WÜRTH ELEKTRONIK

Flyback transformer

more than you expect

Technical ACADEMY
Author : Alain Lafuente

alain.lafuente@we-online.com

Transformer Design: General sequence

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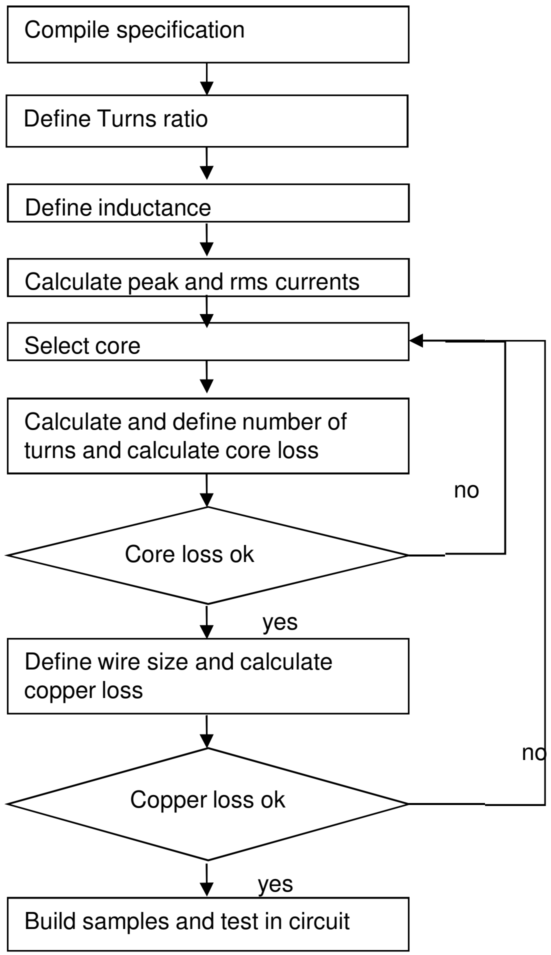
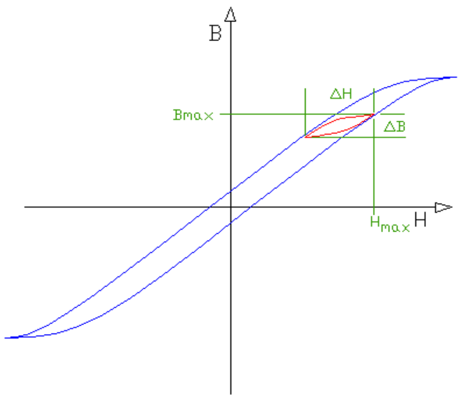
Design of a Custom Flyback transformer

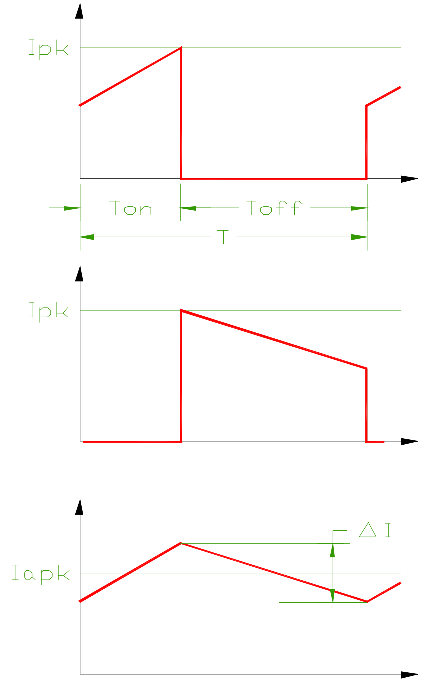


Basic Principles

The Flyback Converter

- CCM
  - The primary current never drops to zero during all operating conditions
  - Primary Inductance value is relatively bigger.
  - Two states per switching cycle:
    - The ON state: Transistor is ON and Diode is OFF
    - The OFF state: Transistor is OFF and Diode is ON
  - Lower ripple currents
  - Right hand plane zero
  - Core losses are lower
  - Flux swing is smaller
  - Improved EMC properties
  - Worst case at low Vin



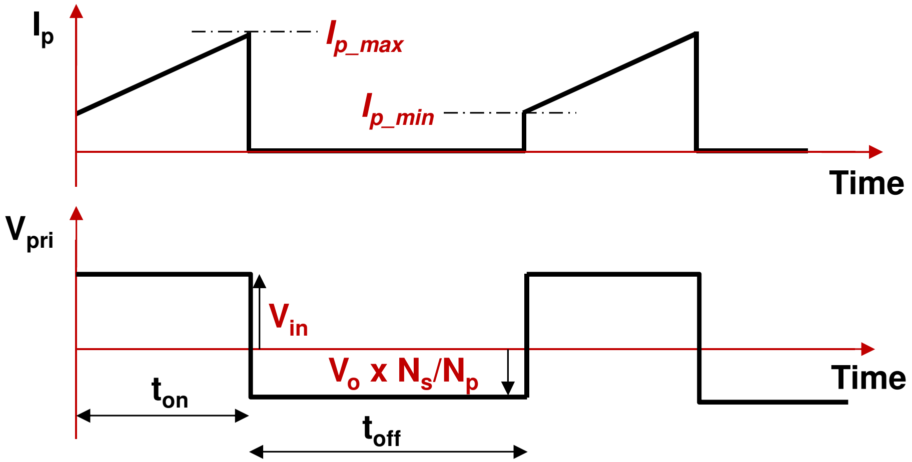


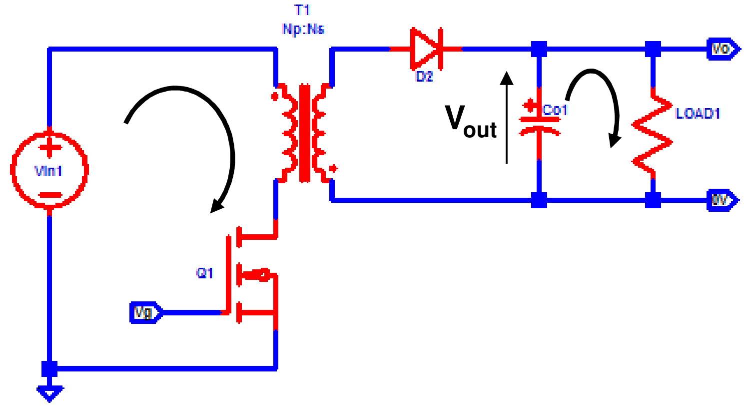
The Flyback Converter (CCM)

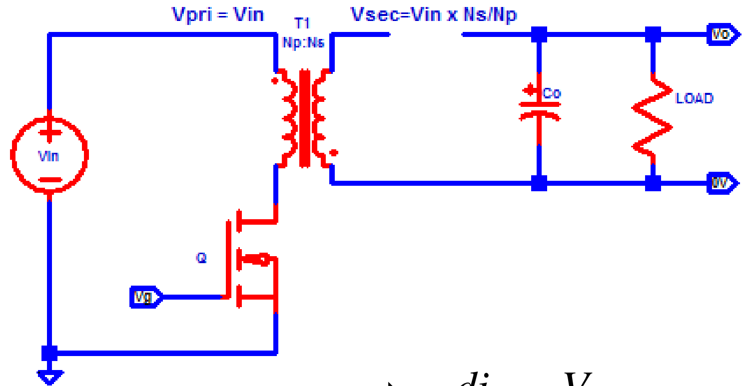
- Switch closed (Transistor ON):
  - Primary winding current rises from Ip_min to Ip_max in t_{on} = DT

$$\Delta I_p = \frac{Vin \times DT}{L_p}$$

$$I_{p\_max} = \frac{Vout \times Iout}{\eta \times D \times Vin} + \frac{\Delta I_p}{2}$$







$$V_{Lp} = V_{in} \Rightarrow \frac{di_L}{dt} = \frac{V_{in}}{Lp}$$

The Flyback Converter (CCM)

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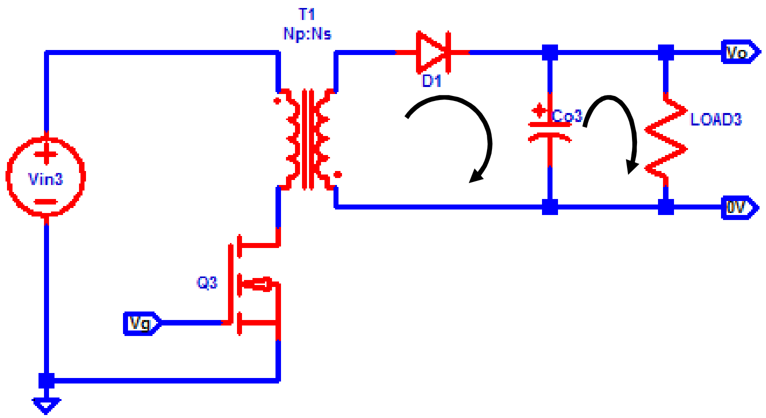
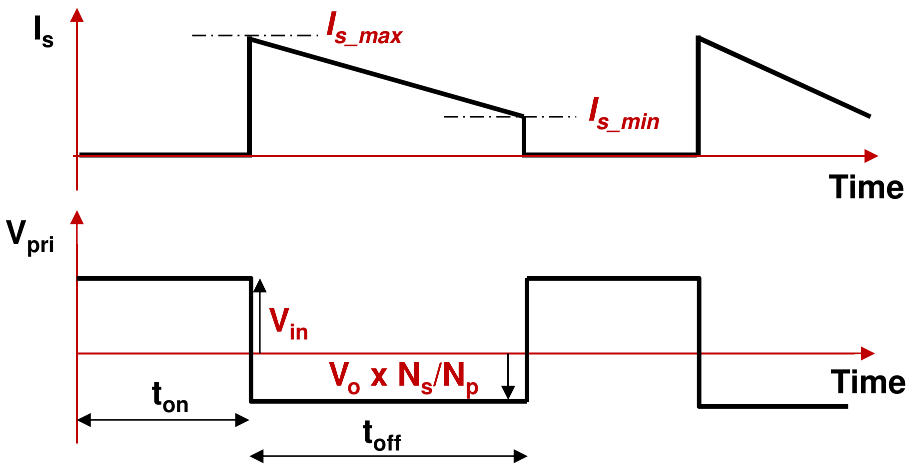
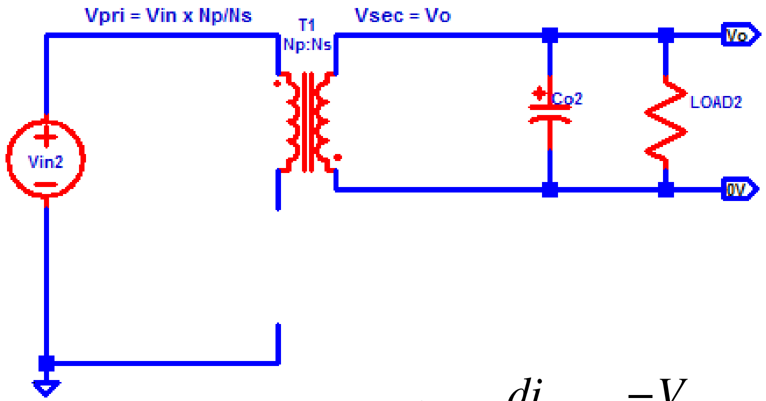
- Switch opened (Transistor OFF):
  - Secondary winding current falls from Is_max to Is_min in $t_{off} = (1\text{-}D)T$.

$$\Delta I_s = \Delta I_p \times \frac{N_p}{N_s} \qquad I_{s\_max} = I_{p\_max} \times \frac{N_p}{N_s}$$







$$V_{Ls} = -V_{out} \Rightarrow \frac{di_{Ls}}{dt} = \frac{-V_{out}}{Ls}$$

The Flyback Converter (CCM)

- **Critical inductance value ($L_{critical}$):**
  - At Boundary of CCM/DCM
  - Minimum inductance to obtain a continuous conduction mode at minimum output power

$$L_{Critical} > \frac{V_{out}^2}{2P_{out\_min} \cdot f_{switch}} \times \frac{1}{\left(\frac{N_s}{N_p} + \frac{V_{out}}{V_{in\_max}}\right)^2}$$

- **Turns Ratio:**

$$\frac{N_s}{N_p} = \frac{V_{out}}{\sqrt{V_{in\_min} \times V_{in\_max}}}$$

The Flyback Converter (CCM)

- **CCM Design Equations:**

$$VCR = \frac{Vout}{Vin} = N \times \frac{D}{1-D} \quad ; \quad where: \quad N = \frac{N_s}{N_P}$$

VCR = Voltage Conversion Ratio

$$\Delta I_p = \frac{Vin \times DT}{L_p}$$

$$L_p = \frac{V_{out}^2}{2 P_{out} \cdot f_{switch}} \times \frac{1}{\left(\frac{N_s}{N_p} + \frac{V_{out}}{V_{in\_max}} \right)^2}$$

$$V_D = Vout + (Vin \times \frac{N_s}{N_p})$$

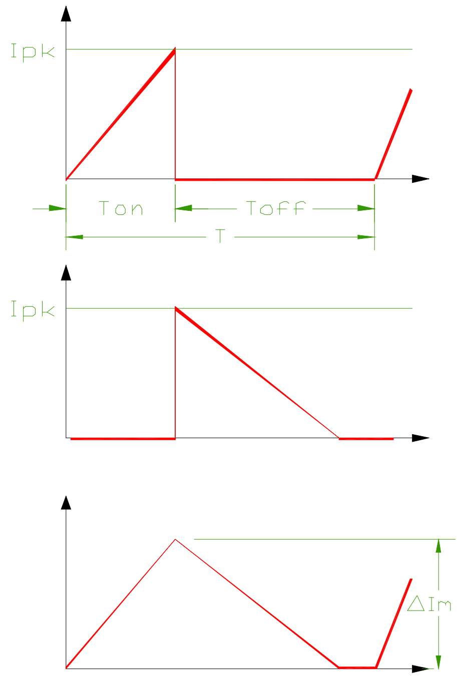
$$V_T = Vin + (Vout \times \frac{N_p}{N_s})$$

