Wurth Electronics (UK) Ltd

Practical EMI Filter Design Considerations – Part 2

19th September 2017

Presented by

Mohamed AlAlami
Field Application Engineer - UK

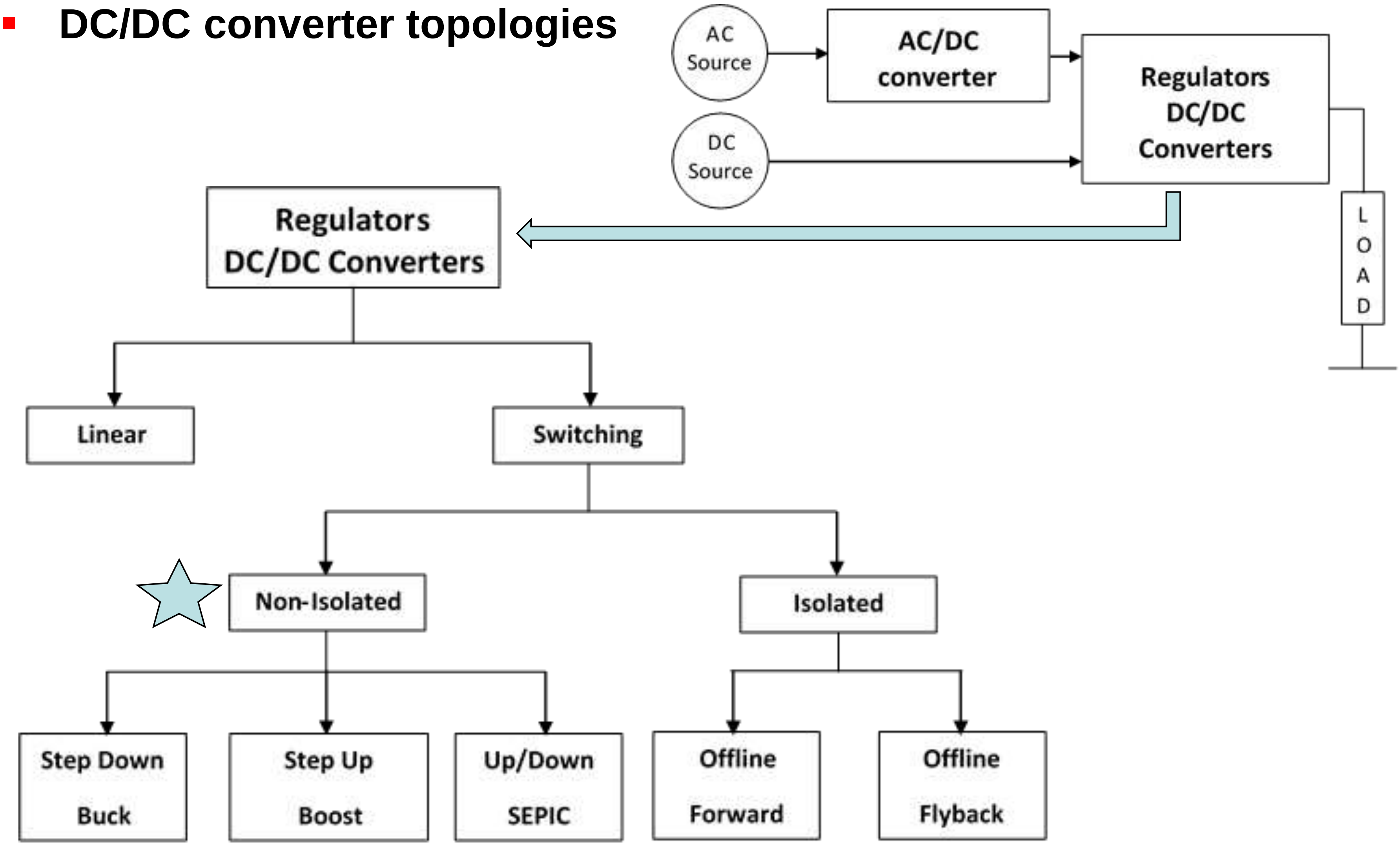
Agenda

- **DC/DC Converter Topologies**
- **Inductor and Capacitor Selection Parameters**
- **Efficiency and Losses**
- **REDEXPERT**
- **Practical DC/DC Converter Input Filter Design Considerations**

DC/DC CONVERTER TOPOLOGIES

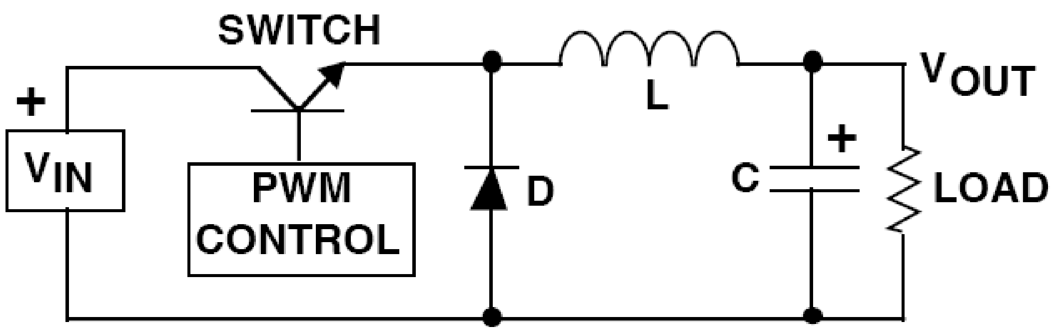
DC to DC Converter Topologies

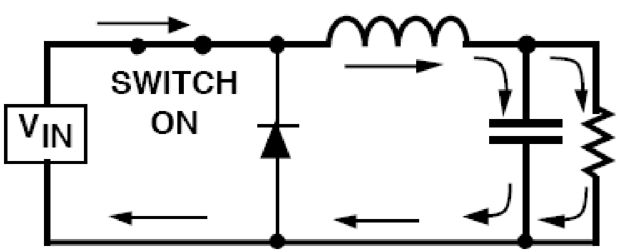
- **DC/DC converter topologies**



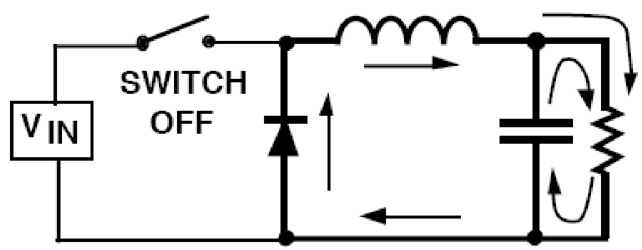
The Buck Converter

- **The Buck Converter (Step Down)**
  - Converts a DC voltage to a lower DC voltage with the same polarity
  - Continuous and discontinuous conduction modes (CCM and DCM)





t_{ON}

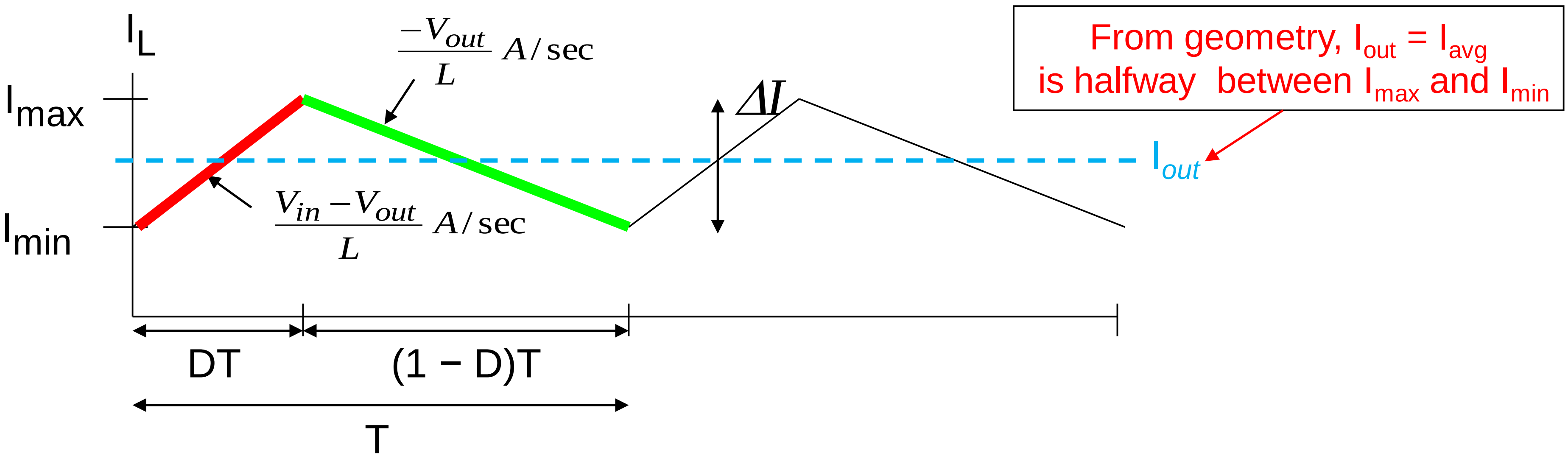


t_{OFF}

The Buck Converter

- **Effects of ripple current (ΔI_L):**

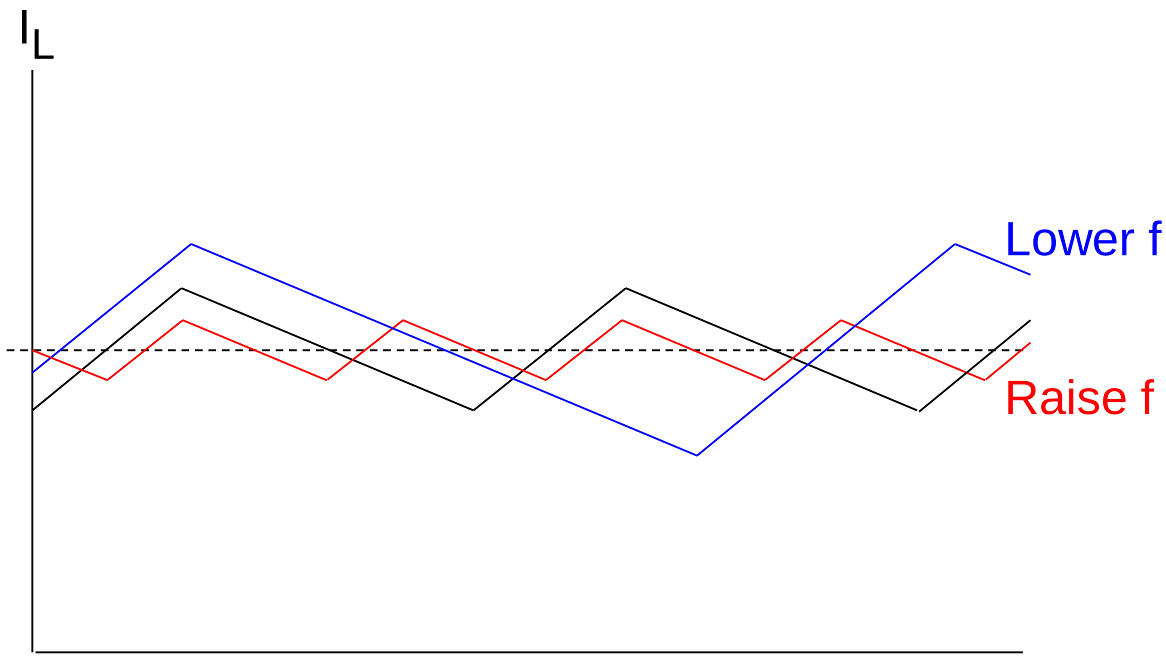
$$\boxed{\Delta I = \frac{V_{in} - V_{out}}{L} \times D \times T}$$



- CCM operation
- Output voltage ripple (with the ESR of C_{out})
- Core losses in the inductor
- Emissions

The Buck Converter

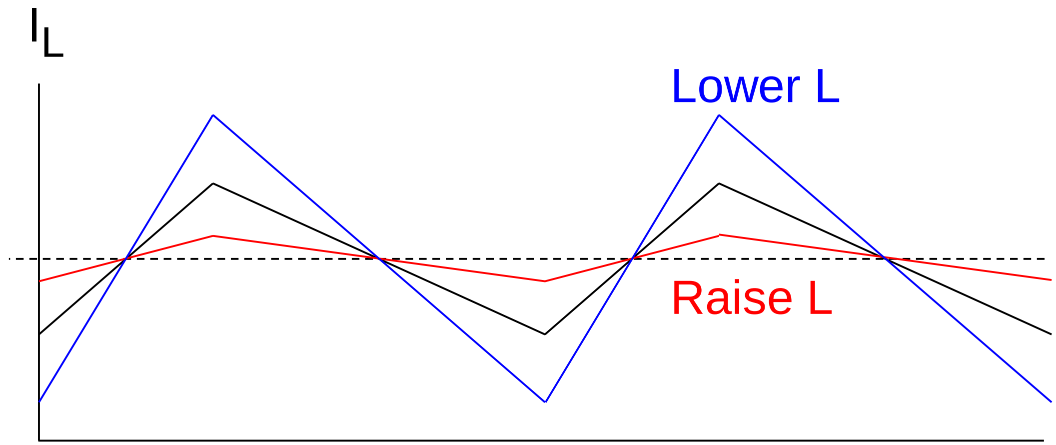
- **Effects of changing switching frequency (f_s):**



  - Slope of I_L unchanged
  - Lowering f_s increases ΔI and can move the circuit towards DCM

The Buck Converter

- **Effects of changing inductance (L):**



  - Slope of I_L changed
  - Lowering L increases ΔI and can move the circuit towards DCM

The Buck Converter

- **Calculating inductance value (L):**

$$L = \frac{(V_{in} - V_{out})}{\Delta I} \times D \times T$$

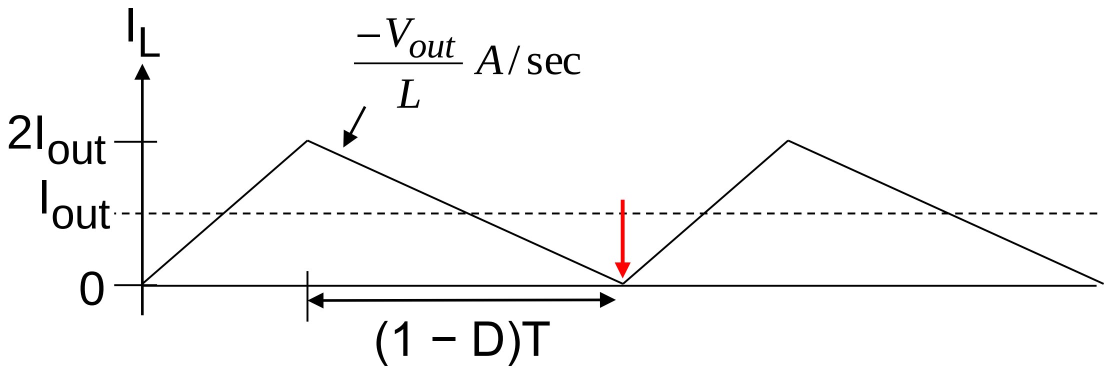
Re-write as

$$L = \frac{V_{out} \cdot (1 - D)}{f_{switch} \cdot r \cdot I_{out}}$$

where r is the percentage ripple of the output load current.

- **Critical inductance value ($L_{critical}$):**
  - At Boundary of CCM/DCM **($\Delta I = 2I_{out}$)**

$$L_{Critical} > \frac{V_{out}(1 - D_{\min})}{2I_{out\_\min} \cdot f_{switch}}$$



The Buck Converter

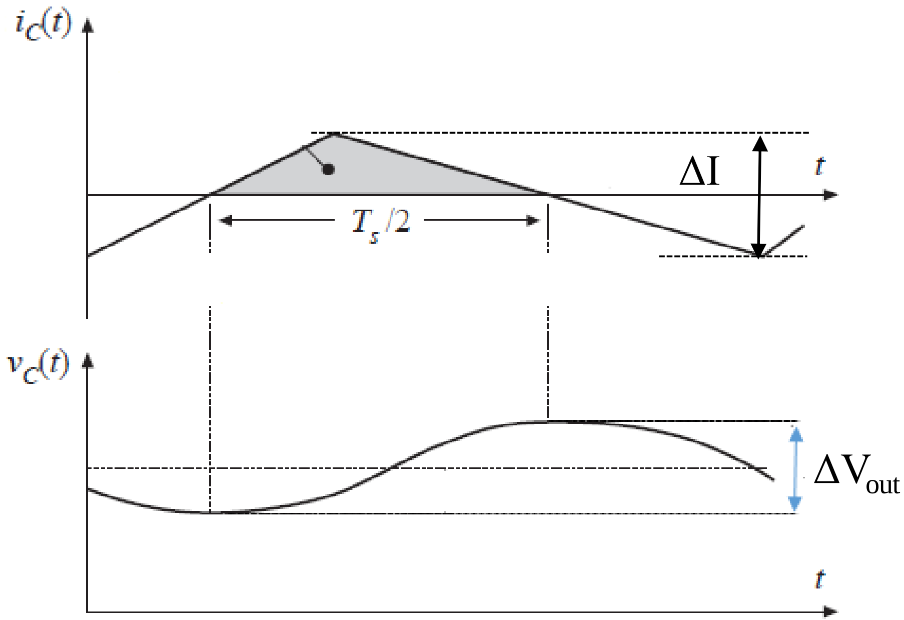
- **Calculating capacitance value (C):**

$$C = \frac{\Delta I}{8 \cdot f_s \cdot \Delta V_{out}}$$

where ΔV_{out} is the specified maximum output voltage ripple.

