



HELLO TÜRKIYE 2026

WÜRTH ELEKTRONIK MORE THAN YOU EXPECT



MAKE OR BREAK YOUR DESIGN;
PRACTICAL DC/DC CONVERTERS
DESIGN CONSIDERATIONS

Mohamed AlAlami
Technical Specialist

WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

AGENDA

- Buck Converter Overview
- Practical Design Considerations & Tips
 - To be or not to be “Saturated”?
 - BH Loop Measurement – Practical Demo
 - Voltage rating; Necessary or a gimmick
 - Percolation Effect – Practical Demo
 - Audible Noise
 - Efficient inductor selection
 - Smart capacitor selection
- Practical tactics for designing SEPICs



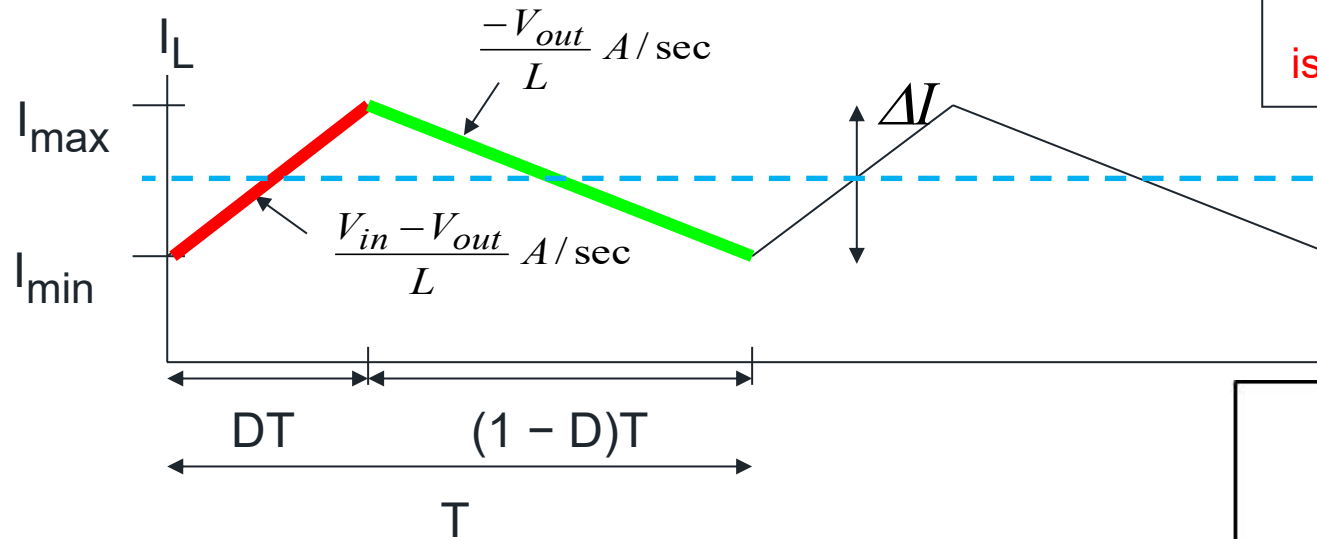
BUCK CONVERTER

OVERVIEW

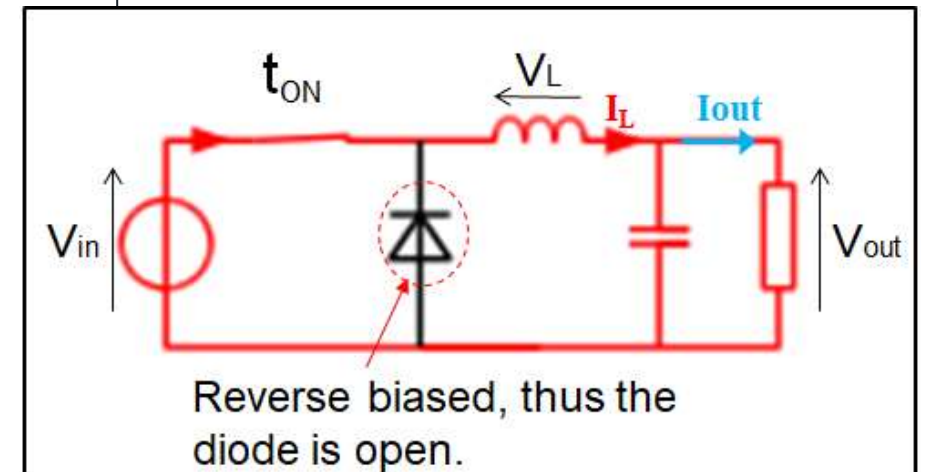
THE BUCK CONVERTER

Continuous Conduction Mode (CCM)

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



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



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

THE BUCK CONVERTER

CCM Design Equations

$$V_{out} = DV_{in} \quad \text{VCR} = \text{Voltage Conversion Ratio}$$

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

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

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

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

$$I_{Lmin} = I_{out} - \frac{\Delta IL}{2}$$

$$I_{Lmax} = I_{out} + \frac{\Delta IL}{2}$$

$$I_{out} = \frac{V_{out}}{R_{load}}$$

$$I_{in} = \frac{P_{in}}{V_{in}} = \frac{P_{out}/\eta}{V_{in}} = \frac{V_{out} \times I_{out}}{\eta \times V_{in}} = \frac{D \times I_{out}}{\eta}$$

PRACTICAL DESIGN CONSIDERATIONS & TIPS

TO BE OR NOT TO
BE "SATURATED"?



SATURATION CURRENT : DO WE HAVE A DEFINITION?

How is saturation current defined?

Is it a standard?

Properties	Test conditions		Value	Unit	Tol.
Inductance	100 kHz/ 5 mA	L	3.3	μH	$\pm 30\%$
Rated current	$\Delta T = 40 \text{ K}$	I_R	5.9	A	max.
Saturation current	$ \Delta L/L < 10\%$	I_{sat}	7.1	A	typ.
DC Resistance	@ 20°C	R_{DC}	0.013	Ω	max.
DC Resistance	@ 20°C	R_{DC}	0.0115	Ω	typ.
Self resonant frequency		f_{res}	40	MHz	typ.

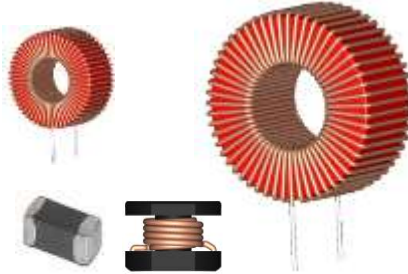
INDUCTANCE INFLUENCING PARAMETERS

Different Material

Fe	Iron Powder
NiZn	Nickel-Zinc
Superflux	Superflux
Metal Alloy	Metal Alloy
WE-PERM	WE-PERM
MnZn	Manganese-Zinc
NiZn / MnZn	Nickel-Zinc / Manganese-Zinc
Hyperflux	Hyperflux
NiZn / MnZn / Metal Alloy	Nickel-Zinc / Manganese-Zinc / Metal Alloy



Different Size and Shape



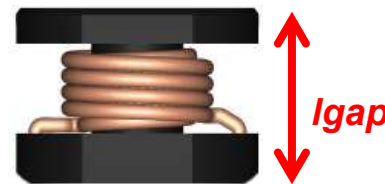
Number of turns



$$L = \frac{(\mu_0 * \mu_r * A_{eff} * N^2)}{l_{eff}}$$

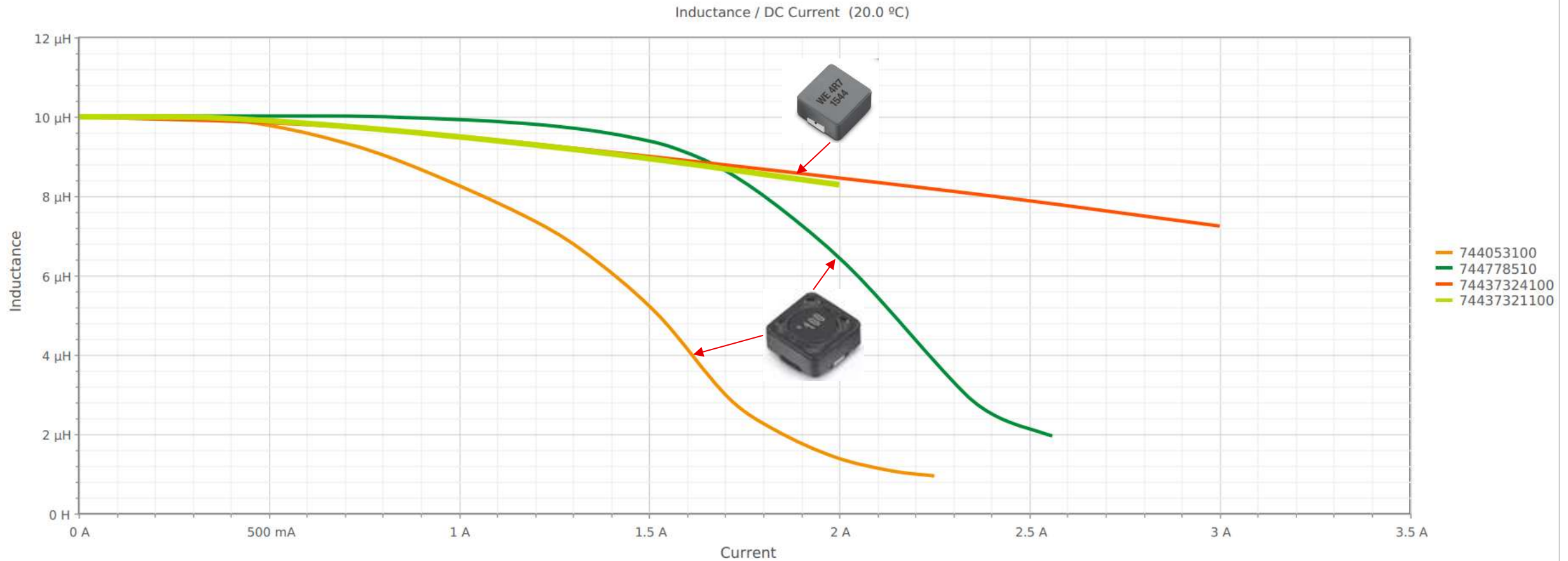
- μ_r = relative permeability
- N = No. of turns
- A_{eff} = effective magnetic area
- l_{eff} = effective magnetic length