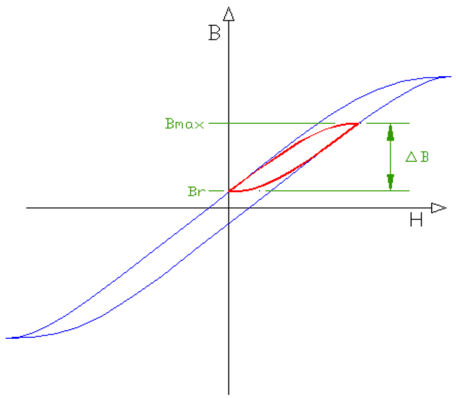
$$I_{p\_max} = \frac{Vout \times Iout}{\eta \times D \times Vin} + \frac{\Delta I_p}{2}$$

$$Iin = \frac{Vout \times Iout}{\eta \times Vin} = \frac{N \times D \times Iout}{(1-D) \times \eta}$$

The Flyback Converter

- DCM
  - The primary current drops to zero.
  - Primary Inductance value is relatively smaller. Capacitance may need to be larger.
  - Three states per switching cycle:
    - The ON state: Transistor is ON and Diode is OFF
    - The OFF state: Transistor is OFF and Diode is ON
    - The IDLE state: Both Transistor and Diode are OFF
  - MOSFET turn on at zero current
  - Worst case at low Vin



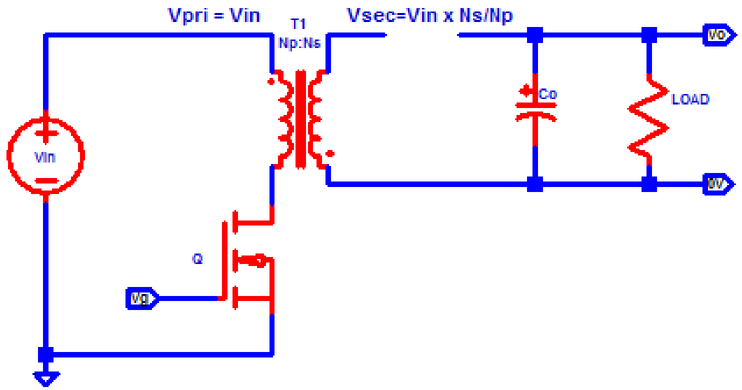


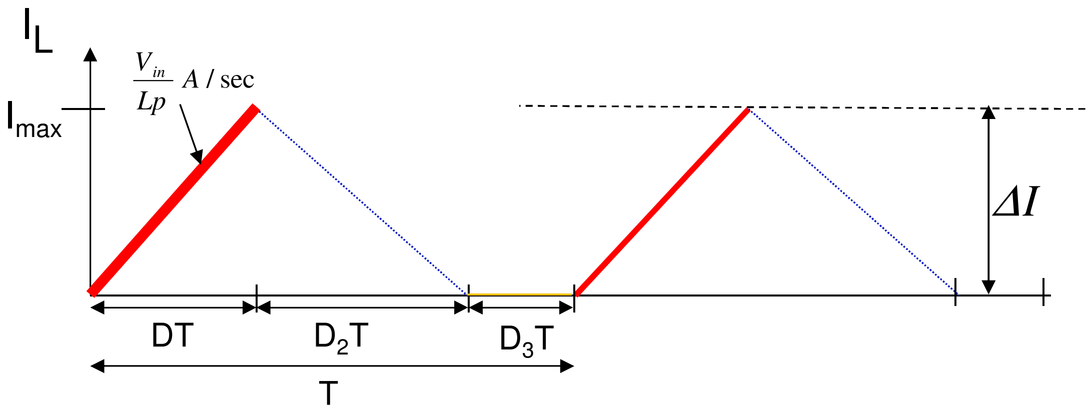
The Flyback Converter (DCM)

- Switch closed (Transistor ON):
  - Primary winding current rises from zero to I_{p_max} in t_{on} = DT

$$I_{p\_max} = \Delta I_p = \frac{Vin \times DT}{L_p}$$

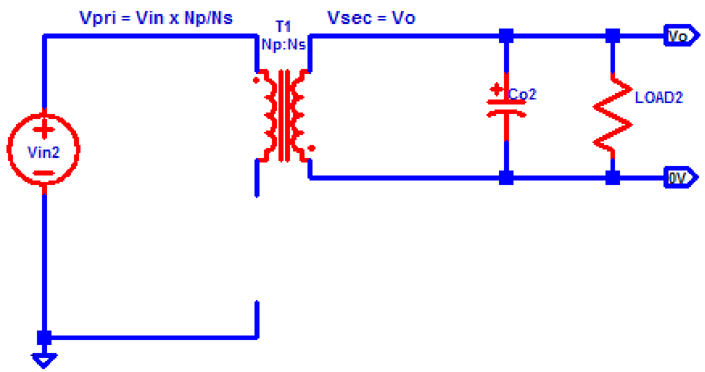
$$D = \frac{\sqrt{2 \times P_{in} \times L_p \times f}}{V_{in}}$$





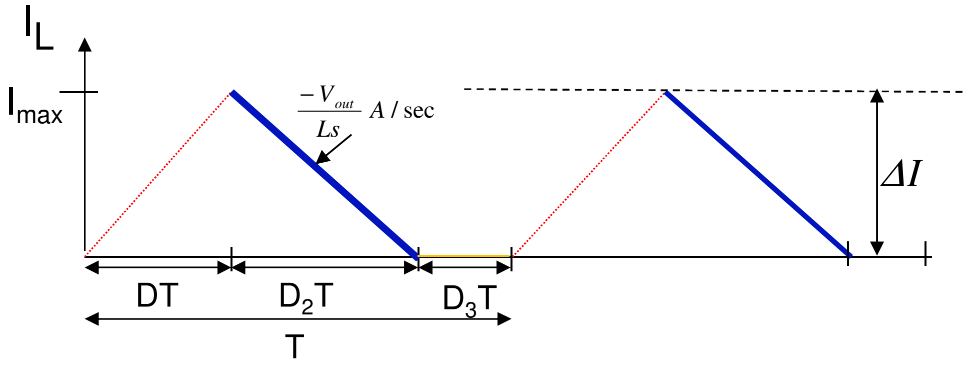
The Flyback Converter (DCM)

- Switch opened (Transistor OFF):
  - Secondary winding current falls from I_{s_max} to zero in $t_{off} = D_2T$.



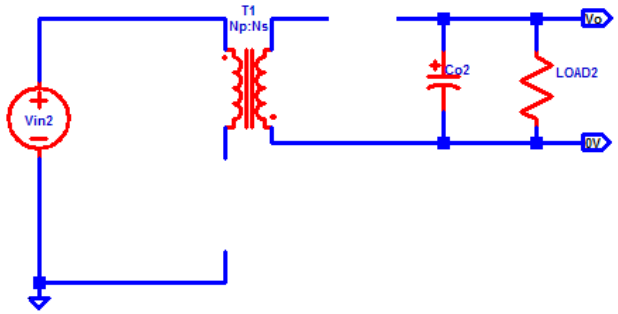
$$I_{s\_max} = I_{p\_max} \times \frac{N_p}{N_s}$$

$$D2 = \frac{\sqrt{2 \times P_{out} \times N^2 \times L_p \times f}}{V_{out}} \qquad N = \frac{N_s}{N_p}$$

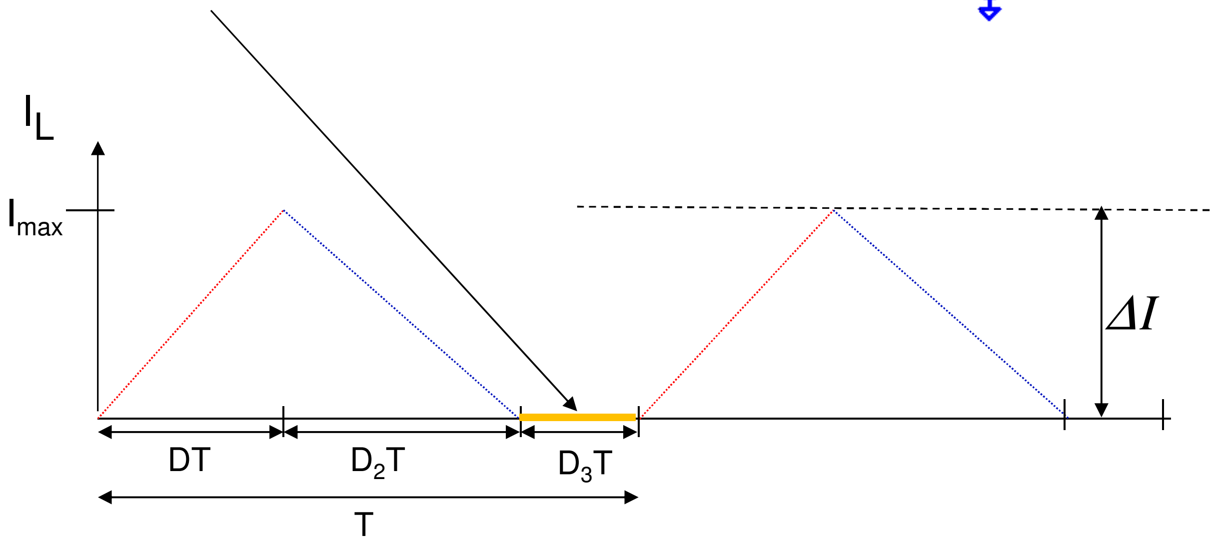


The Flyback Converter (DCM)

- **Idle State (Transistor & Diode OFF):**
  - Only Capacitor delivers energy to load during D_3T



$$D3 = 1 - \mathrm{D} - \mathrm{D2}$$



The Flyback Converter (DCM)

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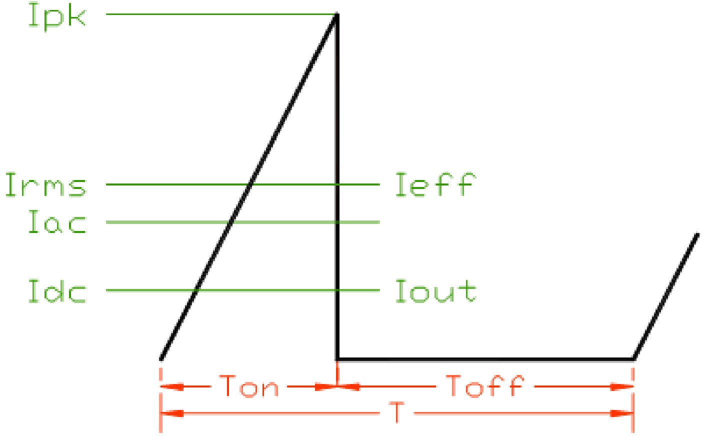
- **Inductance value (L_{DCM}):**
  - Maximum inductance to obtain a discontinuous conduction mode at maximum output power

$$L_{DCM} < \frac{V_{out}^{2}}{2P_{out\_max} \cdot f_{switch}} \times \frac{1}{\left(\frac{N_s}{N_p} + \frac{V_{out}}{V_{in\_min}}\right)^2}$$



Comparison Discontinuous / Continuous Flyback

Continuous Flyback	Discontinuous Flyback
Still current on diode when „switching“ off => needs a ultrafast switching diode	Current on diode already Zero when „switching“ off
No ringing on MOSFET	Ringing at MOSFET when current becomes Zero
Duty cycle is well defined	Duty cycle is not defined because of dead time
Peak currents are variable	Fixed peak current
	Secondary triangle is fix
Low peak current	High peak current
Low ripple current	High ripple current
High inductance	Low inductance

Pick a Core – AP Product

Making the conversion of current density from A/m^2 to cmils/A and units into CGS for convenience we get

$$AP = \frac{506.7 \bullet P_{in} \bullet J_{cmils/A}}{K \bullet f \bullet \Delta B} \text{cm}^4$$

