WÜRTH ELEKTRONIK

Wurth Electronics (UK) Ltd

Practical EMI Filter Design Considerations

22 JAN 2018

Presented by

Gopi Patel
Field Application Engineer
Wurth Electronics UK

https://www.rohde-schwarz.com/uk/seminars___trainings/uk_ireland_seminar_programme/uk-ireland-seminar-programme_230215.html

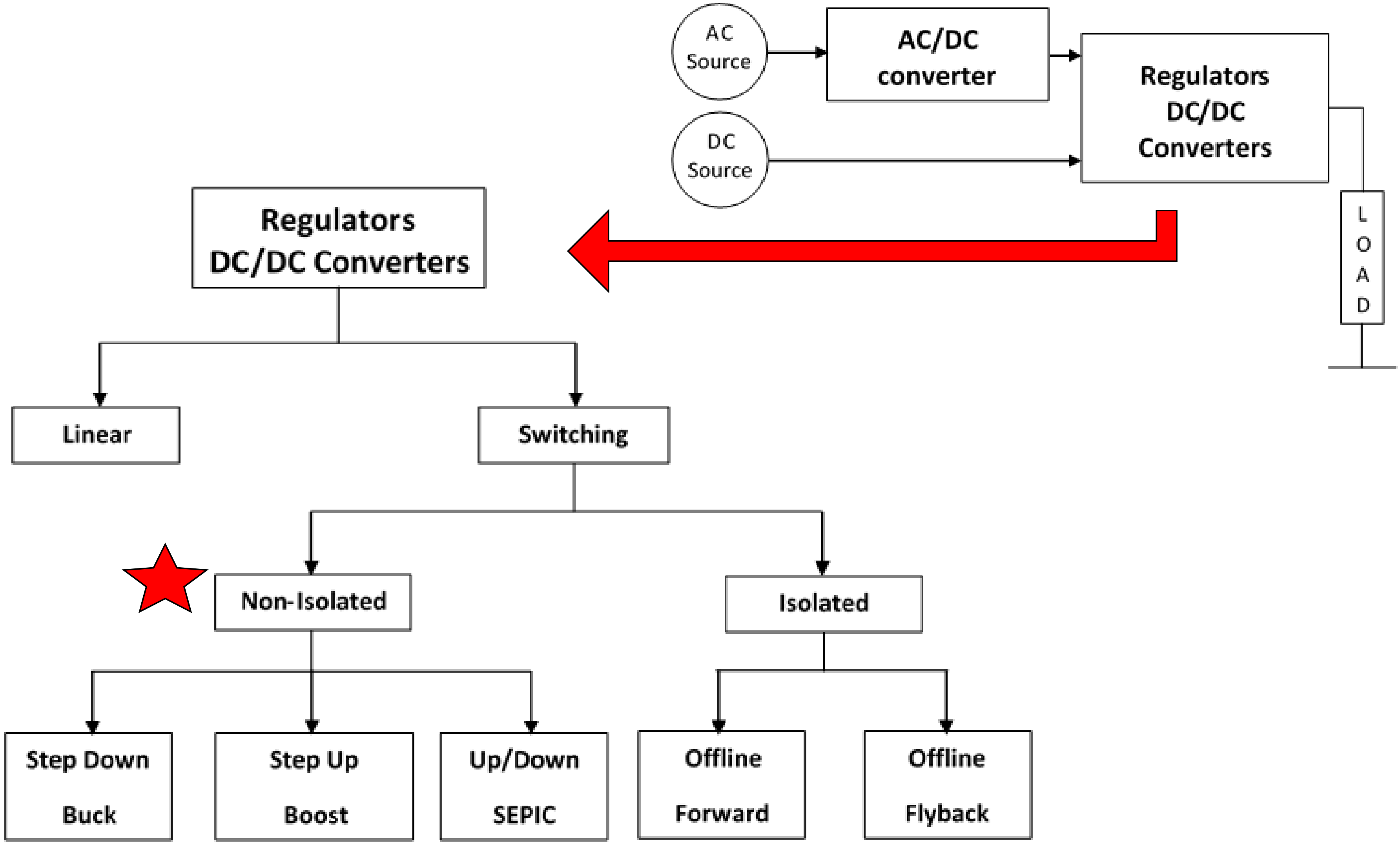
Agenda

- **DC/DC Converter Topologies –** Buck, boost & SEPIC
- **Causes of CM & DM Emissions** – LT Spice
- **Efficiency and Losses –** Core, Copper and AC

- **Criteria for selecting Inductor and Capacitor –** DC Bias
- **Practical Input Filter Design –** LC Filter
- **REDEXPERT –** Interactive component selection

- **DC/DC Converter Topologies –** Buck, boost & SEPIC
- **Causes of CM & DM Emissions** – LT Spice
- **Efficiency and Losses –** Core, Copper and AC
- **Criteria for selecting Inductor and Capacitor –** DC Bias
- **Practical Input Filter Design –** LC Filter
- **REDEXPERT –** Interactive component selection

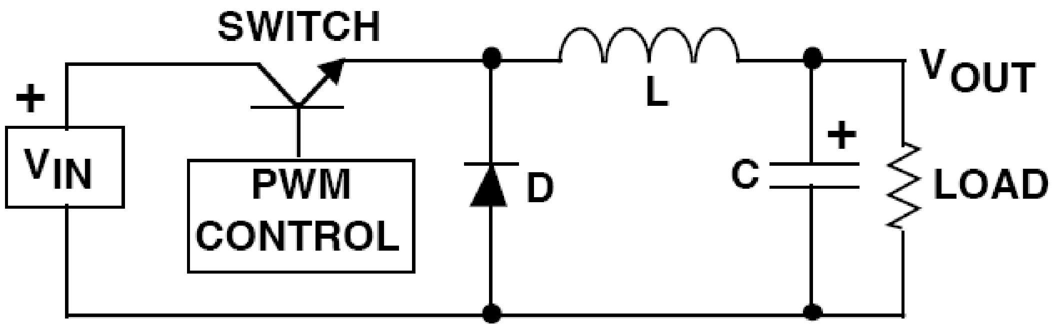
DC to DC Converter Topologies

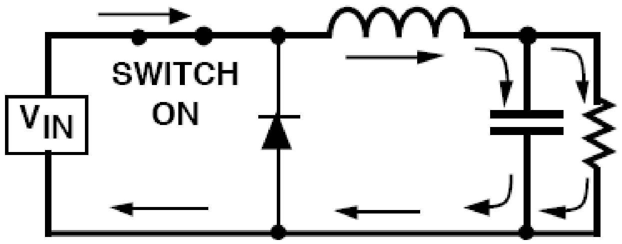


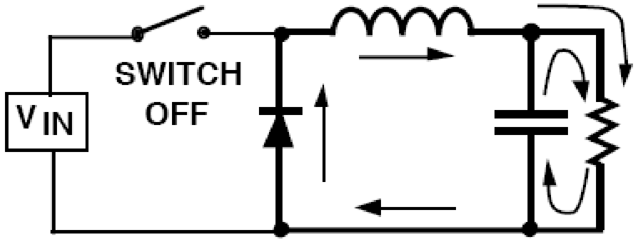
The Buck Converter

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)



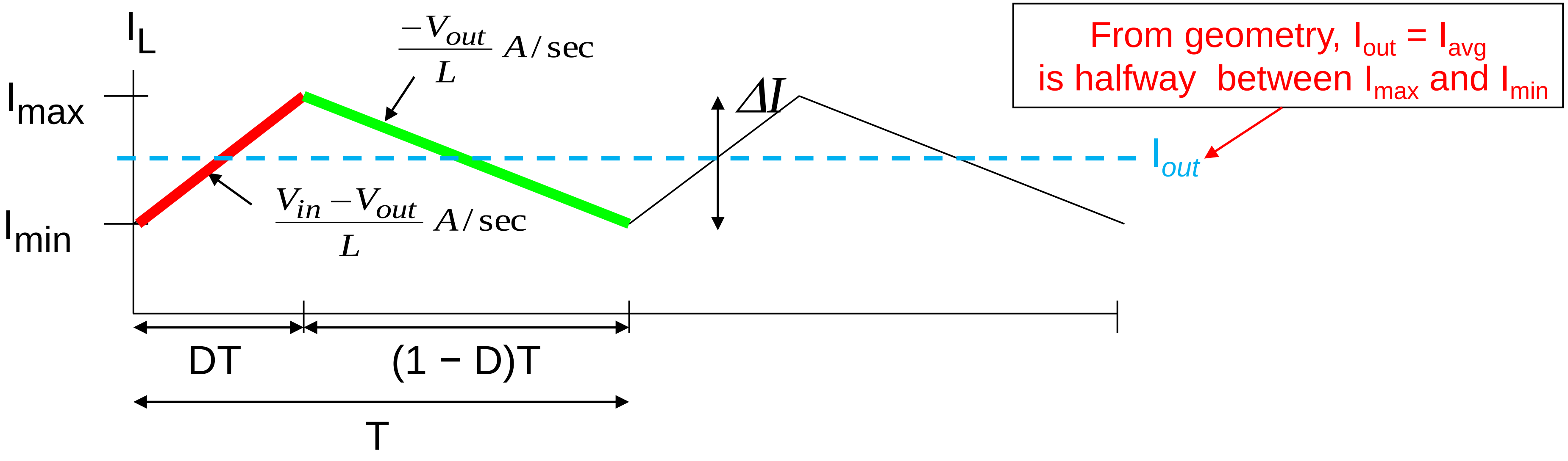




The Buck Converter – Ripple Current

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

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



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

The Buck Converter – Inductance Value

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

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

Re-write as

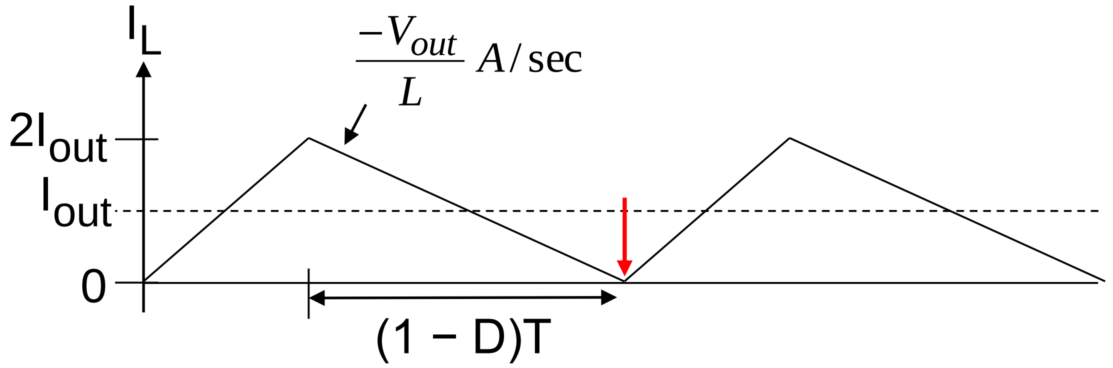
$$L = \frac{V_{out} \cdot (1 - D)}{f_{switch} \cdot r \cdot I_{out}}$$

Terms:

- ✓ *D* = *Duty cycle*
- ✓ *T* = *Time period of a cycle*
- ✓ *r* = *Ripple % of o/p current*
- ✓ *ΔI* = *Maximum ripple current*
- ✓ *Fs* = *Switching Frequency*

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

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



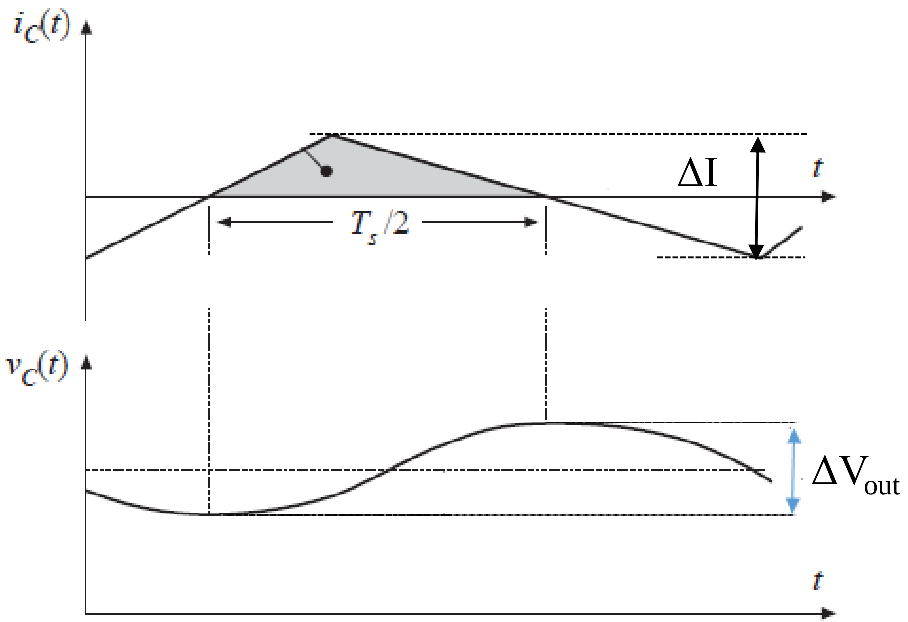
The Buck Converter – Capacitance Value

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

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

Remember:

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



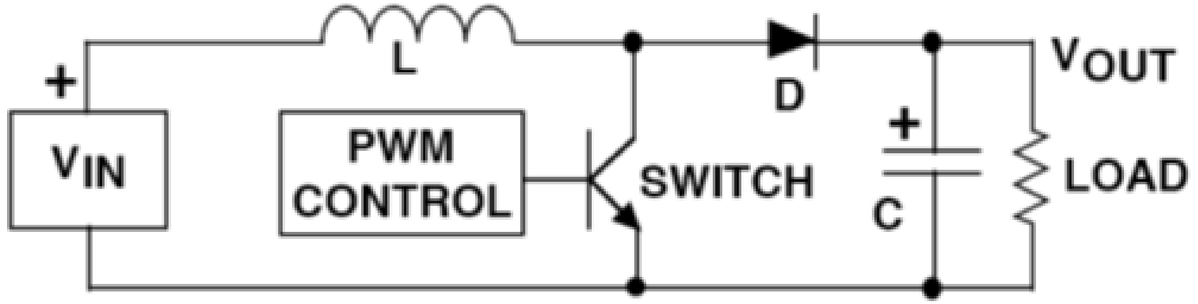
- **Consider dynamic response**
  - **Overshoot, Undershoot**
  - **Damping, Leakage**
- **Think of ripple rating**
- **Estimate max ESR**
- **Don't forget dissipation factor**

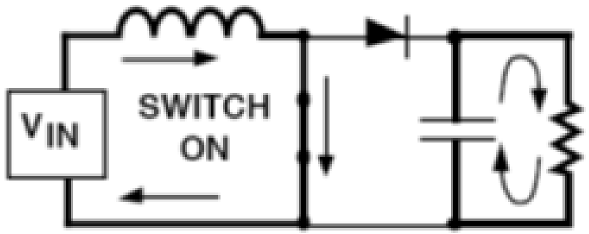
Terms:

- ✓ *ΔV_{OUT} = Maximum output tipple voltage.*
- ✓ *ΔI = Maximum ripple current.*
- ✓ *ESR = Equivalent Series Resistance of C.*
- ✓ *Fs = Switching Frequency.*

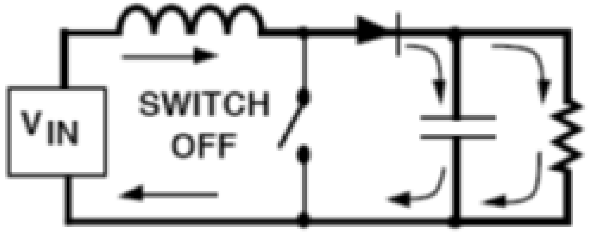
The **Boost** Converter

- **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}



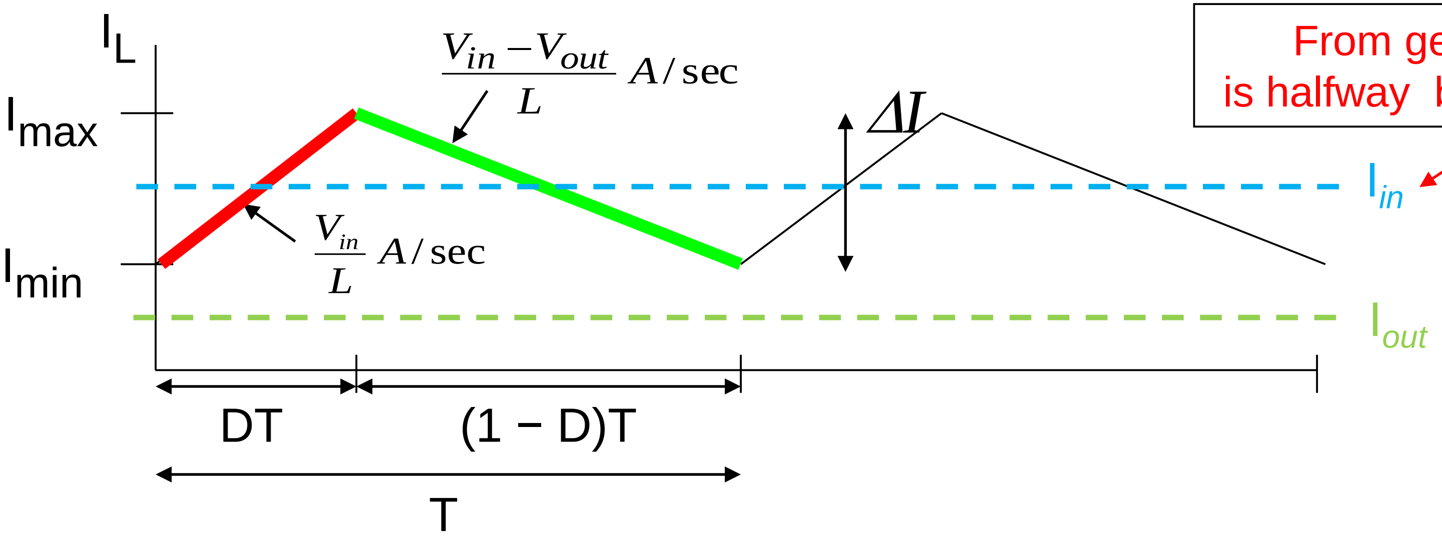
t_{OFF}

The Boost Converter – Ripple Current

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

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

From geometry, $I_{in} = I_{avg}$ is halfway between I_{max} and I_{min}



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

The Boost Converter – Inductance Value

WÜRTH ELEKTRONIK

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

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

Re-write as

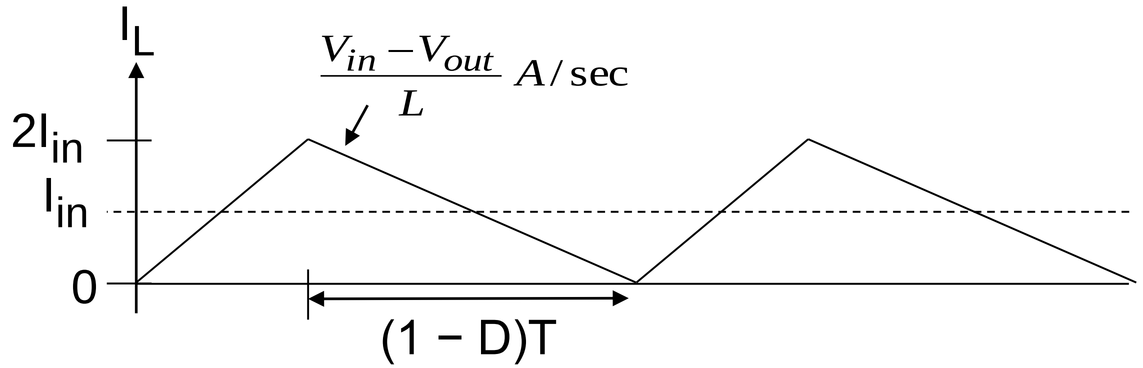
$$L = \frac{D \cdot V_{out} \cdot (1 - D)^2}{f_{switch} \cdot r \cdot I_{out}}$$