$$l'_{eff} \sim l_{eff} + l_{gap} \mu_r$$



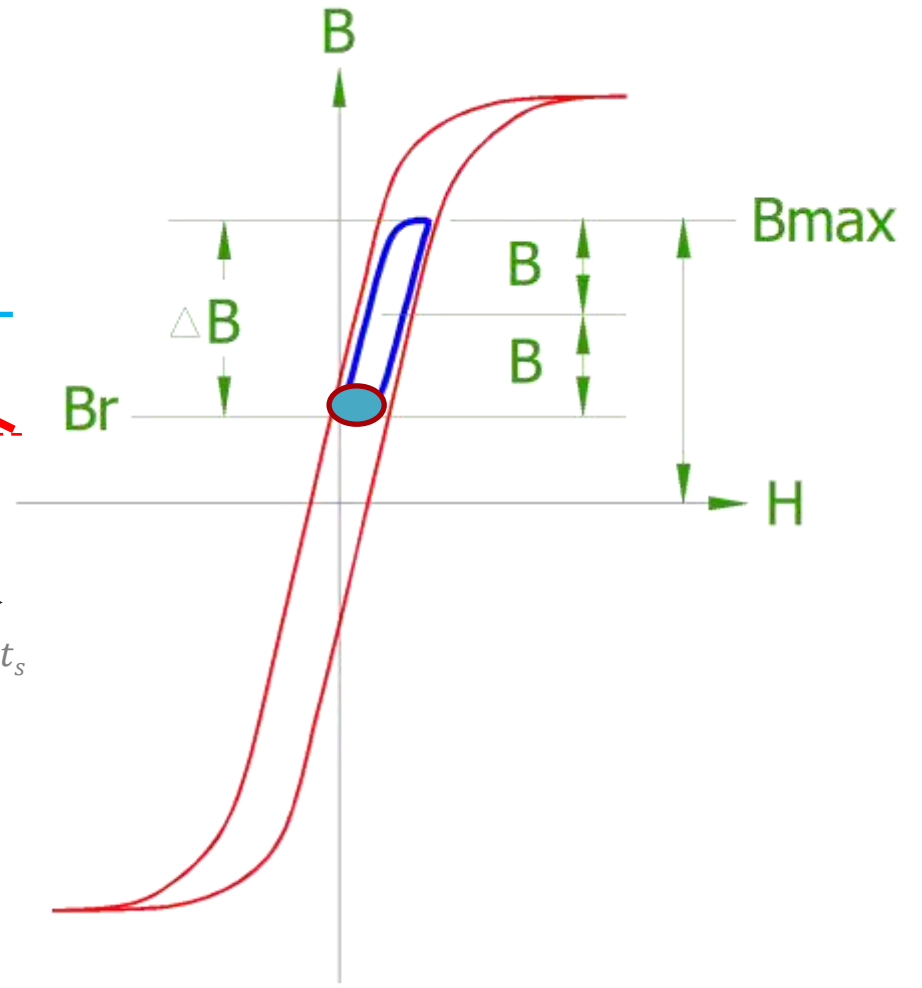
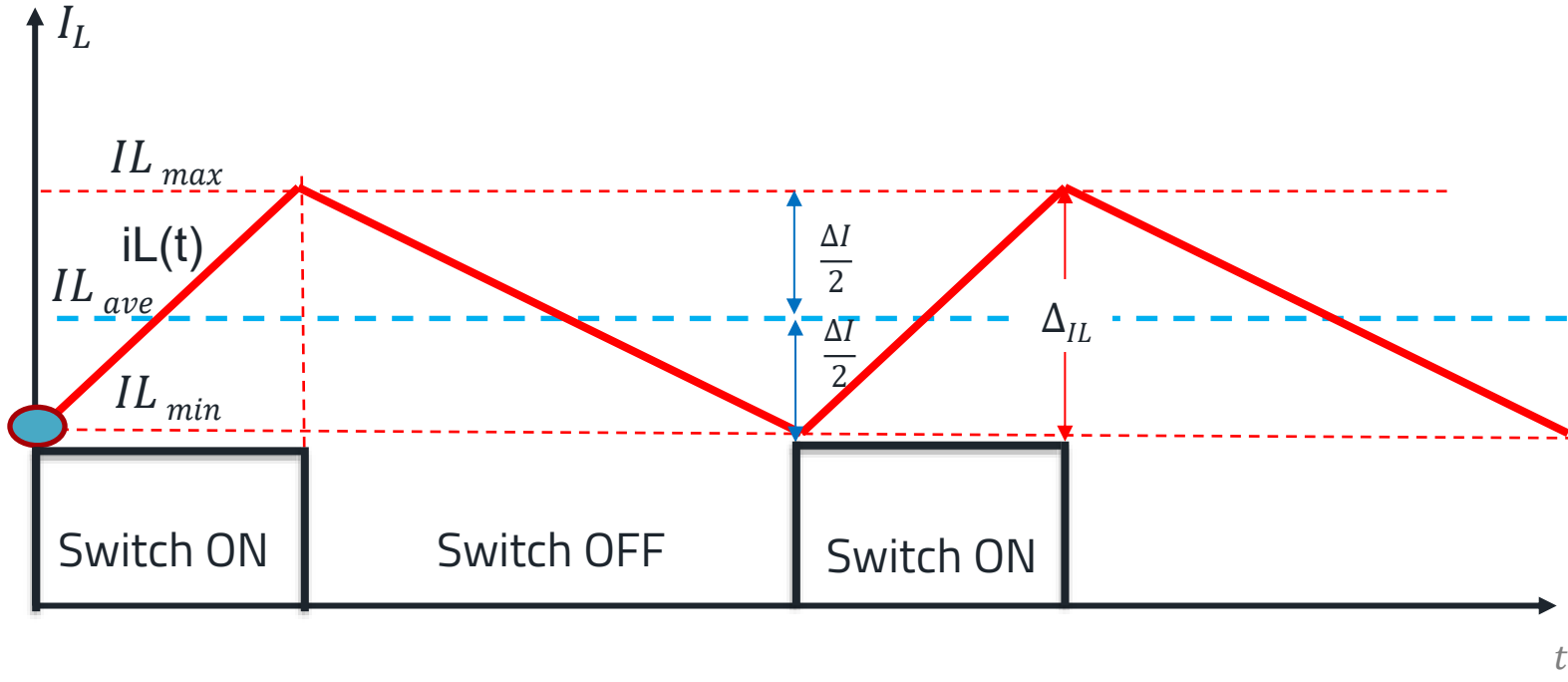
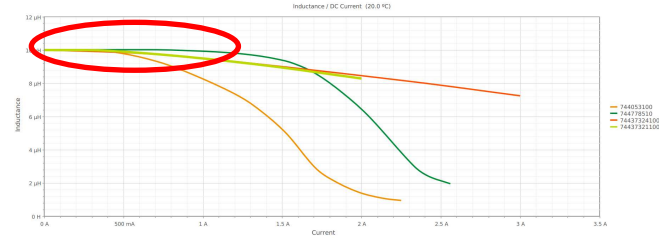
Size of air gap

ARE WE SOFT OR HARD?



POWER INDUCTORS

Cycle explanation : linear behavior (Buck in Steady State)