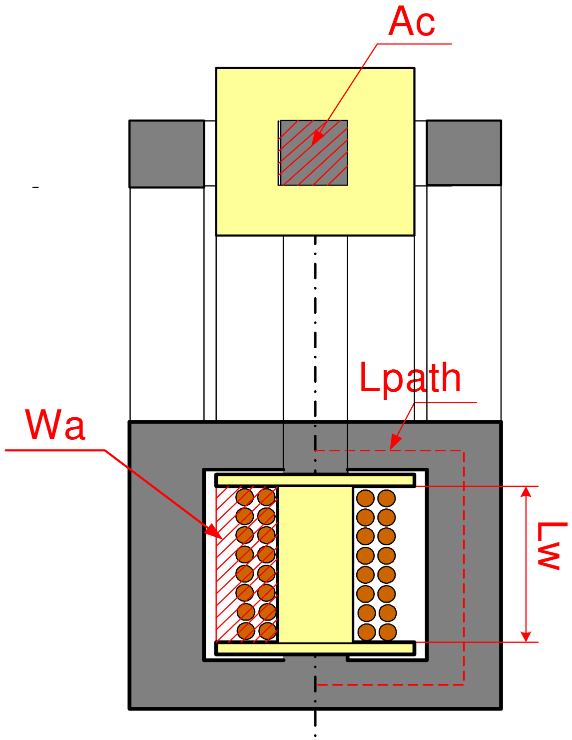
$$AP = WaAc$$

Typical value for K is 0.3-0.4 and for $J_{cmils/A}$ is 300-600

AP EFD15= 0,019

AP EF16= 0,043

AP EFD20= 0,087



Wa = Window Area in cm²

Ac = Core Area in cm²

Safety requirements

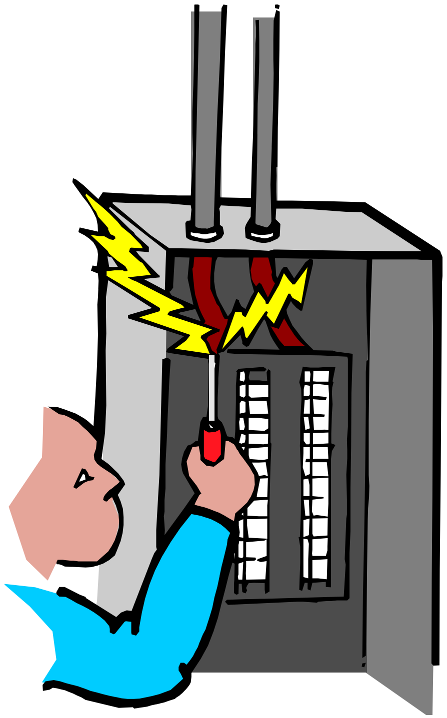
Safety requirements

- standards:
  e.g. EN (IEC)60950, (IT-equipment)
  EN (IEC)61558 Part 2-16 (transformer general)

- standards define
  → Clearance distance
  → Creepage distance
  (depends on pollution degree)
  → Distance through insulation

- standards define
  → electrical breakdown voltage

- There are differences between the standards!



Safety requirements

- Defining the Insulation Level requires:
  - Grade of Insulation (Functional, Basic, Supplementary, Reinforced)
  - Working Voltage
  - Pollution Degree
- This information is application dependent.
- It is not driven by the transformer.
- It's impact on the transformer construction & price can be significant.

Safety requirements

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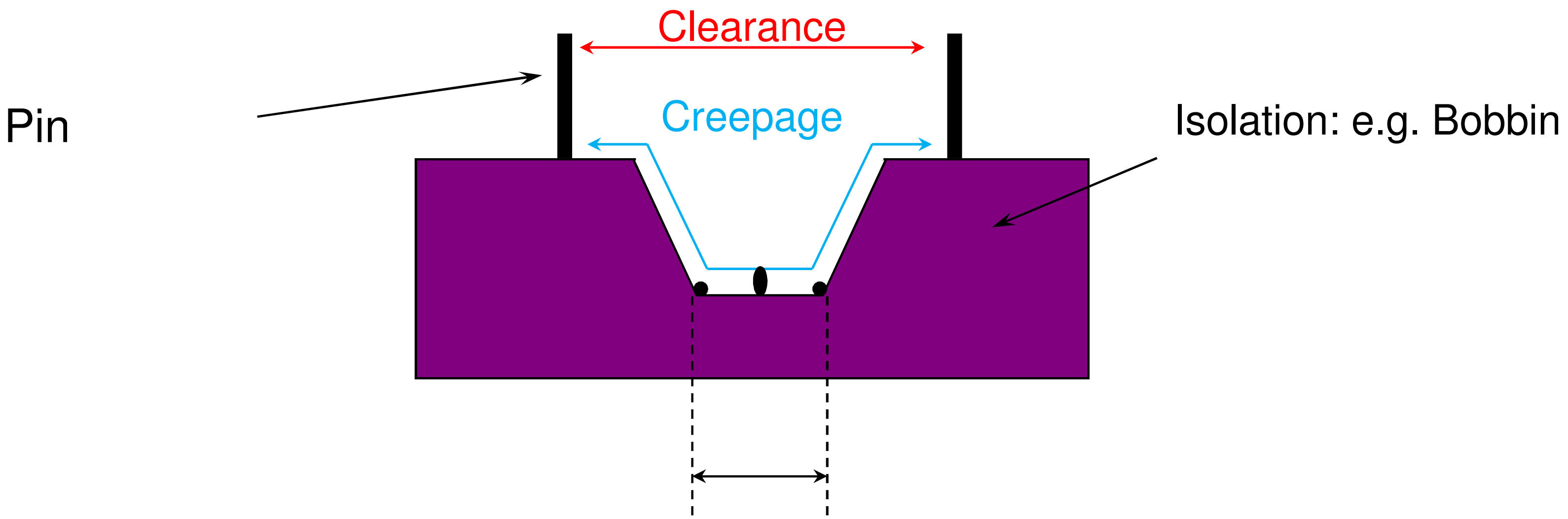
- **Working Voltage**
  - Highest voltage to which the insulation or the component under consideration is, or can be, subjected to when the equipment is operating under conditions of normal use.
- **Pollution Degrees**
  - Degree 1 – Assemblies which are sealed so as to exclude dust and moisture.
  - Degree 2 - Office and laboratory areas are considered pollution degree 2 environments
  - Degree 3 - Conductive pollution or dry nonconductive pollution that becomes conductive when condensation occurs. To be found in industrial environment or construction sites.
- **Creepage Distance**
  - Shortest distance through air along the surface of an insulation material between two conductive parts
- **Clearance Distance**
  - Shortest distance in air between two conductive parts

Clearance and creepage distance



e.g. Pollution degree 2
→ distance has to be min. 1 mm
→ if distance is less than 1mm than creepage = clearance

- **Clearance**
  → distance in air (conductor to conductor)
- **Creepage**
  → distance along surface (conductor to conductor)

Isolation test voltage

- **Isolation test voltages according to EN61558**

Operating voltage [V_{RMS}]	Isolation test voltage [V_{RMS}]	
	Basic insulation	Reinforced insulation
50	250	500
150	1400	2800
300	2100	4200
400	2200	4500
1000	2750	5500

→ It is not enough to mention ONLY a test voltage as safety requirement

Safety requirements

- **Creepage distances for different working voltages**

  Example: Pollution degree 2 according to IEC61558-2-16

Working voltage (RMS)	Creepage distance pollution degree 2 [mm]					
	Basic insulation			Reinforced insulation		
	CTI>600	400<CTI<600	CTI<400	CTI>600	400<CTI<600	CTI<400
100	0,8	1,1	1,5	1,1	1,5	2,2
150	0,9	1,2	1,8	1,7	2,2	3,3
300	1,7	2,3	3,3	3,3	4,7	6,6
400	2,2	3,1	4,4	4,4	6,4	8,8
600	3,3	4,7	6,6	6,6	9,5	13,2
1000	6,1	2,4	11,0	11,0	15,4	22,0

→ the creepage distance cannot be less than clearance distance

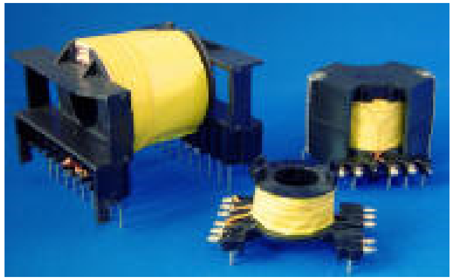
Safety requirements

- **Comparative Tracking Index (CTI)**

  → CTI of raw material effects the creepage distance

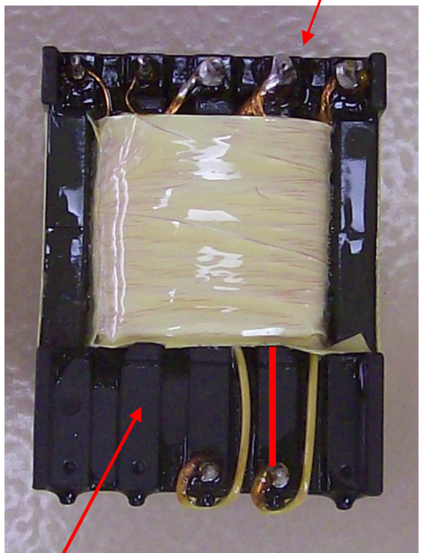
  → CTI value is a measure of the resistance to surface tracking that a particular material exhibits under specific test conditions

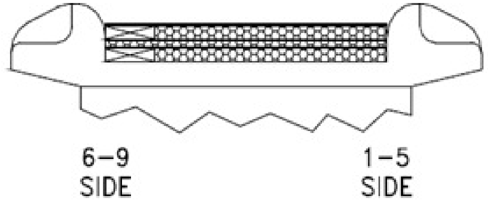
  → the smaller the CTI for that material, the bigger the creepage distance required

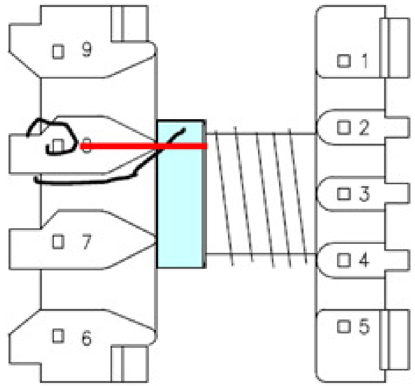


How to Achieve Creepage Distances

- **Use extended rail bobbin and / or margin tape to increase distance from SEC pins to PRI winding**

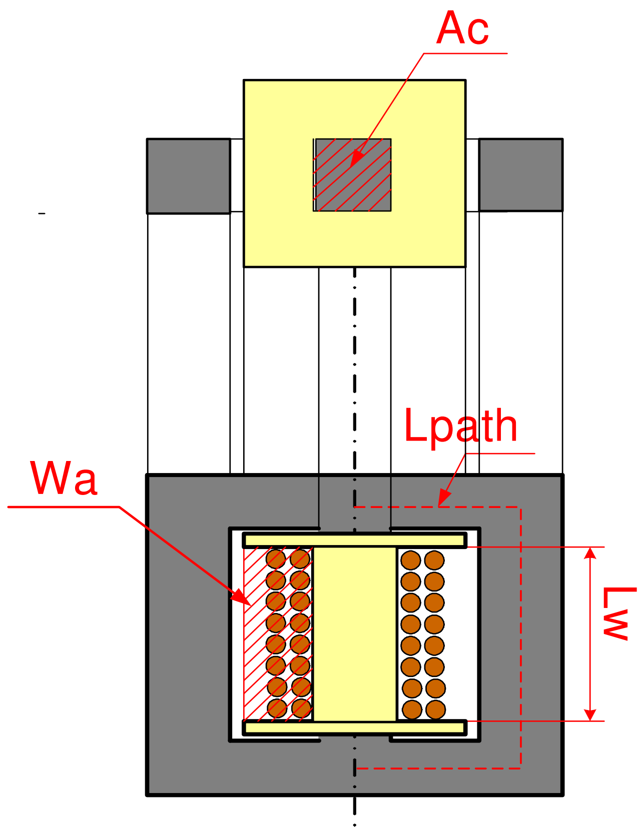


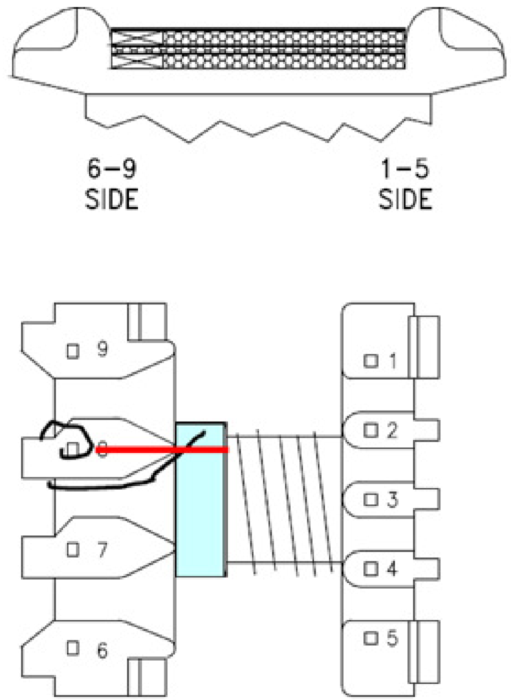




Triple Insulated Wire on SEC to insulate windings

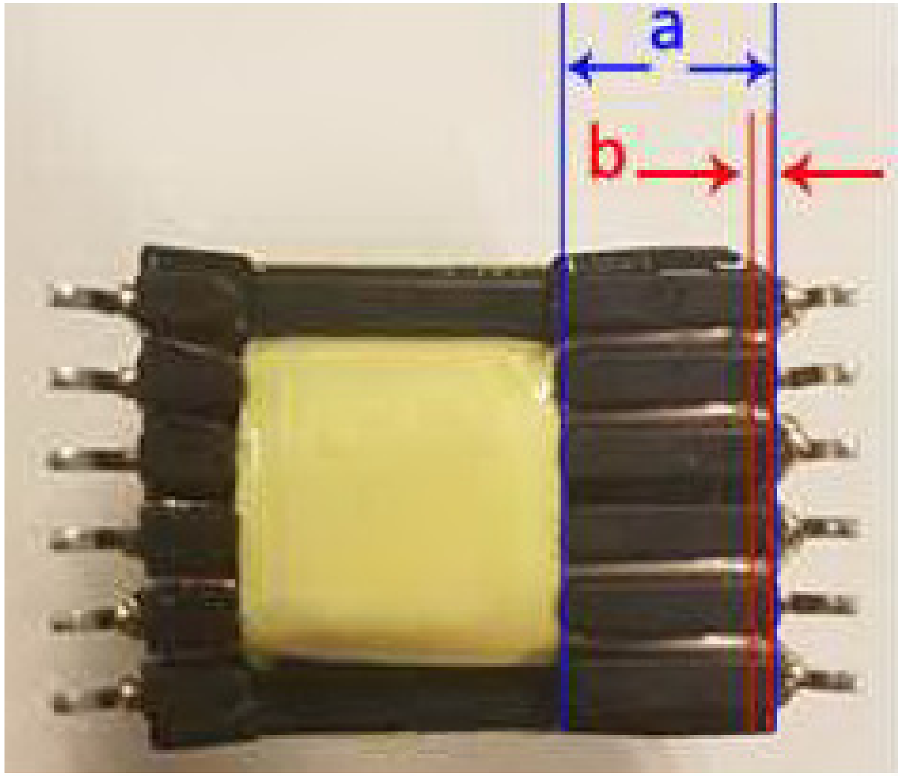
AP product Vs Creepage- Warning





WE-UOST example

It is recommended that the temperature of the component does not exceed +125°C under worst case conditions	
Storage Temperature (in original packaging)	-20 °C up to +60 °C
Operating Temperature	-40 °C up to +125 °C
Test conditions of Electrical Properties: +20°C, 33% RH if not specified differently	
Designed to comply with the following requirements as defined by IEC61558-2-16; Reinforced insulation for a working voltage of 375 V_{RMS}	



a : 7,14 mm min

b : 0,5 mm allowed of wires burnt back

=> Creepage distance minimum 6,6 mm

Manufacturing

Why do we do design for Manufacturing?