Remember:

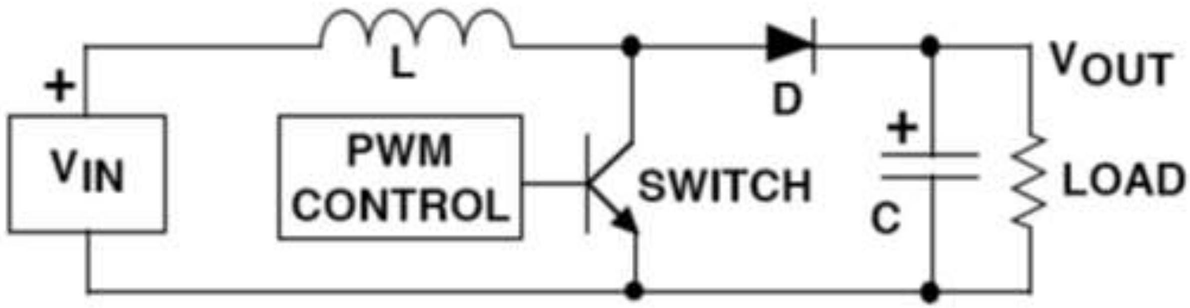
$$ESR << \frac{\Delta V_{out}}{\Delta I}$$

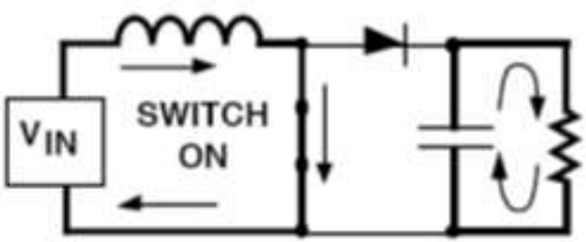


- **Considering Dynamic response**

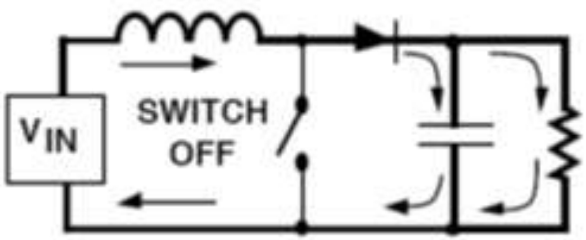
The Boost Converter

- **The Boost Converter (Step Up)**
  - Converts a DC voltage to a higher DC voltage with the same polarity
  - Continuous and discontinuous conduction modes (CCM and DCM)





t_{ON}



t_{OFF}

The Boost Converter

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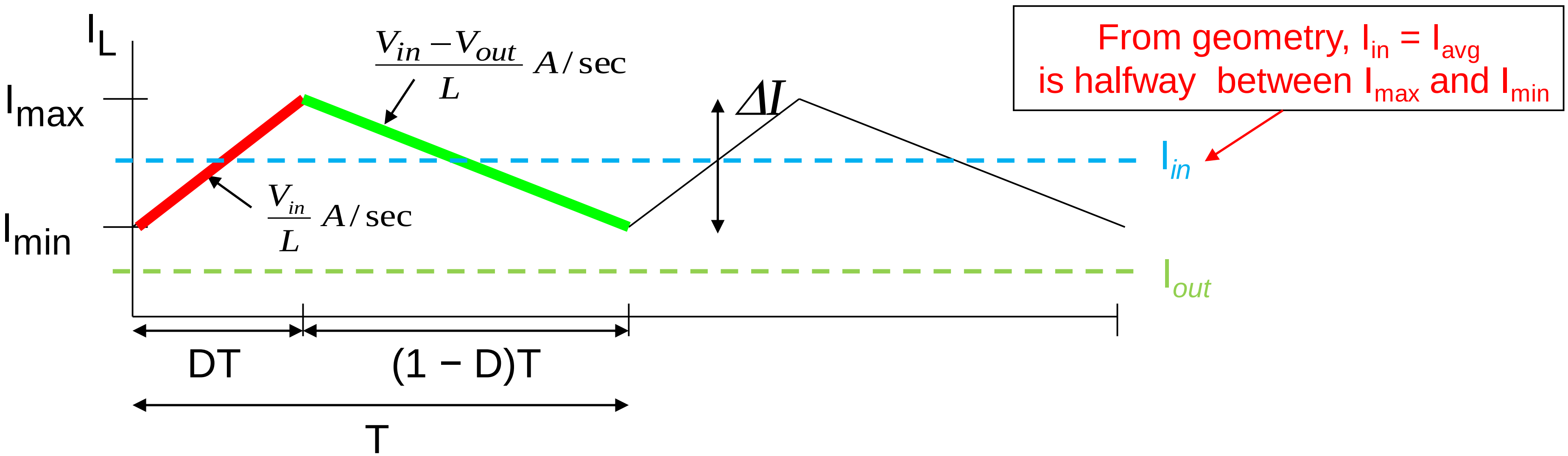
- **Effects of ripple current (ΔI_L):**

$$\boxed{\Delta I = \frac{V_{in}}{L} \times D \times T}$$



– CCM operation (as with the Buck)
– Output voltage ripple (with the ESR of C_{out})
– Core losses in the inductor
– Emissions

The Boost Converter

- **Calculating inductance value (L):**

$$\boxed{L = \frac{V_{in}}{\Delta I} \times D \times T}$$

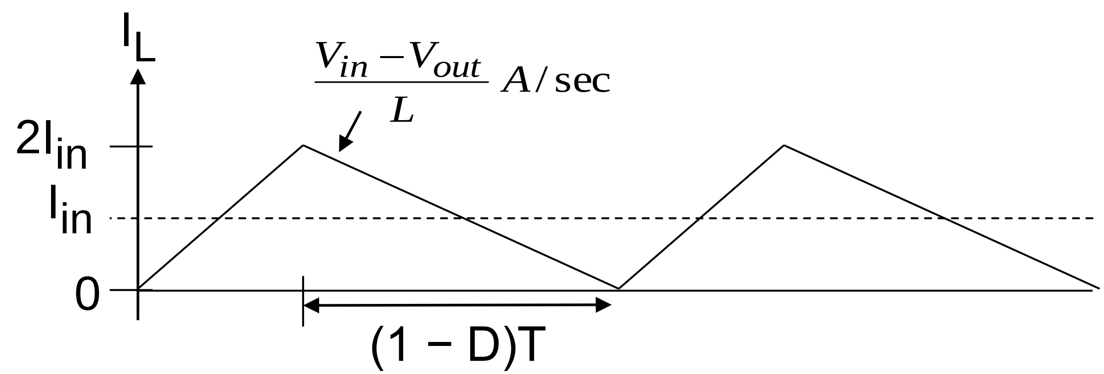
Re-write as ⇒

$$\boxed{L = \frac{D \cdot V_{out} \cdot (1-D)^2}{f_{switch} \cdot r \cdot I_{out}}}$$

where r is the percentage ripple of the input inductor current.

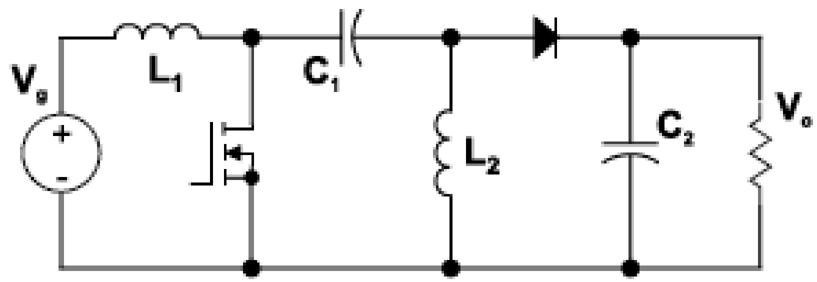
- **Critical inductance value ($L_{critical}$):**
  - At Boundary of CCM/DCM **($\Delta I = 2I_{in}$ and $D = 0.33$)**

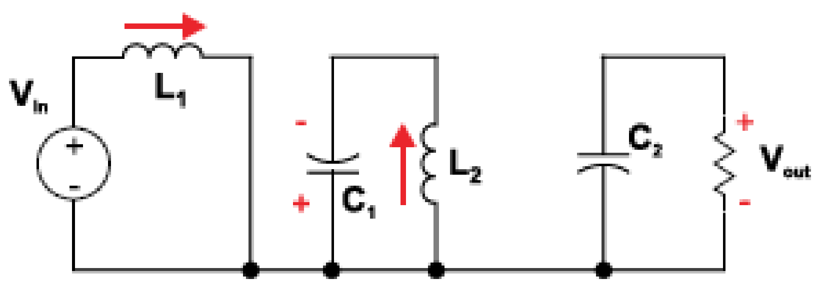
$$\boxed{L_{Critical} > \frac{V_{out} \cdot D_{0.33} \cdot (1-D_{0.33})^2}{2I_{out\_min} \cdot f_{switch}}}$$



The SEPIC Converter

- **The SEPIC Converter (Buck-Boost)**
  - Single Ended Primary Inductance Converter
  - Converts a DC voltage to a lower or higher DC voltage with the same polarity





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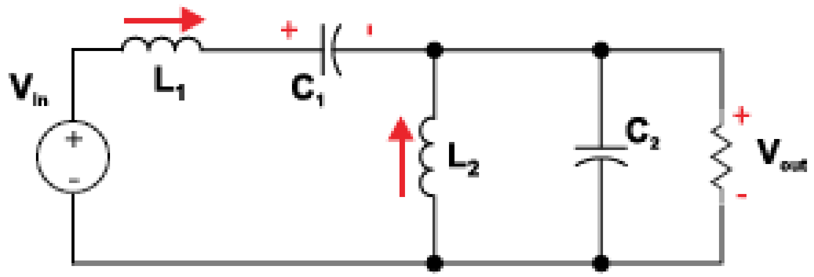
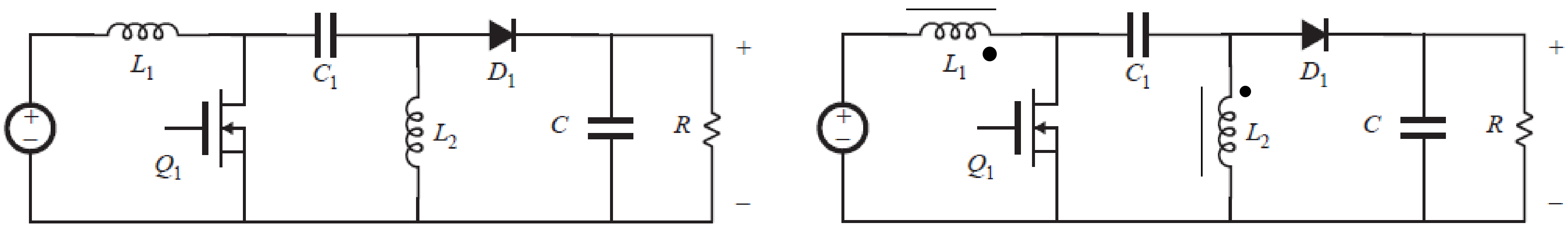


tOFF

The SEPIC Converter

▪ Single Inductors vs a Coupled Inductor

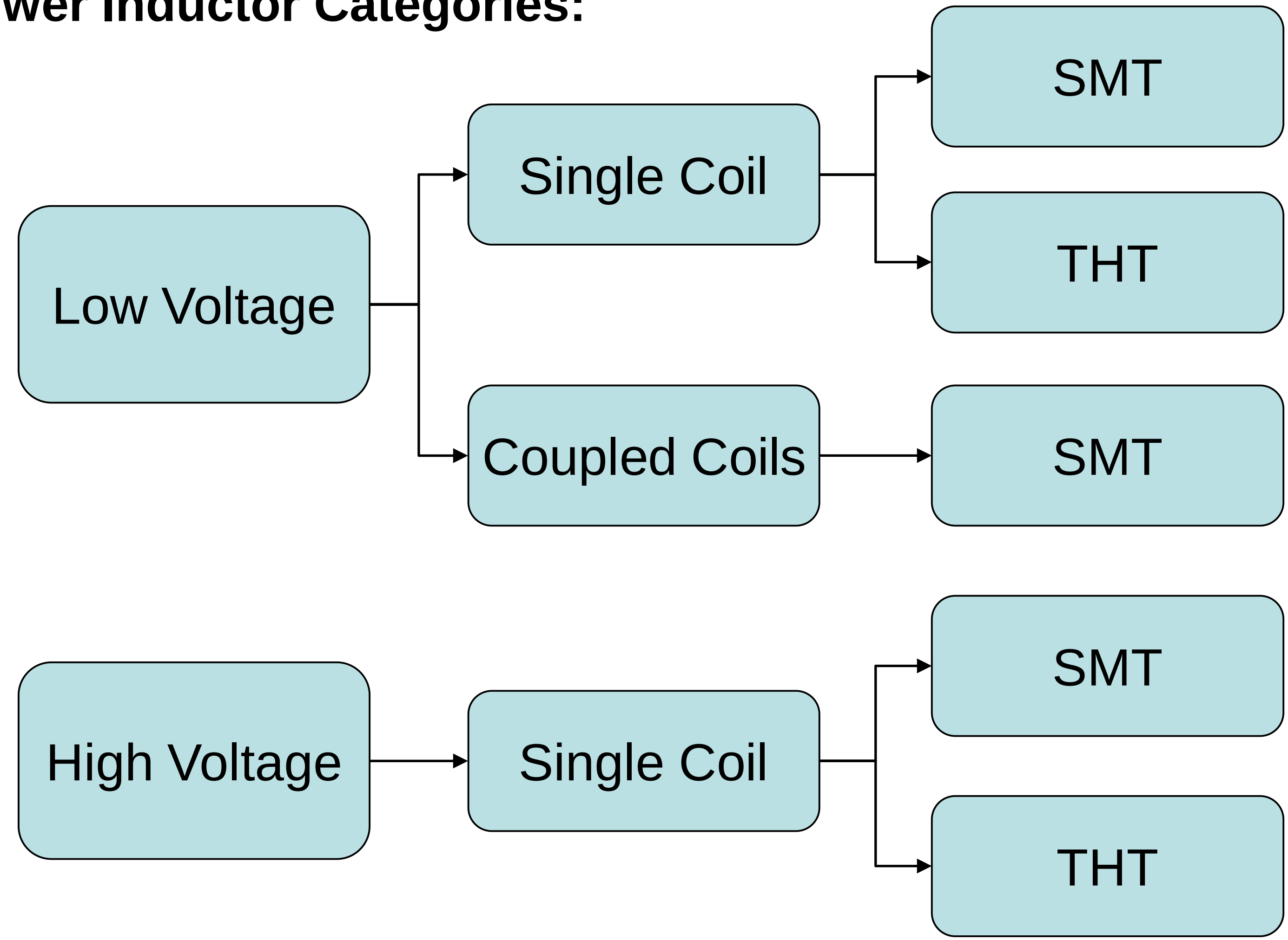


– A coupled inductor is often selected due to:
  - Lower inductance requirement compared to using two single inductors (half).
  - Reduced component count,
  - Improved efficiency,
  - Reduced circuit area
  - Less cost
  - Input ripple current cancellation (resulting in smaller input capacitor and simpler EMI input filter)

INDUCTOR AND CAPACITOR SELECTION PARAMETERS

Inductor Selection Parameters

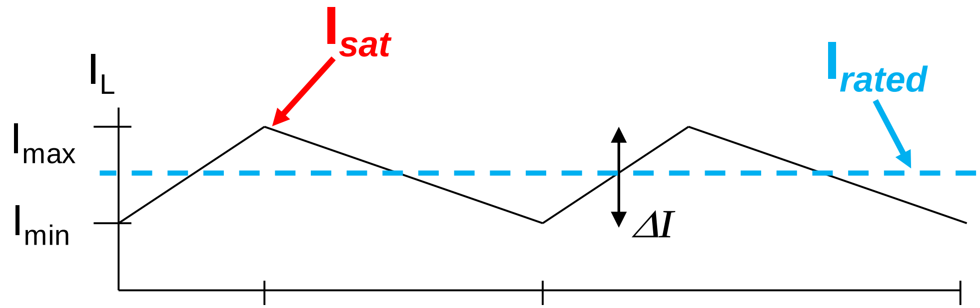
- **Power Inductor Categories:**

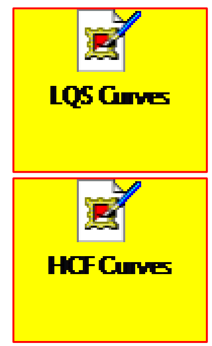


MAPI

Inductor Selection Parameters

- **Inductor Catalogue Parameters:**
  - Rated Current
  - Saturation Current
  - R_{DC}
  - Resonant Frequency/Q
  - Impedance vs Frequency Curve
  - Inductance vs Current Curve
  - Temperature rise vs Current Curve





Inductor Selection Parameters

- **Saturation Current**

Spezifikation für Freigabe / specification for release

Kunde / customer :

Artikelnummer / part number : **7447709001/LF**

Bezeichnung : **SPEICHERDROSSEL WE-PD**
description : **POWER-CHOKE WE-PD**

LEAD FREE

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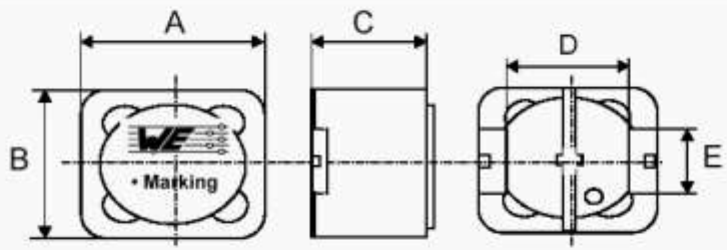
DATUM / DATE : 2004-06-03

A Mechanische Abmessungen / dimensions:



	Typ XXL	
A	12,0 ± 0,5	mm
B	12,0 ± 0,5	mm
C	10,0 max.	mm
D	7,6 ref	mm
E	5,0 ref	mm
F		mm

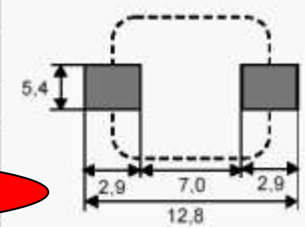
● = Start of winding   Marking = Inductance code

B Elektrische Eigenschaften / electrical properties:

Eigenschaften / properties	Testbedingungen / test conditions		Wert / value	Einheit / unit	tol.
Induktivität / inductance	1 kHz / 0,25V	L_N	1,0	µH	±20%
DC-Widerstand / DC-resistance	@ 20°C	$R_{DC\ typ}$	3,86	mΩ	typ.
DC-Widerstand / DC-resistance	@ 20°C	$R_{DC\ max}$	5,60	mΩ	max.
Nennstrom / rated current	ΔT=40 K	I_{DC}	13,00	A	max.
Sättigungsstrom / saturation current	|ΔL/L|<10%	I_{sat}	25,00	A	typ.
Eigenres.-Frequenz / self-res.-fequency		SRF	120,0	MHz	typ.