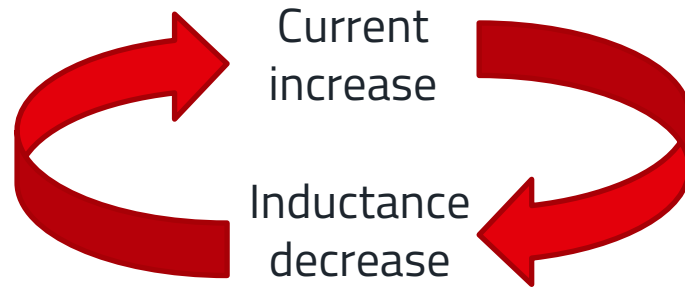
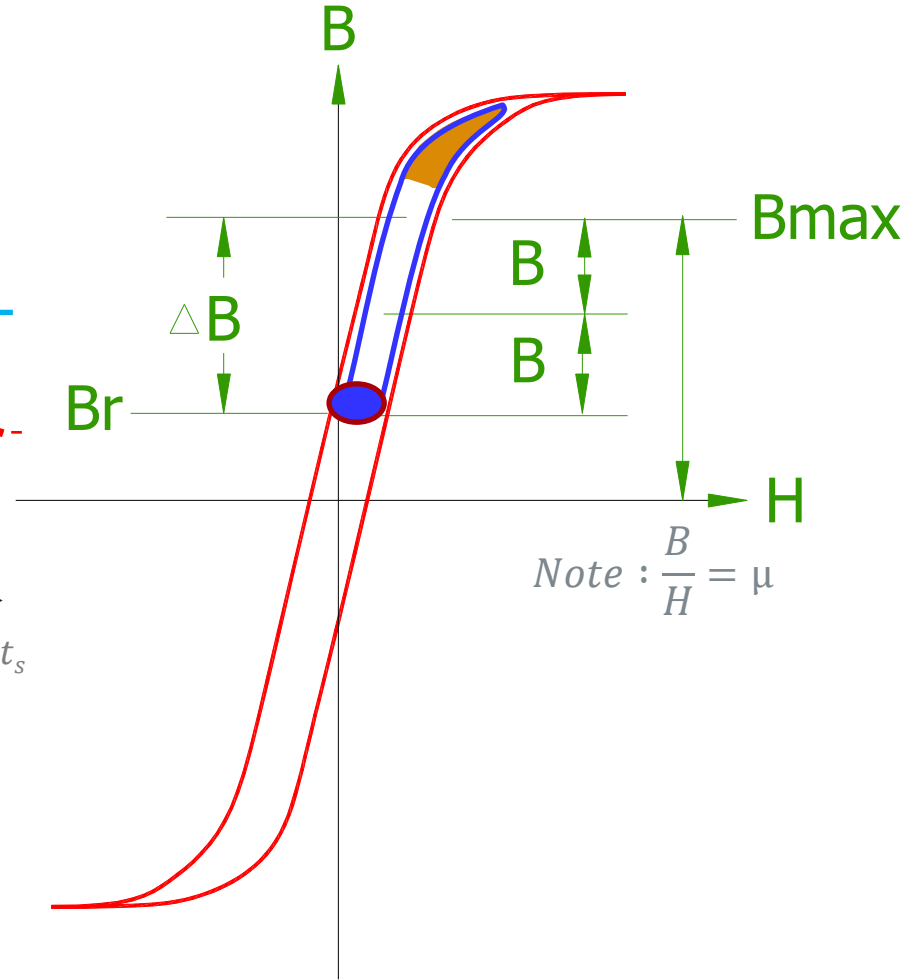
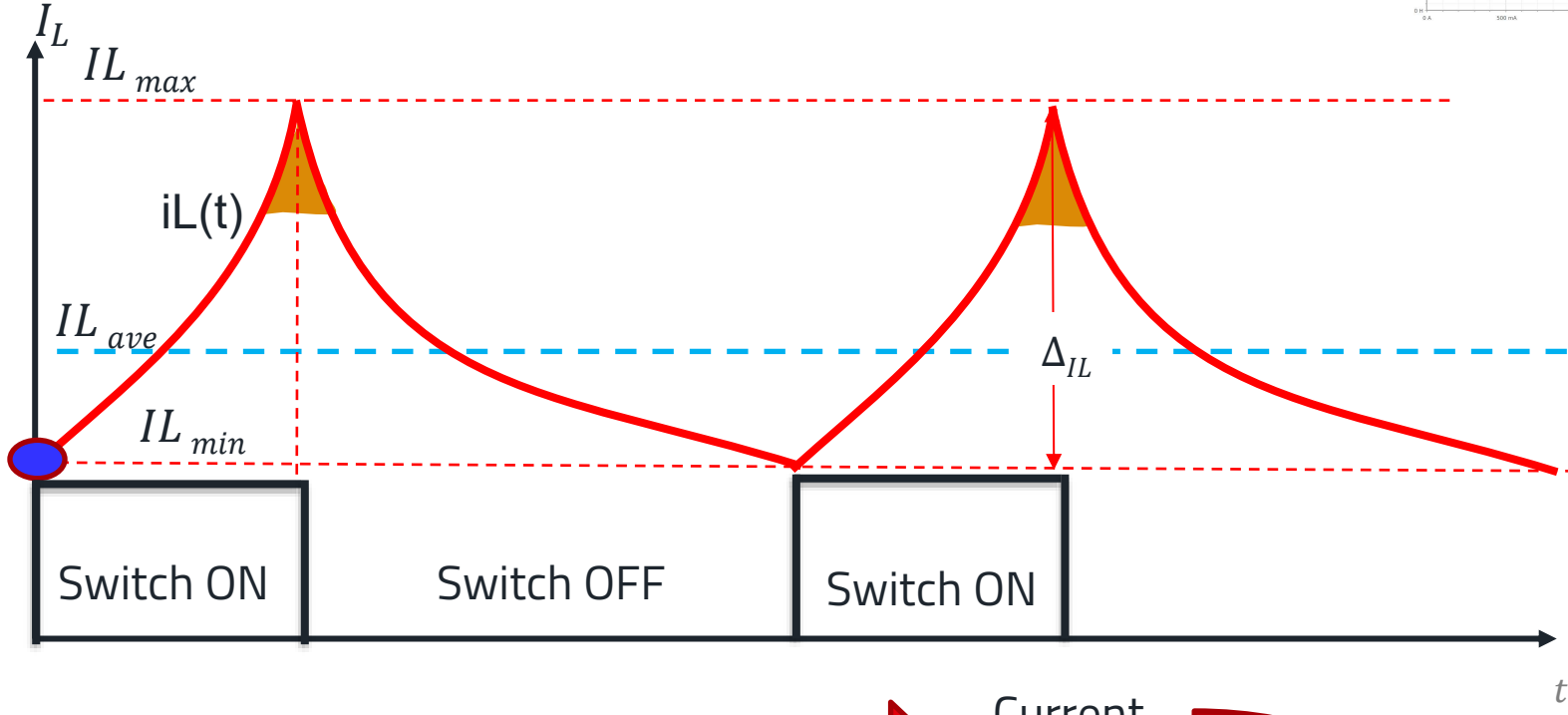
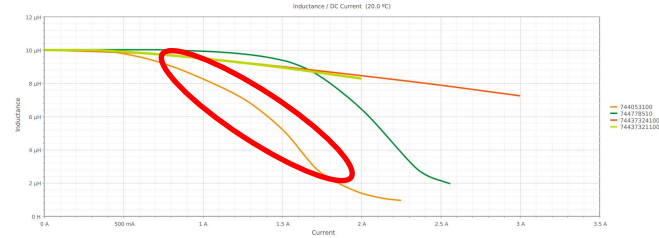


$$V = L \frac{di}{dt}$$



POWER INDUCTORS

Cycle explanation : saturation behavior



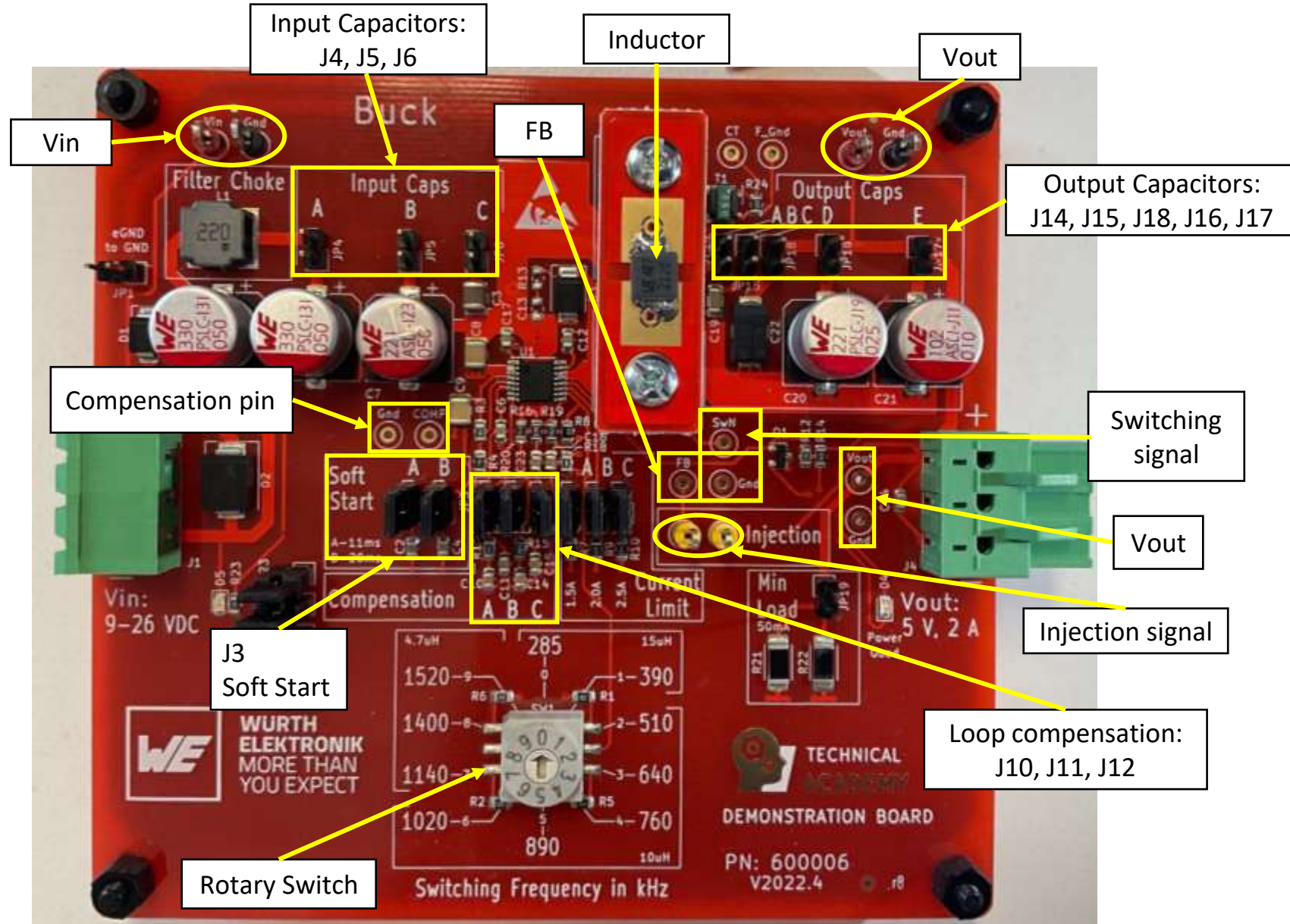
BUCK DEMO BOARD

Overview

General Specification

- DC/DC Buck Converter
 - *CCM*
 - $V_{in} = 9-26V$
 - $V_{out} = 5V$
 - $I_{out,max} = 2A$
 - $P_{out,max} = 10W$
 - $f_{sw} = 285kHz - 1.52MHz$