Terms:

- ✓ *D* = *Duty cycle*
- ✓ *T* = *Time period of a cycle*
- ✓ *r* = *Ripple % of o/p current*
- ✓ *ΔI* = *Maximum ripple current*
- ✓ *Fs* = *Switching Frequency*

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

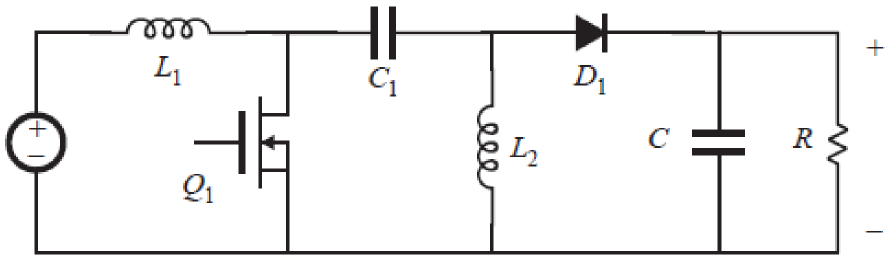
$$L_{Critical} > \frac{V_{out} \cdot D_{0.33} \cdot (1 - D_{0.33})^2}{2I_{out\_min} \cdot f_{switch}}$$

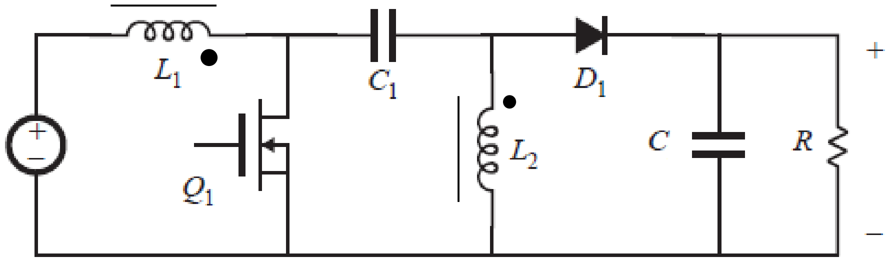


The SEPIC Converter

- **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

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





- **DC/DC Converter Topologies –** Buck, boost & SEPIC
- **Causes of CM & DM Emissions** – LT Spice
- **Efficiency and Losses –** Core, Copper and AC

- **Criteria for selecting Inductor and Capacitor –** DC Bias
- **Practical Input Filter Design –** LC Filter
- **REDEXPERT –** Interactive component selection

Causes of EM Emissions – Where to look ??

WÜRTH ELEKTRONIK

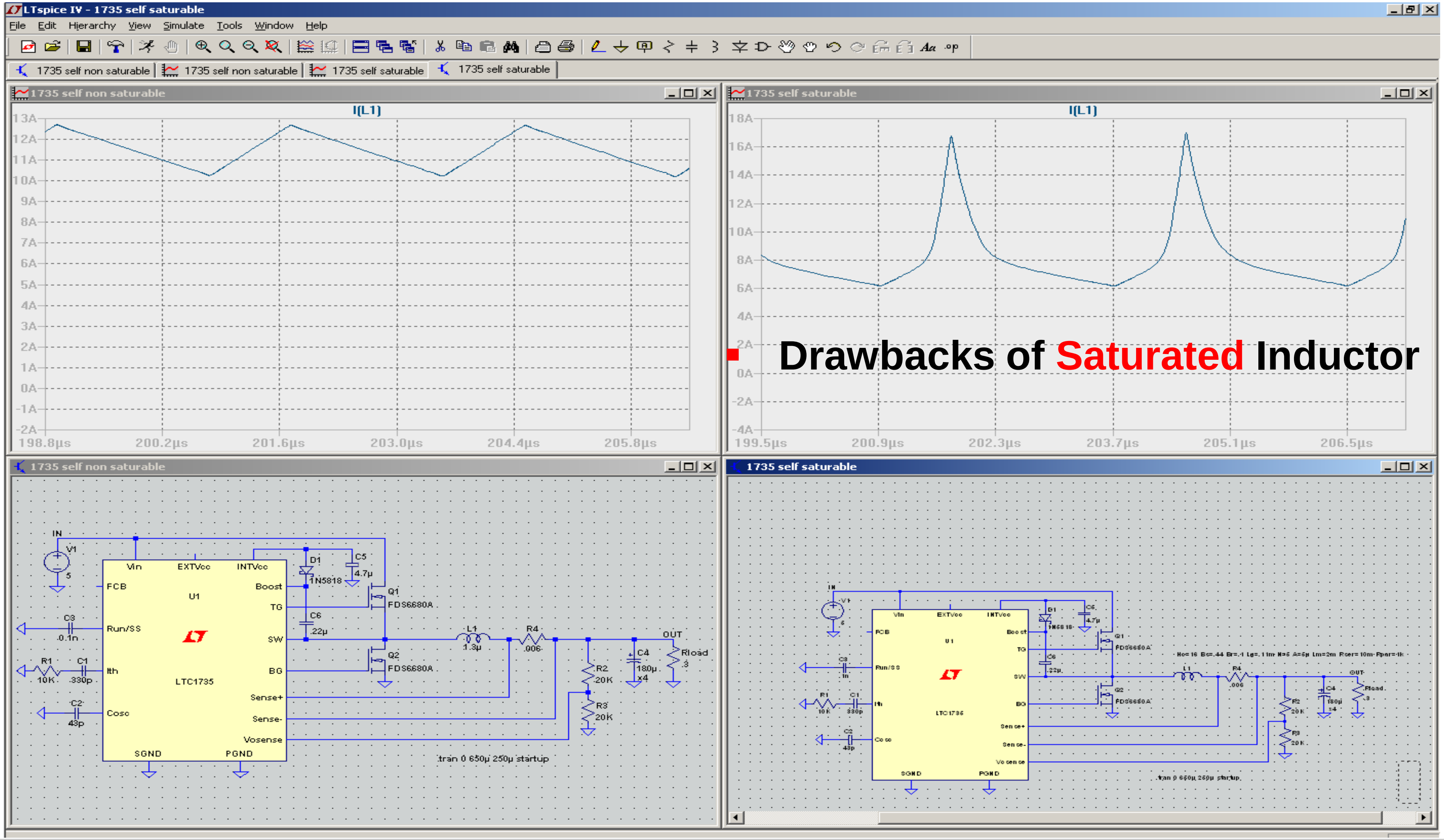
- ✓ There are many ways unwanted “Electromagnetic” waves can escape

- ✓ Circuit that switches fast can become source of noise
- ✓ Every wave have harmonics, except pure sinusoidal
- ✓ Square wave have infinite number of ODD harmonics

- ✓ Differential noise is caused by flow of circuit current
- ✓ Common mode noise is mainly due to parasitic / stray capacitance

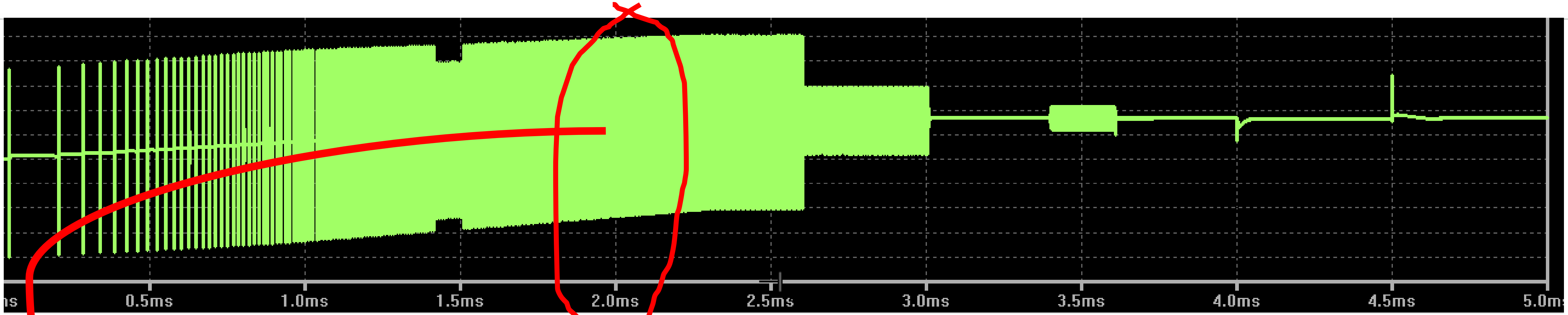
- ✓ Leakage inductance of transformer
- ✓ Track length of ¼ or Half wavelength
- ✓ Earthing, PCB Ground or power plane
- ✓ MCU or FPGA – Clock, Data bus, I^2C and SPI …
- ✓ Loose cable – Ethernet, HDMI, RS485, CAN, Mains …
- ✓ Metallic coupling – enclosure, connector, cover, heatsink …
- ✓ LCD – Processor, touch screen, frame, cable, connector …

Causes of EM Emissions - Wrong or Missing Filter ??

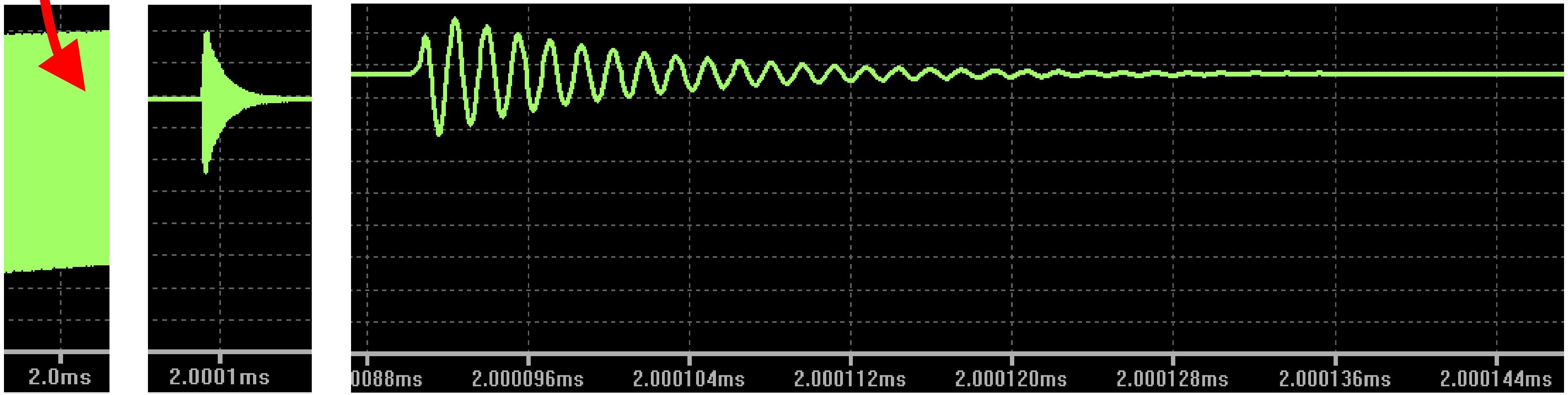


- Drawbacks of Saturated Inductor

Causes of EM Emissions → Rectangular + Sine wave = Ringing



Buck Filtering Real Time.asc



Buck Filtering Real Time.asc

- **DC/DC Converter Topologies –** Buck, boost & SEPIC
- **Causes of CM & DM Emissions** – LT Spice
- **Efficiency and Losses –** Core, Copper and AC
- **Criteria for selecting Inductor and Capacitor –** DC Bias
- **Practical Input Filter Design –** LC Filter
- **REDEXPERT –** Interactive component selection

Efficiency - Importance

WÜRTH ELEKTRONIK

Advantages of Highly Efficient Design

- ✓ Smaller size
- ✓ Lower costs
- ✓ Higher reliability
- ✓ Longer battery life
- ✓ Low thermal losses
- ✓ Better performance
- ✓ Longer operating life
- ✓ Higher power density
- ✓ Reduced maintenance
- ✓ Less cooling, no fan, small heatsink

- ❑ Difficult to copy
- ❑ Brand reputation
- ❑ Sustainable design
- ❑ Customer satisfaction
- ❑ Competitive advantage
- ❑ "Green" environmentally friendly

$$P = I^2 RT \quad ??$$

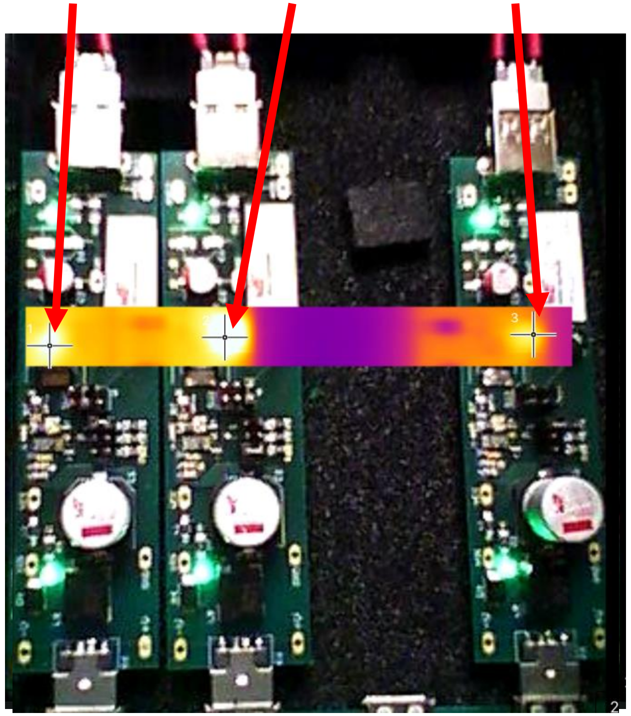
A small efficiency increase

greatly reduce losses !!

No Fan – No bulky heat sink

INDUCTOR LOSSES

T1 = 58°C T2 = 69°C T3 = 50°C



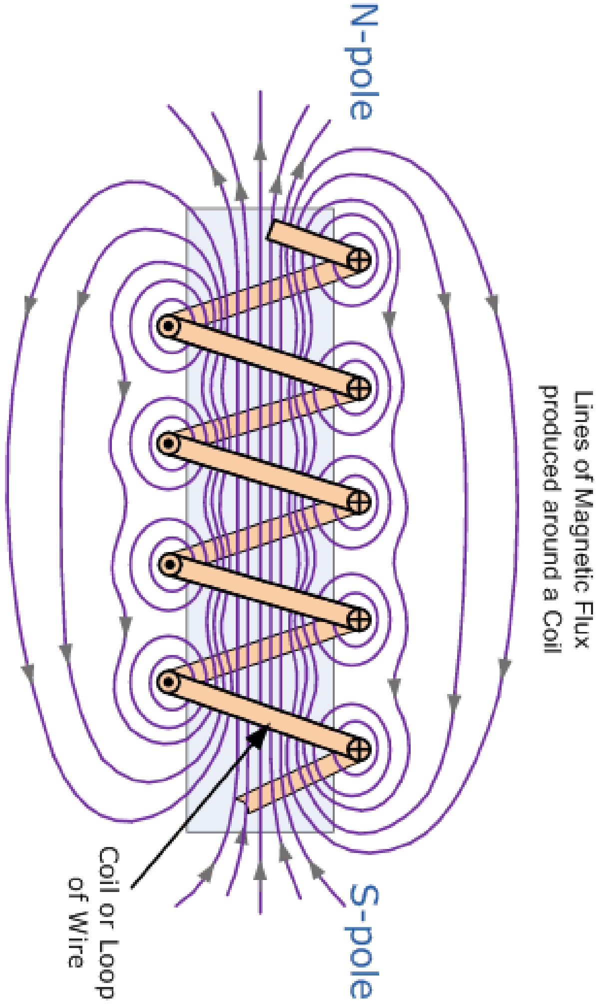
What causes self-heating of the inductor ?