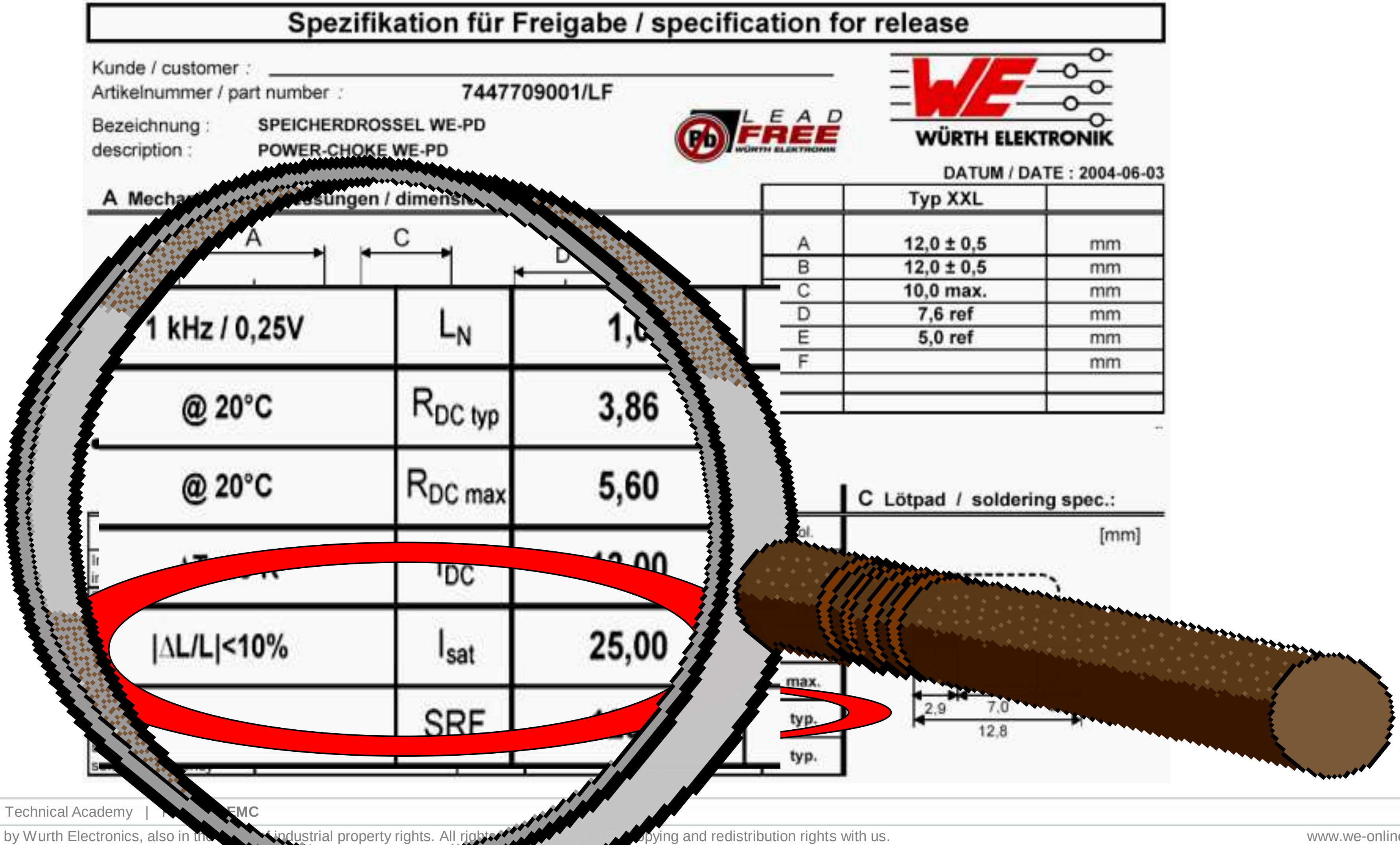
C Lötpad / soldering spec.:

[mm]



Inductor Selection Parameters

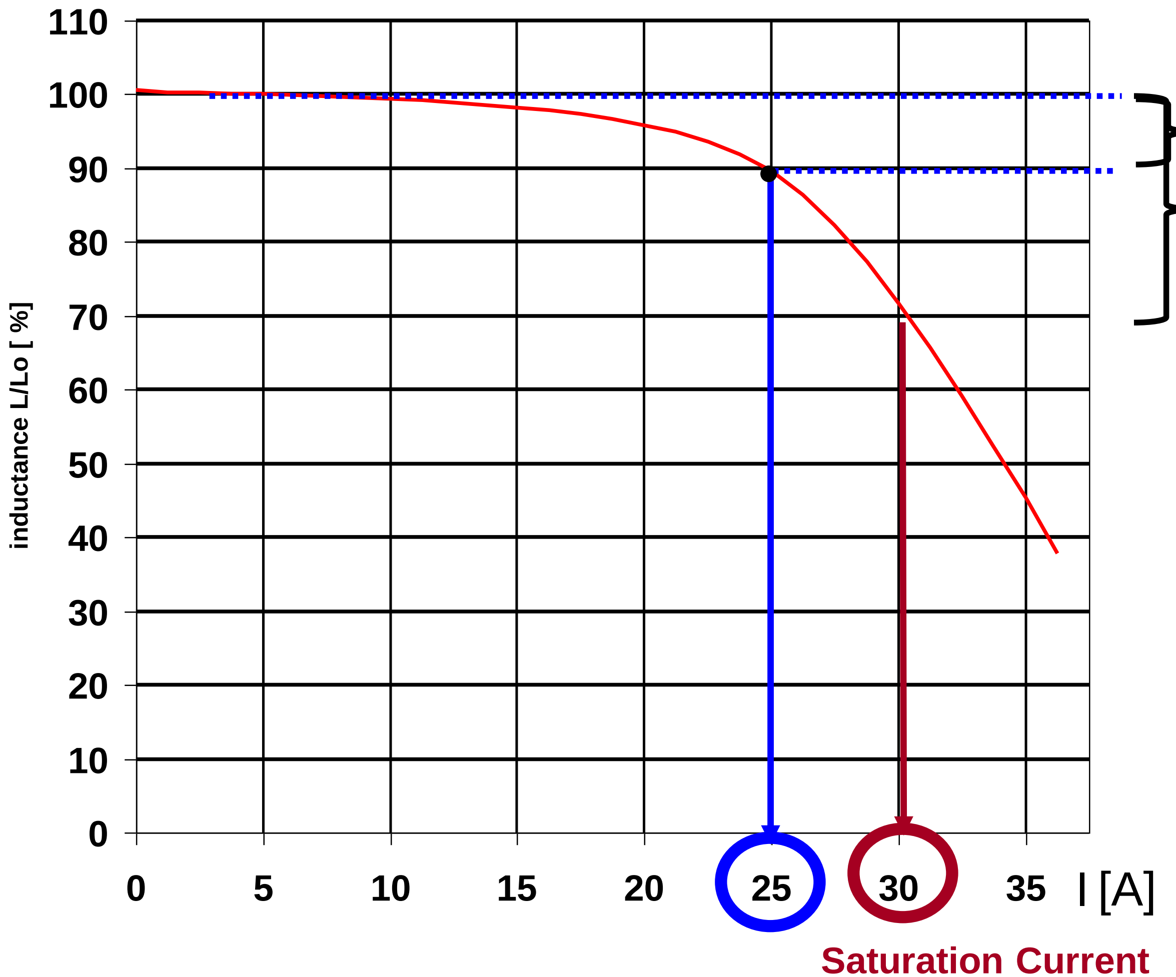
=> *Print in the data sheet and in the catalogue, drop of the inductance value*



Inductor Selection Parameters

- **Saturation Current**

Definition
Wurth Elektronik:
e.g. WE-PD

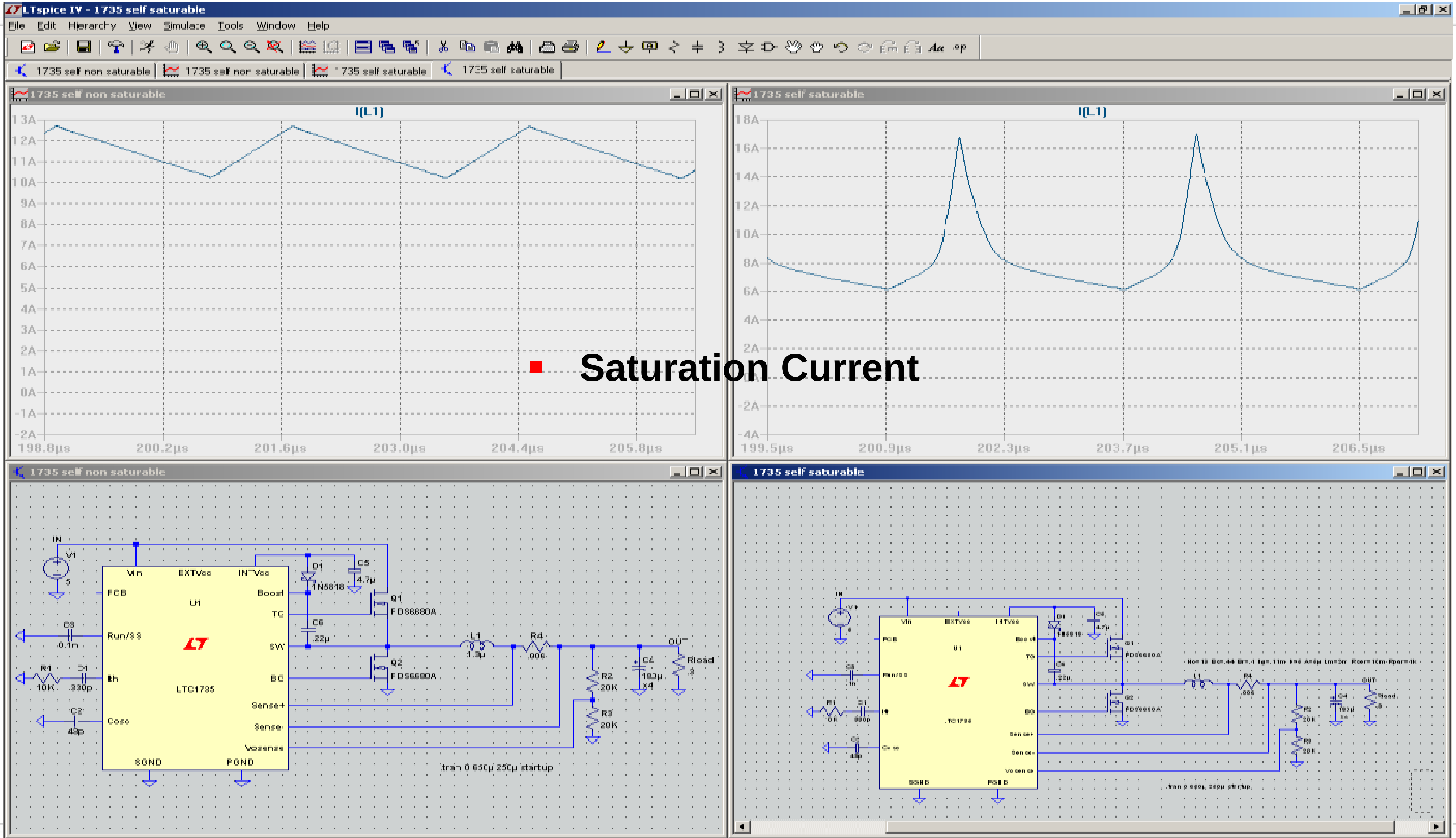


Isat = 25 A

Isat = 30 A

- the saturation current always refers to a certain inductance drop

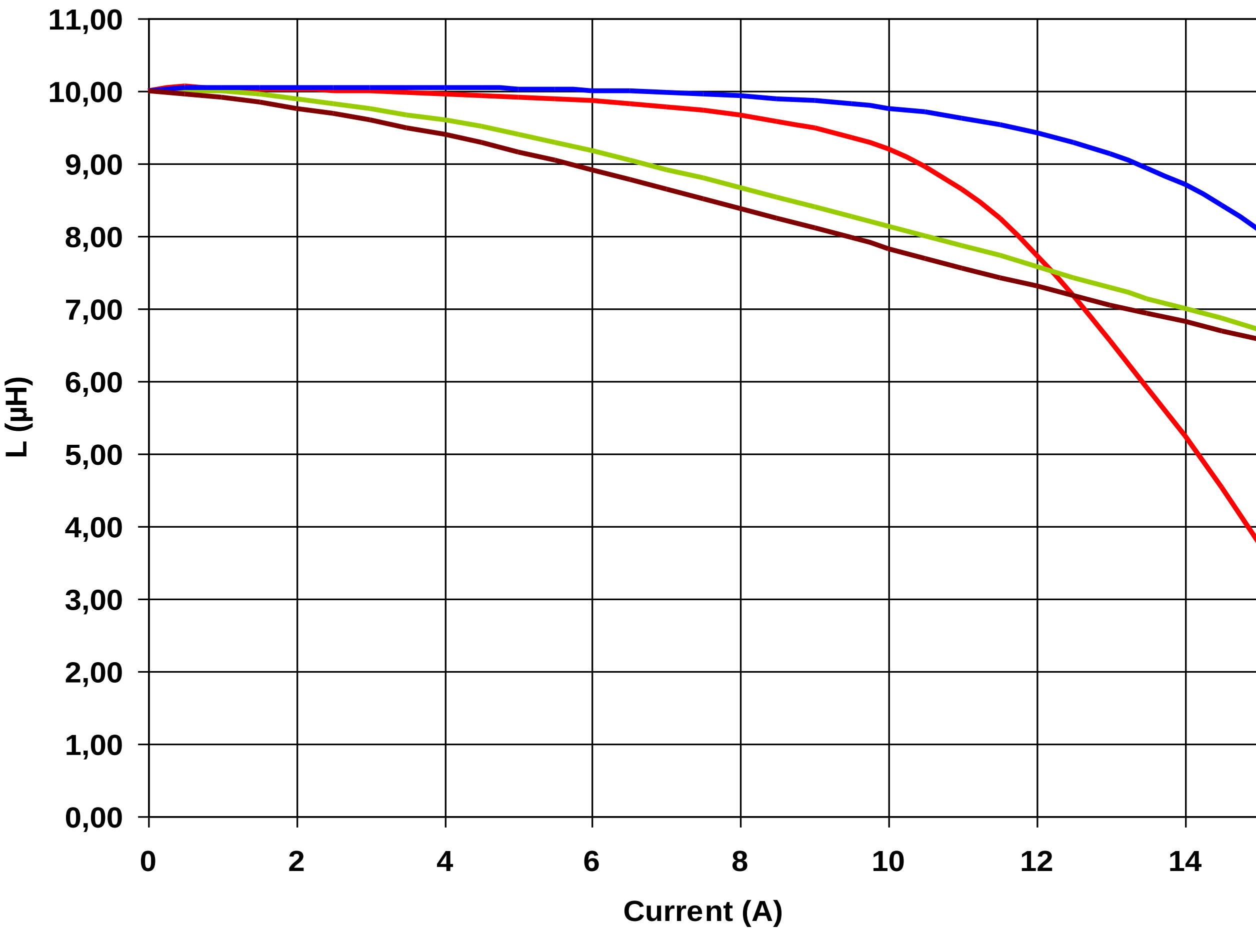
Inductor Selection Parameters



- Saturation Current

Inductor Selection Parameters

- ## Saturation Current vs material



WE-SD

Material: NiZn
AirGap: big

WE-HCI

Material: WE-Perm
AirGap: small

WE-SI

Material: Iron
AirGap: distributed

WE-PD

Material: NiZn
AirGap: small

Inductor Selection Parameters

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- **Rated Current**

=> **Increase temperature with a DC current**

Demo

Spezifikation für Freigabe / specification for release

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LEAD FREE

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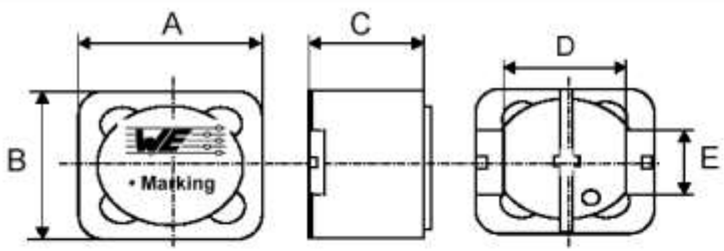
DATUM / DATE : 2004-06-03

