Electromagnetic Noise in Power Electronics

Seminar

2020-11-24/25

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and Electrical Drives

First Day's Schedule

Time	Title	Topic
09:00 - 09:30	Introduction	
09:30 - 10:15	Fundamentals	Why are we here? (Except ECTS)
10:15 - 10:30	Quiz + Break	
10:30 - 11:15	Models 1	Where do the emissions come from?
11:15 - 11:30	Quiz + Break	
11:30 - 12:15	Models 1	How can emission be described?
12:15 - 12:30	Quiz	
12:30 - 13:30	Lunch Break	
13:30 - 14:00	Q&A	
14:00 - 14:30	LTspice introduction	
14:30 - 14:45	Quiz + Break	
14:45 - 15:00	Task description	
15:00 - 16:00	Simulation Tasks	Let's work!
16:00 - 16:15	Break	
16:15 - 17:00	Simulation Tasks	Let's work!
17:00	End	

Second Day's Schedule

Time	Title	Topic
09:00 - 09:45	Measurement 1	Which setup and equipment is used?
09:45 - 10:00	Quiz + Break	
10:00 - 10:45	Measurement 2	How do we measure?
10:45 - 11:00	Quiz + Break	
11:00 - 11:45	Noise Mitigation	What concepts exist to reduce EME?
11:45 - 12:00	Quiz	
12:00 - 13:00	Lunch Break	
13:00 - 13:45	Filter Design	How to apply countemeasures and filters?
13:45 - 14:00	Quiz + Break	
14:00 - 14:30	Q&A	
14:30 - 15:00	Report Topics	
15:00	End	

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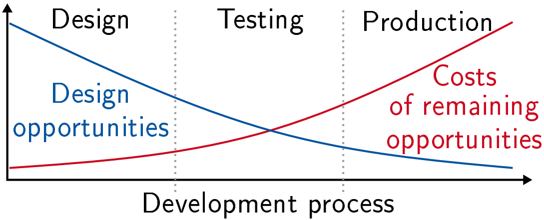
Why EMC in Power electronic (PE)?

- Electromagnetic compatibility (EMC) is a **non-functional** topic!
- It deals with the disturbance **between** and **inside** systems
- Power electronic converters are high-amplitude noise sources
- Early understanding of disturbance paths and noise sources saves time and costs



What is electromagnetic compatibility (EMC)?

EMC Definition by the IEC

Ability of an apparatus or system

to function satisfactorily in its electromagnetic environment

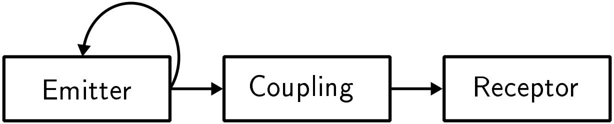
without introducing intolerable electromagnetic disturbances

to anything in that environment.

All definitions available at: `http://www.electropedia.org`

Is a System Electromagnetically Compatible?

Interference model:

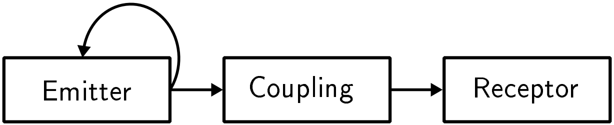


- **Emitter:** *The phenomenon by which electromagnetic energy emanates from a source.*
- **Coupling:** *The path over which part or all of the electromagnetic energy from a specified source is transferred to another circuit or device.*
- **Receptor:** *Every device in the electromagnetic environment.*

All definitions available at: `http://www.electropedia.org`

Is a System Electromagnetically Compatible? [1, p. 2]

Interference model:



1. It does not cause interference with other systems.
2. It is not susceptible to emission from other systems.
3. It does not cause interference with itself.

Interference and Disturbance

Electromagnetic disturbances:
Any electromagnetic phenomenon which can degrade the performance of a device, equipment or system, or adversely affect living or inert matter.

Electromagnetic interference (EMI):
Degradation of the performance of an equipment, transmission channel or system caused by an electromagnetic disturbance

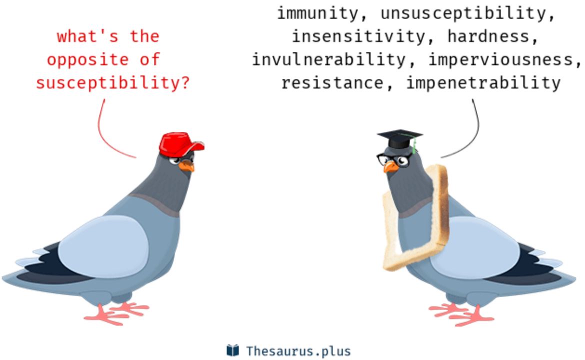
Source: www.pinterest.de

All definitions available at: `http://www.electropedia.org`

Immunity and Susceptibility

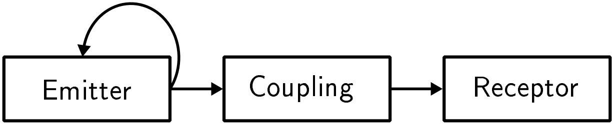
Electromagnetic susceptibility (EMS):
The inability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance.

Immunity:
The ability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance.



All definitions available at: `http://www.electropedia.org`

Interference Model

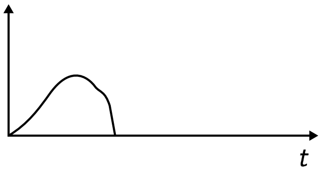


What are the characteristics of each element?

Fundamentals: Signals and Coupling Paths

Emissions in Time Domain [1, p.92]

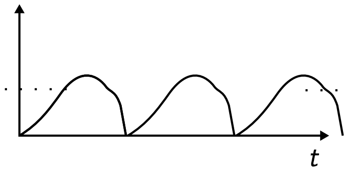
Non-periodic/energy signal:



Examples:

- Lightning
- Switching impulse
- Electrostatic discharge (ESD)

Periodic/power signal:

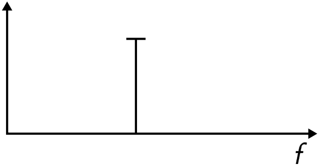


Examples:

- Power-line voltage
- Digital oscillators
- Pulse width modulation (PWM)

Emissions in Frequency Domain [2, p. 65]

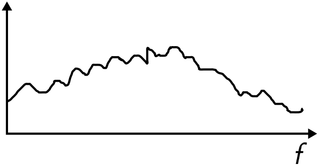
Narrow band:



Examples:

- Power line voltage
- Radio broadcasting
- Digital oscillators

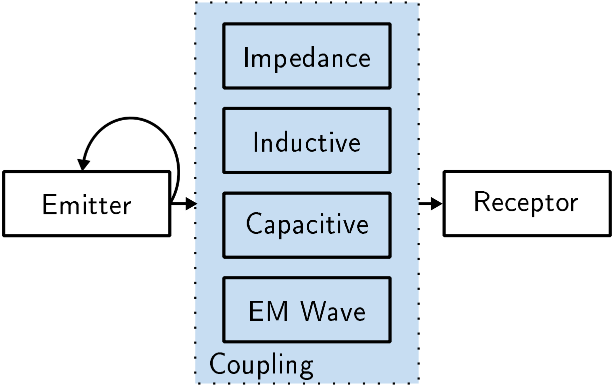
Broadband:



Examples:

- Noise (White, pink, red, gray)
- Lightning
- PWM

Coupling Mechanisms [2, p. 26]

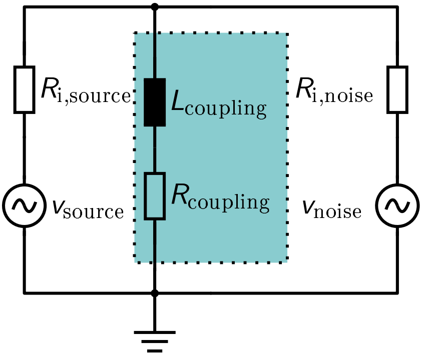


Electromagnetic noise: *A time-varying electromagnetic phenomenon apparently not conveying information and which may be superimposed on or combined with a wanted signal.*

Impedance Coupling

- Two circuits share a common impedance
- Sometimes called galvanic or resistive coupling

  Resistive coupling is misleading, an impedance coupling includes more than a resistor.
- Includes shared ground path!



In time domain:

$$v_{\mathrm{coupling}} = \left(R_{\mathrm{coupling}} + L_{\mathrm{coupling}} \cdot \frac{\mathrm{d}}{\mathrm{d}t}\right) \cdot \left(i_{\mathrm{source}} + i_{\mathrm{noise}}\right)$$

In frequency domain:

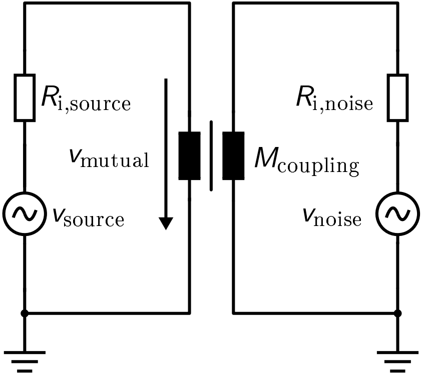
$$\underline{V}_{\mathrm{coupling}} = \left(R_{\mathrm{coupling}} + \mathrm{j}2\pi f \cdot L_{\mathrm{coupling}}\right) \cdot \left(\underline{I}_{\mathrm{source}} + \underline{I}_{\mathrm{noise}}\right)$$

Inductive Coupling

- Mutual coupling between two loops
- Coupled by common magnetic field (H-Field)
  → Currents are required
- Parallel wires:

$$M = \frac{\mu_0 \cdot \mu_r}{4\pi} \ln\left(1 + 4\frac{h^2}{s^2}\right)$$

with h height above ground and s distance of wires



Sinusoidal voltage induced in the source circuit:

$$\underline{v}_{\mathrm{mutual}} = \mathrm{j}2\pi f \cdot M_{\mathrm{coupling}} \cdot \underline{I}_{\mathrm{noise}}$$

Capacitive Coupling

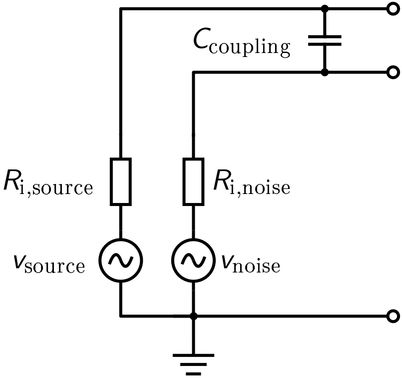
- Transport of energy with displacement current
- Coupled by common electric field (E-Field)
- Often parasitic capacitance through ground
- High ${}^{\mathrm{d}v}/_{\mathrm{d}t}$ required
- Parallel plate capacitor:

$$C = \epsilon_0 \epsilon_\mathrm{r} \cdot \frac{A}{d}$$

with A area and d distance of plates

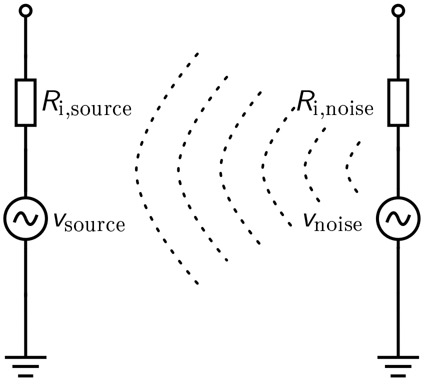
- Admittance depends on frequency:

$$\underline{Y} = \mathrm{j}2\pi f \cdot C$$



EM Wave Coupling [2, p. 29]

- Electromagnetic (EM) wave
- Coupled E/H field (see EMF)

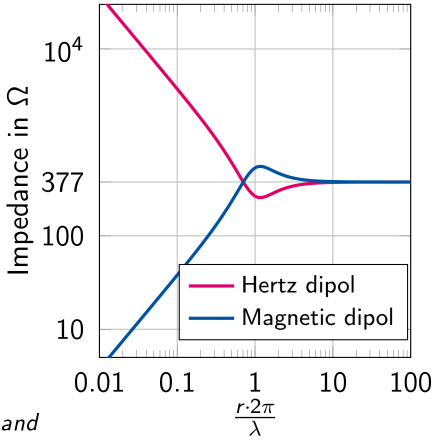


But:
Where is the difference between the inductive/capacitive coupling and the EM wave coupling?

Fundamentals: Signals and Coupling Paths

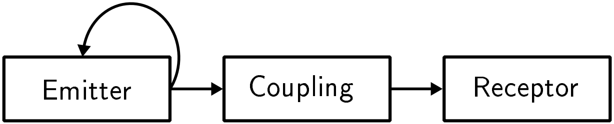
Field Type Depending on the Distance [3, p. 55]

- Near field: $r < \frac{\lambda}{2 \cdot \pi}$
  - Field depending primarily on the source
  - Depending on the electric or magnetic dipole
- Far field: $r > \frac{\lambda}{2 \cdot \pi}$
  - Coupled electromagnetic-fields
  - Characteristic impedance of air or free space is $377\,\Omega$



Note: *These are only elementary electric and magnetic dipoles! Each antenna has its own characteristics.*

Receptor: Radiated or Conducted Emissions?



Conducted disturbance:
Electromagnetic disturbance for which the energy is transferred via one or more conductors.

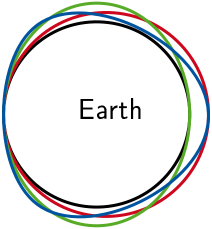
Radiated disturbance:
Electromagnetic disturbance for which the energy is transferred through space in the form of electromagnetic waves.

All definitions available at: `http://www.electropedia.org`

A brief history of time- and frequency-domain

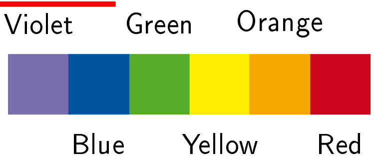
Minimum and Maximum Frequencies

Schumann resonances (3 Hz – 30 Hz/$10 \cdot 10^5$ km – $10 \cdot 10^4$ km)



Fundamental mode: 7.83 Hz
Second order: 14.3 Hz
Third order: 20.8 Hz

Visible light (385 THz – 750 THz/400 nm – 780 nm)



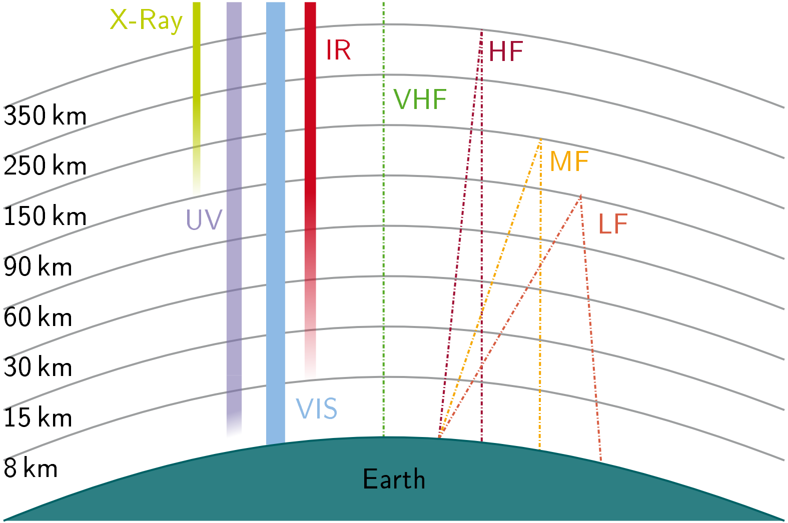
Visible range: 430 to 770 THz
Red: 400 to 484 THz
Green: 526 to 606 THz
Violet: 668 to 789 THz

Radio Bands Defined in the ITU Radio Regulations

Range	Wavelength	Name (Abbreviation)	Use
3 Hz – 30 Hz	$10 \cdot 10^5$ km – $10 \cdot 10^4$ km	Extremely low frequency (ELF)	Schumann resonance
30 Hz – 300 Hz	$10 \cdot 10^4$ km – $10 \cdot 10^3$ km	Super low frequency (SLF)	AC power grids
300 Hz – 3 kHz	$10 \cdot 10^3$ km – 100 km	Ultra low frequency (ULF)	Military purpose, (earthquake warning systems)
3 kHz – 30 kHz	100 km – 10 km	Very low frequency (VLF)	Submarine communication
30 kHz – 300 kHz	10 km – 1 km	Low frequency (LF)	AM radio broadcasting, aircraft beacons
300 kHz – 3 MHz	1 km – 100 m	Medium frequency (MF)	AM radio broadcasting, maritime ship-to-shore communication
3 MHz – 30 MHz	100 m – 10 m	High frequency (HF)	Amateur radio, weather and government time stations
30 MHz – 300 MHz	10 m – 1 m	Very high frequency (VHF)	FM radio and television broadcasting, amateur radio, marine and air traffic communication
300 MHz – 3 GHz	1 m – 10 cm	Ultra high frequency (UHF)	Cell phones, GPS, Wi-Fi, Bluetooth
3 GHz – 30 GHz	10 cm – 1 cm	Super high frequency (SHF)	Wi-Fi, Radar, Satellite television
30 GHz – 300 GHz	10 mm – 1 mm	Extremely high frequency (EHF)	Radar, directional radio
300 GHz – 385 THz	1 mm – 0.78 μm	Infrared (IR)	Security, remote control, fiber optics
385 THz – 750 THz	780 nm – 400 nm	Visible light (VIS)	Fiber optics, Visible light

Note: The usage are only selected examples!

Propagation and reflection [4, p.25]



Measurement Devices for Time and Frequency Domain?

Time domain:

Oscilloscope

- x axis: Linear time
- y axis: Linear voltage

Note: *Visibility of effects within one decade.*

Frequency domain:

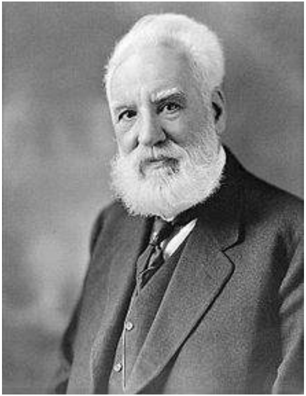
Measuring receiver and spectrum analyzer

- x axis: Logarithmic frequency
- y axis: Logarithmic voltage

Note: *Visibility of effects over many decades.*

What is a dB? [2, p. 8]

- Decibel (dB) is a logarithmic unit named after Alexander Graham Bell
- Common scale in the frequency domain
- Logarithmic scale with the base "10" → Deci-Bel



Alexander Graham Bell

Source: en.wikipedia.org

Note: *The logarithmic scale with base "e" is called Neper (Np).*

Calculation with dB Units [5]

Multiplication and division:

$$\log(x \cdot y) = \log(x) + \log(y)$$

$$\log(x/y) = \log(x) - \log(y)$$

Base transformation:

$$\log_b x = \frac{\log_a(x)}{\log_a(b)}$$

Exponent and root:

$$\log(x^y) = y \cdot \log(x)$$

$$\log(\sqrt[y]{x}) = \frac{1}{y} \cdot \log(x)$$

Power and Field Units in dB [1, p. 23-43]

Power units:

$$P_{(\mathrm{dB})} = \mathbf{10} \cdot \log_{10}\left(\frac{P_{(\mathrm{W})}}{1\,\mathrm{W}}\right)$$

$$P_{(\mathrm{dBm})} = \mathbf{10} \cdot \log_{10}\left(\frac{P_{(\mathrm{W})}}{1\,\mathrm{mW}}\right)$$

$$P_{(\mathrm{dB\mu})} = \mathbf{10} \cdot \log_{10}\left(\frac{P_{(\mathrm{W})}}{1\,\mu\mathrm{W}}\right)$$

Field units:

$$V, I_{(\mathrm{dBV},\mathrm{dBA})} = \mathbf{20} \cdot \log_{10}\left(\frac{V, I_{(\mathrm{V},\mathrm{A})}}{1\,(\mathrm{V},\mathrm{A})}\right)$$

$$V, I_{(\mathrm{dBmV},\mathrm{dBmA})} = \mathbf{20} \cdot \log_{10}\left(\frac{V, I_{(\mathrm{V},\mathrm{A})}}{1\,(\mathrm{mV},\mathrm{mA})}\right)$$

$$V, I_{(\mathrm{dB\mu V},\mathrm{dB\mu A})} = \mathbf{20} \cdot \log_{10}\left(\frac{V, I_{(\mathrm{V},\mathrm{A})}}{1\,(\mu\mathrm{V},\mu\mathrm{A})}\right)$$

Relationship of power to field values:

$$\mathrm{dB} = 10 \cdot \log_{10}\left(\frac{P_1}{P_2}\right) = 10 \cdot \log_{10}\left(\frac{V_1}{V_2}\right)^2 = 2 \cdot 10 \cdot \log_{10}\left(\frac{V_1}{V_2}\right) = 20 \cdot \log_{10}\left(\frac{V_1}{V_2}\right)$$

with $P_1 = V_1^2/R$ and $P_2 = V_2^2/R$

Important Values of Power and Field Units in DB [1, p. 23-43]

Power units:

dB	Factor
0 dB	1
3 dB	2
6 dB	4
10 dB	10

Field units:

dB	Factor
0 dB	1
6 dB	2
12 dB	4
20 dB	10

Conversion of power units:

$$\mathrm{dB} = \mathrm{dBm} - 30$$
$$\mathrm{dBm} = \mathrm{dB} + 30$$
$$\mathrm{dB} = \mathrm{dB\mu} - 60$$
$$\mathrm{dB\mu} = \mathrm{dB} + 60$$

Conversion of field units:

$$\mathrm{dBV} = \mathrm{dBmV} - 60$$
$$\mathrm{dBmV} = \mathrm{dBV} + 60$$
$$\mathrm{dBV} = \mathrm{dB\mu V} - 120$$
$$\mathrm{dB\mu V} = \mathrm{dBV} + 120$$

Conversion between DB Units [6, p. 30]

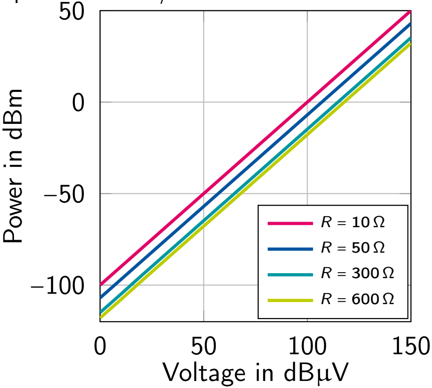
dBµV and dBµA:
$I_{\mathrm{dB\mu A}} = \mathrm{dB\mu V} - 20 \cdot \log_{10}(R_{\mathrm{S}})$
with a small series resistance to measure the current.

Based on $I_{\mathrm{dB\mu A}} = \frac{U_{\mathbf{dB\mu V}}}{R_{\mathrm{S},\Omega}}$

With $R_{\mathrm{S}} = 1\,\Omega$ dBµA and dBµV are equal.

Note: *Noise currents are rarely measured directly.*

dBµV and dBm:
$P_{\mathrm{dBm}} = V_{\mathrm{dB\mu V}} - 90 - 10 \cdot \log_{10}(R)$
equivalent to $P = V^2/R$ in dB



Common Mistake: Subtraction and Addition of DB Units

Normal units can be added:

$$X + Y$$

Summation with dB units:

$$\log(x+y) = \log(x) + \log\left(1 + \frac{y}{x}\right)$$

Example of a 50 Ω system:

$10\,\mathrm{mW}$	$\equiv 10\,\mathrm{dBm}$	$\equiv 117\,\mathrm{dB\mu V}$
$+5\,\mathrm{mW}$	$+\,7\,\mathrm{dBm}$	$+\,114\,\mathrm{dB\mu V}$
$=15\,\mathrm{mW}$	$\neq 17\,\mathrm{dBm}$	$\neq 231\,\mathrm{dB\mu V}$
	$= 50.1\,\mathrm{mW}$	$= 1.26 \cdot 10^{+23}\,\mathrm{mW}$

Fundamentals: A Brief History of Time- and Frequency-Domain Units for Radiated Emissions [1, p. 27]

- Radiated emissions are given in specific field quantities per meter ($\frac{1}{\mathrm{m}}$)
- Otherwise, it is equal to:
  - Voltage: E in V/m
  - Current: H in A/m
  - Power: Pd in W/m^2

Electric field:

$$E_{\mathrm{dB\mu V/m}} = 20 \cdot \log_{10}\left(\frac{V_{\mathrm{V/m}}}{1\,\mathrm{\mu V/m}}\right)$$

Magnetic field:

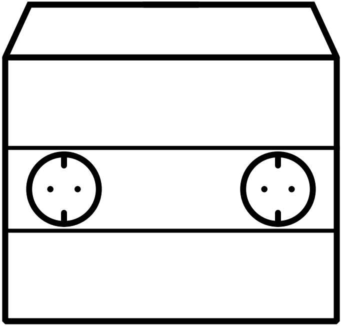
$$H_{\mathrm{dB\mu A/m}} = 20 \cdot \log_{10}\left(\frac{I_{\mathrm{A/m}}}{1\,\mathrm{\mu A/m}}\right)$$

Surface power density:

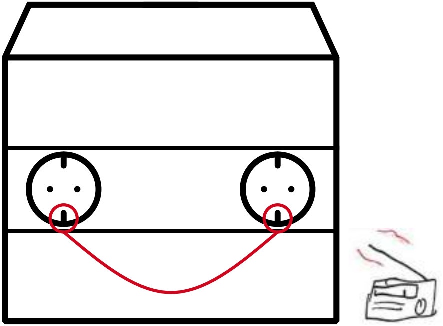
$$Pd_{\mathrm{dB\mu/m^2}} = 20 \cdot \log_{10}\left(\frac{P_{\mathrm{W/m^2}}}{1\,\mathrm{\mu W/m^2}}\right)$$

Do we have electromagnetic emission (EME) in a building?

Radio Hum Problems with Ground Currents



Radio Hum Problems with Ground Currents

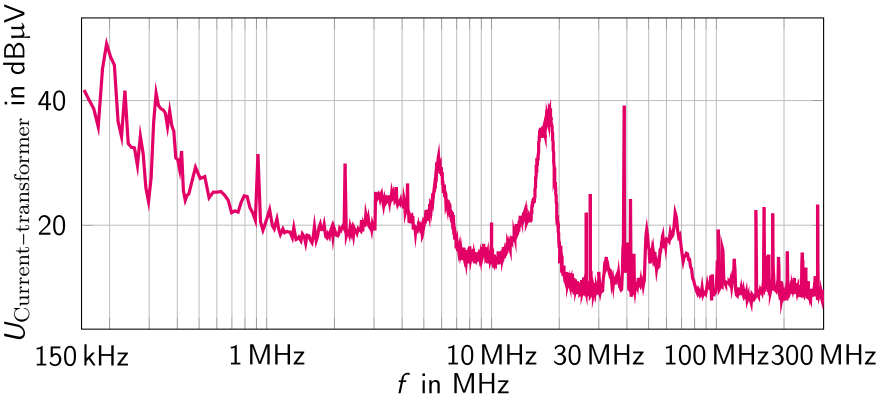


This time, the example is shown in the lab exercise.

Measurement of Emission

- Measuring ground current
- Equipment
  - Current transformer
  - Electromagnetic interference (EMI) receiver

Measurement of Emission



Calculation of Emission at 18 MHz

$$V, I_{(\mathrm{dBV},\mathrm{dBA})} = \mathbf{20} \cdot \log_{10}\left(\frac{V, I_{(\mathrm{V},\mathrm{A})}}{1\,(\mathrm{V},\mathrm{A})}\right)$$

With the inverse function:

$$10^{\mathbf{40\,dB\,\mu V}/20} = 100\,\mu\mathrm{V}$$

Continuous and Discontinuous Disturbance

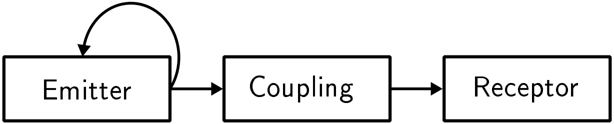
Continuous disturbance:
*Electromagnetic disturbance, the effects of which on a particular device or equipment **cannot** be resolved into a succession of distinct effects.*

Discontinuous disturbance:
*Electromagnetic disturbance, the effects of which on a particular device or equipment **can** be resolved into a succession of distinct effects.*

***Note** – It is recognized that this definition does not characterize the disturbance independently of the effect that it produces. As a practical matter, any measure of a disturbance should be relatable to its effect on a susceptible device.*

All definitions available at: `http://www.electropedia.org`

Interpretation with the Interference Model



- **Emitter:** *Switched-mode power supplies in the building*
- **Coupling:**
  - *Protective earthing conductor in the building (impedance coupling)*
  - *Inductive coupling from cable to radio*
- **Receptor:** *AM radio*

Break

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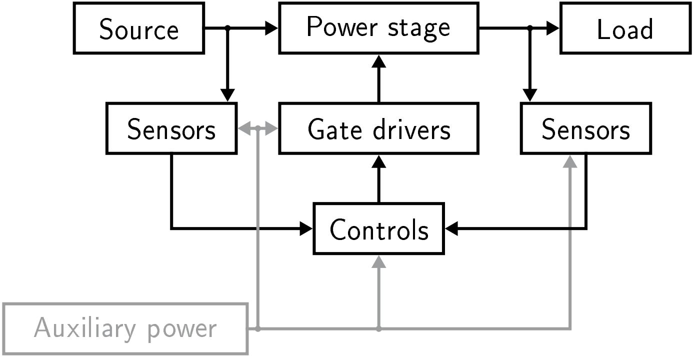
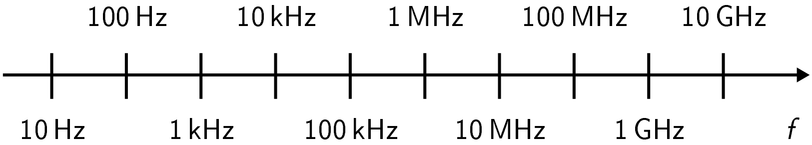
Structure of a Power Electronic System



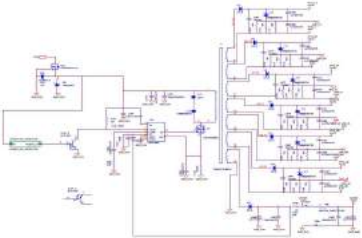
What frequencies do power electronic systems contain?

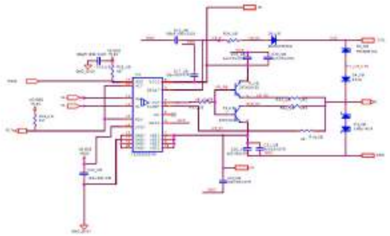
Frequencies in Power Electronics [7, s. 5]

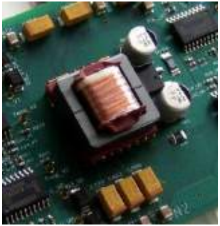


- Nine decades of frequencies (from 10 Hz to 10 GHz)
- Different reasons
  - Fundamental frequency (Grid and motor frequencies)
  - PWM frequencies and harmonics
  - Switching slopes and module resonances
  - Digital clocks and logic
- Both, broadband and narrow band emissions are in the spectrum!