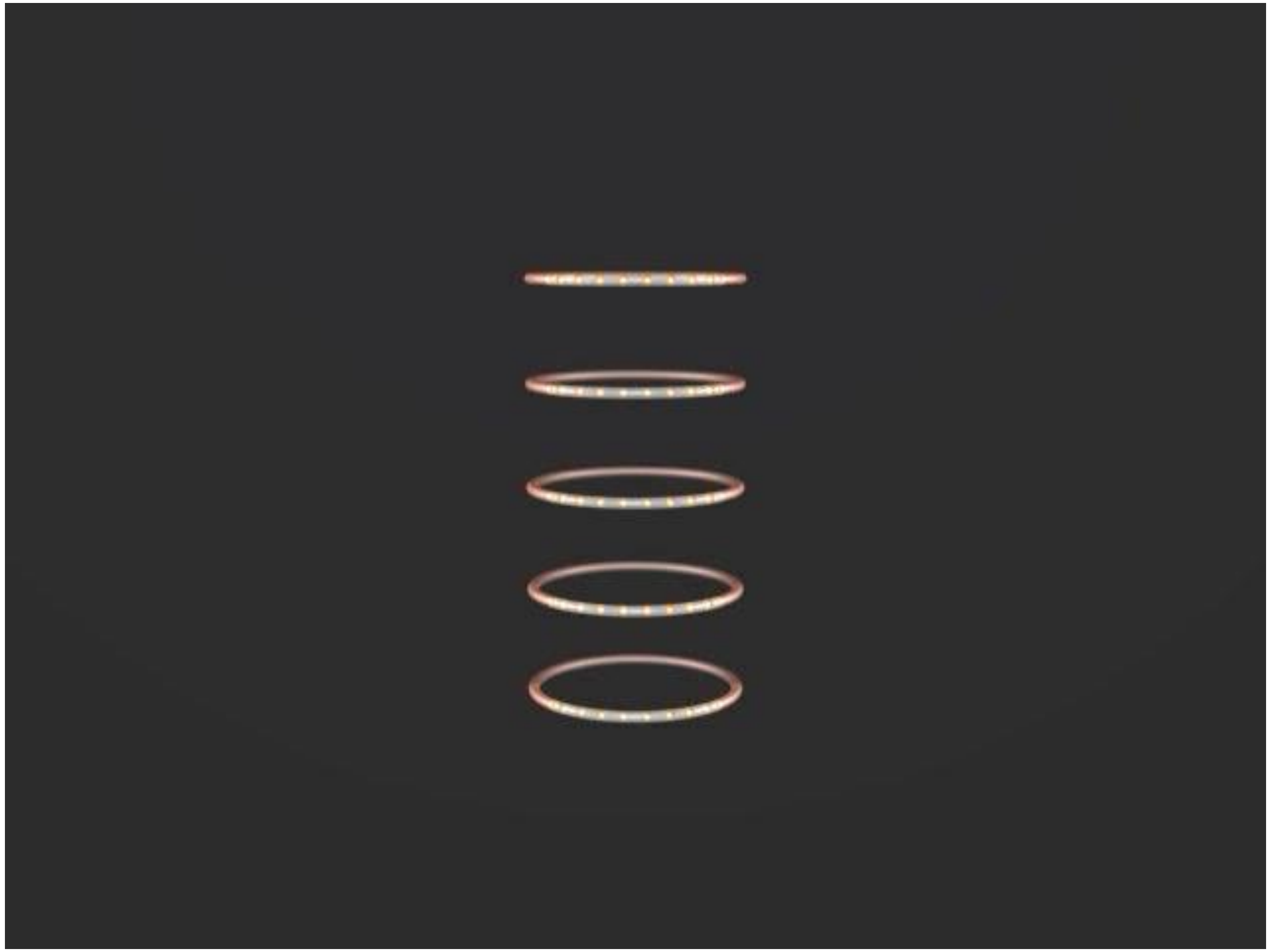
- **Can you estimate ?**
- **Can you reduce ?**

<u>TYPE of LOSSES</u>

- Core Losses – *Eddy, Flux, Field, µ, etc.*
- Copper Losses – *RDC, CSA, Current, Length, Litz*
- Switching Losses – *RDS, ON Time, F, V*
- Leakage Losses – *Snubber, reflections*
- AC Losses – *F, DS%, Waveform, Skin, Proximity*
- *EMI Radiations – CM, DM, C, R, shielding*

Magnetic Fields – The magnetic field



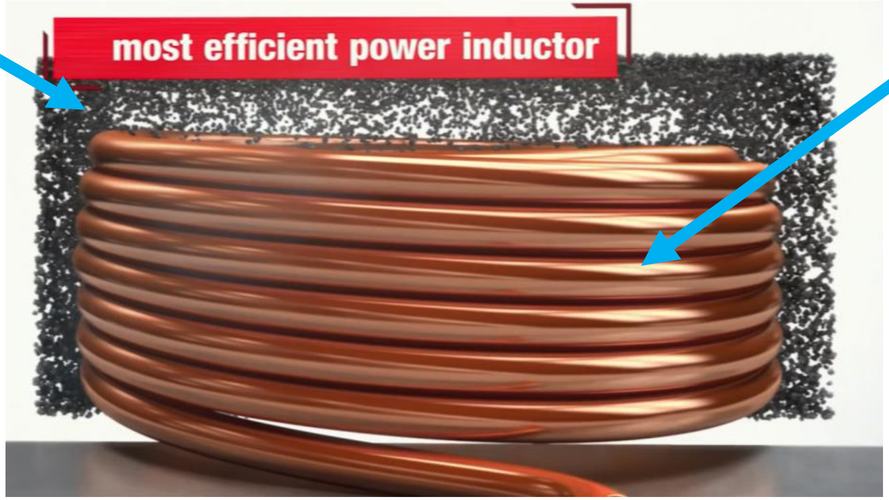


INDUCTOR LOSSES

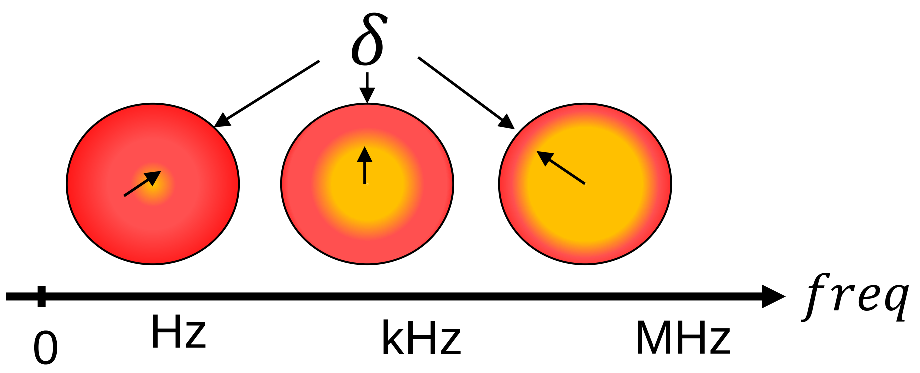
$$Ptotal = Pcore + Pcopper$$

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 AC Losses, Skin effect (River Rafting)

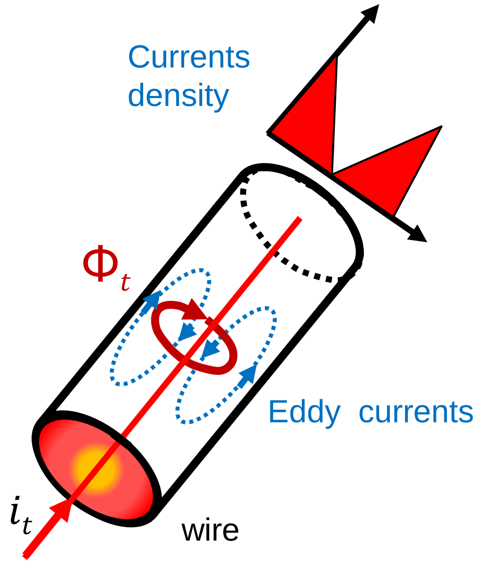


$$\delta = \sqrt{\frac{2 * \rho}{w * \mu}}\, mm \qquad \delta = \frac{76}{\sqrt{f}}\, mm \quad @\ 100°C$$

<u>For Copper</u>

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

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



Terms:
δ = skin depth
ρ = resistivity
w = angular frequency 2pf
μ = permeability

INDUCTOR LOSSES : Copper AC losses, Skin effect

Flat Wire vs. **Round Wire**

- ✓ Cross section of both wires = $10mm^2$
- ✓ Flatwire has much more bigger surface
- ✓ Flat wire surface = $22mm^2$ / Round wire = $11mm^2$ S_{FLAT} =1.9 x S_{RUND}
- ✓ High frequency currents only uses the surface → Skin effect

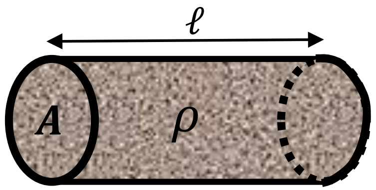
Flat wire has a higher surface,
thus less copper losses at higher frequencies !

WE Vishay

INDUCTOR LOSSES : DC Copper Losses

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

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



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

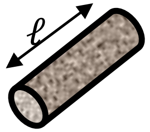
$R_{DC} \downarrow \Rightarrow Pcu \downarrow$

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

Optimization

ℓ=1m

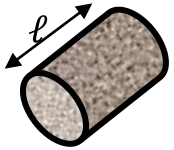
$\emptyset = 1mm$



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

$R_{DC} = 23m\Omega$

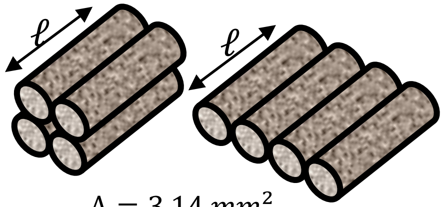
$\emptyset = 2mm$



$A = 3{,}14 \; mm^2$

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

$\Rightarrow 4 * 1mm \; \emptyset$

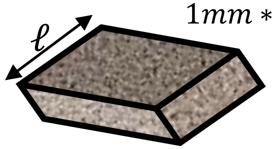


$A = 3{,}14 \; mm^2$

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

Flat wire

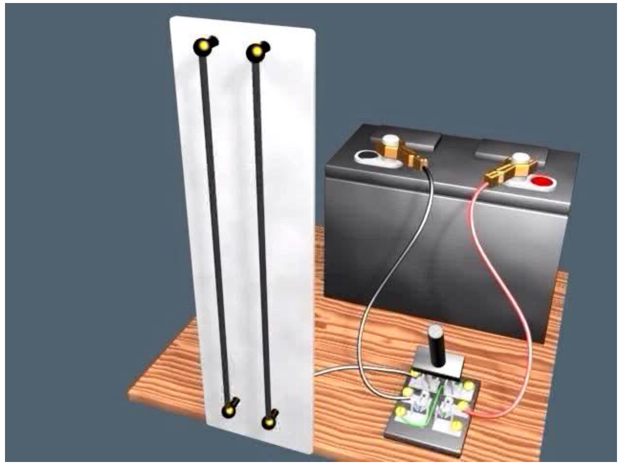
$1mm * 4mm$

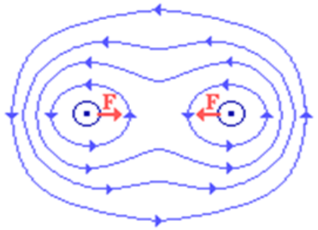


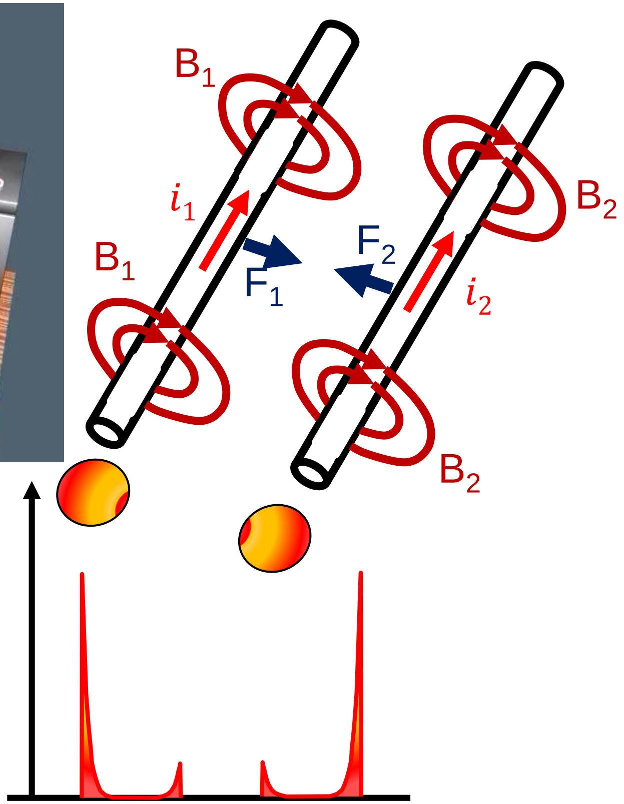
$A = 4 \; mm^2$

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

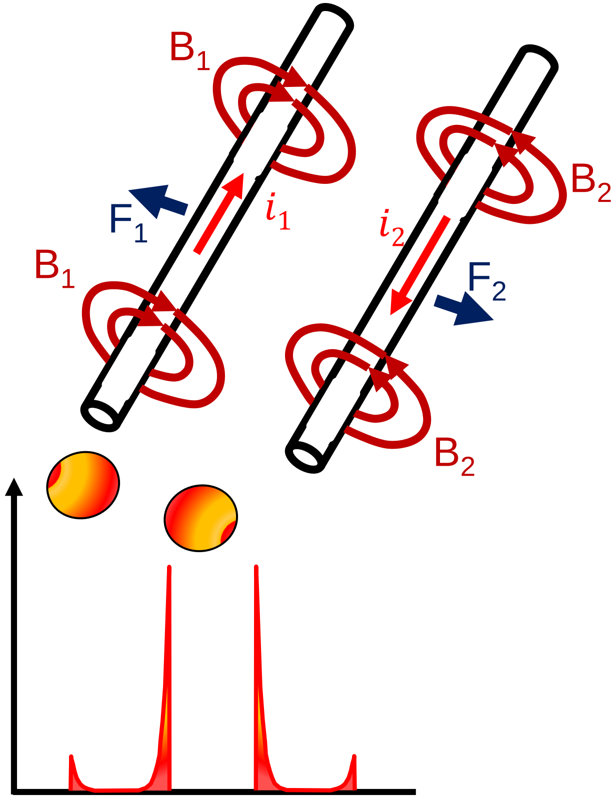
INDUCTOR LOSSES : AC Copper losses, Proximity effect



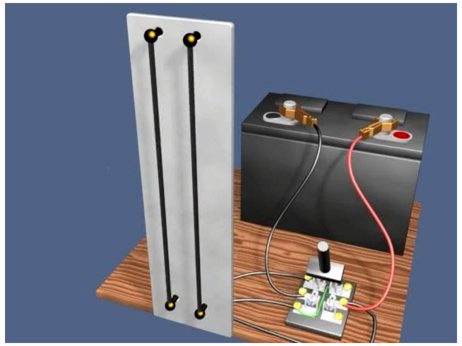


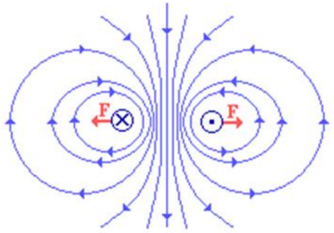


Current in same direction



Current in opposite direction





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

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

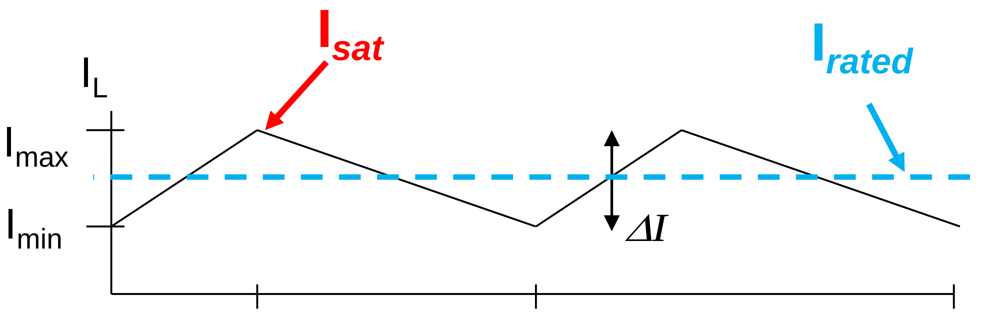
Like the skin effect, the distribution of current inside the wire is reduced

- **DC/DC Converter Topologies –** Buck, boost & SEPIC
- **Causes of CM & DM Emissions** – LT Spice
- **Efficiency and Losses –** Core, Copper and AC

- **Criteria for selecting Inductor and Capacitor –** DC Bias
- **Practical Input Filter Design –** LC Filter
- **REDEXPERT –** Interactive component selection

Inductor Selection Parameters

- **Inductor Parameters:**
  - Rated Current
  - Saturation Current
  - DC Losses - R_{DC}
  - AC Core Losses
  - AC Copper Losses
    - Proximity effect
    - Skin effect
  - Resonant Frequency / Q
  - Inductance vs Current Curve
  - Impedance vs Frequency Curve
  - Temperature rise vs Current Curve

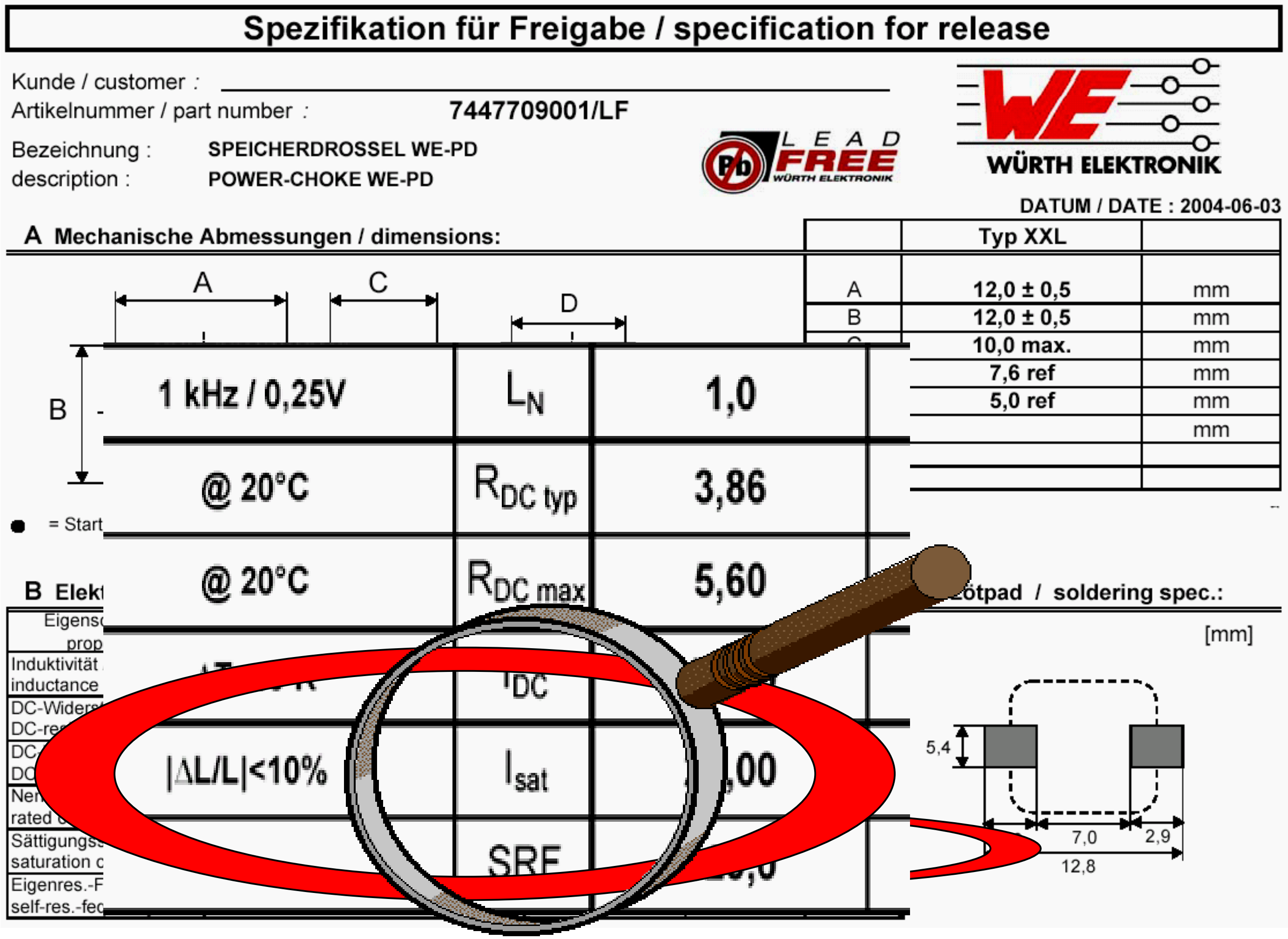


- **Other Criteria:**
  - Size
  - Approvals*
  - Availability
  - Shielding – E, B, H Fields
  - Material, manufacturing techniques