- Inductor: 10 μ H/3A WE-LHMI 74437346100

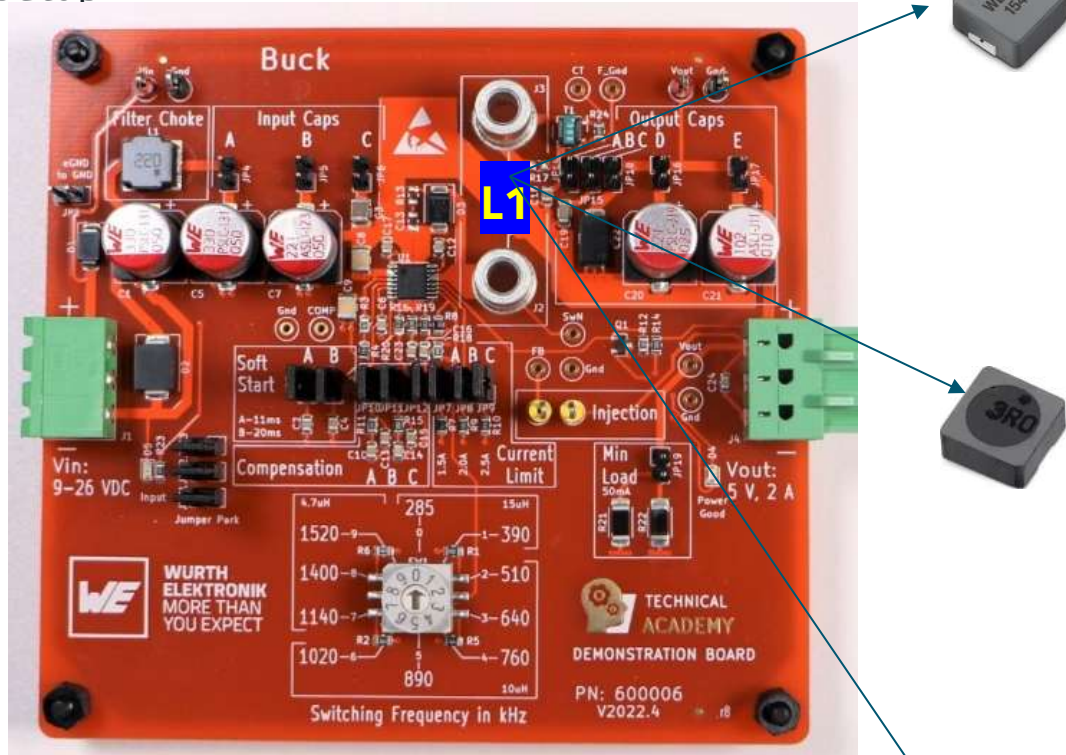


POWER INDUCTORS

Theory : Ripple vs Inductor Saturation

■ Buck_Board Setup:

- 19V input
- 5V output
- 510kHz,
- output 1A



■ REDEXPERT: Compare values for I_{sat}

Electrical Properties: [10μH WE-LHMI#74437324100](#)

Properties		Test conditions	Value	Unit	Tol.
Inductance	L	100 kHz/ 10 mA	10	μH	±20%
Performance Rated Current ¹⁾	$I_{RP,40K}$	$\Delta T = 40 K$	1.95	A	max.
Saturation Current @ 10%	$I_{SAT,10\%}$	$ \Delta L/L < 10 \%$	1.5	A	typ.
Saturation Current @ 30%	$I_{SAT,30\%}$	$ \Delta L/L < 30 \%$	3.15	A	typ.

Electrical Properties: [10μH WE-TPC#744053100](#)

Properties		Test conditions	Value	Unit	Tol.
Inductance	L	100 kHz/ 100 mV	10	μH	±30%
Rated Current	I_R	$\Delta T = 30 K$	1.5	A	max.
Saturation Current	I_{SAT}	$ \Delta L/L < 35 \%$	1.4	A	typ.

Electrical Properties: [10μH WE-PD# 744778510](#)

Properties		Test conditions	Value	Unit	Tol.
Inductance	L	100 kHz/ 250 mV	10	μH	±25%
Rated Current	$I_{R,40K}$	$\Delta T = 40 K$	1.9	A	max.
Performance Rated Current ¹⁾	$I_{RP,40K}$	$\Delta T = 40 K$	2	A	max.
Saturation Current @ 10%	$I_{SAT,10\%}$	$ \Delta L/L < 10 \%$	1.6	A	typ.

POWER INDUCTORS

Theory : some calculations

- Maths with formulas (option)
 - Tip : take into account V_f of diode 0,5V, more precise calculation onto low voltage (5V)

$$D = \frac{V_{out} (+V_f)}{V_{in}} = \frac{5 (+0,5)}{19} = 26\% \sim 29\% \text{ with diode}$$

$$\Delta_{IL} = \frac{(V_{in} - V_{out}) * V_{out}}{f_{switch} \cdot L \cdot V_{in}} = \frac{(19 - 5) \cdot 5}{510k \cdot 10\mu \cdot 19} = \frac{70}{97} = 0,72A \sim 0,77A \text{ with diode}$$