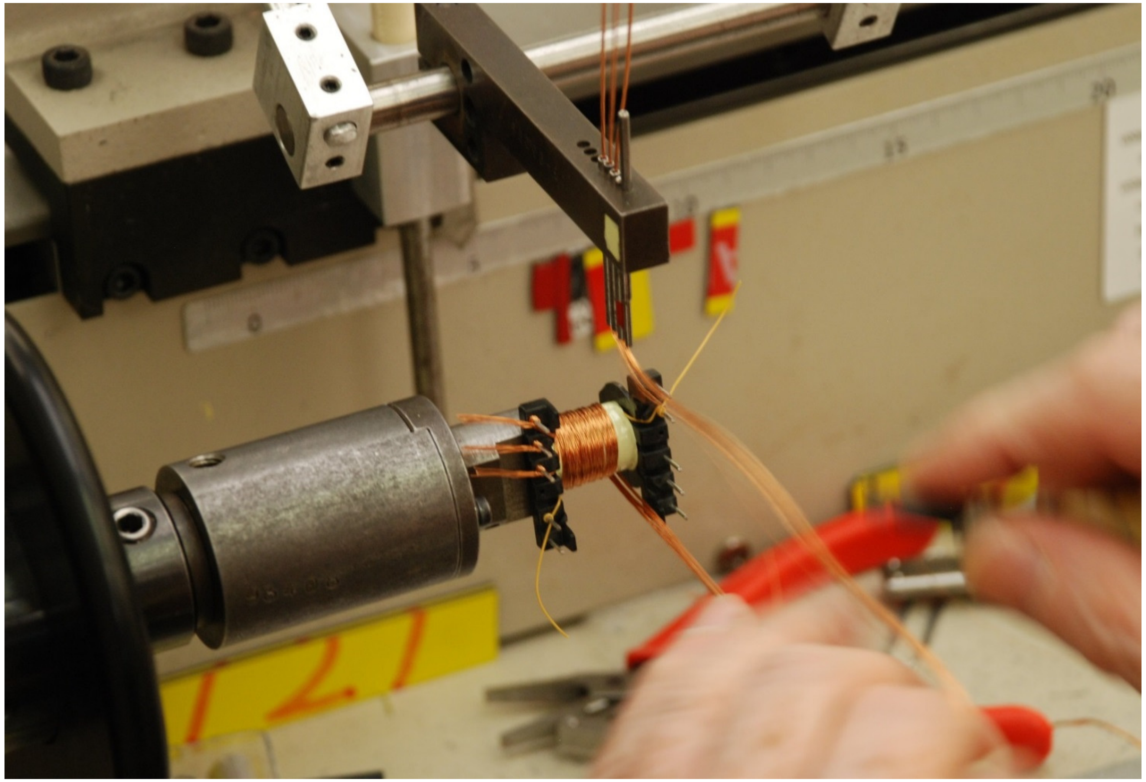
- **To increase reliability**
  - Adapt the design to use proven and repeatable processes
- **To reduce cost**
  - Use automated processes where possible
  - Reduce scrap
- **To reduce lead time**
  - Higher throughput using standard processes
  - Reduce rework
  - Use standard components

The Transformer Manufacturing Process

Considerations:

- Winding
- Termination
- Soldering

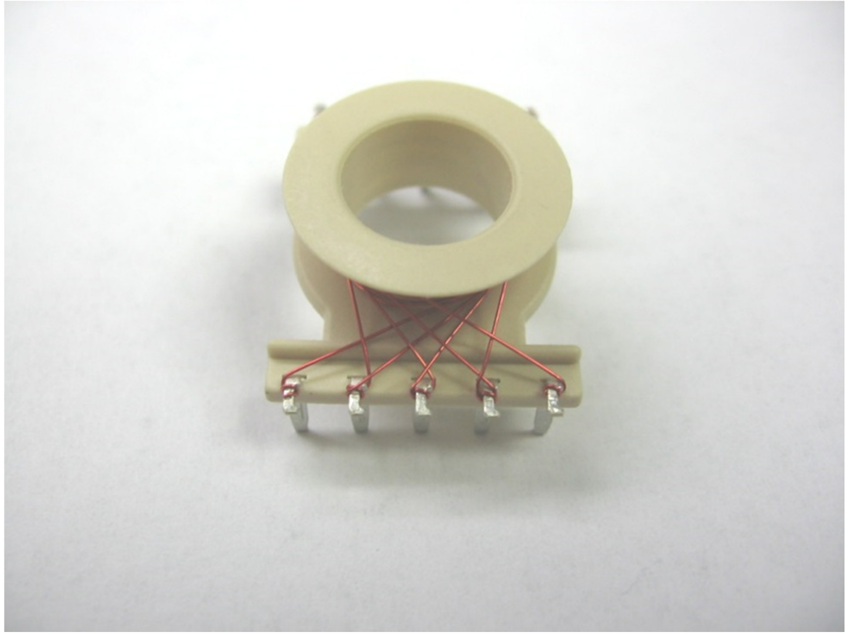
Winding



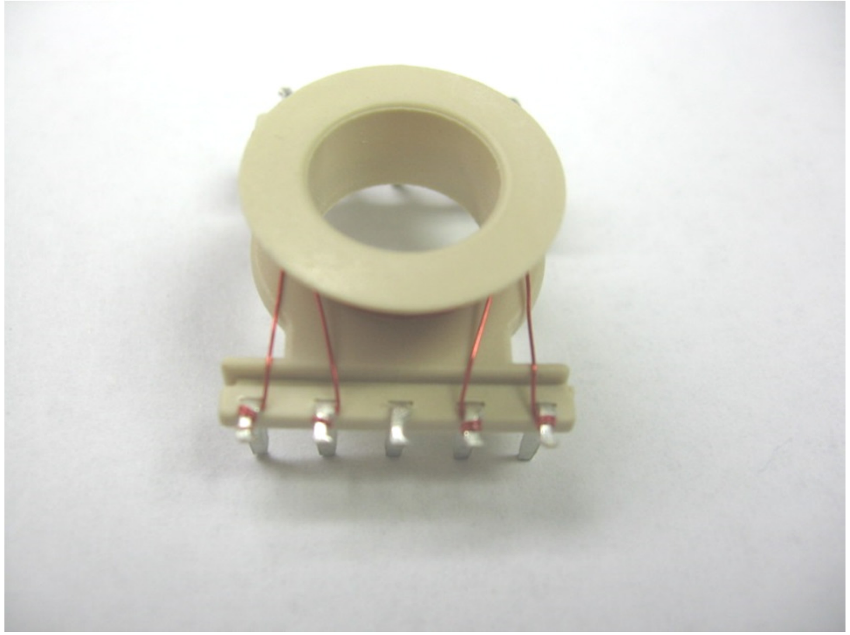
Considerations:

- **Pinout**
- **Layering**
- **Dragbacks**

Pinout – Wires crossing



Wire crossings can cause both mechanical and dielectric stress

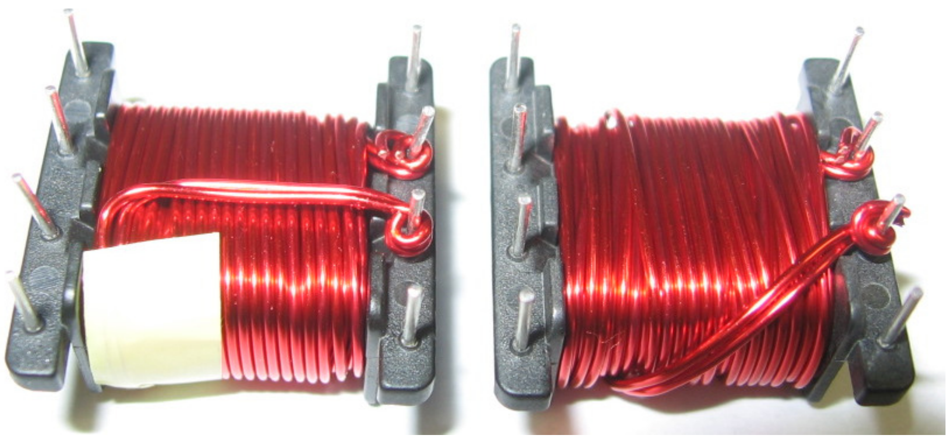


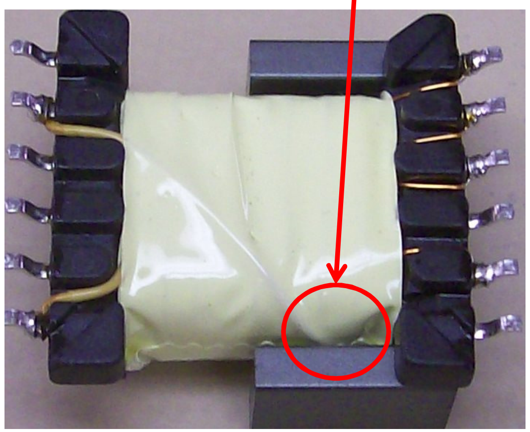
This is the ideal pin assignment

Wire Dragbacks

- **Dragbacks can be damaged by winding pressure from subsequent layers**
  - Start tape before dragback (higher labour)
- **90° dragbacks increase labor and may need extra tape**
- **Spiral dragbacks can cause core fit issues**

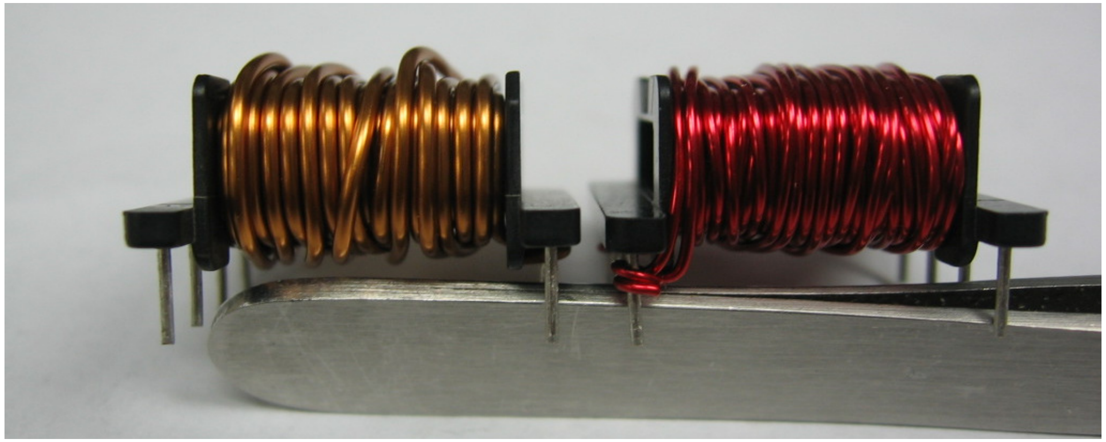
Potential core fit issue here





Layering

- **Adjust wire diameter and number of strands to fill layers**



The coil on the right uses a two-bi winding to achieve the same DC resistance, but better layering.