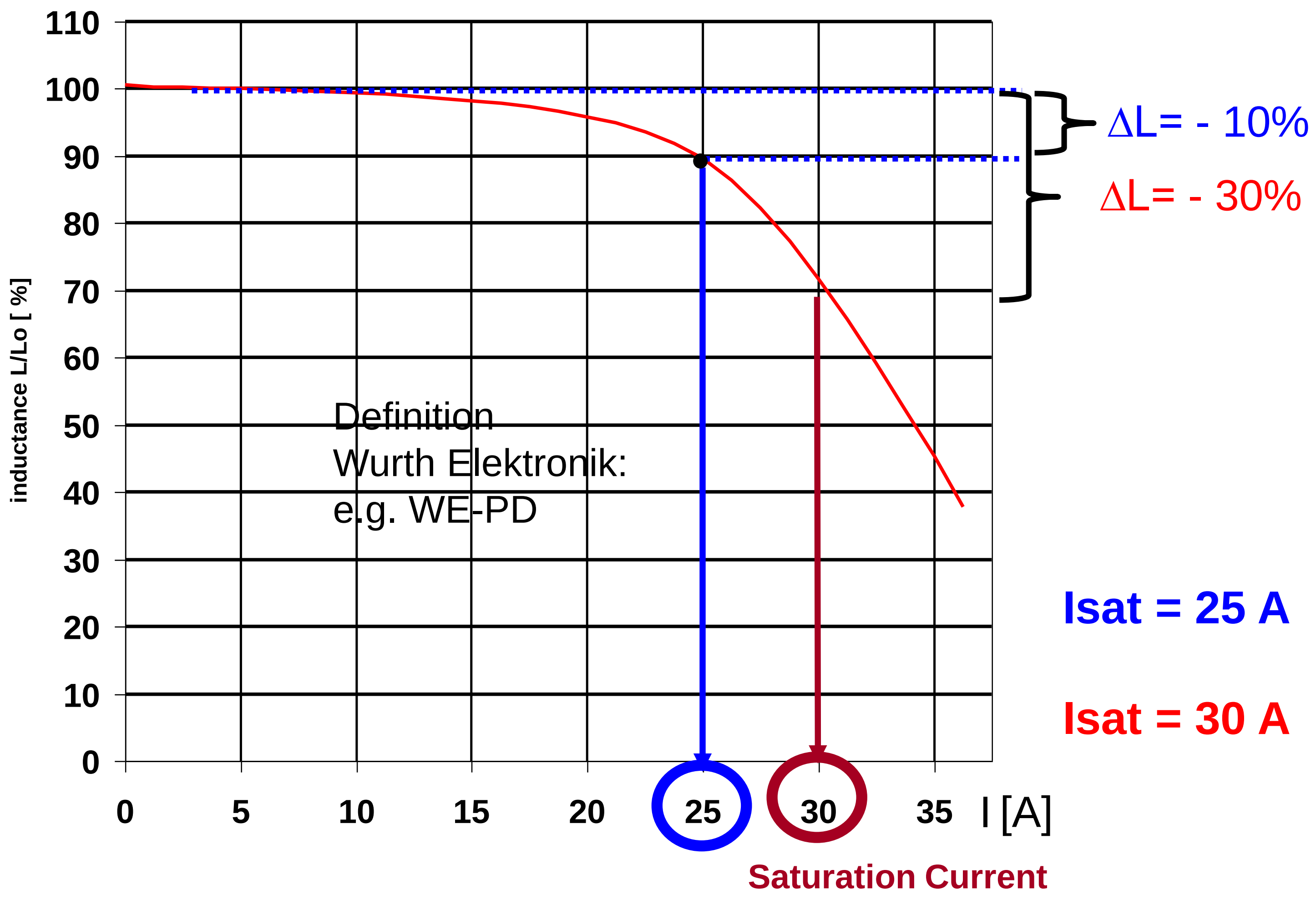
Inductor Selection Parameters – Saturation Current

WÜRTH ELEKTRONIK

Drop of the inductance value



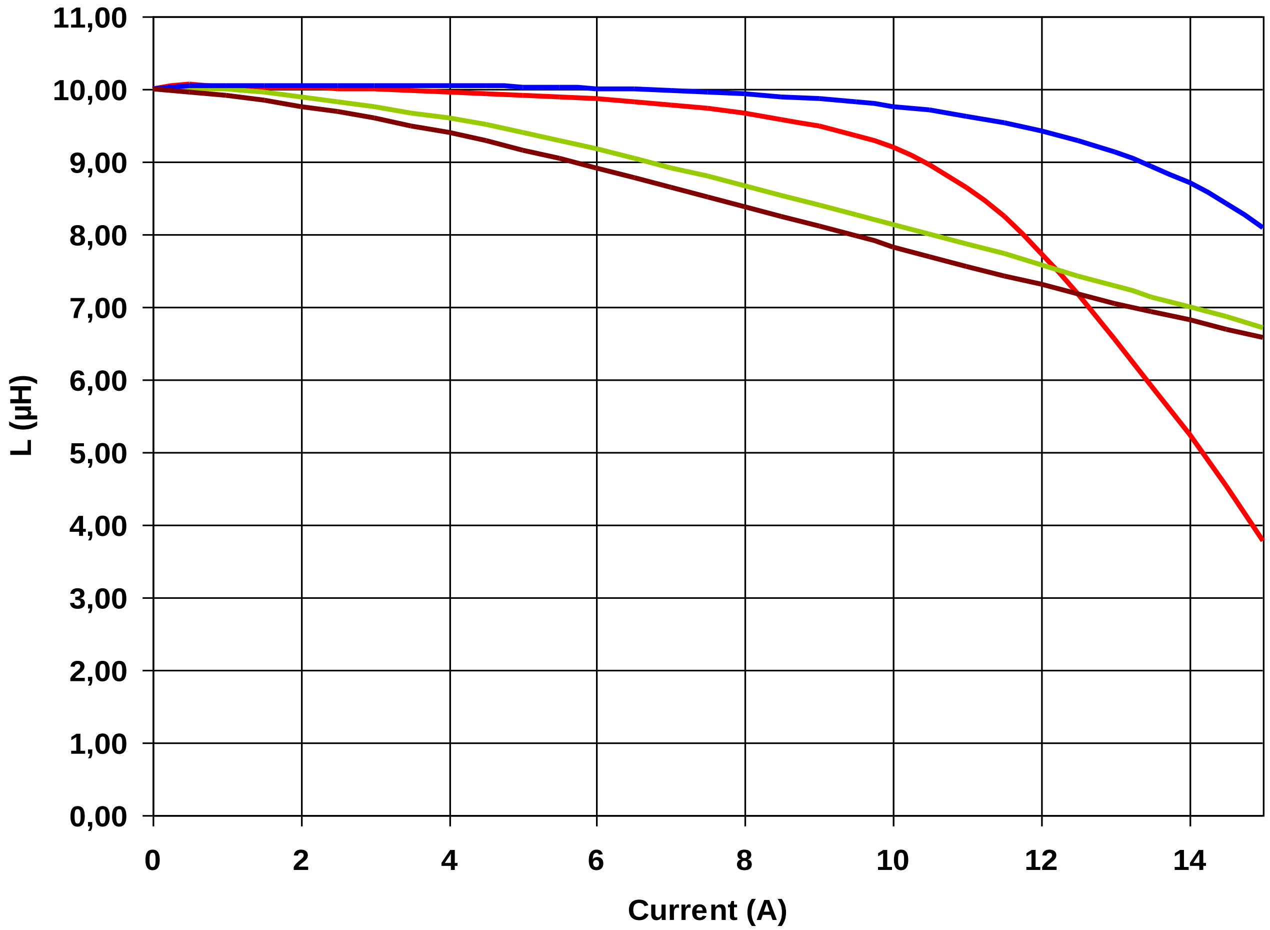
Inductor Selection Parameters – Saturation Current

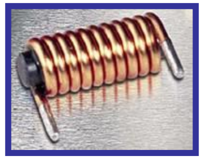


- the saturation current always refers to a certain inductance drop

Inductor Selection Parameters – Material

- **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 – Rated Current

=> Increase temperature with a DC current

Demo

Spezifikation für Freigabe / specification for release

Kunde / customer :

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

Bezeichnung : **SPEICHERDROSSEL WE-PD**

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

LEAD FREE WÜRTH ELEKTRONIK

WÜRTH ELEKTRONIK

DATUM / DATE : 2004-06-03

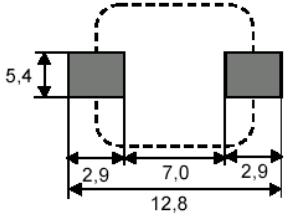
A Mechanische Abmessungen / dimensions:

	Typ XXL	
A	12,0 ± 0,5	mm
B	12,0 ± 0,5	mm

A C D

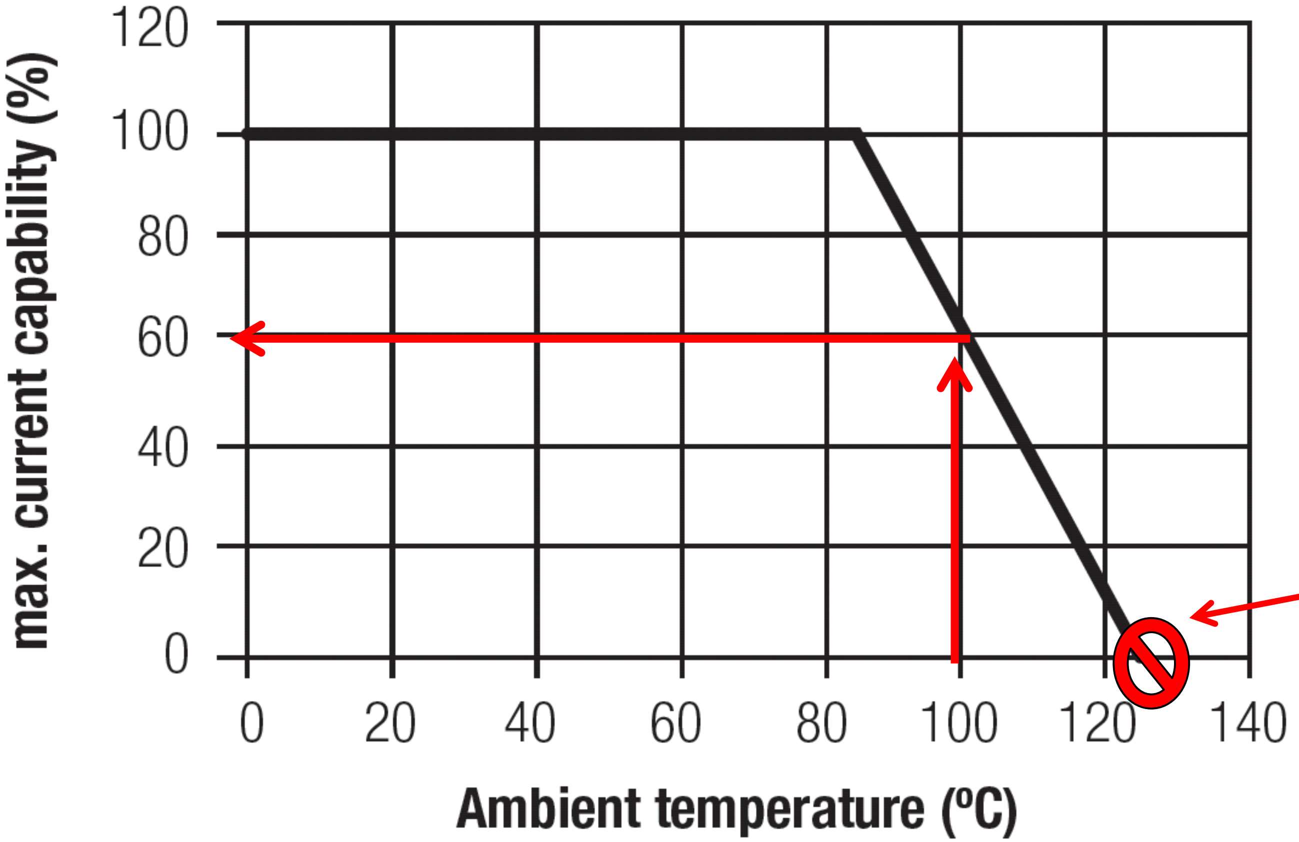
DC-Widerstand / DC-resistance	@ 20°C	$R_{DC\ max}$	5,60	mΩ	
Nennstrom / rated current	ΔT=40 K	I_{DC}	13,00	A	
Sättigungsstrom/	|ΔL/L|<10%		25,00	A	

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.



Inductor Selection Parameters – Current De-rating

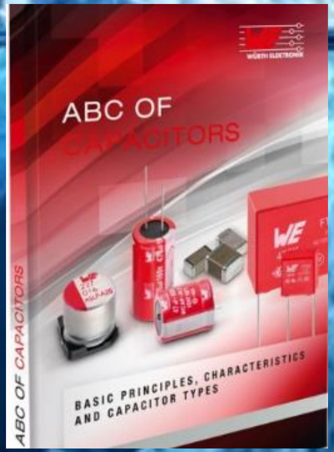
At 100°C ambient Temp. only 60% of the rated current can be used
Derating of 40 %



The max operating temperature of the inductor is 125°C

Can be higher 155°C, like PDF series

Capacitor Selection Parameters

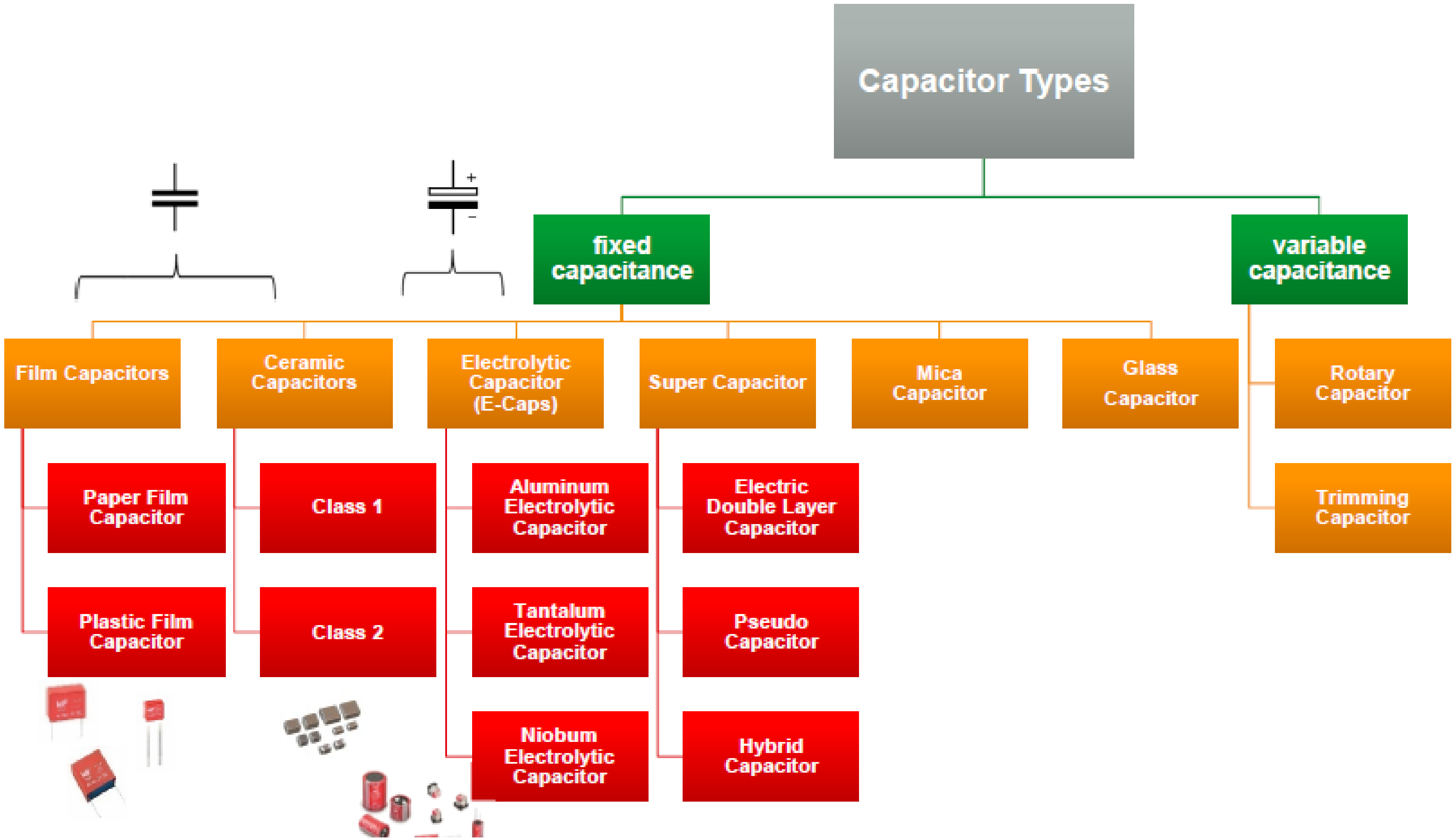


- **Top 20% :**
  - Voltage, Operating Temperature
  - Expected Life, ESR, Ripple Current
  - Leakage Current, Dissipation Factor

- **Bottom 80%:**
  - Impedance, resonance frequency, Q/DF factor
  - Drying out of electrolyte, self-healing
  - Ambient → Capacitance vs Temperature Curve
  - DC Bias → Capacitance vs Voltage Curve
  - Durability → Capacitance vs Time Curve
  - MLCC Class → 1 (NPO/COG, low perm) and 2 (X7R, Y5V)

Expected Life

Capacitors Selection



Electrolytic vs Polymer Capacitors

Electrolytic Caps:

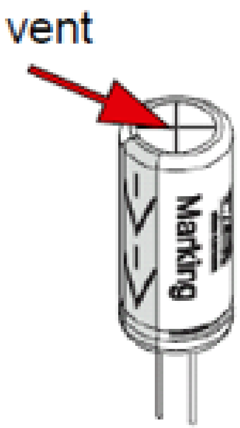
- ✓ Higher voltage rating up to 600v
- ✓ Relatively lower prices
- ✓ Better leakage current behaviour

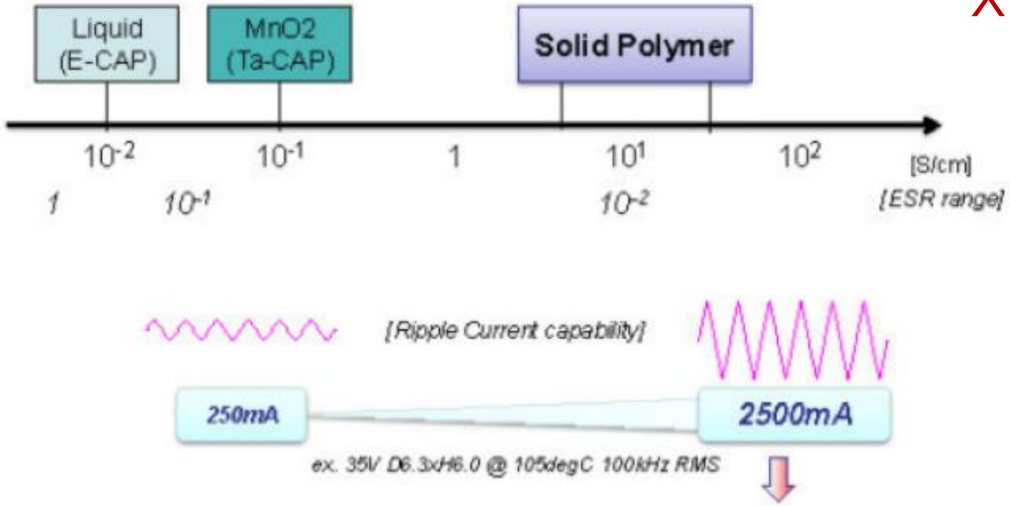
- X Liquid electrolyte, drying out
- X Lower volumetric capacity
- X Lower life expectancy

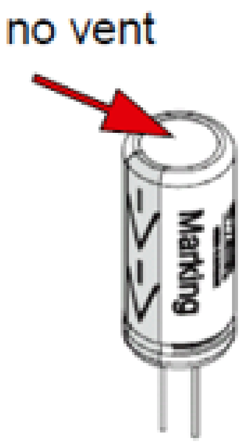
Polymer Caps:

- ✓ Lower ESR
- ✓ Higher ripple rating
- ✓ Solid polymer, No drying out effect
- ✓ Longer expected life
- ✓ Higher operating temperature

- X Limited can size
- X Not more than 200v



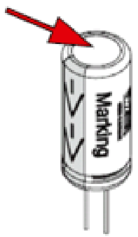




Electrolytic vs Polymer Capacitors

WÜRTH ELEKTRONIK

no vent



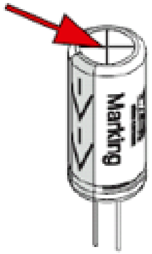
Aluminum Polymer Capacitors:

$$L_x = L_{Nom} * 10^{\frac{T_{max} - T_A}{20}}$$

Aluminum Electrolytic Capacitors

$$L_x = L_{Nom} * 2^{\frac{T_{max} - T_A}{10}}$$

vent

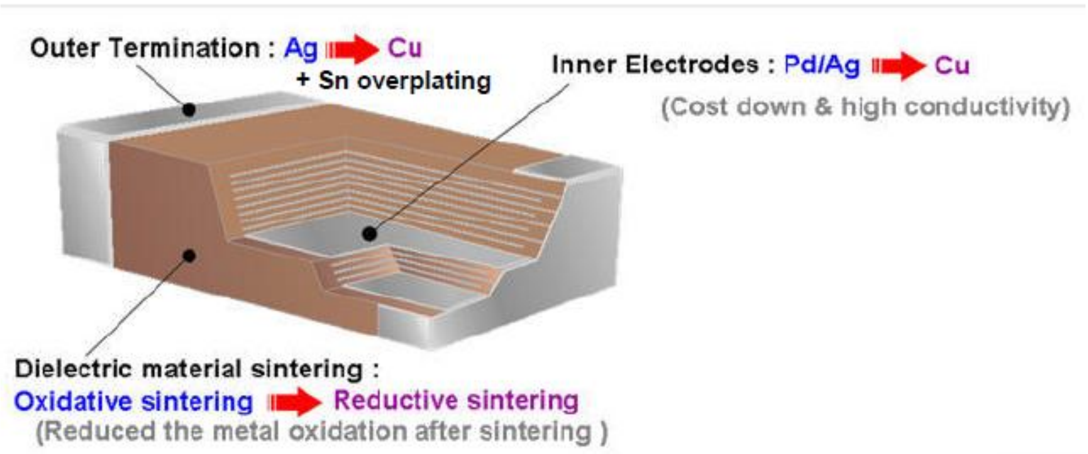


Capacitor Temperature	Aluminum Polymer Capacitor		Aluminum Electrolytic Capacitor				
125 °C	**2.000 h**	-	-	-	-	-	-
115 °C	6.325 h	-	-	-	-	-	-
105 °C	20.000 h	**2.000 h**	**5.000 h**	**2.000 h**	-	-	
95 °C	63.246 h	6.325 h	10.000 h	4.000 h	-	-	
85 °C	200.000 h	20.000 h	20.000 h	8.000 h	**5.000 h**	**2.000 h**	
75 °C	632.455 h	63.246 h	40.000 h	16.000 h	10.000 h	4.000 h	
65 °C	2.000.000 h	200.000 h	80.000 h	32.000 h	20.000 h	8.000 h	

MLCC - Classifications

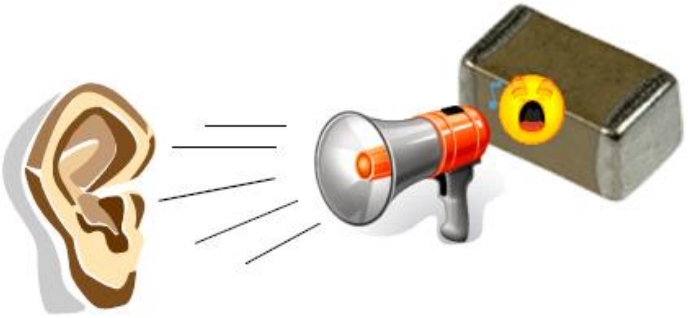
Class 1 ceramics (NP0 = C0G)

- ✓ Built with titanium oxide
- ✓ Minimum aging behaviour
- ✓ Linear temperature dependency
- ✓ Low (down to none) voltage dependency
- ✓ Low relative permittivity ε_r ➔ smaller capacitance



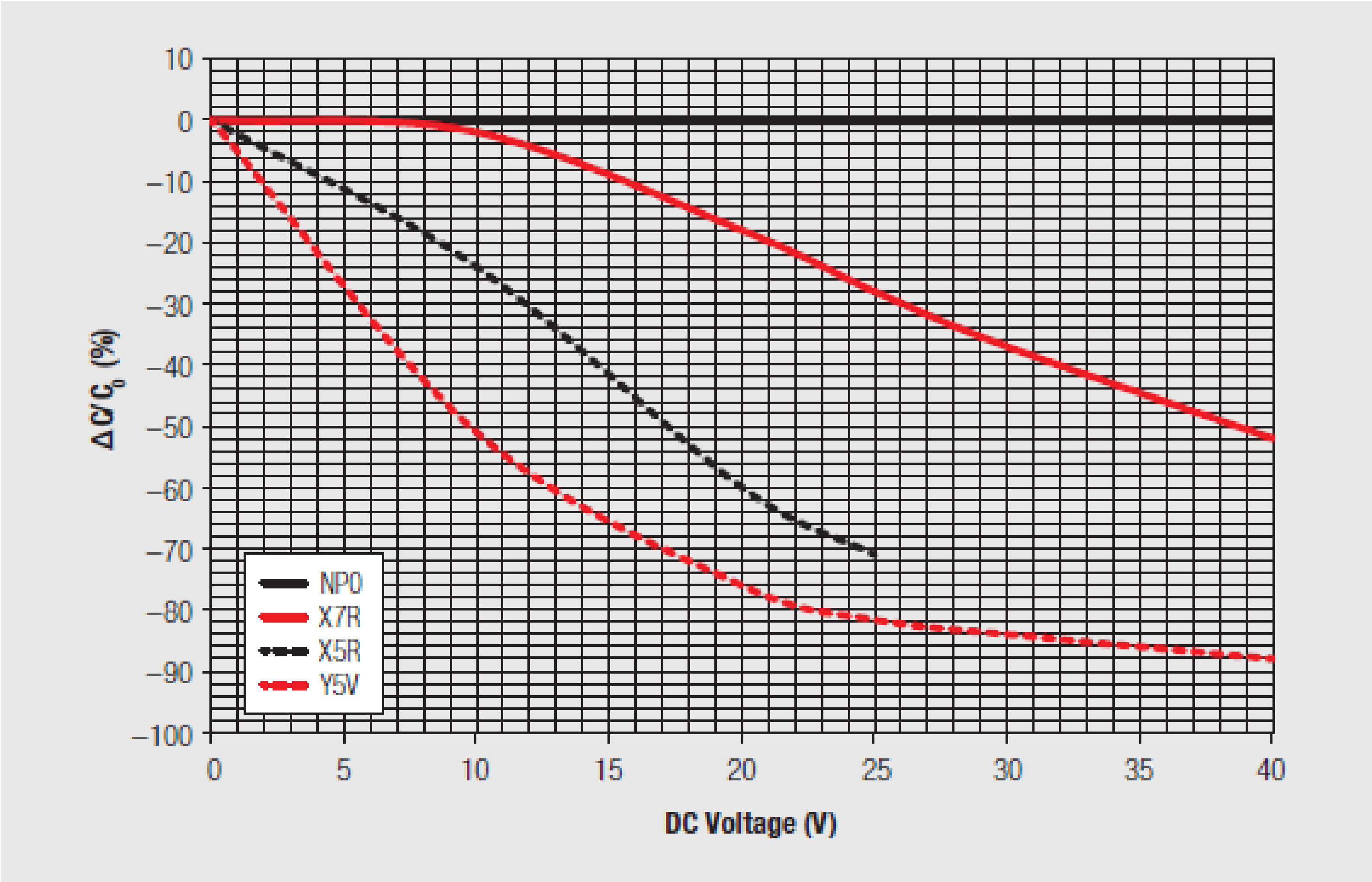
Class 2 ceramics (X7R, X5R, Y5V)

- ✓ Built with barium titanate
- ✓ Higher relative permittivity ε_r ➔ higher capacitance
- ❑ Aging behaviour
- ❑ High voltage dependency
- ❑ Piezoelectric effects can result in microphonic noise
- ❑ Not linear (and stronger distinct) temperature dependency

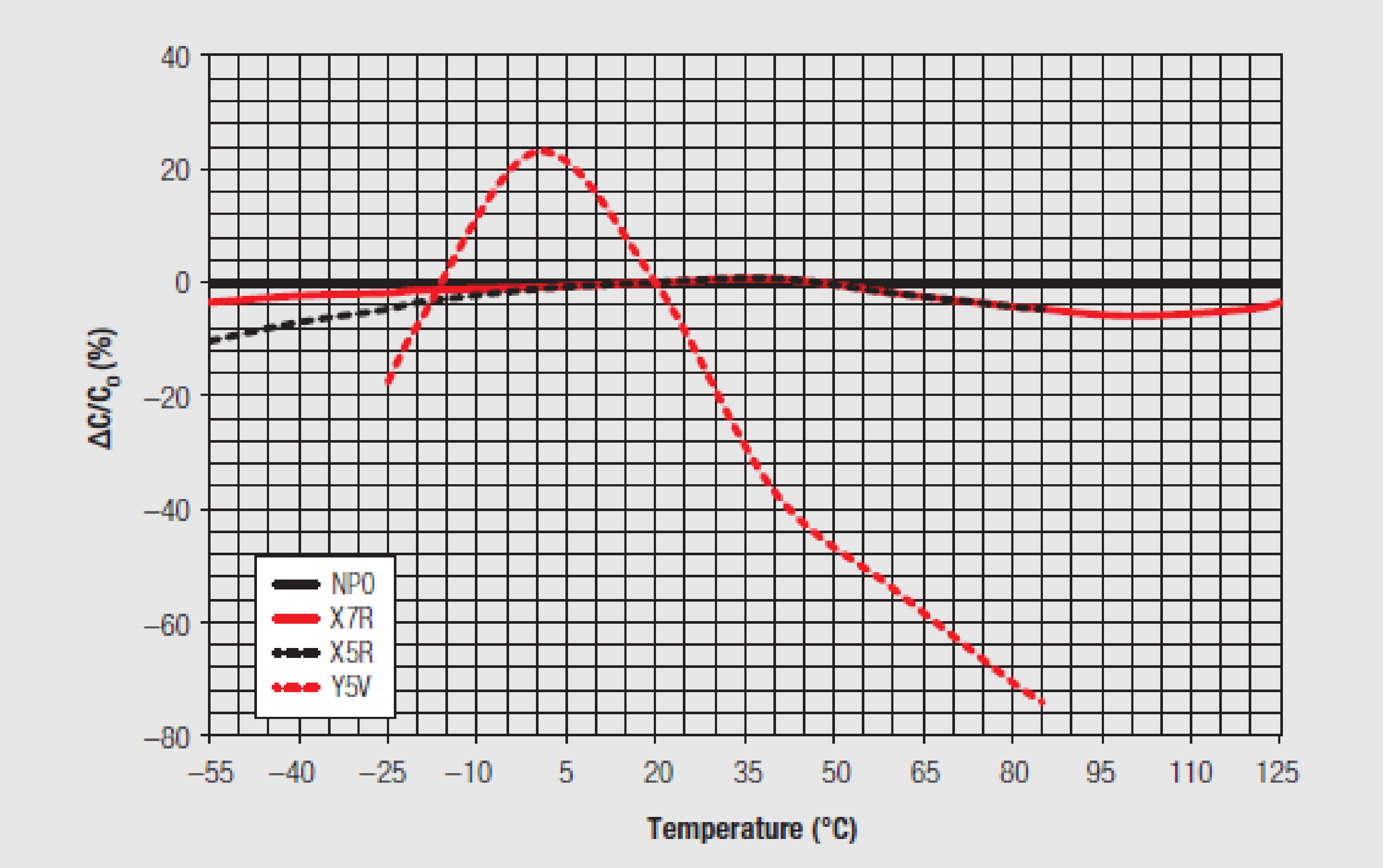


MLCC – DC Bias Effect → ΔC/C0 vs DC Voltage

WÜRTH ELEKTRONIK



Temperature Dependency of Ceramic



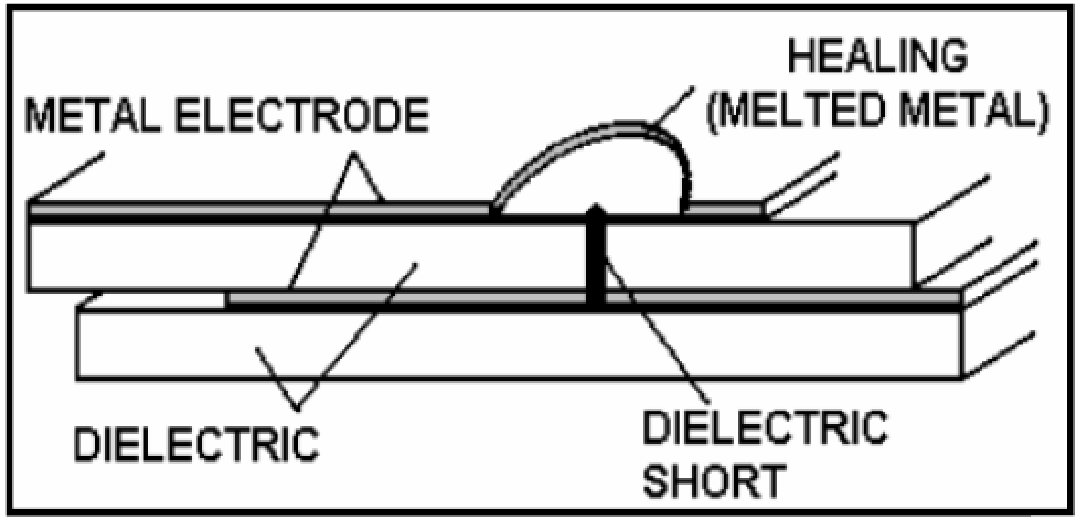
EIA-RS-198 Coding for Ceramic Caps

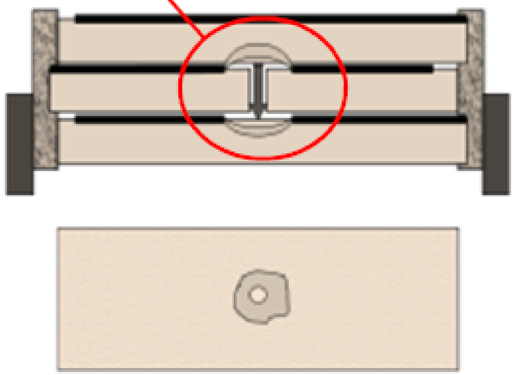
EIA-RS-198 coding for class 2 ceramic capacitors					
1st character		2nd character		3rd character	
Letter	Lower temperature limit	Number	Upper temperature limit	Letter	Capacitance change over the permissible temperature range
X	–55 °C	**2**	+45 °C	**A**	±1.0%
Y	–30 °C	**4**	+65 °C	**B**	±1.5%
Z	+10 °C	**5**	+85 °C	**C**	±2.2%
		6	+105 °C	**D**	+3.3%
		7	+125 °C	**E**	+4.7%
		8	+150 °C	**F**	+7.5%
		9	+200 °C	**P**	±10%
				R	±15%
				S	±22%
				T	+22/–33%
				U	+22/–56%
				V	+22/–82%

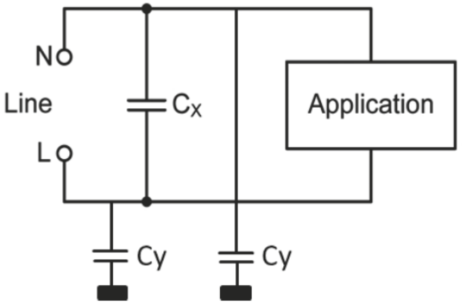
Self-Healing of Film Capacitors

X & Y Safety Classes
According IEC 60384-14 / UL 60384-14:

Safety Class	Max. Impulse according IEC-60384-14
X1	4kV (C≤ 1µF)
X2	2,5 kV (C≤ 1µF)
Y1	8 kV
Y2	5 kV
Y3	Not anymore in IEC standard (in the past defined by manufacturer)