$$\Delta_{IL\%} = \frac{\Delta_{IL}}{I_{Lave}} = 72\%$$

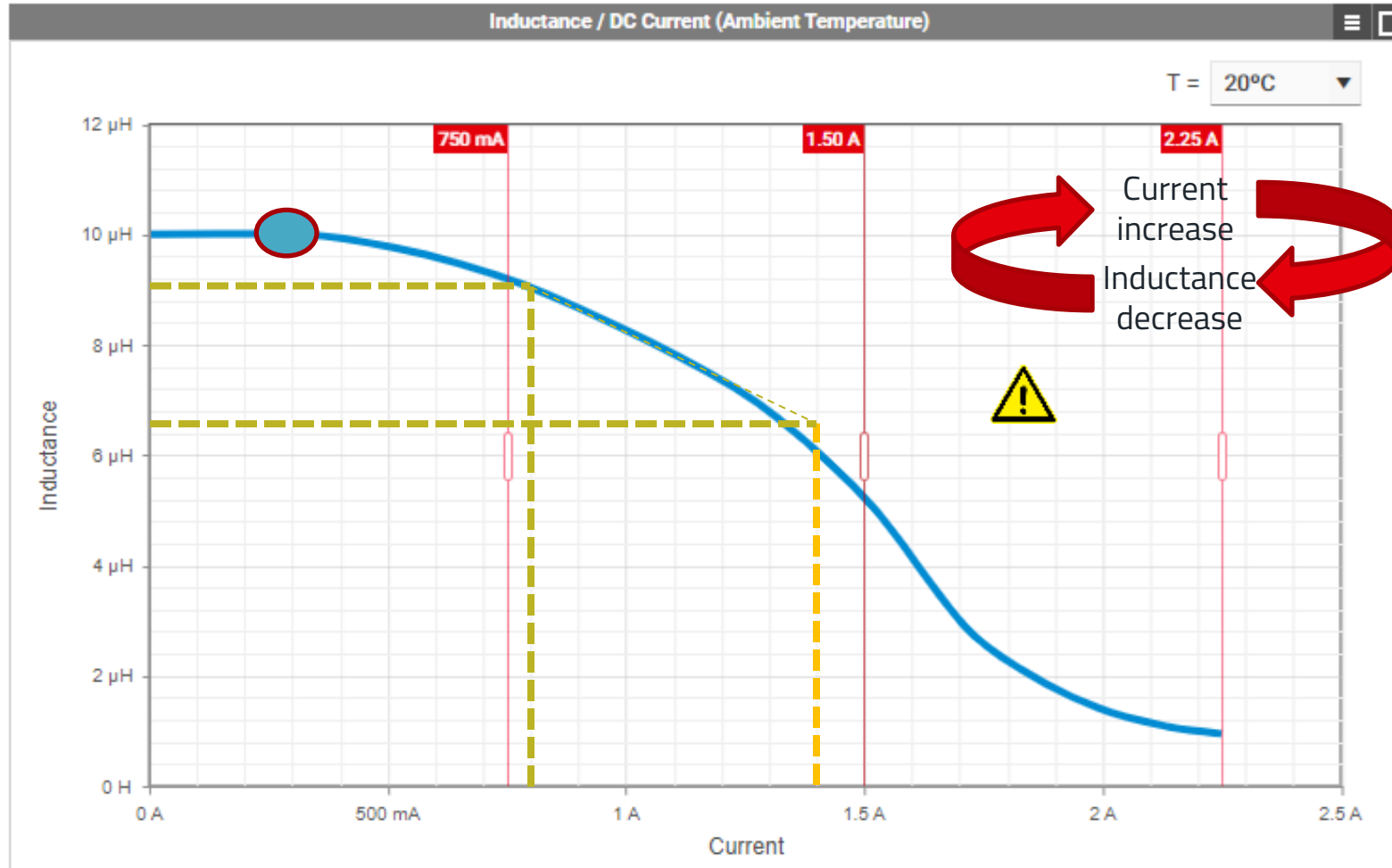
$$I_L \in [0,64; 1,36]A$$

$$\Delta_{IL\%} = \frac{\Delta_{IL}}{I_{Lave}} = 77\% \text{ with diode}$$

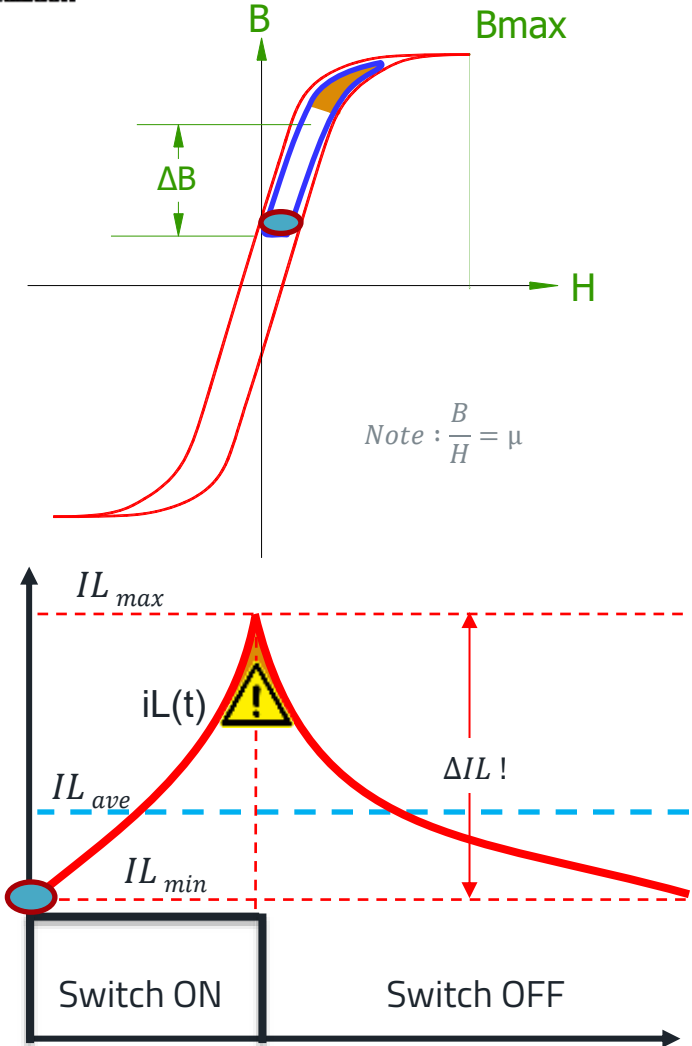
$$I_L \in [0,61; 1,39]A$$

POWER INDUCTORS

REDEXPERT [WE-TPC# 744053100](#) deviation explanation for 10 μ H $I_{sat} = 1,40A$



Calculation



POWER INDUCTORS

REDEXPERT: **Expected $\Delta I_L \approx 720mA$**



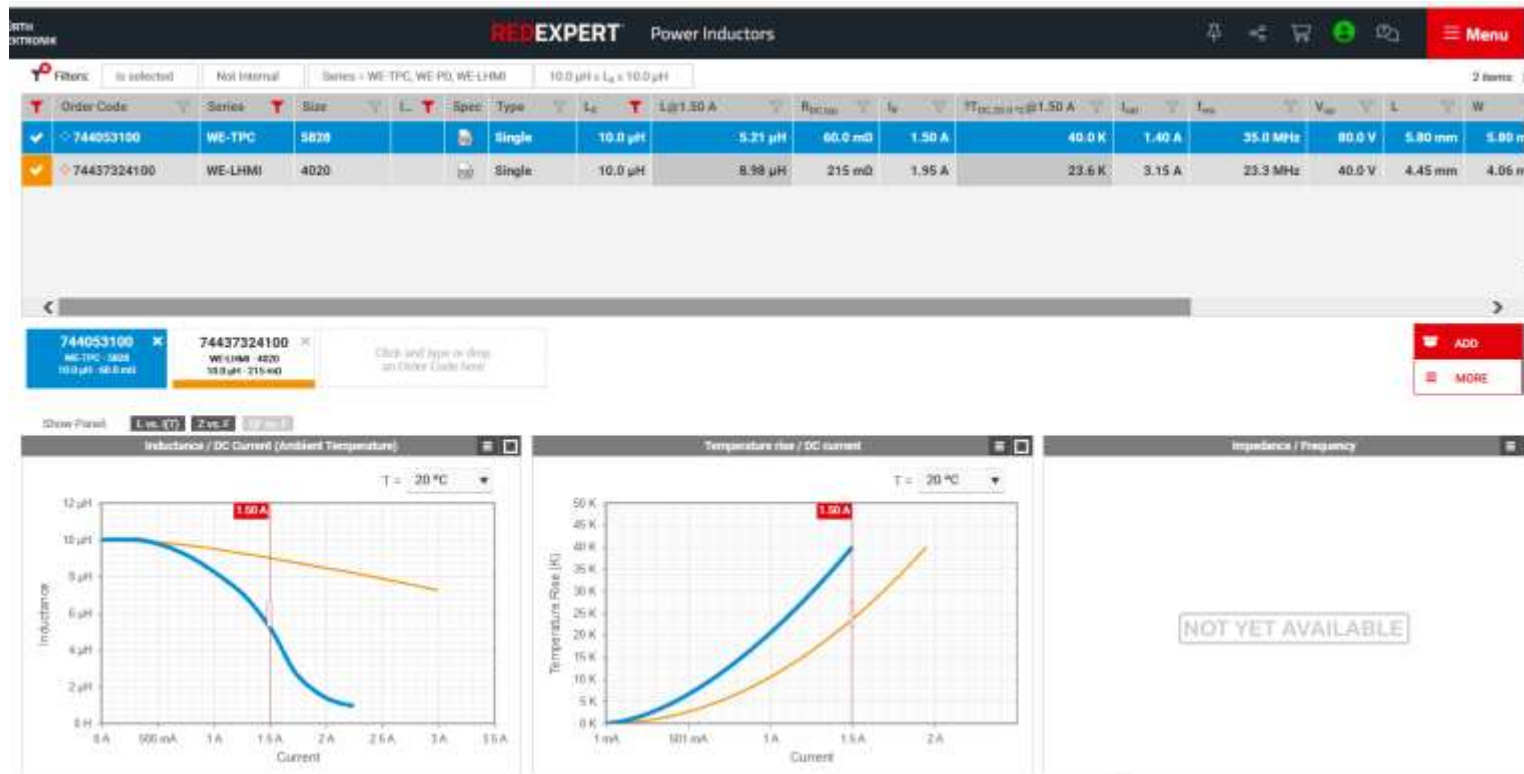
10 μ H WE-LHMI#74437324100 $I_{sat}=1,5A$

Vs

10 μ H WE-TPC#744053100 $I_{sat}=1,4A$



- **Measurement vs Redexpert !**
 - Expected **HARD** saturation effect for $I_L \approx 1A, P_o = 5W$



POWER INDUCTORS

Practical Measurement: **Expected $\Delta I_L \approx 720mA$**

- **Measurement vs [Redexpert](#) !**
 - Expected **HARD** saturation effect for $I_L \approx 1A, P_o = 5W$

10 μ H [WE-LHMI#74437324100](#) Isat=1,5A



Vs

10 μ H [WE-TPC#744053100](#) Isat=1,4A



Practical Measurement

BH CURVES MEASUREMENTS

Scope setup

Make comparison between two inductors

- Inductor:

- **10μH** [WE-LHMI#74437324100](#)

- 1.5A Saturation current

- **10μH** [WE-TPC #744053100](#) [5828]

- 1,4A Saturation current

- Scope

- X axis (H)

- CH3 (current inside the inductor)

- Y axis (B)

$Math1 = CH2(V_{sw}) - CH1(V_{out})$ (Voltage across the inductor)

- $Math2 = \int Math1 = \int CH2 - CH1 = \int V_L dt$

$$H(t) = \frac{n \cdot I(t)}{l_{eff}}$$

H is directly related to current

- $V_L(t) = n \cdot \frac{d\Phi(t)}{dt} \quad \& \quad B(t) = n \frac{\Phi(t)}{A_c}$

$$\Rightarrow V_L(t) = n \cdot A_c \frac{dB(t)}{dt}$$

$$\Rightarrow \frac{dB(t)}{dt} = \frac{V_L(t)}{n \cdot A_c}$$

$$B(t) = \frac{1}{n \cdot A_c} \cdot \int V_L(t) dt$$

B is directly related to \int the inductor voltage

TEMPERATURE EFFECT



POWER INDUCTORS

Temperature effect

- **Measurement VS Redexpert** ! 1.5A load / 5Vout
 - Expected **HARD** saturation effect (Small Air gap WE-PD)
 - Expected **SOFT** saturation effect (Molded WE-LHMI)

10 μ H WE-PD# 744778510 Isat=1,9A **Ambient 25 DegC** Vs **10 μ H WE-PD# 744778510** Isat=1,9A **Hot 60-80 DegC**