Example: Equivalent Circuit of a Driver Unit [9]



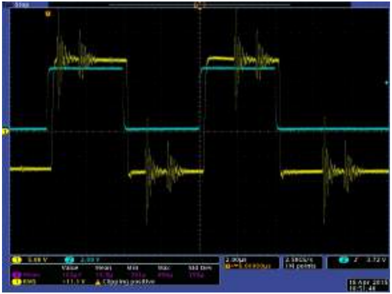




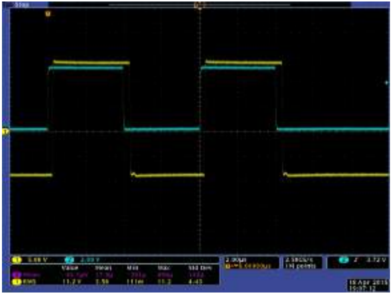
- Setup without a power load (only semiconductor)
- Passive probe used for measurement
- Auxiliary gate driver power supply produces high noise

Example: Measurement of Driver Voltage

- CH1: v_{ge} of the insulated-gate bipolar transistor (IGBT)
- CH2: 5 V PWM signal



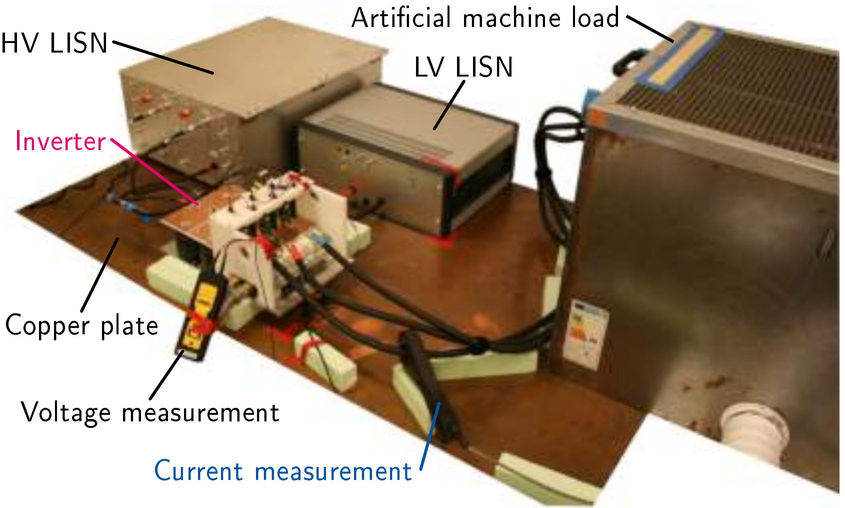
Hybrid Kit supply [9]



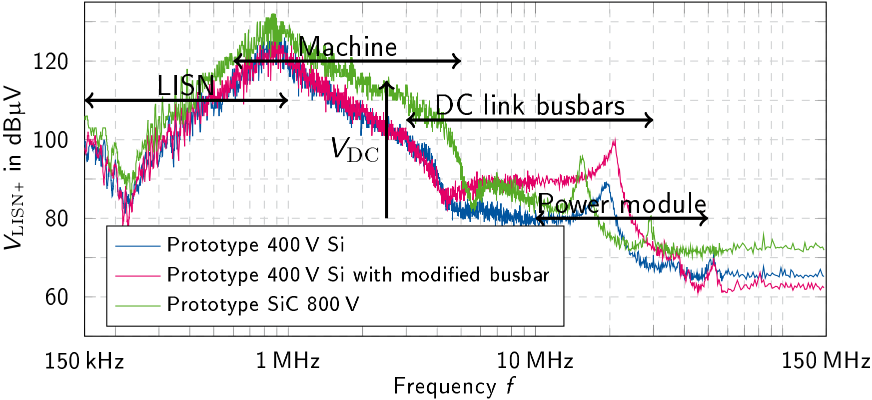
Another power supply

Note: *The Hybrid Kit is only an evaluation board and no productive system.*

Example: 3ph Inverter Test Bench [10]



Example: 3ph Inverter Test Bench [10]

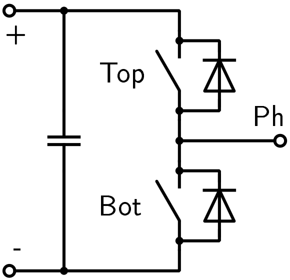


- Each setup component influences another frequency range.
- It can be analyzed by experience or a IS/IS NOT analysis.

How to describe a switching semiconductor?

Models 1: Source

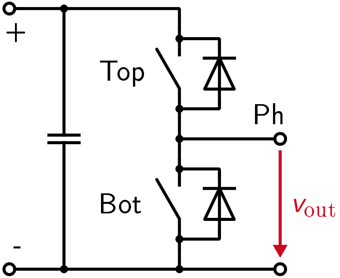
Single-Phase/Halfbridge



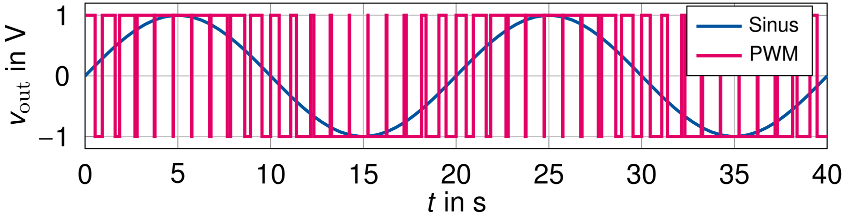
- Basic element of a voltage source inverter (VSI)
- A half bridge consists of two unidirectional switches with anti-parallel diode
- Fast switching between positive and negative voltage at the output Ph [11, p. 156]
- Operation with PWM or pulse frequency modulation (PFM)

Models 1: Source

Fundamental Frequencies



- Modulation of fundamental frequencies with a PWM
- Examples:
  - Motor frequencies
  - Grid frequencies
- Modeling of this behavior is covered in the lecture PE-CSA.



Models 1: Source

Rectangular Signal [12, p. 779]

- Infinite rise and fall times
- In time domain:

$$v_{\mathrm{out}} = A \cdot \mathrm{rect}\left(\frac{t}{T} - 0.5 \cdot D\right)$$

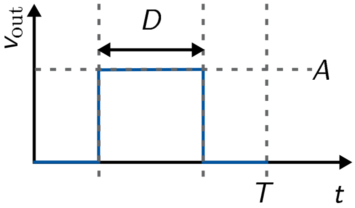
- In frequency domain:

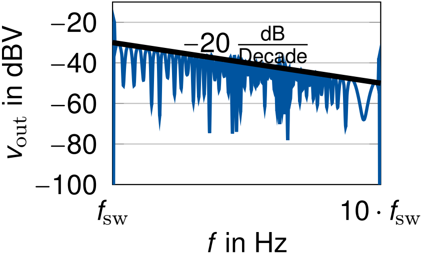
$$c_{n,rect} = 2AD \cdot \frac{\sin\left(\pi n D\right)}{\pi n D}$$

- First harmonic frequency f_{sw}
- Reduction of $-20\,\frac{\mathrm{dB}}{\mathrm{Decade}}$

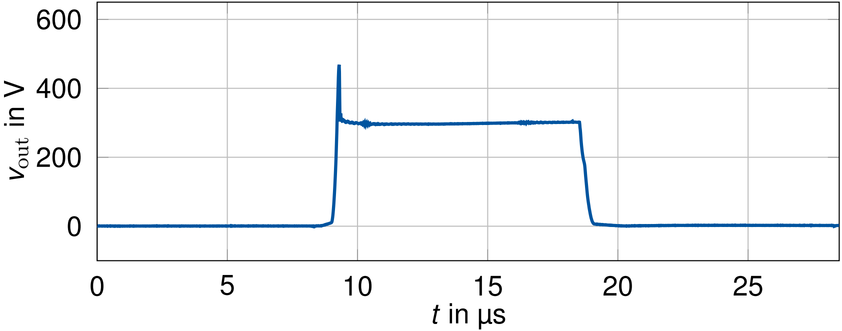
Fourier series:

$$v_{\mathrm{CE}} = \sum_{n=-N}^{N} \underline{c}_n \cdot e^{-\mathrm{j}2\pi f_{\mathrm{sw}} nt}$$





Example: IGBT Switching Behavior



- DC-link voltage of $V_{\text{DC}} = 300\,\text{V}$
- **Finite** switching times (here in the range of 100 ns)
- Overshoots at turn-off of the IGBT

Symmetric Trapezoidal Signal

- **Finite** switching slope:

$$t_{\text{rise}} = t_{\text{fall}} \text{ with } f_{\text{rise}} = \frac{1}{t_{\text{rise}}}$$

- Boundary condition:

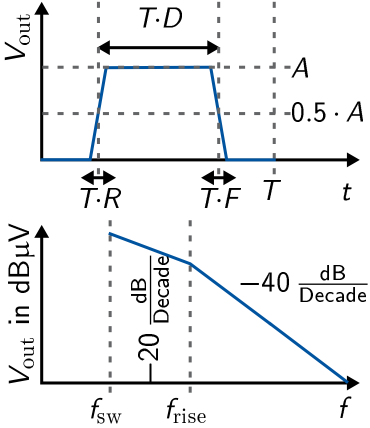
$$D + \frac{R}{2} + \frac{F}{2} \leq 1$$

with $F = t_{\text{fall}}/T$ and $R = t_{\text{rise}}/T$

- Two cut-off frequencies each with $-20\,\frac{\text{dB}}{\text{Decade}}$
- Real Fourier coefficients:

$$c_{\text{sym,trap}} = 2AD \cdot \frac{\sin(\pi nD)}{\pi nD} \cdot \frac{\sin(nR)}{nR}$$

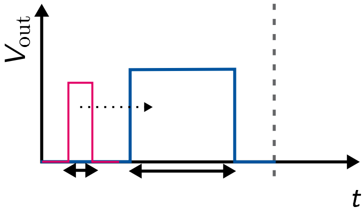
with: $R = t_{\text{rise}}/T$



Symmetric Trapezoidal Signal in Frequency Domain [13]

- Direct model in frequency domain
- Usage of convolution:

$$s_{\mathrm{trap}}(t) = s_{\mathrm{pwm}}(t) * s_{\mathrm{slope}}(t)$$

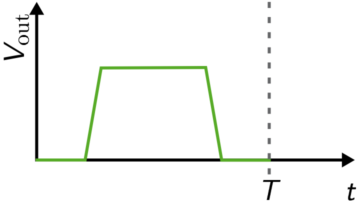


- Graphical model with
  - Rectangular switching function:

$$s_{\mathrm{pwm}}(f) = 2 \cdot DA \cdot \mathrm{sinc}(\pi f \cdot DT)$$

  - Smoothening function:

$$s_{\mathrm{pwm}}(f) = \mathrm{sinc}(\pi \cdot f \cdot t_{\mathrm{slope}})$$



Models 1: Source

Asymmetric Trapezoidal [14], [15]

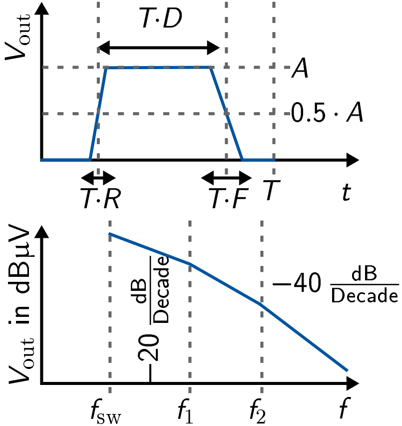
- **Finite** switching slope:

$$t_{\mathrm{rise}} \neq t_{\mathrm{fall}}$$

- Transition between the $-20\,\frac{\mathrm{dB}}{\mathrm{Decade}}$ and $-40\,\frac{\mathrm{dB}}{\mathrm{Decade}}$
- Complex Fourier coefficients:

$$\underline{c}_{\mathrm{n,unsym}} = \frac{\mathrm{j}2A}{\pi n} \cdot \left(\mathrm{sinc}(nR)\, \exp^{\mathrm{j}\pi nD} - \mathrm{sinc}(\pi nF)\, \exp^{-\mathrm{j}\pi nD} \right)$$

with $\mathrm{sinc}(x) = {}^{\sin(x)}/_{x}$,
$f_1 = {}^{1}/_{\max(t_{\mathrm{rise}}, t_{\mathrm{fall}})}$ and $f_2 = {}^{1}/_{\min(t_{\mathrm{rise}}, t_{\mathrm{fall}})}$

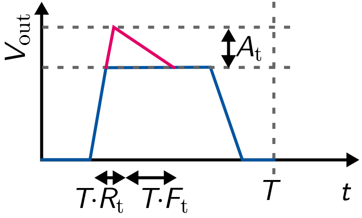


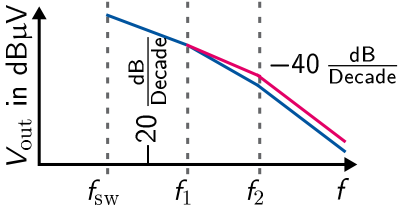
Model of Switch: Unsymmetrical Trapezoidal with Overshoot [16]

- Model of an overshoot with a triangle
- Additional components in the transition range
- Complex Fourier coefficients:

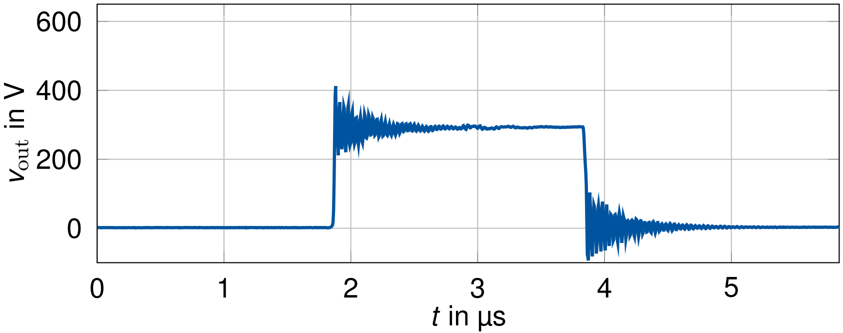
$$\underline{c}_{\mathrm{n,tri}} = \underline{c}_{\mathrm{n,unsym}} + \frac{\mathrm{j}2A_{\mathrm{t}}}{\pi n} \cdot \exp^{\mathrm{j}\pi n(D+R+R_{\mathrm{t}}+D_{\mathrm{t}})} \left(\mathrm{sinc}(\pi n R_{\mathrm{t}}) \exp^{\mathrm{j}\pi n D_{\mathrm{t}}} - \mathrm{sinc}(\pi n F_{\mathrm{t}}) \exp^{-\mathrm{j}\pi n D_{\mathrm{t}}}\right)$$

with $F_{\mathrm{t}} = t_{\mathrm{fall,t}}/T$, $R_{\mathrm{t}} = t_{\mathrm{rise,t}}/T$ and $D_{\mathrm{t}} = (R_{\mathrm{t}}+F_{\mathrm{t}})/2$





Example: Switching of Silicon carbide (SiC) MOSFETs



- Module oscillations in frequencies above 10 MHz
- Often caused by parasitic elements of the module.

Model of Switch: Asymmetric Trapezoidal with Oscillation [16]

- Additional damped sinusoidal signal:

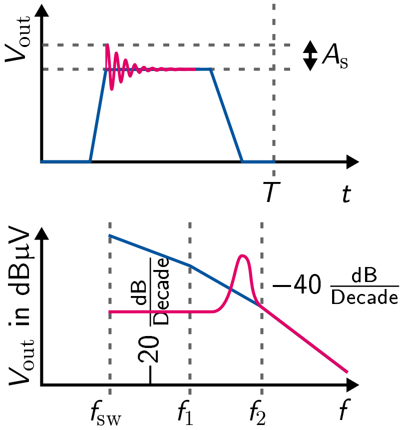
$$s_{\sin}(t) = A_{\mathrm{s}} \cdot \sin\left(\frac{2\pi t}{T}\right) \exp^{-t/B_{\mathrm{s}}}$$

B_{s} is damping factor

- Often based on module internal parasitic elements
- Complex Fourier coefficients:

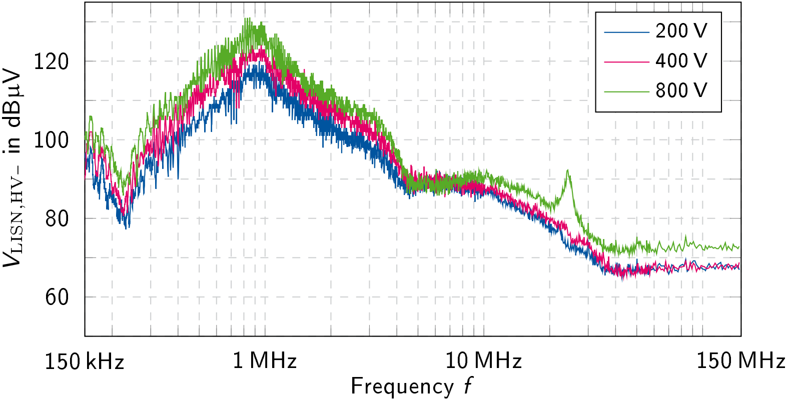
$$\underline{c}_{\mathrm{n,sin}} = \underline{c}_{\mathrm{n,unsym}} + \frac{\mathrm{j}2A_{\mathrm{s}}k_{\mathrm{s}}}{\pi} \cdot \frac{1 - \exp^{-(1/B_{\mathrm{s}} + \mathrm{j}2\pi n)}}{n^2 + k_{\mathrm{s}}^2 - (2\pi B_{\mathrm{s}})^{-2} + \mathrm{j}n(\pi B_{\mathrm{s}})^{-1}} \cdot \exp^{-\frac{\mathrm{j}\pi n}{2}(n(D+R)+1)}$$

with $k_{\mathrm{s}} = f_{\sin} T$



Models 1: Source

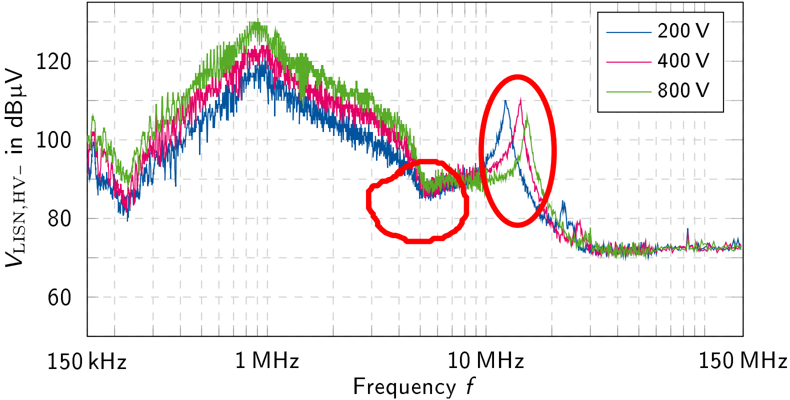
Emissions of an Si IGBT [10]



- Si 1.2 kV IGBT with different dc-link voltages
- Emission above 10 MHz does not occur with lower voltages.

Models 1: Source

Emissions of an SiC MOSFET [10]

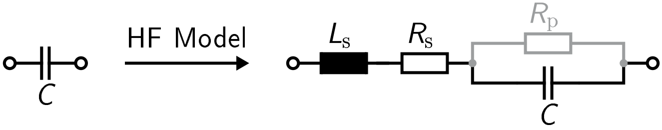


- SiC 1.2 kV MOSFET with different dc-link voltages
- Compared to Si IGBT, the resonance above 10 MHz changes with the voltage.

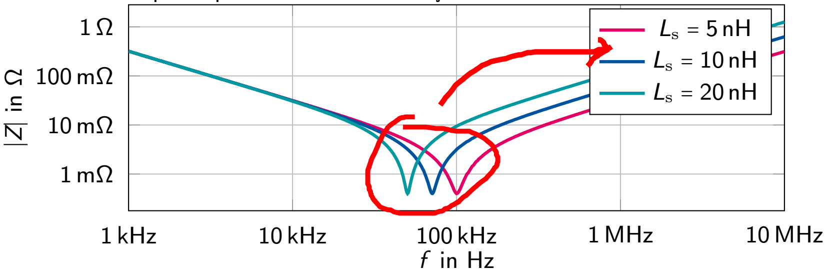
How to describe passive components?

Models 1: Passives

High-Frequency Capacitor Model [17, p. 32]



Example: Epcos FS800R07 for HybridPACK 2™:

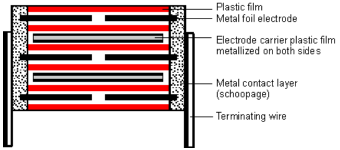


with $C = 500\,\mu\text{F}$, $R_s = 0.1\,\text{m}\Omega$ and $R_p \rightarrow \infty$

Models 1: Passives

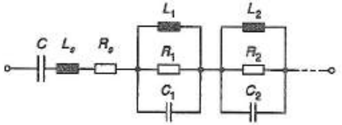
Impact of Floating Electrodes [18]

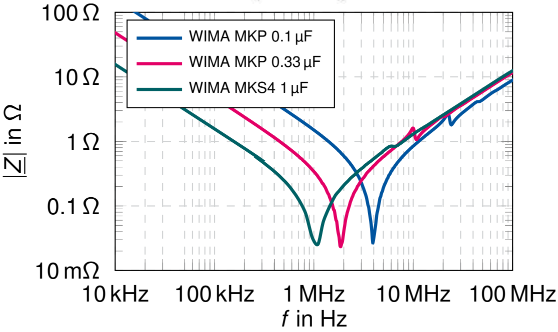
- Used in high-voltage capacitors for pulse currents (snubbers, filters)
- Resonance due to floating electrodes occurs.



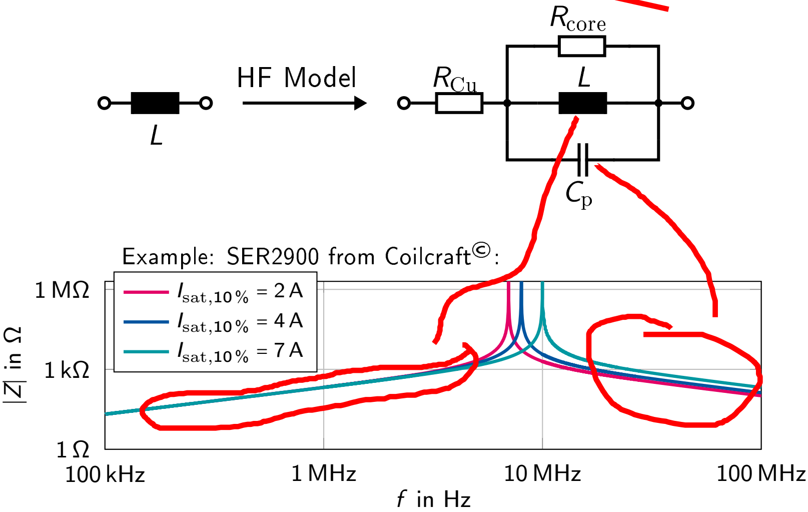
Source: www.wima.de

Capacitor with floating electrodes [18]



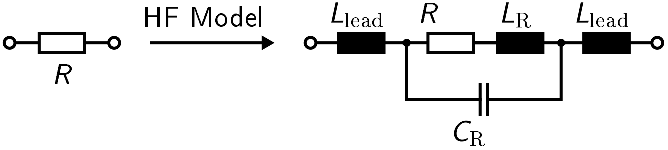


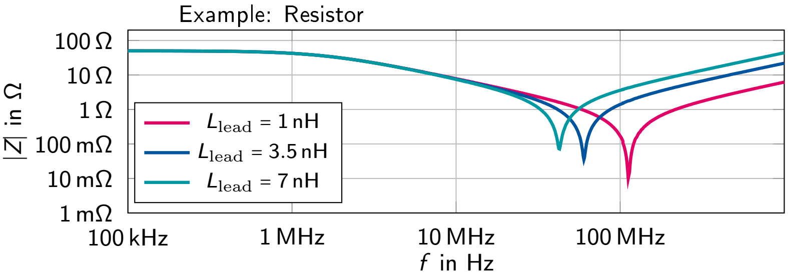
High-Frequency Inductor Model [17, p. 34]



with $L = 33\,\mu\mathrm{H}$, $R_{\mathrm{s}} = 1.5\,\mathrm{m}\Omega$ and $R_{\mathrm{core}} \to \infty$

High-Frequency Resistor Model [6, p. 134] [19, p. 72]

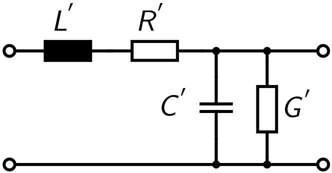


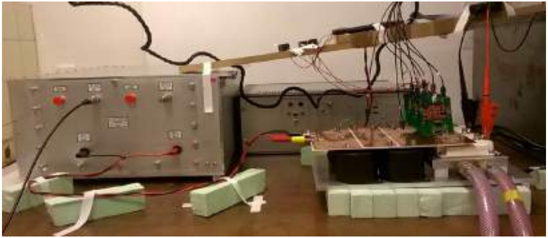


with $R = 50\,\Omega$, $L_{\mathrm{r}} = 5\,\mathrm{nH}$ and $C_{\mathrm{p}} = 2\,\mathrm{nF}$

High-Frequency Conductor Model [20, p. 149] [21]

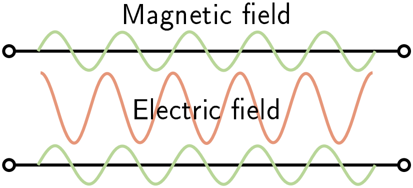
- Often **not** recognized as a component
- Immensely important for EMC
- Modeled with the telegraph equations

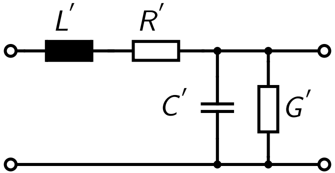




Telegrapher's Equations [21]

- Transmission line model
- Developed by Oliver Heaviside in 1880
- Modeled with the telegraph equations





Characteristic impedance:

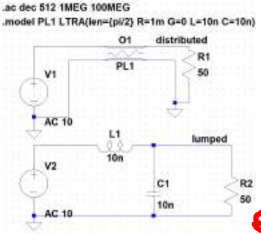
$$Z_c(\omega) = \sqrt{\frac{j\omega L + R}{j\omega C + G}}$$

Propagation function:

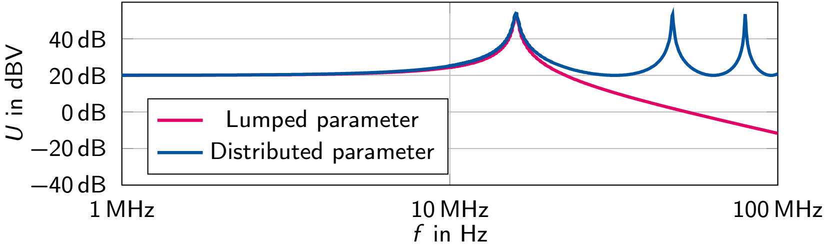
$$H(\omega, l) = \exp^{-l\sqrt{(j\omega L+R)(j\omega C+G)}}$$

Distributed vs. Lumped Element Model

- Depending on the frequency the lumped parameter model is valid.
- Above resonance the frequency the *CL* model is **invalid**.



