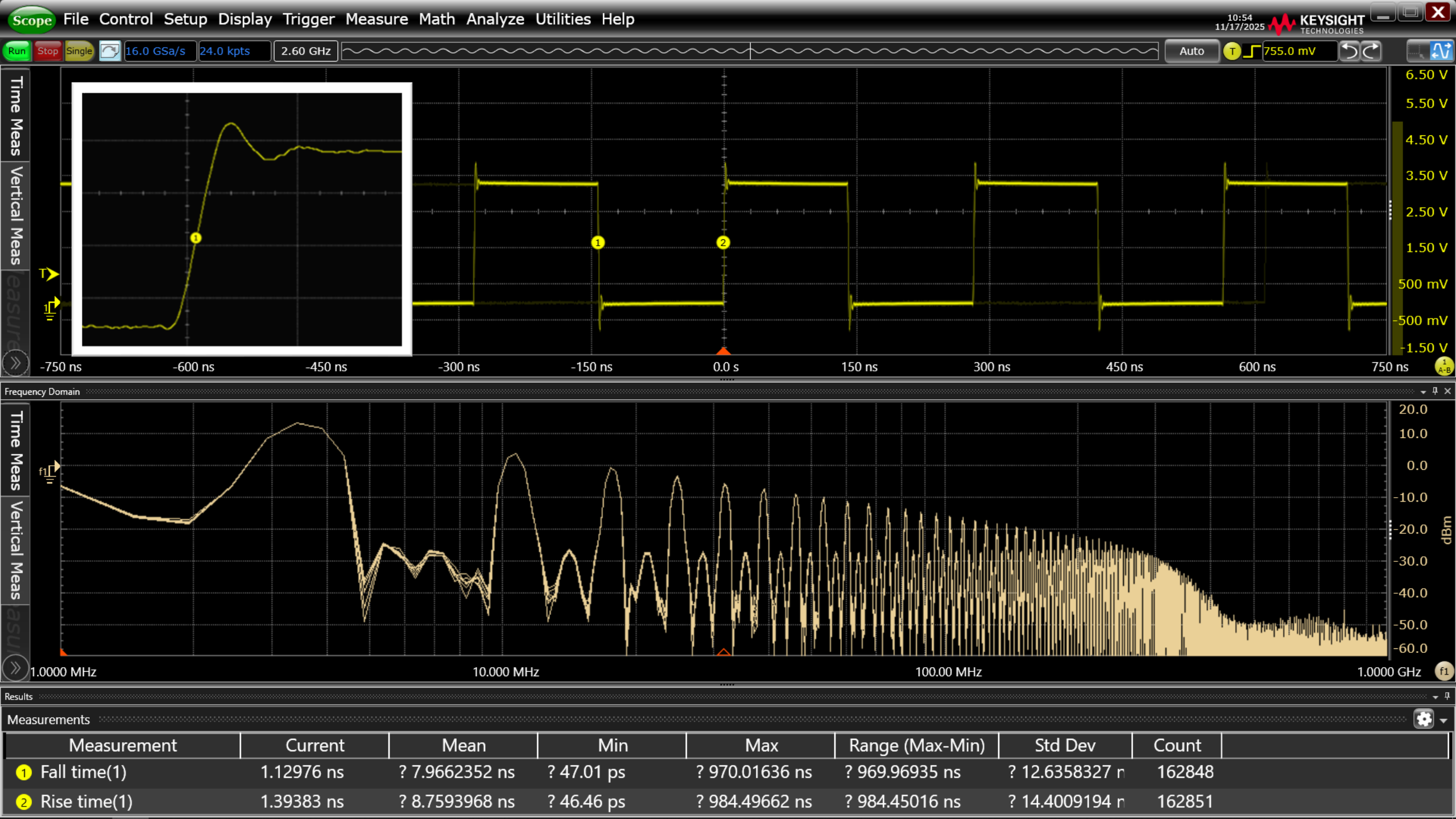


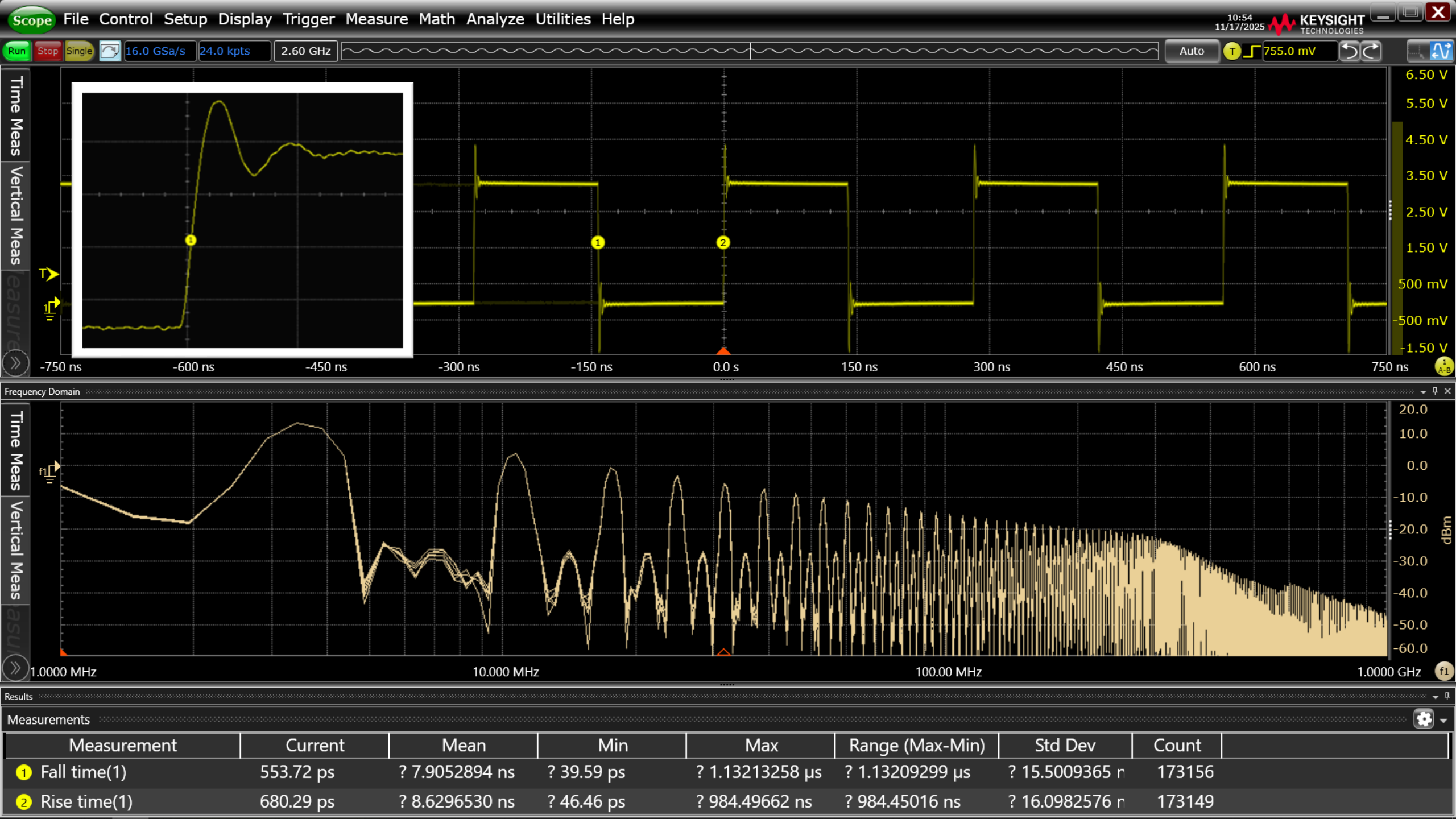





Scope
File Control Setup Display Trigger Measure Math Analyze Utilities Help
10:51
11/17/2025
KEYSIGHT
TECHNOLOGIES
Run
Stop
Single
16.0 GSa/s
24.0 kpts
2.60 GHz
Auto
755.0 mV
Time Meas
Vertical Meas
6.50 V
5.50 V
4.50 V
3.50 V
2.50 V
1.50 V
500 mV
-500 mV
-1.50 V
-750 ns
-600 ns
-450 ns
-300 ns
-150 ns
0.0 s
150 ns
300 ns
450 ns
600 ns
750 ns
Frequency Domain
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
dBm
1.0000 MHz
10.000 MHz
100.00 MHz
1.0000 GHz
Results
Measurements
Measurement
Current
Mean
Min
Max
Range (Max-Min)
Std Dev
Count
1 Fall time(1)
8.47220 ns
8.4519280 ns
7.92861 ns
13.88107 ns
5.95245 ns
424.5413 ps
114783
2 Rise time(1)
9.23300 ns
9.2367024 ns
8.73201 ns
14.65537 ns
5.92336 ns
443.4773 ps
114783


Scope
File Control Setup Display Trigger Measure Math Analyze Utilities Help
10:53
11/17/2025
KEYSIGHT TECHNOLOGIES
Run Stop Single
16.0 GSa/s
24.0 kpts
2.60 GHz
Auto
755.0 mV
Time Meas
Vertical Meas
6.50 V
5.50 V
4.50 V
3.50 V
2.50 V
1.50 V
500 mV
-500 mV
-1.50 V
-750 ns
-600 ns
-450 ns
-300 ns
-150 ns
0.0 s
150 ns
300 ns
450 ns
600 ns
750 ns
Frequency Domain
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
dBm
1.0000 MHz
10.000 MHz
100.00 MHz
1.0000 GHz
Results
Measurements
Measurement
Current
Mean
Min
Max
Range (Max-Min)
Std Dev
Count
1 Fall time(1)
2.20840 ns
? 8.1165358 ns
? 50.60 ps
? 879.28354 ns
? 879.23293 ns
? 10.0161528 n
150049
2 Rise time(1)
2.65932 ns
? 8.9124102 ns
? 50.02 ps
? 984.49662 ns
? 984.44659 ns
? 11.1925007 n
150053

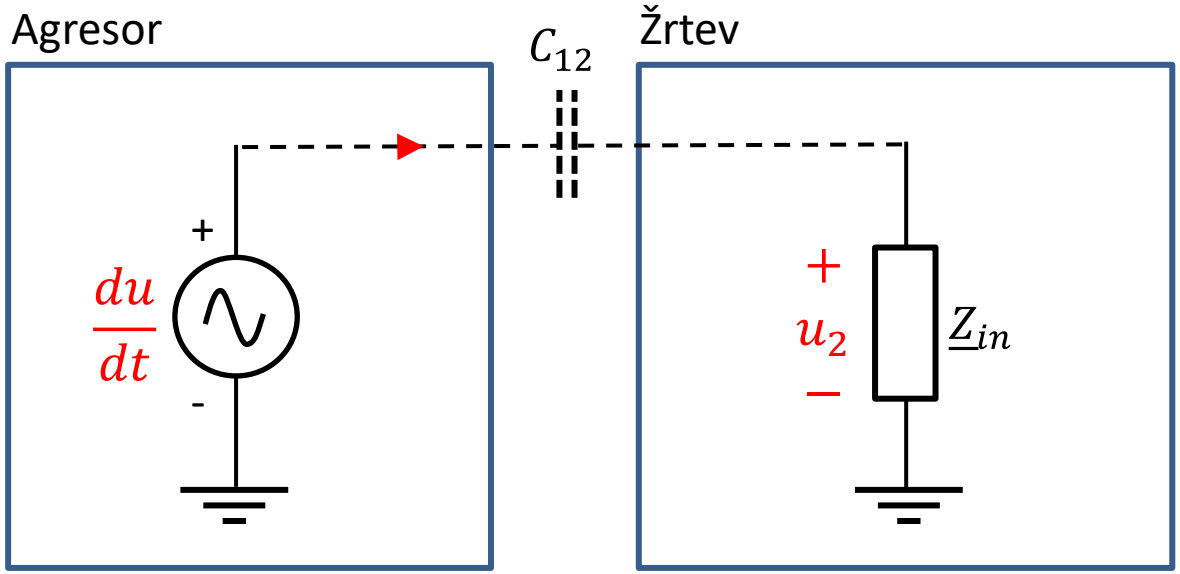

Scope
File Control Setup Display Trigger Measure Math Analyze Utilities Help
10:54
11/17/2025
KEYSIGHT TECHNOLOGIES
Run Stop Single
16.0 GSa/s
24.0 kpts
2.60 GHz
Auto
755.0 mV
Time Meas
Vertical Meas
6.50 V
5.50 V
4.50 V
3.50 V
2.50 V
1.50 V
500 mV
-500 mV
-1.50 V
-750 ns
-600 ns
-450 ns
-300 ns
-150 ns
0.0 s
150 ns
300 ns
450 ns
600 ns
750 ns
Frequency Domain
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
dBm
1.0000 MHz
10.000 MHz
100.00 MHz
1.0000 GHz
Results
Measurements
Measurement
Current
Mean
Min
Max
Range (Max-Min)
Std Dev
Count
1 Fall time(1)
1.12976 ns
? 7.9662352 ns
? 47.01 ps
? 970.01636 ns
? 969.96935 ns
? 12.6358327 n
162848
2 Rise time(1)
1.39383 ns
? 8.7593968 ns
? 46.46 ps
? 984.49662 ns
? 984.45016 ns
? 14.4009194 n
162851


Scope
File Control Setup Display Trigger Measure Math Analyze Utilities Help
10:54
11/17/2025
KEYSIGHT TECHNOLOGIES
Run Stop Single
16.0 GSa/s
24.0 kpts
2.60 GHz
Auto
755.0 mV
Time Meas
Vertical Meas
6.50 V
5.50 V
4.50 V
3.50 V
2.50 V
1.50 V
500 mV
-500 mV
-1.50 V
-750 ns
-600 ns
-450 ns
-300 ns
-150 ns
0.0 s
150 ns
300 ns
450 ns
600 ns
750 ns
Frequency Domain
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
dBm
1.0000 MHz
10.000 MHz
100.00 MHz
1.0000 GHz
Results
Measurements
Measurement
Current
Mean
Min
Max
Range (Max-Min)
Std Dev
Count
1 Fall time(1)
553.72 ps
? 7.9052894 ns
? 39.59 ps
? 1.13213258 µs
? 1.13209299 µs
? 15.5009365 n
173156
2 Rise time(1)
680.29 ps
? 8.6296530 ns
? 46.46 ps
? 984.49662 ns
? 984.45016 ns
? 16.0982576 n
173149