- **Choose pinout that promotes good layering**
  - Same rail pinout for even number of layers
  - Cross bobbin pinout for odd number of layers

Soldering

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- **A large single strand is more difficult to solder than multiple lighter strands**

  - Large strands: more heat, more time - more insulation damage

- **Avoid using heavy or litz windings on same bobbin rail with fine wire windings**

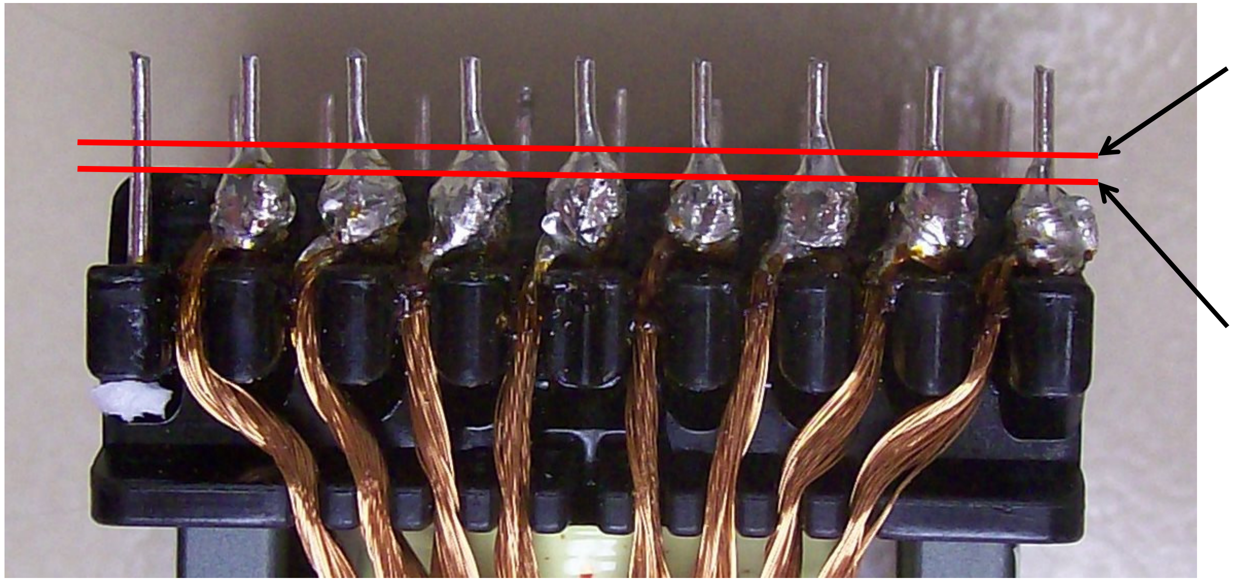
  - Ideally windings on same bobbin rail should be within 3 gauges

- **Sometimes it makes sense to use heavier wire than necessary for soldering – e.g. matching aux wire size to primary, even if current density doesn't require it (also reduces BOM)**

  - May need two soldering operations if wire mismatch is unavoidable

Solder Terminations

- **Large wire terminations on TH parts can cause height issues**

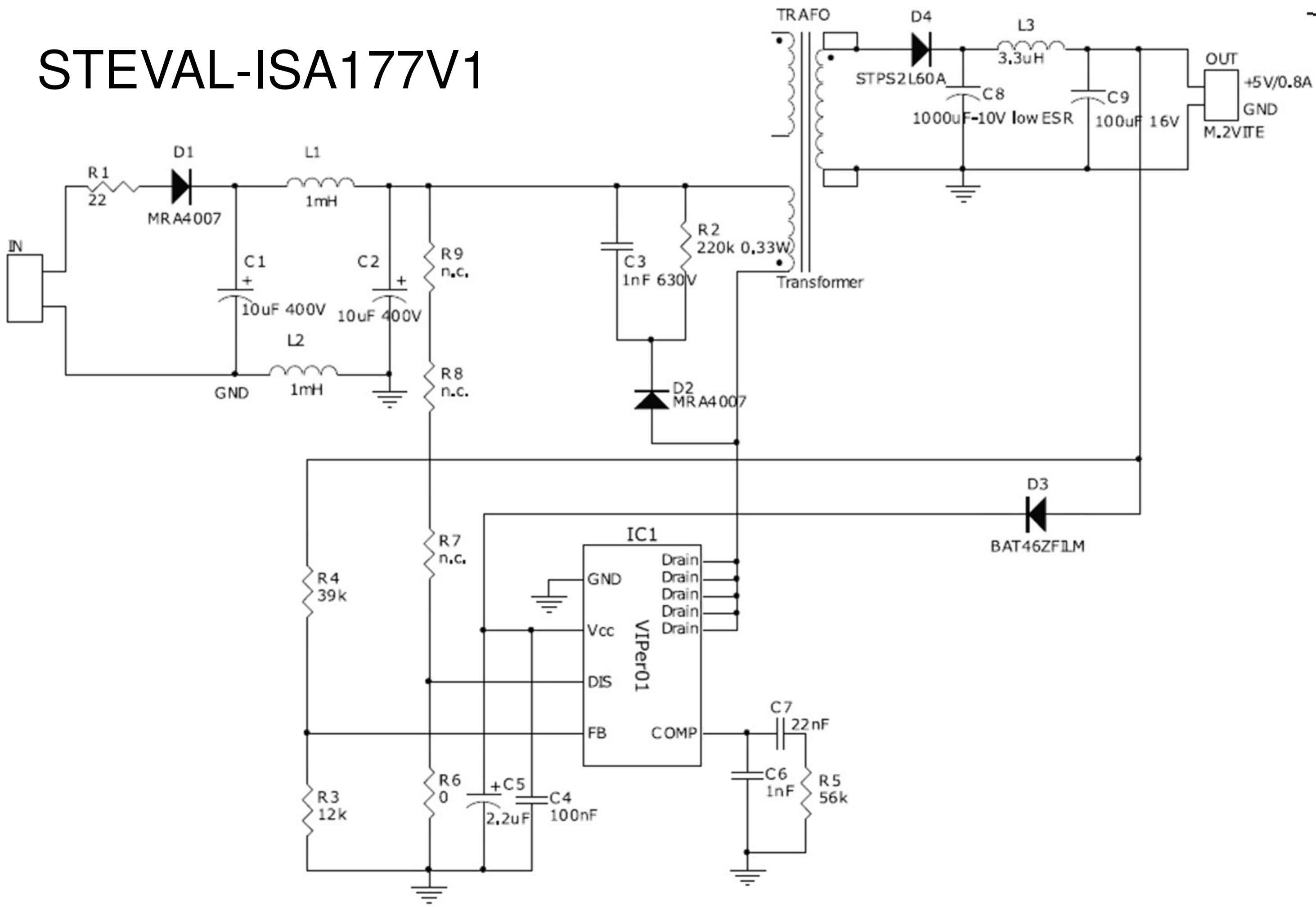


Large Wire Wraps – this is where part will actually contact PCB

Bobbin Standoff – this surface should contact PCB

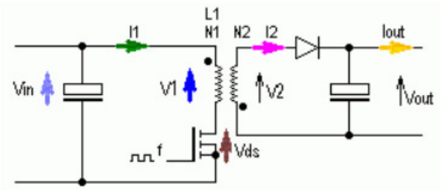
Example Eval board VIPer013XS

- STEVAL-ISA177V1



Example Transfo 750317396

Fly-back Converter



V_{in_min} / V: 120
V_{in_max} / V: 350
V_{in} / V for the calculations: 120

V_{out} / V: 5
I_{out} / A: 0.85
f / kHz: 60

Calculate

☐ **Proposal** **L_1 / H :** 2E-3

☐ **Proposal** **N_1 / N_2 :** 13.93

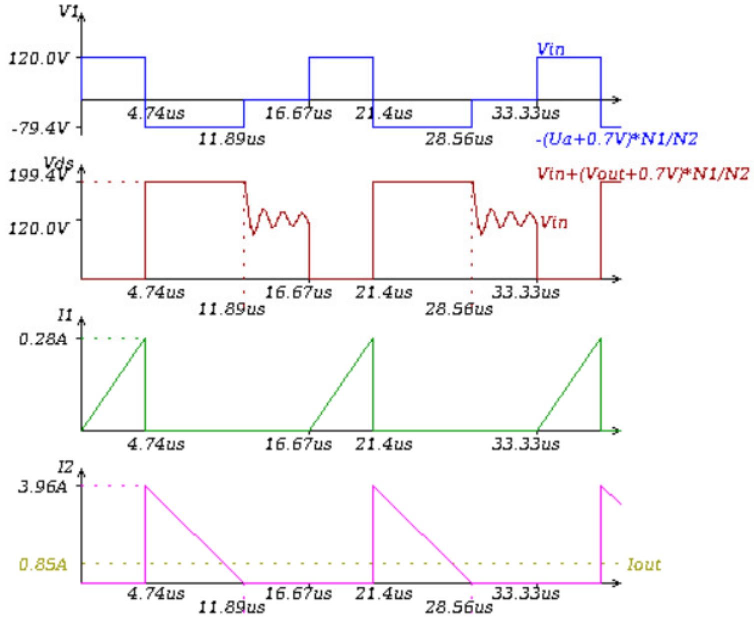
Transformer Data

The values of all input fields can be changed.
The proposed values for L_1 and for the turns ratio N_1 /N_2 are chosen such that the converter works at the border between continuous and discontinuous mode for the average input voltage and with a duty cycle of 50%.
Tip: The higher N_2 , the lower the maximum transistor voltage V_{ds} during its blocking phase.
Tip: The lowest size of the transformer is achieved if the converter works at the border between continuous and discontinuous mode for V_{in_min} .
Tip: The highest voltage V_{ds} occurs when V_{in}=V_{in_max} .

By Dr. Heinz Schmidt-Walter, Holger Wenzel, Thomas Zänker, Richard Morgan and Johnalan Kegan.

Flyback Converter

V_{in_min} = 120.0V	V_{in_max} = 350.0V	V_{in} = 120.0V
V_{out} = 5.0V	I_{out} = 0.85A	f = 60.0kHz
L = 2.0mH	N_1/N_2 = 13.93	



To Summarize….

Design For Manufacturing:

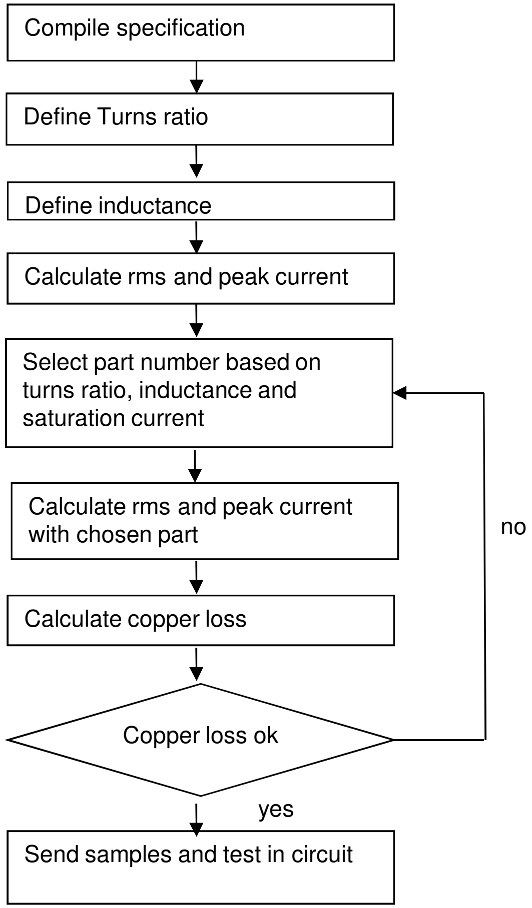
The practice of considering the manufacturing process during the design stage

To increase reliability

To reduce cost and lead time

Involve us as early as possible in design phase!

Selection of a standard flyback transformer



Calculation Idea

1) **Turns ratio:**

1) $\frac{N_1}{N_2} \leq \frac{V_{DS\,max} - V_{in}}{V_{out}}$ =

2) $\frac{N_1}{N_2} \geq \frac{V_{in}}{V_{D\,max} - V_{out}}$

2) **Duty Cycle:**

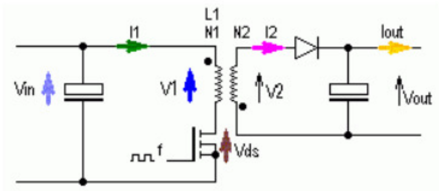
$$DC = \frac{t_{on}}{T} = \frac{\frac{N_1}{N_2} \cdot V_{out}}{V_{in} + \frac{N_1}{N_2} \cdot V_{out}}$$

3) **Inductance:**

$$L = \frac{V_{out} \cdot (1 - DC)}{(\frac{N_2}{N_1})^2 \cdot \Delta I \cdot f}$$

Example with UOST serie

Fly-back Converter



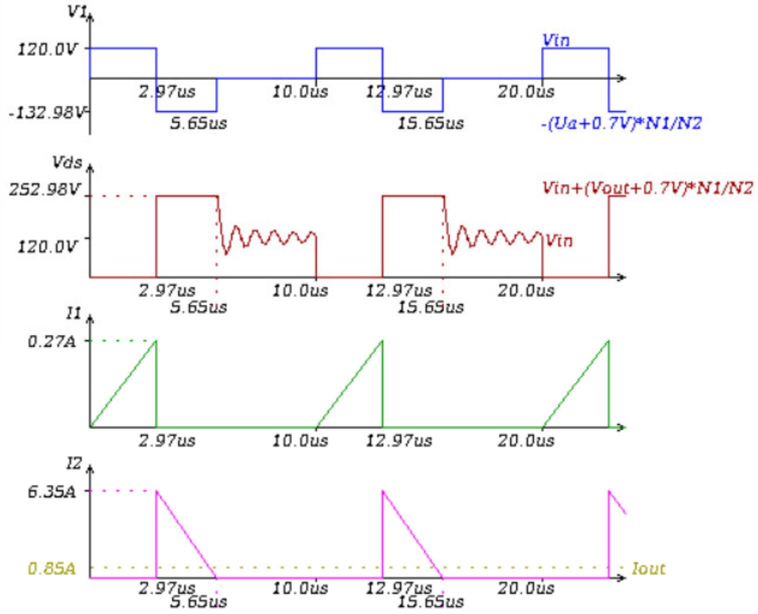
V_{in_min} / V	V_{in_max} / V		V_{in} / V for the calculations
120	350		120
V_{out} / V	I_{out} / A	f / kHz	
5	0.85	100	Calculate
☐ Proposal	L_1 / H :	1.31E-3	Transformer Data
☐ Proposal	N_1 / N_2 :	23.33	

The values of all input fields can be changed.
The proposed values for L_1 and for the turns ratio N_1 /N_2 are chosen such that the converter works at the border between continuous and discontinuous mode for the average input voltage and with a duty cycle of 50%.
Tip: The higher N_2 , the lower the maximum transistor voltage V_{ds} during its blocking phase.
Tip: The lowest size of the transformer is achieved if the converter works at the border between continuous and discontinuous mode for V_{in_min} .
Tip: The highest voltage V_{ds} occurs when V_{in}=V_{in_max} .