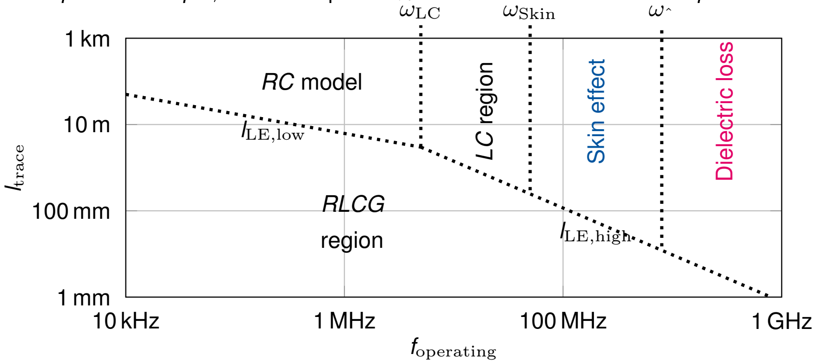
lumped
3/4
elmnt



Generalized Model for Conductive Media [21, p. 129]

$$\text{Characteristic impedance:} Z_c(\omega) = \sqrt{\frac{j\omega L(\omega) + R(\omega)}{j\omega C(\omega) + G(\omega)}}$$

Example: $w = 150\,\mu\text{m}$, $\Delta = 0.25\,\text{Np} \approx 3.2\,\%$ *error and* $50\,\Omega$ *with FR-4 strip line*



Conductor: *RC* Region [21, p. 150]

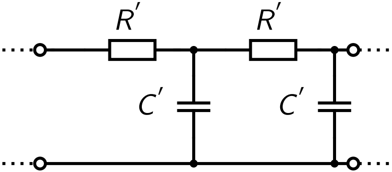
- Series inductance is neglected
- Critical length:

$$l_{\mathrm{LE,low}} \approx \frac{\Delta}{R_{\mathrm{DC}}}\sqrt{\frac{L}{C}}$$

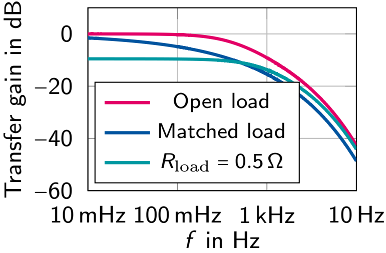
is valid for $\omega < R_{\mathrm{DC}}/L$

- Characteristic impedance:

$$Z_{\mathrm{C,RC}} = \sqrt{\frac{R}{\mathrm{j}\omega C}}$$



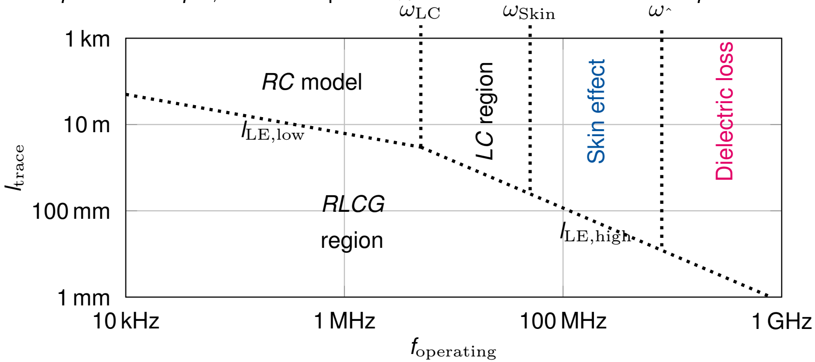
Example: $R = 1\,\Omega/\mathrm{m}$, $C = 1\,\mathrm{F/m}$ and $l = 1\,\mathrm{m}$



Generalized Model for Conductive Media [21, p. 129]

Characteristic impedance: $Z_c(\omega) = \sqrt{\frac{j\omega L(\omega)+R(\omega)}{j\omega C(\omega)+G(\omega)}}$

Example: $w = 150\,\mu m$, $\Delta = 0.25\,Np \approx 3.2\,\%$ *error and 50 Ω with FR-4 strip line*



Models 1: Passives

Conductor: LC Region [21, p. 166]

- Known as constant loss region
- Lower limit of LC region:

$$\omega_{\mathrm{LC}} = \frac{R_{\mathrm{DC}}}{L}$$

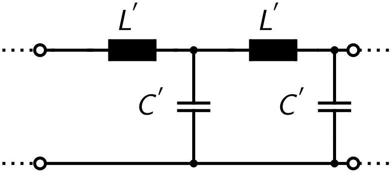
- Critical length for above behavior:

$$l_{\mathrm{LE,high}} \approx \frac{\Delta}{\omega\sqrt{LC}}$$

is valid for $\omega > R_{\mathrm{DC}}/L$

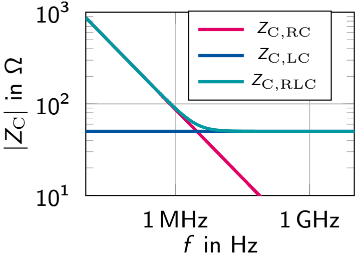
- Characteristic impedance:

$$Z_{\mathrm{C,LC}} = \sqrt{\frac{L}{C}}$$



Example: FR-4 50 Ω strip line with

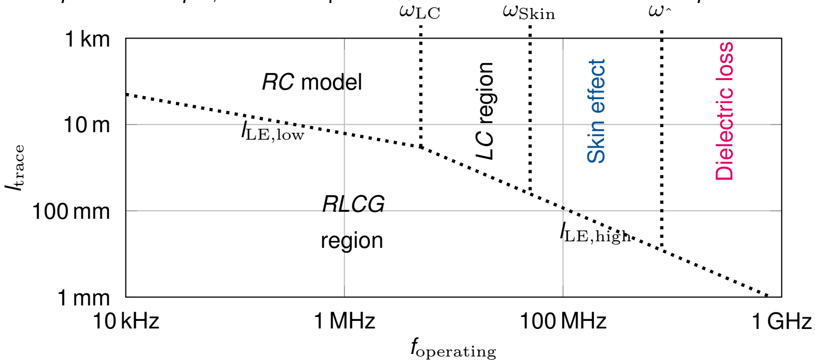
$L = 346\,\mathrm{nH/m}$, $C = 138\,\mathrm{pF/m}$



Generalized Model for Conductive Media [21, p. 129]

$$\text{Characteristic impedance:} Z_c(\omega) = \sqrt{\frac{j\omega L(\omega) + R(\omega)}{j\omega C(\omega) + G(\omega)}}$$

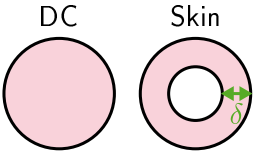
Example: $w = 150\,\mu\text{m}$, $\Delta = 0.25\,\text{Np} \approx 3.2\,\%$ *error and 50 Ω with FR-4 strip line*



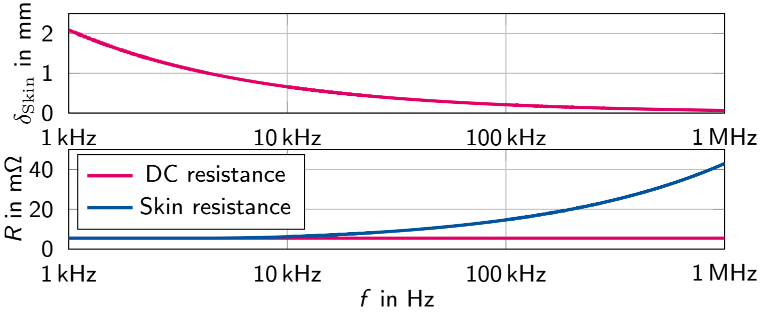
Conductor: Skin-Effect Region [1, p. 304f]

- Lower limit of skin-effect region:

$$\omega_{\text{skin}} = \frac{2}{\mu\sigma}\left(\frac{k_{\text{a}}p}{k_{\text{p}}a}\right)^2$$



Example: Round copper wire with $r_{\text{w}} = 1\,\text{mm}$ and $l = 1\,\text{m}$



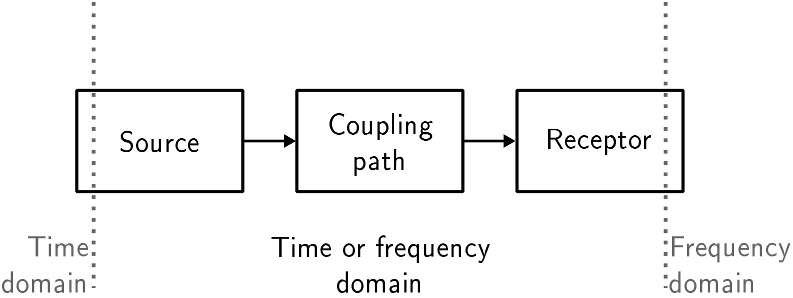
Break

Table of Contents

How do we put these components into a single simulation model?

Should we model in time or frequency domain?

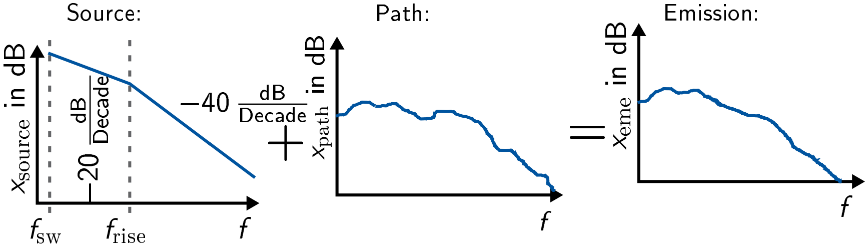
Why do we need both? [22], [23]



- Power electronic behavior is usually described in time domain.
- Assessment of electromagnetic emission (EME) is usually performed in frequency domain.

Models 2: Principles

Simulation in the Frequency Domain

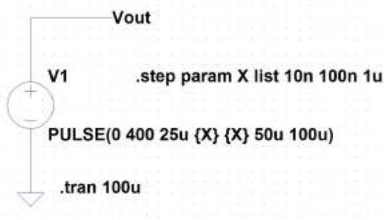


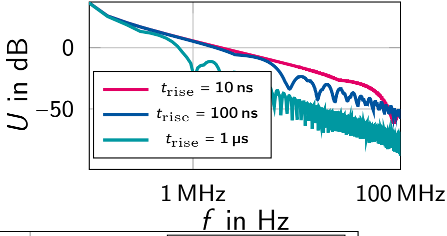
- Calculation

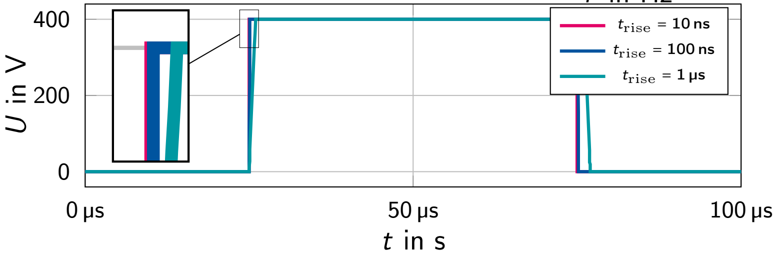
$$\log_{10}(x_{\text{source}} \cdot x_{\text{path}}) = \log_{10}(x_{\text{source}}) + \log_{10}(x_{\text{path}})$$

- Non-linearities in time domain not modeled
  e.g. saturation of inductors or voltage dependent capacitances
- Short simulation time (e.g. for filter design)

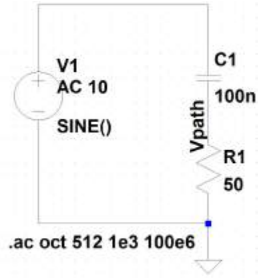
Simulation in the Frequency Domain: Source

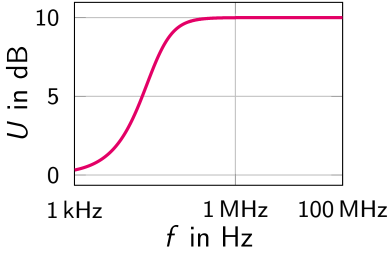






Simulation in the Frequency Domain: Path

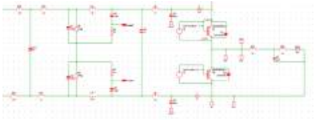


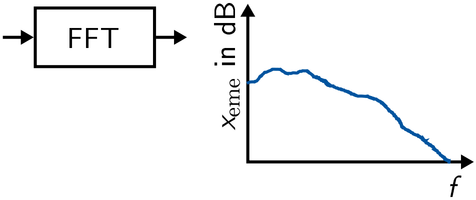


- Simple LTspice model is used to simulate the output signal of a path.

Models 2: Principles

Simulation in the Time Domain





- Usage of traditional software (e. g. LTspice, SIMetrix).
- Including non-linearities in time domain, but not frequency domain (Skin effect).
- High simulation time.
- FFT with windows and coherent gain necessary.

Comparison: Time and Frequency Domain

Time domain:

- Non-linearities in time-domain (e.g. saturation, voltage dependent capacitors)
- Relatively slow
- Adaptive step size
- Non-linearities in frequency domain
- Fast Fourier transform (FFT) can cause numerical errors

Frequency domain:

- Non-linearities in frequency domain (Skin effect)
- Regulatory limits checked in frequency domain
- Linear system in one operating point $C = f(V)$

Conversion from Time to Frequency Domain [24, p. 30]

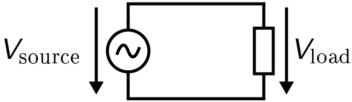
1. Simulation in time domain and evaluation in time domain.
2. Simulation in time domain and transformation of results.
3. Simulation of switching behavior in time domain, but disturbance path in frequency domain.
4. Sources and disturbance path in frequency domain.

Concept	1	2	3	4
Work effort	☹☹	☹☹	neutral	☺
Computational effort	☹☹	☹☹	neutral	☺☺
Noise source evaluation	☹	☹	☹	☺☺
Troubleshooting	☹☹	☹☹	☺	☺☺
Non-linearities	☺☺	☺☺	☹	☹☹

How to understand complex propagation paths?

Models 2: Principles

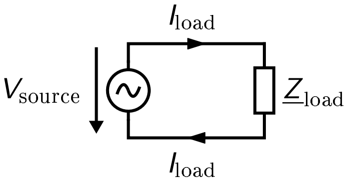
One Path



$$V_{\text{source}} = V_{\text{load}}$$

- Okay, this is obvious.

One Path with Currents

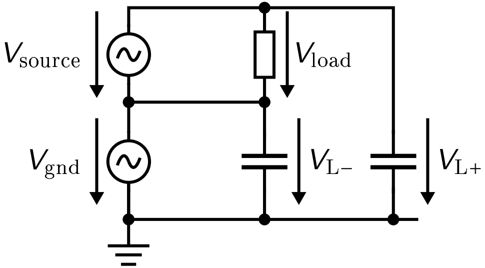


- We added the currents.
- Still obvious.

$$V_{\text{source}} = \underline{Z}_{\text{load}} \cdot I_{\text{load}}$$

But: Where is the ground?

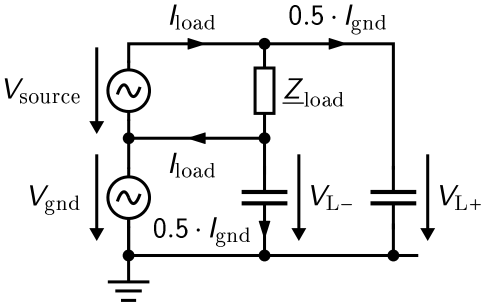
Ground Path



- We add capacitors to ground.
- First, we look again at the voltages.
- **Now:** Two circuits!

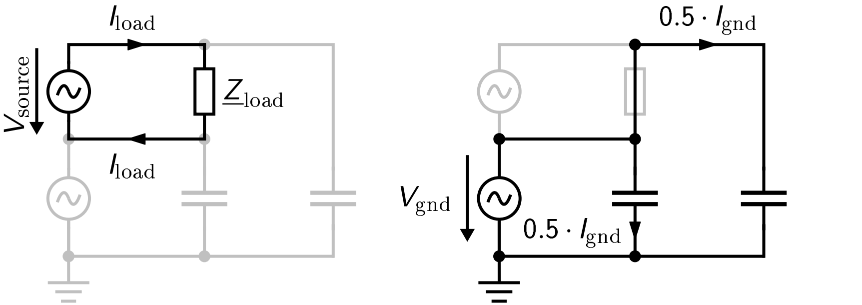
Models 2: Principles

Ground Path with Currents



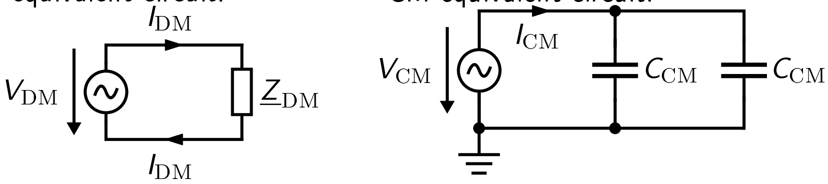
- **Assume:** Symmetric system.
- Currents can be added using the superposition principle.
- A system symmetric to ground is separable:
  - Common mode (CM)
  - Differential mode (DM)

Common and Differential Mode



DM equivalent circuit:

CM equivalent circuit:



Calculation of CM Elements

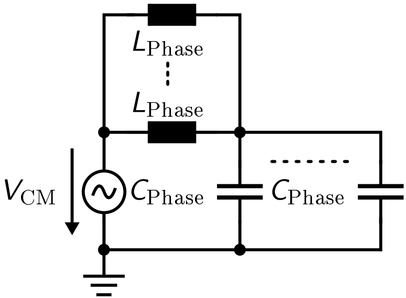
- Number of phases: p
- Calculation for parallel inductors:

$$L_{\mathrm{x,CM}} = \frac{1}{p} \cdot L_{\mathrm{x,Phase}}$$

Equal relation for resistor

- Calculation for parallel capacitor:

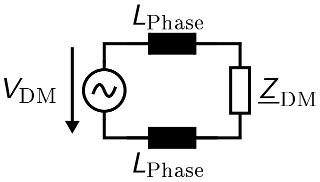
$$C_{\mathrm{x,CM}} = p \cdot C_{\mathrm{x,Phase}}$$



Models 2: Principles

Calculation of DM Elements

- Number of phases: p
- Calculation for parallel inductors:



$$L_{\mathrm{x,DM}} = p \cdot L_{\mathrm{x,Phase}}$$

Equal relation for resistor

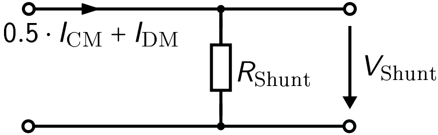
- Calculation for parallel capacitor:

$$C_{\mathrm{x,DM}} = \frac{1}{p} \cdot C_{\mathrm{x,Phase}}$$

Models 2: Principles

Limitations of Separation

- A separate ground is necessary
  → *Not at low voltage (LV) where GND conducts the return current.*
- Linear time-invariant system
  → *Superposition must be possible!*
- Keep in mind where you measure: V_{shunt}
  → *A shunt conducts common **and** differential mode*

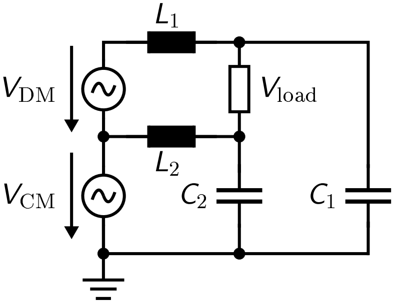


- Complete symmetric system (usually valid until 5 MHz [25])
  → *otherwise conversion from CM to DM.*

CM to DM Mode Conversion

- What if the system is not symmetric?
  $L_1 \neq L_2$ or/and $C_1 \neq C_2$

  Equal relation for resistor
- V_{CM} is measured in V_{load}
- Filtering and counter measures are more complicated.
- Symmetry also depends on the frequency range.



How to extract parameters for a complex propagation path?

Models 2: Principles

Parameter Extraction [10]

Tool chain for parameter extraction:

2D/3D modeling → Material definition → Lumped parameter extraction → Circuit simulation

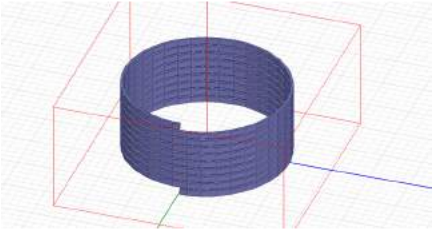
- **Lumped parameter extraction tools:**
  - Ansys Q3D Extractor
  - Fast Henry (free)
  - Fast Cap (free)
  - PEEC Methods [26]–[28]
- **SPICE based circuit simulators:**
  - LTspice (free)
  - Ansys Simplorer
  - PSpice
  - SIMetrix
- **Important file formats:**
  - ***.step**: Standardized format for 3D objects (ISO 10303-21)
  - ***.cir**: Circuit file to define lumped parameter extraction

SPICE (Simulation Program with Integrated Circuit Emphasis)
STEP (STandard for the Exchange of Product model data)

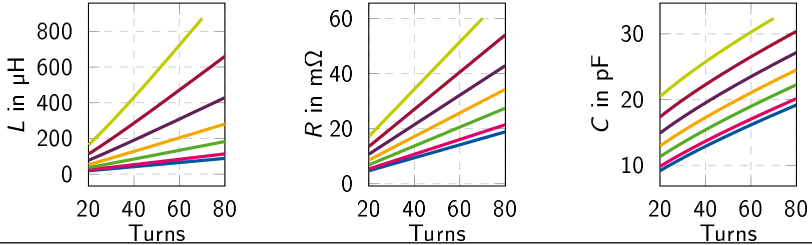
Example: Parameterized Helix Inductor [10]

- Helix simulation with Ansys Q3D Extractor
- Variable parameters:
  - Turns
  - Diameters
  - Wire distance
  - etc...

Helix Simulation with Q3D Extractor:



Diameter $D = 110\,\mathrm{mm} \ldots 400\,\mathrm{mm}$:

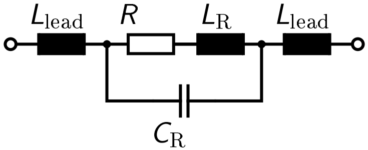


Let's apply the models to power electronic components.

Models 2: Components

Load

- Resistors
  - Breaking chopper
  - Balancing resistors
  - Heaters
- Machines
  - One phase
  - Three phase



150 Ω wire resistor with:

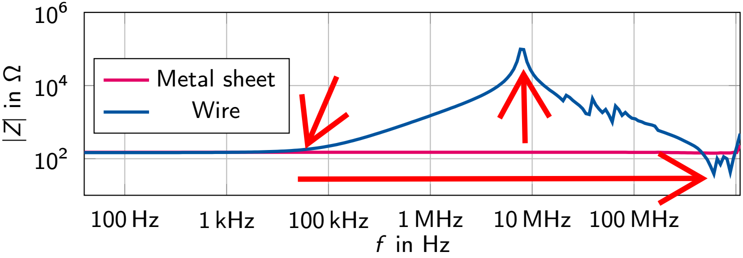
150 Ω metal sheet resistor:

Models 2: Components

Example: Resistor of 150 Ω

Wire resistor with 150 Ω:

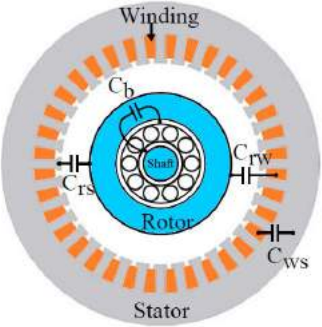
Metal sheet resistor with 150 Ω:



Electric Machine with Parasitic Elements [29], [30]

- Every model is different. It depends on the geometry.
- Parameters are normally determined by curve-fitting or FEM simulation

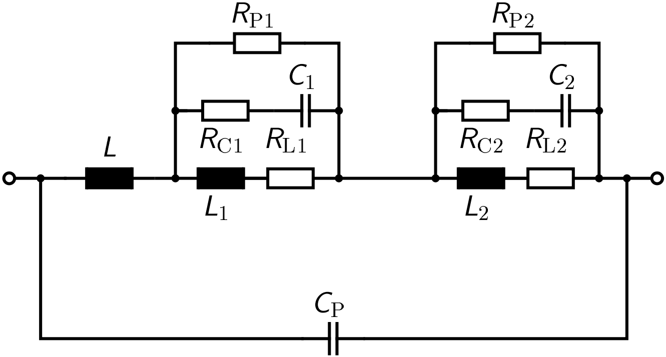
Parameters inside a machine:



Electric Machine with Parasitic Elements [29], [30]

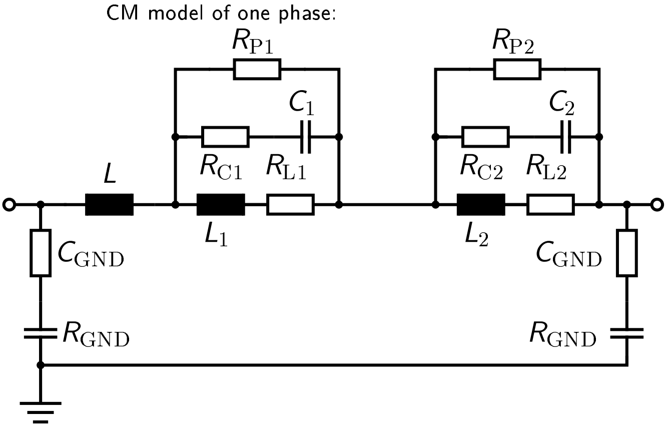
- Separation in CM and DM
- Parameters are normally determined by curve-fitting or FEM simulation

DM model of one phase:



Electric Machine with Parasitic Elements [29]

- To ground:

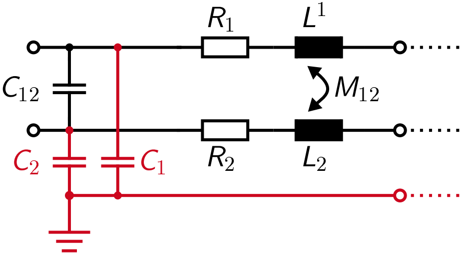


Cable [19, p. 117]

- Consists of
  two or more conductors
- Often overseen component
- Always (coupled) current loops
- Important for EME and EMS
- Important parameters:
  - Transfer impedance
  - Cross talk
- Cable variants:
  - Signal or power interconnects
  - Unshielded or shielded
  - Single or multi conductor
  - Electrically short or long

Models 2: Components

Cables Equivalent Circuit [19, p. 121]



- RL: Model of each conductor
- M: Mutual inductance between conductors
- C: Capacitances between wires and ground

Capacitance of Two Parallel Wires [31, p. 124]

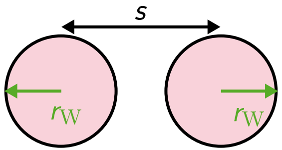
- Approximate Capacitance for $r_\mathrm{W} \ll s$:

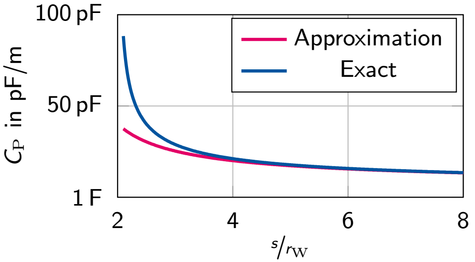
$$c \approx \frac{\pi\epsilon}{\ln\left(\frac{s}{r_\mathrm{W}}\right)}$$

- Exact:

$$c = \frac{\pi\epsilon}{\cosh^{-1}\left(\frac{s}{2r_\mathrm{W}}\right)}$$

- Wire to ground can easily be calculated with this equation and method of virtual charge.





Parasitic Elements Perspective

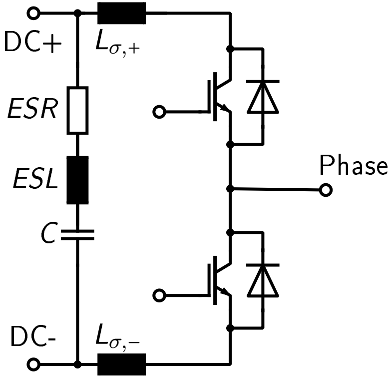
- The converter consists of several different parasitics.
- Causes significant resonances in the frequencies above 10 MHz.
- Detailed analysis of each module and converter is necessary.
- Different perspectives:
  - Chip
  - Gate driver
  - Switching cell
  - Dc link

Different 62 mm modules:

Parasitic Elements: Switching Cell with DC Link [16], [32]

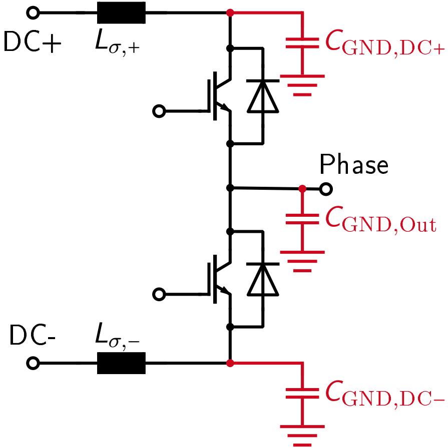
- Dc link is part of the switching cell
- Commutation inductance:

$$L_{\sigma,\mathrm{tot}} = L_{\sigma,+} + ESL + L_{\sigma,-}$$



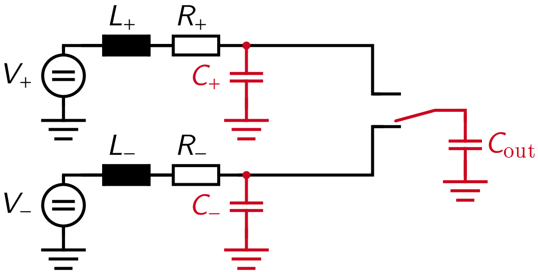
Parasitic Elements: Switching Cell with GND [10], [33], [34]

- Ground path via power electronic substrate or cooler.
- $C_{\mathrm{GND,Out}}$ is charged and discharged depending on the switching state.

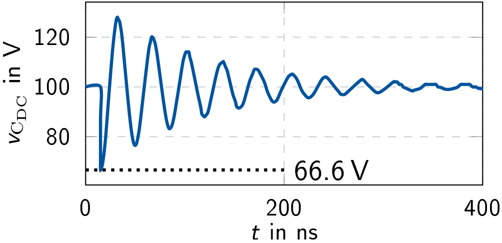


Models 2: Components

Half bridge with base plate capacitance[10]



Component	Value
L_+, L_-	50 nH
R_{ESL}	1 Ω
C_+, C_-	500 pF
$C_{\mathrm{out+}}$	100 pF
V_+	100 V
V_-	−100 V

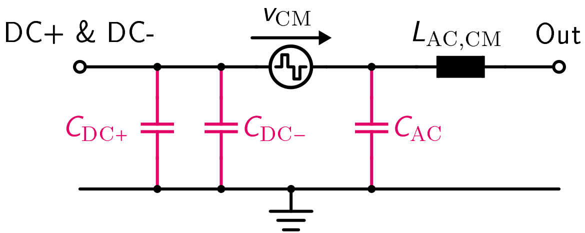


$$Q_{\mathrm{C+}} = 500\,\mathrm{pF} \cdot 100\,\mathrm{V} = 50\,\mathrm{nC}$$

$$Q_{\mathrm{Cout}} = 100\,\mathrm{pF} \cdot (-100\,\mathrm{V}) = -10\,\mathrm{nC}$$

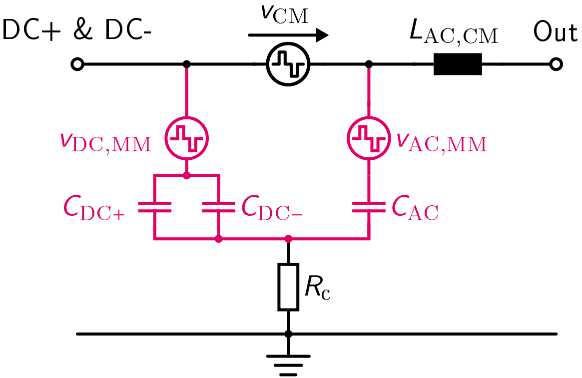
$$V_{\mathrm{step}} = \frac{40\,\mathrm{nC}}{600\,\mathrm{pF}} = 66.66\,\mathrm{V}$$

Half bridge: Common Mode[36], [37]



- Functional system is not included in this model.
- Top and bottom switches are replaced by single voltage source.
- Differential mode emissions are not modeled with this approach.

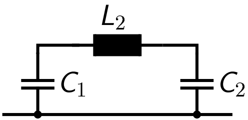
Half bridge: Mixed Mode Model [38], [39]



- One approach to include CM/DM conversion into this model.
- This should fix the inherent problem, of the CM/DM approach, using mixed mode.

Simulation of Parallel Capacitors: Setup

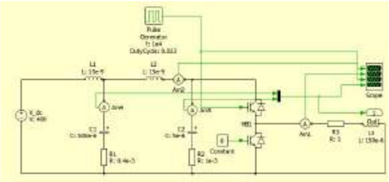
Simulation in time and frequency domain:



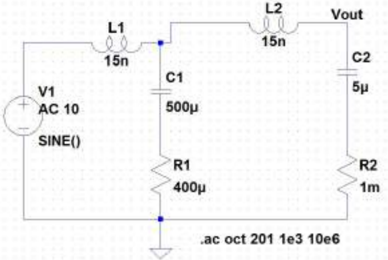
Resonance frequency:

$$f_{\text{res}} = \frac{1}{2\pi \cdot \sqrt{L_2 \cdot \frac{C_1 \cdot C_2}{C_1 + C_2}}}$$

Simulation with PLECS:

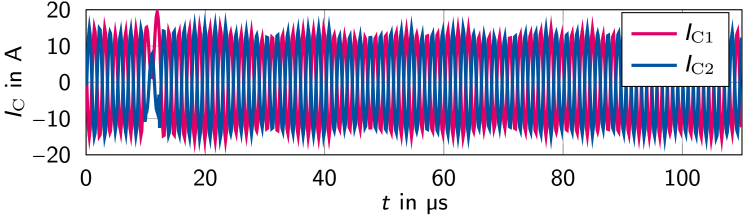


Simulation with LTspice:

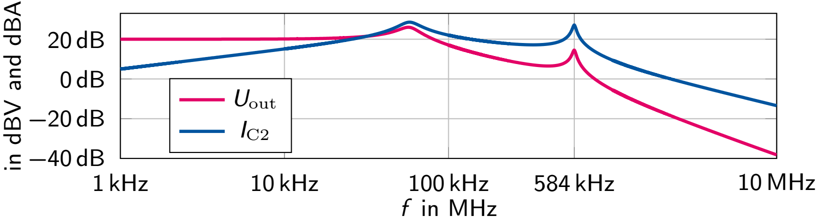


Simulation of Parallel Capacitors: Results

Results of simulation with PLECS:



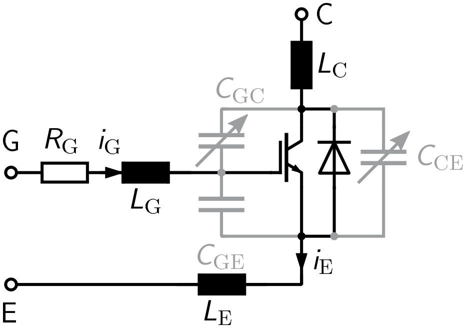
Results of simulation with LTspice:



Models 2: Components

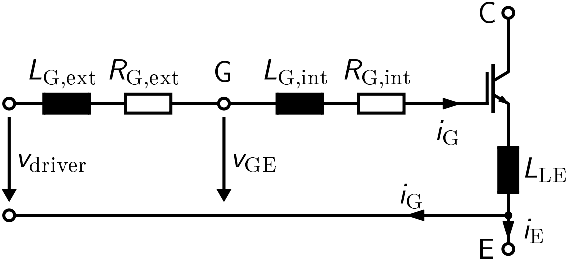
Parasitic Elements: Chip [33], [40], [41]

- Partial inductances impact the switching behavior.
- Different impact of all chip parasitic elements.
- Voltage dependent capacitances impact resonance frequencies.