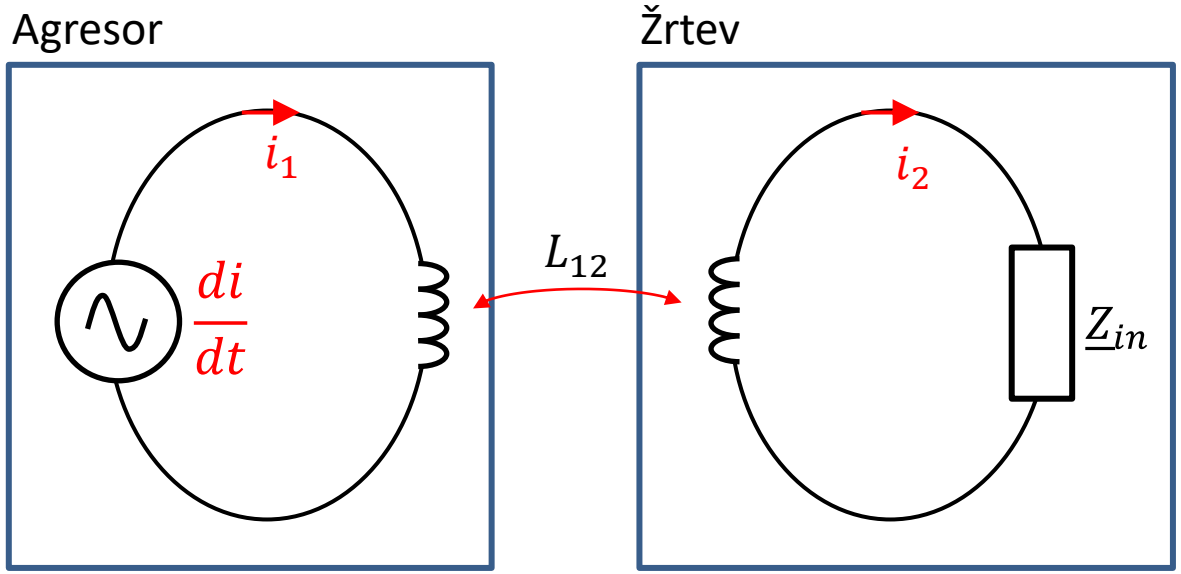
Model EMC

Sevalni prenos motenj

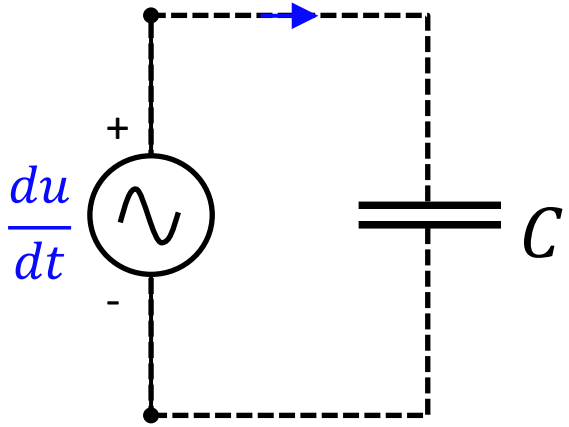
Kapacitivni

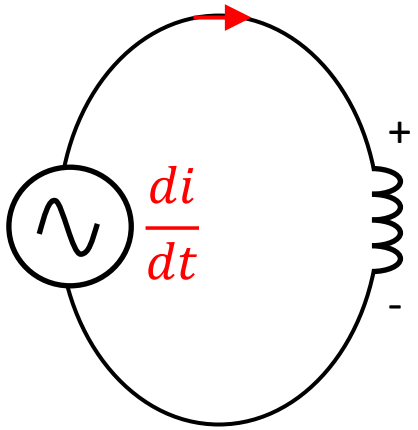


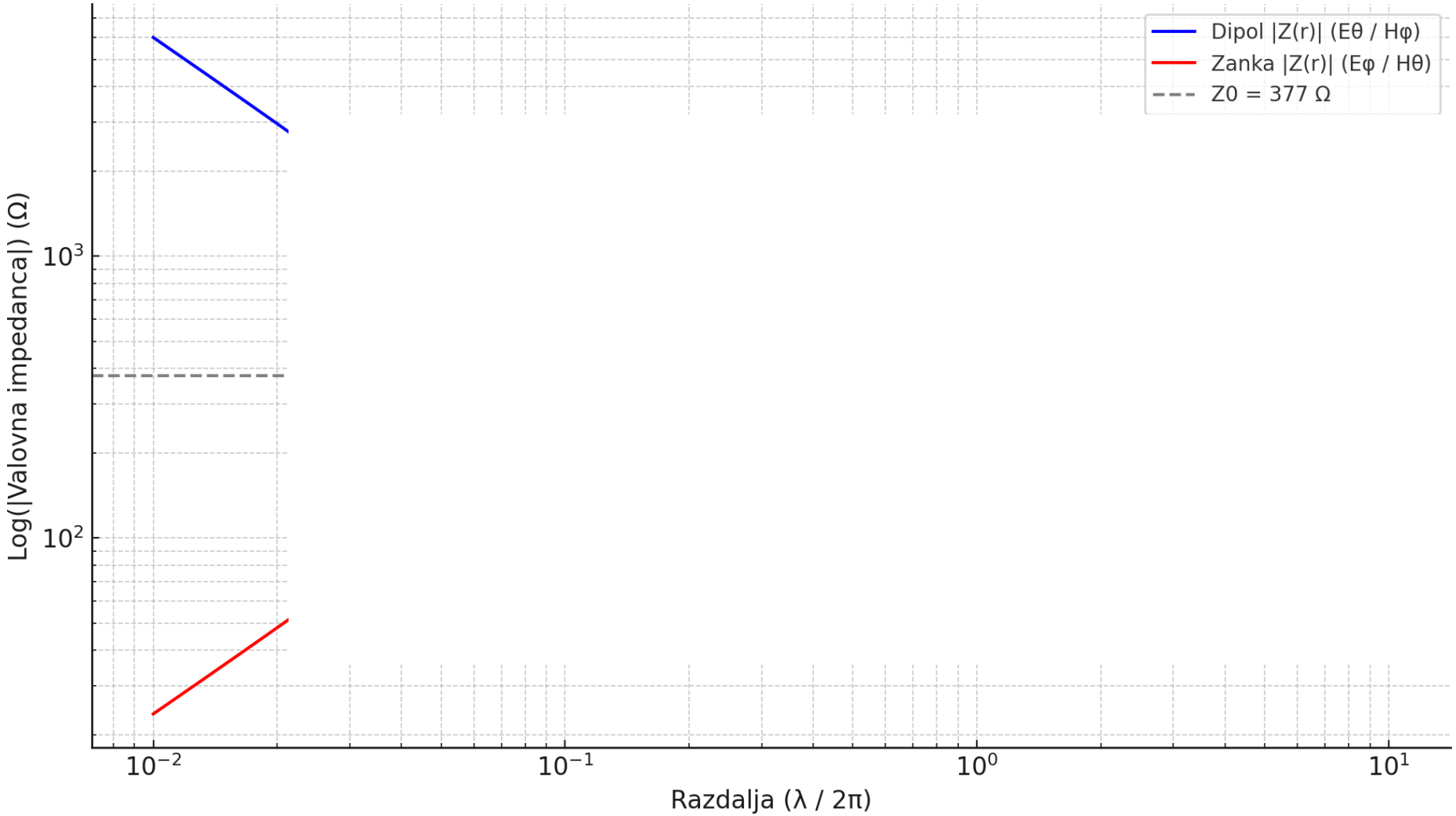
Induktivni

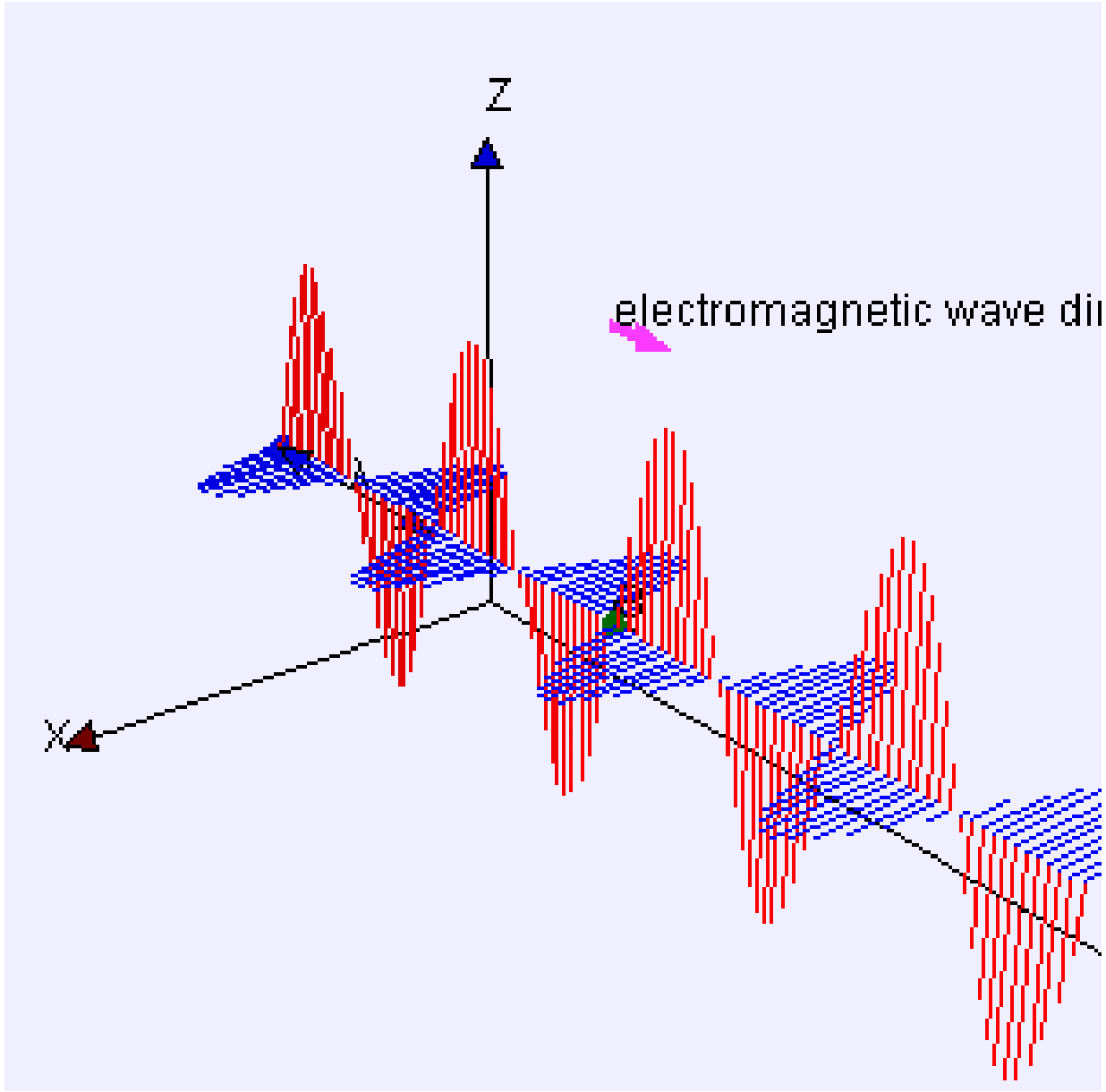


Bližnje in daljne EM polje

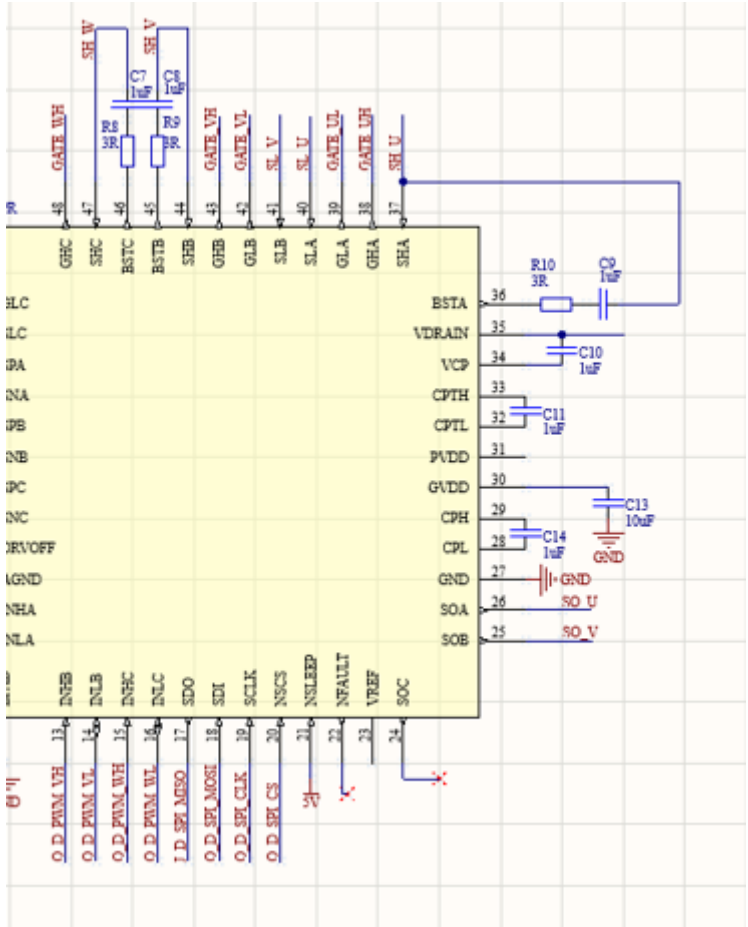


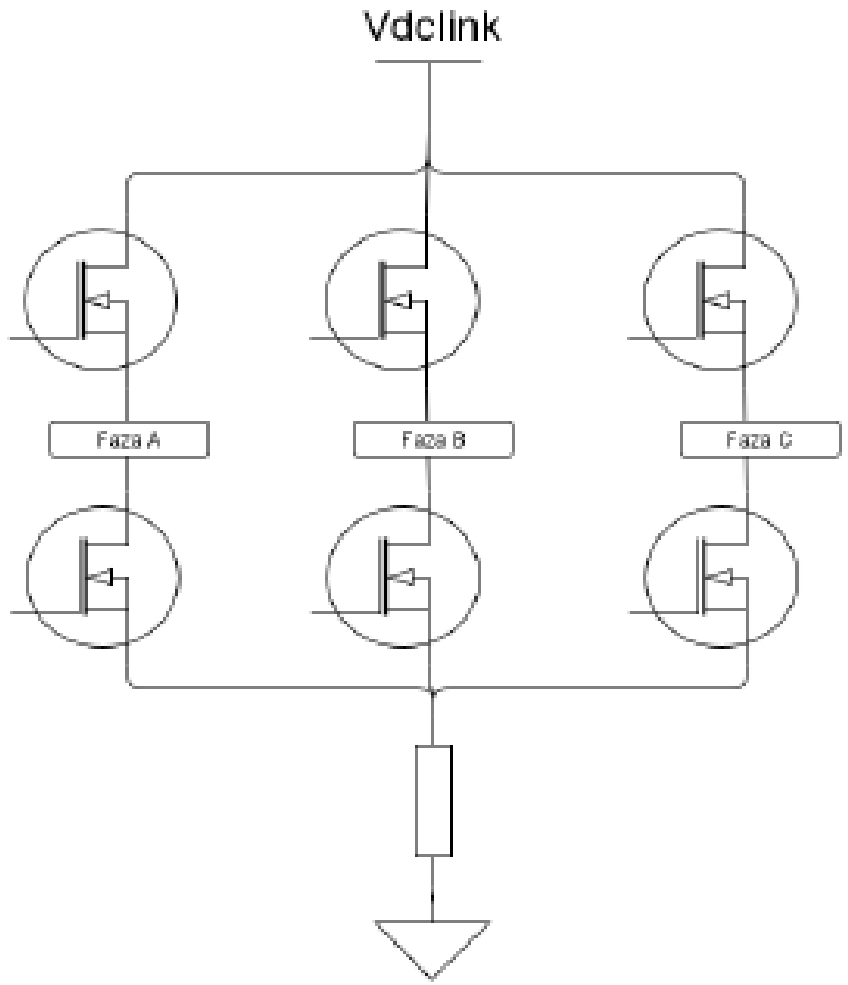





Z
electromagnetic wave di
X

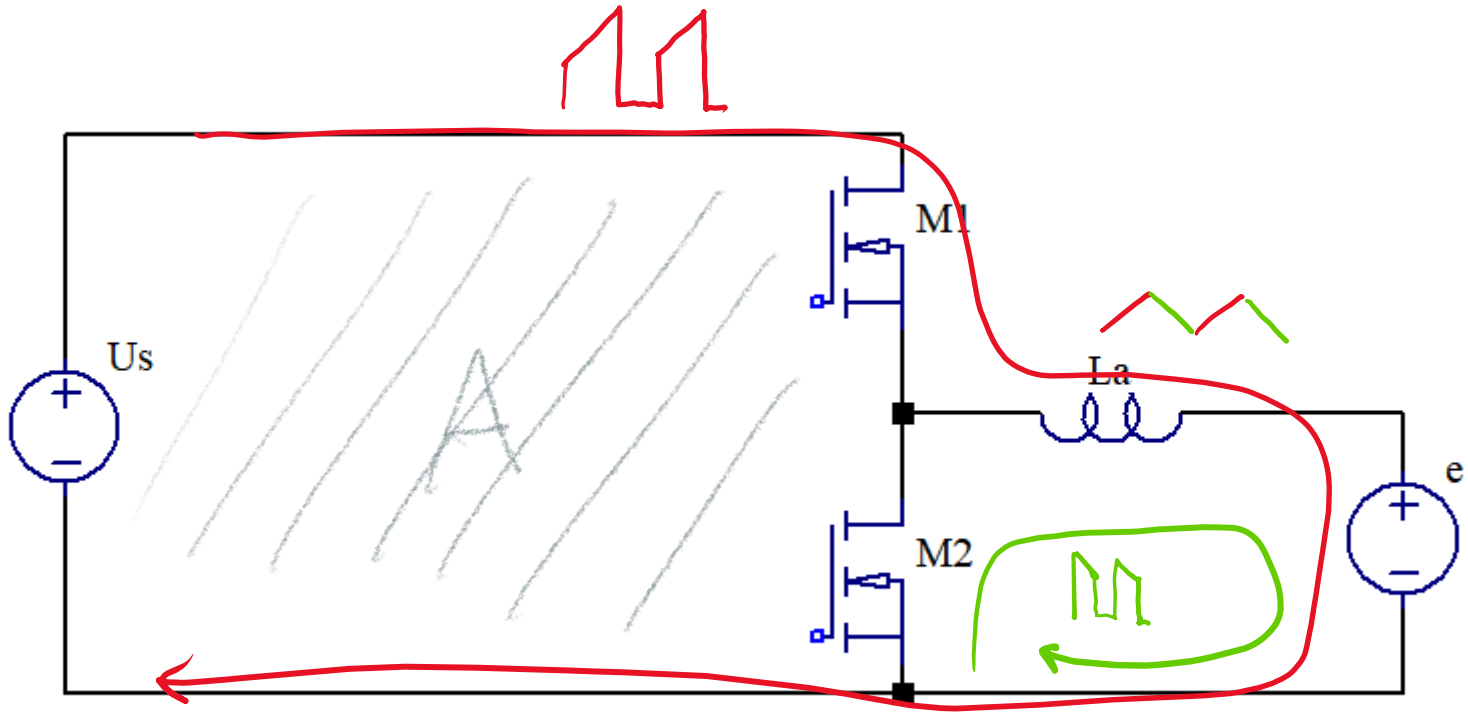
Izhodna stopnja razsmernika za BLAC motor





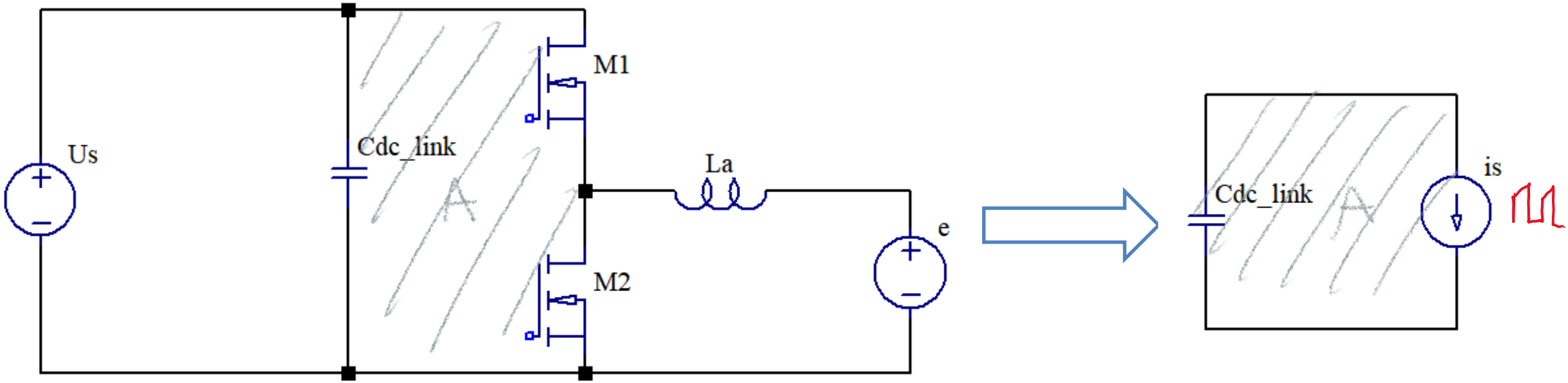
Primer 1/3 izhodne stopnje razsmernika

- Katera zanka je najbolj kritična?



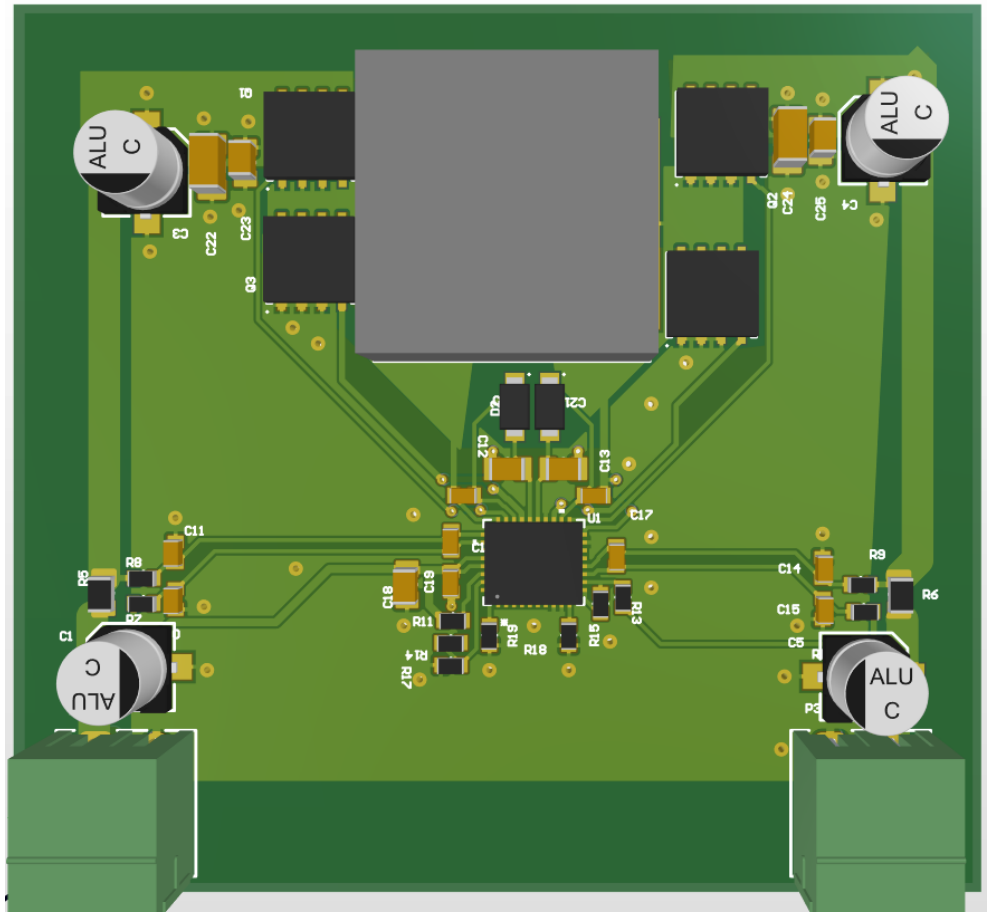
Primer 1/3 izhodne stopnje razsmernika

Kaj določa velikost kritične zanke?