By Dr. Heinz Schmidt-Walter, Holger Wenzel, Thomas Zänker, Richard Morgan and Johnalan Kegan.

Flyback Converter

V_{in_min} = 120.0V	V_{in_max} = 350.0V	V_{in} = 120.0V
V_{out} = 5.0V	I_{out} = 0.85A	f = 100.0kHz
L = 1.31mH	N_1/N_2 = 23.33	



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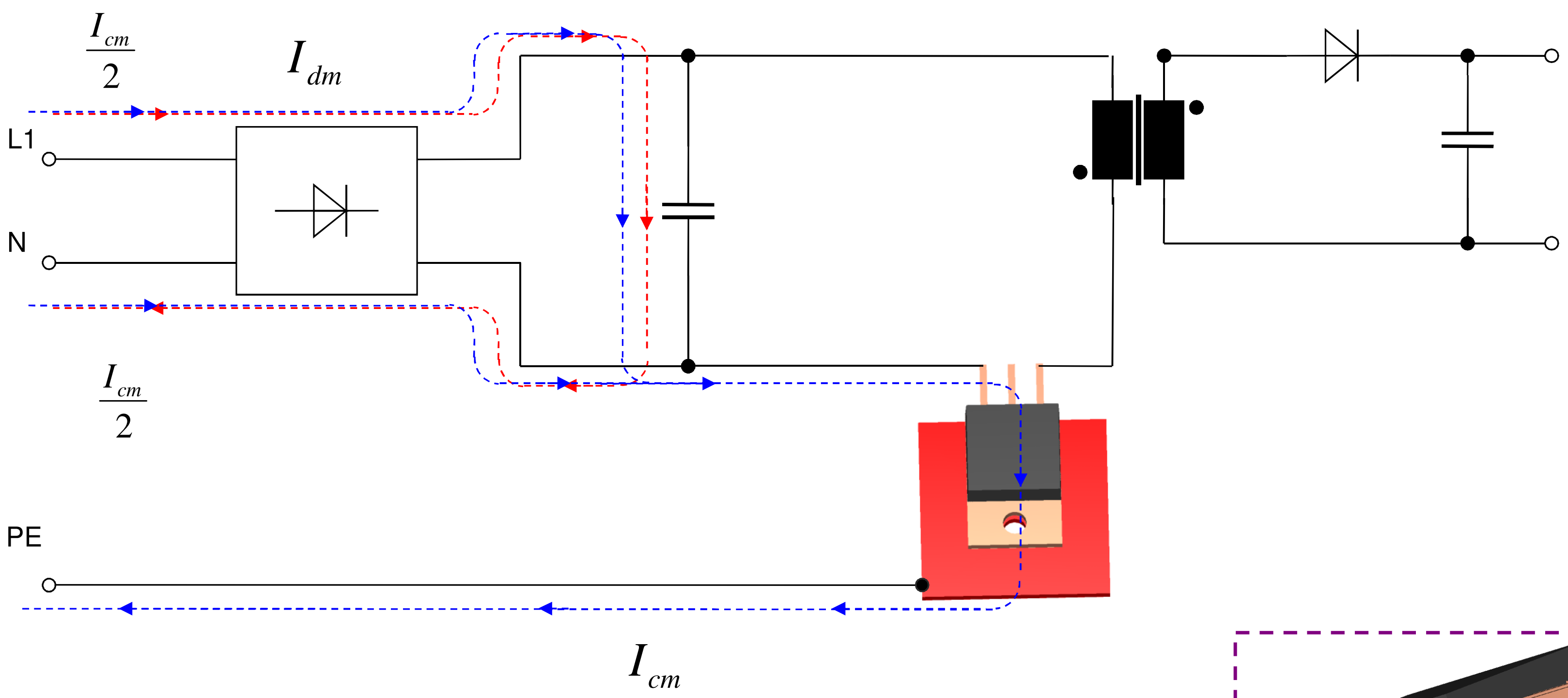
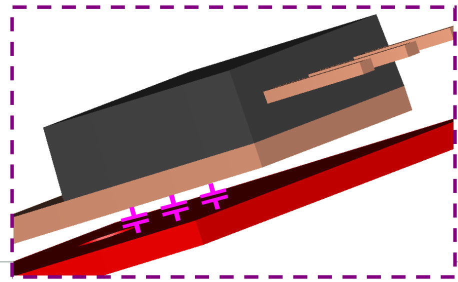
DO NOT FORGET EMC

What noise I'm facing



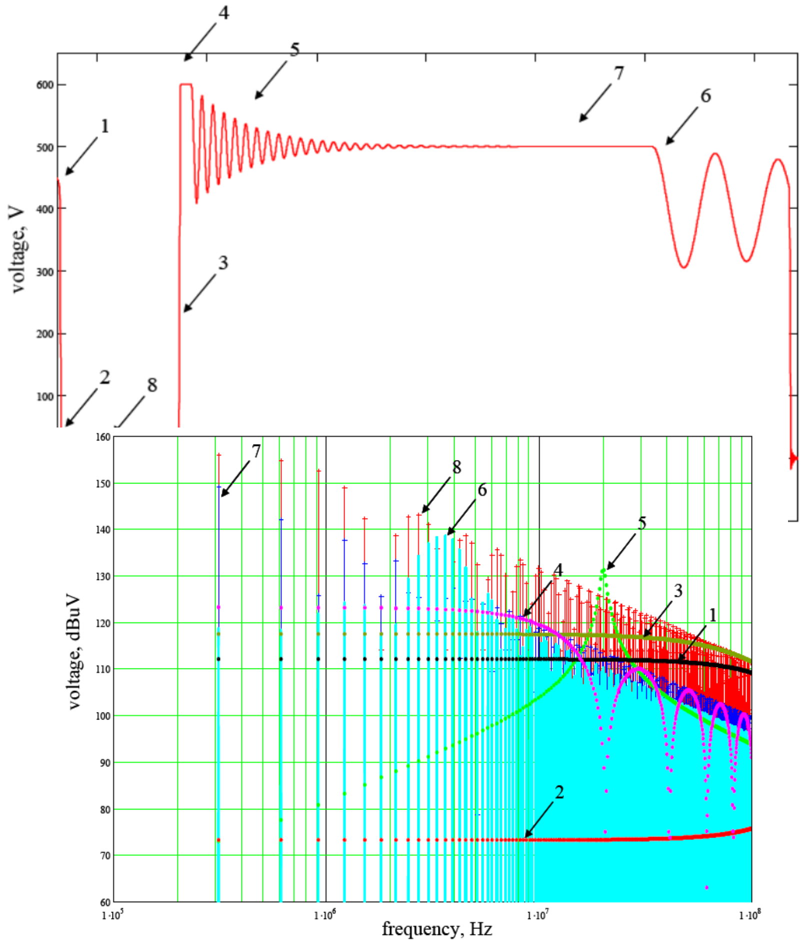
→Parasitic capacities

e.g.: collector to cooling element

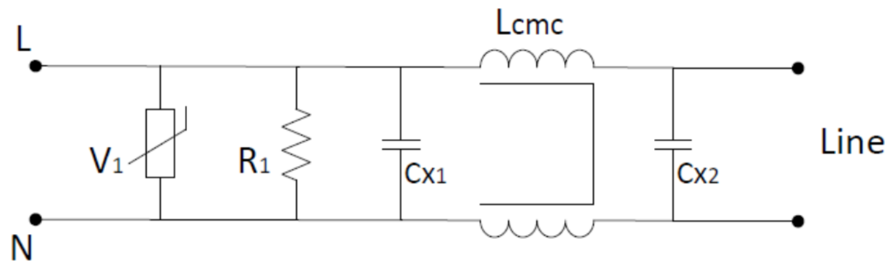


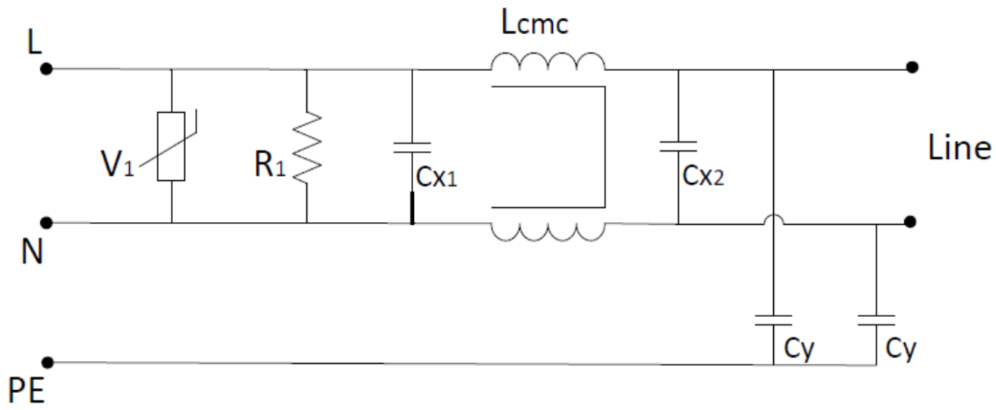
Signal on Vds

- 1 voltage falls during turn on.
- 2 Parasitic oscillation due to current spike (on time).
- 3 voltages rises during off time.
- 4 Clamping voltage snubber.
- 5 Parasitic oscillation after clamping (due to leakage inductance of transformer and Mosfet capacitance).
- 6 parasitic oscillation after flyback phase (due to Mosfet capacitance and primary inductance of transformer.