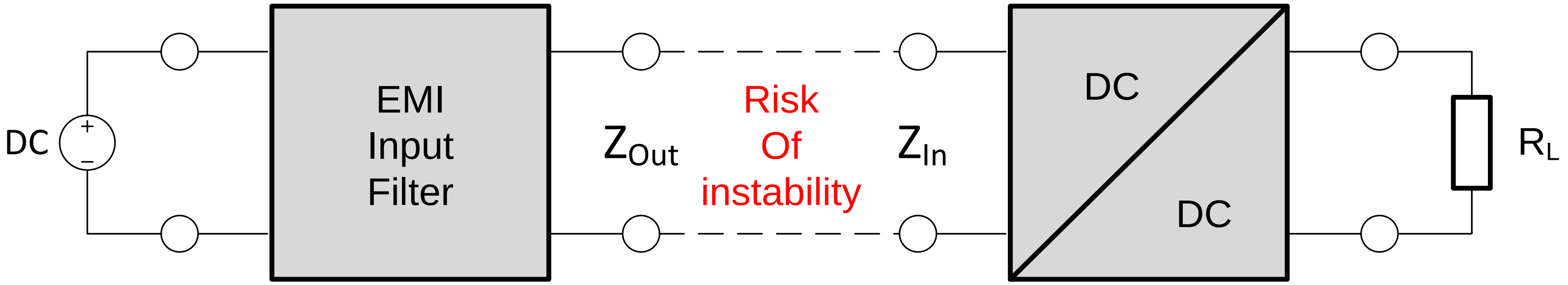




- **DC/DC Converter Topologies –** Buck, boost & SEPIC
- **Causes of CM & DM Emissions** – LT Spice
- **Efficiency and Losses –** Core, Copper and AC

- **Criteria for selecting Inductor and Capacitor –** DC Bias
- **Practical Input Filter Design –** LC Filter
- **REDEXPERT –** Interactive component selection

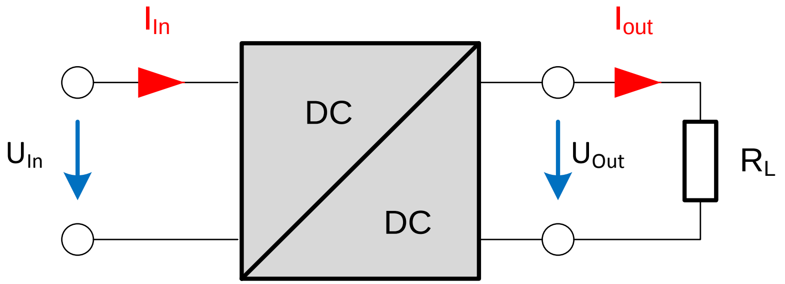
Oscillation At Converter Input

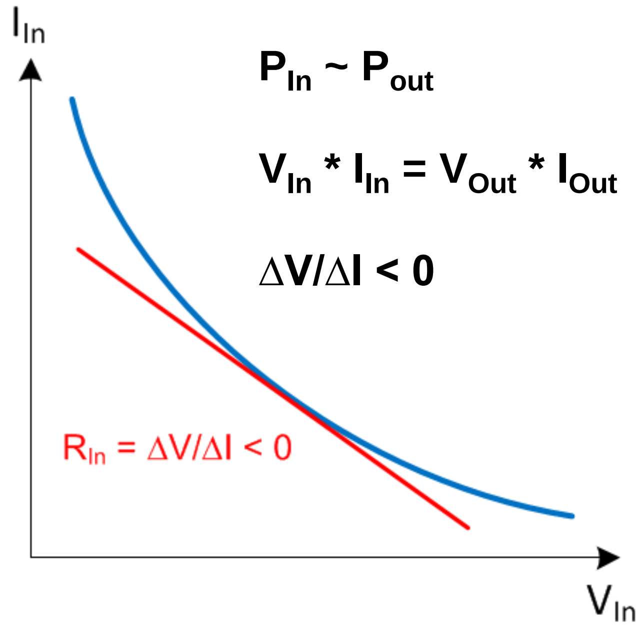


- Adding an input filter may cause oscillations
- Converter no longer meets response specs, and may become unstable
- Why?

(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**





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

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

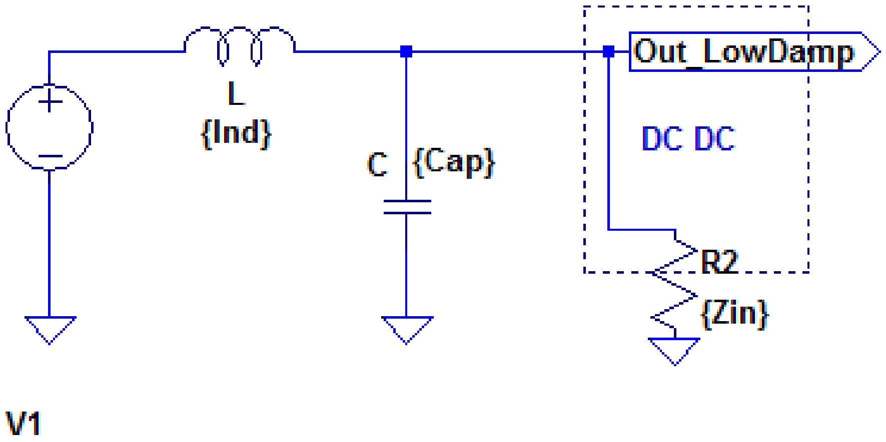
$$\Delta V/\Delta I < 0$$

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

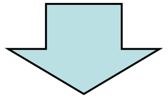
NEGATIVE DC INPUT RESISTANCE

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)**

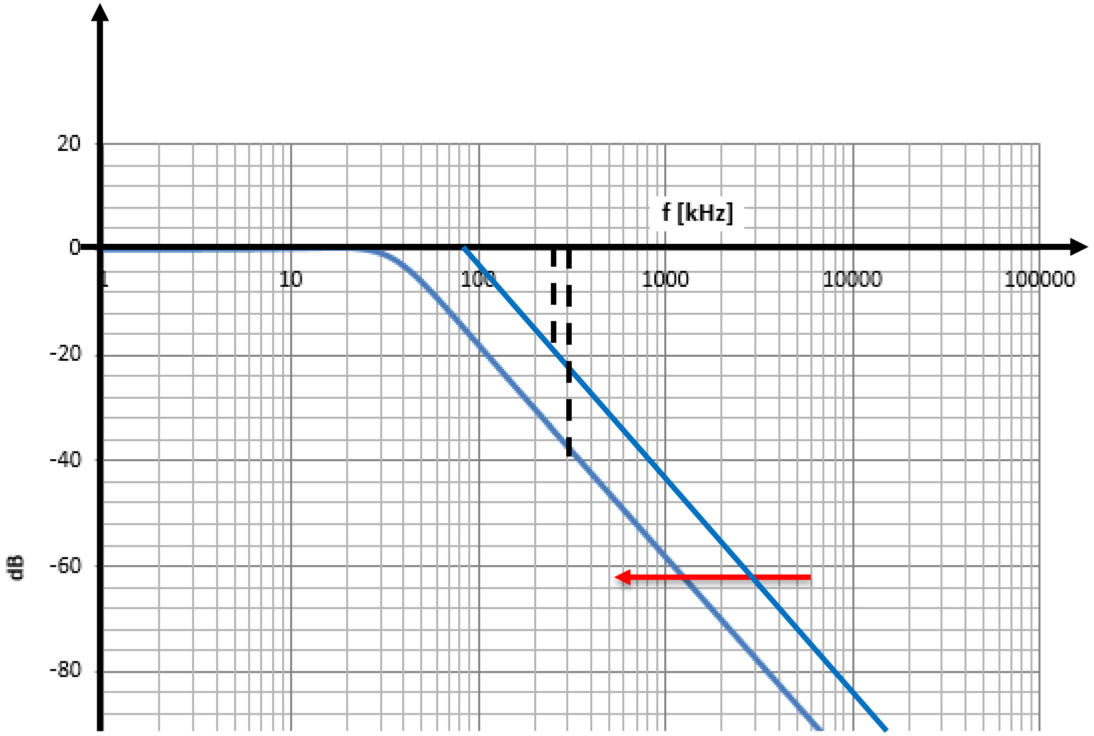


- **This is a LC filter loaded by a negative resistance!!!!!**

- **NICE WAY TO CREATE OSCILLATORS**

Calculating Input Filter Components values → Fx

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



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

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

→ F_{0calc}: 23 kHz

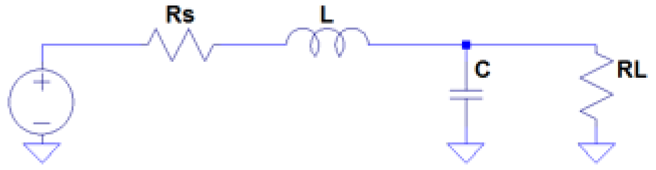
- **Adb**: attenuation required
- **n**: filter order
- **Fsw**: switching frequency
- **Fco**: filter cut off frequency

Calculating Input Filter Components values → L + C

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

$$f_0 = \frac{1}{2 \cdot \pi \cdot \sqrt{(L \cdot C)}}$$ ≈ 21kHz (20,65kHz calculated)

 www.we-online.com

Calculating Input Filter Components values → Cd + Rd

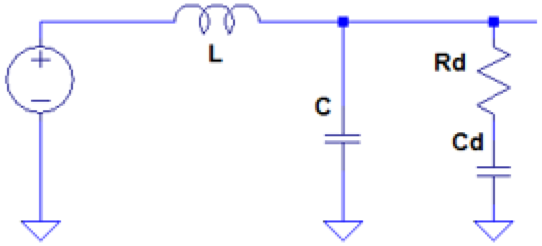
1) Calculate damping capacitor $C_d = \mathrm{n} \cdot Cf \qquad with\; n = 4\; or\; 6$

2) Calculate damping Resistor

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

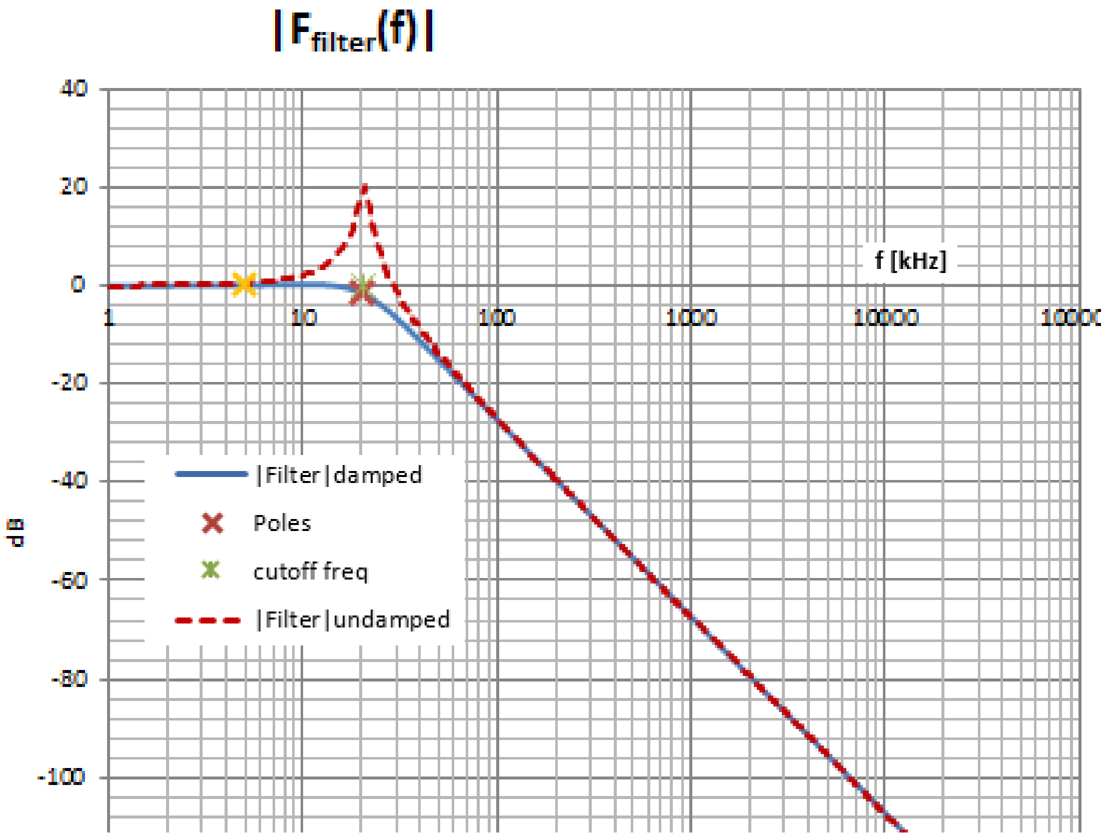
Keeping the same values of undamped filter, we can add an Rd and a Cd as follows:

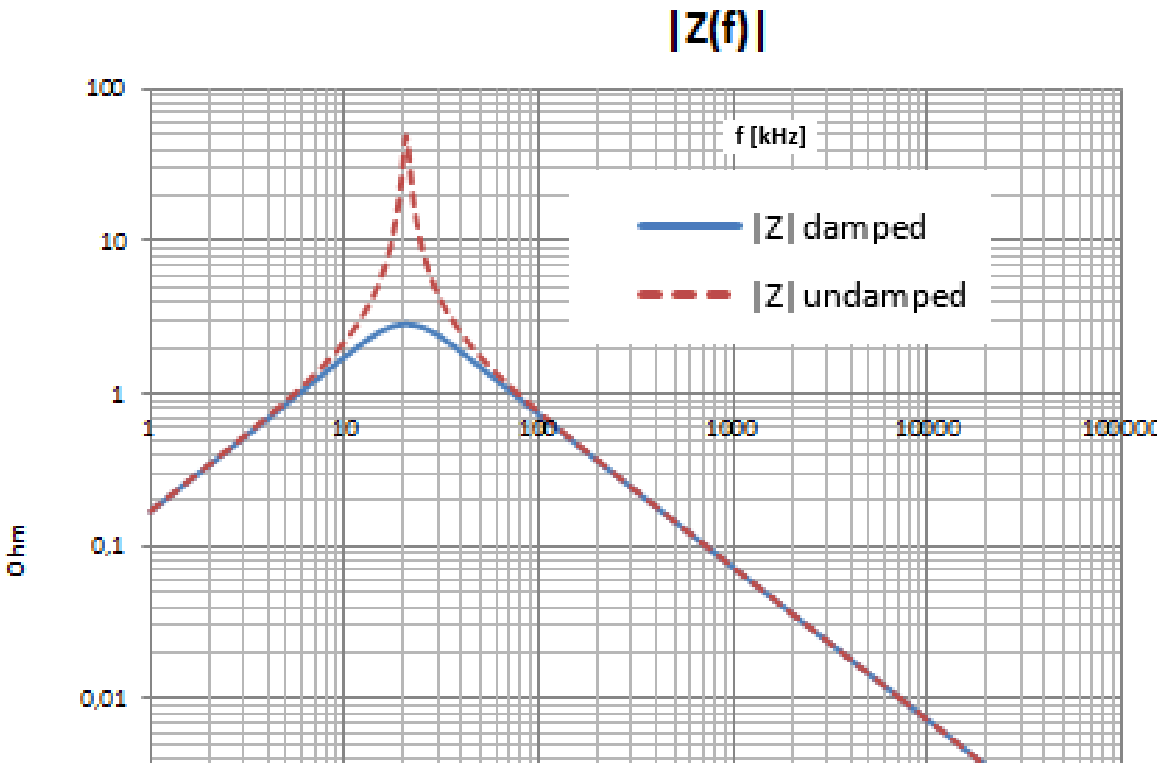
Rd	3,57548	Ω
Cd	8,8	uF
C	2,2	uF
L	27	uH
n	4	



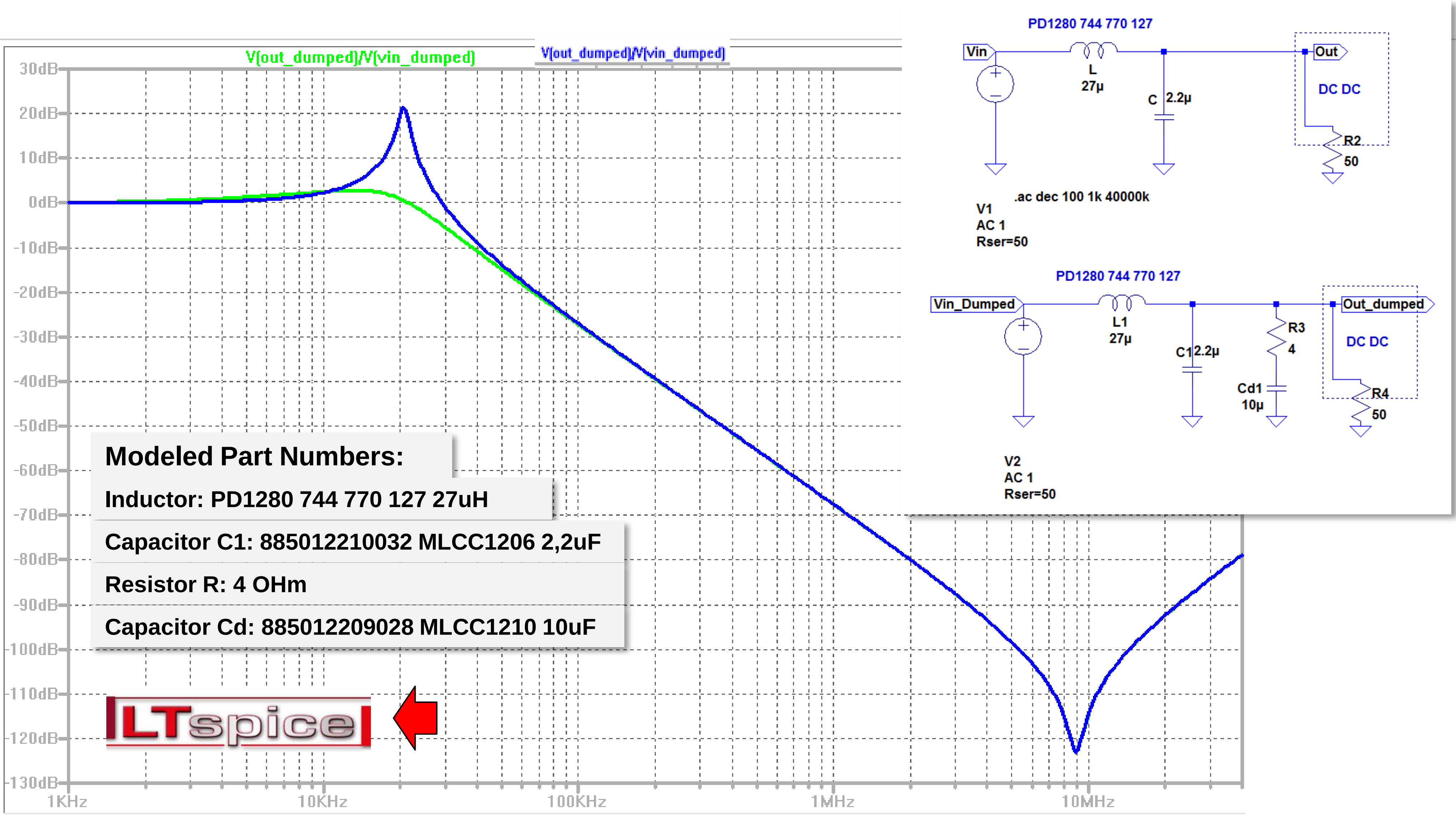
*See Input Filter Design for Switching Power Supplies, Michele Sclocchi – National App Note 2010