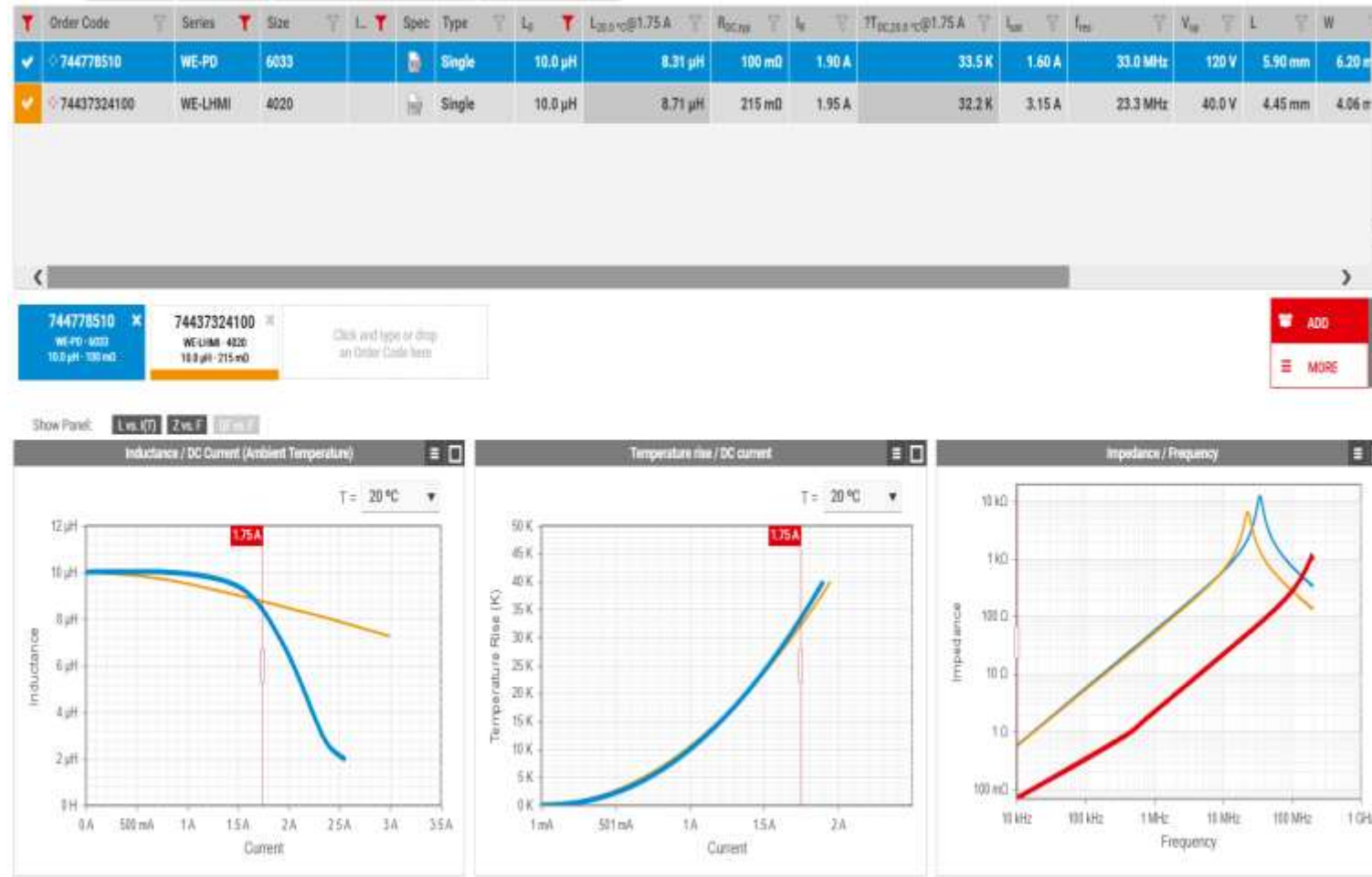


10 μ H WE-LHMI#74437324100 Isat=1,5A **Ambient 25DegC** Vs **10 μ H WE-LHMI#74437324100** Isat=1,5A **Hot 60-80DegC**



POWER INDUCTORS

REDEXPERT - Temperature effect Ambient 25 DegC



POWER INDUCTORS

REDEXPERT - Temperature effect Hot 60-80 DegC



POWER INDUCTORS

Practical Measurement - **Temperature effect**

- Measurement VS [Redexpert](#) ! 1.5A load / 5Vout
 - Expected **HARD** saturation effect (Small Air gap WE-PD)
 - Expected **SOFT** saturation effect (Molded WE-LHMI)

10 μ H WE-PD# 744778510 Isat=1,9A **Ambient 25 DegC** Vs **10 μ H WE-PD# 744778510** Isat=1,9A **Hot 60-80 DegC**



10 μ H WE-LHMI#74437324100 Isat=1,5A **Ambient 25DegC** Vs **10 μ H WE-LHMI#74437324100** Isat=1,5A **Hot 60-80DegC**



Practical Measurement

VOLTAGE RATING;
NECESSARY OR A GIMMICK



MOLDED INDUCTOR VOLTAGE RATING

App Note 126

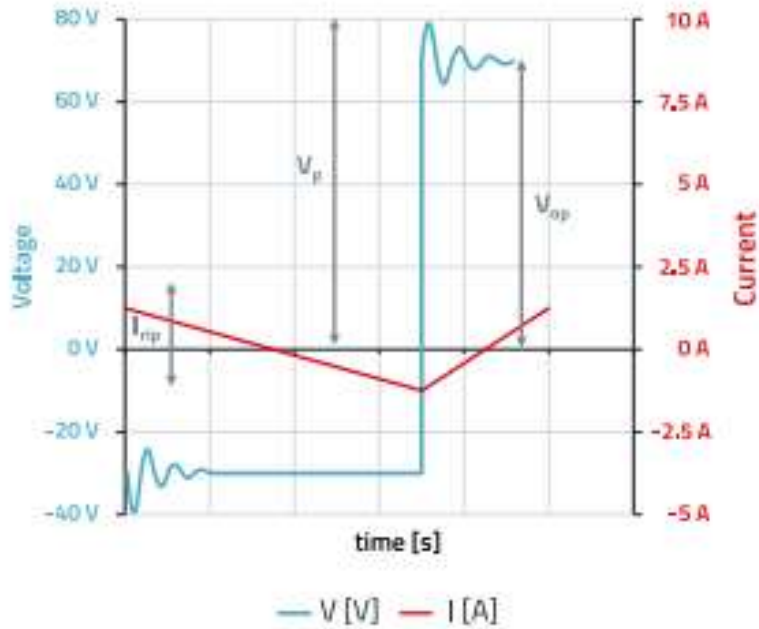


Figure 2: Inductor waveform – Delimitation V_p and V_{op}

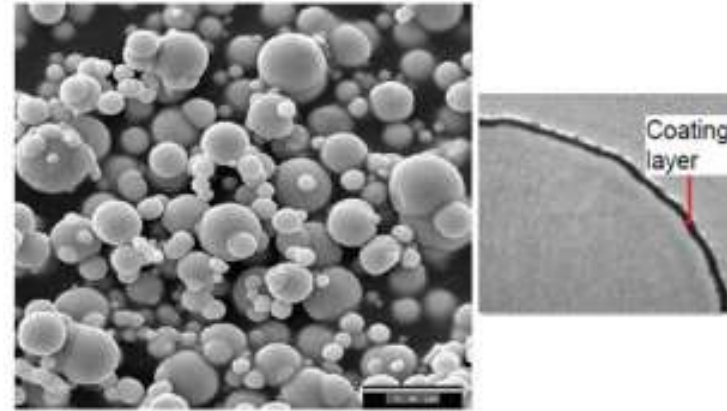


Figure 3: Microscopic analyze of a powder structure of a molded inductor [Zoom: $5\mu\text{m}$]

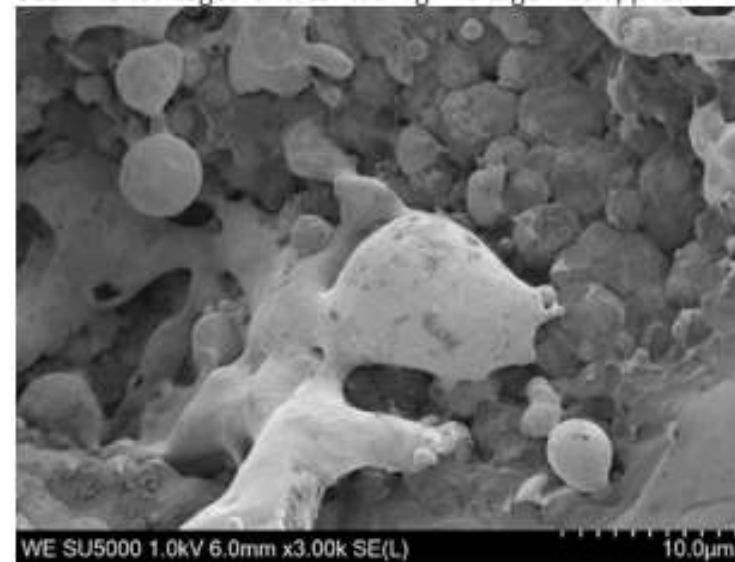


Figure 4: Microscopic analyze of a melted powder structure of a molded inductor [Zoom: $10\mu\text{m}$]

MOLDED INDUCTOR VOLTAGE RATING

[App Note 126](#)



Figure 6: RDC and inductance measurement of component without voltage defect (left) and with voltage defect (right)



Figure 8: Screen capture of the ripple current undamaged component (left) and damaged component (right)