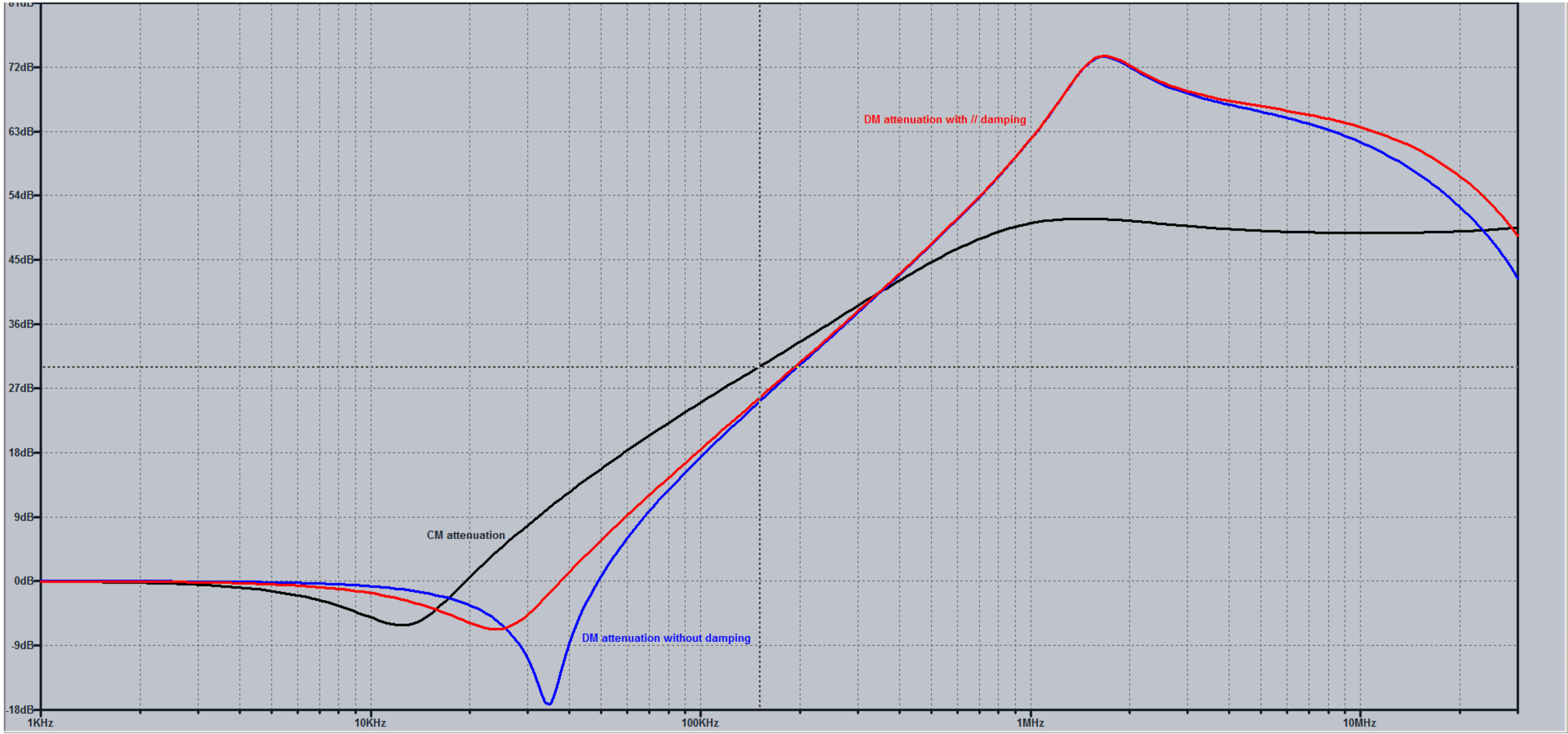


Input filter ideas

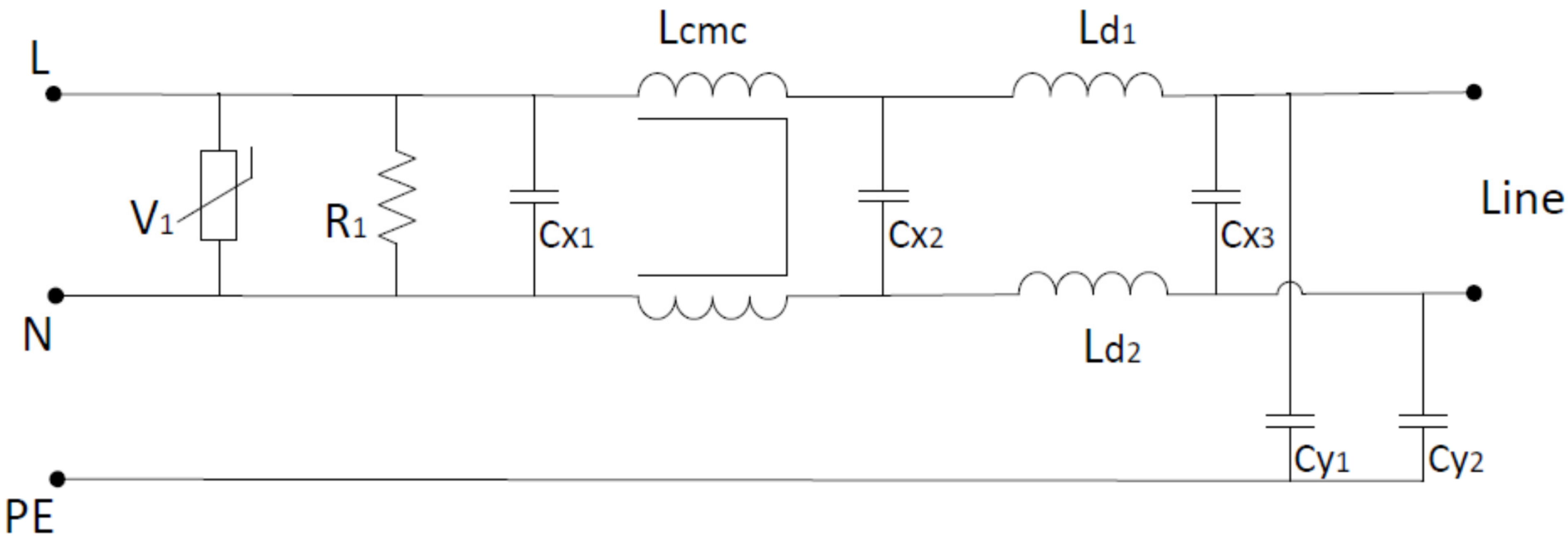




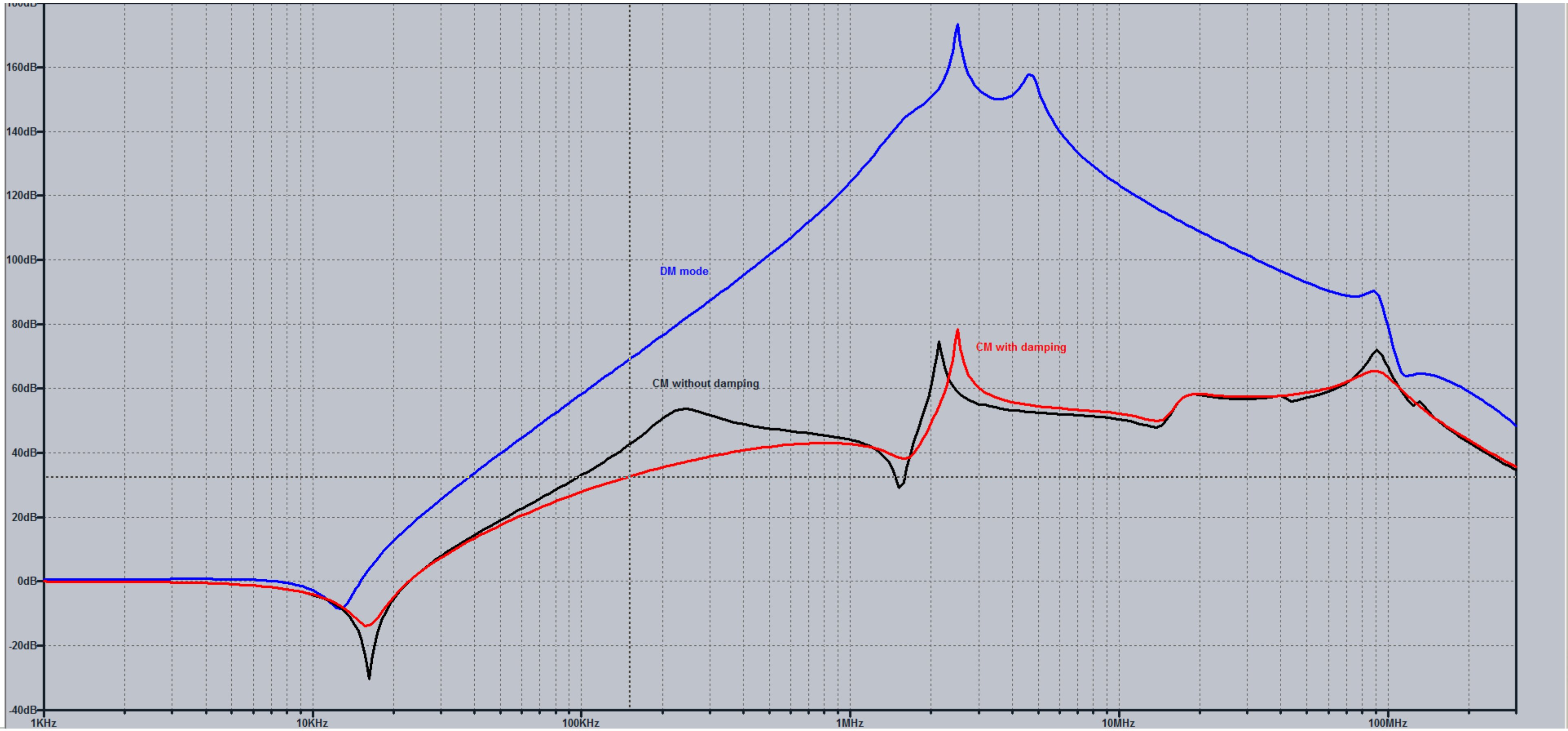
Example of attenuation



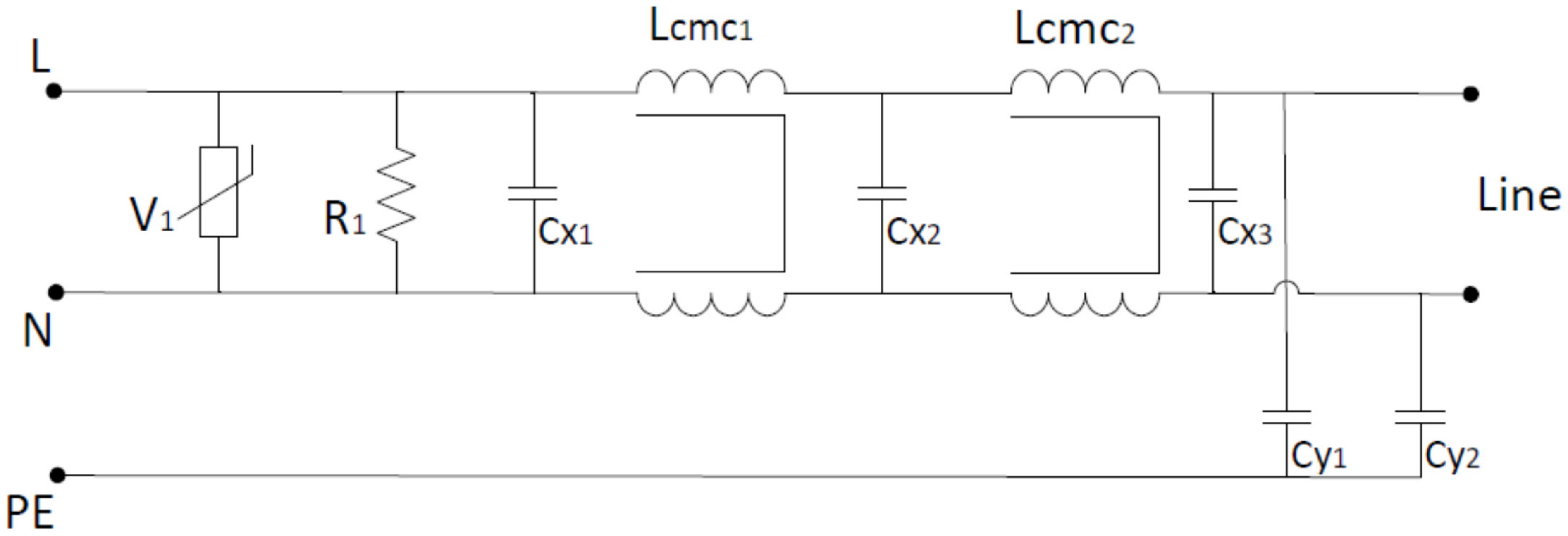
Input filter ideas



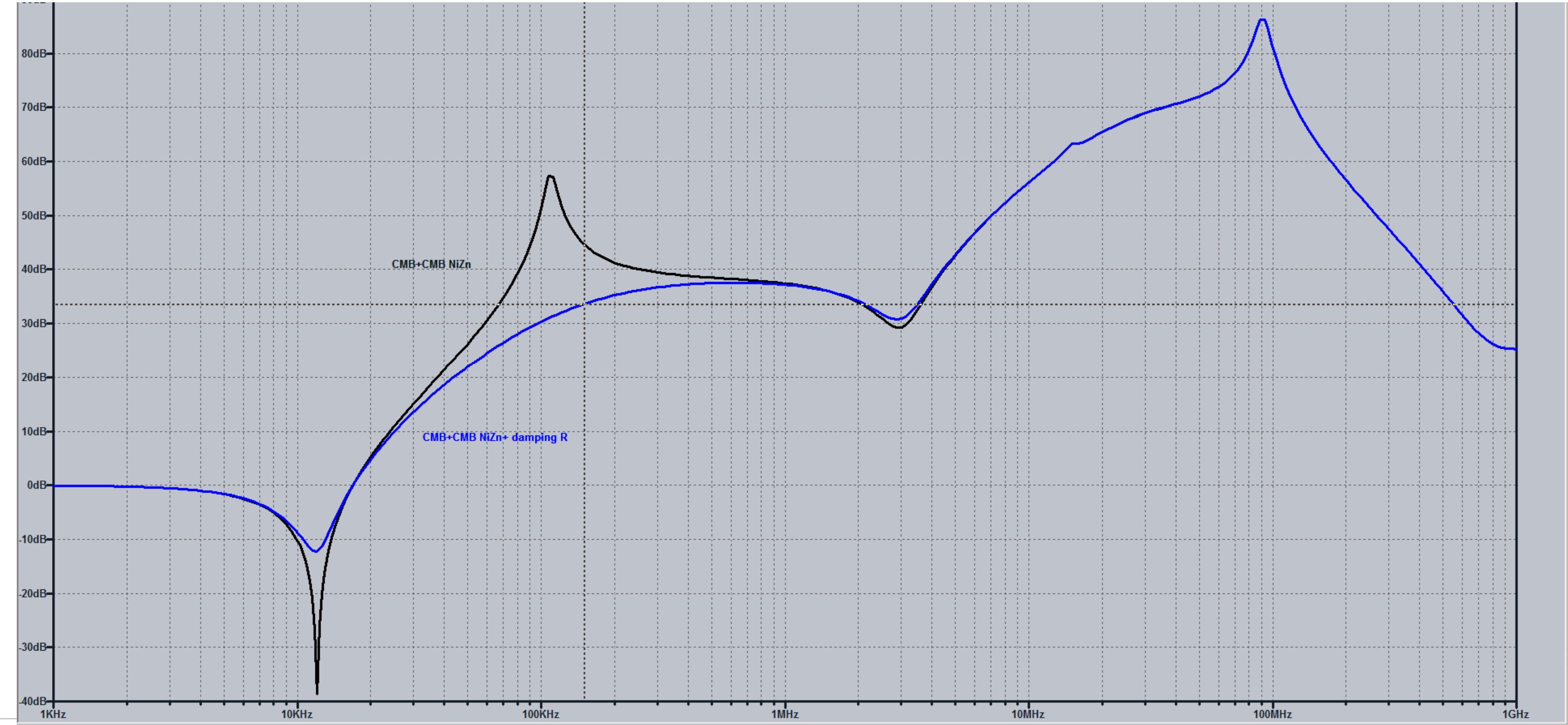
Example of attenuation



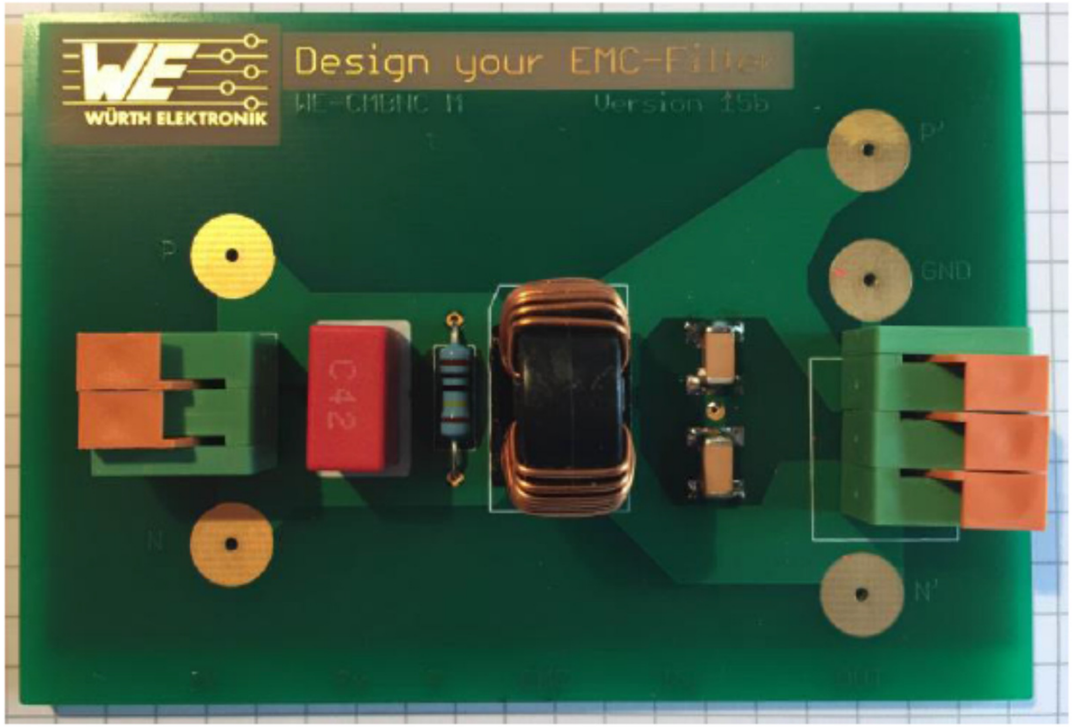
Input filter ideas



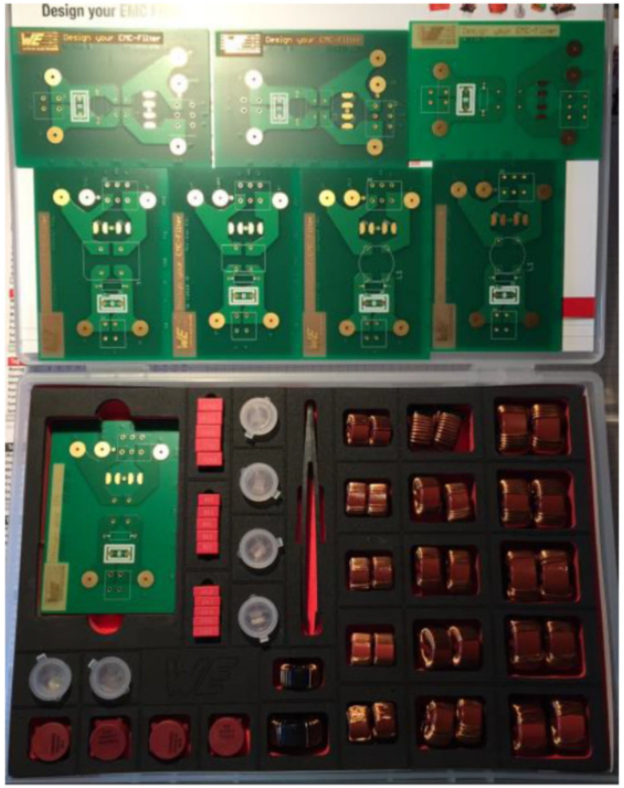
CMB+CMB NiZn +R damping



Design your EMC filter

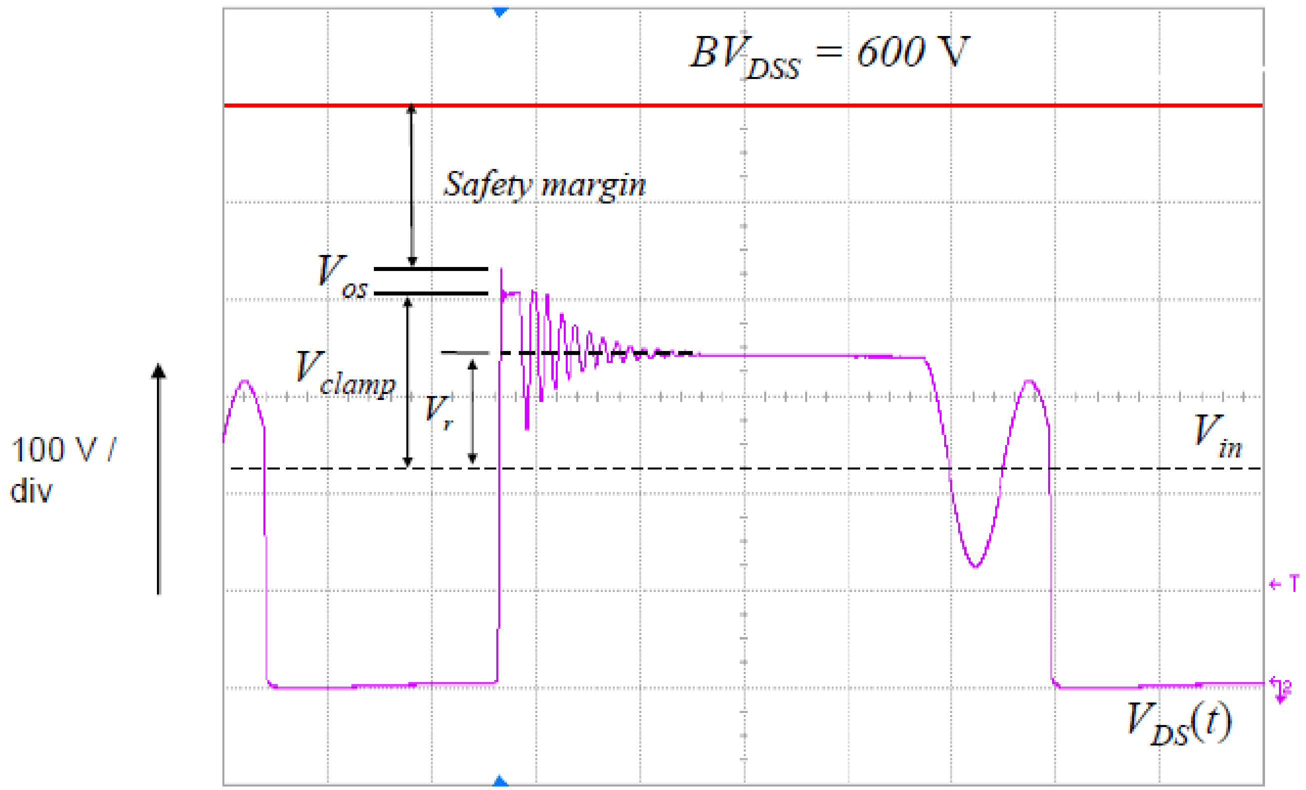


Design kit

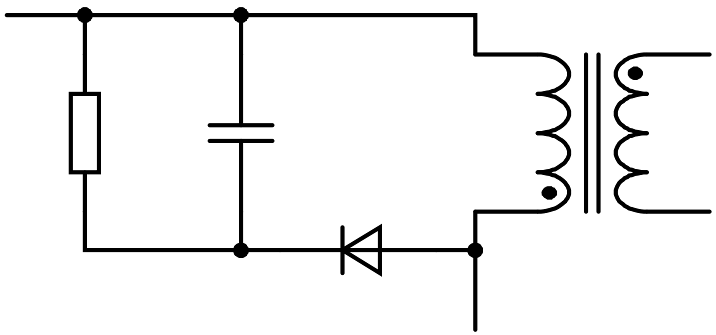


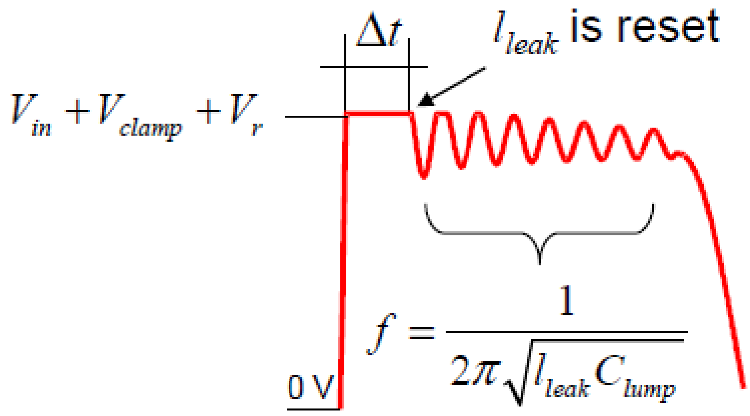
Snubber

Snubber design



Snubber design: First pass selection





Select desired maximun voltage

$$\mathrm{V}_{\mathrm{clamp}} = V_{dss\,\mathrm{max}} - safety\ \text{margin}$$

$$\mathrm{V}_{\mathrm{snub}} = V_{clamp} - Vin$$

Energy stored into inductor

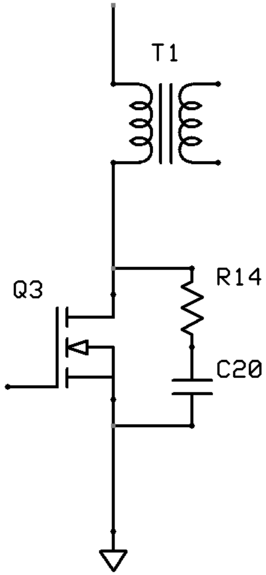