A Mechanische Abmessungen / dimensions:



	Typ XXL	
A	12,0 ± 0,5	mm
B	12,0 ± 0,5	mm
C	10,0 max.	mm
D	7,6 ref	mm
E	5,0 ref	mm
F		mm

● = Start of winding

Marking = Inductance code

B Elektrische Eigenschaften / electrical properties:

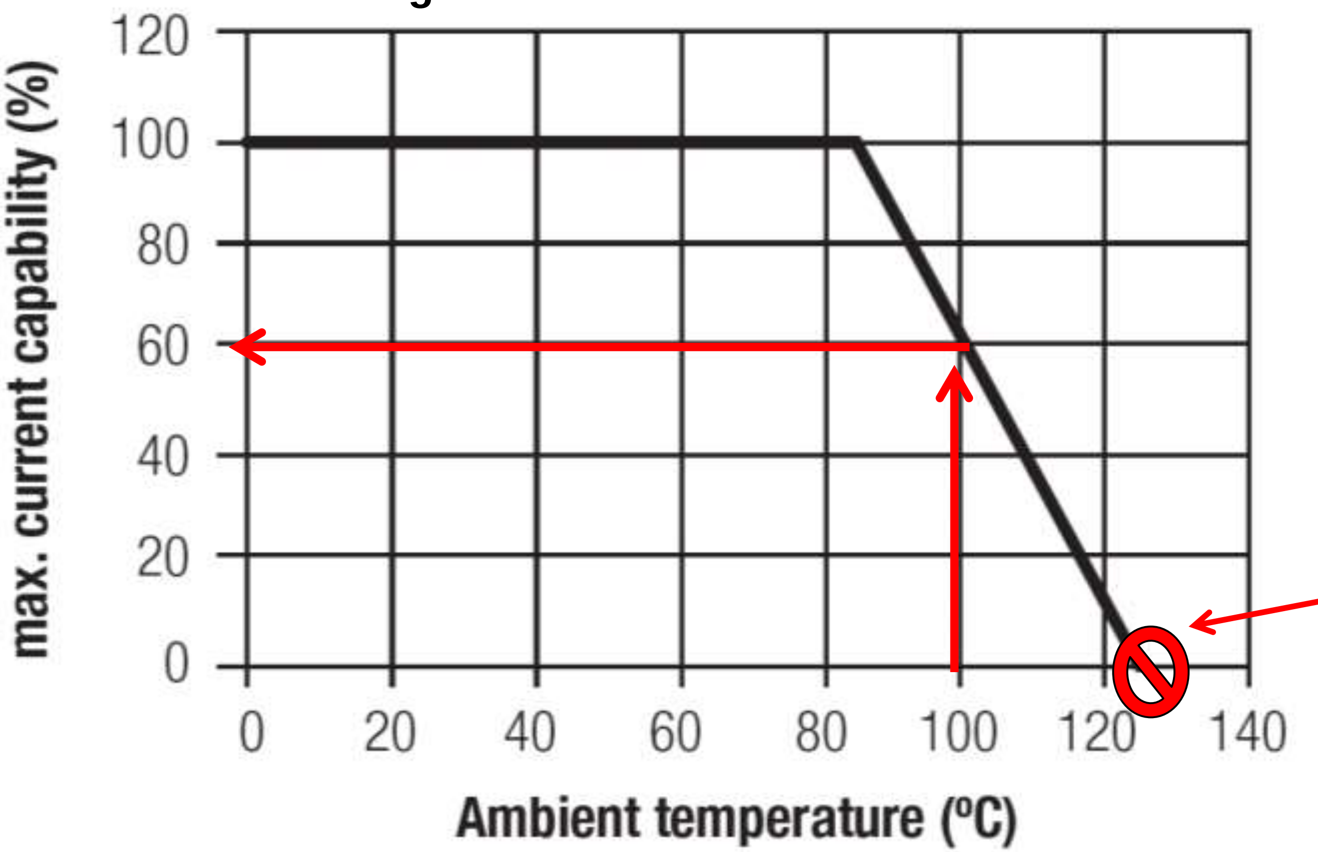
C Lötpad / soldering spec.:

DC-Widerstand / DC-resistance	@ 20°C	$R_{DC\ max}$	5,60	mΩ
Nennstrom / rated current	ΔT=40 K	I_{DC}	13,00	A
Sättigungsstrom/	|ΔL/L|<10%		25,00	A

Inductor Selection Parameters

- **Rated Current – De-rating**

At 100°C ambient Temp. only 60% of the rated current can be used
Derating of 40 %



The max operating temperature of the inductor is 125°C

Can be higher 155°C, like PDF series

Capacitor Selection Parameters

Caps

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- **Capacitor Categories:**
  - Electrolytic
    - THT
    - SMT
    - Snap in
  - Polymer
    - THT
    - SMT
  - Ceramic
    - SMT
  - Film
    - THT

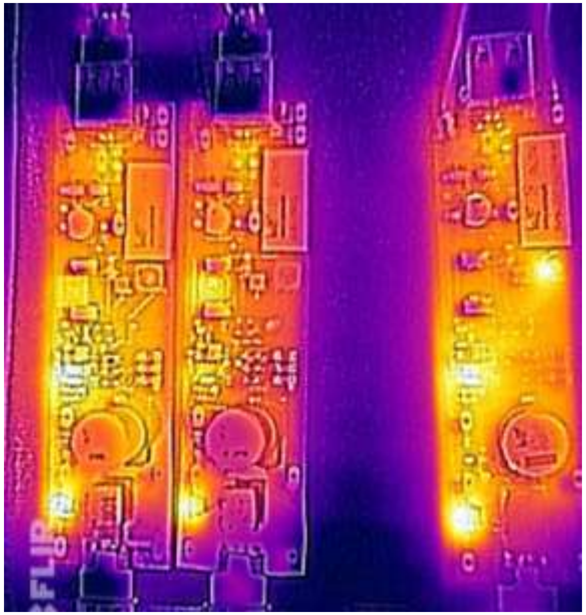
Electrolytic & Polymer

MLCC & FILM

Capacitor Selection Parameters

- **Capacitor Catalogue Parameters:**
  - Voltage Rating
  - Ripple Current (rms)
  - Leakage current
  - Dissipation Factor
  - Expected Life
  - MLCC Capacitance vs Temperature Curve
  - MLCC Capacitance vs Voltage Curve
  - MLCC Capacitance vs time Curve
  - MLCC Class 1 and 2


Expected Life



EFFICIENCY & LOSSES

Efficiency - Importance

- Advantages

→ „green design“

→ sustainable products

→ less cooling efforts

→ cost savings

→ high power density

→ size shrinks

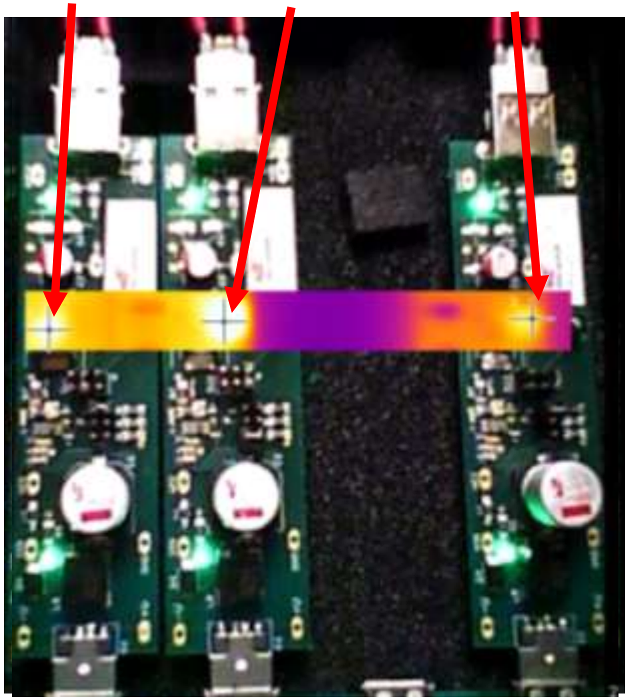
A small efficiency increase

greatly reduce losses !!

No Fan – No bulky heat sink

INDUCTOR LOSSES

T1 = 58°C   T2 = 69°C   T3 = 50°C



Self Heating of the inductor can be estimate

INDUCTOR LOSSES

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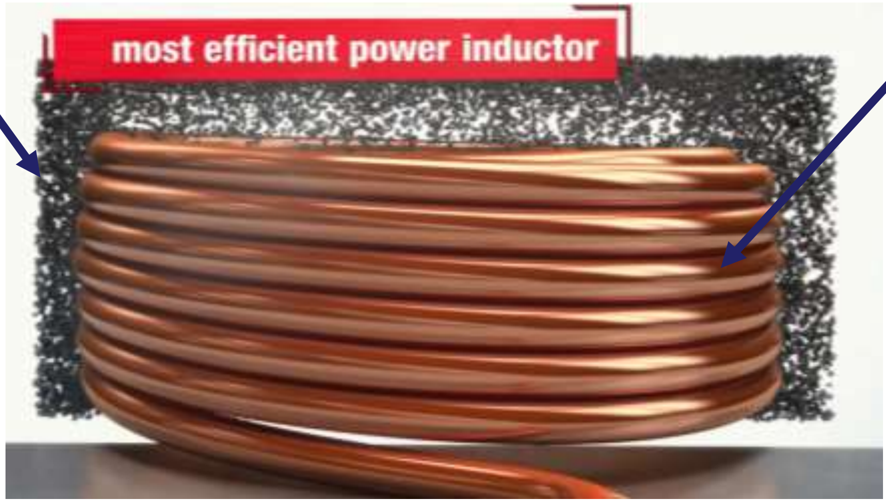
$$P_{total} = P_{core} + P_{copper}$$

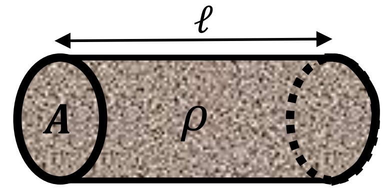
Core losses:
Hysteresis losses
Eddy current losses

Copper losses:
DC losses – depending on DCR
AC losses – dep. on winding structure
→ Skin-Effect
→ Proximity-Effect



INDUCTOR LOSSES : Copper DC losses

$$P_{cu} = RDC * {I^2}_{RMS}$$



$$R_{DC} = \rho * \frac{l}{A}$$

$$\rho = 1{,}78 * 10^{-2} \frac{\Omega \,.\, mm^2}{m}$$

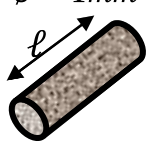
$$R_{DC} \downarrow \Rightarrow Pcu \downarrow$$

- ρ : Resistivity of copper
- ℓ : Length of wire
- A : Cross Sectional area

Optimization

ℓ=1m

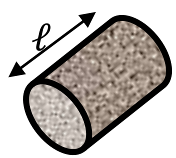
$\emptyset = 1mm$



$A = 0{,}78\ mm^2$

$R_{DC} = 23m\Omega$

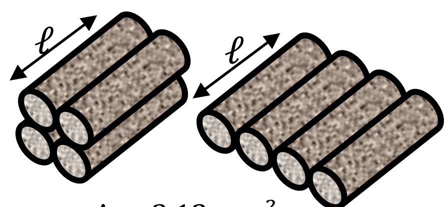
$\emptyset = 2mm$



$A = 3{,}714\ mm^2$

$R_{DC} = 5{,}7m\Omega$

$\Rightarrow 4 * 1mm\ \emptyset$

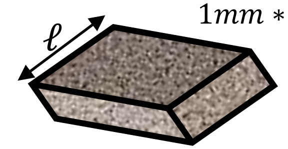


$A = 3{,}12\ mm^2$

$R_{DC} = 5{,}75m\Omega$

Flat wire

$1mm * 4mm$

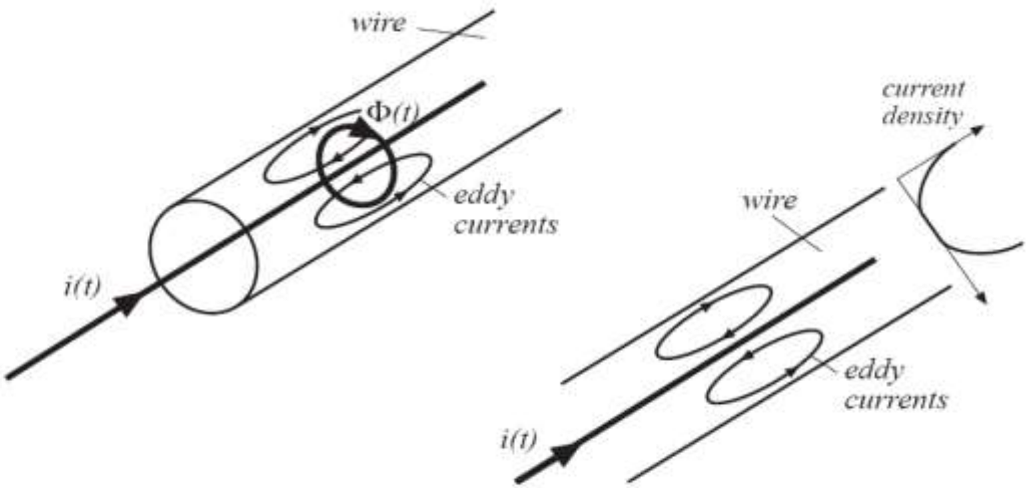


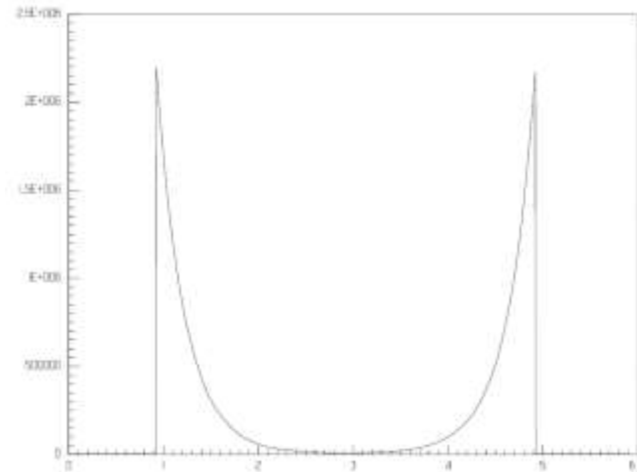
$A = 4\ mm^2$

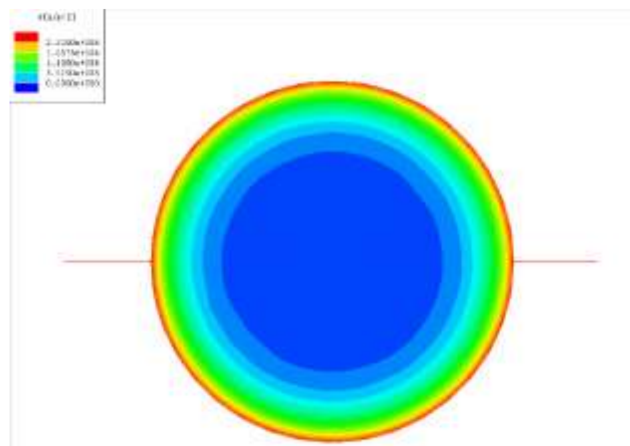
$R_{DC} = 4{,}48m\Omega$

INDUCTOR LOSSES : Copper AC losses

Eddy Currents in Wire







INDUCTOR LOSSES : Copper AC losses, Skin effect

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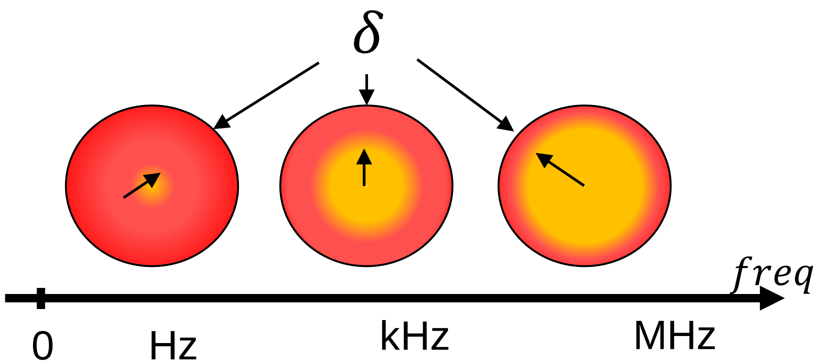
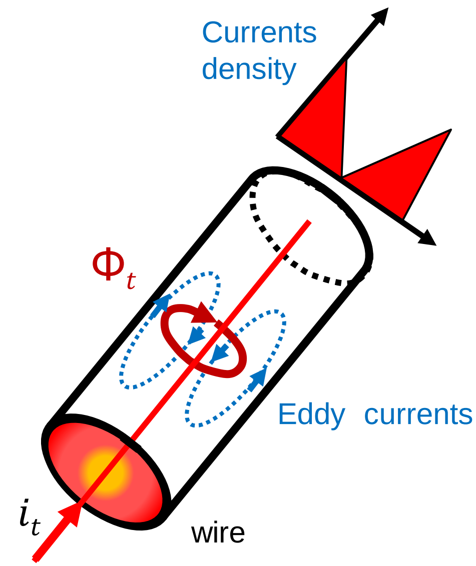