Calculating Input Filter Components values - Damping





Check using LT Spice Simulation



Modeled Part Numbers:

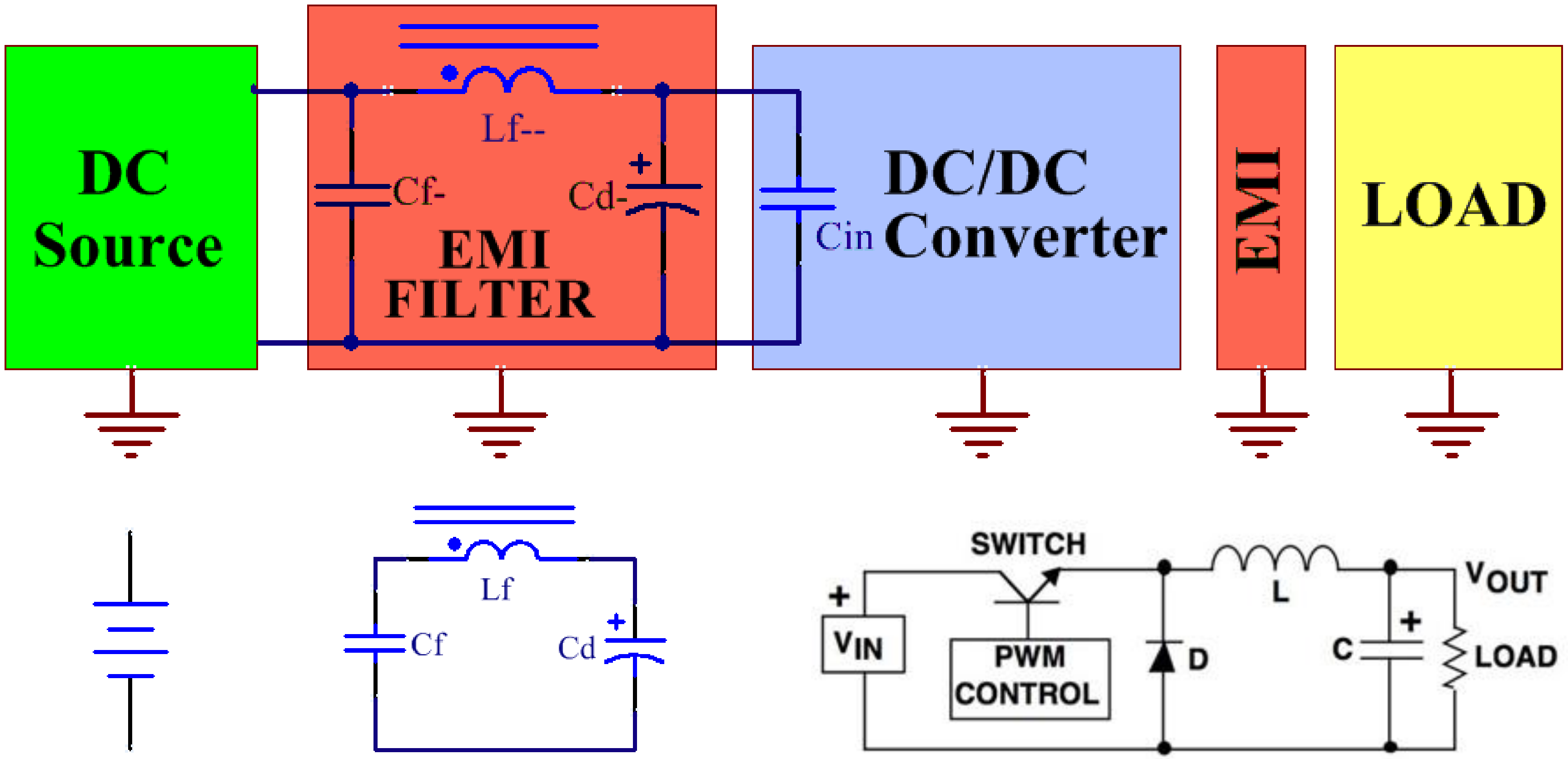
Inductor: PD1280 744 770 127 27uH

Capacitor C1: 885012210032 MLCC1206 2,2uF

Resistor R: 4 OHm

Capacitor Cd: 885012209028 MLCC1210 10uF

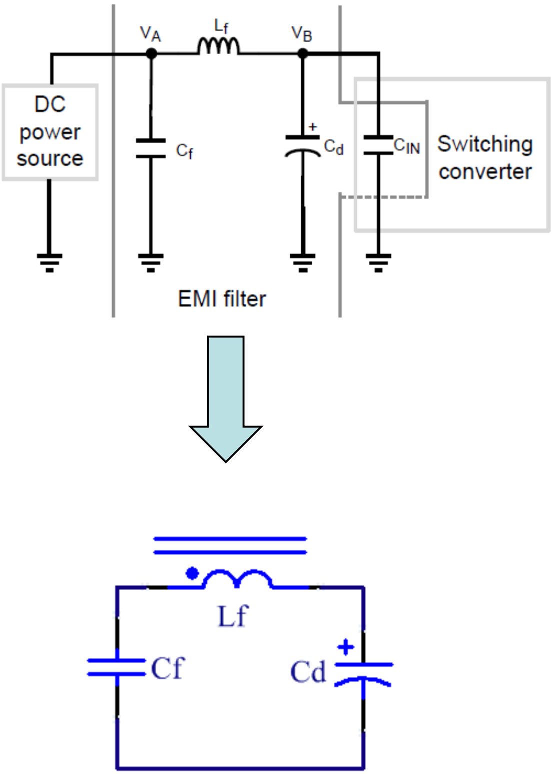
EMI Component for DC/DC Converter



Calculate Required Attenuation

- Know input voltage, output voltage and ripple voltage
- Calculate required attenuations using formula

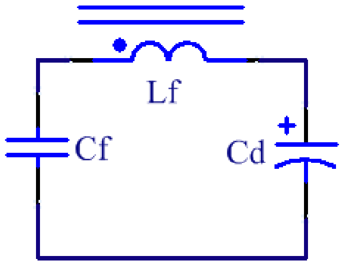
- E.g. to design an input filter for a 12v to 5v converter
  - **Vripple = 0.5v, Vmax = 7v ➔ 13dB Attenuation(+)**



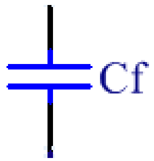
$$|\mathrm{Attn}|\mathrm{dB} = 20\ \mathrm{Log}\left(\frac{\mathrm{Vripple}}{1\mu\mathrm{V}}\right) - \mathrm{Vmax}$$

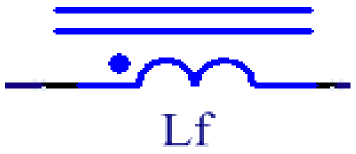
* Vmax is difference between Vin and Vout (differential noise)

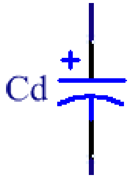
Calculate Cf, Lf and Cd



- Cf = EMI Filter Capacitance (greater of Cfa or Cfb, 100nF)
- Lf = EMI Filter Inductance (key EMI resonance value, 5uH)
- Cd = Damping Capacitance (four times bigger than Cin, 330nF)







$$C_{fa} = \frac{C_{IN}}{C_{IN} L_f (2\pi f_s/10)^2 - 1}$$

$$F_{osc} = \frac{1}{2\pi\sqrt{LC}}$$

$$C_d \geq 4 \times C_{IN}$$

$$C_{fb} = \frac{1}{L_f}\left(\frac{10^{|Att|_{dB}/40}}{2\pi f_s}\right)^2$$

$$L_F = \frac{1}{C\,(2\pi F)^2}$$

$$ESR_d \approx \sqrt{L_f/C_{IN}}$$

Lf uH	2xPi	Fs KHz	2PiF	|Att|dB	Attn/40	10^	Cf nF	Cd uF
5	6.28	500	3140	13	0.325	2.11	91	0.36
10	6.28	500	3140	13	0.325	2.11	45	0.18
100	6.28	500	3140	13	0.325	2.11	5	0.02

WÜRTH ELEKTRONIK

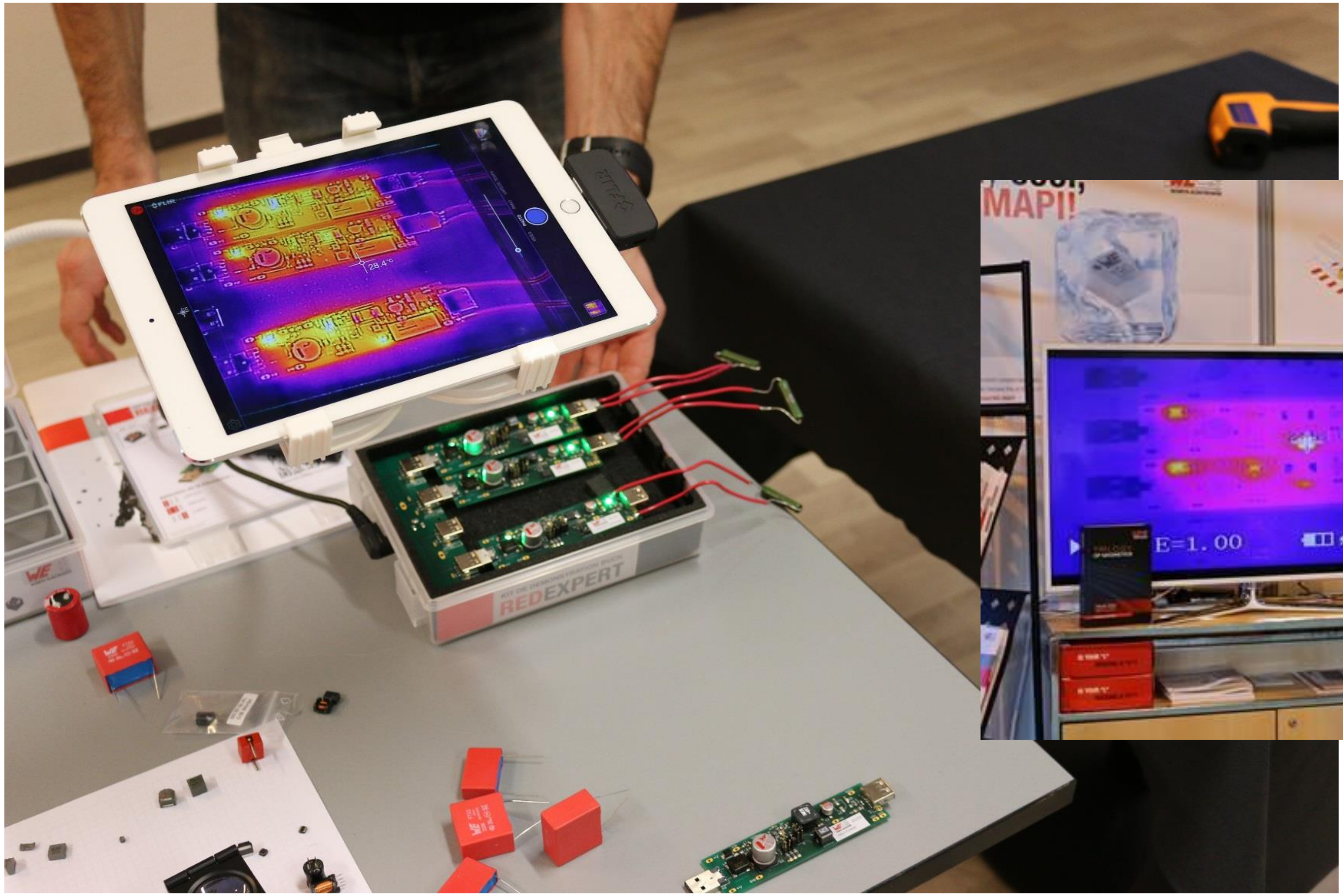
- **DC/DC Converter Topologies –** Buck, boost & SEPIC
- **Causes of CM & DM Emissions** – LT Spice
- **Efficiency and Losses –** Core, Copper and AC

- **Criteria for selecting Inductor and Capacitor –** DC Bias
- **Practical Input Filter Design –** LC Filter
- **REDEXPERT –** Interactive component selection