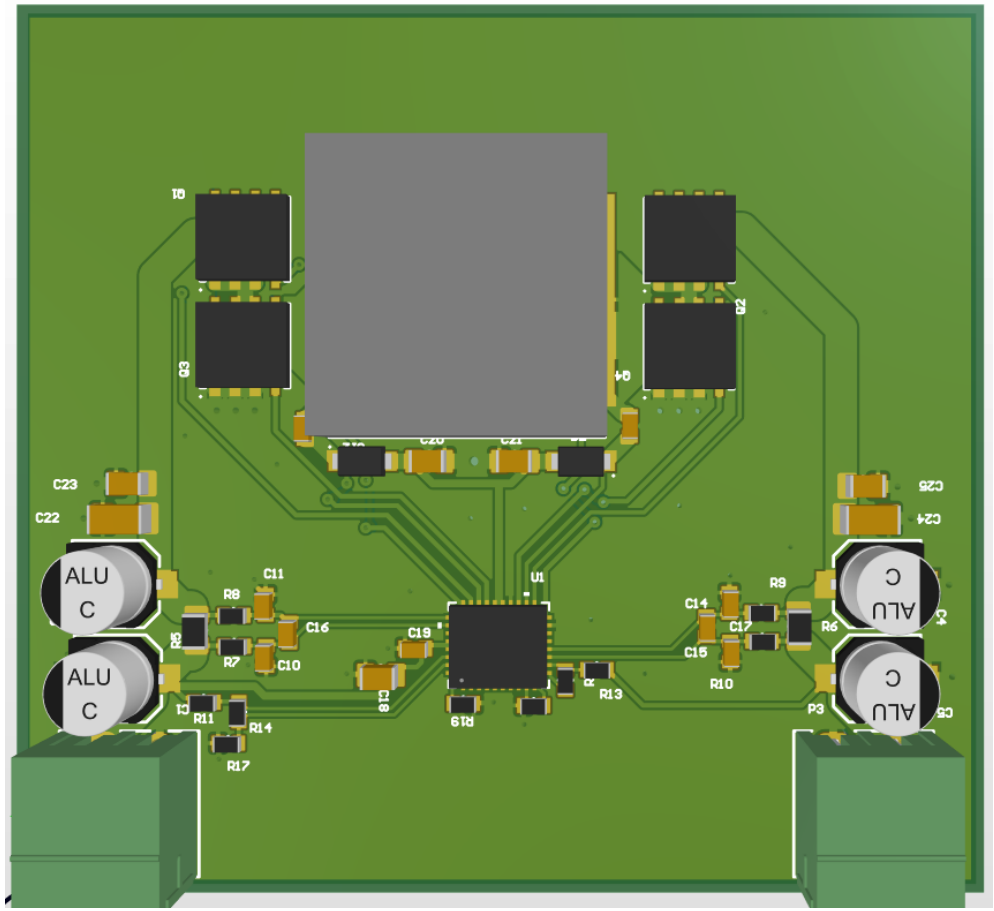


Velikost zanke

Dobro

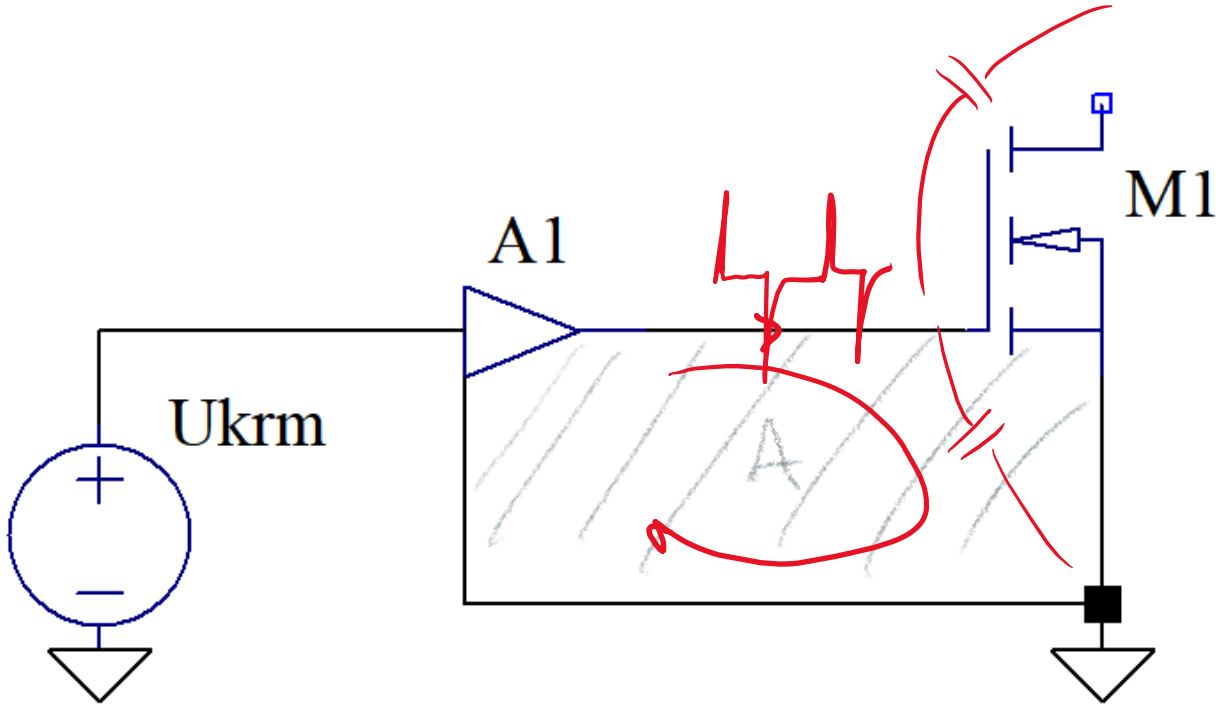


Slabo

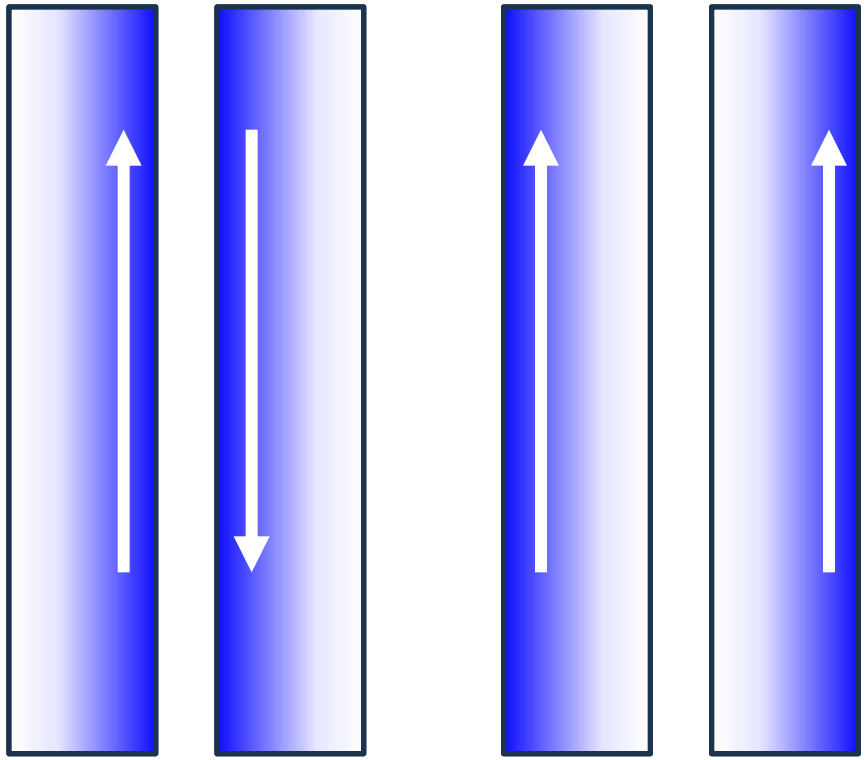


Primer 1/3 izhodne stopnje razsmernika

Kaj pa krmiljenje MOS?



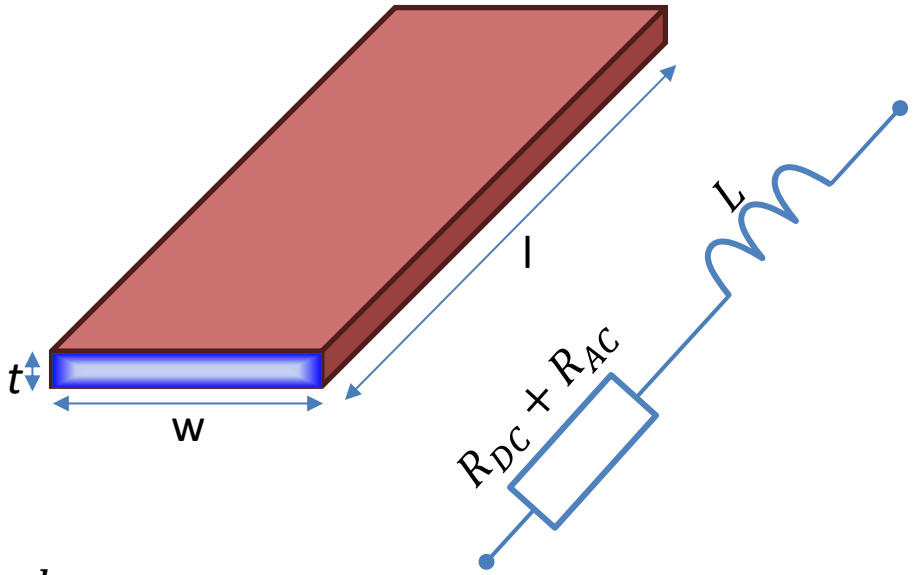
Pojav bližine in kožni pojav

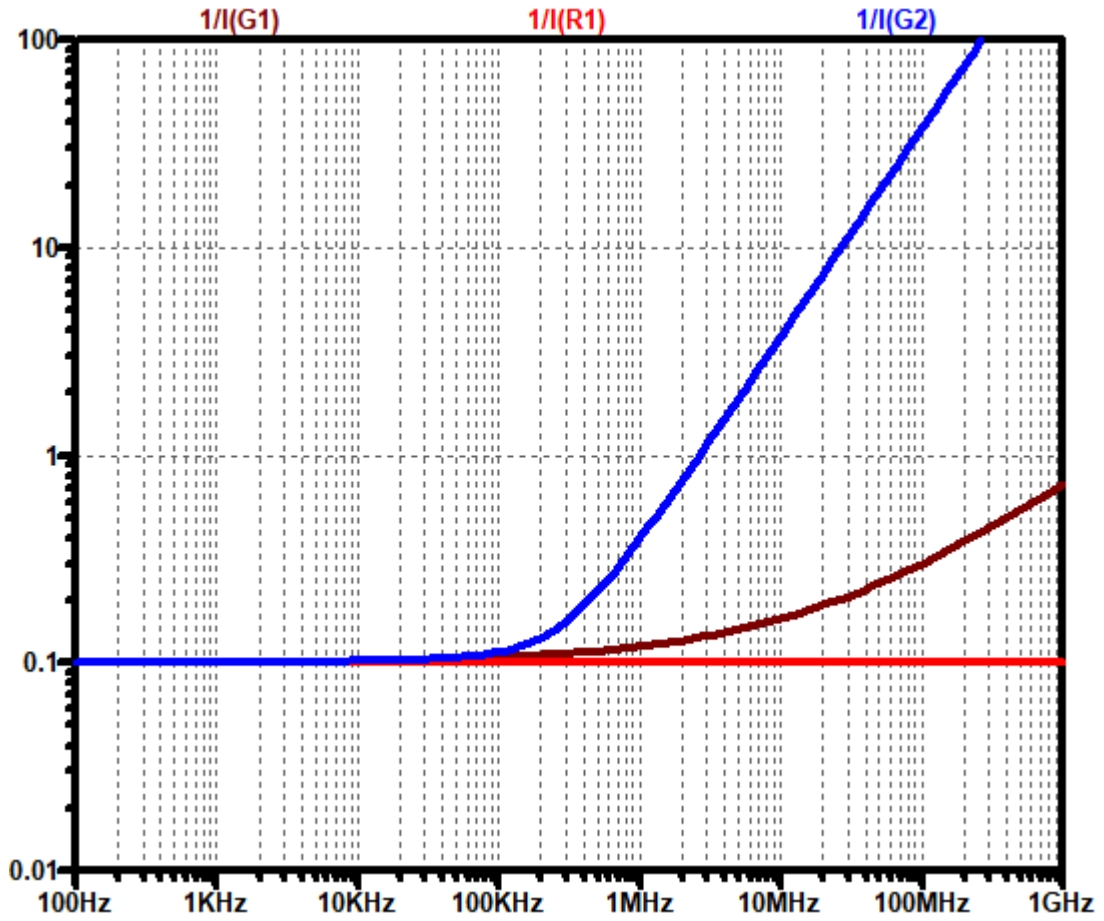


$$\delta = \sqrt{\frac{\rho}{\pi f \mu_r \mu_0}}$$

	ρ [$\Omega \frac{mm^2}{m}$]	μ_r	δ [mm]	μ_r	δ [µm]	μ_r	δ [µm]
frekvenca		**50 Hz**		**1 MHz**		**100 MHz**	
Baker	0,0172	1	9,3	1	66	1	7

Lastnosti povezav



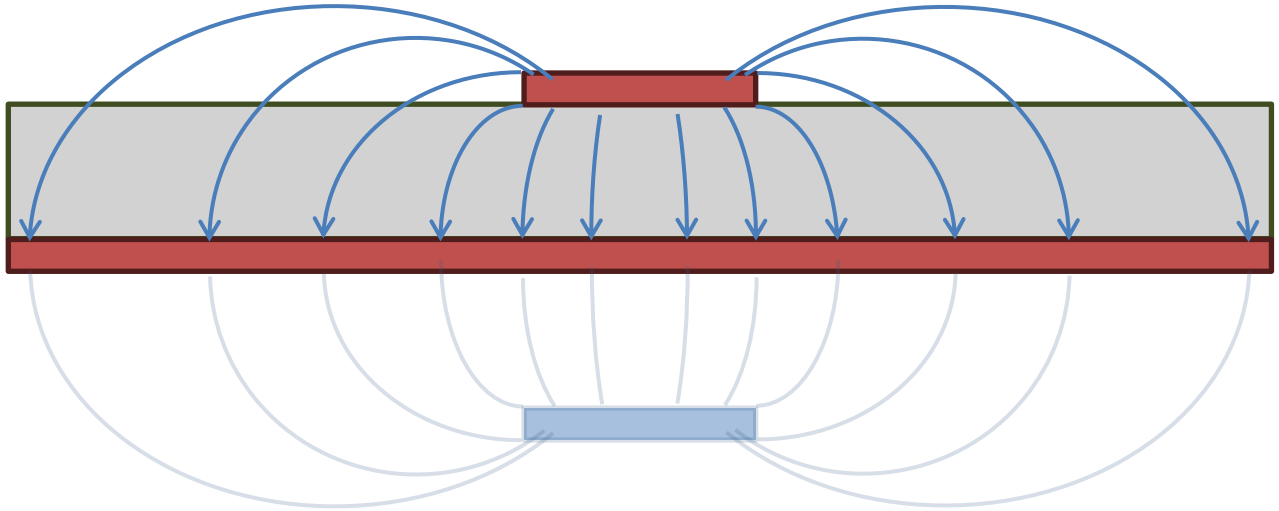


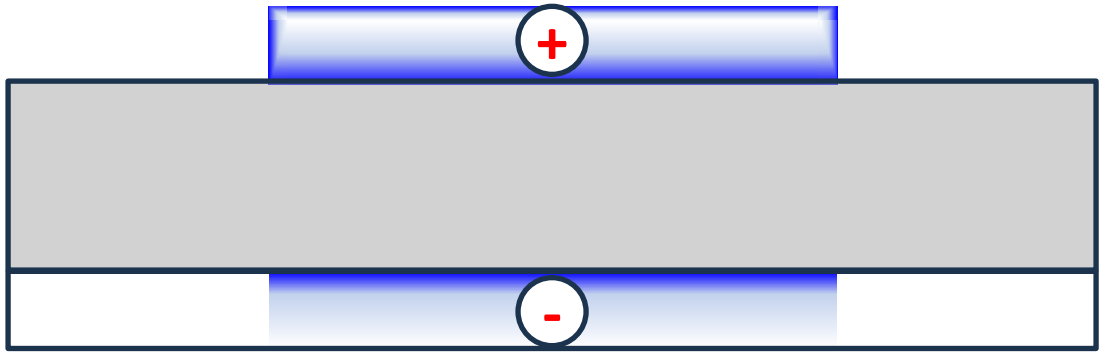
$$R_{DC} = \frac{\rho \cdot l}{w \cdot t}$$

$$\delta = \sqrt{\frac{\rho}{\pi f \mu_r \mu_0}} \qquad R_{AC} = \frac{\rho \cdot l}{2(w+t)\delta}$$

$$L = 0{,}0051 \cdot l \cdot \ln\left(4 \cdot \frac{l}{w} - 0{,}75\right)\ \mu\text{H}$$

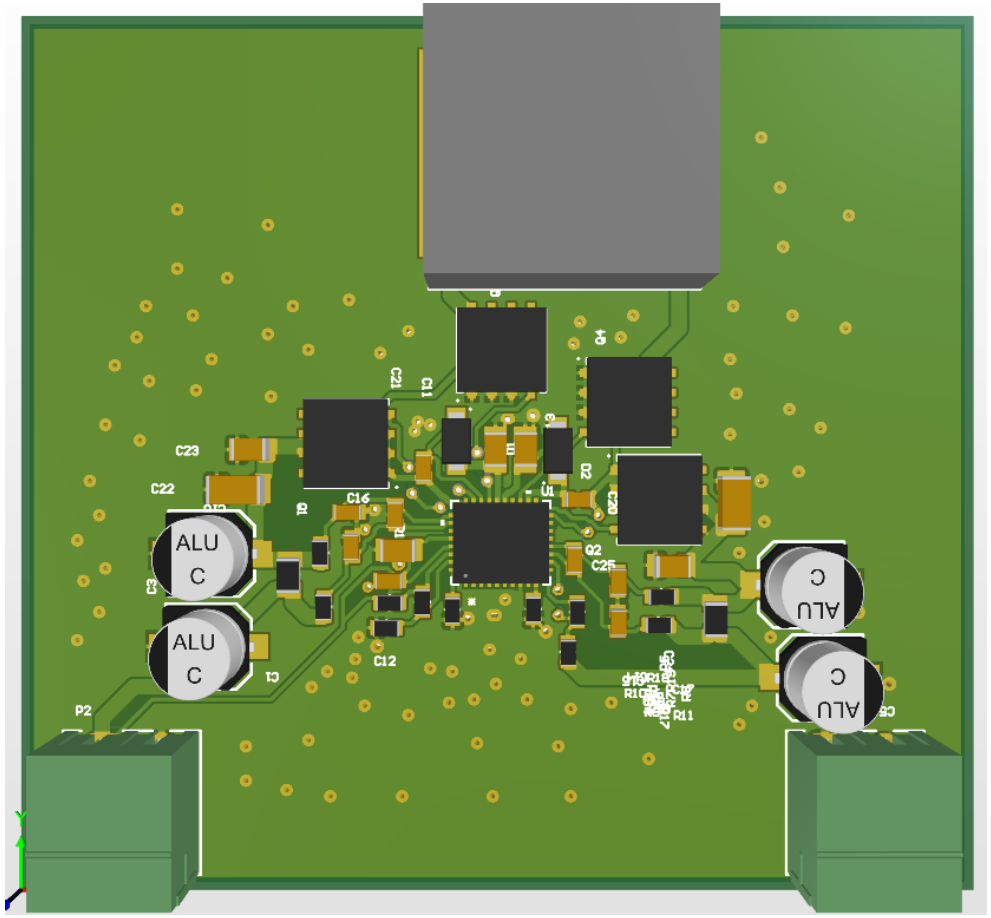
Zrcalna ravnina (Ground plane)