$$\delta = \sqrt{\frac{2 * \rho}{w * \mu}}\ mm$$

$$\delta = \frac{76}{\sqrt{f}}\ mm$$ @ 100°C

δ = skin depth
ρ = resistivity
ω = angular frequency 2πf
μ = permeability

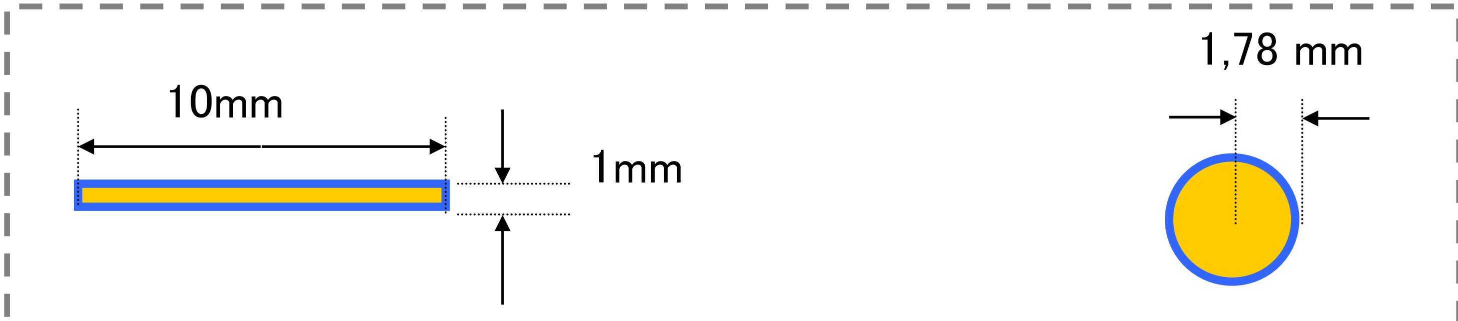
For Copper

δ @	50Hz	= 9.38 mm
δ @	10kHz	= 0.66 mm
δ @	100kHz	= 0.22 mm

$$f \uparrow \rightsquigarrow A_{eff} \downarrow \rightsquigarrow R_{AC} \uparrow \rightsquigarrow P_{winding} \uparrow$$

INDUCTOR LOSSES : Copper AC losses, Skin effect

Comparison: flat wire vs. round wire



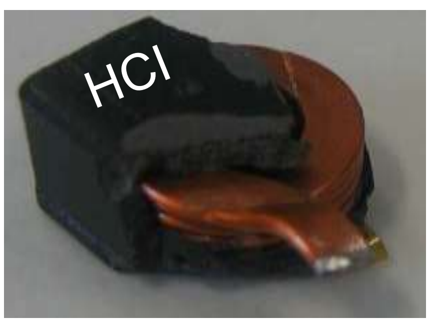
cross section of both wires is $10mm^2$

<u>BUT:</u> flatwire has much more bigger surface
Flat wire surface : 22mm / round wire 11,18mm

$S_{FLAT} = 1{,}96 \times S_{RUND}$

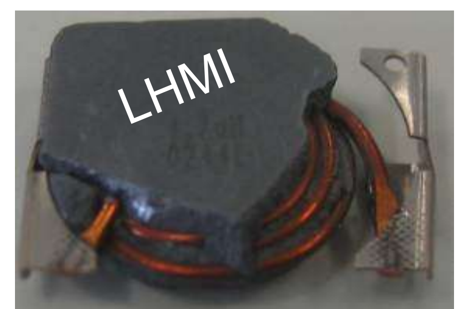
<u>AND:</u> high frequency currents only use the surface

→ Skin effect



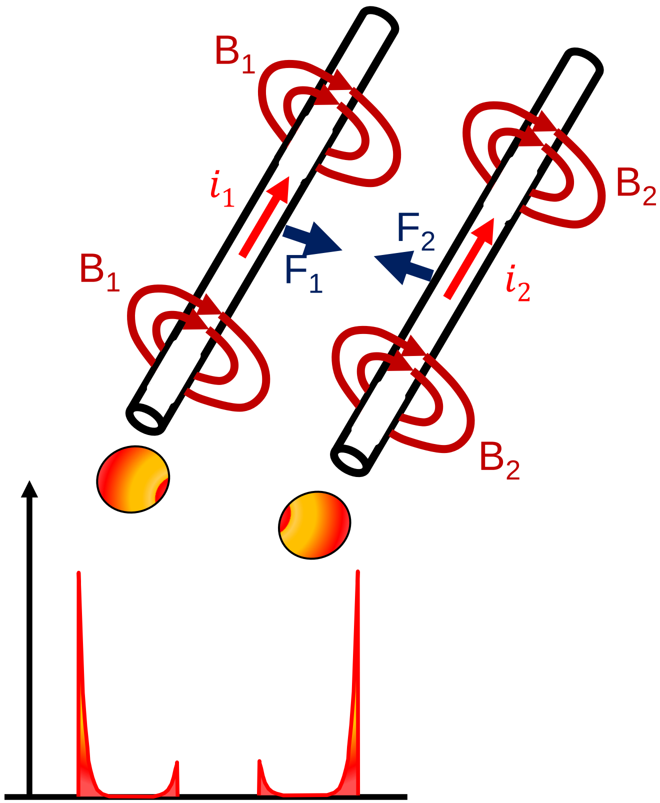
WE

**Flat wire has a higher surface,
thus less copper losses at higher frequencies !**

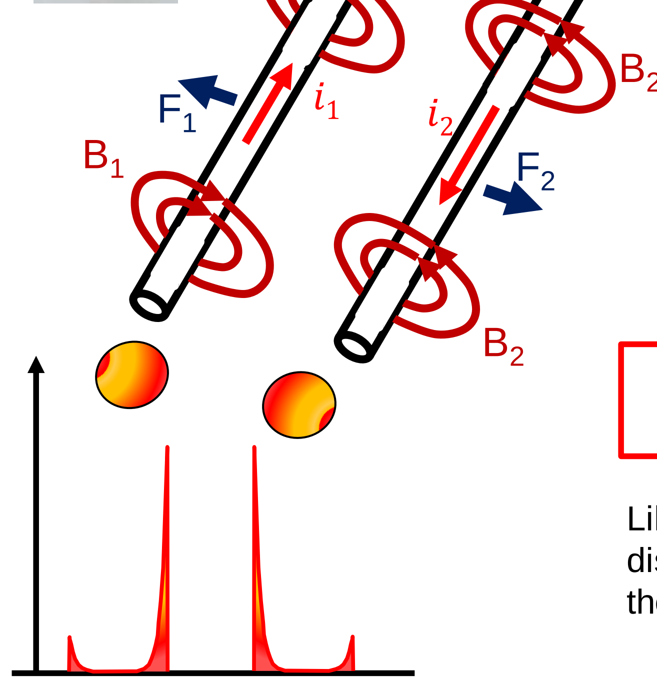


Vishay

INDUCTOR LOSSES : Copper AC losses, Proximity effect



Current in same direction



Current in opposite direction

$$\boxed{f \uparrow \Rightarrow R_{AC} \uparrow}$$

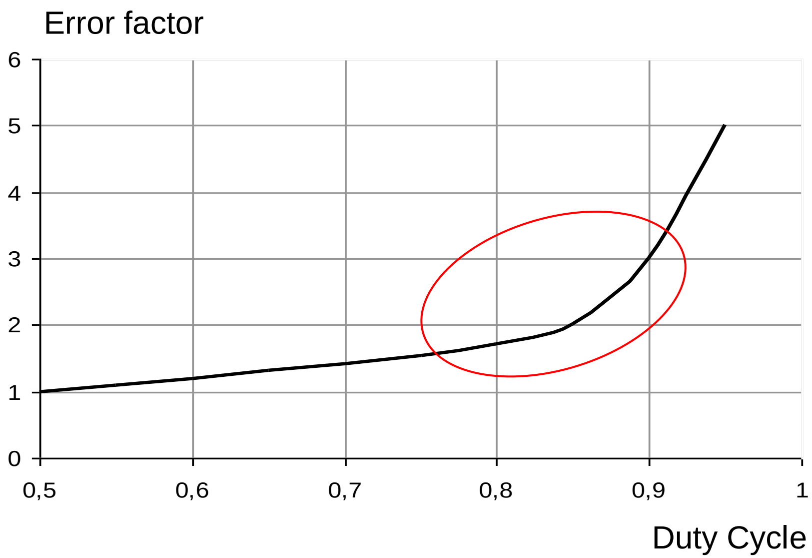
Like the skin effect, the distribution of current inside the wire is reduced

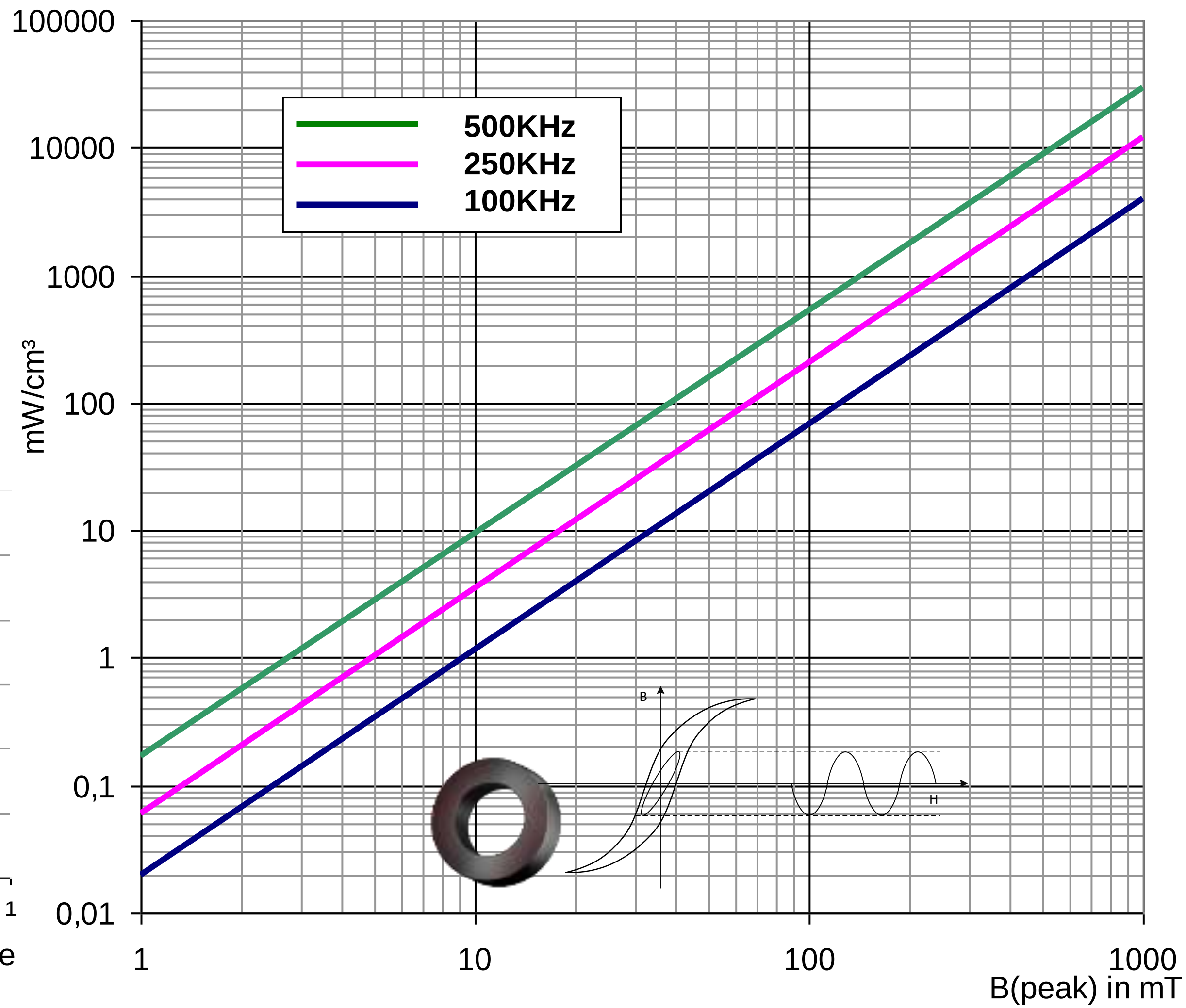
- Proximity Effect creates more loss than Skin Effect
- Approximate Calculations
  - Dowell's curves for simple geometries
  - Bruce Carsten or Charles Sullivan for more in-depth

INDUCTOR LOSSES : Core losses

- Steinmetz formula

$$P_{core} = K \cdot f^{a} \cdot B^{b}$$





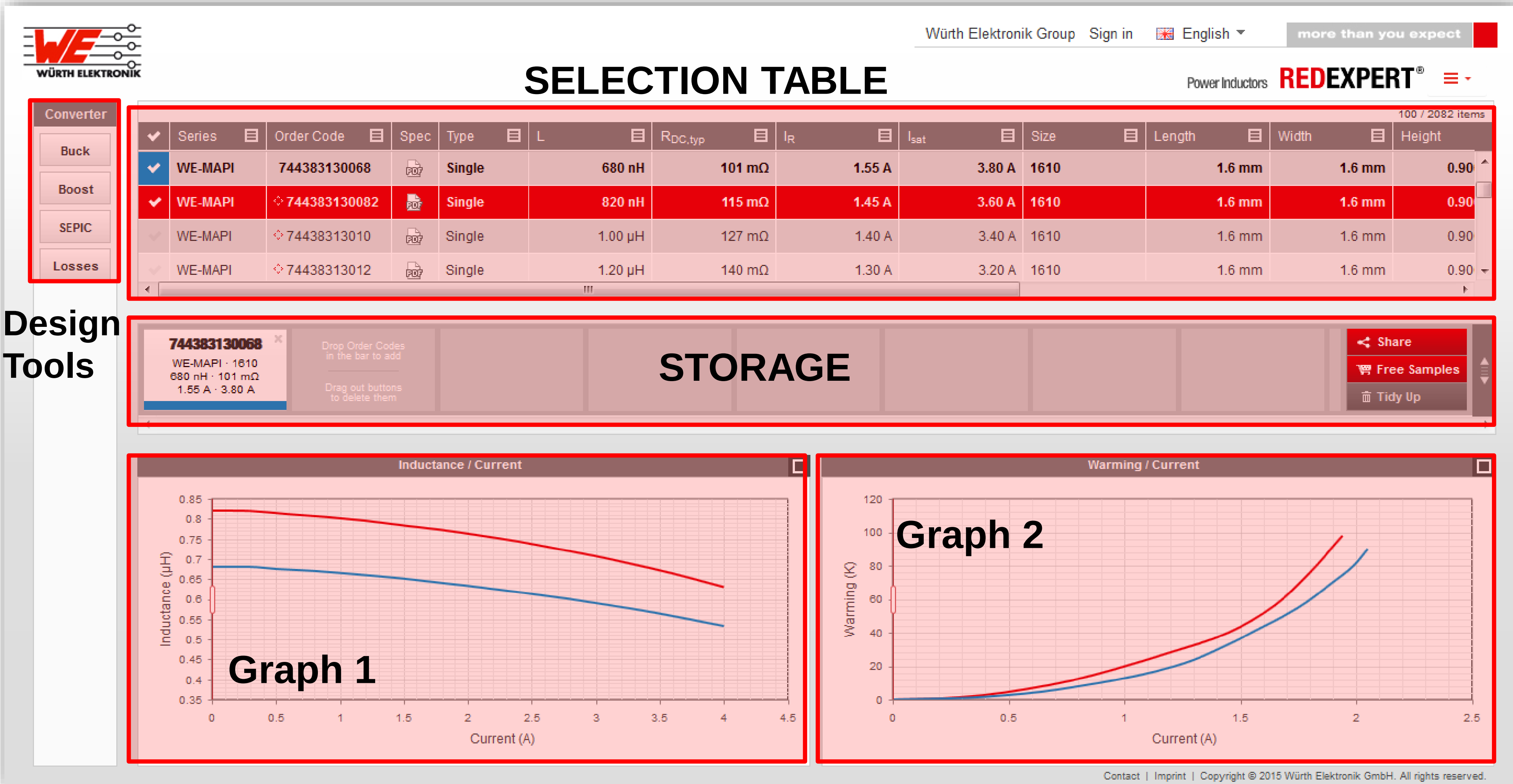
REDEXPERT – The missing link

REDEXPERT

REDEXPERT


World's most accurate AC loss model
The losses determined with REDEXPERT are based on real time DCDC measurements with its typical current and voltage waveforms. Besides all core and winding losses they do also consider losses in the air gap.
Calculate the AC losses
Power Inductors
REDEXPERT