Models 2: Components

Inductive Elements in the Gate Path [41]

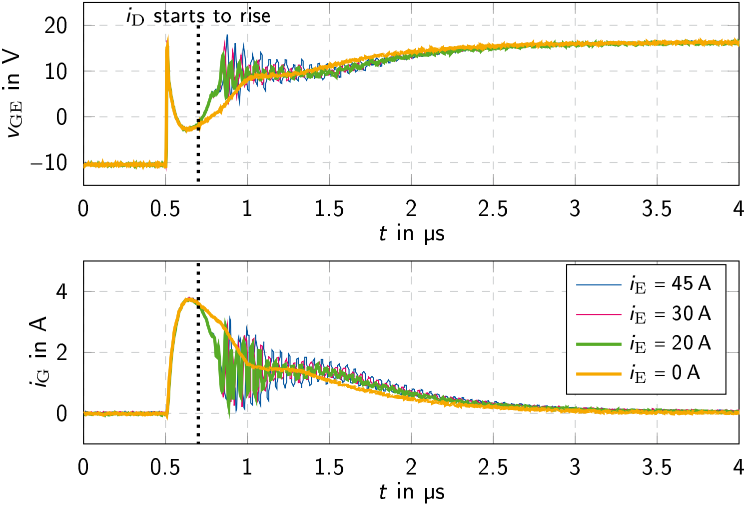


- **Inductive Elements in the Gate Path:**
  - Internal inductance of the package: $L_{\mathrm{G,int}}$
  - External inductance of the driver: $L_{\mathrm{G,ext}}$
  - Coupling inductance of i_{G} and i_{E}: L_{LE}
- **Influence of emitter current on gate path:**

$$v_{L,\mathrm{GE}} = L_{\mathrm{GE}} \cdot \frac{\mathrm{d}(i_{\mathrm{E}} + i_{\mathrm{G}})}{\mathrm{d}t} \tag{1}$$

Example: Power Current effects Gate Voltage

Measurement of gate-emitter voltage and gate current:

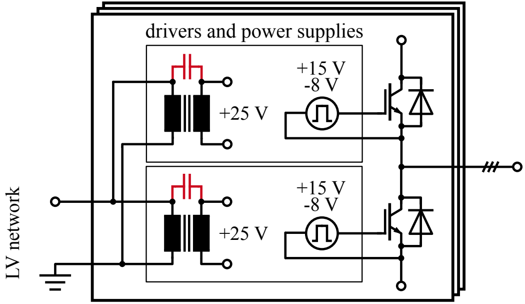


Gate Driver and other Auxiliary Supplies [42]–[44]

- Connection between high voltage (HV) and LV supplies.
- Remember capacitive coupling:

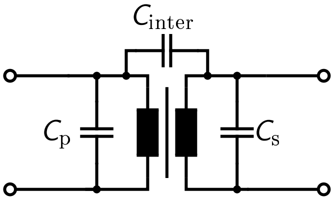
$$i_C = C \cdot \frac{\mathrm{d}v_C}{\mathrm{d}t}$$

- Coupling capacity in the range of a few pF

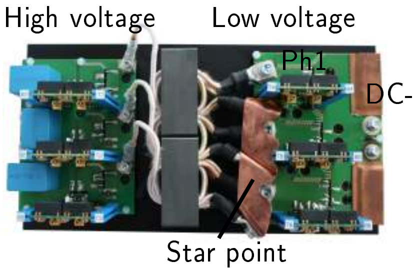


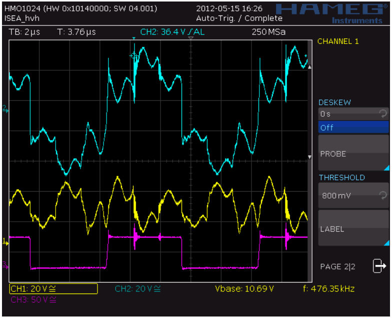
High-Frequency Transformer Model [17, p. 34] [20, p. 145]

- No isolation of a transformer is perfect at all frequencies.
- Parasitic elements strongly depend on the geometric design.



Parasitic Capacitances in a Three-Phase DAB Transformer

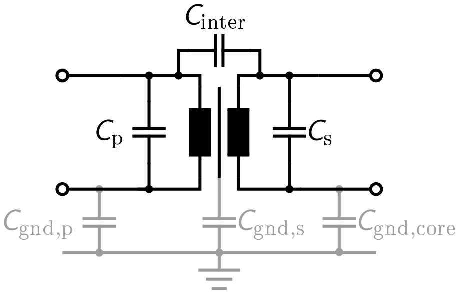




- Output voltage (CH3), star point of transformer to DC- voltage (CH2) and superposition of both (CH1)
- Significant oscillation in the star point due to parasitic capacitance.

High-Frequency Transformer Model with GND [19, p. 73]

- Isolated grids e.g. in high voltage automotive network.
- Extended a transformer to a five/six terminal component.



Break

Table of Contents

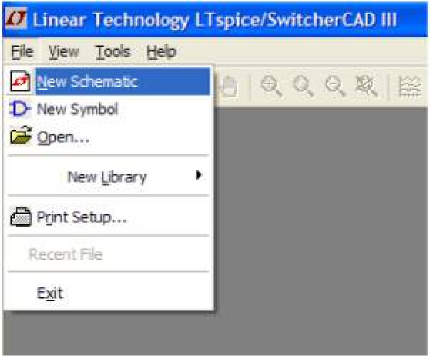
Simulation

Brief Introduction to LTspice

Getting to Know the Software

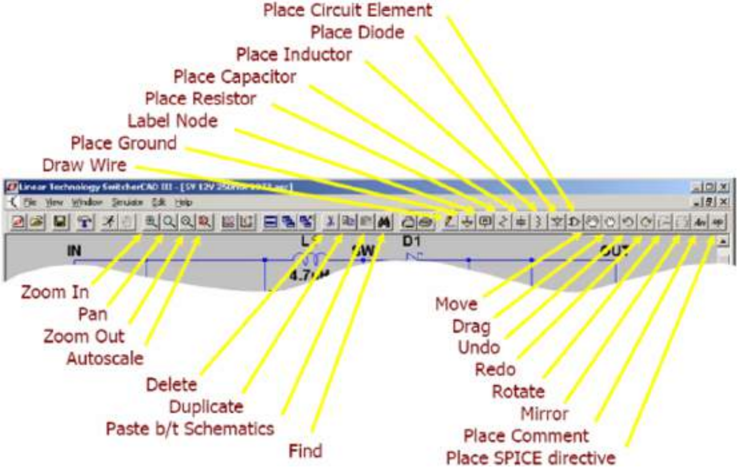
- Install LTspice
- Graphical user interface
  - Which elements?
  - Shortcuts
  - Elementary functions
- Simulation in the time and frequency domain
- Tricks for signal generation

Create a New Schematic



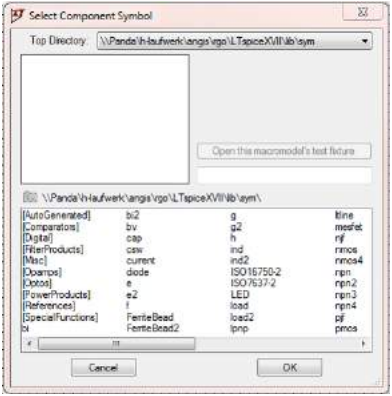
Simulation

Toolbar



Add New Component

- Select component with 



Edit Component Properties

- Edit basic settings → Right click on component

Access to component model libraries from manufacturers & users

- Unit suffix (*Case insensitive*)

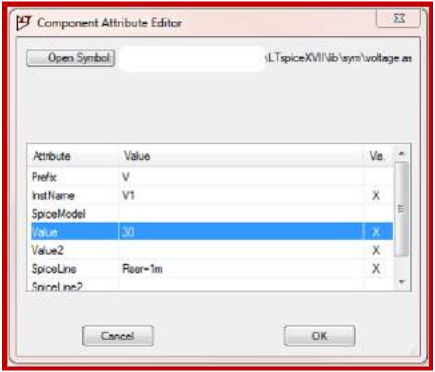
Prefix	Factor	Prefix	Factor	Prefix	Factor
f	10^{-15}	u	10^{-6}	MEG	10^{6}
p	10^{-12}	m	10^{-3}	G	10^{9}
n	10^{-9}	K	10^{3}	T	10^{12}

For 1 Farad, type: 1, NOT 1F!

right click

Component Attribute Editor

- Open with "Ctrl + left click on component"
  - Prefix: Type of component
  - Value: Any expression respecting the LTspice syntax



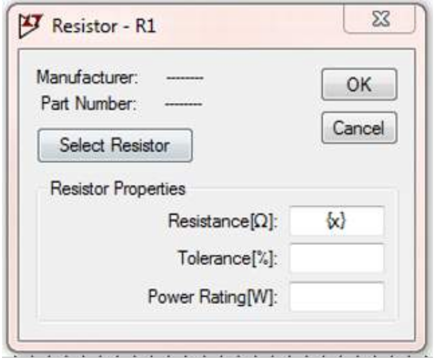
Simulation

Parameters & Variables

- Define variable component parameters:
  - Set component parameter to: {var}
  - Add LTspice directive to the schematic: .param var=val
- Parameter sweep over variable var: *.step param* command
  - Variants:
    - Sweep through a list of values (*val1, val2, ...*):
      .step param var list val1 val2 val3
    - Linear sweep across interval $[val_{start}; val_{end}]$ in finite steps val_{inc}:
      .step param var val_{start} val_{end} val_{inc}
    - Logarithmic sweep across interval $[val_{start}; val_{end}]$ in finite steps $val_{perDecade}$: .step DEC param var val_{start} val_{end} $val_{perDecade}$
  - Right click on cursor relates parameter run and corresponding curves
    - Scroll through the different curves with the cursor by using the "up" and "down" keys.

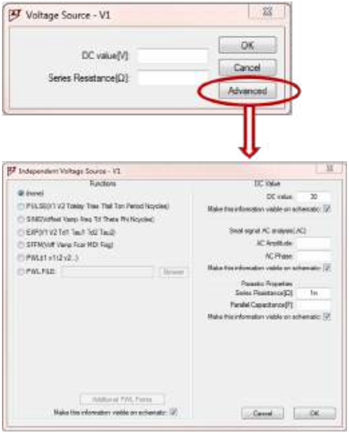
Simulation

Parameters & Variables

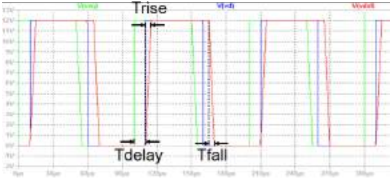



```
.param x = 4
```

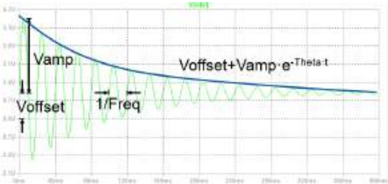
Voltage Source Configuration



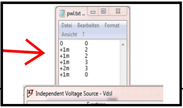
- Pulse



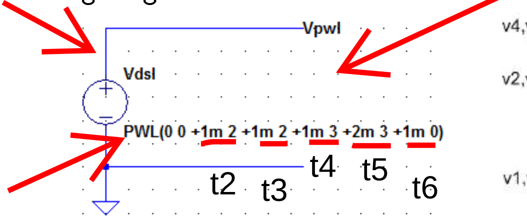
- Sine



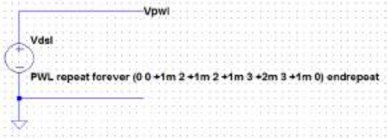
Voltage Source: PieceWise Linear (PWL) functions

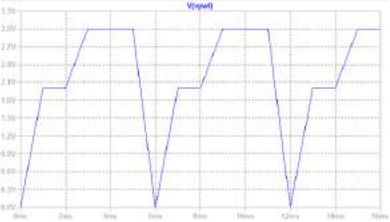


- Single signal:

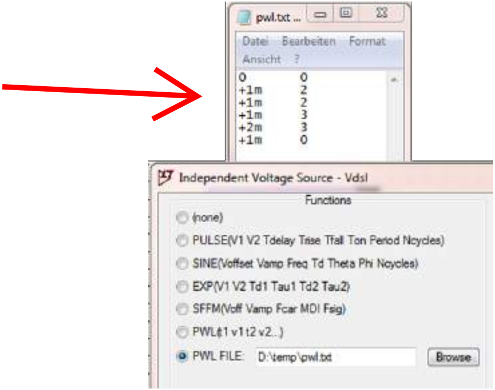


- Repeated signal:





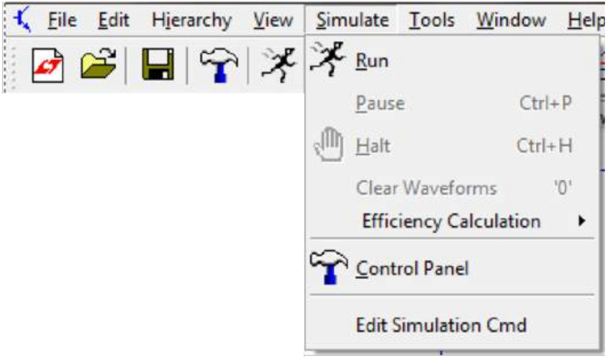
Voltage Source: PieceWise Linear (PWL) file



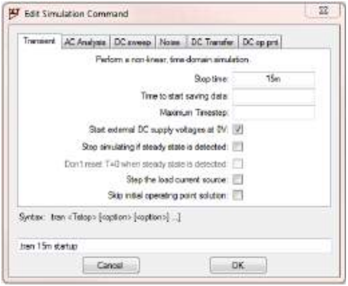
Select Simulation Type

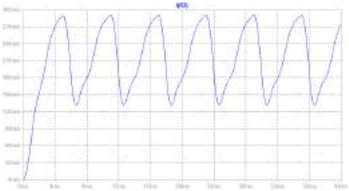
- Start simulation: 

- Edit simulation command:

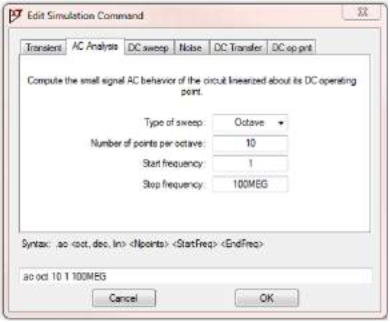


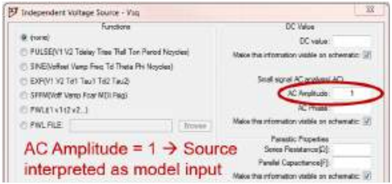
Transient "Time-Domain Simulation" Analysis

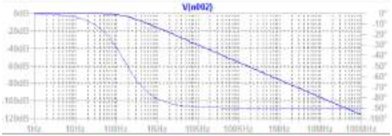




AC Analysis: "Frequency Response"







Suppress phase plot: Right click on phase scale → "Don't plot phase."

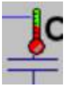
Simulation

Measurements

- Plot simulation results: Hover mouse over component & left click.
  - Voltage probes: 
    - Voltage to ground: Left click → Red voltage probe
    - Voltage across two points:
      Option 1: Left click & hold, drag from one point to the other
      Option 2: Right click on reference node (other tan ground), select "Mark Reference" and left click on any other point of interest:

  - Current probe: 

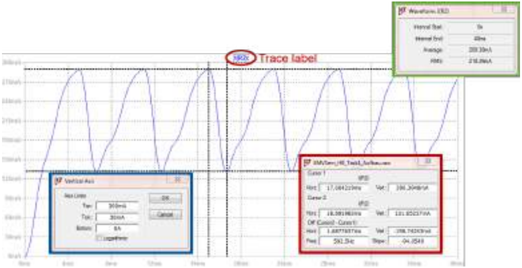
    Current in a wire: Hold down ALT key & left click on wire segment.
- Power measurement: Hold down ALT key & left click on component



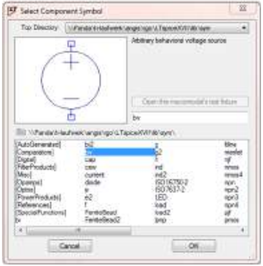
Simulation

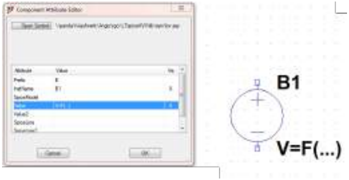
Plot Tools

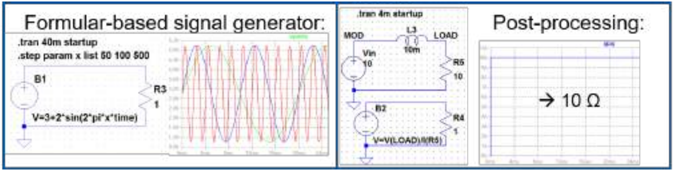
- Use of cursors:
  - Left click on trace label → One cursor.
  - Double left click on trace → Two cursors (+ difference between cursors)
- Scale options: Right click on scale
- Waveform characteristics: Ctrl+left click on trace label



Tips and Tricks: Behavioral Voltage Source



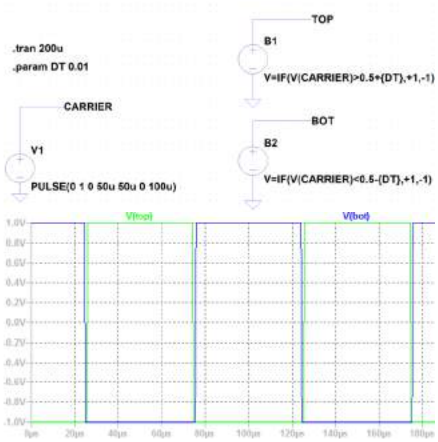




Simulation

Tips and Tricks: Behavioral Voltage Source

- Use of behavioral voltage source to compose PWM carrier signals for high-side and low-side switches



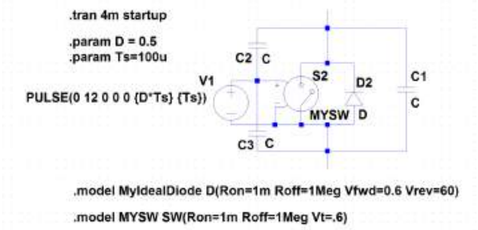
Tips and Tricks: Ideal Switch Cell Model

- Ideal switch model with tunable parameters: .model MYSW
- Ideal diode model with tunable parameters: .model MyIdealDiode
- Modulator: Pulsed voltage source V1
- Parasitic capacitances C, C2, C3

Keep in mind:

Care must be taken when using the component models from available LTspice libraries, as the underlying assumptions are not always clear!

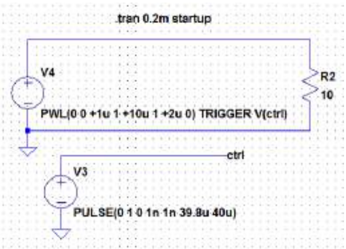
→ *By defining an own ideal switch cell model, implicit assumptions are made explicit.*

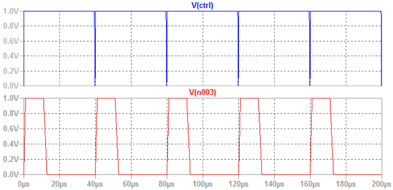


Simulation

Triggered Source

- Command suffix: TRIGGER var > val
  → Default: val = 0.5
- V4 is triggered every time V(ctrl) exceeds val (here: 0.5 V)
- Applicable to all kinds of sources by simply appending the trigger command.





Simulation

Hot Keys

Function	Hot Key
Place Component	F2
Draw Wire	F3
Place Netname	F4
Delete	F5
Duplicate	F6
Move (w/o wires)	F7
Drag (incl. wires)	F8
Undo	F9
Redo	Shift + F9
Comment	T
SPICE Directive	S

Function	Hot Key
Unconnected Pin	U
Text Anchor	A
Ground	G
Resistor	R
Capacitor	C
Inductor	L
Diode	D
Rotate	Ctrl+R
Mirror	Ctrl+E
Zoom to Fit	Space
SPICE Error Log	Ctrl+L

Task Description

Overview

Tasks

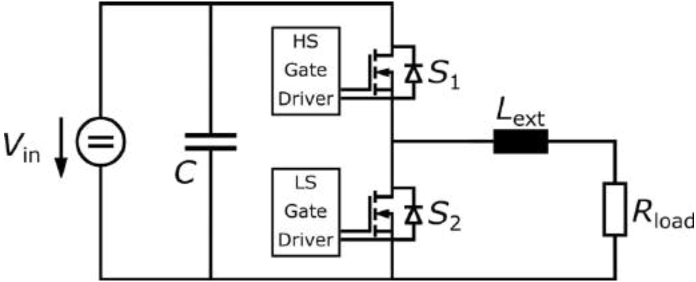
1. Ideal Half Bridge Circuit Model
2. Real Component Models
3. Conductor Model and Ground Path
4. Generic Switch Modeling
5. Frequency-Domain Simulation

Task 1: Ideal Half Bridge Circuit Model

- Implement an ideal circuit model of the depicted half-bridge converter in LTspice using the following parameters:
  - Input voltage: $V_{\mathrm{in}} = 30\,\mathrm{V}$
  - DC-link capacitance: $C = 33\,\mu\mathrm{F}$
  - Filter inductance: $L_{\mathrm{ext}} = 10.4\,\mathrm{mH}$
  - Load inductance: $R_{\mathrm{load}} = 150\,\Omega$
  - MOSFET model: BSZ036NE2LS
- Models the high-side (HS) and low-side (LS) gate drivers as shifted square-wave voltages, such that S_1 and S_2 are turned on alternatively and never conduct at the same time.
- Define variables for the duty cycle D and the switching periods T_{s}, and assign them the following values:
  - $D = 0.5$
  - $T_{\mathrm{s}} = 100\,\mu\mathrm{s}$
- Measure the current ripple at the load.

Simulation

Half-bridge converter with RL load:



Task 2: Real Component Models

- Extend the ideal half-bridge model from task 1 by introducing real component models for the passive elements. Assign the following parameters:
  - Capacitance C (internally):
    - Equivalent Series Resistance (ESR): $1\,\mathrm{n\Omega}$
    - Equivalent Series Inductance (ESL): $1\,\mathrm{nH}$
  - Inductance L_{exp} (internally):
    - ESR: $1\,\mathrm{\mu\Omega}$
    - Parallel resistance: $1\,\mathrm{M\Omega}$
    - Parallel capacitance: $1\,\mathrm{nF}$
  - Resistance R_{load} (additional elements):
    - Series inductance: $0.5\,\mathrm{nH}$
    - Parallel capacitance: $1\,\mathrm{nF}$
    - Lead inductance: $3.5\,\mathrm{nH}$
- Implement a parameter sweep over the resistor's parasitic:
  1. Series inductance L_{R} with $L_{\mathrm{R}} = 1\,\mathrm{nH}, 0.5\,\mathrm{\mu H}, 0.5\,\mathrm{mH}, 2.5\,\mathrm{mH}$ ($C_{\mathrm{R}} = 1\,\mathrm{nH}$)
  2. Parallel capacitances C_{R} with $1\,\mathrm{nF}$, $C_{\mathrm{R}} = 1\,\mathrm{\mu F}, 10\,\mathrm{\mu F}$ ($L_{\mathrm{R}} = 0.5\,\mathrm{\mu H}$)
- Plot the output voltage and the load current and interpret the effects.

Task 3: Conductor Model and Ground Path

- Insert a lumped high-frequency conductor model between the input voltage source V_{in} and the dc-link capacitance C, as well as between the external filter inductance L_{ext} and the load.
  ($L = 7\,\mathrm{nH}$, $R_{\mathrm{S}} = 1\,\mu\Omega$, $R_{\mathrm{P}} = 1\,\mathrm{M}\Omega$, $C_{\mathrm{P}} = 1\,\mathrm{nF}$)
- Introduce ohmic-capacitive ground path to the model, composed of a ground capacitance C_{gnd} and a parallel resistance R_{gnd}.
- Assume equal ground capacitance and resistance values for every ground path:
  - Ground capacitance: $C_{\mathrm{gnd}} = 100\,\mathrm{nF}$
  - Ground resistance: $R_{\mathrm{gnd}} = 1\,\mathrm{M}\Omega$
- Implement a parameter sweep over the ground capacitance C_{gnd} with $C_{\mathrm{gnd}} = 1\,\mathrm{nF}, 10\,\mathrm{nF}, 20\,\mathrm{nF}$. Plot the output voltage and the load current.
- What happens as the ground capacitance value increases?

Task 4: Generic Switch Modeling

- To accelerate the simulation, substitute the switch cell (including the input circuitry) which a voltage source, which generates the following switching signals:
  - Trapezoidal voltage waveform with rise and fall times T_r and T_f respectively.
    - Parameter sweep: $T_\mathrm{r} = T_\mathrm{f} = 1\,\mathrm{ns}, 1\,\mathrm{\mu s}, 5\,\mathrm{\mu s}, 10\,\mathrm{\mu s}$
  - Trapezoidal voltage waveform with dead time T_delay at turn-on.
    - $T_\mathrm{r} = 3\,\mathrm{ns}$
    - $T_\mathrm{f} = 1\,\mathrm{ns}$
    - Parameter sweep: $T_\mathrm{delay} = 0\,\mathrm{s}, 0.5\,\mathrm{\mu s}, 1\,\mathrm{\mu s}$
  - Trapezoidal voltage waveform with a damped oscillation at turn-on.
    - $T_\mathrm{r} = 3\,\mathrm{ns}$
    - $T_\mathrm{f} = 1\,\mathrm{ns}$
    - $T_\mathrm{delay} = 0.2\,\mathrm{\mu s}$
    - Voltage oscillation frequency: $1\,\mathrm{MHz}$
    - Damping factor: $100\,000\,1/\mathrm{s}$
    - Parameter sweep: Voltage oscillation amplitude $V_\mathrm{OSC} = 0\,\mathrm{V}, 1\,\mathrm{V}, 3\,\mathrm{V}, 10\,\mathrm{V}$
- Plot the power at the load. Make use of a behavioral voltage source.

Task 5: Frequency-Domain Simulation

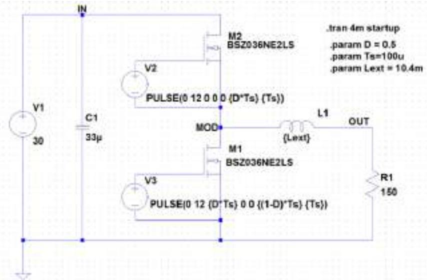
- Plot the frequency response of the circuit for varying cable inductances

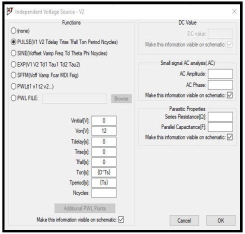
$$L_{\mathrm{cap}} = 7\,\mathrm{nH}, 250\,\mathrm{nH}, 1\,\mathrm{\mu H}, 10\,\mathrm{\mu H}, 0.5\,\mathrm{mH} \tag{2}$$

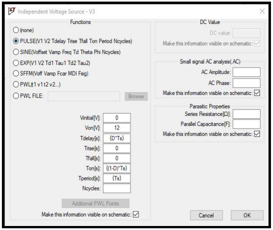
- Suppress the phase plot.
- Which problems may arise with high cable inductances?
- What measures can be taken to minimize the cable inductance?

Simulation Results

Task 1: Ideal Half Bridge Circuit Model



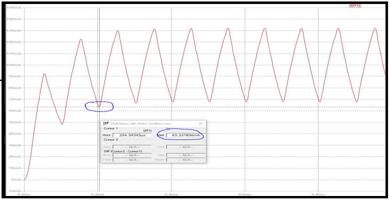




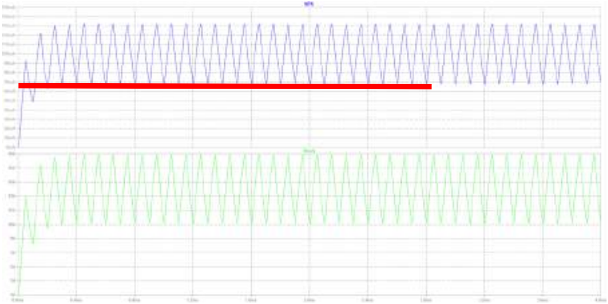
- MOSFET component selection
  - Right click → "Pick NEW MOSFET"
- Define variable component parameters
  - $\{var\}$
  - .param var = val
- Modulator modeled by pulsed voltage source

Simulation

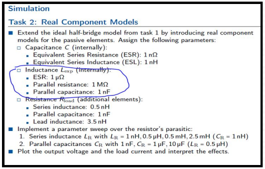
Task 1: Ideal Half Bridge Circuit Model



- Add plot Pane
- Use of scope / add traces
- Move traces
- Use the cursors: *current ripple of 64 mA (approx. 63 %)*

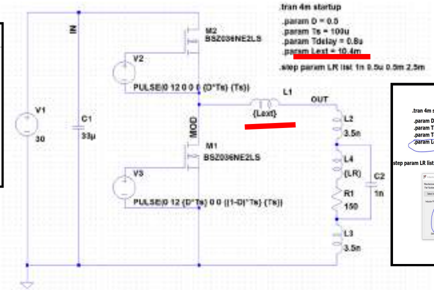


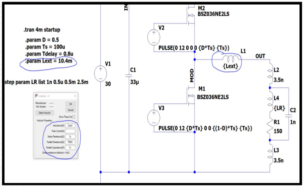
Task 2: Real Component Models (Sweep over L_{R})


Simulation

Task 2: Real Component Models

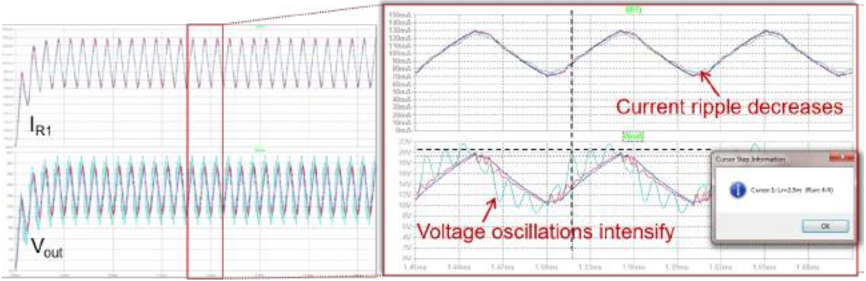
- Extend the ideal half-bridge model from task 1 by introducing real component models for the passive elements. Assign the following parameters:
  - Capacitance C (internally):
    - Equivalent Series Resistance (ESR): 1 nΩ
    - Equivalent Series Inductance (ESL): 1 nH
  - Inductance L_{exp} (internally):
    - ESR: 1 µΩ
    - Parallel resistance: 1 MΩ
    - Parallel capacitance: 1 nF
  - Resistance R_{load} (additional elements):
    - Series inductance: 0.5 nH
    - Parallel capacitance: 1 nF
    - Lead inductance: 3.5 nH
- Implement a parameter sweep over the resistor's parasitic:
  1. Series inductance L_{R} with L_{R} = 1 nH, 0.5 µH, 0.5 mH, 2.5 mH (C_{R} = 1 nH)
  2. Parallel capacitances C_{R} with 1 nF, C_{R} = 1 µF, 10 µF (L_{R} = 0.5 µH)
- Plot the output voltage and the load current and interpret the effects.