$$\mathrm{W}_1 = \frac{1}{2}.L_l.I_{peak}^2$$

Average power transfered to snubber

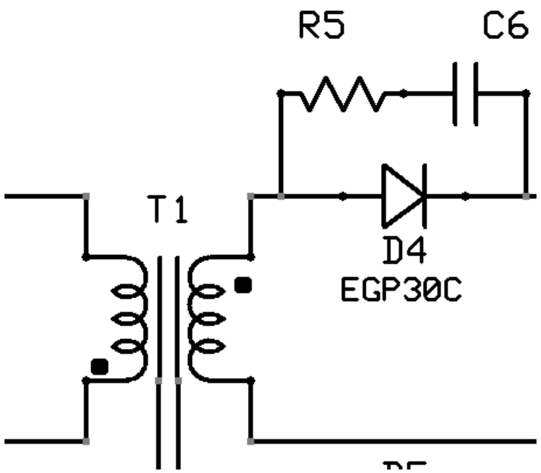
$$\mathrm{P} = \mathrm{W}_1.f_{sw}$$

$$So\ \text{choose}\ \mathrm{R} = \frac{\mathrm{V}_{\mathrm{snub}}^2}{\mathrm{P}}\ \text{and then}\quad \mathrm{RC} = \frac{1}{3}T_{on}$$

Diode and Switch Snubbers



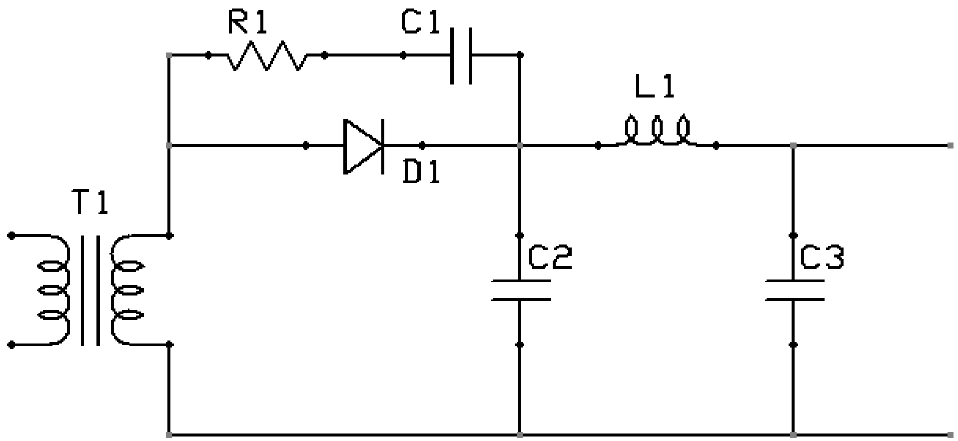
- **Dampens Ringing From**
  - **Parasitic PCB Inductance**
  - **Rectifier Reverse Recovery**
  - **Output Rectifier Capacitance**
- **Capacitor across Diode Reduces Frequency**
- **Resistor to Critically Dampens Ringing**
  - **Power Dissipated in Resistor**



Output Filter

WÜRTH ELEKTRONIK

- Ripple Voltage Determines Capacitance
- ESR Usually Plays a Larger Role
- Often Shown as Single Stage but…
- Two stage can Save Cost by Using Smaller Components
- Second stage often Drum Core Inductor and Ceramic Capacitor



THE END

- **THANK YOU !**