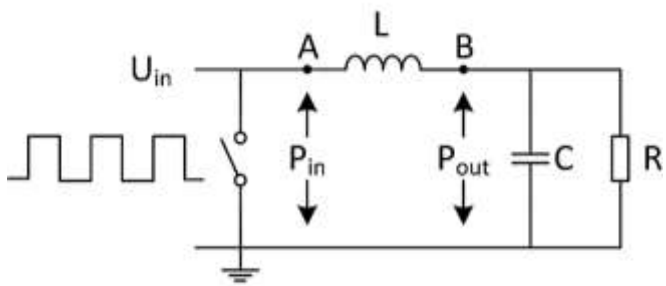
User Interface

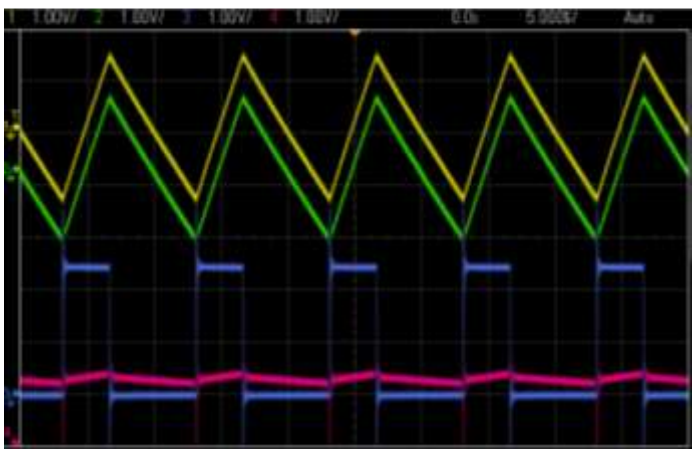


World's Most Accurate AC Loss Model

WÜRTH ELEKTRONIK

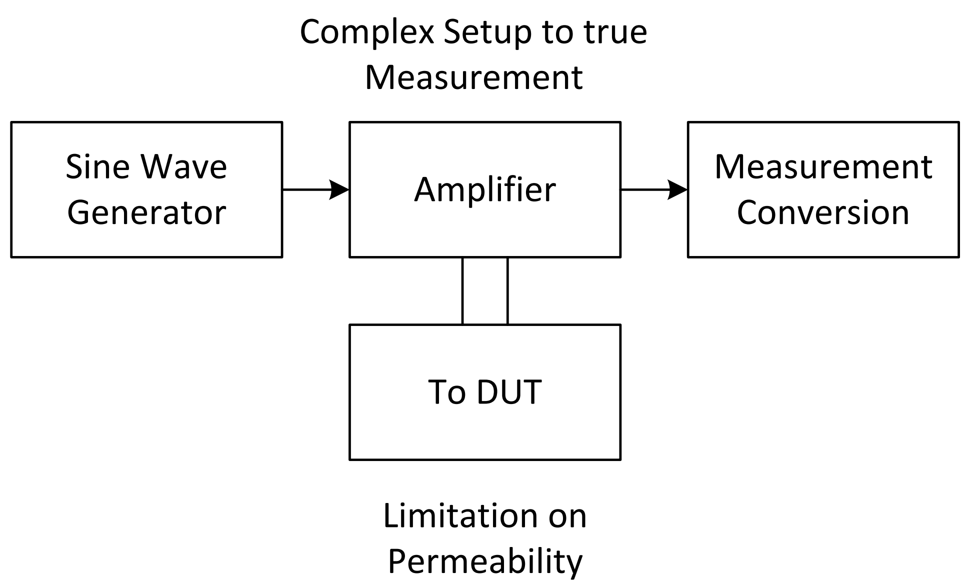
Wurth AC Loss Model





Simple Class-D Amplifier

Steinmetz Models



Complex Setup to Measure

World‘s Most Accurate AC Loss Model

Wurth AC Loss Model:

- Based on real time application set up and measurements
- A pulsating input voltage is applied over the Inductor
- The input and output power is measured
- This process is repeated over wide range of parameters
  incl. variation of peak flux density swing to produce our own empirical data
- This empirical data is used to create the equation for Wurth AC Loss Model

Advantages:

- Accurate calculation of losses for any given Duty Cycle
- Accurate over wide range of frequency (10 kHz to 10 MHz)
- Considers even small change in core material and winding structure

World‘s Most Accurate AC Loss Model

WÜRTH ELEKTRONIK

Wurth AC Loss Model

$$P_{AC} = f\,(\,\Delta I,\ freq,\ DC,\ k1,\ k2\,)$$

Core Loss & AC Wire Loss

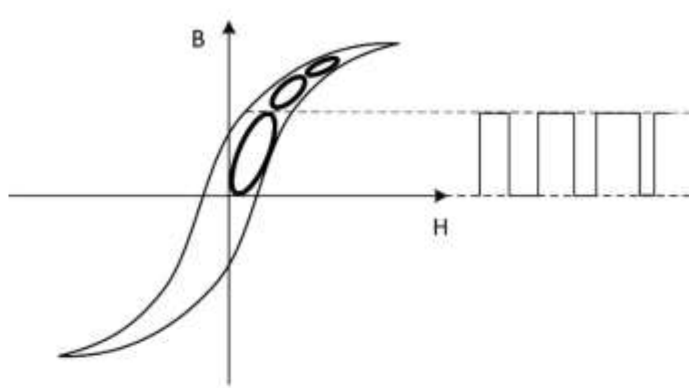
Steinmetz Models

$$P_V = K \cdot f^{\alpha} \cdot \Delta B^{\beta}$$

$$P_V = K \cdot f^{\alpha-1} \cdot \Delta B^{\beta} \times f^{r}$$

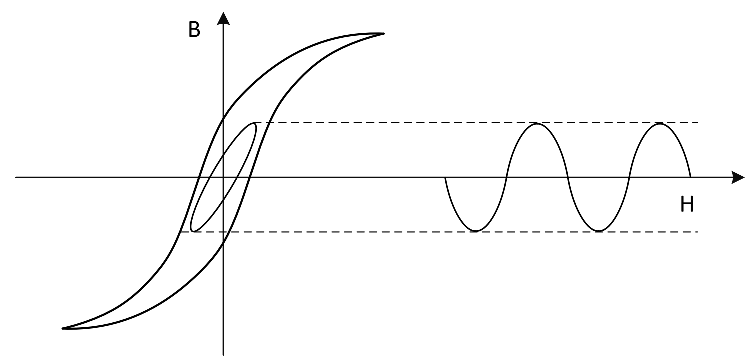
$$P_V = K \cdot f_{eq}^{\alpha} \cdot \Delta B^{\beta}$$