- Right click on component to add parasitics to component properties
  - "Real" Inductor model
  - "Real" Capacitor model
- Component "real" resistor model
- Parameter sweep over resistor's parasitic inductance L_{R}:
  - Here: .step param *var* list *val*1 *val*2 *val*3 ...

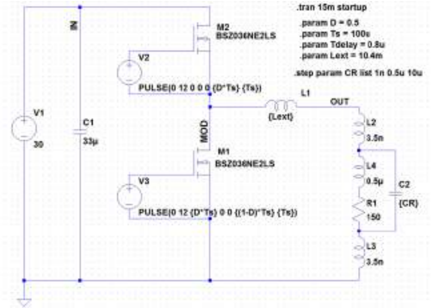
Task 2: Real Component Models (Sweep over L_{R})



?

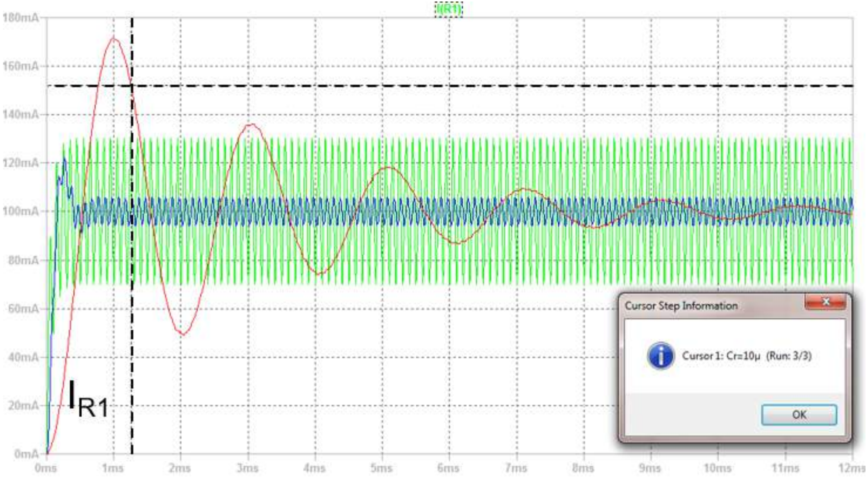
Simulation

Task 2: Real Component Models (Sweep over C_{R})



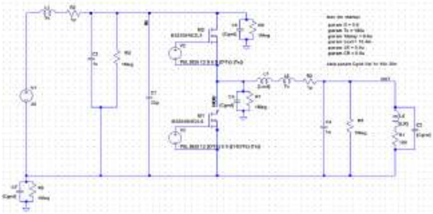
- Parameter sweep over parasitic capacitance C_{R}:
  - Here: .step param *var* list *val*1 *val*2 *val*3 ...
  - Or: linear variation of *var*:
    .step param *var start end increment*
  - Or: logarithmic variation of *var*:
    .step DEC param *var start end valuesPerDecade*

Task 2: Real Component Models (Sweep over C_{R})



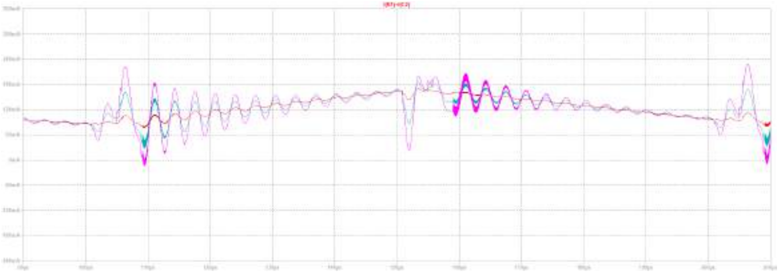
Simulation

Task 3: Conductor Model and Ground Paths



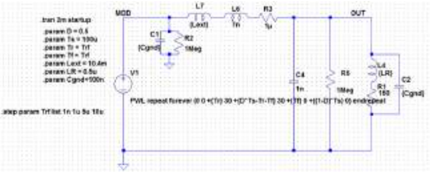
- Insert lumped high-frequency conductor model
- Add ohmic-capacitive ground paths
- Parameter sweep over ground capacitance C_{gnd}
  - Assume equal ground capacitance values for all ground paths

Task 3: Conductor Model and Ground Paths



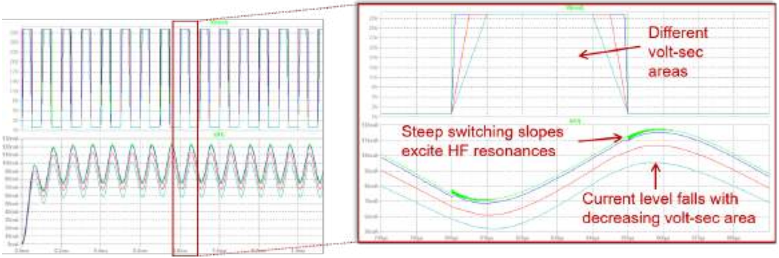
- Current ripple caused by parasitic ground path

Task 4: Generic Switch Modeling: Rise and Fall Times

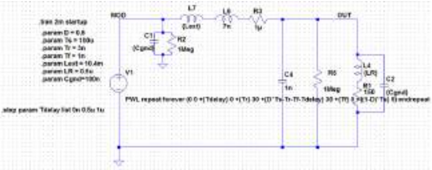


- Substitution of switch cell by modulated voltage source
  - PWL: Piecewise Linear Signal
  - repeat forever (*sig*) endrepeat
- Trapezoidal voltage signal
  - Assumption: Equal rise and fall times ($T_r = T_f = T_{rf}$)

Task 4: Generic Switch Modeling: Rise and Fall Times

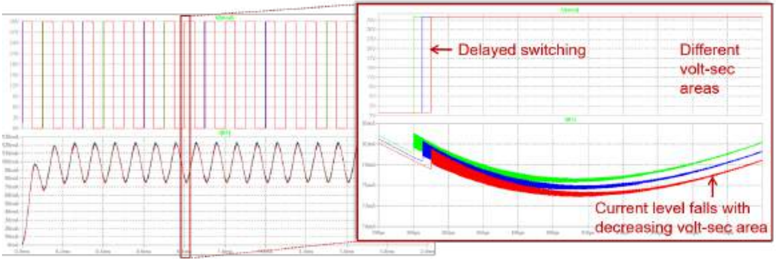


Task 4: Generic Switch Modeling: Dead Time

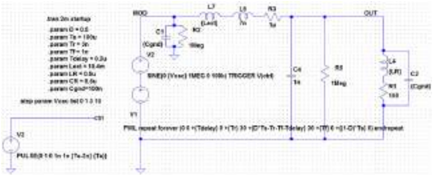


- Fixed rise and fall times
- Parameter sweep over dead time T_{delay}

Task 4: Generic Switch Modeling: Dead Time

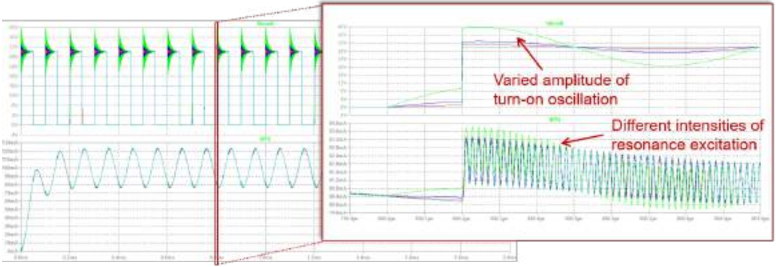


Task 4: Generic Switch Modeling: Turn-On Oscillations

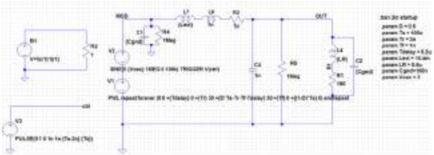


- Superposition of damped sinusoidal
- Additional voltage source (triggered)
- Pulsed voltage source serves as triggering control signal
- TRIGGER *var* > *val*
  → Default: *val* = 0.5
- Parameter sweep over amplitude

Task 4: Generic Switch Modeling: Turn-On Oscillations

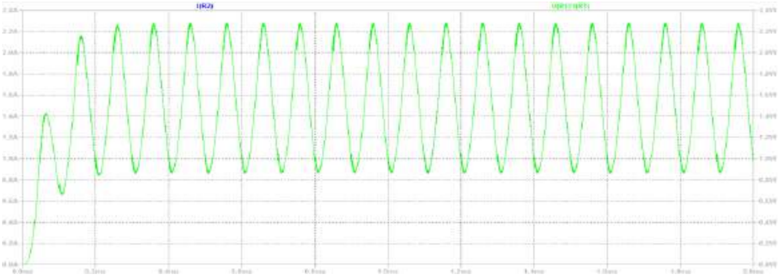


Task 5: Frequency-Domain Simulation



- AC Analysis
  - Tab "Simulate" → "Edit Simulation Cmd" → "AC Analysis"
  - Choose type of sweep, number of points, start/stop frequencies
- Substitute switch model by generic AC voltage source
  - Functions: (none)
  - Set AC Amplitude to 1 ("Small signal AC analysis (.AC)" → "AC Amplitude": 1) *rightarrow* this source is interpreted as the input
- Solid lines: Amplitude
- Dotted lines: Phase
- Phase can be suppressed: Right click on phase scale → *"Don't plot phase."*

Task 5: Frequency-Domain Simulation



Break

Table of Contents

How does a measurement setup look like?

Power Electronic EME Measurement

- Compliance or **pre-compliance**?
- Radiated or **conducted** emissions?
- Measurement requirements from CISPR 16-2:
  - Reproducible: Independent of environment/place including noise.
  - Interaction: Test equipment and measured device should not disturb each other.

Power Electronic EME Measurement

- EUT: Equipment under test
- Artificial mains network (AMN) is the boundary between power and measurement region.
- Frequency range for conducted emissions in PE systems: 150 kHz to 30 MHz
- Signal reduction before measurement device min. 10 dB (CISPR 16)
- Input impedance of measurement device 50 Ω

EUT → AMN → Fixed-attenuator → Separator → Pulse-limiter → Meas. device

?

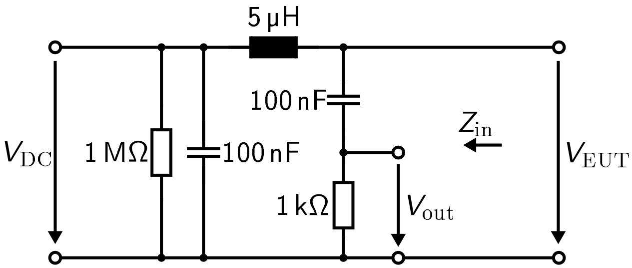
Variants of a AMNs [45]

- Functions of an AMN:
  1. Defined input impedance Z_{in} emulation at V_{EUT}
  2. Supply equipment under test with power at V_{DC}
  3. Decoupling of ambient distortions
  4. Connection for measurement equipment at V_{out} with $50\,\Omega$
- Variants of a AMN:
  - V network (line impedance stabilization network (LISN)): *An artificial mains network enabling the voltages between each conductor and earth to be measured separately.*
  - Δ network: *An artificial mains network enabling the CM and DM voltages of a single phase circuit to be measured separately.*

All definitions available at: `http://www.electropedia.org`

Measurement 1: Measurement Setup

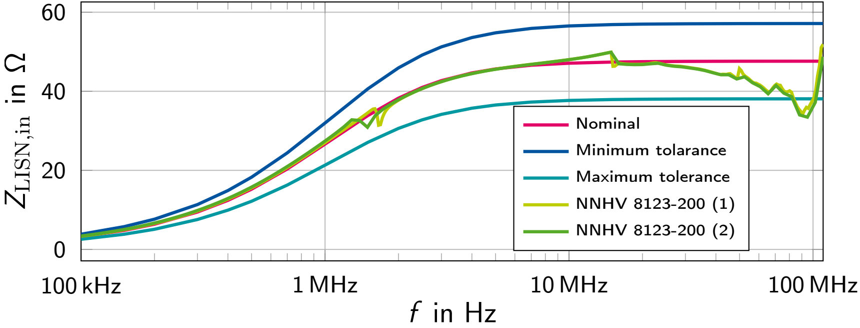
Schematic of a LISN [45]



Measurement 1: Measurement Setup

LISN [47]

- Output is terminated with 50 Ω
- Two LISNs necessary for HV grid.
- Connection to reference ground with less than 50 nH

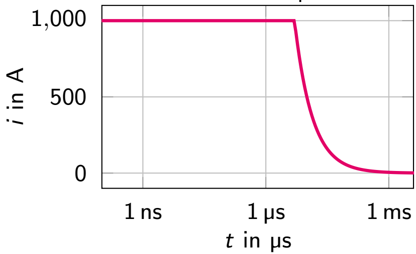


Measurement 1: Measurement Setup

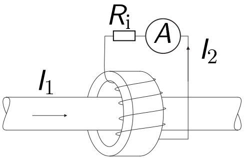
Current Transformer [48]

- Terminated with **external** $R_\mathrm{i} = 50\,\Omega$
- Add common-mode filters close at the coaxial output of the transformer

Limited with maximum $I \cdot t$-product:



Equivalent circuit of transformer:



−3 dB frequency range from 200 Hz to 500 MHz:

Measurement 1: Measurement Setup

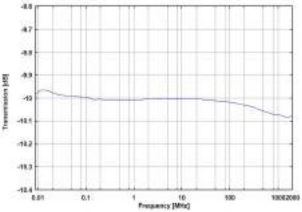
Fixed Attenuator [49]

- Reduce signal amplitude
- Adjust measurement range for:
  - Measurement receiver
  - CM/DM separator
- Different values:

dB	Linear
−3 dB	1/2
−6 dB	1/4
−10 dB	1/10
−20 dB	1/100
−30 dB	1/1000

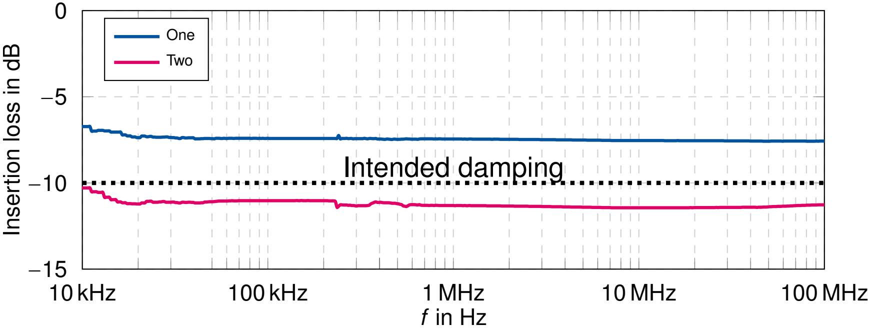
DGA 9553 BNC:

Insertion loss of −10 dB [49]:



Results of Overheat in Attenuators

- Power electronics leads to very high ground currents.
- Damage is not necessary seen from the outside.
- High-frequency equipment is usually limited to a few W.



Hint: *Check the equipment before using it.*

Diode Pulse Limiter [50]

- Protects the measurement receiver
- Limits the voltage below 100 dBµV
- −10 dB fixed attenuator included
- N connector (rated up to 11 GHz)

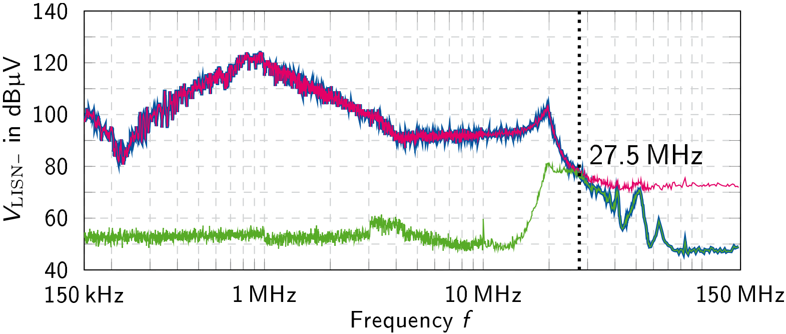
Schwarzbeck VTSD 9561-D

Schwarzbeck VTSD 9561

Measurement 1: Measurement Setup

High-Pass Filter

- Additional device to improve vertical resolution.
- Two measurements (w/o high-pass filter) merged into one final spectrum-
- Example measurement with a 27.5 MHz high pass filter:



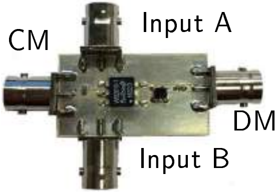
CM DM Separator [51]

- Separation of CM and DM by measurements
- Requirements:
  - Transmission ratios as high as possible
  - Rejection ratios as low as possible
  - Input impedance of $50\,\Omega$ for each input
  - For CM: $R_{\mathrm{CM}} = 25\,\Omega$
  - For DM: $R_{\mathrm{DM}} = 100\,\Omega$

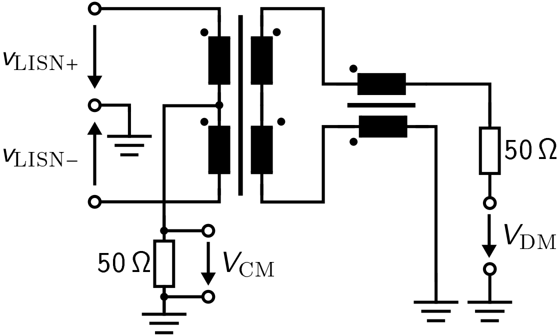
CMDM 8700 from Schwarzbeck

CM DM Separator [52]

- All requirements fulfilled
- Usage of center tap transformer



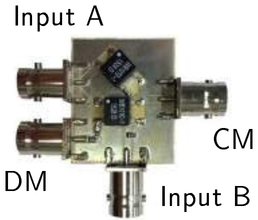
Topology proposed by Nagel:

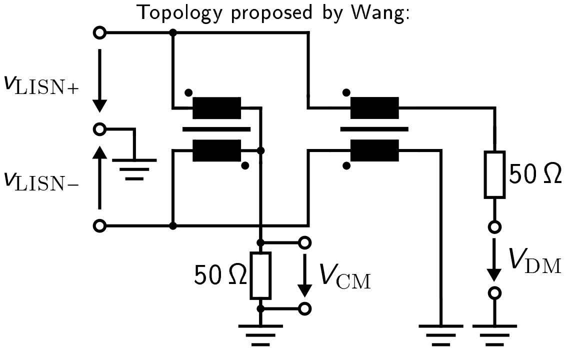


Measurement 1: Measurement Setup

CM DM Separator [53]

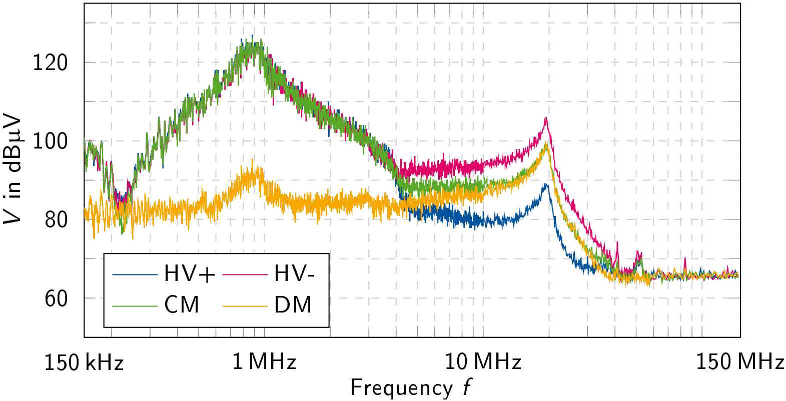
- All requirements fulfilled
- No galvanic isolation





Measurement 1: Measurement Setup

CM DM Separator Measurement [10]



- Common mode is dominant mode.
- 18 MHz emission is also observed in differential mode.
- DC-link capacitors works also as a differential mode filter.

Measurement 1: Measurement Setup

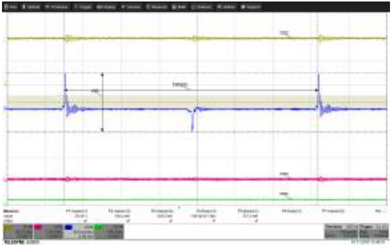
Example: Measurement [54], [55]

Setup with SiC DC/DC converter:

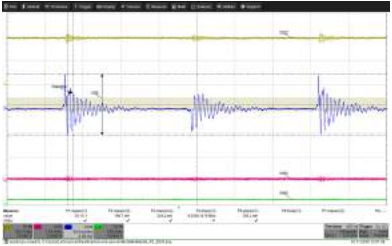
Measurement 1: Measurement Setup

Example: Measurement in Time Domain

Switch on CM:



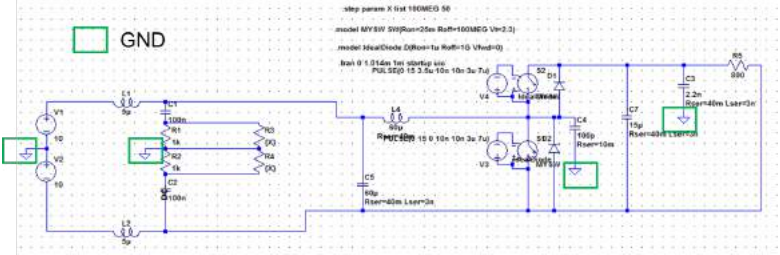
Switch on DM:



- Measurement of ground current with scope.
- Ground current changes due to switch position of CM/DM separator

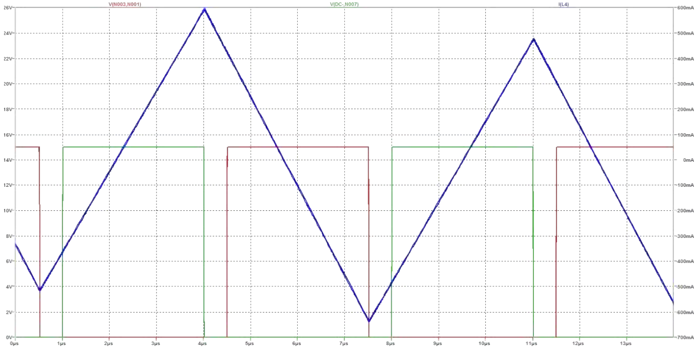
Measurement 1: Measurement Setup

Example: LTspice Simulation



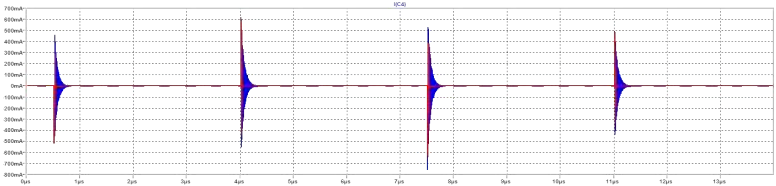
- Simple simulation to understand the oscillation.
- We do not need very complex models to get a certain understanding.

Example: LTspice Simulation Results

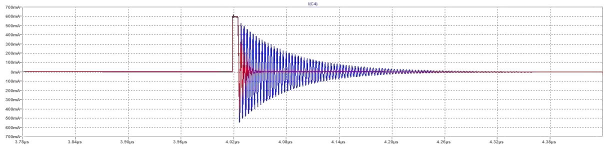


Example: LTspice Simulation Results

Complete time-domain result:



Zoomed result:

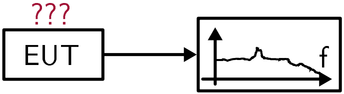


Equipment to characterize in frequency domain.

Measurement 1: Frequency Measurement

Voltage over Frequency: $V = f(f)$

- Scope with FFT
- EMI receivers
- Spectrum analyzers
  - Swept-tuned (superheterodyne receiver)
  - Real-time analyzer
    - Parallel-filter analyzers
    - FFT analyzers

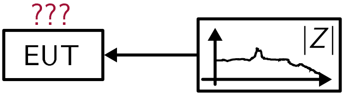


Test receiver:

Test receiver and spectrum analyzer:

Spectrum analyzer with tracking generator:

Characterization over Frequency $x = f(f)$



- Multiple devices exist to extract frequency behavior:

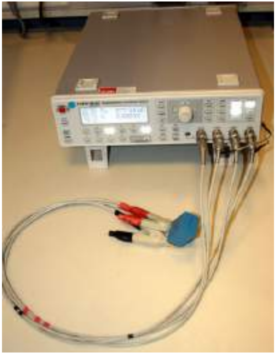
Device	Output	Advantage
RLC Bridge/Meter	R, L, C	Simple & cheap.
Impedance analyzer	$\underline{Z} = f(f)$	Impedance (amplitude & phase)
Spectrum analyzer with tracking generator	$V = f(f)$	Simple with active devices
(Vector) network analyzer	$\underline{S}_{xy} = f(f)$	Scattering parameter

- Frequency limitations due to the connection of the DUTs
- High-voltage decoupling for non-linear capacitances required.
- Two or four terminal measurement possible (depending on measurement device)
- De-embedding of connectors and setup is required.

Characterization: *RLC* Bridge/Meter

- Measurement at a single frequency:
  20 Hz to 200 kHz
- 4-Terminal measurement
- Passive components
- Measurement of amplitude and phase

Example: Hameg HM8118



Characterization: Impedance analyzer

- Frequency range: 40 Hz to 110 MHz
- 4-Terminal measurement
- External capacitor bias up to 40 V
- Passive components
- Fitting of equivalent (RLC) parameters
- Measurement of amplitude and phase

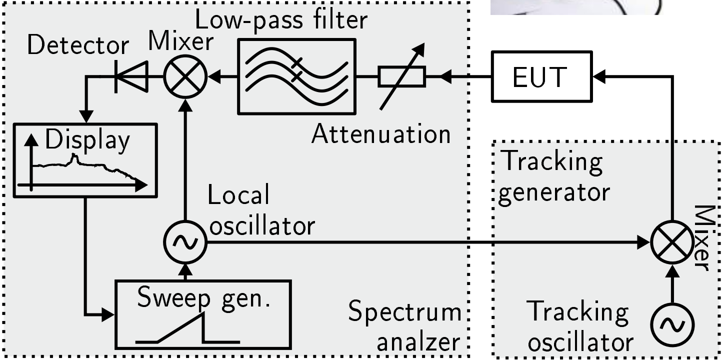
Example: Agilent 4294A

Measurement 1: Frequency Measurement

Characterization: Spectrum analyzer with tracking generator

- Frequency from 9 kHz to 1.5 GHz
- **Only** measurement of amplitude
- Also active amplifier!

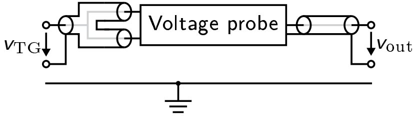
Example: Rigol DSA 815



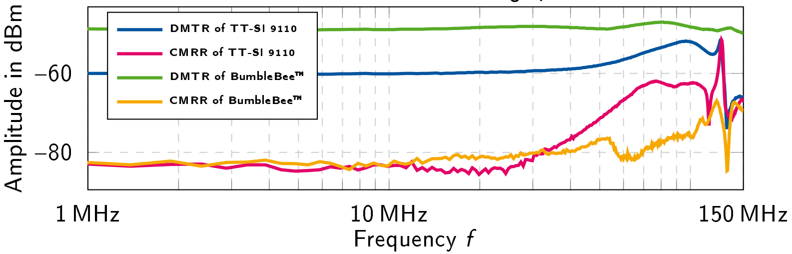
Measurement 1: Frequency Measurement

Example: Characterization of voltage probes

CMRR characterization of the voltage probes:



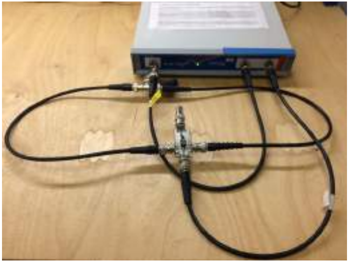
Characteristics of differential voltage probes:



Characterization: (Vector) Network Analyzer (VNA)

- Frequency range: 1 Hz to 40 MHz (Bode 100)
- Signal to noise ratio limits vertical resolution
- Two-port measurement
- Measurement of scatter parameters
- Remote control over pc

Example: Bode 100:



Break

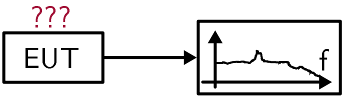
Table of Contents

Equipment to measure in frequency domain.