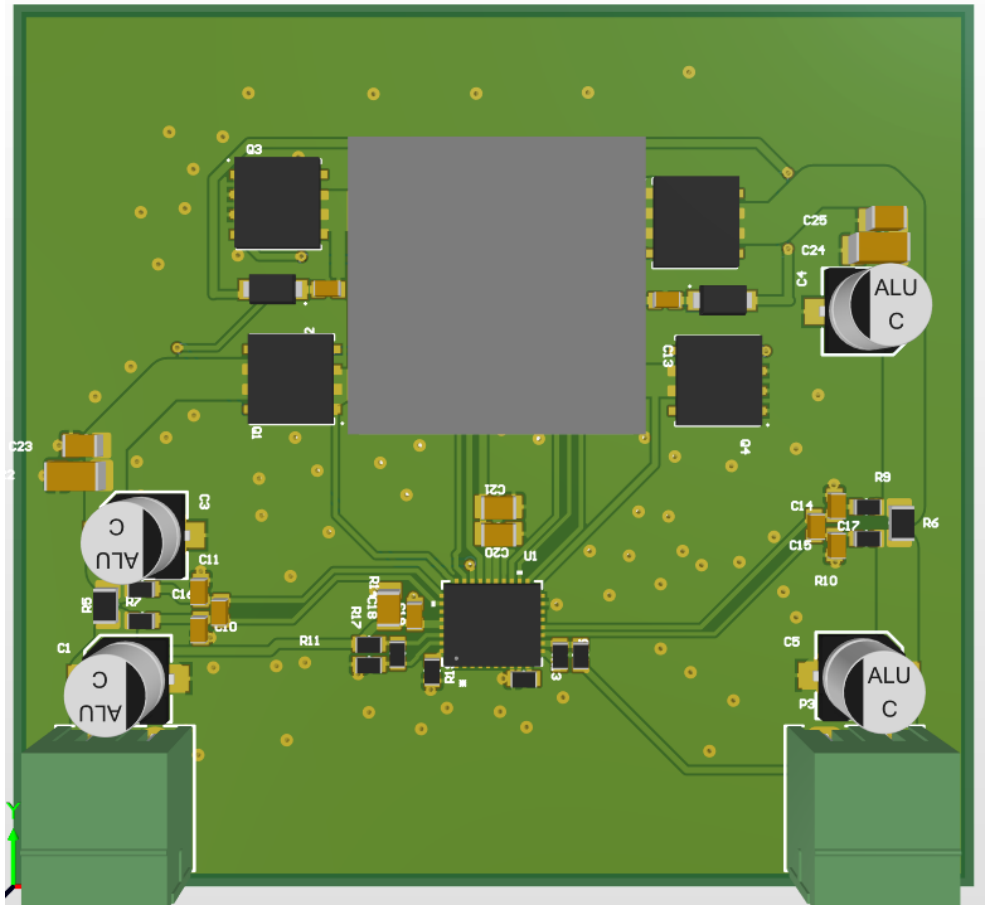


Krmilna zanka

Dobro

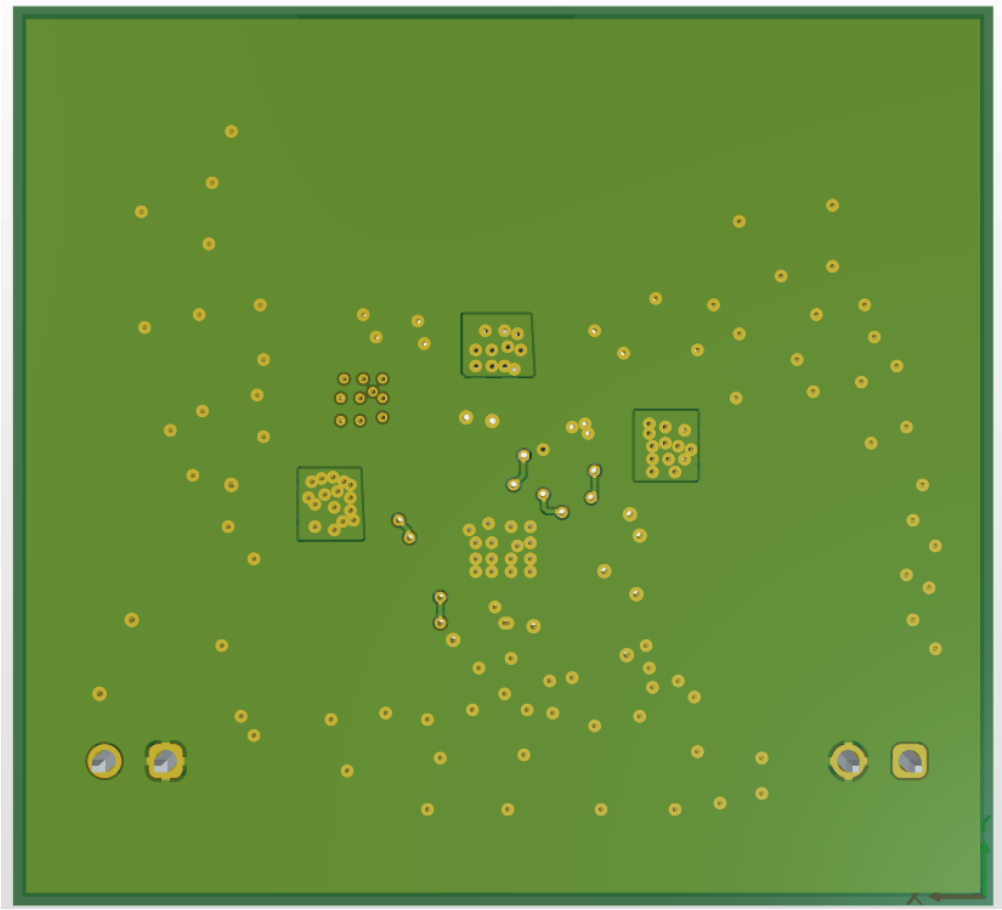


Slabo

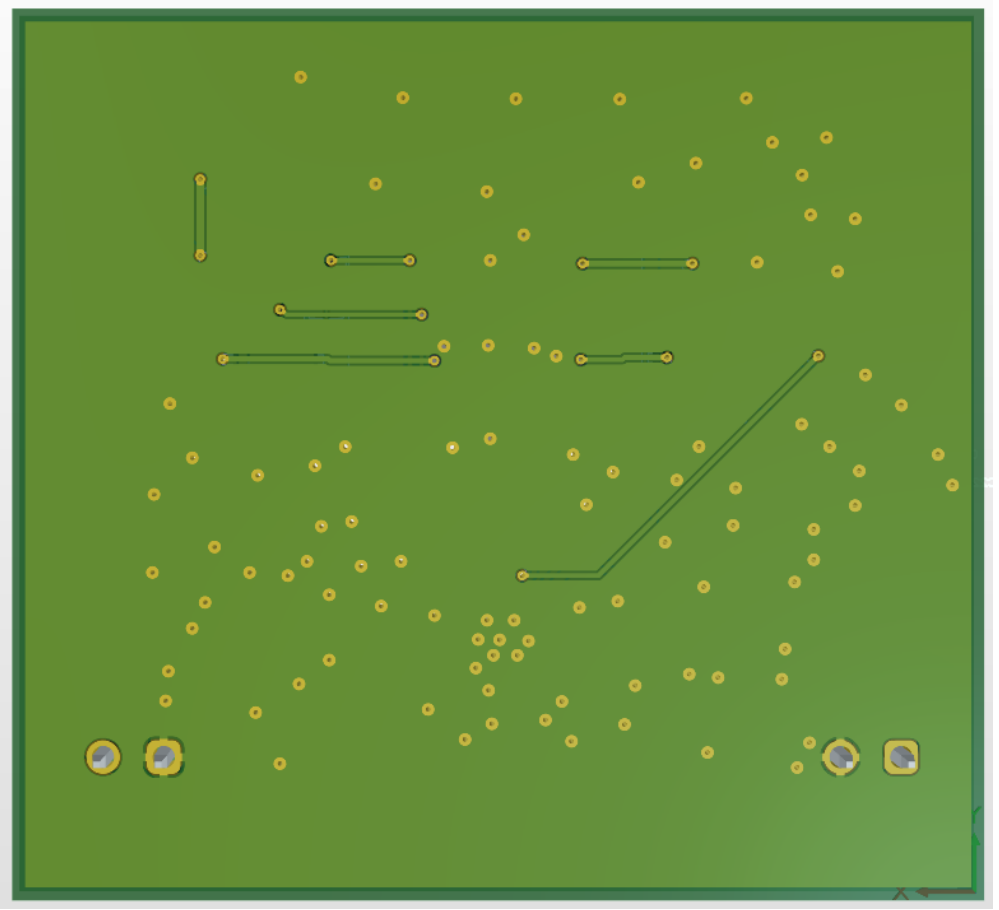


Krmilna zanka

Dobro

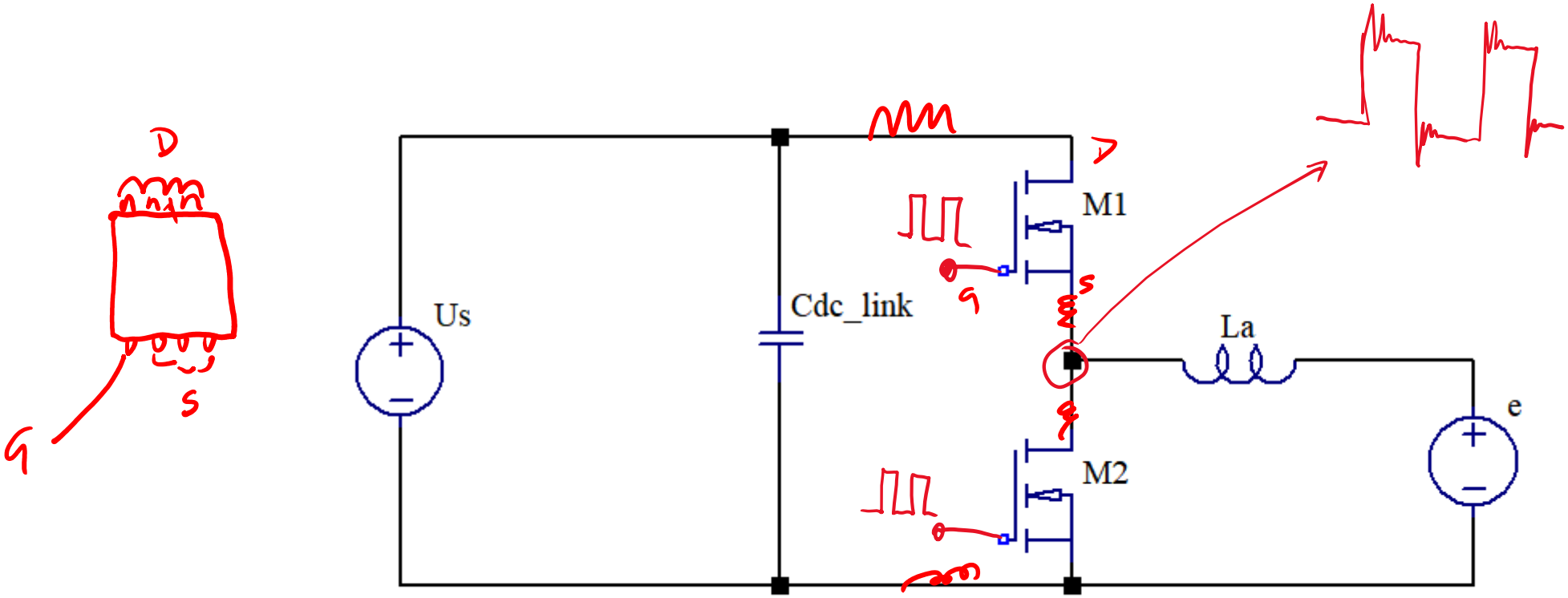


Slabo



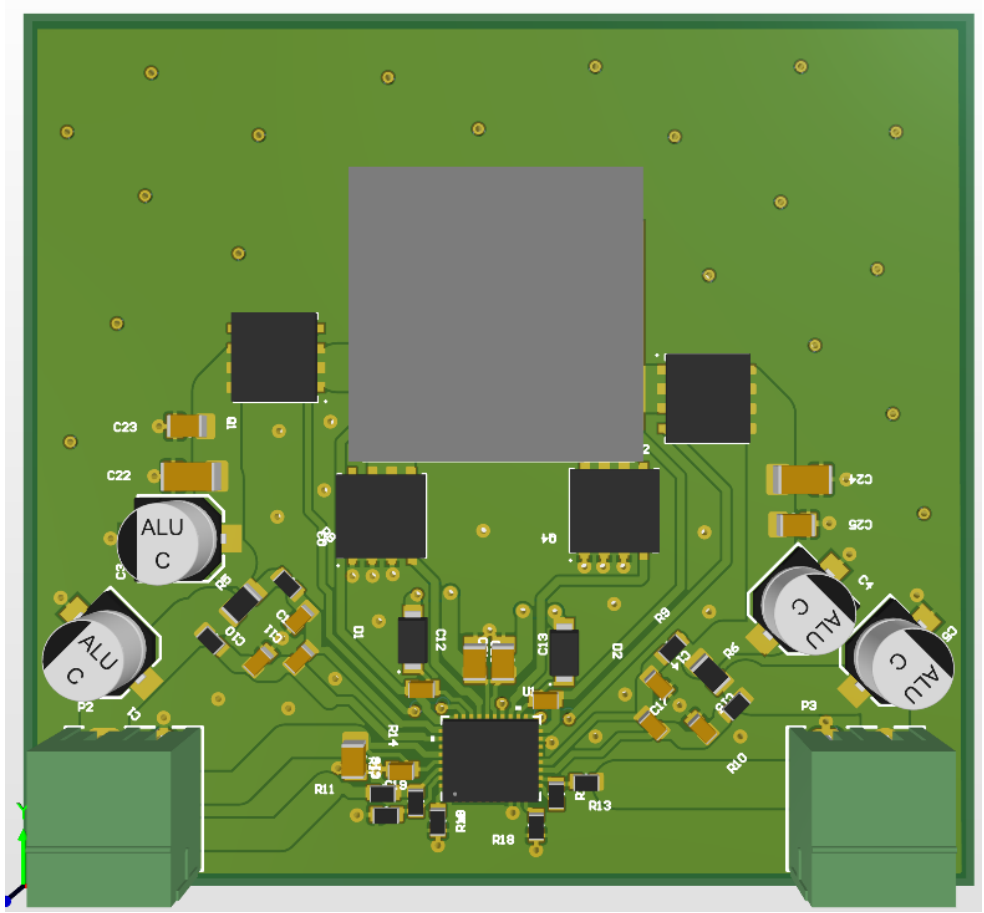
Primer 1/3 izhodne stopnje razsmernika

Kritična napetostna nihanja

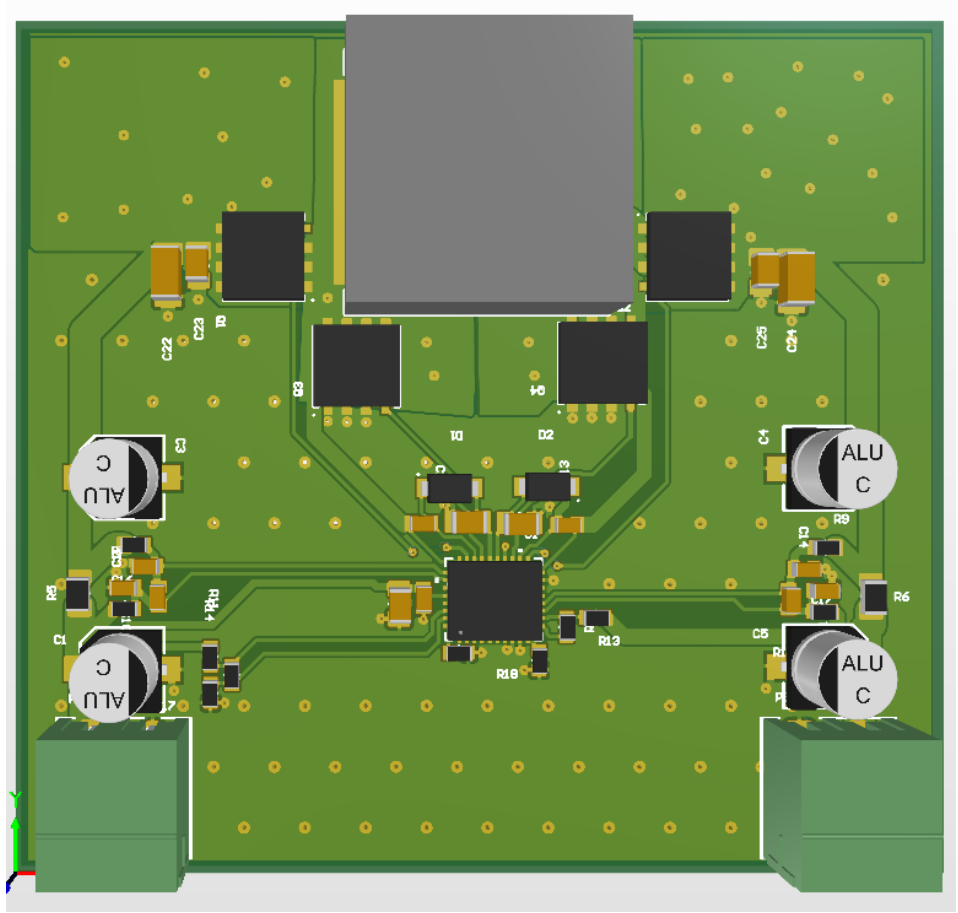


Velikost in pozicija stikalnih vozlišč

dobro

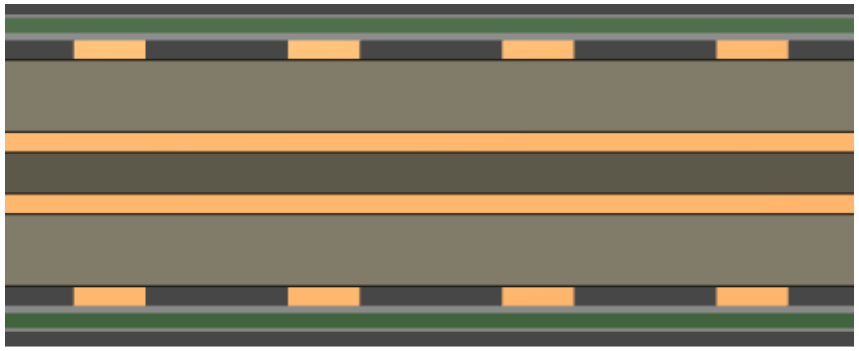


slabo

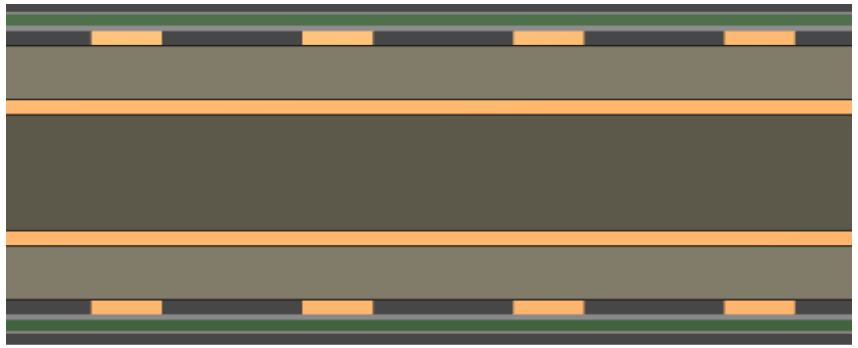


Štiriplastno vezje

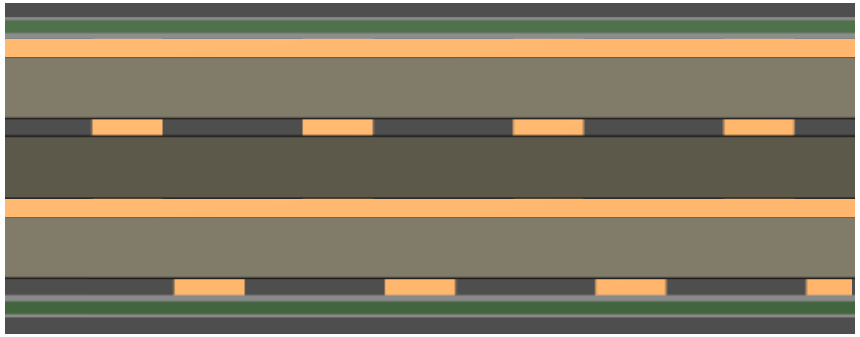
Kvaliteta napajanja pri visokih f



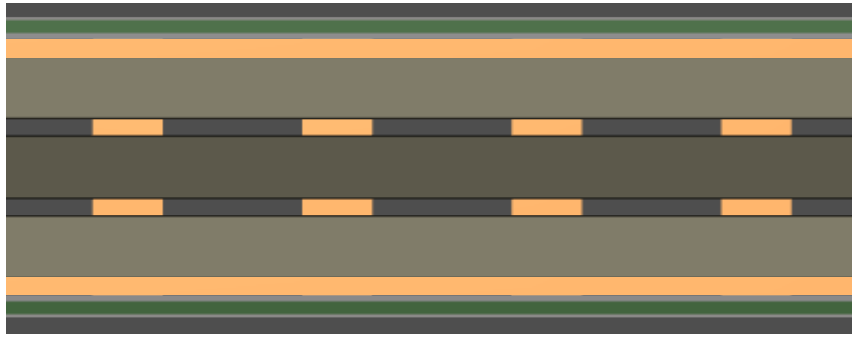
Povratni tokovi hitrih signalov po masi



Zmanjševanje presluha med signali



Prenos motenj napajanja na linije / preprečevanja sevanja linij



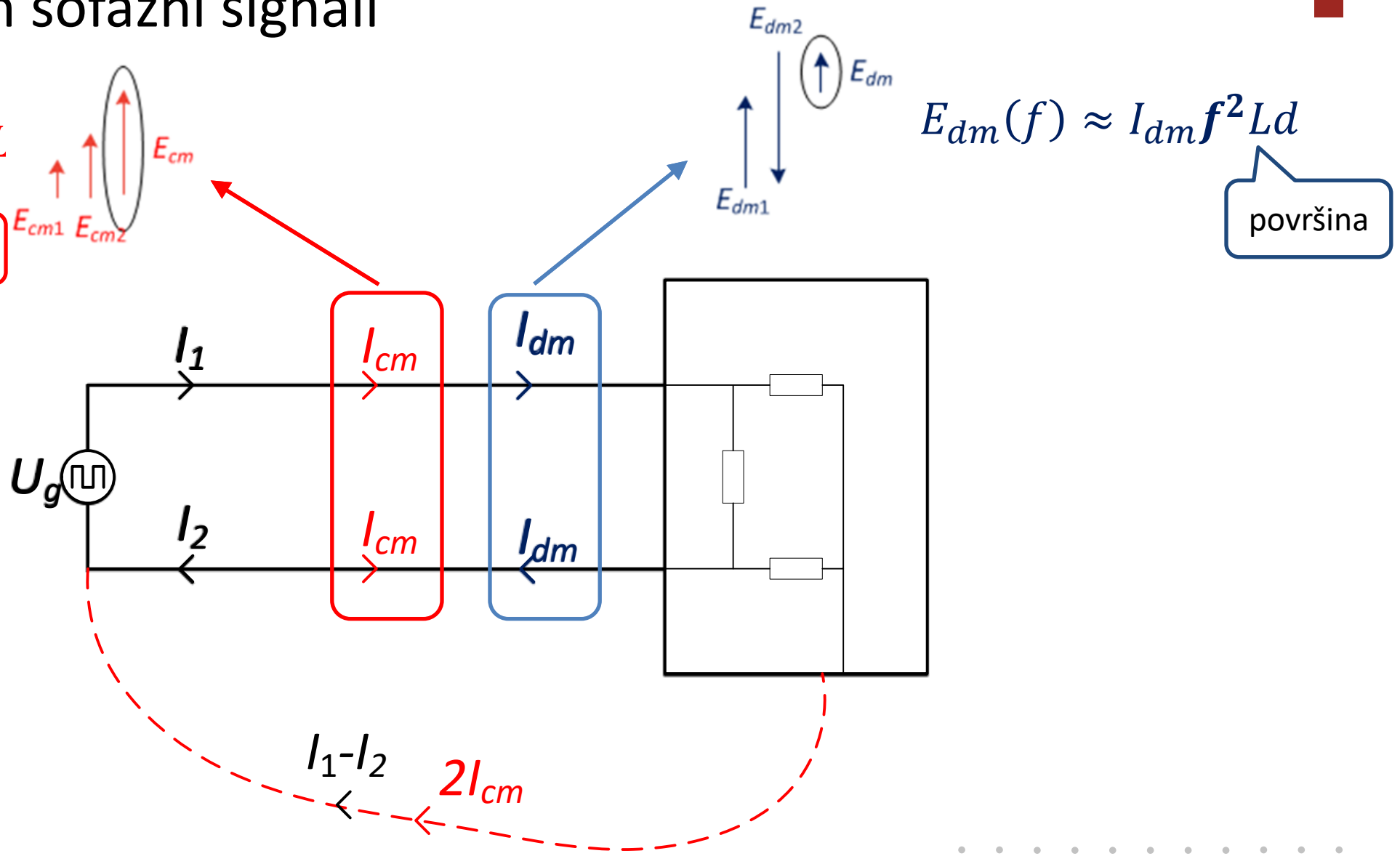
Diferencialni in sofazni signali

$$E_{cm}(f) \approx I_{cm}(f) \boldsymbol{f} L$$

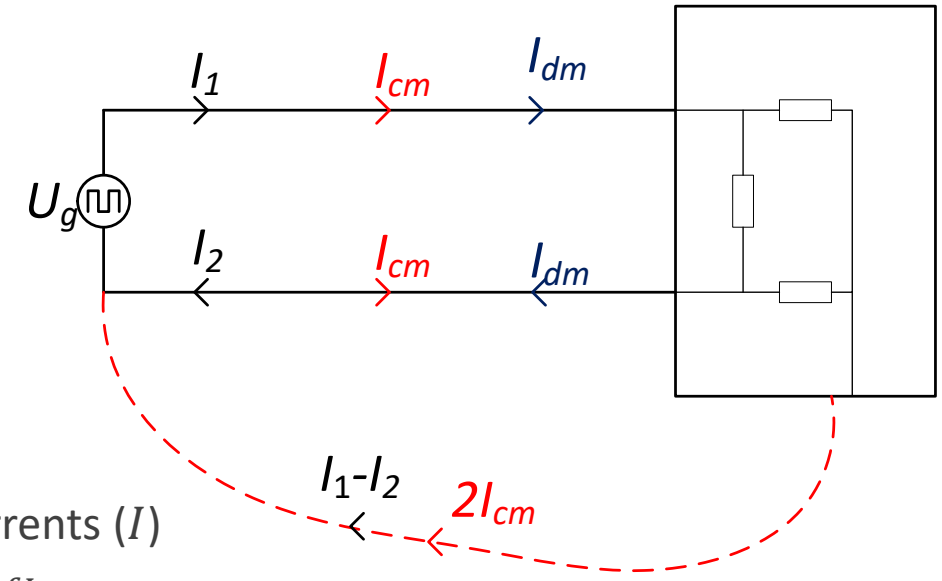
dolžina

$$E_{dm}(f) \approx I_{dm} \boldsymbol{f^2} L d$$

površina