Core Loss Only



Point of Operation Approach

triangular current form

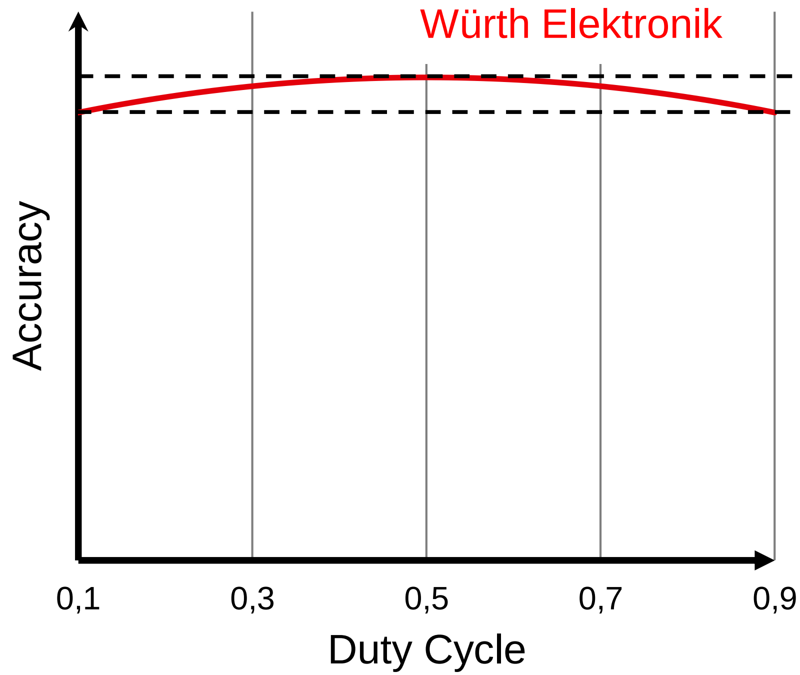


Major Loop Approach

only sine wave

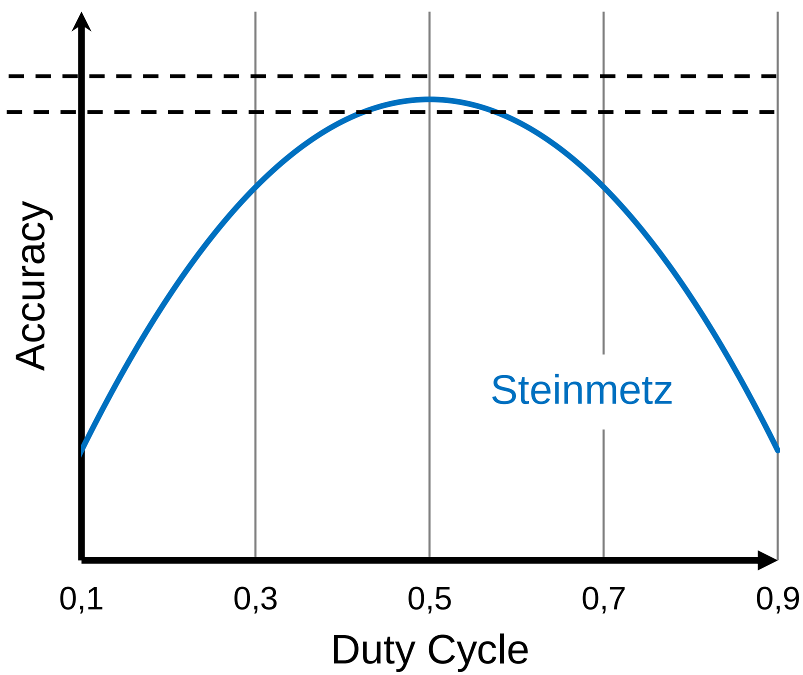
World‘s Most Accurate AC Loss Model

Wurth AC Loss Model



Highest Accuracy over wide DC range

Steinmetz Models



Acceptable Accuracy at 50%, even worse for other DC

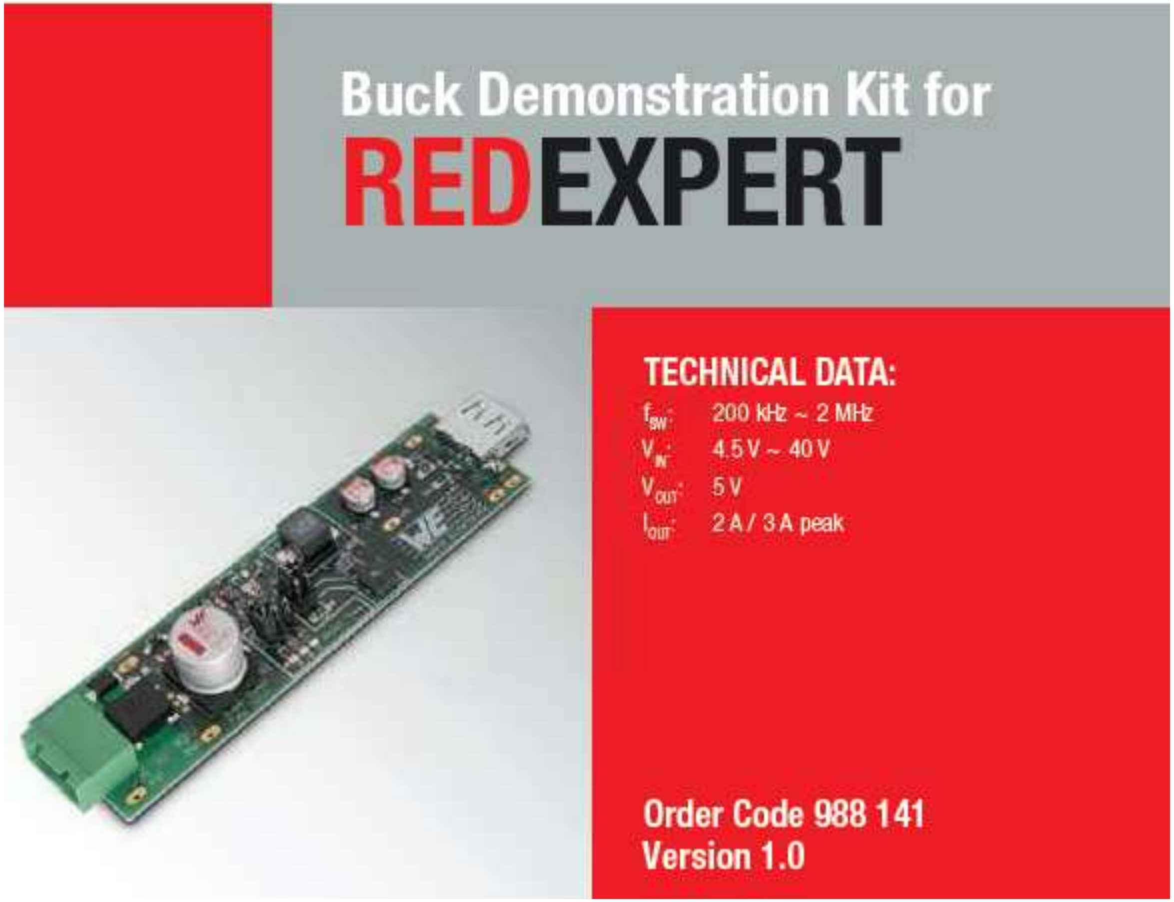
REDEXPERT

https://www.we-online.com/redexpert/#/module/1

www.we-online.com/redexpert

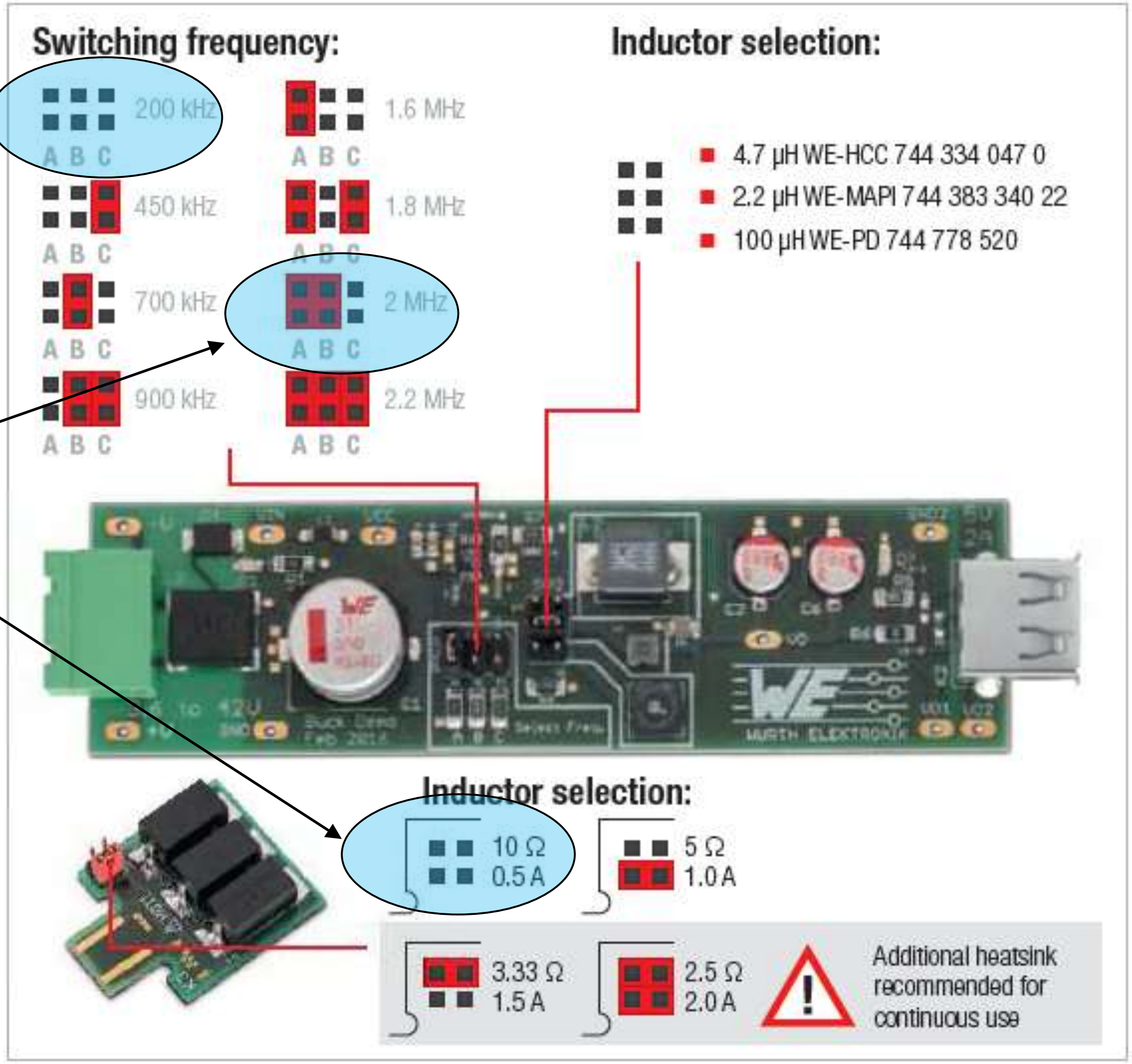
- http://we-online.com/re/3bJFP7JE

Buck Demo Kit for REDEXPERT



Buck Demo Kit for REDEXPERT

Test Conditions

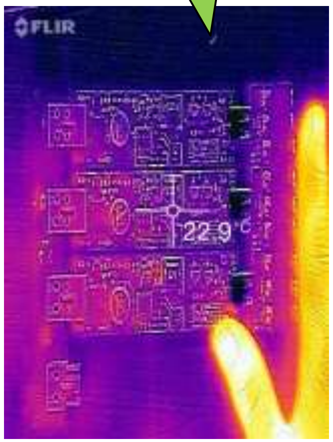


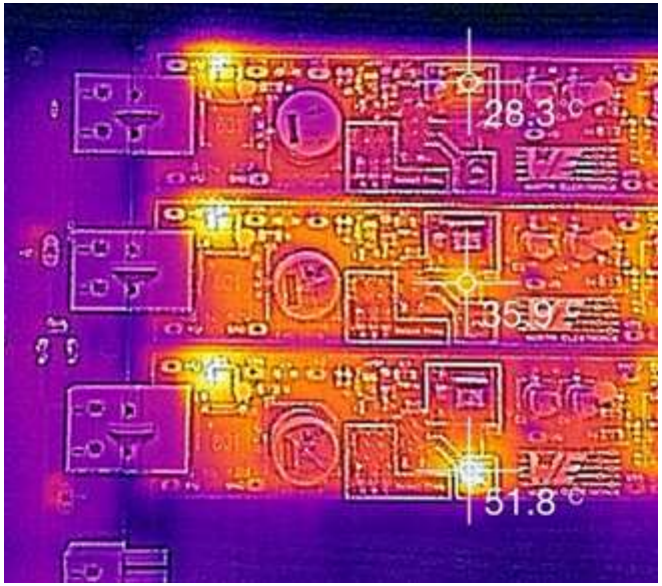
Switching Frequency: 200KHz vs 2MHz

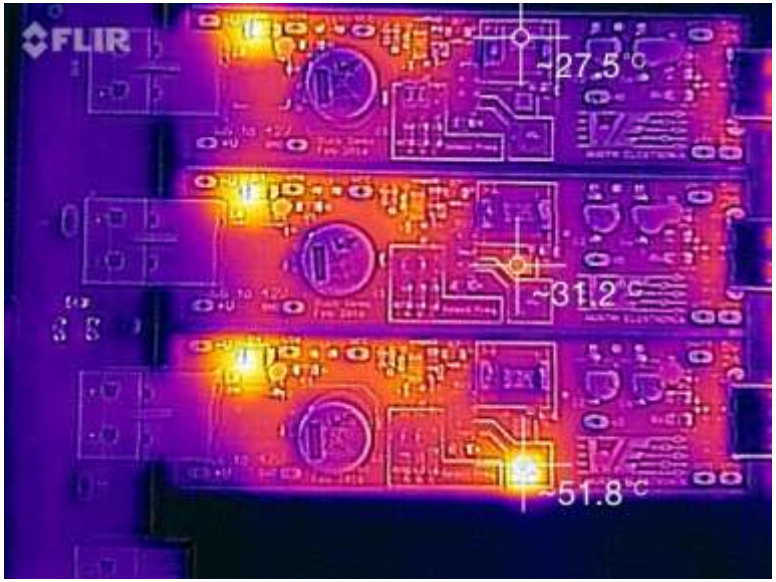
Ambient SAT 22.9˚C

9Vin, 5Vo, 2.5W, **200KHz**

9Vin, 5Vo, 2.5W, **2MHz**







WÜRTH ELEKTRONIK

REDEXPERT

- http://we-online.com/re/3bJFP7JE

Filters: Order Code ∋ 7443340470, 74438334022, 744778520 ✖ | Type = Single ✖

	Order Code	Series	Size	Spec	Type	L	L() @39...	$R_{DC,typ}$	I_R	I_{sat}	P_{AC}	P_{DC}	P_{TOT}	ΔT
✔	7443340470	WE-HCC	8070	PDF	Single	4.70 µH	4.60 µH	12.7 mΩ	7.50 A	8.00 A	64.6 mW	3.18 mW	67.8 mW	7.15 K
✔	74438334022	WE-MAPI	3012	PDF	Single	2.20 µH	2.20 µH	100 mΩ	1.80 A	5.00 A	74.6 mW	25.0 mW	99.6 mW	15.1 K
✔	744778520	WE-PD	6033	PDF	Single	100 µH	99.0 µH	950 mΩ	650 mA	500 mA	4.19 mW	238 mW	242 mW	26.3 K

Buck Converter ✖

Reapply

PARAMETERS EDIT

Input	Output	Switch	Inductor	Diode
8.20 V 8.00-10.0 V	4.90 V 500 mA	200 kHz	40 % Single	0.30 V

DETAILS

I_{rms}	I_{max}	L_{opt}
≥ 500 mA	≥ 600 mA	50.5 µH

200KHz vs 2MHz

Buck Converter ✖

Reapply

PARAMETERS EDIT

Input	Output	Switch	Inductor	Diode
8.20 V 8.00-10.0 V	4.90 V 500 mA	2 MHz	40 % Single	0.30 V

DETAILS

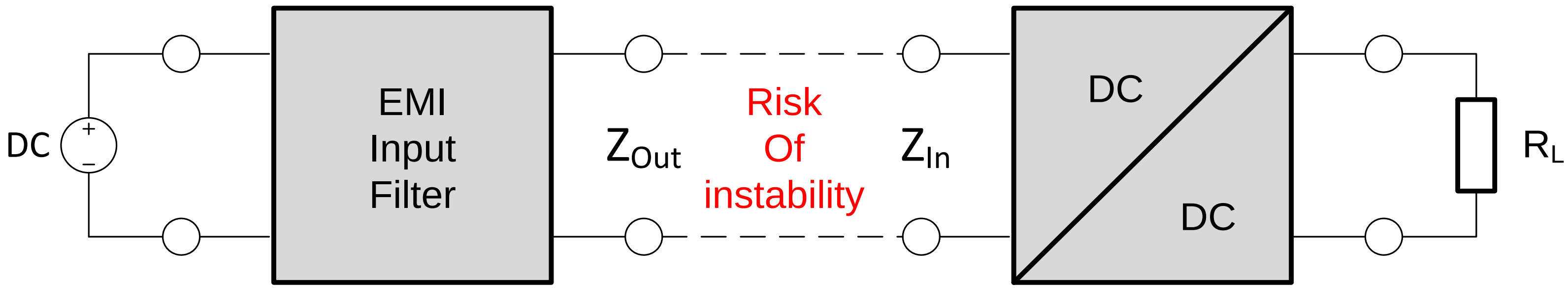
I_{rms}	I_{max}	L_{opt}
≥ 500 mA	≥ 600 mA	5.05 µH

Filters: Order Code ∋ 7443340470, 74438334022, 744778520 ✖ | Type = Single ✖

	Order Code	Series	Size	Spec	Type	L	L() @39...	$R_{DC,typ}$	I_R	I_{sat}	P_{AC}	P_{DC}	P_{TOT}	ΔT
✔	7443340470	WE-HCC	8070	PDF	Single	4.70 µH	4.60 µH	12.7 mΩ	7.50 A	8.00 A	17.7 mW	3.18 mW	20.9 mW	2.70 K
✔	74438334022	WE-MAPI	3012	PDF	Single	2.20 µH	2.20 µH	100 mΩ	1.80 A	5.00 A	20.5 mW	25.0 mW	45.5 mW	7.90 K
✔	744778520	WE-PD	6033	PDF	Single	100 µH	99.0 µH	950 mΩ	650 mA	500 mA	537 µW	238 mW	239 mW	26.1 K

PRACTICAL DC TO DC CONVERTER INPUT FILTER DESIGN CONSIDERATIONS

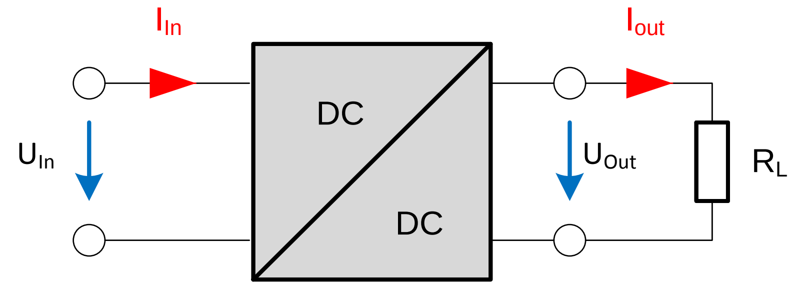
Oscillation At Converter Input



- **Adding an input EMI filter to converter input can cause oscillation at converter input**
- **Problem could arise : the converter no longers meets response specification and may even become unstable!!! Why????**

(DC) Input Impedance Of Converter (an explanation)

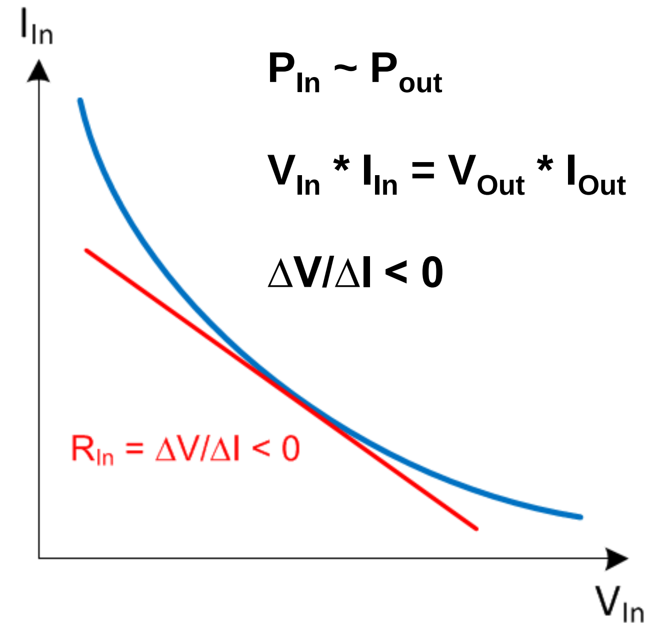
- **Input and output power of converter is near the same (efficiency drop)**
- **Under stable conditions output power is constant**
- **If the input voltage falls, the input current increases**
- **Voltage-current line has a negative slope**



$$P_{In} \sim P_{out}$$

$$V_{In} * I_{In} = V_{Out} * I_{Out}$$

$$\Delta V/\Delta I < 0$$

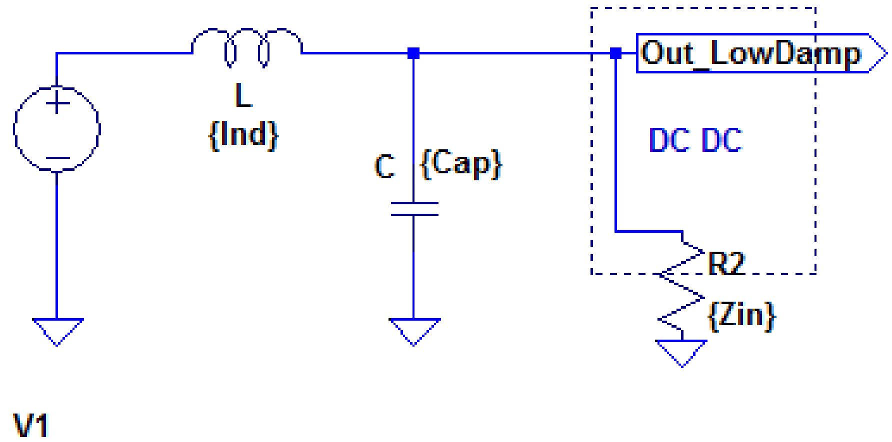


$\boxed{V_{In} \downarrow} \longrightarrow \boxed{I_{In} \uparrow} \longrightarrow \boxed{R_{In} < 0}$

NEGATIVE DC INPUT RESISTANCE

What could happen?

- **Simplified model**



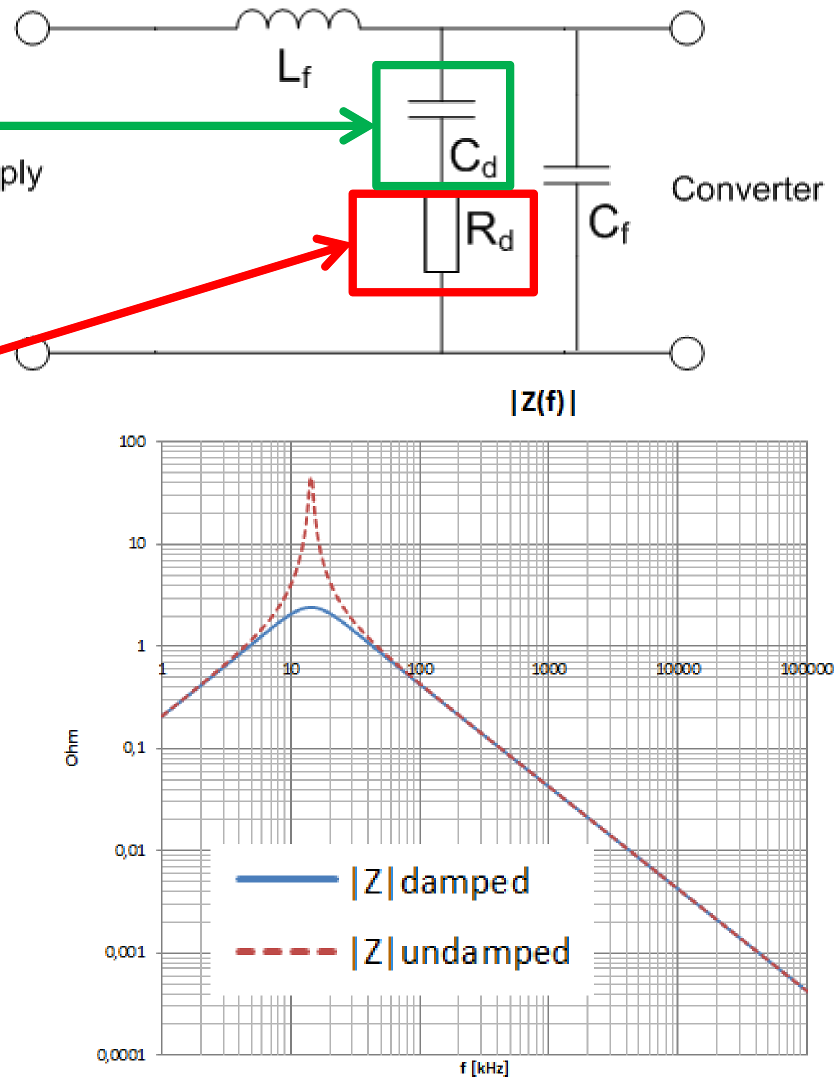
- **R_L: Rdc of the inductor**
- **ESR: serie resisistance of the capacitor**
- **Input impedance of the buck converter (looking negative – see previous slide)**

- **This is a LC filter loaded by a negative resistance!!!!!**

- **NICE WAY TO CREATE OSCILLATORS**

Damping Input Filter

- **Damping capacitor C_d blocks DC current**
- **Damping resistor R_d reduces dip magnitude of filter at resonant frequency f_0**