Measurement 2: Measurement Receiver

Voltage over Frequency: $V = f(f)$

- Scope with FFT
- EMI receivers
- Spectrum analyzers
  - Swept-tuned (superheterodyne receiver)
  - Real-time analyzer
    - Parallel-filter analyzers
    - FFT analyzers

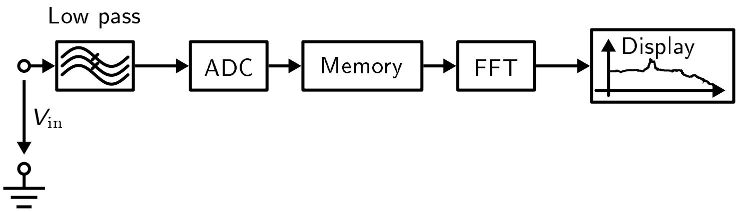


Test receiver:

Test receiver and spectrum analyzer:

Spectrum analyzer with tracking generator:

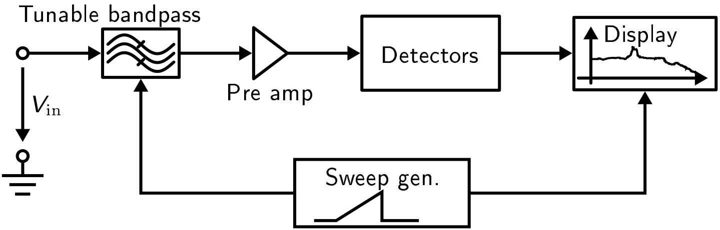
FFT Analyzer [56, p. 26f]

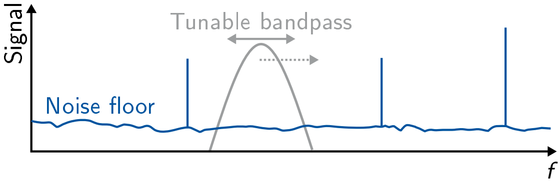


- Minimum Nyquist theorem must be fulfilled.
  - Requirements for analog-digital converter (ADC) are crucial.
  - FFT can cause spectral leakage and picket fence effect.
- Limitation
  - Dynamic range
  - Frequency range

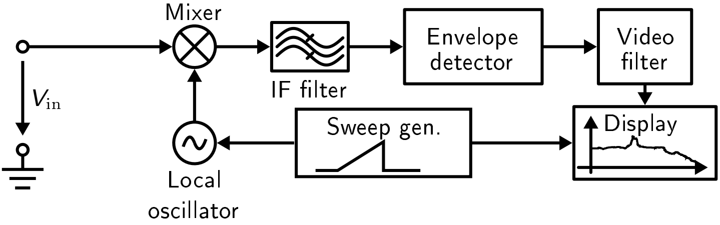
Measurement 2: Measurement Receiver

Sweep Analyzer [56, p. 29f]





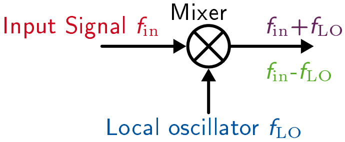
Why Heterodyne Principle?

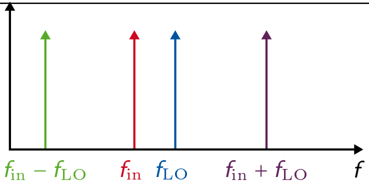


- Difficult to implement amplifiers, detectors and filters that
  - have an equal amplitude for different frequencies
  - have an equal bandwidth over tuning range
- Easy implementation of a tunable local oscillator.

Measurement 2: Measurement Receiver

Receiver: Mixer [58, p. 562f]





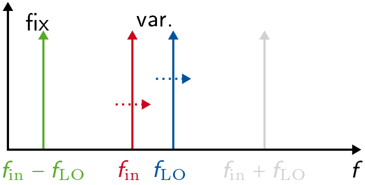
- The output is an addition and subtraction of the input signals:

$$\sin(2\pi f_1 t)\cdot\sin(2\pi f_2 t) = \frac{1}{2}\cdot\cos(2\pi(f_1 - f_2)t) + \frac{1}{2}\cdot\cos(2\pi(f_1 + f_2)t)$$

- A mixer doesn't "mix" it multiplies! (see trigonometric equation)
- The unused (higher) frequency is eliminated with low-pass filtering.
- Basic technique of RF systems:
  Shift to intermediate frequency!

Receiver: Other Reasons for IF Concept? [59, ch. 8][60]?

- Low gain of active devices (transistors) at very high frequencies (in GHz region)
- Better frequency selectivity
  - Signal bandwidth can be smaller
  - Better reduction of unwanted signals



Selectivity:
The ability or a measure of the ability of a receiver to discriminate between a given wanted signal and unwanted signals.

All definitions available at: `http://www.electropedia.org`

Bandwidth of a Signal [61, p. 26]

Bandwidth of a device:

Width of a frequency band over which a given characteristic of an apparatus or transmission channel does not differ from its reference value by more than a specified amount or ratio.

Bandwidth of a signal:

The width of the frequency band outside which the level of any spectral component does not exceed a specified percentage of a reference level.

Band	Range	Reference BW_6
A	9 to 150 kHz	200 Hz
B	0.15 to 30 MHz	9 kHz
C	30 to 300 MHz	120 kHz
D	0.3 to 1 GHz	120 kHz
E	1 to 18 GHz	1 MHz (BW_{imp})

Broad- and narrow band:

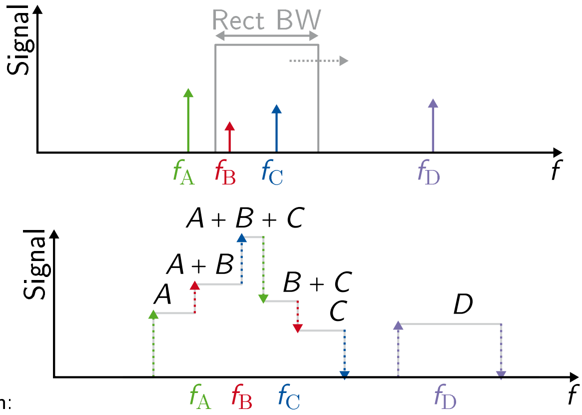
- Continuously and narrow band:
  $$BW_{\mathrm{signal}} < BW_{\mathrm{device}}$$
- Continuously and broadband:
  $$BW_{\mathrm{signal}} > BW_{\mathrm{device}}$$
- Transients or pulses:
  Repetitive pulse rate

Measurement 2: Measurement Receiver

Bandwidth: Illustration of Measured Spectrum [1, p. 144]

Signal spectrum:

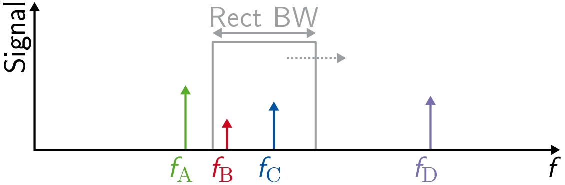
Measured spectrum:



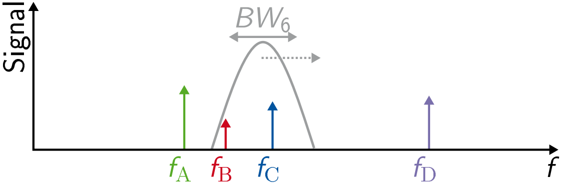
Measurement 2: Measurement Receiver

Bandwidth: Rectangular and BW_6 Filter

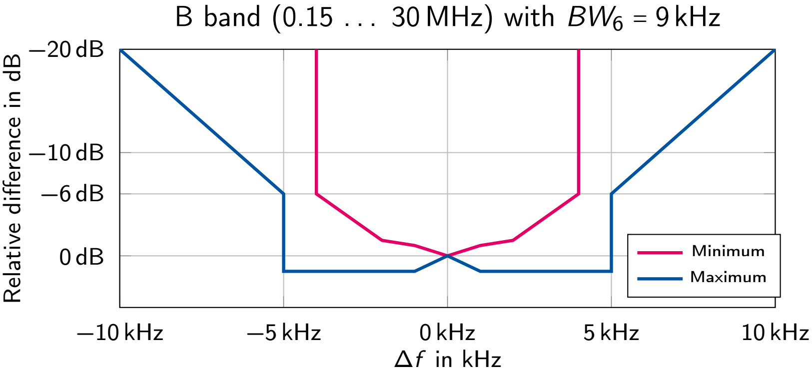
With rectangular filter:



BW_6 "real" filter:



Receiver: Selectivity [61]



- CISPR 16 regulations only define minimum and maximum curves.
- Only the total selectivity of the device is regulated

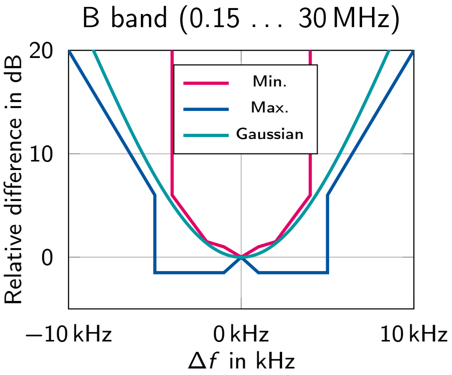
Receiver: Model of the IF Filter [62]–[64]

- Model can be included via post processing.
- Usage of Gaussian window:

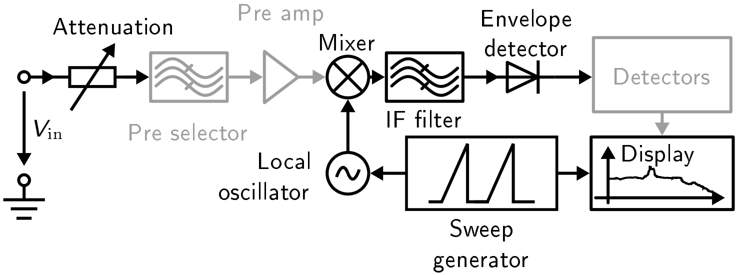
$$w(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-0.5 \cdot \frac{t}{\sigma}^2}$$

- Model of IF filter with short time FFT (STFFT):

$$S[n,k] = \sum_{m=0}^{L-1} s[m+n] \cdot w[m] e^{-j\frac{2\pi}{N}km}$$

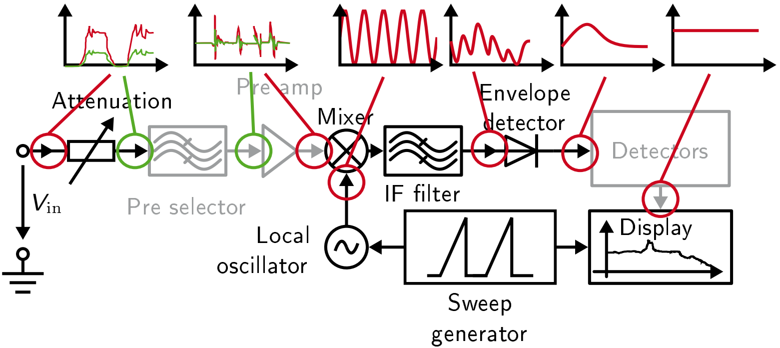


Test Receiver and Spectrum Analyzer [61, p. 79f] [66]

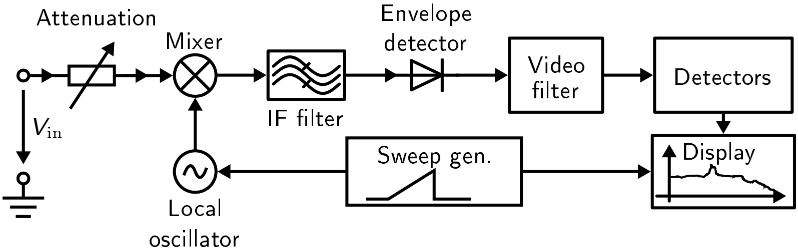


- Test receiver: Step-wise measurement through frequency
  - Step by step evaluation with up to one million points.
  - Bandwidth depending on selected frequency range.
- Spectrum analyzer: Full-span with sub-ranging
  - Evaluation of the complete signal at once (max. 32 001 points).
  - One bandwidth for all measured frequencies.

Test Receiver and Spectrum Analyzer [61, p. 79f]



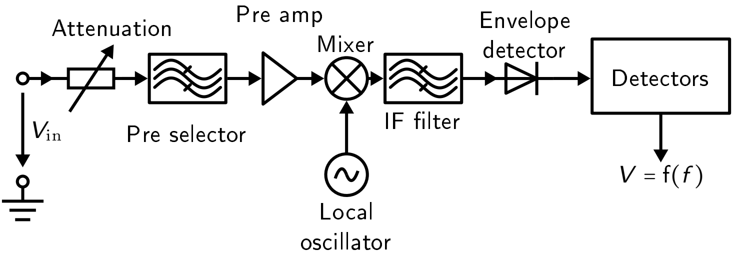
Spectrum Analyzer [56, p. 30f]



Parameters:

- Start / stop frequency
- Resolution bandwidth filter and type (3 dB or 6 dB)
- Detector(s)
- Sweep time
- Video bandwidth

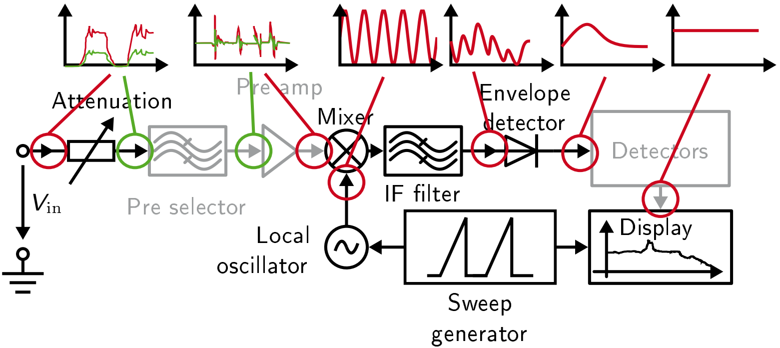
Test Receiver [61]



Parameters:

- Start / stop frequency
- Resolution bandwidth filter for each frequency range
- Detector(s)
- Measurement (dwell) time for each frequency range
- Step size for each frequency range

Test Receiver and Spectrum Analyzer [61, p. 79f]



Envelope Detector [56, p. 58ff] [69]

- An envelope detector makes a spectrum analyzer to a voltmeter.
- Crucial for dynamic range.
- Envelope of impulse response:

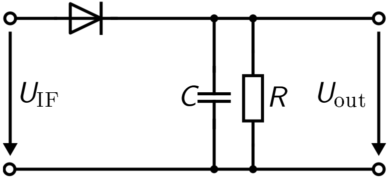
$$A(t) = 4\omega_0 \exp^{-\omega_0 t} \left(\sin(\omega_0 t) - \omega_0 t \cdot \cos(\omega_0 t)\right)$$

with $\omega_0 = (\pi/\sqrt{2})BW_6$

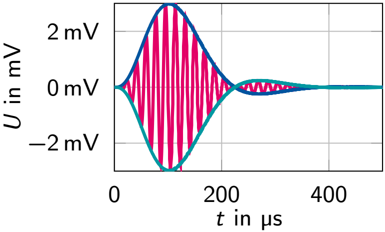
- Selectivity:

$$F(f) = G \cdot \frac{2\omega_0^2}{((\omega_0 + \underline{\omega})^2 + \omega_0^2)}$$

Simple envelope detector:



Impulse response for $f_{\sin} = 55\,\mathrm{kHz}$:



Video Filter [56, p. 62ff]

- Smoothen the trace seen on the screen.
- Easier identification of low-level signals.
- Selection of video bandwidth VBW:
  - Set narrow to filter noise [67, p. 145]:

$$\Delta(NF_1 2) = 10 \cdot log_{10}\left({}^{BW_1}/_{BW_2} \right)$$

Noise floor (NF) depends on selected bandwidth (BW)

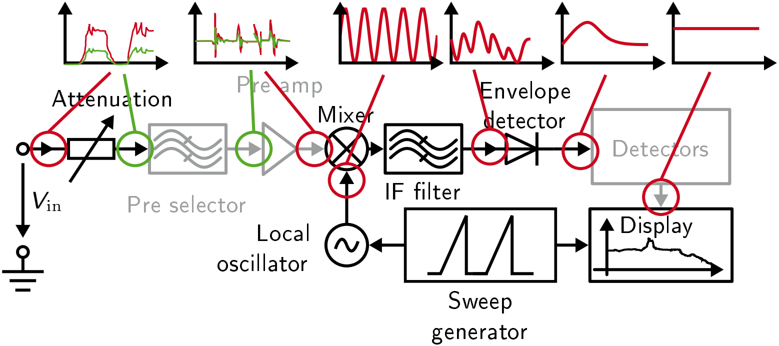
  - Reduction increases sweep time:

$$t_{\mathrm{sweep}} \propto \frac{\Delta f_{\mathrm{span}}}{RBW \cdot VBW}$$

  - Sinus signals: $VBW \geq RBW$
  - Pulsed signals $VWB \gg RBW$

Measurement 2: Measurement Receiver

Test Receiver and Spectrum Analyzer [61, p. 79f]

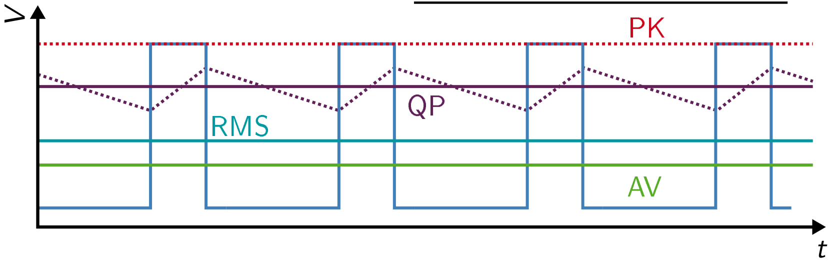


Receiver: Detectors [69]

- Peak: PK
- Quasi peak: QP
- Average: (CISPR)-AV
- Root mean square: RMS (also called: RMS-Average)

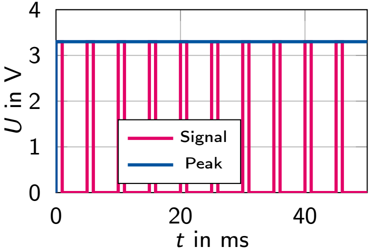
Minimum measurement time from CISPR 16

Band	$T_{\mathrm{s,peak}}$	$T_{\mathrm{s,QP}}$
A	14.1 s	47 min
B	2.985 s	1 h 39 min
C / D	0.97 s	5 h 23 min

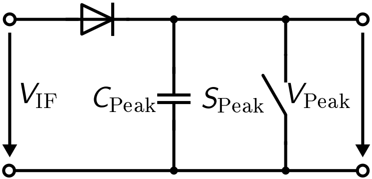


Detector: Peak [1, p. 146f] [61]

- Maximum amplitude of rectified signal.
- Voltage is constant until switch is closed.
- Independent of the pulse repetition frequency.



Peak detector [2, p. 308]:



Time constants from CISPR 16

Band	$\tau_{\mathrm{charge}}/\tau_{\mathrm{discharge}}$
A	$1.89 \cdot 10^4$
B	$1.25 \cdot 10^6$
C / D	$1.67 \cdot 10^7$
E	$1.34 \cdot 10^8$

Measurement 2: Measurement Receiver

Detector: Quasi Peak [2, p. 311] [69]

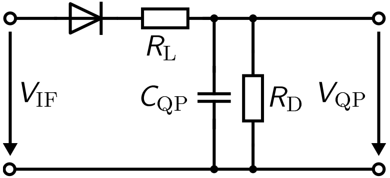
- Regulatory limits are measured with quasi-peak
- **But:** Measurement is time consuming.

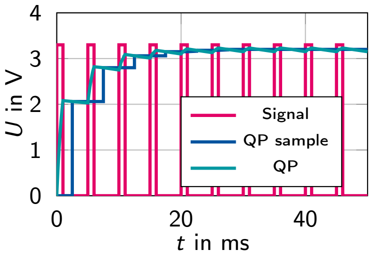
Time constants from CISPR 16

Band	τ_{charge}	$\tau_{\mathrm{discharge}}$
A	45 ms	500 ms
B	1 ms	160 ms
C	1 ms	550 ms
D	1 ms	550 ms
E	not defined	not defined

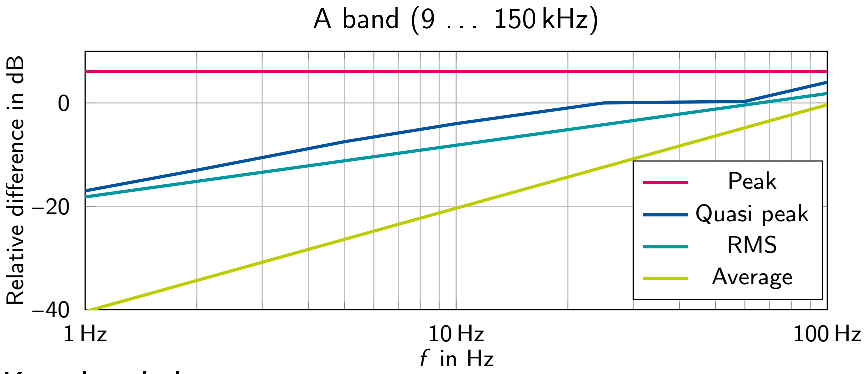
$$\tau_{\mathrm{charge}} = R_{\mathrm{L}} \cdot C_{\mathrm{QP}}$$
$$\tau_{\mathrm{discharge}} = R_{\mathrm{D}} \cdot C_{\mathrm{QP}}$$

Schematic of quasi-peak detector:





Detector: Pulse Weighting Characteristic [69]

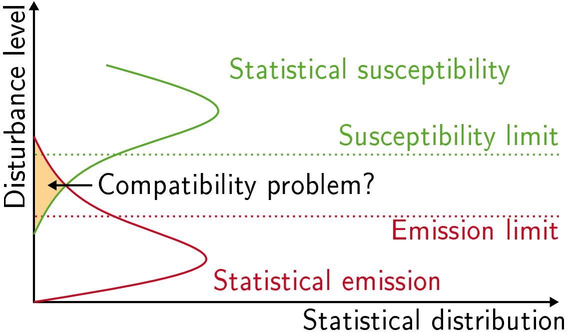


Keep in mind:

- Pulsed signals: $PK > QP > RMS > AV$
- Not modulated sinusoidal signals: $PK = QP = RMS = AV$

Is a product/converter good enough?

Safety Margins in EMC



- Emissions are statistically distributed (e.g. on the operating point)
- Worst case point must be checked.
- It is not compulsory that the nominal operating point has the worst case emission.

Measurement 2: Rules, Laws and Regulations

What Limits Exist?

- Creator:
  - Governmental rules
  - Manufacturer rules
- Areas:
  - Commercial
  - Military
- Types:
  - Electromagnetic emission (EME)
  - Electromagnetic susceptibility (EMS)

What contains a regulation?

- Measurement setups
- Device parameters
- Limits for product classes

Note: *Specifications are done for a complete system, not separate components.*

Although: *Purchaser can define specific limits.*

Overview: `https://en.wikipedia.org/wiki/List_of_common_EMC_test_standards`

EMC and the Environment [72]

- "Technical" EMC
  - Covers regulation and limits between technical devices.
  - A part of this topic is interesting for power electronics.
- EMC and the environment
  - Influence on people and the environment
  - Based on the WHO and ICNIRP [71]
  - German: Elektromagnetische Verträglichkeit zur Umwelt (EMV-U)
- Organizations

World Health Organization

ICNIRP
INTERNATIONAL COMMISSION ON NON-IONIZING RADIATION PROTECTION

`http://www.who.int/peh-emf/en/`

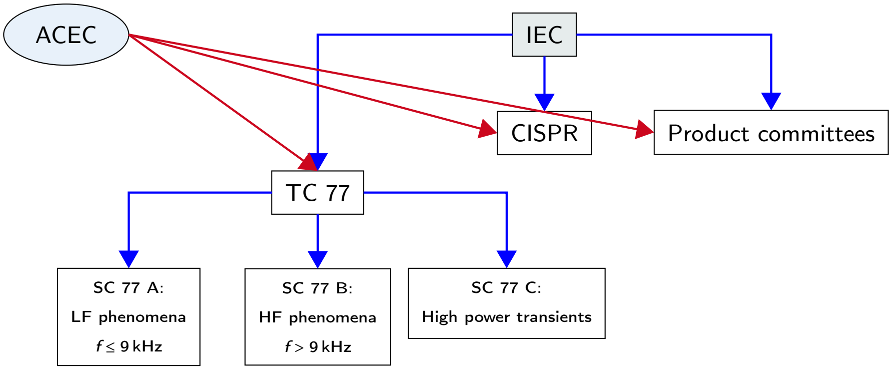
`http://www.icnirp.org`

Pre-Compliance and Compliance Measurements [73, p. 9]

- Compliance measurements
  - Does a equipment pass or fail the regulatory testing?
  - Specific equipment and test setup necessary.
  - Expensive and time consuming
  - Carried out by specialized labs!
- Pre-compliance Measurements
  - Parallel during the development.
  - But: It is unofficial.
  - To minimize chance of failure during compliance testing.
  - Equipment is still expensive

Note: *If pre-compliance measurements in the lab are successful, it does necessary pass the final compliance test.*

International Organizations [67]



- IEC regulations: IEC 61000
- CISPR regulations: CISPR XY

Source: `http://www.iec.ch/emc/iec_emc/`

IEC TC 77: Electromagnetic Compatibility

- The TC 77 covers the following aspects of EMC:
  - Immunity and related items, over the whole frequency range: basic and generic standards;
  - Emission in the low frequency range: basic, generic and product family standards;
  - Emission in the high frequency range: disturbances not covered by but in co-ordination with CISPR (e.g. mains signaling).
- Three sub-committees for different signal types
- Product immunity standards are not included, but preparation in cooperation with ACEC

Source: `www.iec.ch/tc77`

CISPR: General Information

- Technical committee of IEC
- Founded in 1934
- `http://www.iec.ch/cispr`
- Range of 9 kHz to 400 GHz
- It defines for EMC tests:
  - Equipment requirements
  - Procedures and methodologies
  - Recommends limits for emissions and immunity
- CISPR: Implementation in Germany
  - CISPR xy is implemented in european regulation EN 550xy of CENELEC
  - European regulation is implemented in german regulation DIN VDE 0876/0877-xy, DIN VDE 0879-1 (CISPR 12) and 0879-2 (CISPR 25)

CISPR: Sub-Committees

Label	Title
CIS/A	Radio-interference measurements and statistical methods
CIS/B	Interference relating to industrial, scientific and medical radio-frequency apparatus, to other (heavy) industrial equipment, to overhead power lines, to high voltage equipment and to electric traction
CIS/D	Electromagnetic disturbances related to electric/electronic equipment on vehicles and internal combustion engine powered devices
CIS/F	Interference relating to household appliances tools, lighting equipment and similar apparatus
CIS/H	Limits for the protection of radio services
CIS/I	Electromagnetic compatibility of information technology equipment, multi-media equipment and receivers
CIS/S	Steering Committee of CISPR

CISPR: Important Technical Standards [73, p. 13]

CISPR 11	Industrial, Scientific and Medical (ISM)
CISPR 12	Vehicles, boats, and internal combustion engine driven devices
CISPR 13	Sound and Television Broadcast Receivers and Associated Equipment
CISPR 14	Household Appliance, Electric Tools, and Similar Apparatus
CISPR 15	Electrical lighting and similar equipment.
CISPR 16	Specification for radio disturbance and immunity measuring apparatus and methods.
CISPR 17	Suppression Characteristics of Passive Radio Interference Filters and Suppression Components.
CISPR 18	Overhead Power Lines and High-Voltage Equipment
CISPR 20	Sound and television broadcast receivers and associated equipment
CISPR 21	Interference to Mobile Radio communications
CISPR 22	Information Technology Equipment–Radio Disturbance Characteristics
CISPR 24	Information Technology Equipment—Immunity characteristics
CISPR 25	Receivers used on board vehicles, boats, and on devices
CISPR 32	Multimedia equipment - Emission requirements. This replaced CISPR 13 and CISPR 22.
CISPR 35	Multimedia equipment - Immunity requirements This will replace CISPR 20 and CISPR 24
CISPR 36	Electric and hybrid road vehicles for magnetic radiated field measurements below 30 MHz

CISPR 16: Measuring Apparatus and Methods [61], [74]

- Frequency range between 9 kHz and 18 GHz
- Defines characteristics and performance for measurement equipment:
  - EMI measuring receivers
  - Spectrum analyzers
- Uses a "Black-Box-Approach" independent of a specific measurement device.
- Definition of
  - Detector implementation
  - IF filters
  - Selectivity
  - Overload capability
  - Dynamic range
  - Input levels and maximum measurement error: e.g. ± 2 dB for sinusoidal signals

CISPR 16: Structure

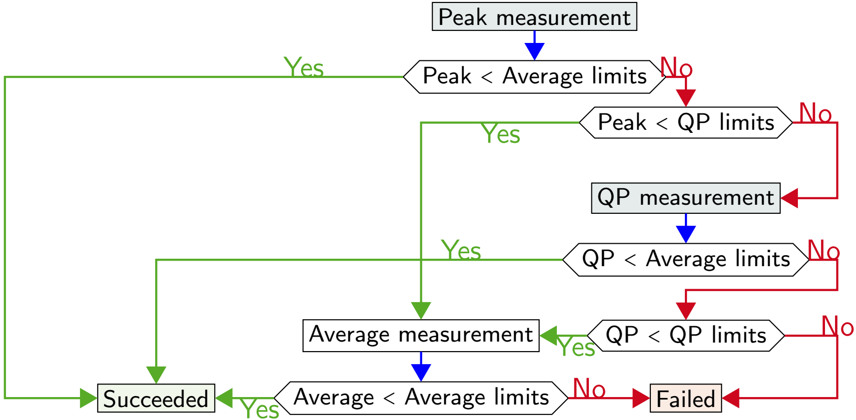
- CISPR 16
  - CISPR 16-1: Voltage, current and field measuring test sites with calibration and verification
    - 1-1: Measuring apparatus
    - 1-2: Conducted disturbances
    - 1-3: Disturbance power
    - 1-4: Radiated disturbances
    - 1-5: Antenna calibration test sites for 30 MHz to 1000 MHz
    - 1-6: Antenna calibration
  - CISPR 16-2: Methods for measuring HF EMC phenomena (disturbances and immunity)
    - 2-1: Conducted disturbance
    - 2-2: Disturbance power
    - 2-3: Radiated disturbance
    - 2-4: Immunity
    - 2-5: Measurements for emissions from physically large equipment
  - CISPR 16-3: Technical report including the history of CISPR
  - CISPR 16-4: Uncertainties, statistics and limit modeling
    - 4-1: Uncertainties in standardized tests
    - 4-2: Uncertainty in EMC
    - 4-3: Statistical considerations for compliance of mass-produced products
    - 4-4: Statistics of complaints and a model for the calculation of limits
    - 4-5: Conditions of alternative test methods

More information: `www.iec.ch/emc/basic_emc/basic_cispr16.htm`

Regional and National Organizations [2, p. 466]

- International
  - Organization: IEC (TC 77 and CISPR), ISO (for automotive)
  - Regulations: IEC 61 000 and CISPR XY regulations
- Europe (regional)
  - Organizations: CEN, CENELEC and ETSI
  - Regulations: European standardization (generic, basics and products) including EU commission
- Germany (national)
  - Organizations: VDE with DKE
  - Regulations: Translation into german VDE and DIN regulations including BNetzA.