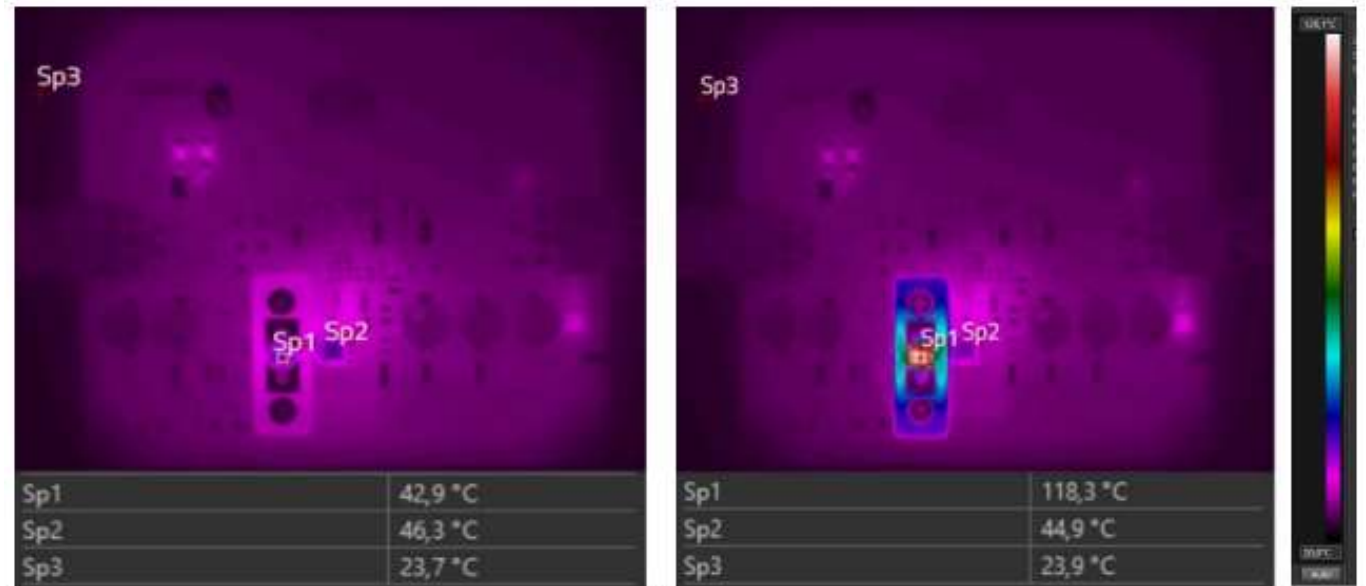
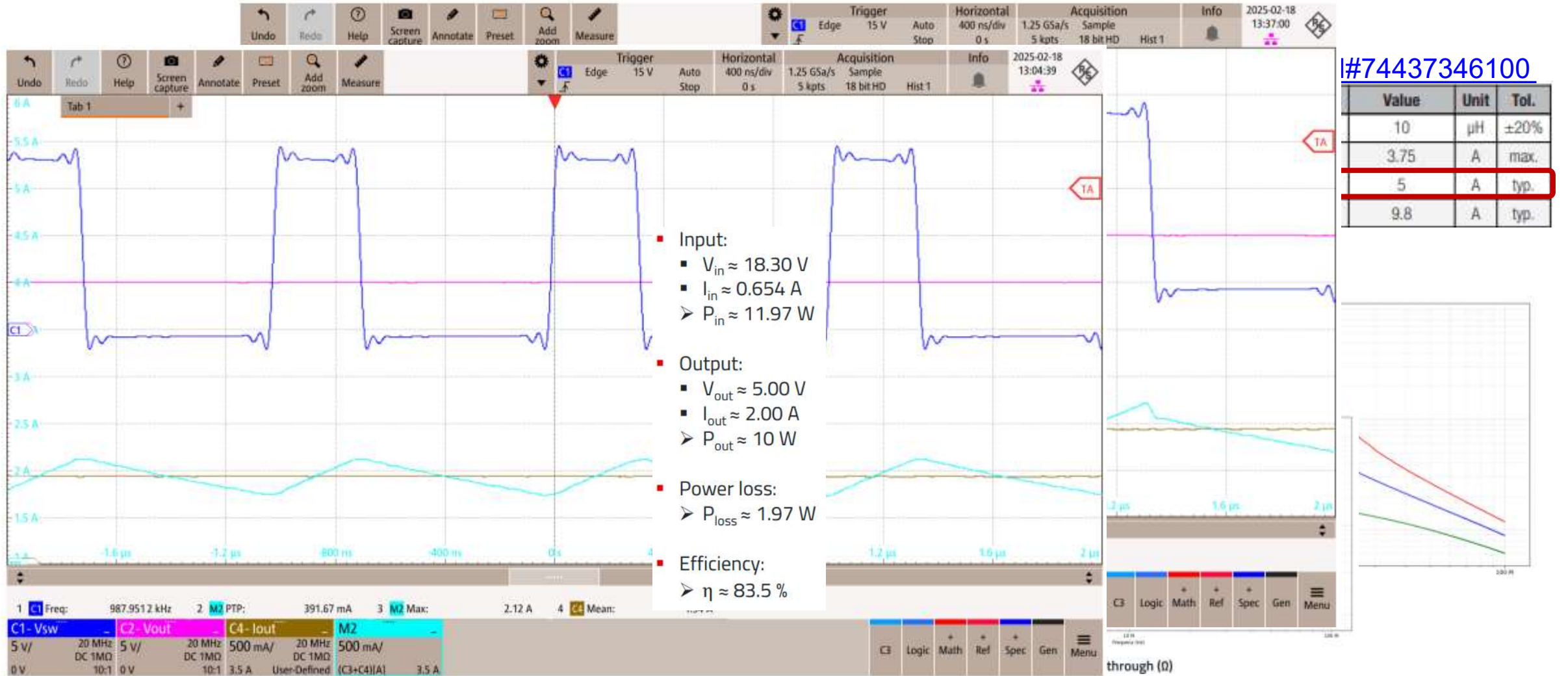


Figure 11: Self-heating recording of the undamaged component (left) and damaged component (right)

MOLDED INDUCTOR VOLTAGE RATING

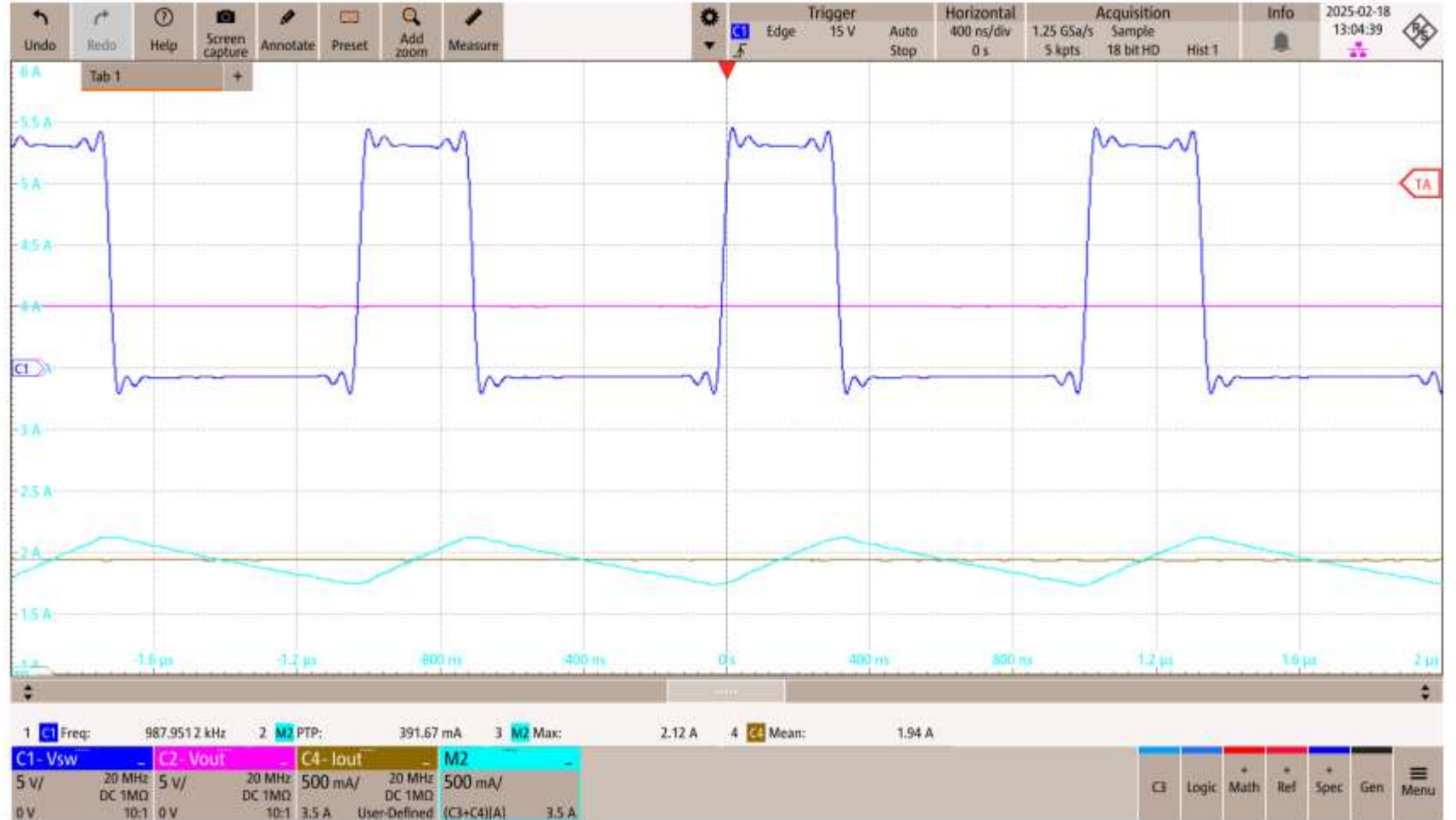
Practical measurement



MOLDED INDUCTOR VOLTAGE RATING

Practical measurement – New Part

- Input:
 - $V_{in} \approx 18.30 \text{ V}$
 - $I_{in} \approx 0.654 \text{ A}$
 - $P_{in} \approx 11.97 \text{ W}$
- Output:
 - $V_{out} \approx 5.00 \text{ V}$
 - $I_{out} \approx 2.00 \text{ A}$
 - $P_{out} \approx 10 \text{ W}$
- Power loss:
 - $P_{loss} \approx 1.97 \text{ W}$
- Efficiency:
 - $\eta \approx 83.5 \%$