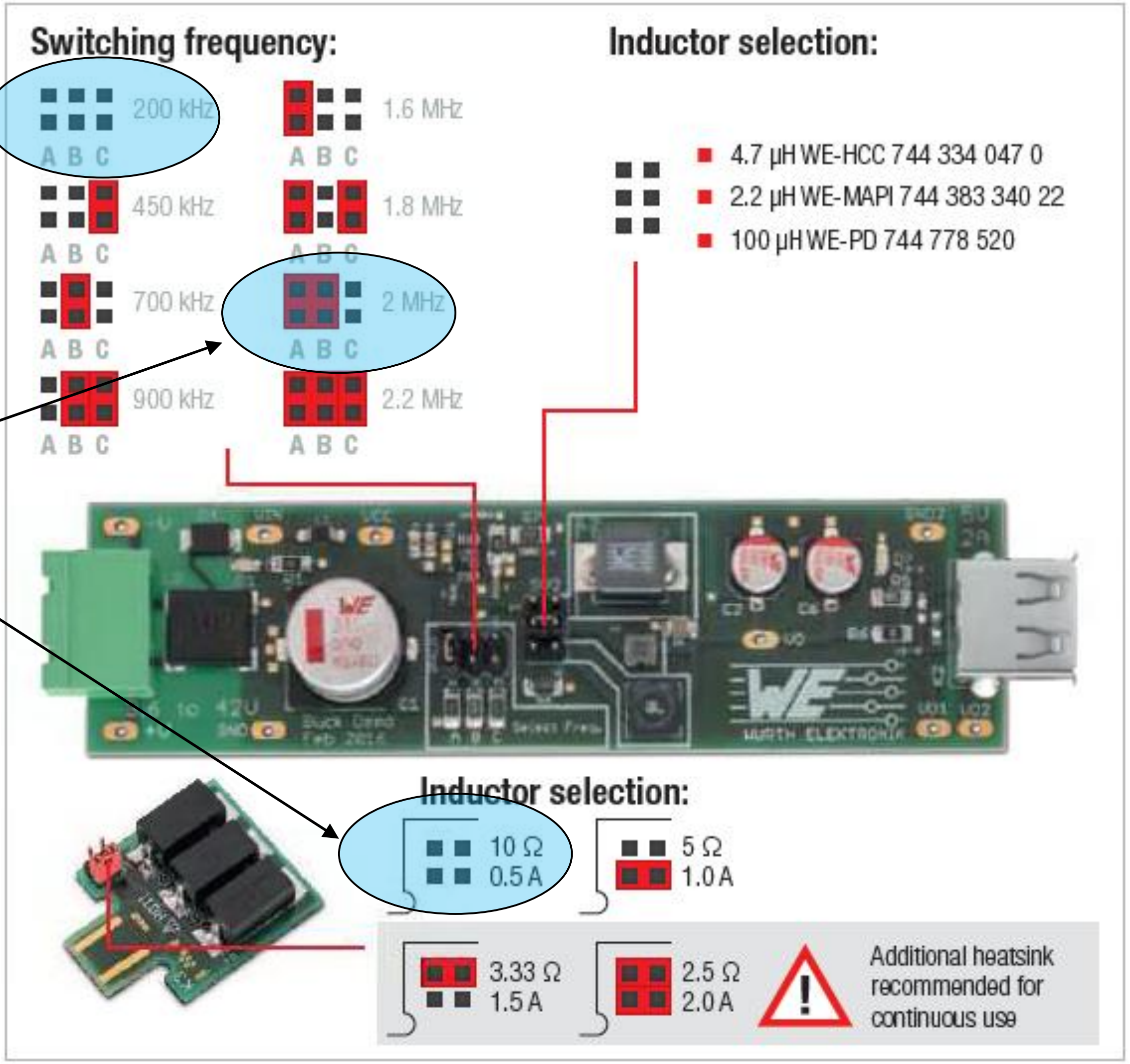
REDEXPERT

www.we-online.com/redexpert

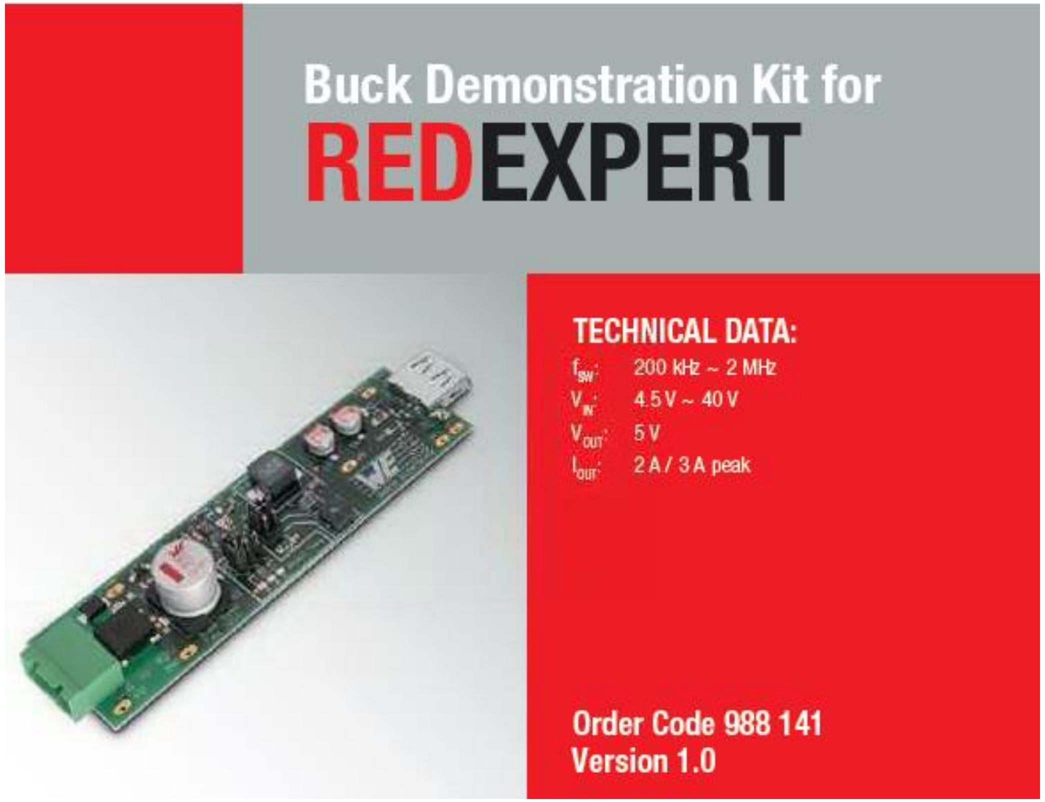
REDEXPERT – *Demystifying EMC*



Buck Demo Kit for REDEXPERT



Test Conditions

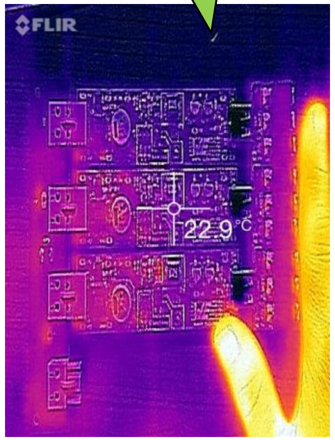


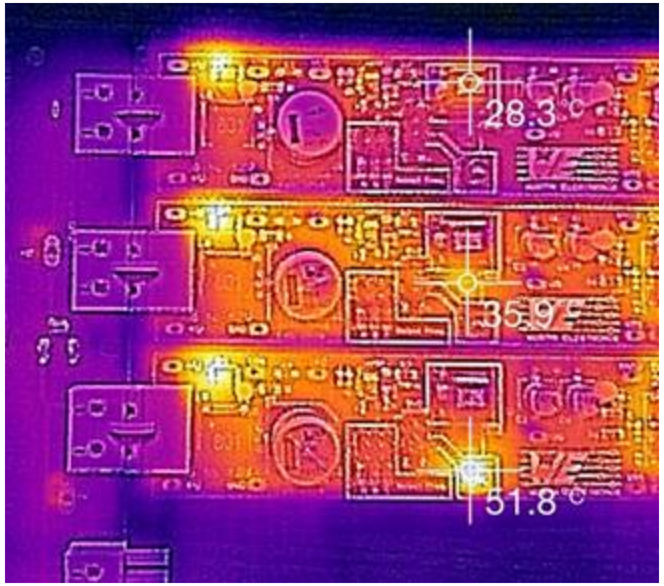
Switching Frequency: 200KHz vs 2MHz

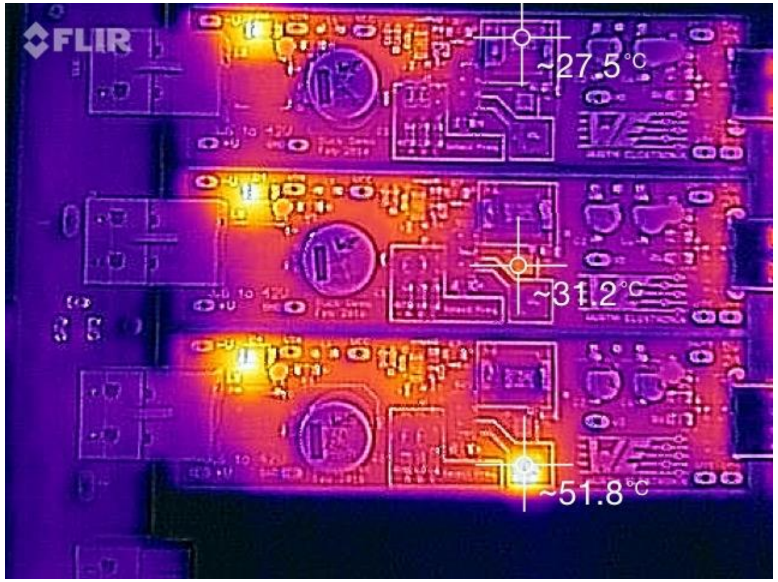
Ambient
SAT
22.9˚C

9Vin,
5Vo,
2.5W,
200KHz

9Vin,
5Vo,
2.5W,
2MHz







REDEXPERT

WÜRTH ELEKTRONIK

- 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

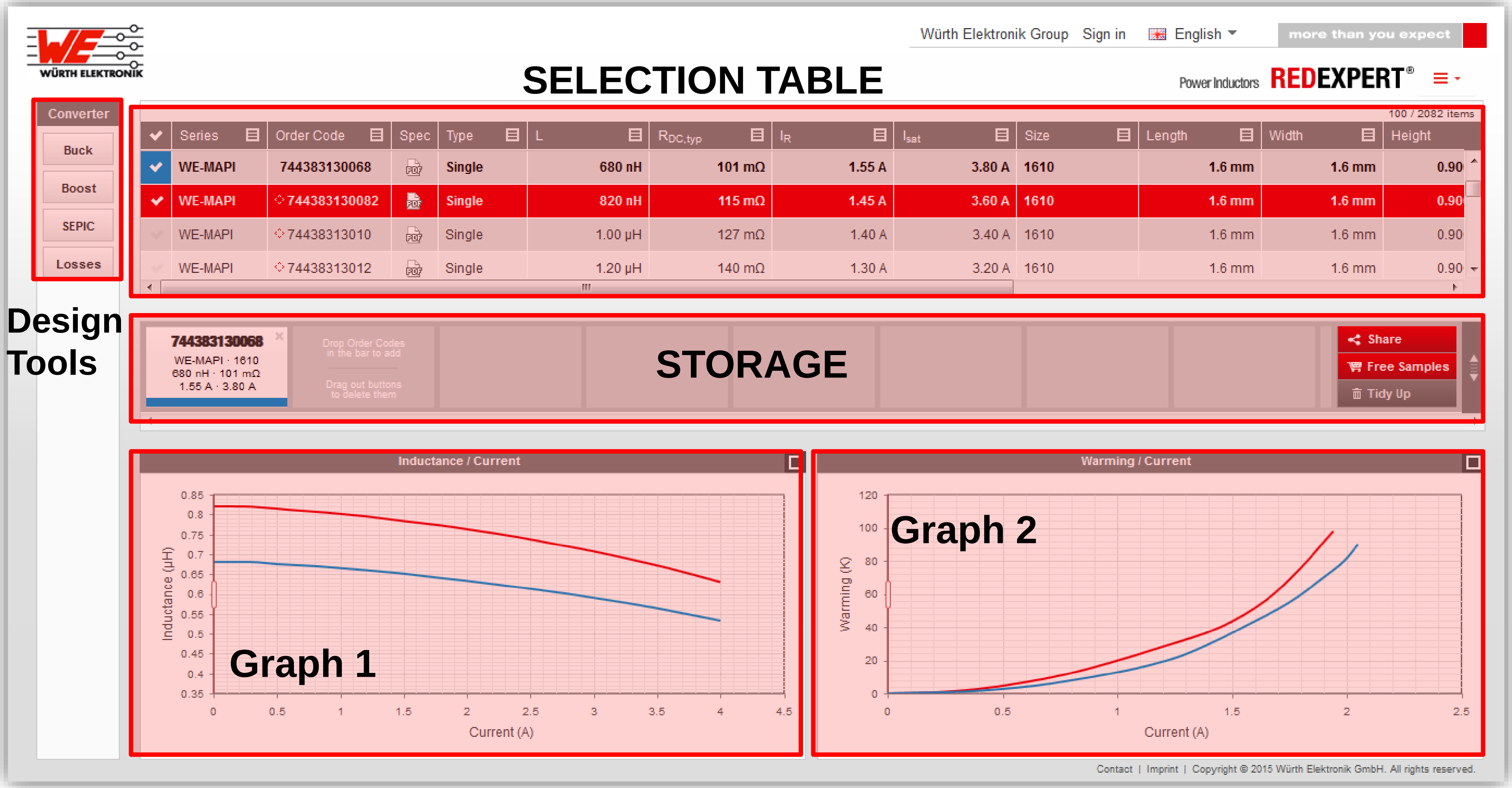
DETAILS

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

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

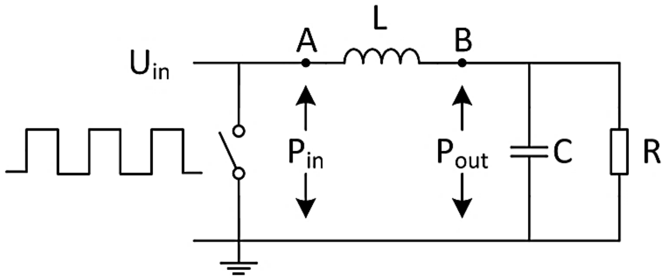
	Order Code ▲	Series	Size	Spec	Type	L	L() @39...	$R_{DC,typ}$	I_R	I_{sat}	P_{AC}	P_{DC}	P_{TOT}	ΔT
✔	7443340470	WE-HCC	8070	PDF	Single	4.70 µH	4.60 µH	12.7 mΩ	7.50 A	8.00 A	17.7 mW	3.18 mW	20.9 mW	2.70 K
✔	74438334022	WE-MAPI	3012	PDF	Single	2.20 µH	2.20 µH	100 mΩ	1.80 A	5.00 A	20.5 mW	25.0 mW	45.5 mW	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

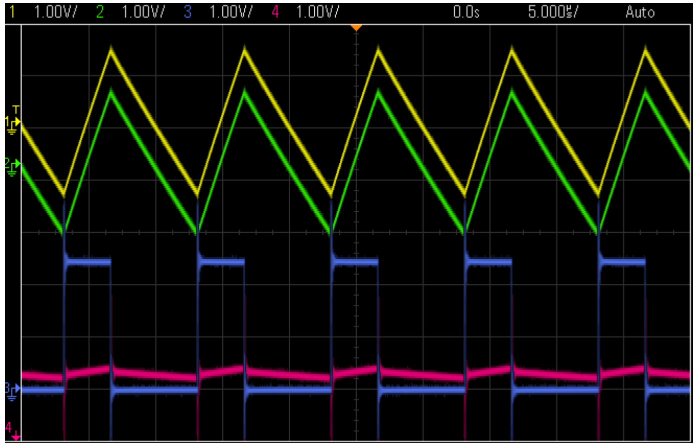
User Interface



World's Most Accurate AC Loss Model – Wave Signal

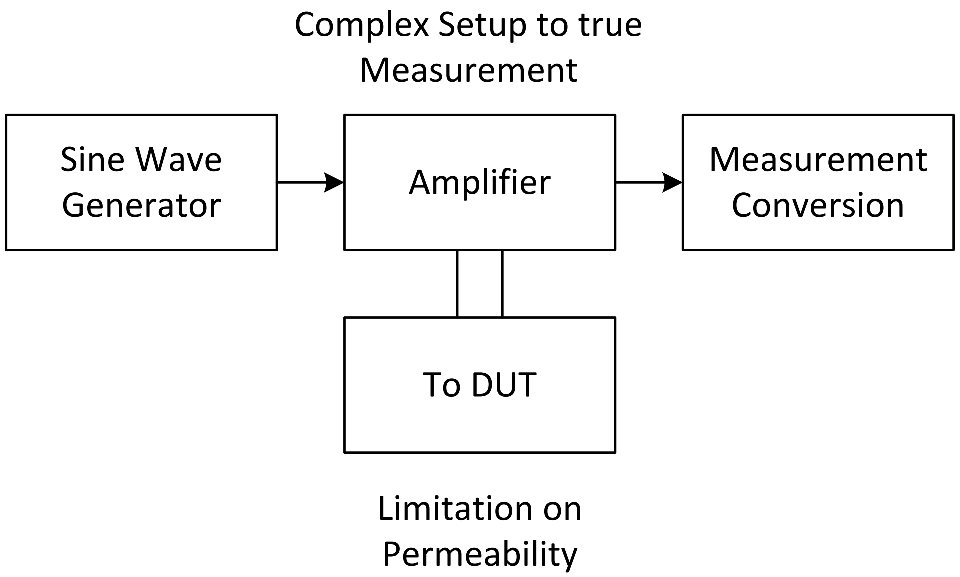
Wurth AC Loss Model





Simple Class-D Amplifier

Steinmetz Models



Complex Setup to Measure

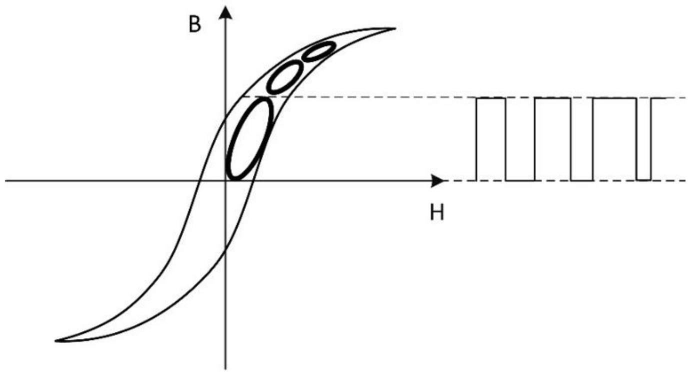
World‘s Most Accurate AC Loss Model – Signal Loop

WÜRTH ELEKTRONIK

Wurth AC Loss Model

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

Core Loss & AC Wire Loss



Point of Operation Approach

Triangular current form

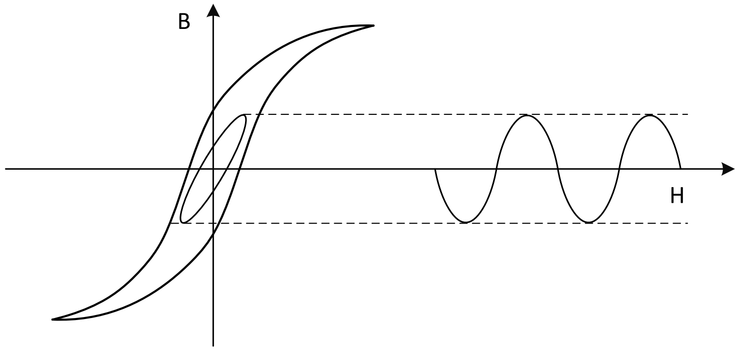
Steinmetz Models

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

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

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

Core Loss Only

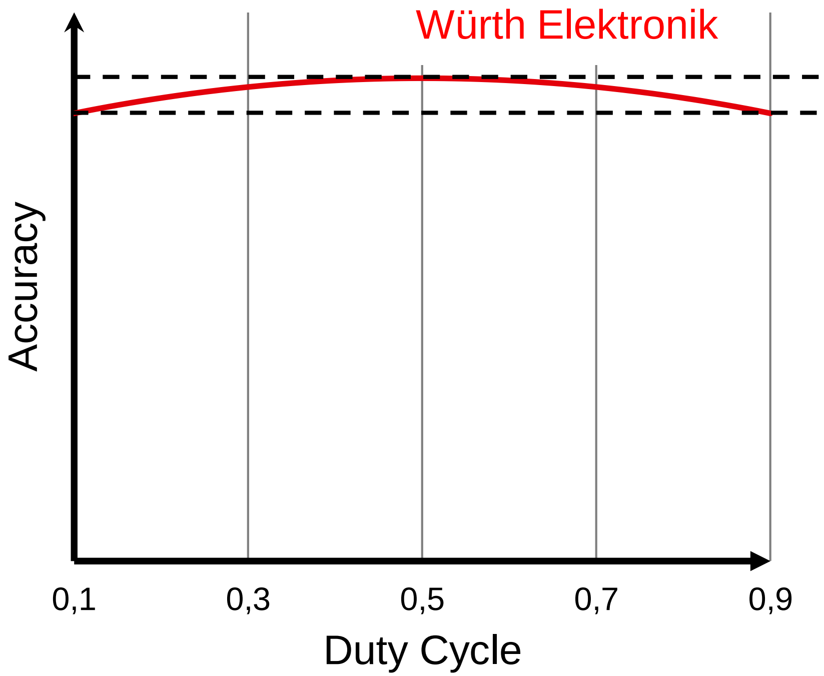


Major Loop Approach

only sine wave

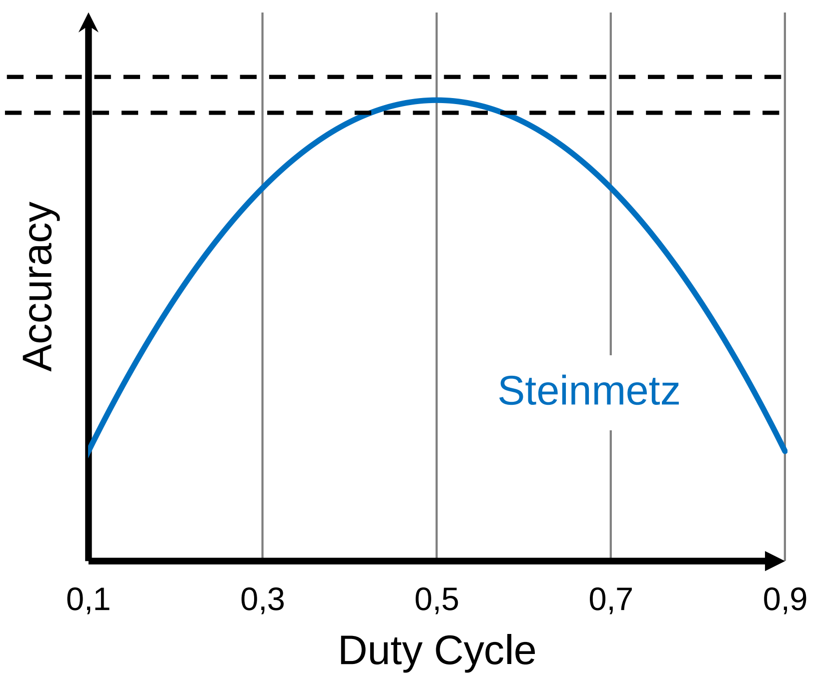
World's Most Accurate AC Loss Model – Duty Cycle

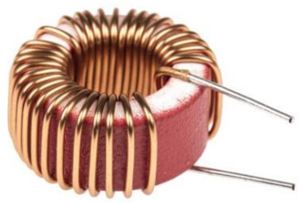
Wurth AC Loss Model



Highest Accuracy over wide DC range

Steinmetz Models





Acceptable Accuracy at 50%, even worse for other DC

World's Most Accurate AC Loss Model

WÜRTH ELEKTRONIK

Wurth AC Loss Model:

- Based on real time application set up and measurements
- A pulsating input voltage is applied over the real 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

All Inclusive – Full On Board Dc/Dc Modules

Thank you

Any Questions