CISPR 16-2: Decision Tree [61]

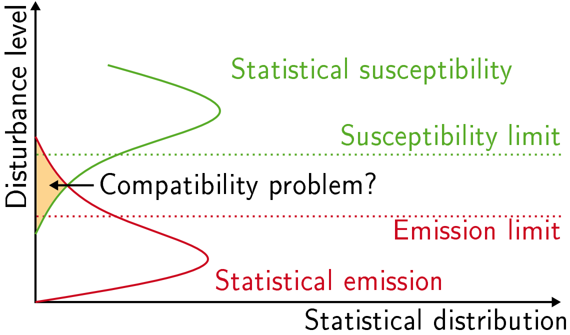


Break

Table of Contents

Noise Mitigation: Fundamentals

Does a EMC Problem Exist? [2, p. 16]



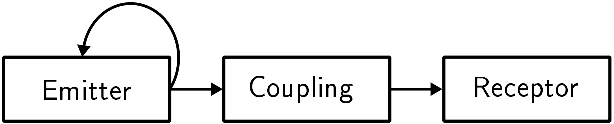
- Mitigation needs are determined by the worst case operation point
- Emissions and receptors are broad and narrow band

What can we do?

What are possible countermeasures? [1]

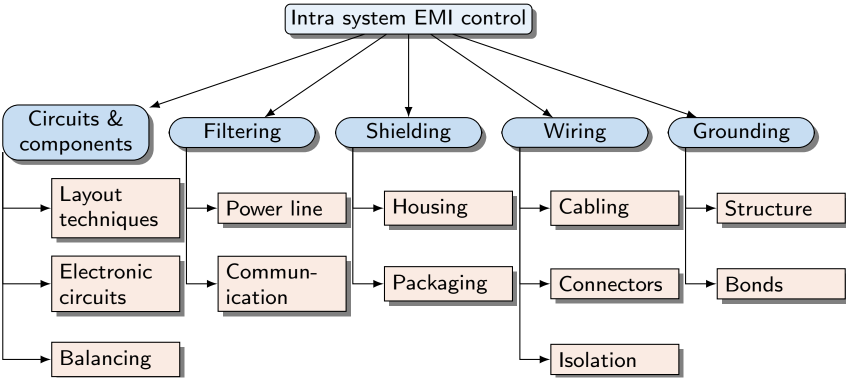
1. Suppress the emission at its source.
2. Make the coupling path as inefficient as possible.
3. Make the receptor less susceptible to the emission.

With the interference model (see Fundamentals):



Noise Mitigation: Fundamentals

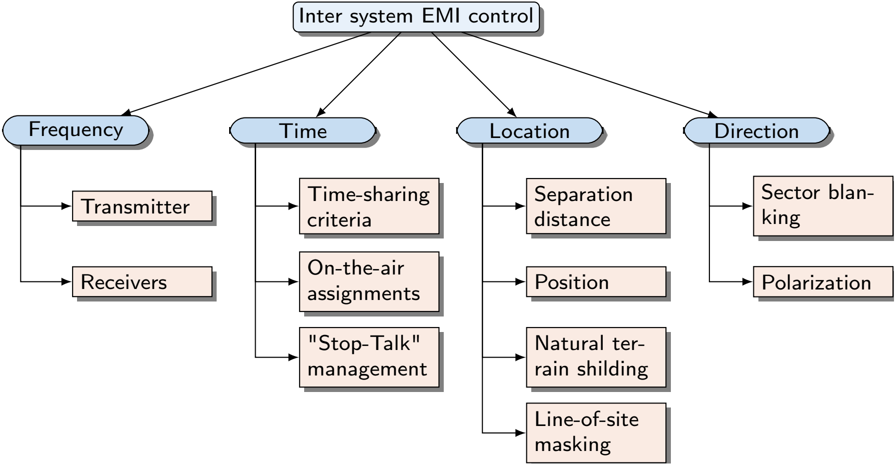
Intra-System EMI Control [76, p. 1-20]



Note: *To every rule there is a situation where it is not valid!*

Noise Mitigation: Fundamentals

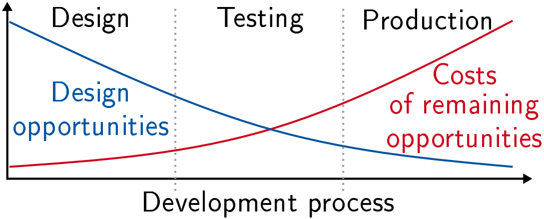
Inter-System EMI Control [76, p. 5.114]



Note: *Inter- and intra- techniques are not strictly distinct*

Noise Mitigation: Fundamentals

Opportunities in the development process [75]



- System design:
  Consider EMC from the beginning. ☺
- Crises management:
  Fix problems if needed. ☹

How do we locate a problem?

And we don't want to guess.

Noise Mitigation: Locate Problem

Three Step Procedure [3, p. 76]

1. Only the impact of disturbance is known.
   - Does the source violate limits or is a device malfunctioning?
   - Does the disturbance occur permanently or temporarily?
   - Can the disturbance be reproduced or does it appear randomly?
2. Location of the technical disturbance source
   - Easy if it is a permanent reproducible disturbance.
   - Difficult if events are random.
   - Locate critical amplitude and frequency.
3. Investigation of coupling path.
   - Is the device working in the lab but not in the field?
   - Can I change grounding or wiring?

Keep in mind: *Also test equipment impacts the measurement!*

Equipment to Locate the Problem?

- Equipment locate the emission/source
  - CM/DM separator
  - Near field probes
  - Current monitors
  - Passive and active probes
- Equipment to locate the victim
  - Measurement at LISN
  - Burst generator
  - Tester for electrostatic discharge (ESD)
  - Tester for conducted immunity testing
  - Pulse generators
  - Monitoring of signal transmission

Noise Mitigation: Locate Problem

Near-field Probes [77, part 1]

- Depending on probe:
  Electric or magnetic probe with a certain direction
- Can measure at areas that are hard to access
- Low frequency:
  100 kHz to 50 MHz
- Radio frequency:
  30 MHz to 3 GHz
- Must be terminated with 50 Ω

Probes from

Langer EMV-Technik:

Noise Mitigation: Locate Problem

Pre Amplifier for Near Field Probes

- Equipment for near-field probes
- Amplification of weak signals
- Rated between 100 kHz and 3 GHz
- Connected to 50 Ω input of scope or spectrum analyzer
- Amplification of signals with +20 dB and +30 dB

PA303 BNC from

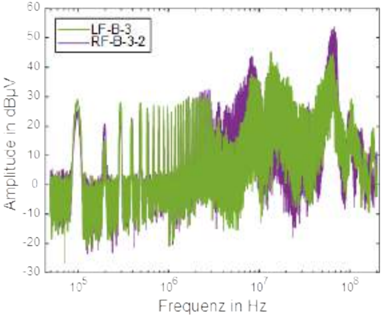
Langer EMV-Technik:

Demonstration with near-field probes

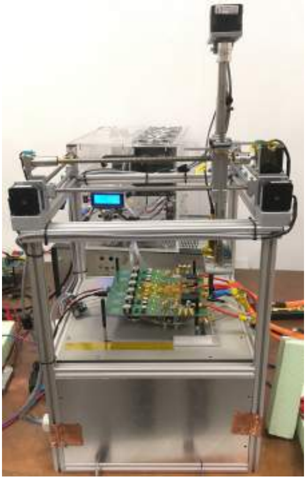
Noise Mitigation: Locate Problem

3D Scanner with Near-field Probes

- Spatial resolution of H & E fields
  Depending on probes.
- Real system behavior
  (not only extracted by simulation)
- Results depending on probe:



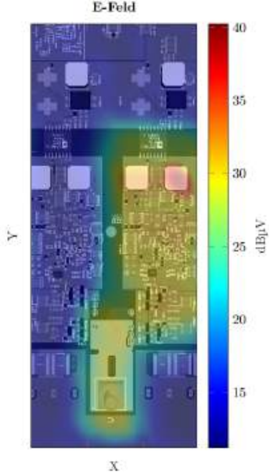
ISEA 3D Scanner:



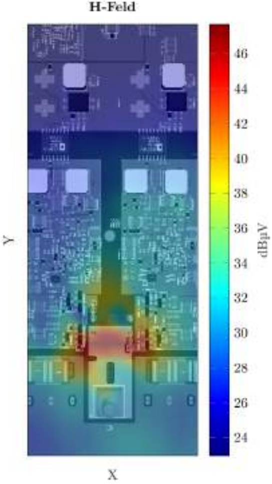
Noise Mitigation: Locate Problem

Example: 3D Scan of PCB

Electric field:



Magnetic field:



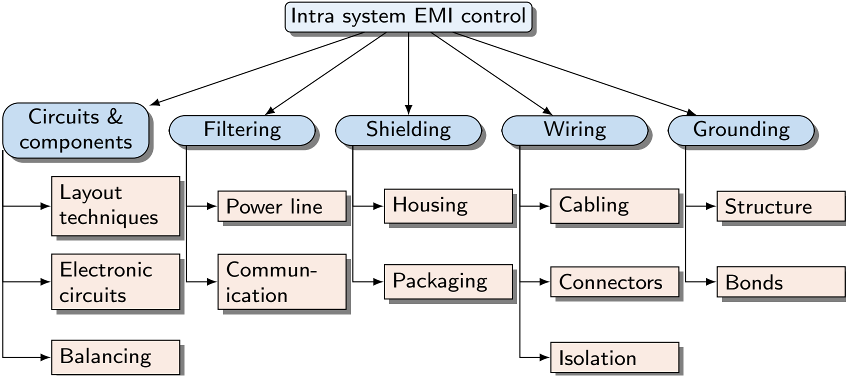
Note: *Measured in 50 ˙ system.*

What are noise mitigation techniques?

What can we do with problems inside a component?

Noise Mitigation: Countermeasures

Intra-System EMI Control [76, p. 1-20]



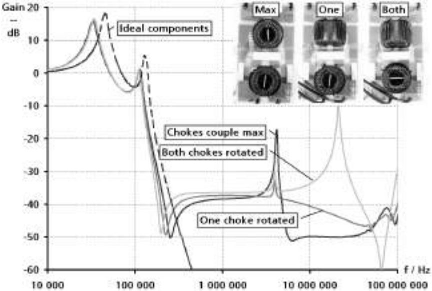
Note: *To every rule there is a situation where it is not valid!*

Noise Mitigation: Countermeasures

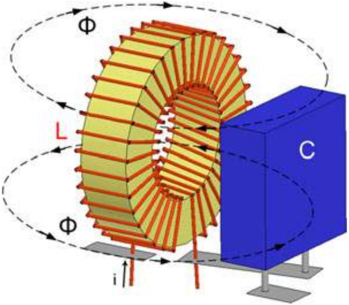
Circuits & Components: Rotation [78], [79]

- Correct circuit coupling depends on the rotation of elements.
- Crucial points of coupling needs experience.

Filter attenuation depending on rotation [78]:



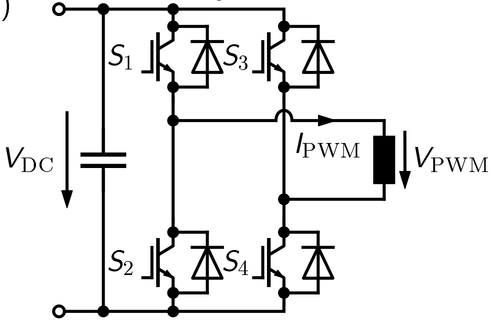
Parallel connection of L and C [79]:



Circuits & Components: Modulation Strategies [80]

- Impact of modulation strategies:
  - Total harmonic distortion (THD)
  - EME
  - Thermal balancing of switches
  - Acoustics in machine control
- Example full bridge:
  - Unipolar operation
  - Bipolar operation
  - Totem-pole operation
- In literature, optimizations are available for nearly every topology.

Full bridge inverter:

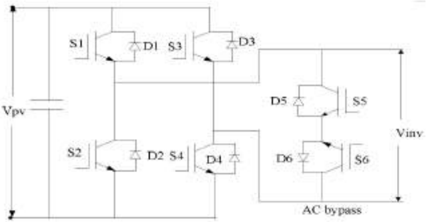


Noise Mitigation: Countermeasures

Circuits & Components: Topologies [80]

- New topologies invented for PV inverters:
  - DC bypass: H5, H6 topology
  - AC bypass: HERIC
- Mitigation of leakage current and increase of efficiency.
- Usually new switches are used to add further degrees of freedom
- Keep in mind:
  Each new switch leads to conduction and switching losses.

Highly efficient and reliable inverter concept (HERIC) topology [80]:

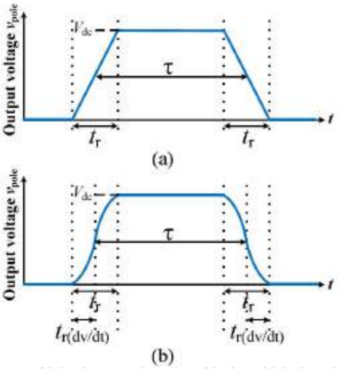


Noise Mitigation: Countermeasures

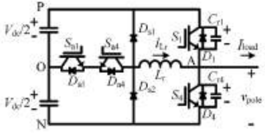
Circuits & Components: ARCP Converter [81], [82]

- Auxiliary Resonant Commutated Pole
- Using soft switching behavior
- Advantages in the range 1 to 20 MHz

Switching behavior [81]:



Schematic of ARCP [81]:



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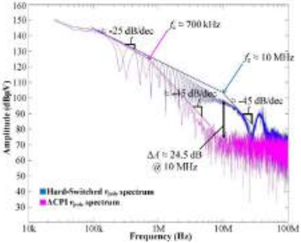
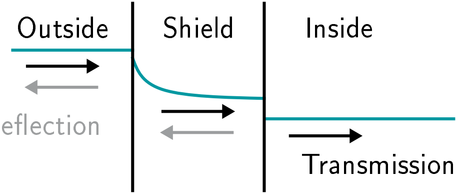


Noise Mitigation: Countermeasures

Shielding [2, p. 265ff] [20, p. 180]

Transmission and reflection at shields:

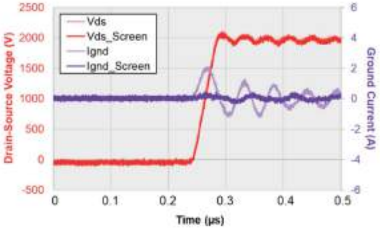


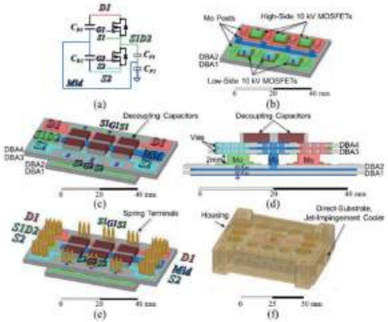
$$S = R + A + B$$

- S: Shielding effectiveness
- R: Reflection loss
- A: Absorption loss
- B: Thin shield correction factor

Packaging: Additional Ground Screen inside a Power Module [83]

- SiC requires advanced module packaging
- Stacked direct bonded aluminum (DBA)
- Reduction of ground current

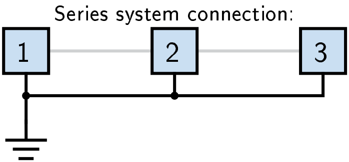


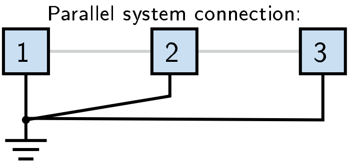


Keep in mind:
Numerous promising concepts are proposed in literature by pulse measurement. Yet, they are not demonstrated during continuous operation.

Grounding: Series and Parallel Connection [17, p. 128ff]

- In high-frequency range, ground planes have not the same potential.
- Return path of current depends on the lowest impedance.
- Parallel ground connection decouples the systems.



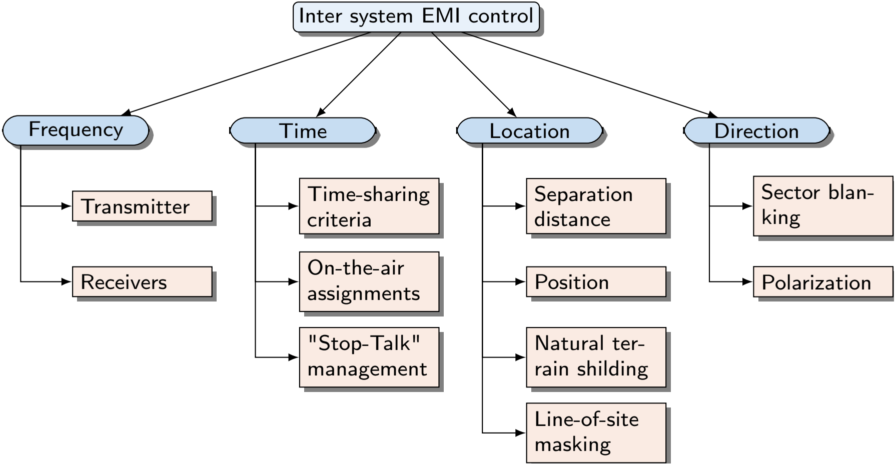


Note: *Concepts can be mixed to multiple ground connections.*

What can we do between systems?

Noise Mitigation: Countermeasures

Inter-System EMI Control [76, p. 5.114]

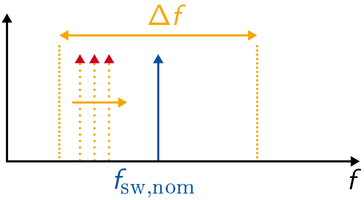


Note: *Inter- and intra- techniques are not strictly distinct*

Spread Spectrum Technique [84], [85]

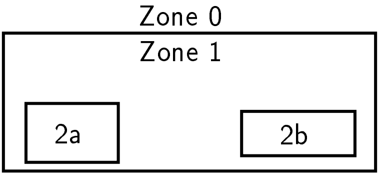
- Controlled Δf to avoid periodic behavior of the system.
- Transform a narrow-band emission into a broad-band one.
- Different methods to control Δf to avoid sub harmonic.

Principle of spread spectrum:



Noise Mitigation: Countermeasures

Location: Zoning [17, p. 150]



- Adapted from lightning protection.
- Group components into sub-systems to maximize EMC.
- Used for protection against ESD.

Noise Mitigation: Countermeasures

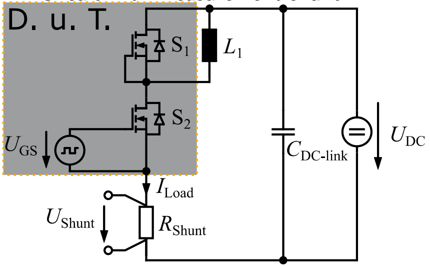
Quick Troubleshooting in the Lab

- Snap-on ferrite
- Grounding including measurement probes
- Different Supplies (including auxiliary supplies)
- Magnetic shielding with ferrite sheets
- Electric shielding with copper foil
- Twisted pair of wires

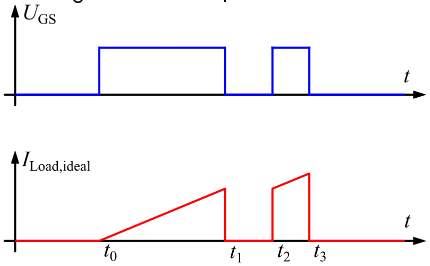
Noise Mitigation: Countermeasures

Example Shunt-Measurement: Setup

Circuit with measurement shunt:

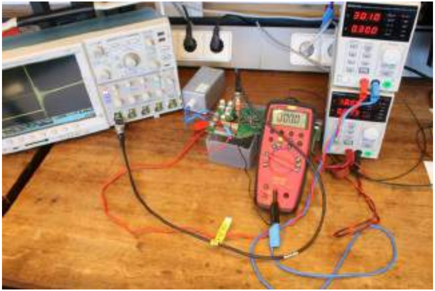


Signals of double pulse test:

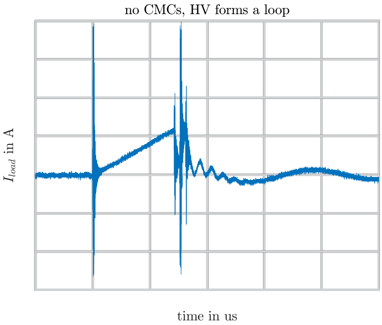


Noise Mitigation: Countermeasures

Example: First Measurement

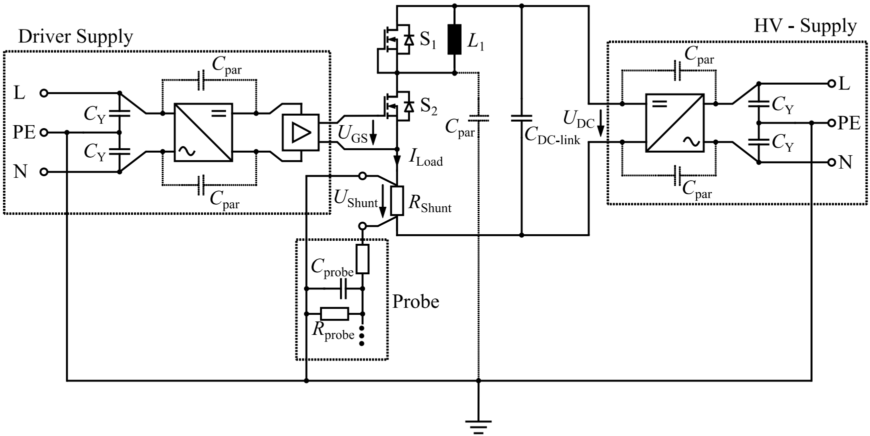


Always take a picture of your setup!



Noise Mitigation: Countermeasures

Example: Equivalent Circuit with Parasitic Elements



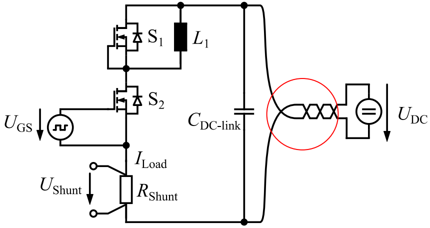
Lets check the setup with all parasitics that we know!

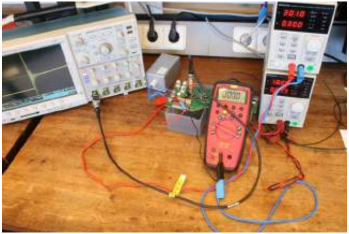
Example: List used Equipment!

- High voltage source: Korad KA3005D
- Auxiliary voltage for gate driver: Korad KA3005D
- Oscilloscope: Tektronix DPO4034 (350 MHz, 2.5GSa/s)
- Shunt: T&M Research Products, SDN-015 (Bandwidth 1200 MHz)
- BNC: Radiall R284C0351005 (Bandwidth 1000 MHz)
- Feed-through termination (50 Ω): HZ-22

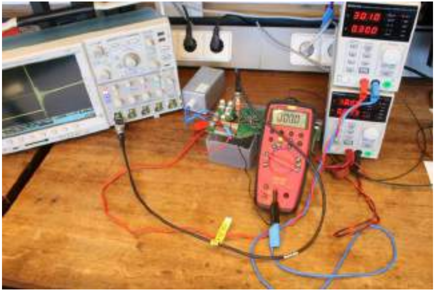
Noise Mitigation: Countermeasures

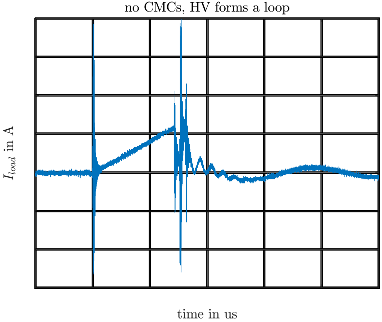
Example: First Idea





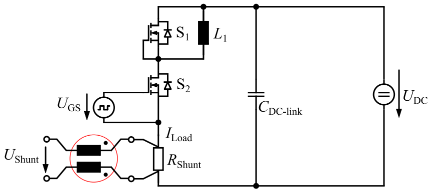
Example: Twisted Supply Wires





Noise Mitigation: Countermeasures

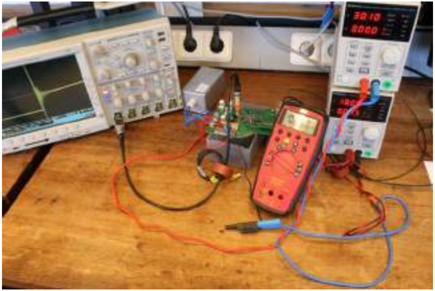
Example: Second Idea

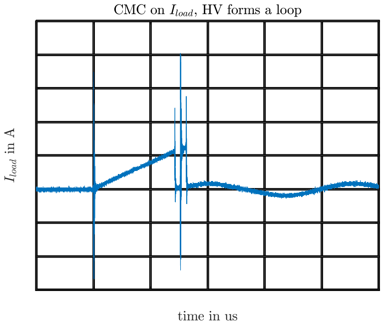


Warning: A Common-Mode Choke in the measurement path reduces the bandwidth of the measurement.

Noise Mitigation: Countermeasures

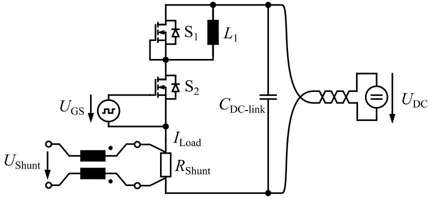
Example: Add Common-Mode Choke at BNC Cable





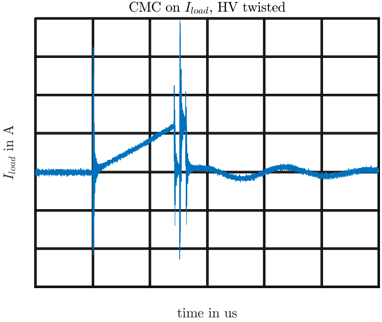
Noise Mitigation: Countermeasures

Example: Both Together



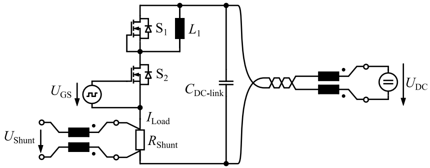
Noise Mitigation: Countermeasures

Example: Both Together



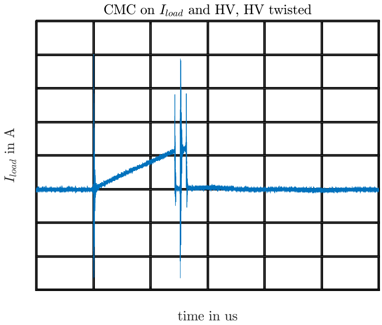
Noise Mitigation: Countermeasures

Example: Common-Mode Damping at the Supply



Noise Mitigation: Countermeasures

Example: Common-Mode Damping at the Supply



Noise Mitigation: Countermeasures

Example: Other Ideas?

- Other supplies
- Other probes
- ...