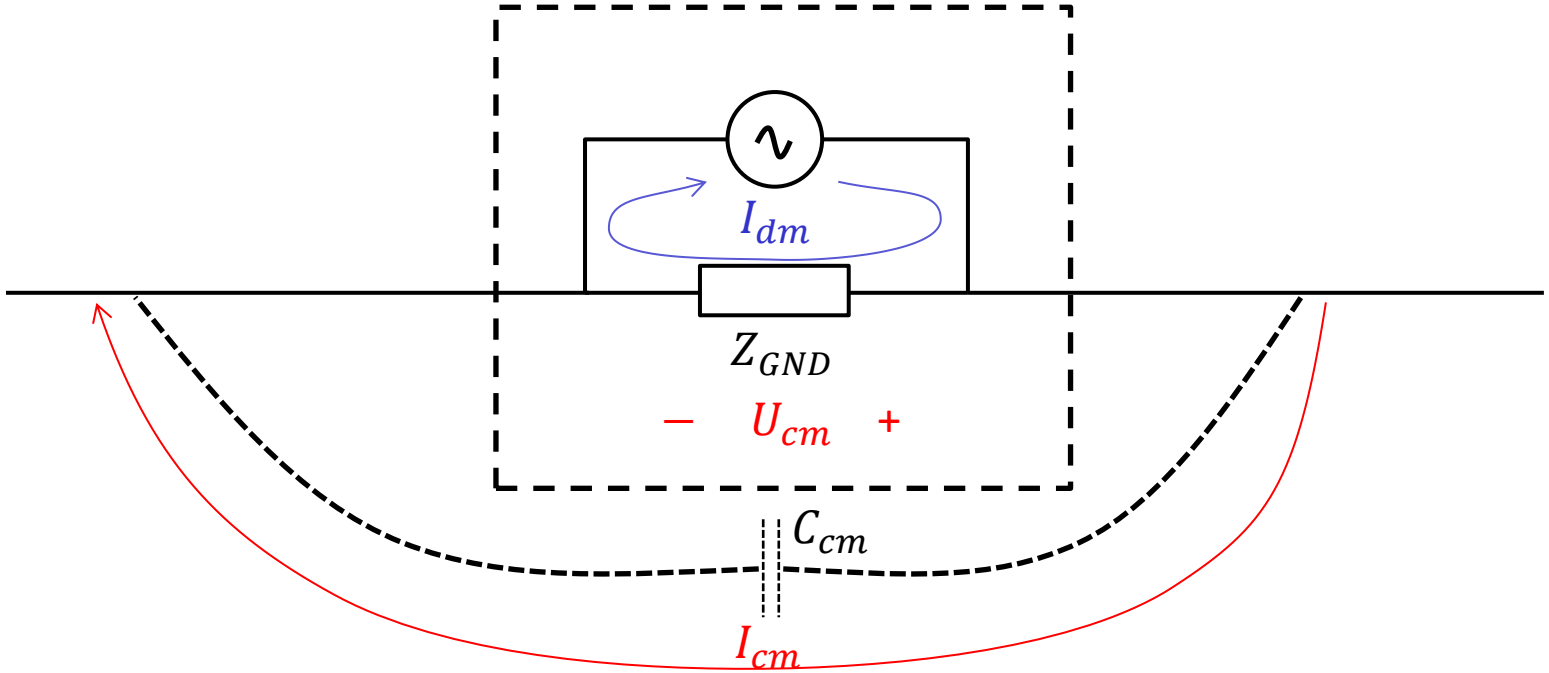
Diferencialni in sofazni signali



- Signali na kablih
  - Long antennas (L)
  - Common mode currents (I)
  - $E_{cm} = \pi \cdot 10^{-7} \frac{I_{cm} f L}{R}$
- $I = 0.8\ \mu\text{A}, f = 100\ \text{MHz}, L = 1\ \text{m}$
- $E = 26 \frac{\mu\text{V}}{\text{m}} @\ 1\ \text{m}$

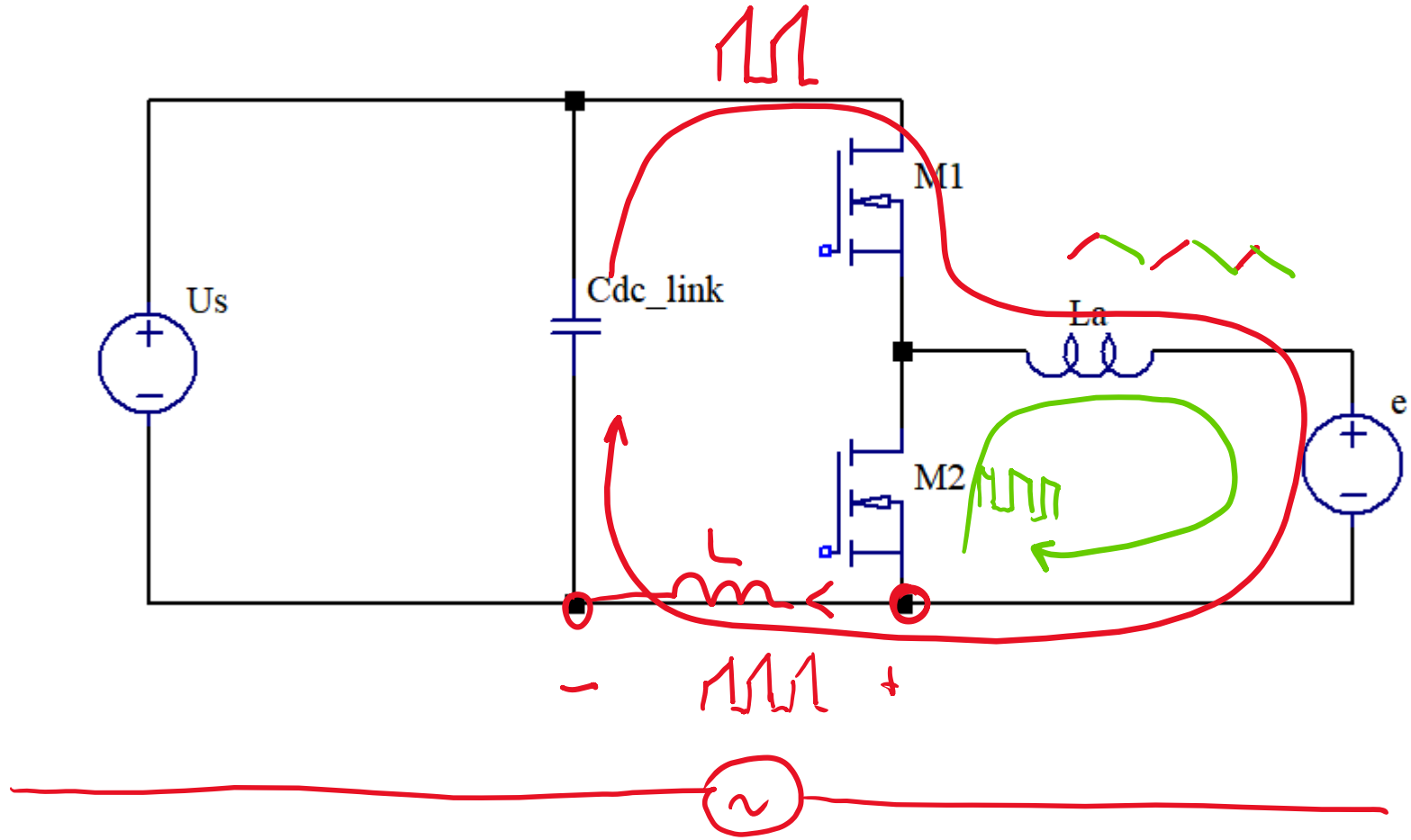
- Signali na tiskanem vezju
  - Current loop area (A)
  - Diferential currents(I)
  - $E_{dm} = 2{,}63 \cdot 10^{-14} \frac{I_{dm} A f^2}{R}$
- $I = 1\ \text{mA}, f = 100\ \text{MHz}, A = 1\ \text{cm}^2$
- $E = 26 \frac{\mu\text{V}}{\text{m}} @\ 1\ \text{m}$

Tokovno generirane sofazne motnje



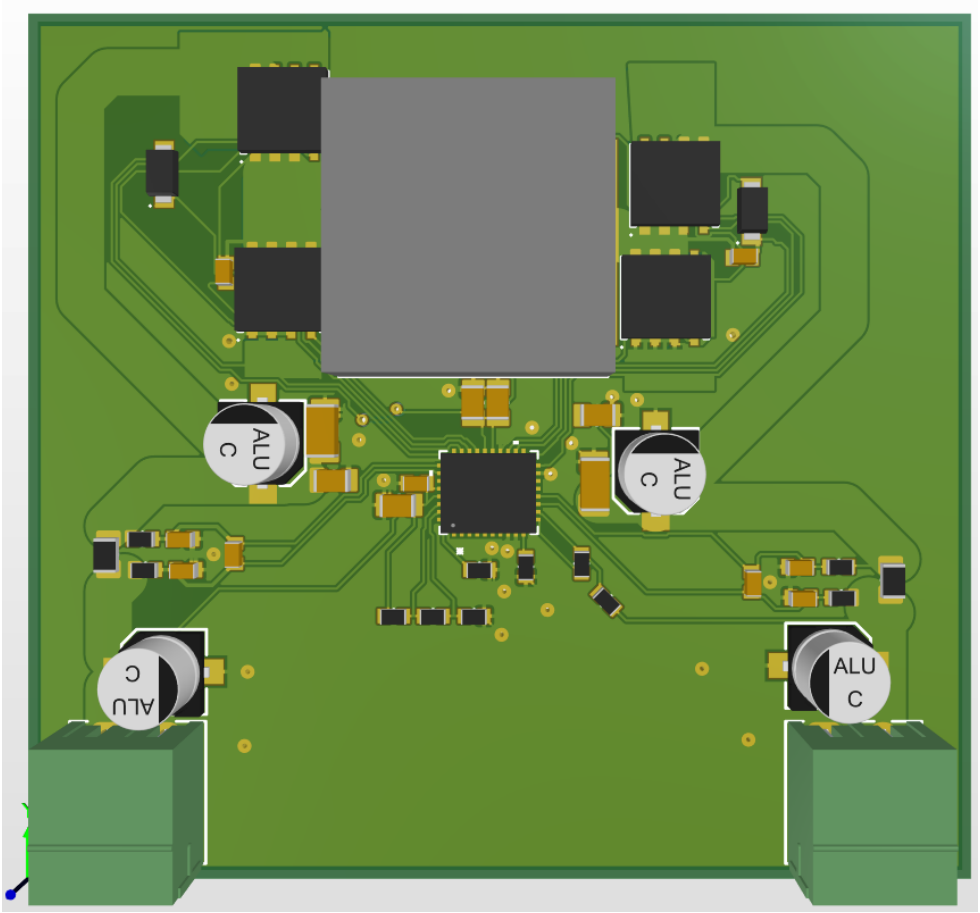
Primer 1/3 izhodne stopnje razsmernika

Kje se ustvari tokovno generirana sofazna motnja?

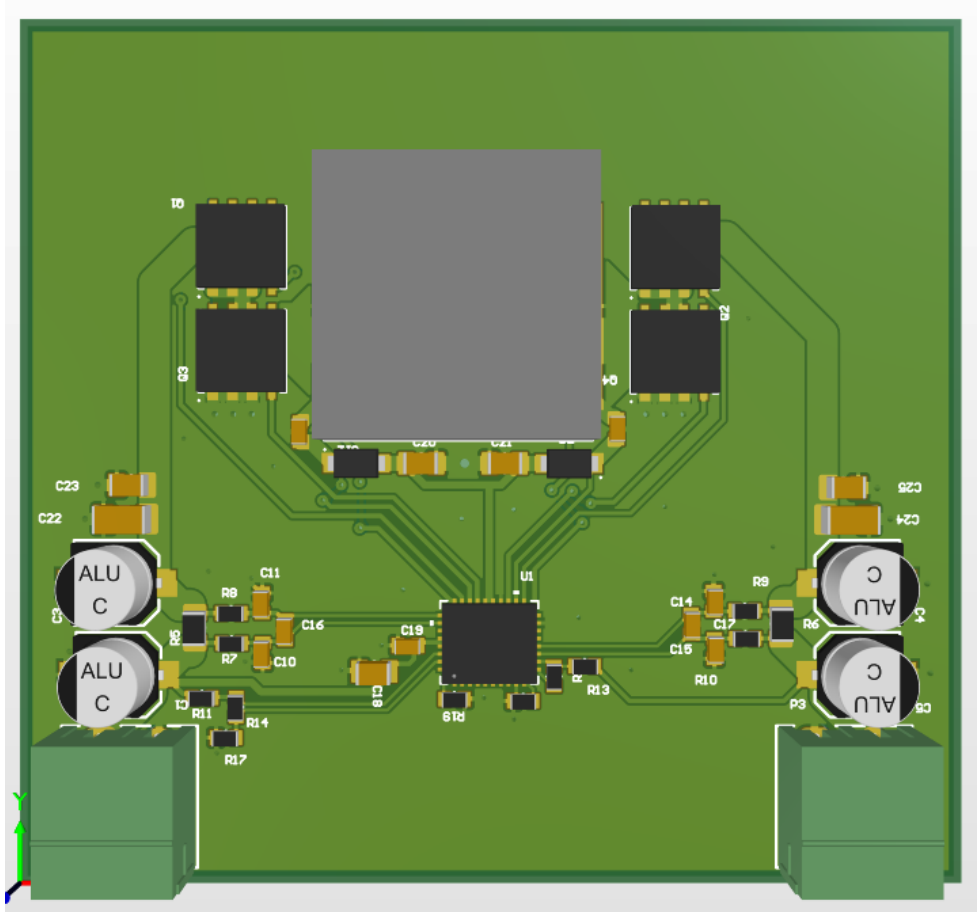


Impedanca po masi

Dobro

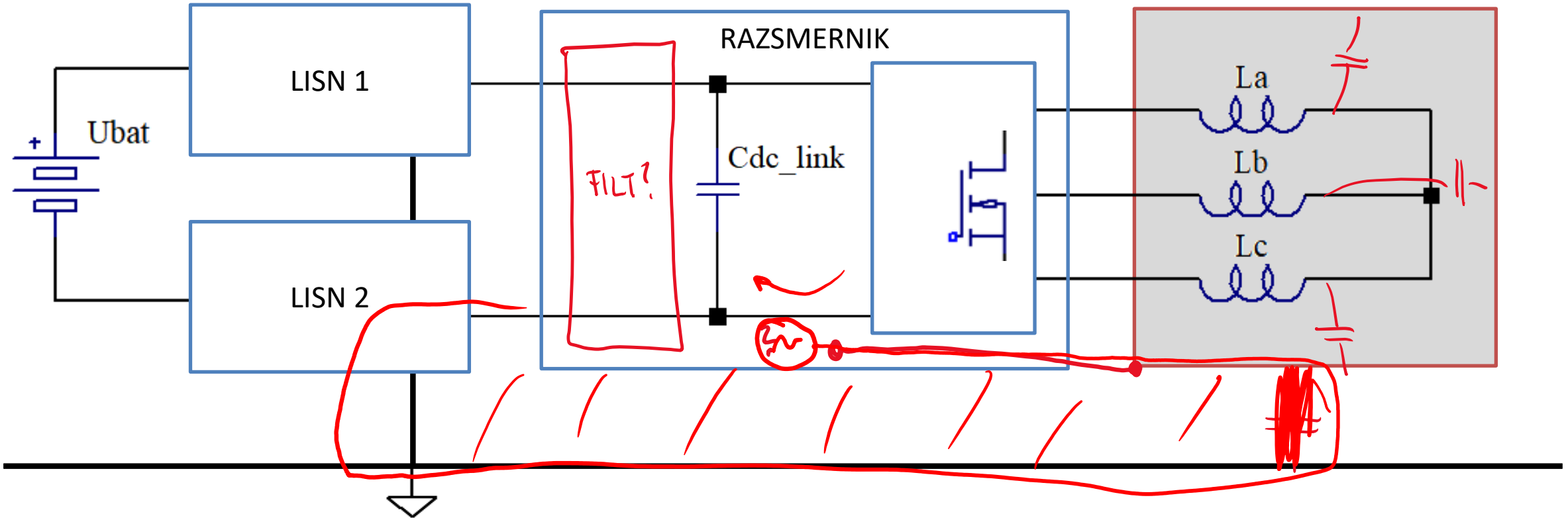


slabo

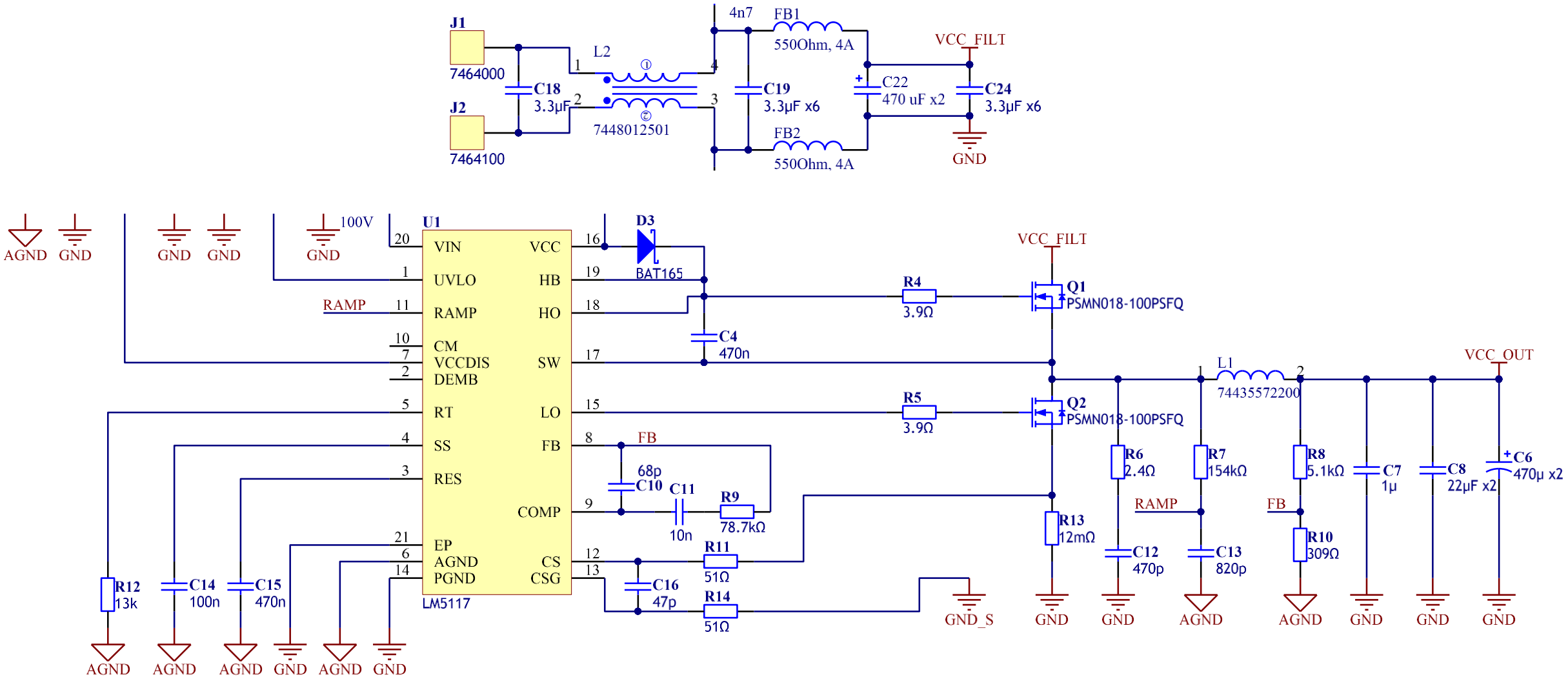


Primer celotnega sklopa

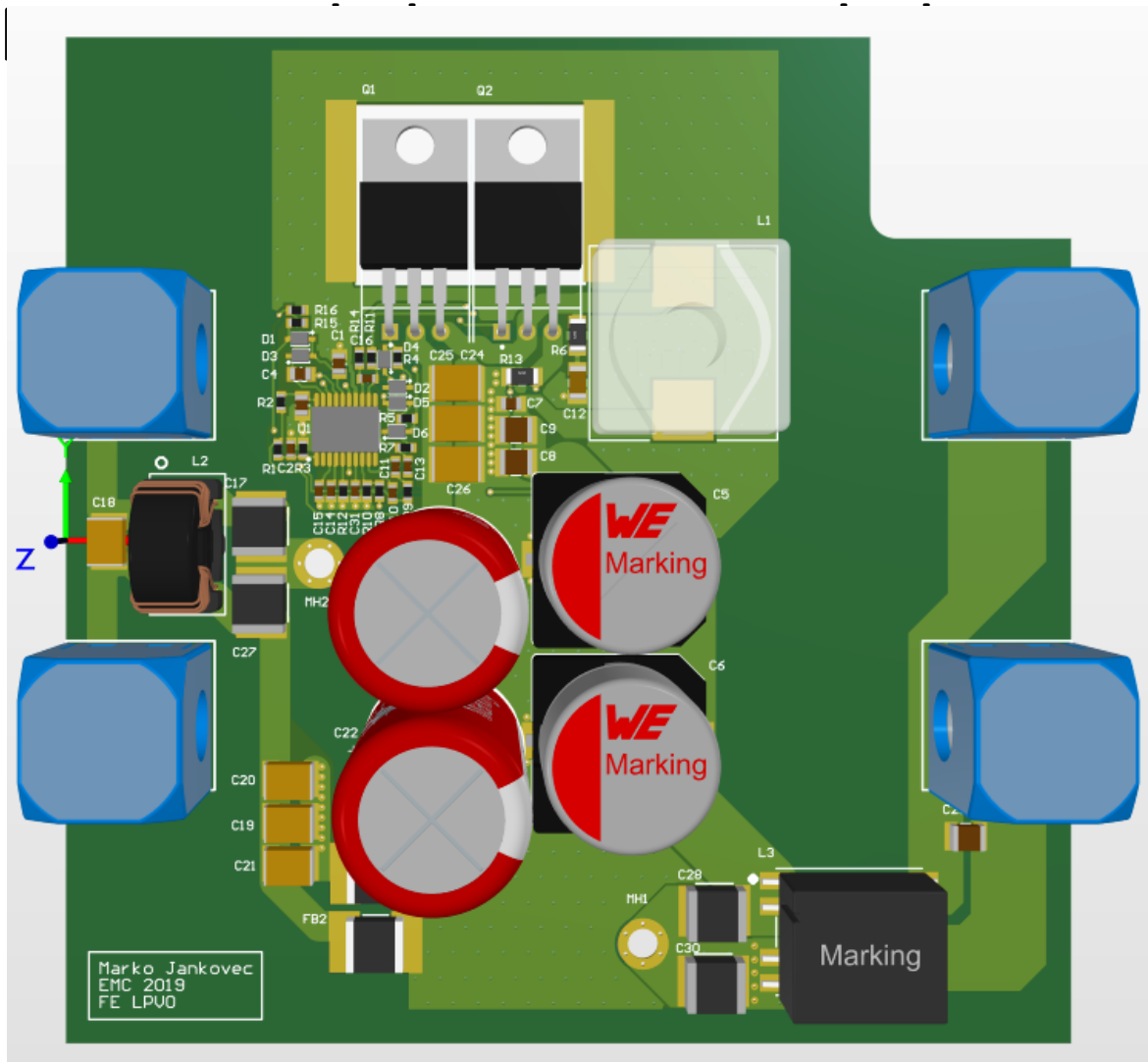
Kje se generirajo motnje?