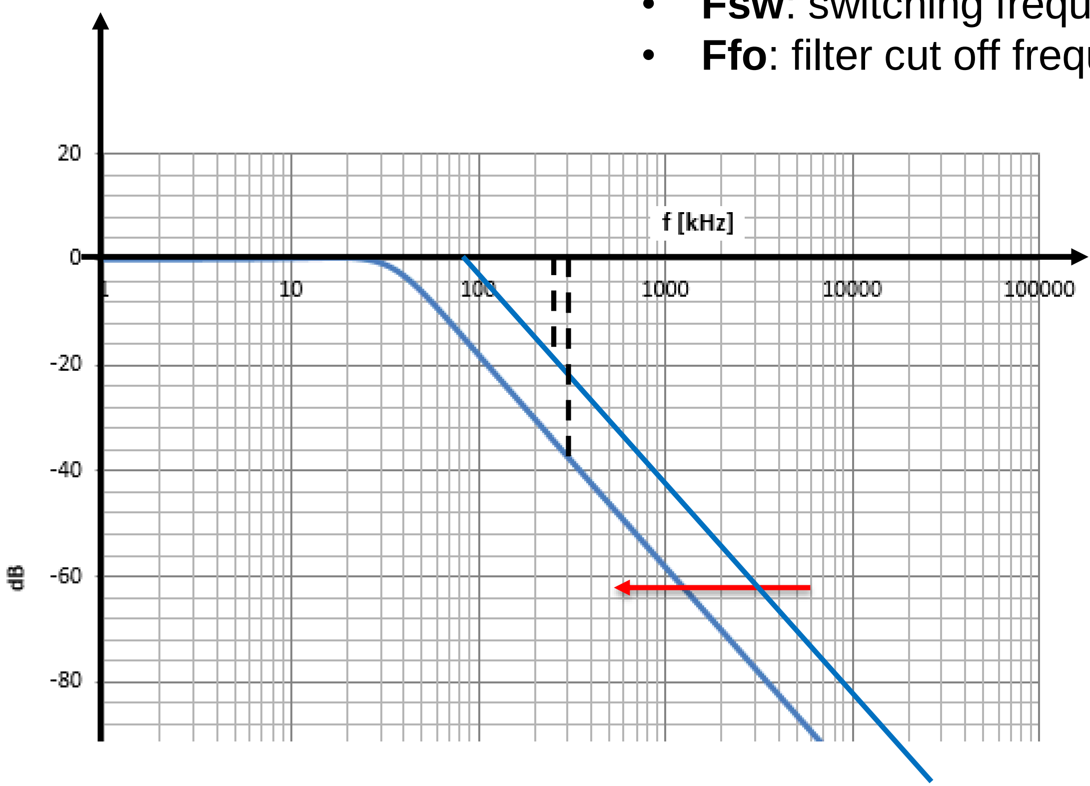


Calculating Input Filter Components values

Gain-Bandwith product:
Give the right filter cutoff freq to have the attenuation required with the choosed filter topology (order)

$$f_{co} = f_{sw} \cdot 10^{\left(\frac{-A_{db}}{n \cdot 20}\right)}$$

- **Adb**: attenuation required
- **n**: filter order
- **Fsw**: switching frequency
- **Ffo**: filter cut off frequency



Our design:
Adb: 32 dbuV
2nd order filter
Fsw: 150kHz

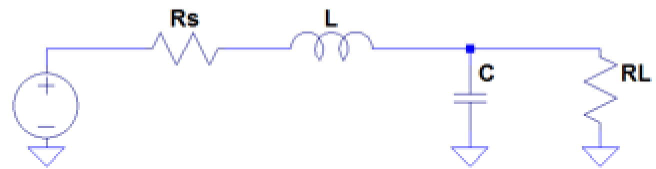
F_{0calc}: 23,77kHz

Calculating Input Filter Components values

Selection of the L and C value:

Different values for L and C occurs. In our design we can choose as follows:

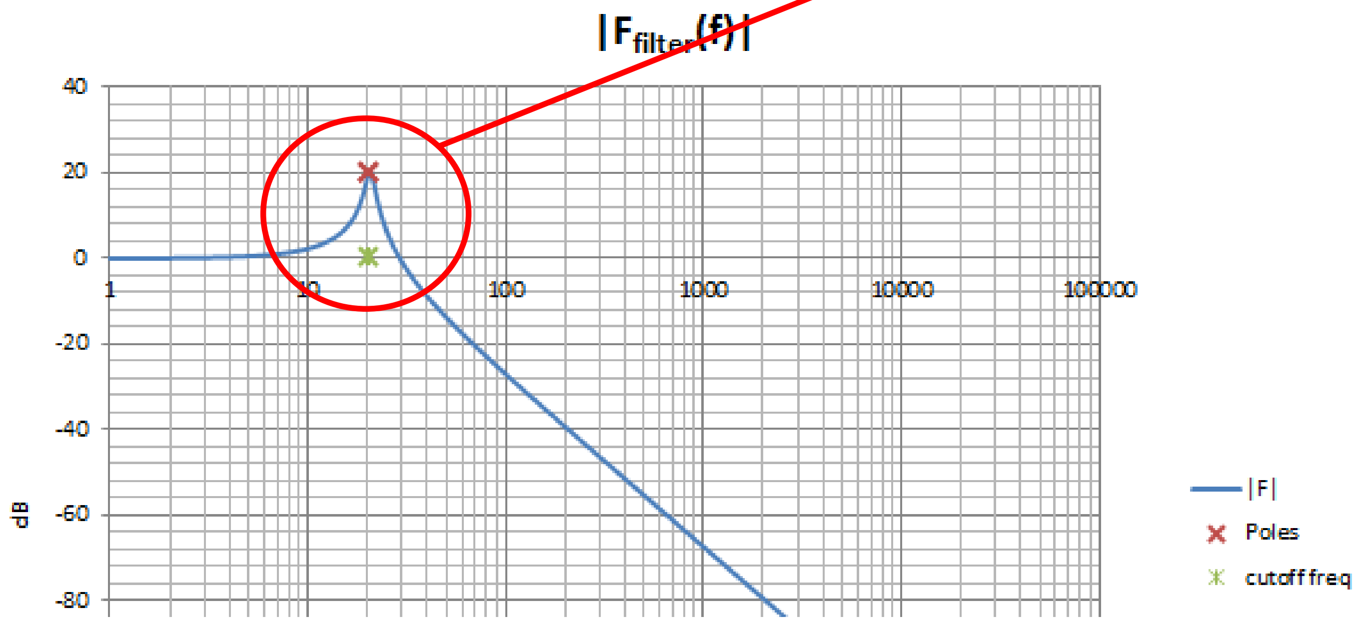
C	2,2	uF
L	27	uH



In order to have

$$f_0 = \frac{1}{2 \cdot \pi \cdot \sqrt{(L \cdot C)}} \approx 21\text{kHz}$$

(20,65kHz calculated)



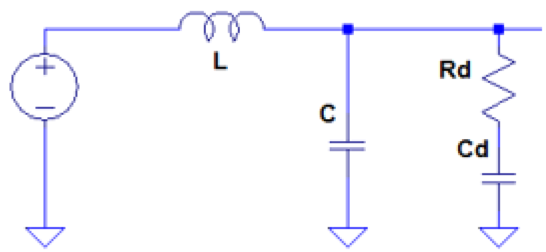
Calculating Input Filter Components values*

1) Calculate damping capacitor $C_d = \mathrm{n} \cdot Cf \qquad with\ n = 4\ or\ 6$

2) Calculate damping Resistor $$R_d = \sqrt{\frac{L_f}{C_f}} \frac{(n+1)}{2n} \sqrt{\frac{2n^2(4+n)}{(2+n)(4+3n)}}$$

Keeping the same values of undamped filter, we can add an Rd and a Cd as follows:

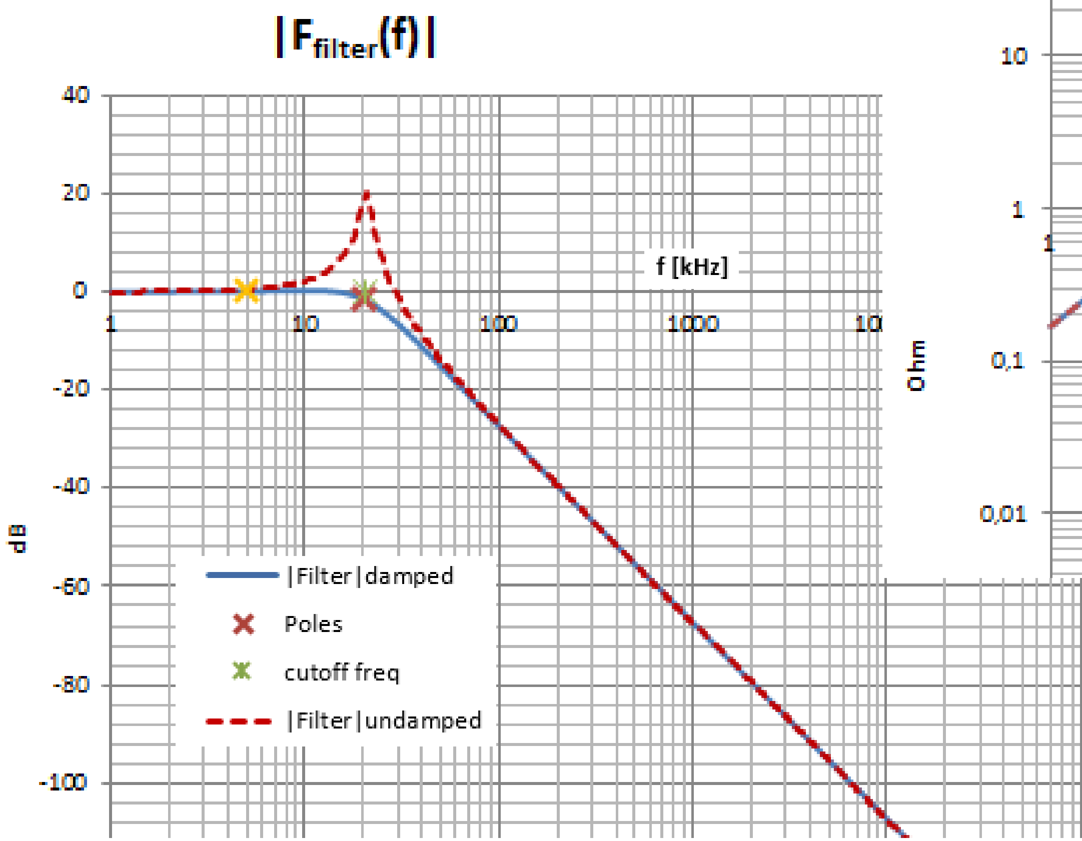
Rd	3,57548	Ω
Cd	8,8	uF
C	2,2	uF
L	27	uH
n	4	

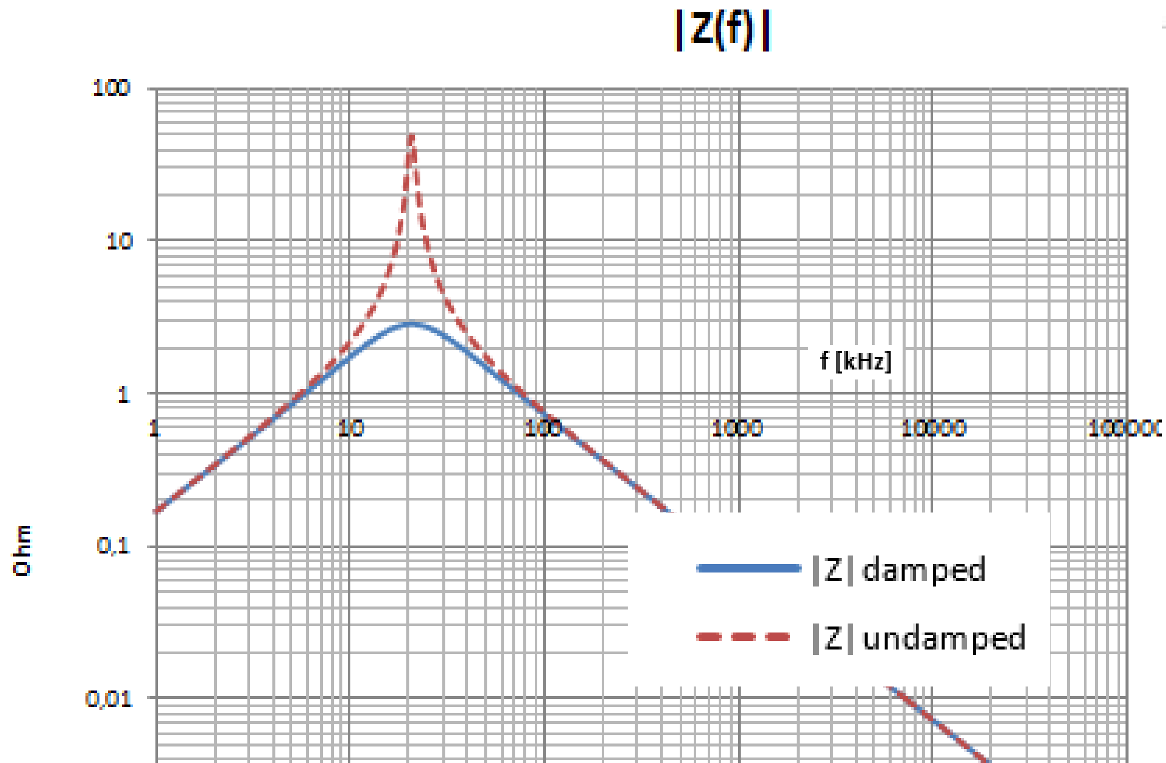


*See Input Filter Design for Switching Power Supplies, Michele Sclocchi – National App Note 2010

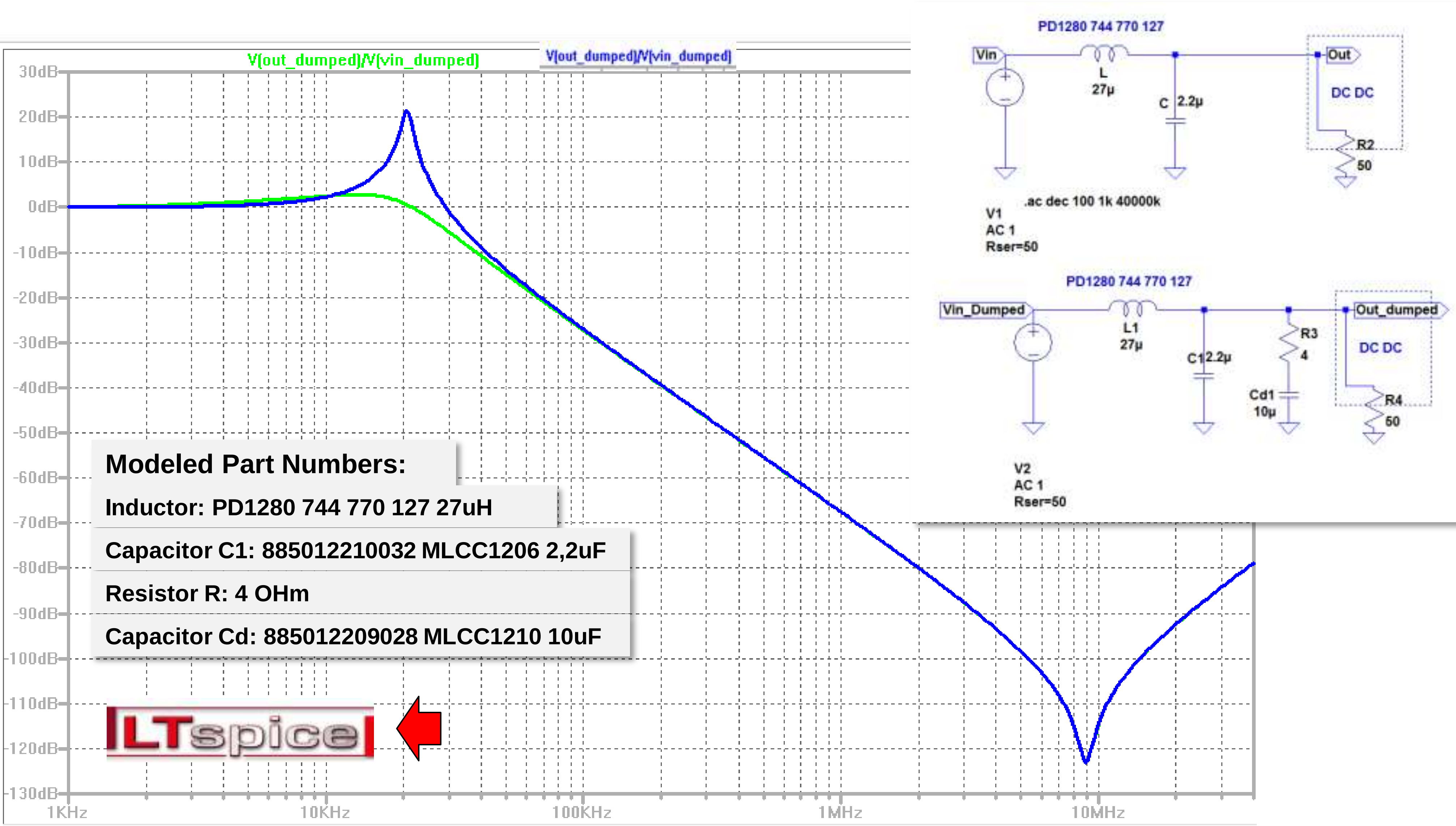
Calculating Input Filter Components values

Damping the filter:





Check using LT Spice Simulation



Modeled Part Numbers:

Inductor: PD1280 744 770 127 27uH

Capacitor C1: 885012210032 MLCC1206 2,2uF

Resistor R: 4 OHm

Capacitor Cd: 885012209028 MLCC1210 10uF

SEPIC Converter Example

Thank you

Any Questions