Break

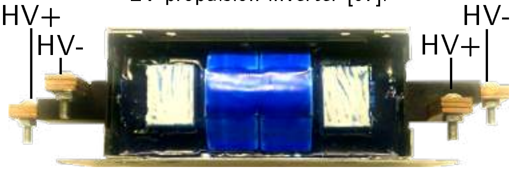
Table of Contents

Filter Design: Introduction

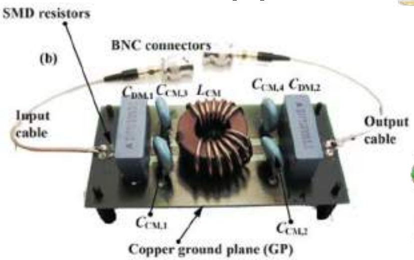
Filter Examples

- Generic/individual filters
- Integrated/sepearate setups
- Low/High-current levels

EV propulsion inverter [87]:



PCB based filter [86]:



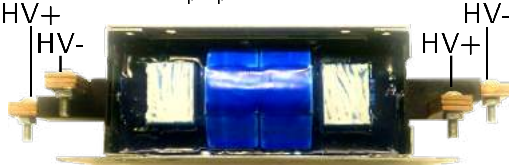
Stationary application [88]:

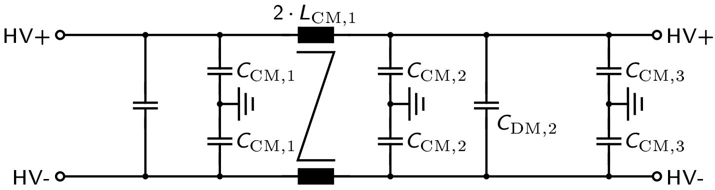
Filter Design: Introduction

EV Filter Examples [87]

- Copper busbar design
- Metal housing
- 80 % potted
- *CLC* topology
- 600 V, 150 A
- Weight: 960 g
- Volume: 0.3 l

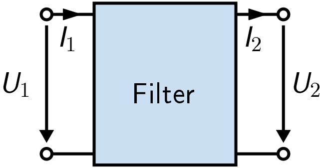
EV propulsion inverter:





Filter: Requirements for Power Electronics [6, p. 165]

- Design options:
  - Type (Active or Passive)
  - Structure (L, C, LC, CL, CLC, LCL ...)
  - Parameters
  - Parasitic elements (including coupling)
- Rated for nominal currents and voltages of the system.
- Limitations of capacitive ground currents (e.g. for chassis or VDE-100)
- Defined insertion losses (IL):



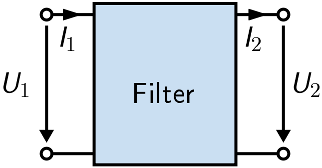
$$IL(f) = 10 \cdot \log_{10}\left(\frac{P_1}{P_2}\right)$$

Filter: Insertion Losses [6, p. 165]

- Defined insertion losses (IL):

$$IL(f) = 10 \cdot \log_{10}\left(\frac{P_1(f)}{P_2(f)}\right)$$

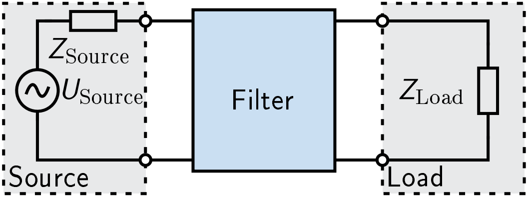
- Measurement with high impedance load $Z_{\mathrm{load}} \rightarrow \infty$



Impedances:

$$Z_{11} = \frac{U_1}{I_1} \text{ with } I_2 = 0$$
$$Z_{21} = \frac{U_2}{I_1} \text{ with } I_2 = 0$$
$$Z_{22} = \frac{U_2}{I_2} \text{ with } I_1 = 0$$
$$Z_{12} = \frac{U_1}{I_2} \text{ with } I_1 = 0$$

Filter: Load- and Source Impedance [6]



Impedances:

$$Z_{11} = \frac{U_1}{I_1} \text{ with } I_2 = 0$$
$$Z_{21} = \frac{U_2}{I_1} \text{ with } I_2 = 0$$
$$Z_{22} = \frac{U_2}{I_2} \text{ with } I_1 = 0$$
$$Z_{12} = \frac{U_1}{I_2} \text{ with } I_1 = 0$$

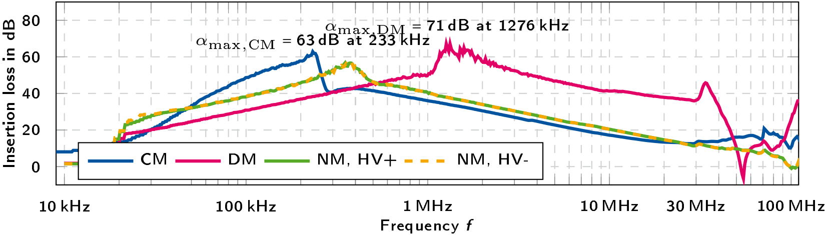
- Mismatched impedance conditions of load and source $Z_{\mathrm{Load}} \neq Z_{\mathrm{Source}}$
- Insertion factor:

$$IF(f) = 20 \cdot \log_{10}\left(\frac{U_1}{U_2}\right) = \frac{(Z_{11} + Z_{\mathrm{Source}}) \cdot (Z_{\mathrm{Load}} + Z_{22}) - Z_{12}Z_{21}}{(Z_{\mathrm{Source}} + Z_{\mathrm{Load}}) \cdot Z_{21}} \tag{3}$$

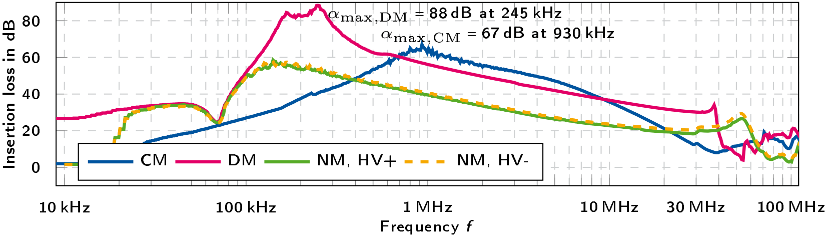
Filter Design: Introduction

Filter Example Insertion Loss in 50 ˙ system [10]

EV propulsion inverter [87]:

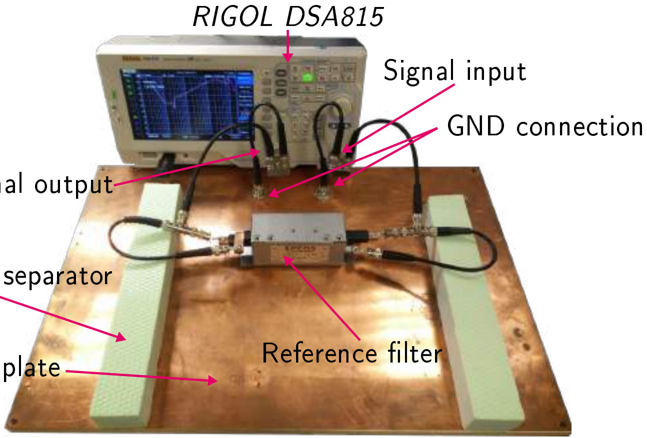


Stationary application [88]:



Filter Design: Introduction

Measurement of insertion loss [10]

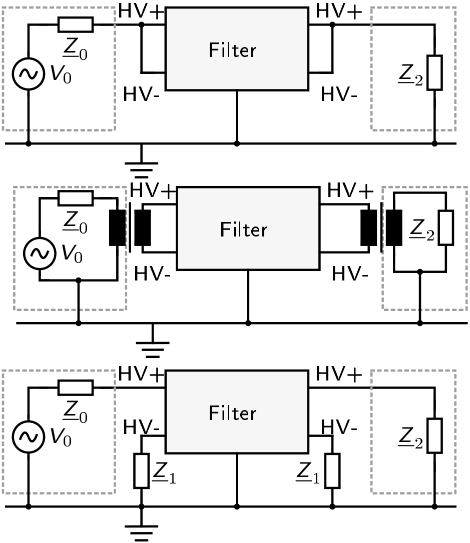


- The results consists of DUT (filter), setup and connectors.
- Different modes are realized by different adapters (CM, DM, NM+/-)

Filter Design: Introduction

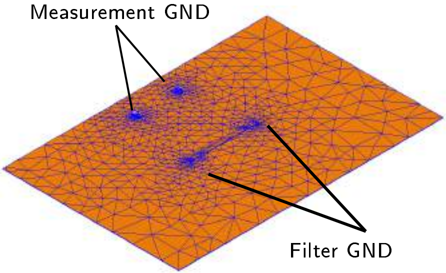
Measurement of insertion loss [10]

- Common Mode (CM)
  - with 0° phase shift
  - power splitter improves symmetry
- Differential Mode (CM)
  - with 180° phase shift
  - using a transformer or 180° power splitter
- Normal Mode (CM)
  - phases are connected separately
  - one measurement for each phase
  - termination of unused inputs

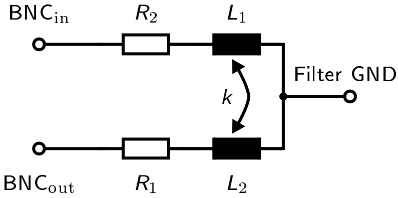


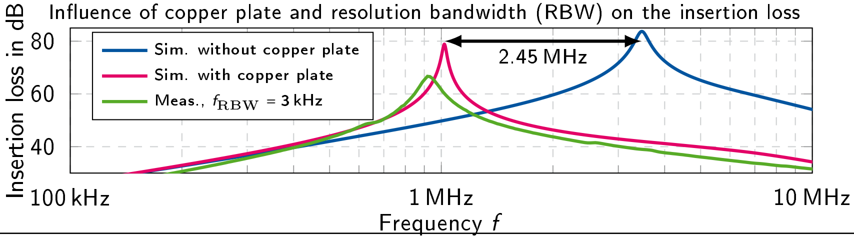
Simulation of insertion loss [10]

FEM model of copper plate:



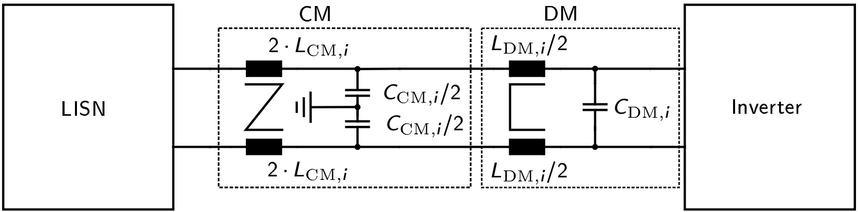
Extracted schematic of copper plate:





Filter Design: Basic Components

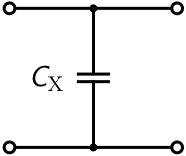
Filter Structure [10]



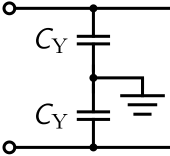
- Passive filter consists of *RLC* elements.
- Elements have an impact on CM or/and DM.
- Order and impact of the elements
- Optimal filter design require an understandign of load and source impedance.

Filter: Basic Elements [89]

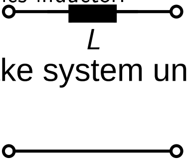
X Capacitor:



Y Capacitor:

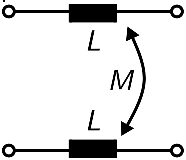


Series inductor:



can make system unstable

Coupled inductor:



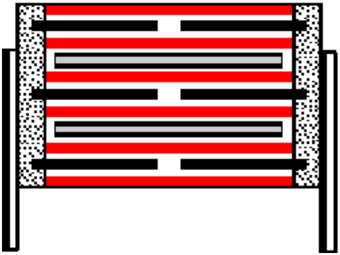
Keep in mind: *An element at the wrong place has no effect or increases the problem.*

Filter Design: Basic Components

Filter Capacitors types

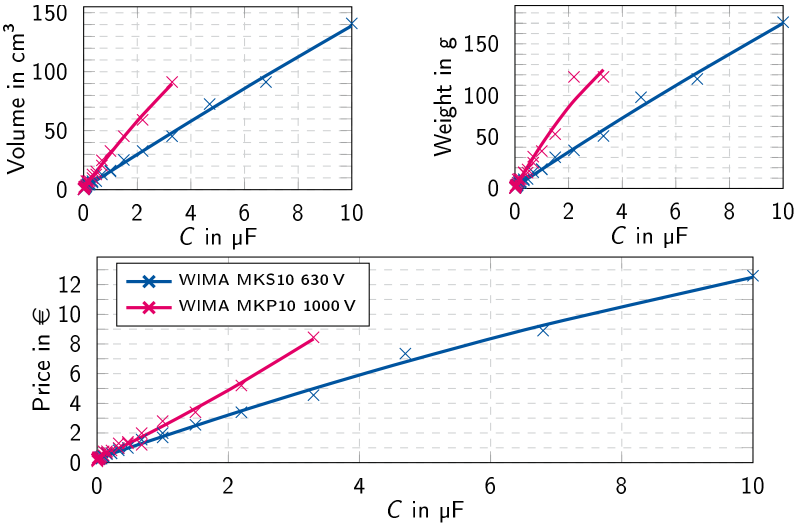
- High pulse current capability
- Low stray inductance
- Good termination contact
- High insulation resistance
- Self-healing capability
- Foating electrodes
- Limited to low capacitor values
- Temperature and long-term stability
- Available in SMD or plastic housing *(screw, trough hole assembly)*

Y-Capacitor: Source: www.wima.de (FKP1)



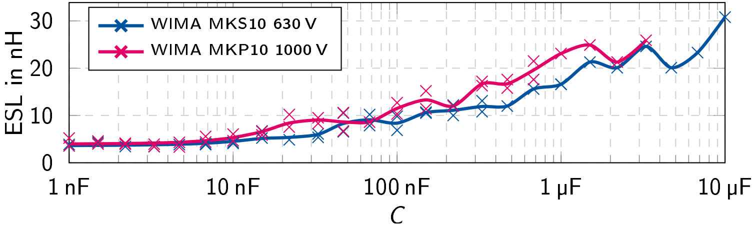
Filter Design: Basic Components

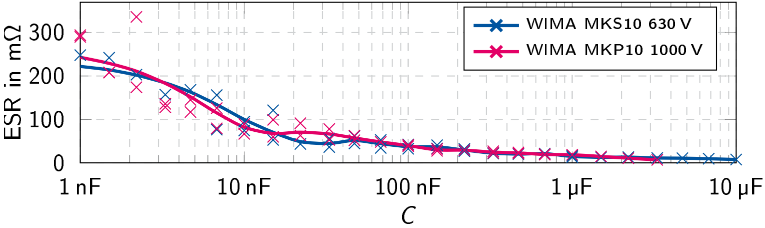
Volume/Weight/Price of Film Capacitors [10]



Filter Design: Basic Components

Parasitic Elements of Film Capacitors [10]

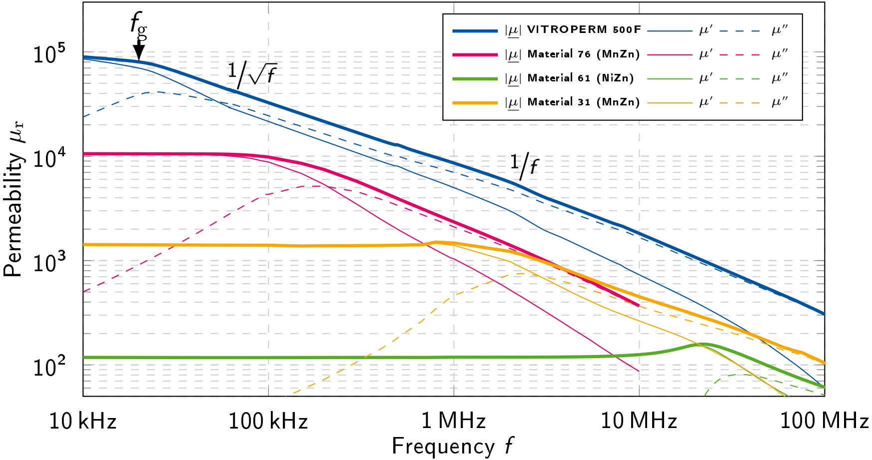




- Characterized with an impedance analyzer (incl. meas uncertainty)
- Example devices (due to aviability), may differ from other suppliers.

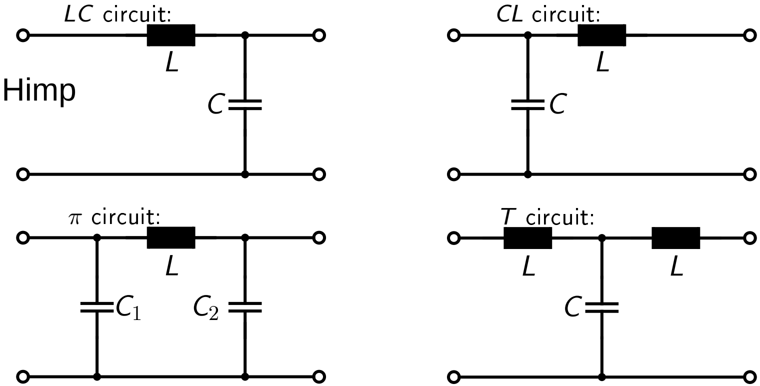
Filter Design: Basic Components

Material of Filter Inductors [90]



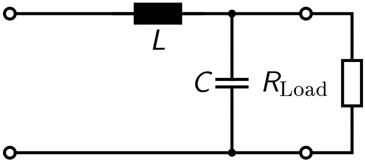
- Inductor material of e.g. DC/DC and filters differ in cmplx. periability
- Fiter material can have high dissipation factor at damping frequency.

Filter: Basic Structures [6, p. 170]



Filter Design: Basic Components

Filter: LC circuit with R load [6, p. 172]



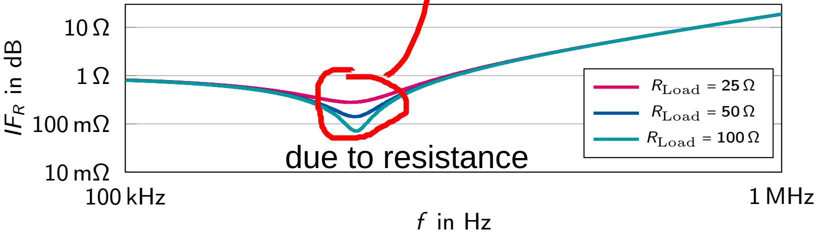
$$IF_R(\omega) = \sqrt{\left(1 - \frac{\omega^2}{\omega_0^2}\right)^2 + \left(\frac{\omega L}{R_{\text{Load}}}\right)^2}$$

Calculate insertion factor with:

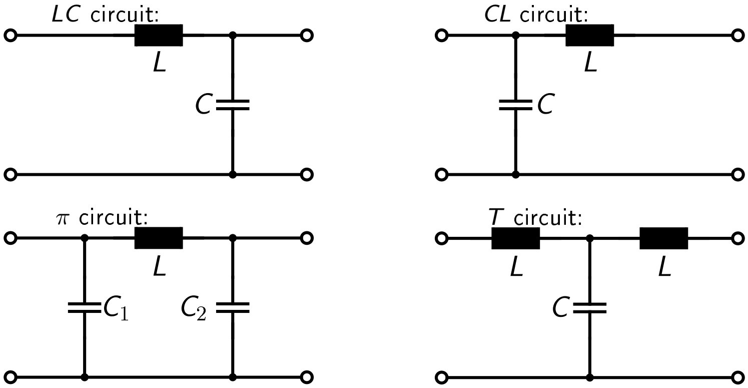
$$Z_{11} = \mathrm{j}\omega L + \frac{1}{\mathrm{j}\omega C}$$

$$Z_{12} = Z_{21} = Z_2 = \frac{1}{\mathrm{j}\omega C}$$

$$Z_{\text{Load}} = R \text{ and } Z_{\text{Source}} = 0$$



Filter: Basic Structures [6, p. 170]



Filter: Selection of Filter Topology

- Selection of filter structure depending circuit impedance:

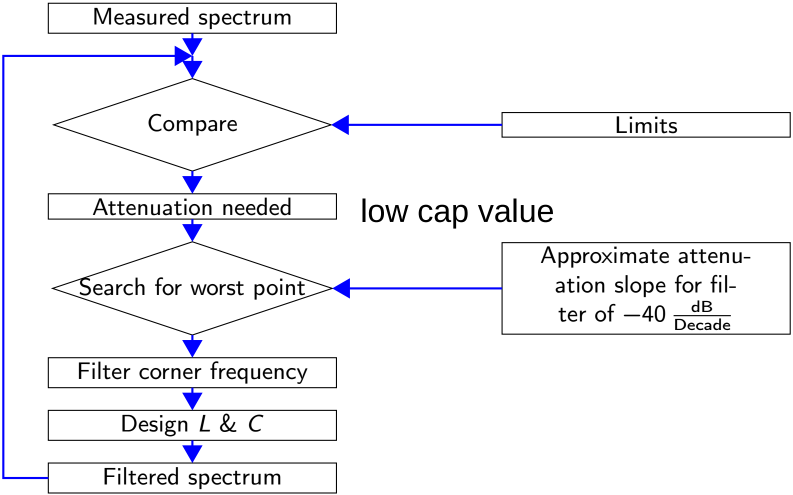
		Z_{load} Low	Z_{load} High
Z_{source}	Low	T (LCL) circuit	LC circuit
	High	CL circuit	π (CLC) circuit

- The insertion losses must be selected for CM and DM separately.
  - A DC link with a low series inductance is a perfect DM filter stage.
  - The energy to ground is limited by regulations:
    (e. g. for automotive 0.2 J in ISO6469-3 [91]):

$$C_{\max} = \frac{2 \cdot E_{\max}}{V^2} \tag{4}$$

Ground capacitance on the complete setup:
2.5 µF for 400 V and 625 V for 800 V

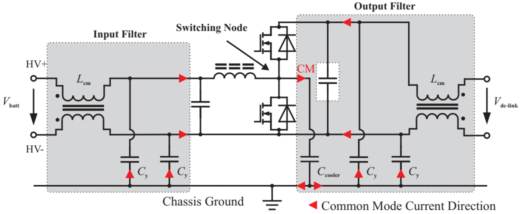
Try & Error Filter Design Procedure [92]



low cap value

Filter Design: Try & Error

Example of a SiC Dc/Dc Converter [54]

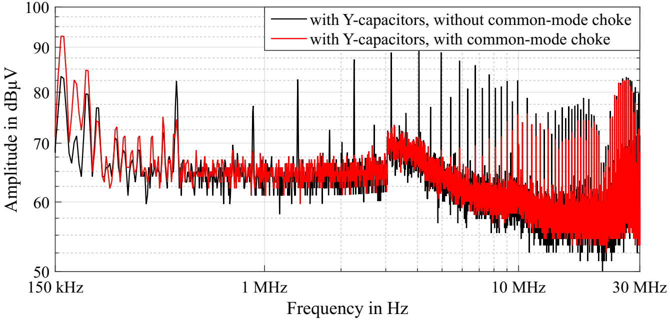


- Buck boost converter for update from 400 V to 800 V
- Two stage CM EMI filter

Filter Design: Try & Error

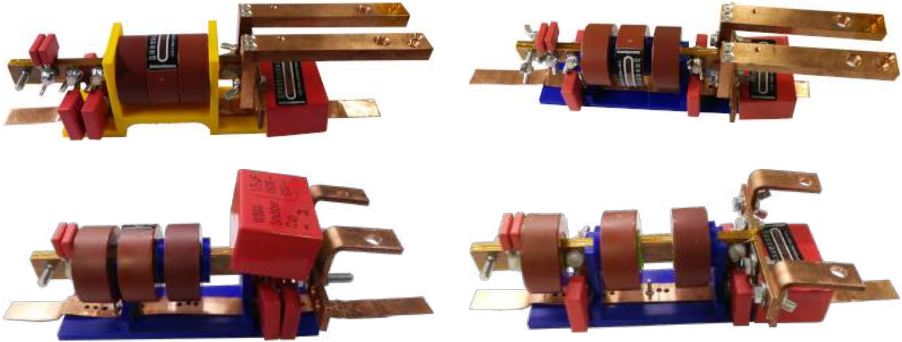
Example of a SiC Dc/Dc Converter [54]

Measurement with WE-TOF EMI Suppression Toroidal Ferrite (WE 74270191)



Filter Design: Try & Error

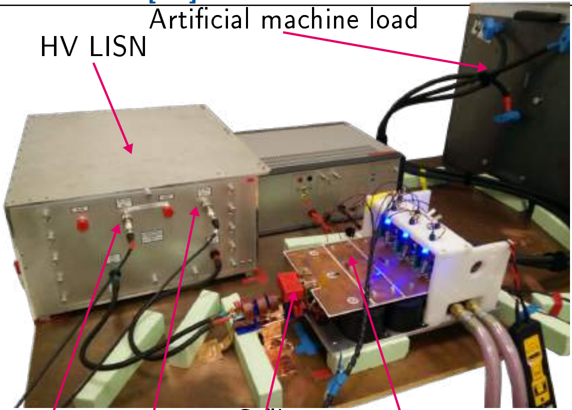
Rapid Prototyping with 3D printed brackets [10]



- Rapid prototyping technique based on 3D printed filter brackets
- Enables quick filter reconfiguration
- High current and high voltage applications
- Multi-stage filter designs feasible

Filter Design: Try & Error

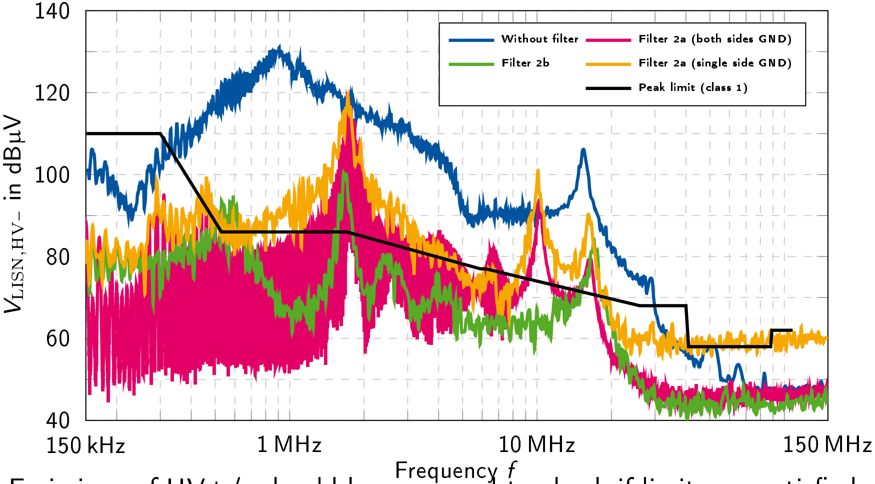
Filter with SiC Inverter [10]



- Simple setup based on CISPR-25 configuration
- 800 V dc-link voltage
- Machine is replaced by an artificial machine load.

Filter Design: Try & Error

Filter with SiC Inverter [10]



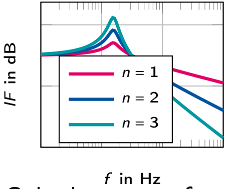
- Emissions of HV+/- should be measured to check if limits are satisfied.
- Grounding of filters have a significant impact.

Model Based Design [6], [93, p. 176]

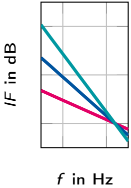
- Degrees of freedom
  - Sizes of elements
  - Stages
- Requirements
  - Insulation requirements
  - Current load capability
  - Noise limit
  - Maximum ground capacitance
- Defining a cost function
  - Cost of depending on size Ls and Cs: $K_{L,C} = K_0 + x \cdot K_\mathrm{x}$
  - Manufacturing costs: Depending on stage
  - Additional costs for mobile applications: *Volume, weight and power losses*

Optimization of Filter [93]

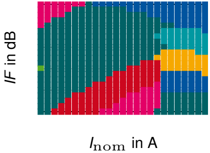
1. Select frequencies where maximum damping is required (depending on CM and DM)
2. Select filter order by use of high-frequency simplification



→



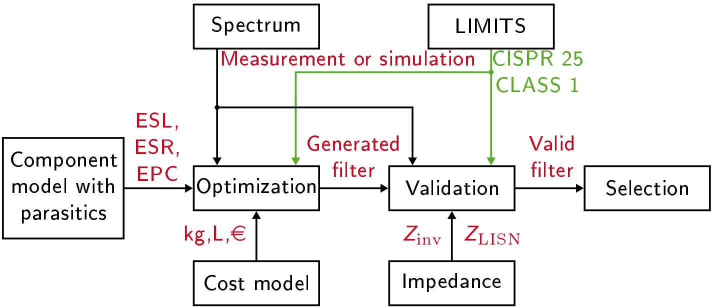
3. Calculate cost for each filter configuration



4. Select required filter depending on current and insertion factor.

Filter Design: Model-Based Design

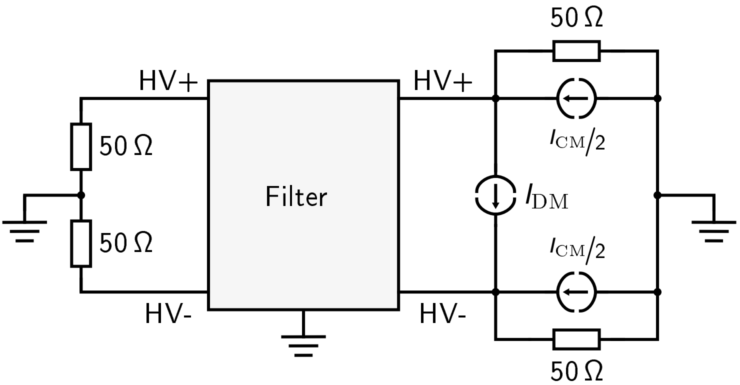
Structure for Optimization [10]



- Generalized structure for filter optimization
- Implementations for different elements possible.
- Allows hollistic comparisons of technologies.

Filter Design: Model-Based Design

Simulation in Frequency Domain [10]



- Load (LISN) and source (converter) are modeled as 50 ˙
- If more realistic, this must be replaced with setup impedance.
- Same phase (source event) assumed for CM & DM.

Filter Design: Model-Based Design

Cost Structure [10]

- Total costs:

$$p_{\text{tot}} = p_{\text{comp}} + p_{\text{´kW h}} \tag{5}$$

- Component costs:

$$p_{\text{comp}} = p_L + p_C + p_{\text{manufacturing}} \tag{6}$$

- kW h costs (only for battery applications) consists of:

$$p_{\text{´kW h}} = V \cdot K_{\text{vol}} + W \cdot K_{\text{weight}} + E_{\text{losses}} \cdot K_{\text{losses}} \tag{7}$$

- General problems with *absolute* cost models:
  - Based on assumptions (markets/suppliers, contracts, yield...)
  - Cost changes over time and quantity
  - Usually developed in conecpt phase, based on minimal data
  - Even relative costs are critical (offset cost and linear factors)

Break

Report

- Each student or a group writes a report to a specific topic!
- Use the template of the IEEE (LaTeX and Word are accepted)
- The document should have
  - Single column
  - Five pages including references
  - Font-size of 10 pt
  - Line spacing of one and a half
- Send a PDF document with a maximum file size of 5 MB.
- Selection of the topic: Date of laboratory exercise.
- Deadline for the report: One month after the laboratory exercise.
- If grading is requested by the student, it is carried out on the basis of the written report.

Note: *If the report is not handed in, the course is not passed.*

Example Topics for your Reports

- Setup and measurement principles (including CISPR 16 and CISPR 25)
- Measurement results (with oscilloscope and testing receiver measurements)
- Laws, rules and regulations
- Countermeasures (Design of the filter)
- Simulation of the laboratory setup

Note:

- The report of each group should compliment each other.
- Not all topics must be covered in one group.
- Please correct your reports in the group before hand them in.

Follow Up

- Date: tbd
- Location: zoom
- Topic
  - Welcome
  - Presenting the reports
  - Course feedback

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Vocabulary with Abbreviation

Abbreviation	English	German
EMC	Electromagnetic compatibility	Elektromagnetische Verträglichkeit
EMI	Electromagnetic interference	Elektromagnetische Funktionsstörung
EME	Electromagnetic emission	Elektromagnetische Aussendung
EMS	Electromagnetic susceptibility	Elektromagnetische Störempfindlichkeit
ESD	Electrostatic discharge	Entladung statischer Elektrizität
CE	Conducted emission	Leitungsgebundene Störungen
RE	Radiated emission	Feldgebundene/Abgestrahlte Störungen

Source: `http://www.electropedia.org`

Vocabulary without Abbreviations

English	German
Electromagnetic environment	Elektromagnetische Umgebung
Electromagnetic disturbance	Elektromagnetische Störgröße
Electromagnetic noise	Elektromagnetisches Geräusch
Inter-system interference	Intersystem-Störung
Intra-system interference	Intrasystem-Störung
Man-made noise	Technisch bedingtes Geräusch/Störung
Natural noise	Natürliches Geräusch/Störung
Continuous disturbance	Kontinuierliche Störgröße
Discontinuous disturbance	Diskontinuierliche Störgröße
Immunity	Störfestigkeit (gegenüber einer Störgröße)
Emitter	Störquelle
Coupling path	Kopplungspfad

Source: `http://www.electropedia.org`

CEN Comité Européen de Normalisation, engl.: European Committee for Standardization) 219
CENELEC Comité Européen de Normalisation Electrotechnique, engl.: European Committee for Electrotechnical Standardisation 214, 219
CISPR Comité international spécial des perturbations radioélectriques 212–216, 219

DIN Deutsches Institut für Normung 219
DKE Deutsche Kommission Elektrotechnik Elektronik Informationstechnik 219

ETSI European Telecommunications Standards Institute 219

GPS Global positioning system 23

ICNIRP International Commission on non-ionizing radiation protection 210
IEC International Electrotechnical Commission 6, 212–214, 219
IEEE Institute of Electrical and Electronics Engineers 275
ISEA Institut für Stromrichtertechnik und elektrische Antrieb 277
ISO International Organization for Standardization 219
ITU International Telecommunication Union 23

PE-CSA Power Electronics - Control, Synthesis and Applications 50

VDE Verband der Elektrotechnik, Elektronik und Informationstechnik, engl.: Association for Electrical, Electronic and Information Technologies 219

WHO World Health Organization 210

ANSYS® Q3D Extractor by ANSYS®, parasitic extraction tool for electronics design. For the scope of this thesis, the software version 15.0 was used. 92

LTspice® by Linear Technology, SPICE based simulator for electronic circuits. In the scope of this thesis, the software version 4.22i was used. 77, 78, 107, 108, 180–182

PLECS® by Plexim, simulation of power electronic systems including magnetics, thermal aspects and control, `http://www.plexim.com`. In the scope of this thesis, the software version 4.1.2 was used. 107, 108

SIMetrix by SIMetrix Technologies, SPICE simulator with good accurarcy and performance for a broad range of analog and mixed signal applications. For the scope of this thesis, the software version 8.10 was used. 78

Thank you for your kind attention!

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