Primer stikalnega napajalnika navzdol



zdc


Q1
Q2
L1
L2
L3
C5
C6
C17
C18
C19
C20
C21
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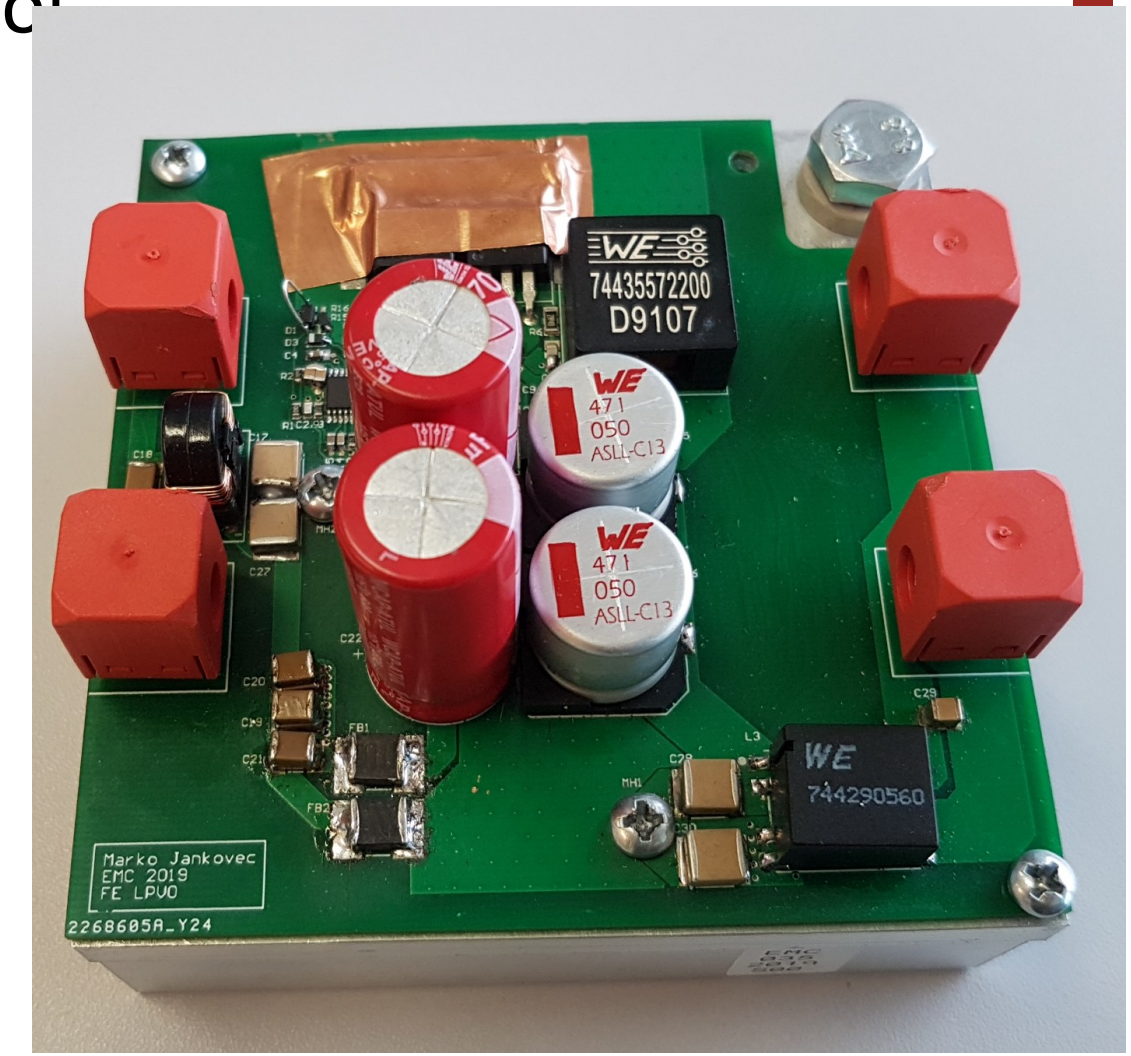
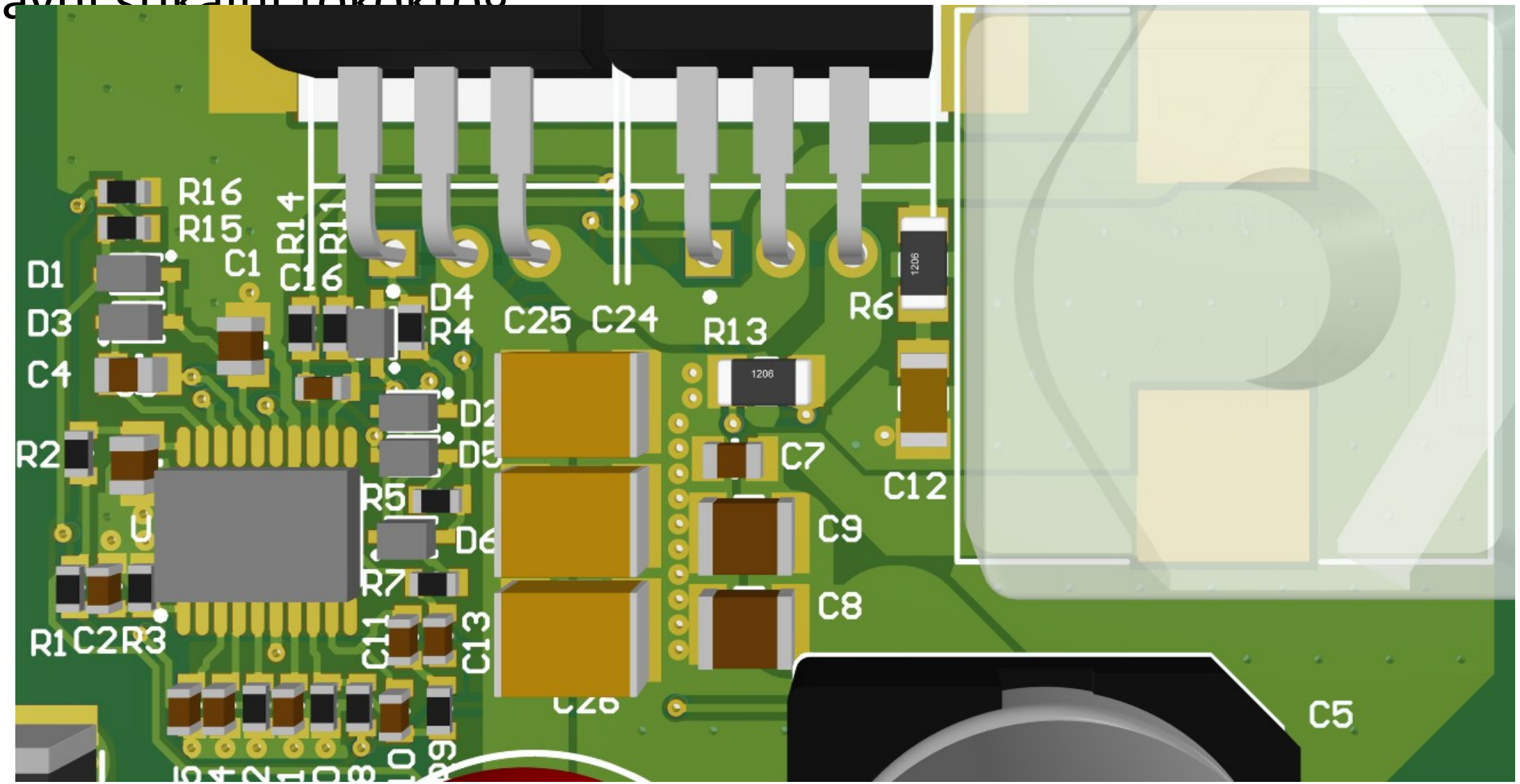
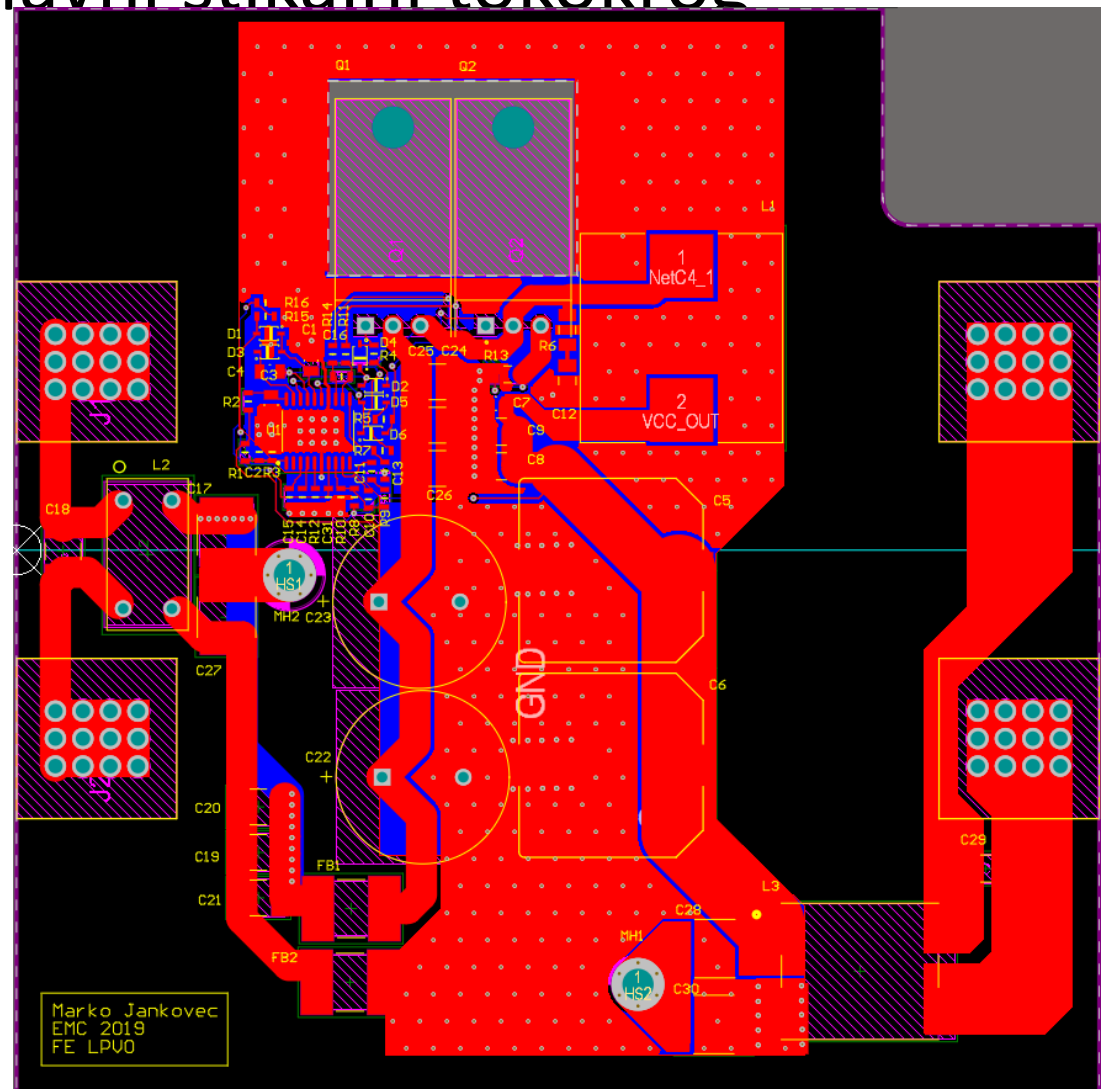
C30
MH1
MH2
FB2
Z
Marko Jankovec
EMC 2019
FE LPVO
Marking
Marking
Marking

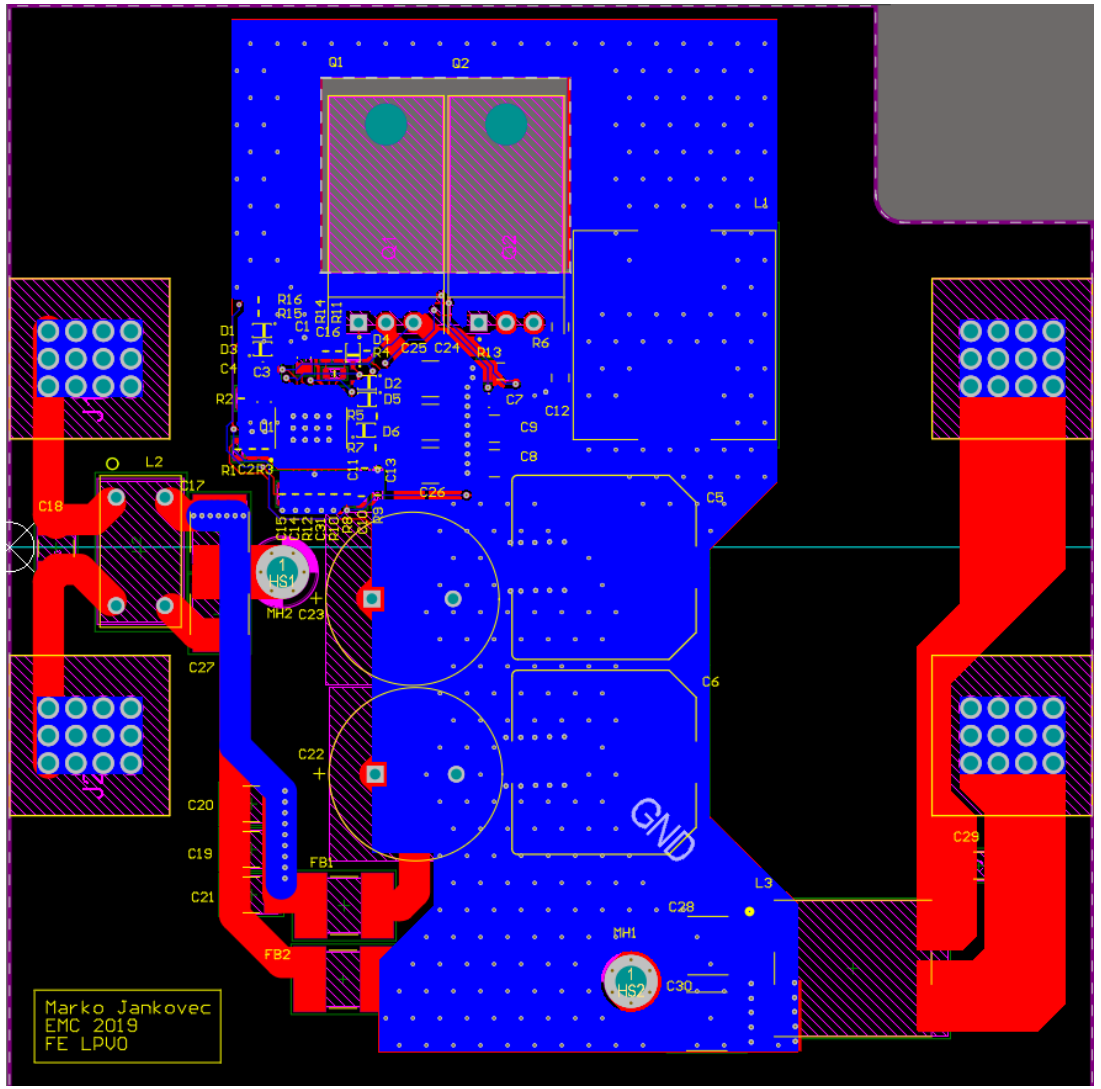

74435572200
D9107
471
050
ASLL-C13
471
050
ASLL-C13
744290560
Marko Jankovec
EMC 2019
FE LPVO
2268605A_Y24

Glavni stikalni tokokrog

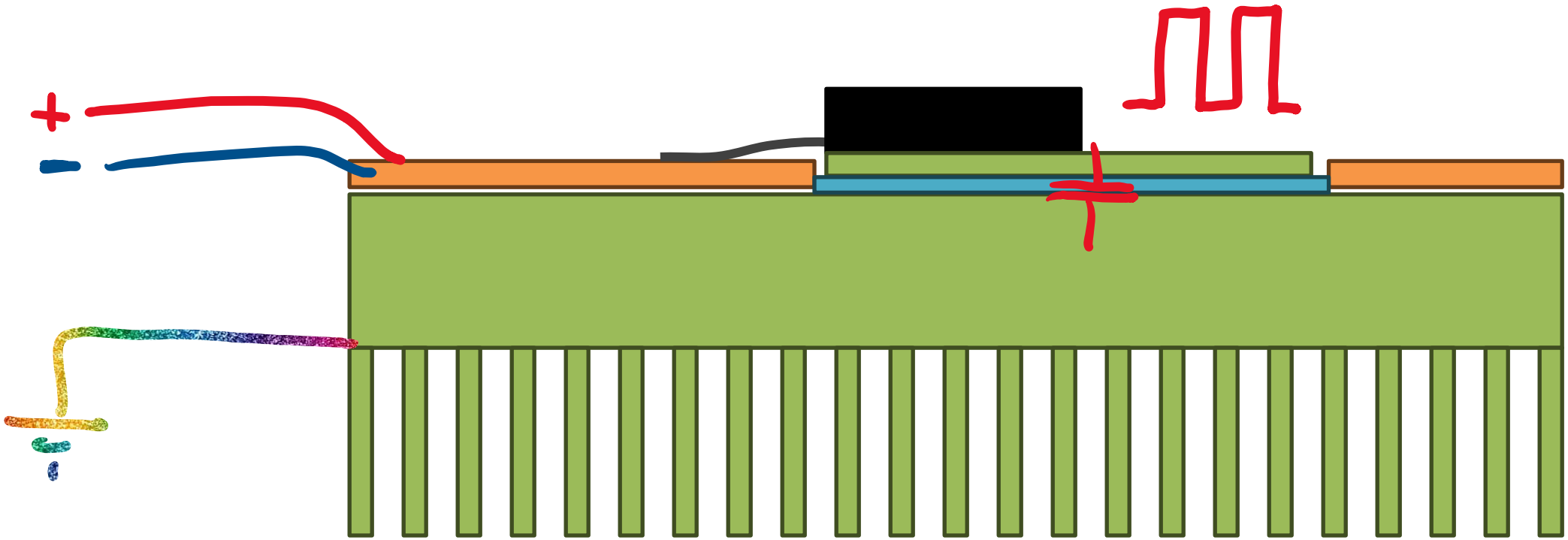


Glavni stikalni tokokrog

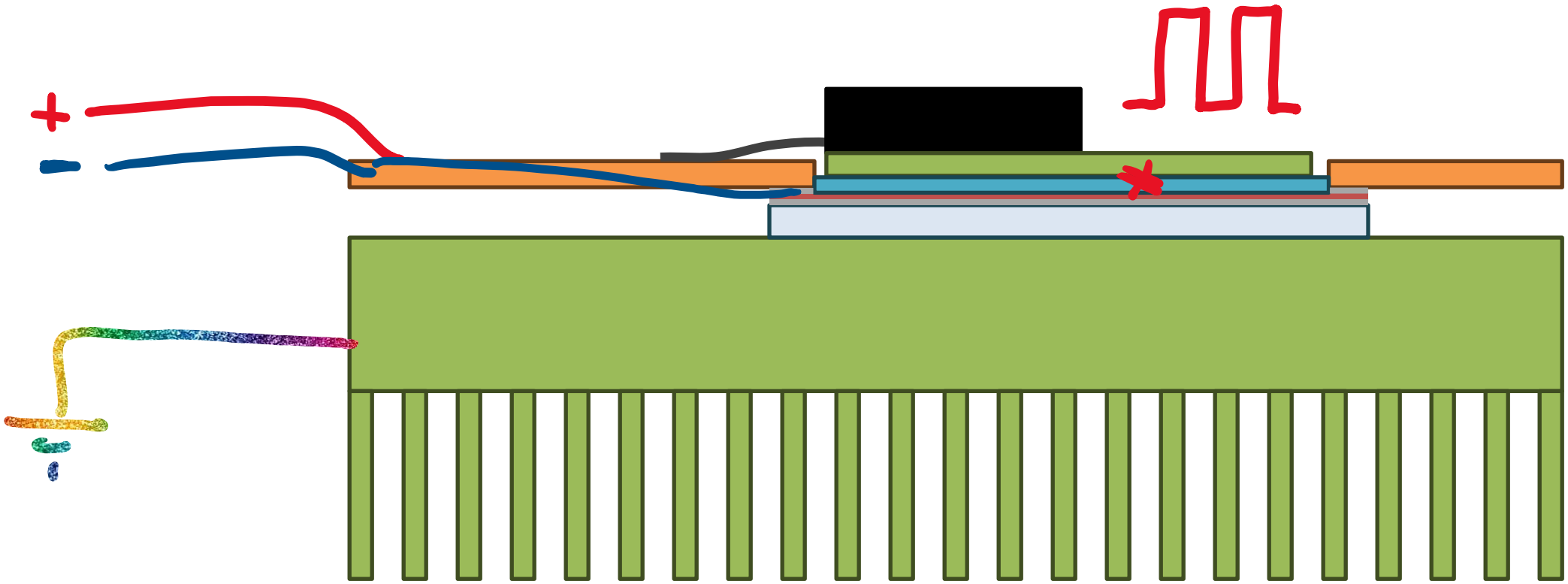




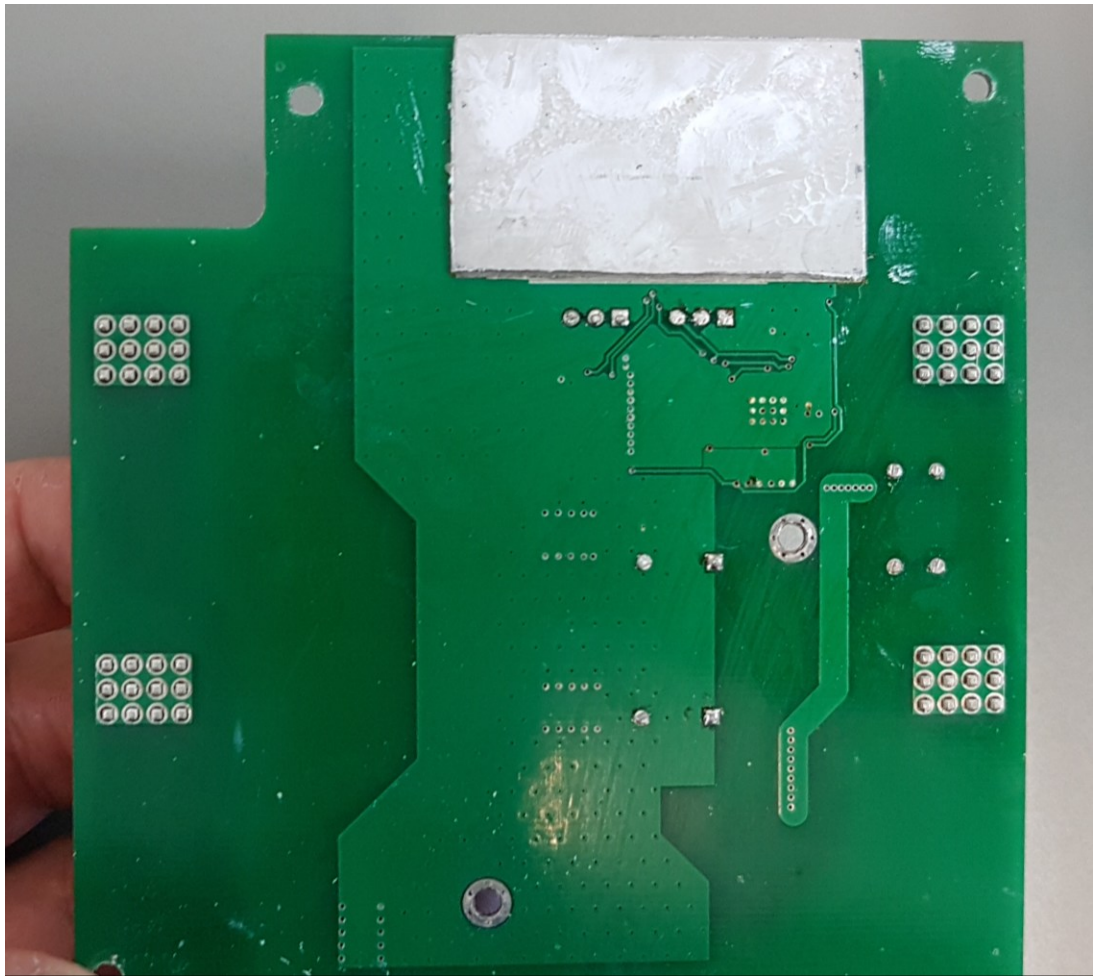
Napetostno generirane sofazne motnje

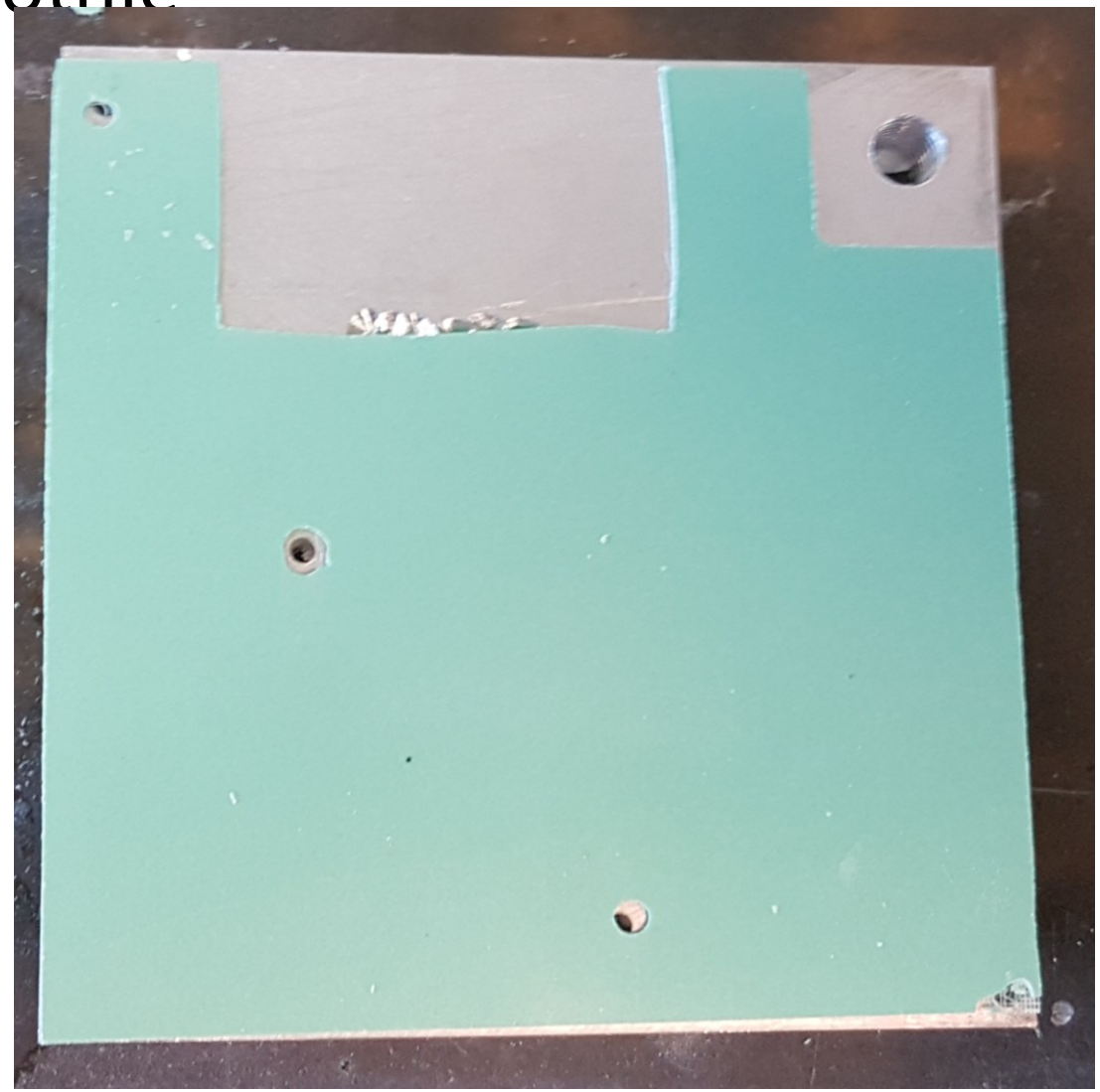


Napetostno generirane sofazne motnje

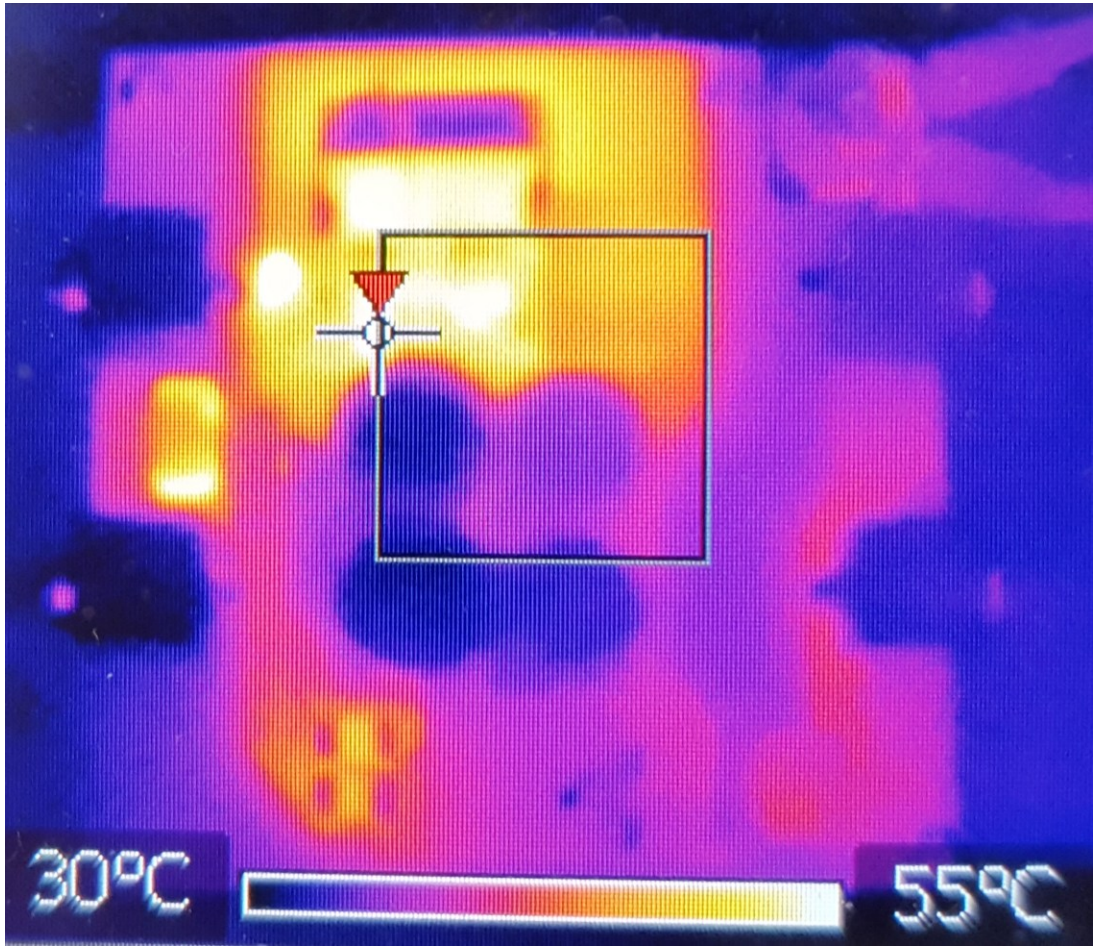


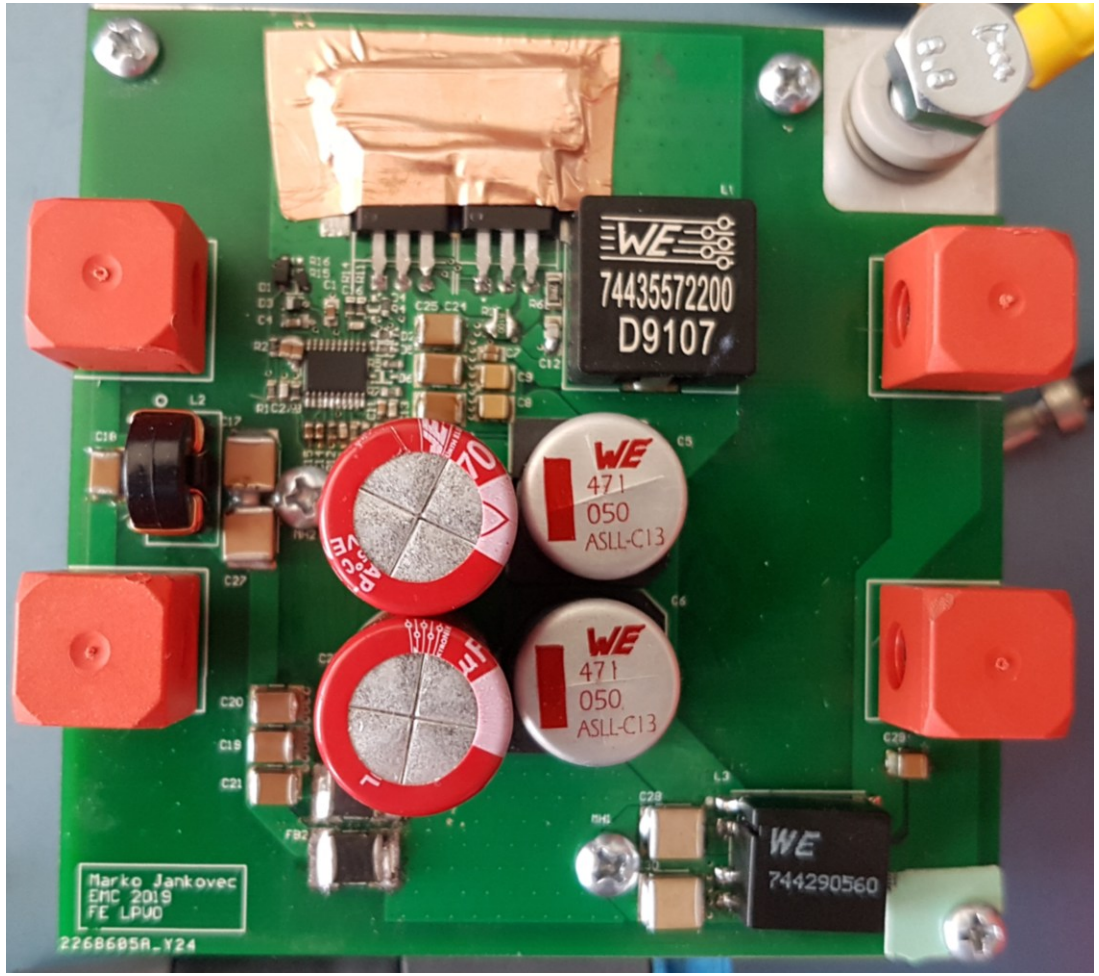
Napetostno generirane sofazne motnje



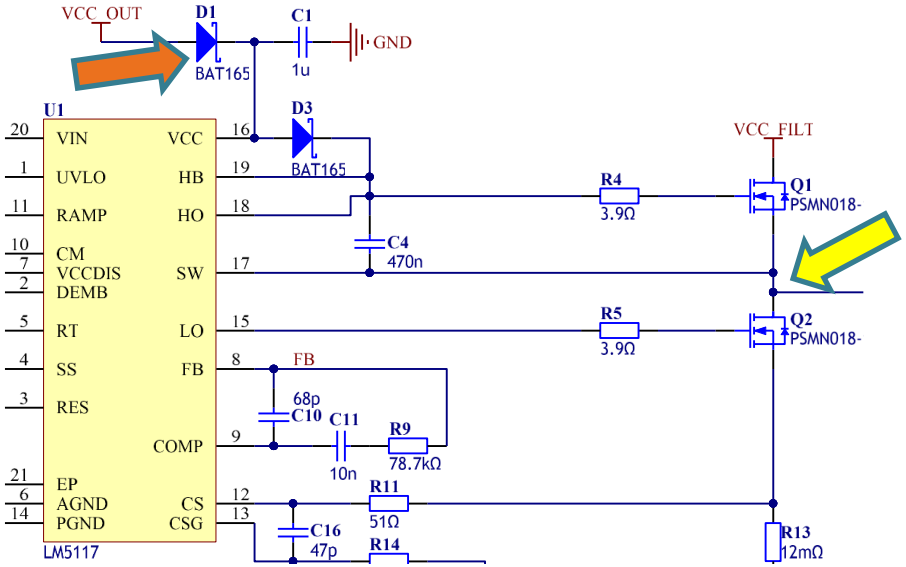


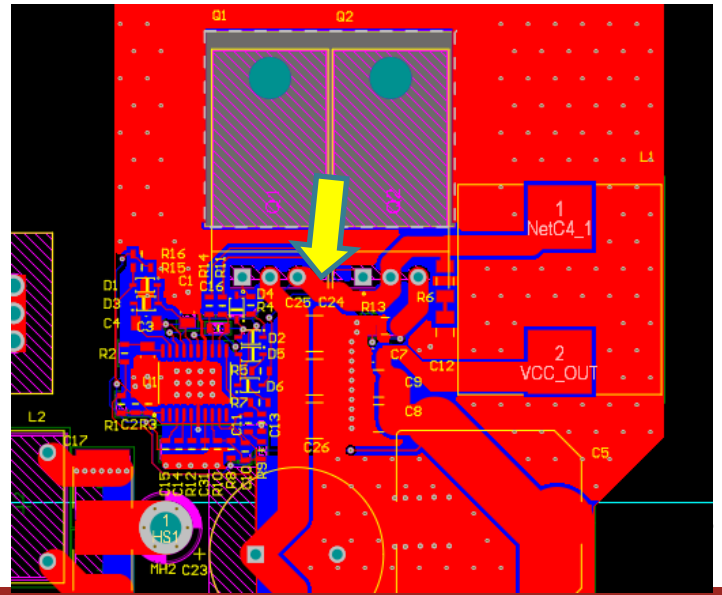
Napetostno generirane sofazne motnje

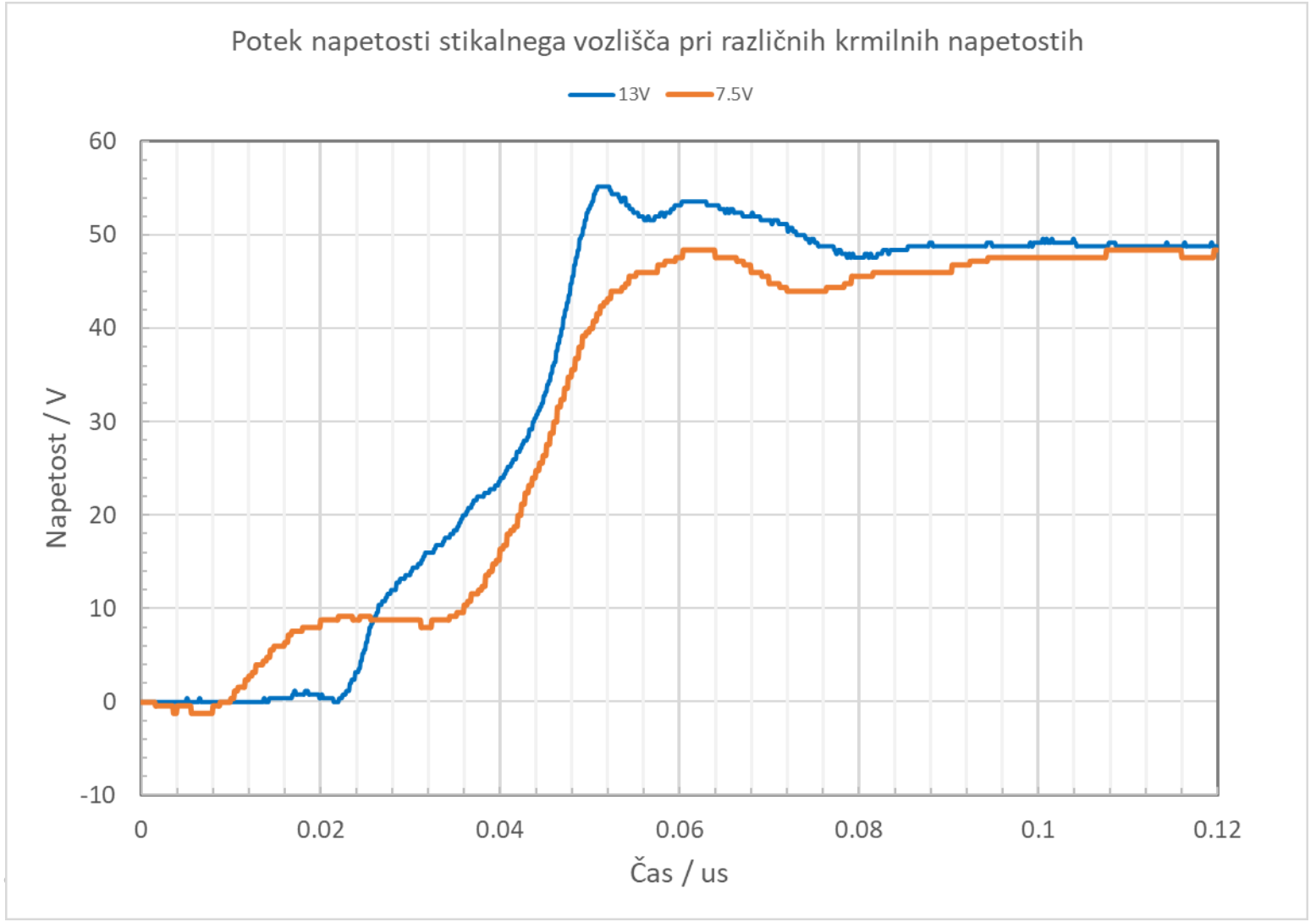




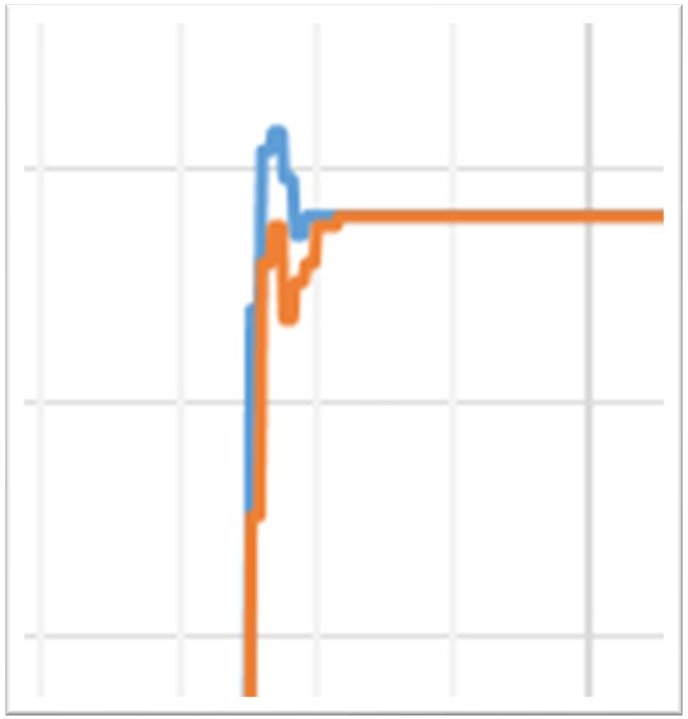
Stikalno vozlišče

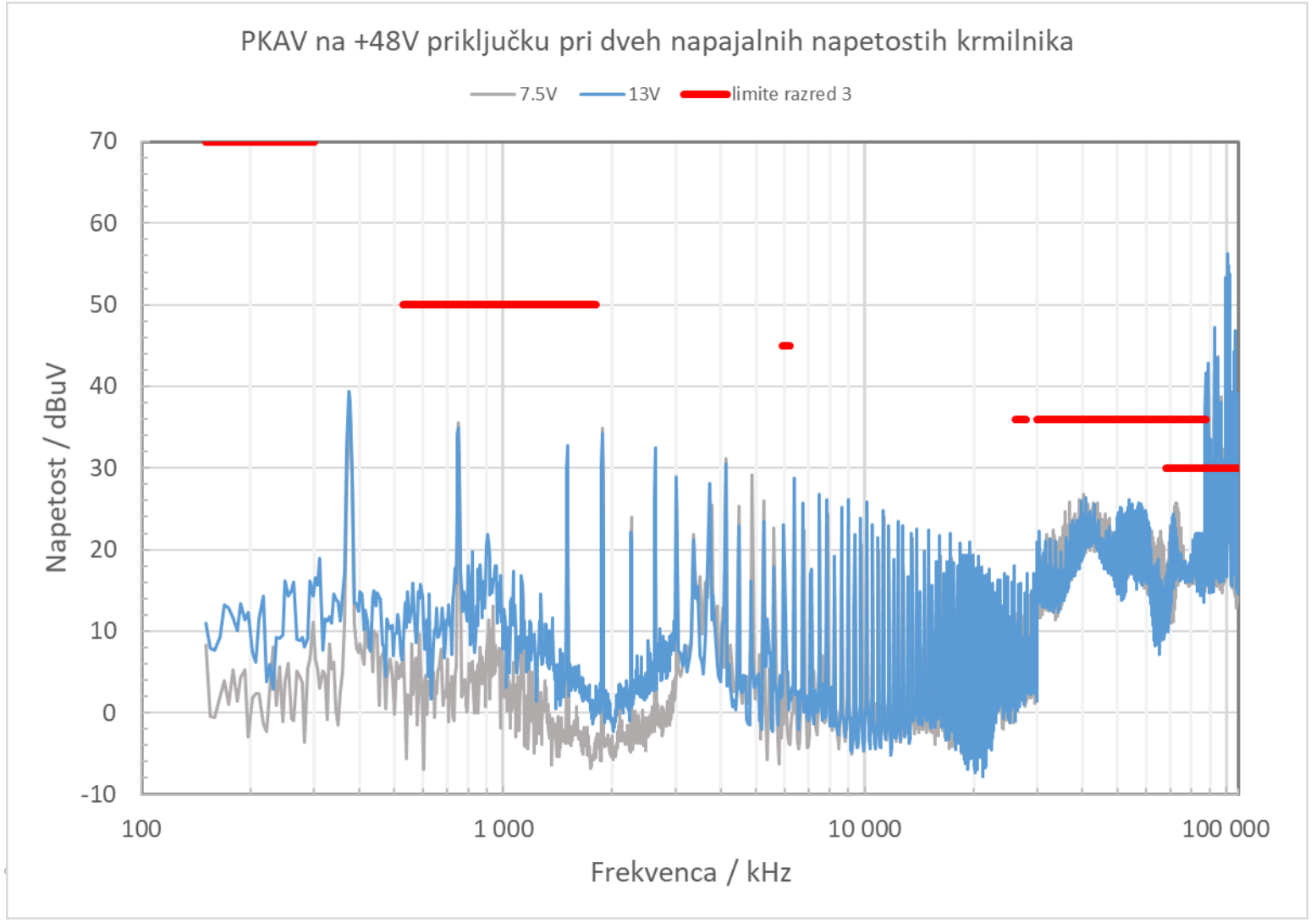




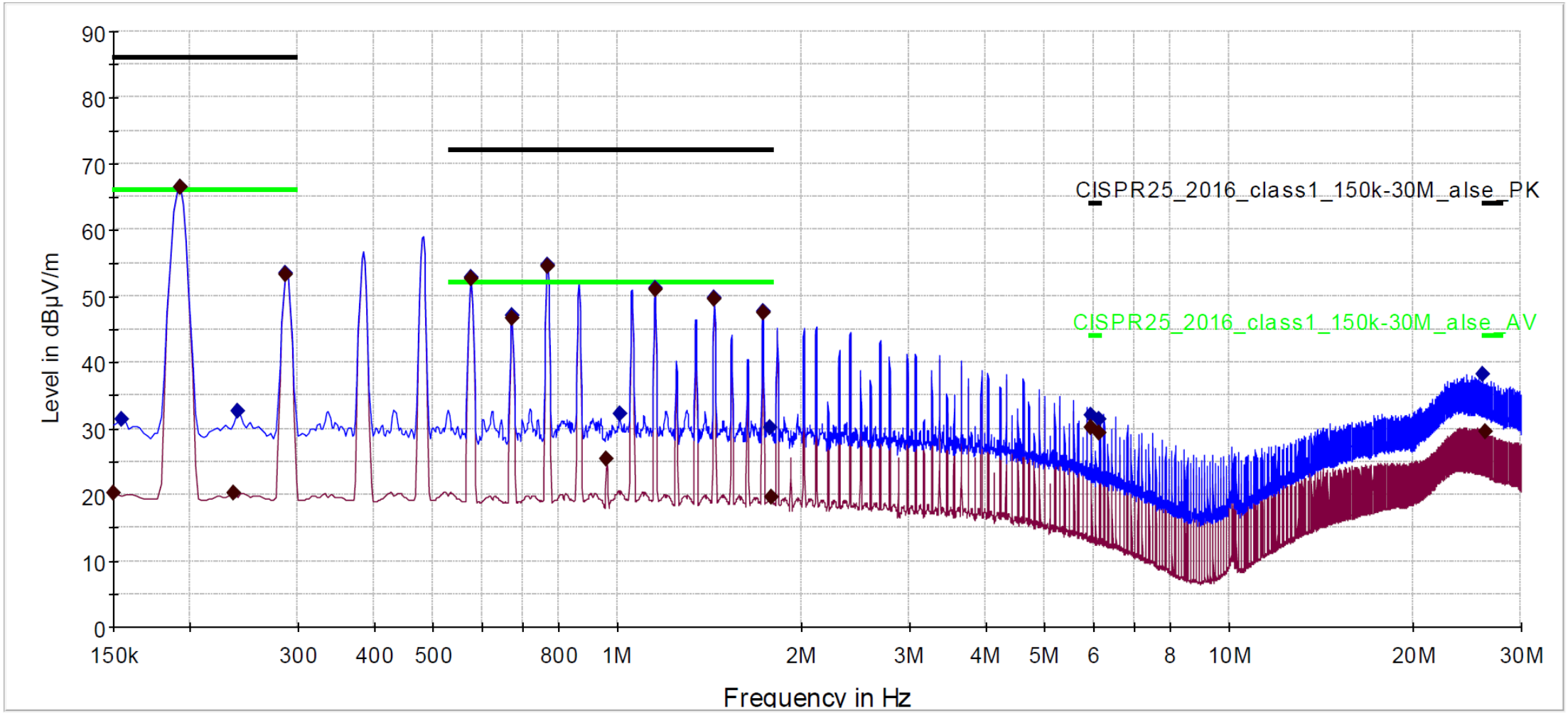


Prevodne motnje – Vpliv krmilne napetosti

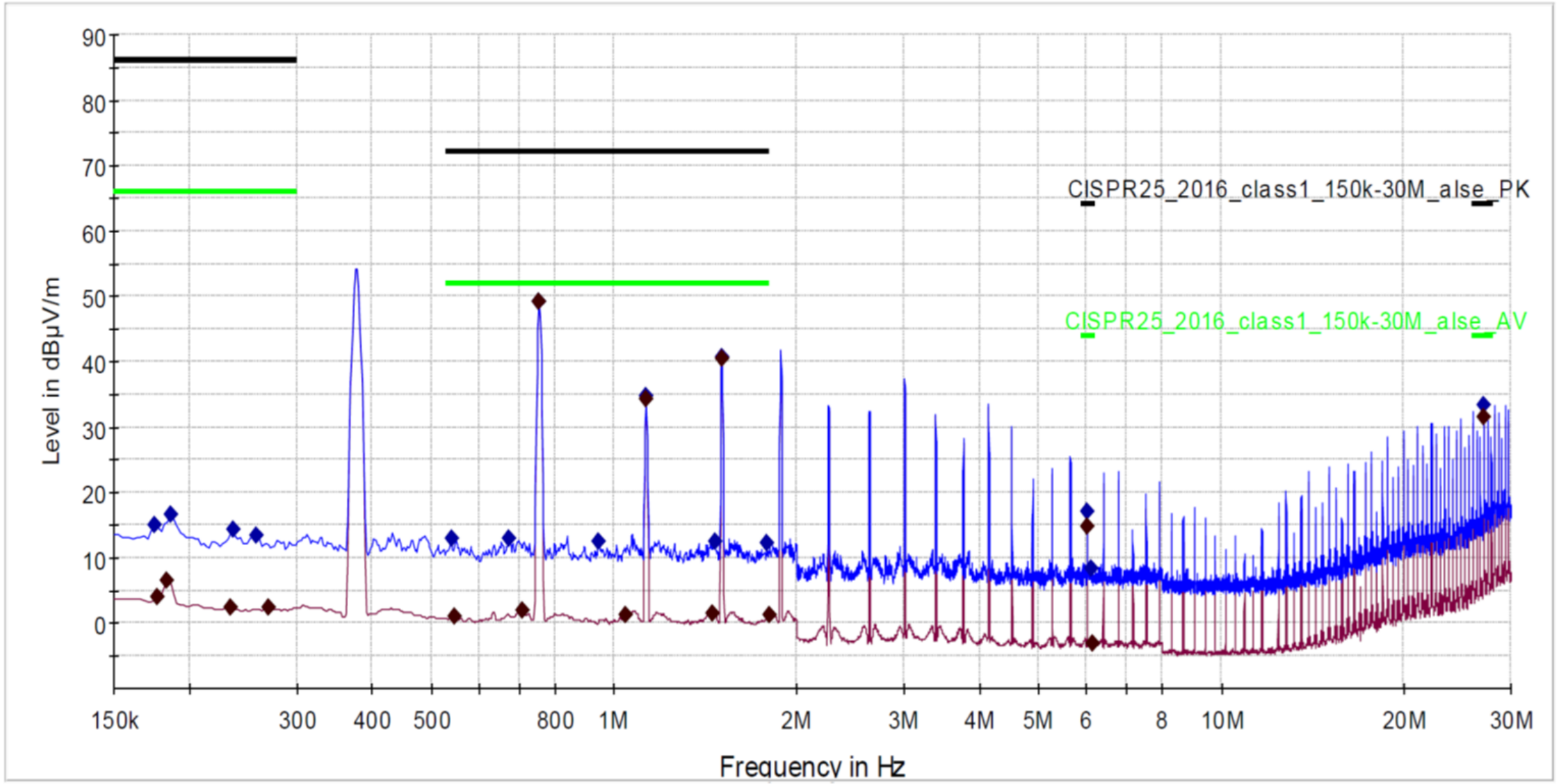




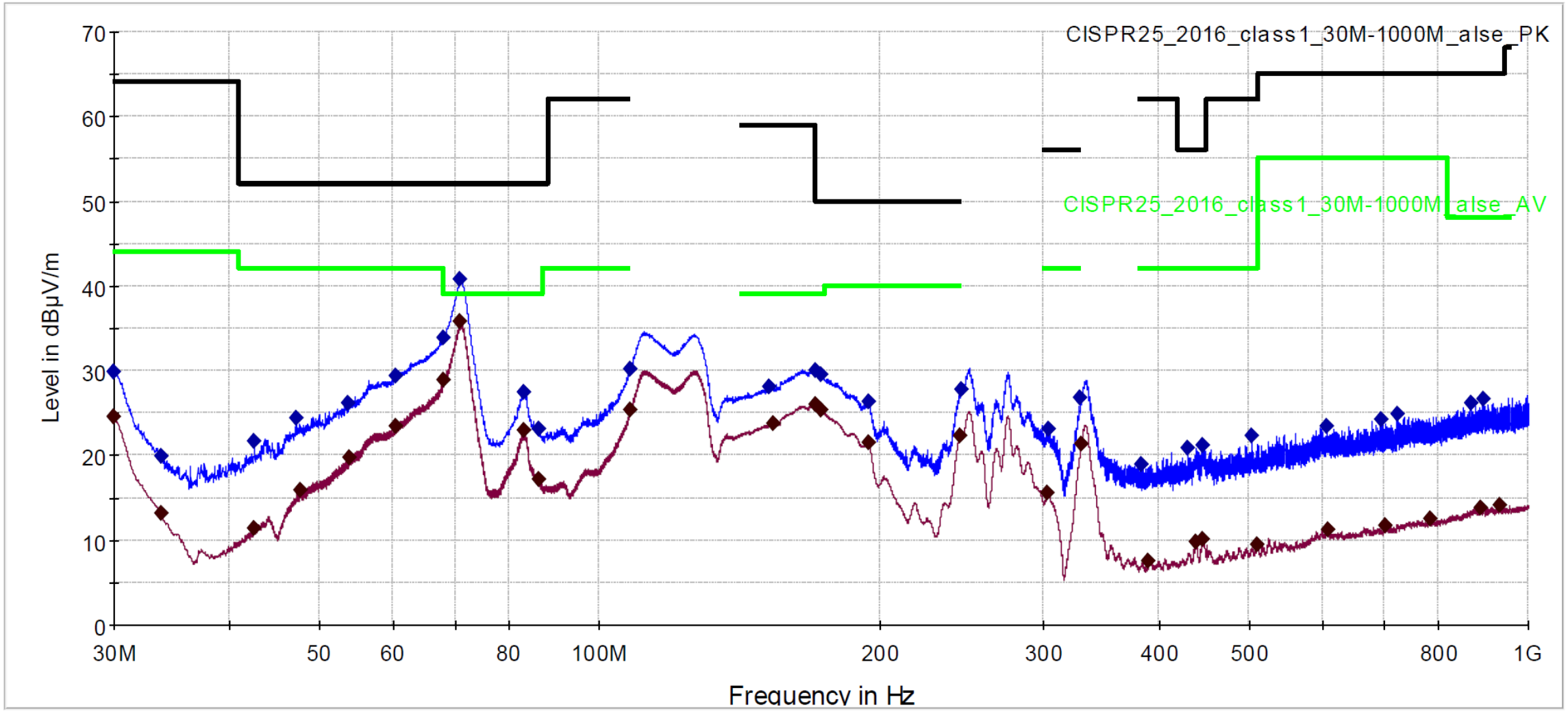
Rezultati do 30 MHz - študent



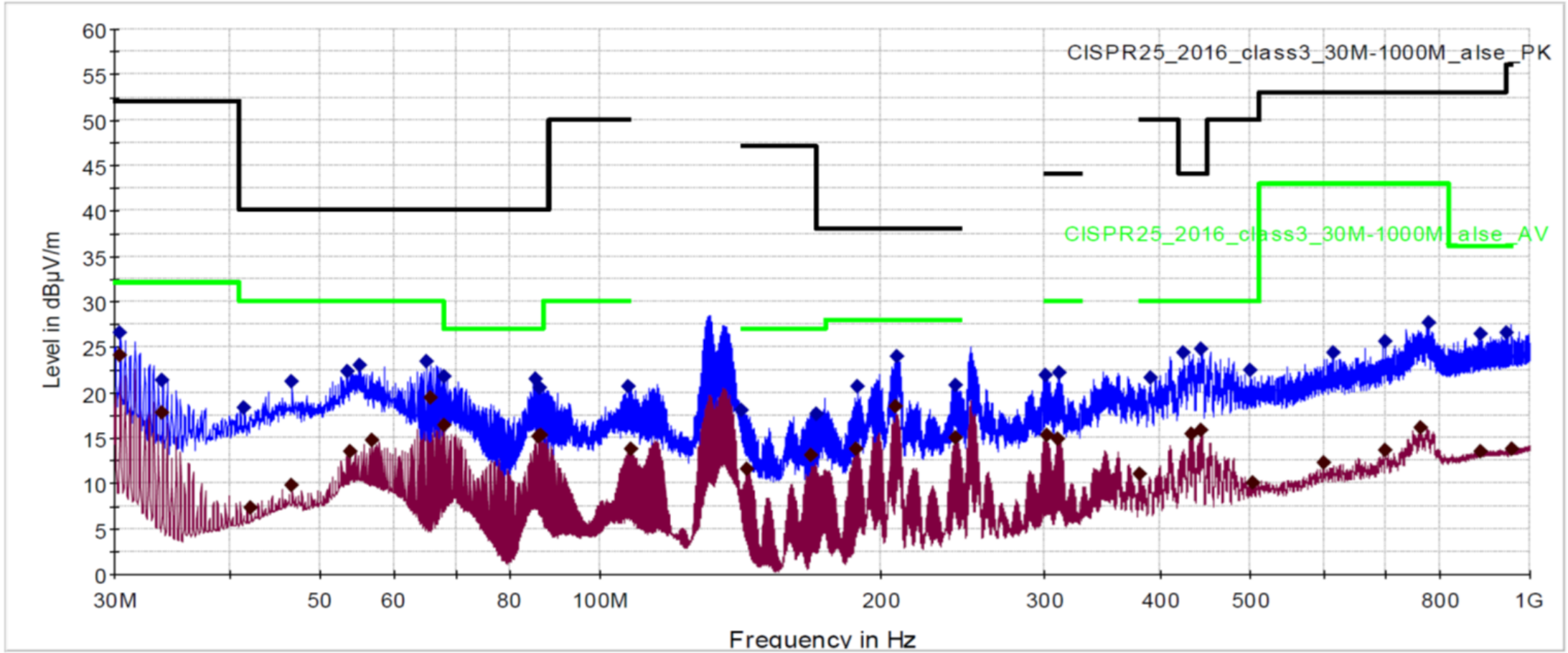
Rezultati do 30 MHz - FE



Rezultati nad 30 MHz - študent



Rezultati nad 30 MHz - FE



Resnica

"Some of the worst printed circuit boards we've seen were designed by engineers who were trying to comply with a list of EMC design rules.„

Todd Hubing