MOLDED INDUCTOR VOLTAGE RATING

Practical measurement – HV Pulsed Part

- Input:
 - $V_{in} \approx 18.30 \text{ V}$
 - $I_{in} \approx 0.691 \text{ A}$
 - $P_{in} \approx 12.65 \text{ W}$
- Output:
 - $V_{out} \approx 5.00 \text{ V}$
 - $I_{out} \approx 2.00 \text{ A}$
 - $P_{out} \approx 10 \text{ W}$
- Power loss:
 - $P_{loss} \approx 2.65 \text{ W}$
- Power loss increase
 - $P_{loss} \approx 1.97 \text{ W}$ before
 - $P_{loss,inc} \approx 680 \text{ mW}$
- Efficiency:
 - $\eta \approx 79.1\%$



AUDIBLE NOISE



DC/DC CONVERTER AUDIBLE NOISE (BUZZING)

Cause

- Excitation in the audible frequency range of an inductor
- Audible frequency range is from 20Hz to 20kHz (Depending on your age)
- Switching frequencies >> audible range. Why do we hear it !!! ???
- Go to [APP NOTE 118 - Acoustic noise & Coil whine effect](#)

DC/DC CONVERTER AUDIBLE NOISE

ACTIVE EXAMPLE – Selecting the wrong inductance

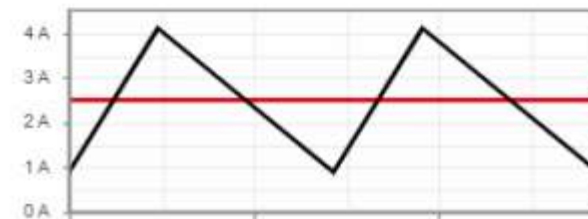
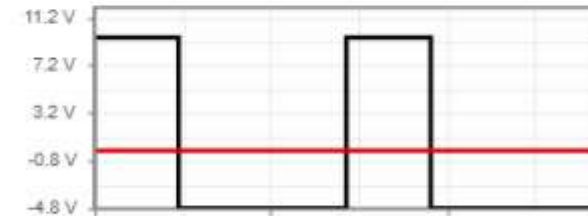
- Using MP8759
- Using 1.5uH Inductance value
- Rather low by our standards at Würth, we suggest 40% ripple.
- Even MPS in their own datasheet recommend 30-40% ripple factor yet they recommend 1.5uH!

Selecting the Inductor

The inductor is necessary for supplying a constant current to the output load while being driven by the switched input voltage. An inductor with a larger value results in less ripple current and lower output ripple voltage. However, it also has a larger physical footprint, higher series resistance, and lower saturation current. A good rule for determining the inductance value is to design the peak-to-peak ripple current in the inductor to be in the range of 30% to 40% of the maximum output current to ensure that the peak inductor current is below the maximum switch current limit. The inductance value can be

- Using the 1.5uH at 700kHz, will give > 100% ripple.

Buck Converter			
PARAMETERS			EDIT
Input	Output	Switch	Inductor
11.7-14.3 V	4.80 V 2.50 A	700 kHz	100 %
DETAILS			
$I_{L,max,opt}$	L_{opt}	$I_{L,avg}$	
3.75 A	1.82 μ H	2.50 A	
74438334015			
DC	ΔI_L	$I_{L,peak}$	T_{on}
0.34	3.21 A	4.10 A	480 ns

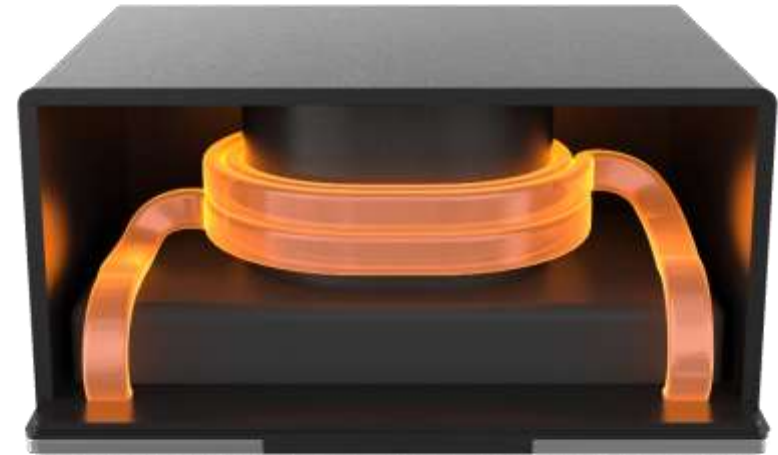
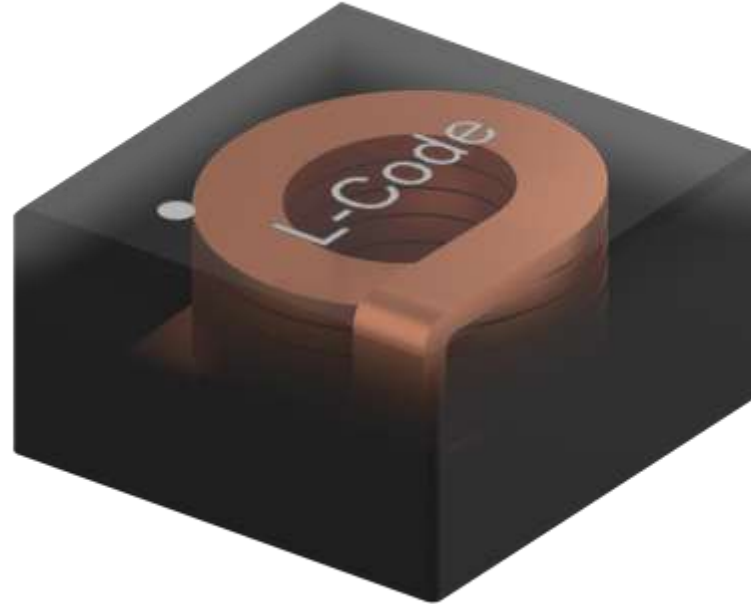


DC/DC CONVERTER AUDIBLE NOISE

One Option

Use inductors with low magnetostrictive deformation

- Ferrite-based inductors deform more and can cause noise.
- Inductors made of iron or iron alloy powder (WE-MXGI/LHMI/MAP/XHMI/....etc.) deform very little under the action of the ripple current and therefore are much less likely to cause noise.



EFFICIENT POWER INDUCTOR



INDUCTOR LOSSES

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

Core losses:

Hysteresis losses

Eddy current losses

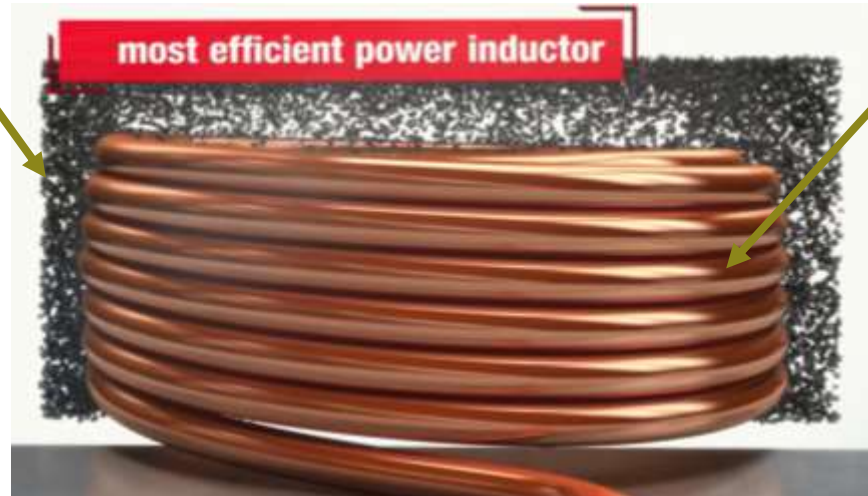
Copper losses:

DC losses – depending on DCR

AC losses – dep. on winding structure

→ Skin-Effect

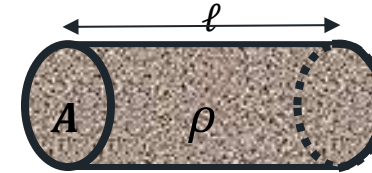
→ Proximity-Effect



INDUCTOR LOSSES : COPPER DC LOSSES



$$P_{cu} = R_{DC} * I_{RMS}^2$$



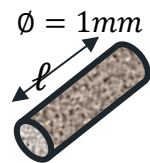
$$R_{DC} = \rho * \frac{l}{A}$$

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

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

$$R_{DC} \downarrow \Rightarrow P_{cu} \downarrow$$

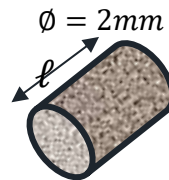
Optimization



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

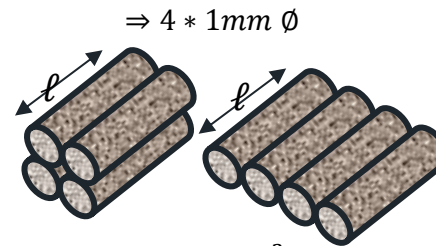
$$R_{DC} = 23 \text{ m}\Omega$$

$$l=1\text{m}$$



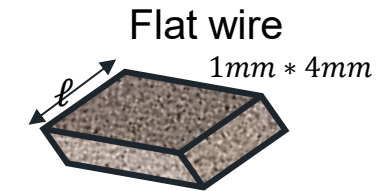
$$A = 3,714 \text{ mm}^2$$

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



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

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

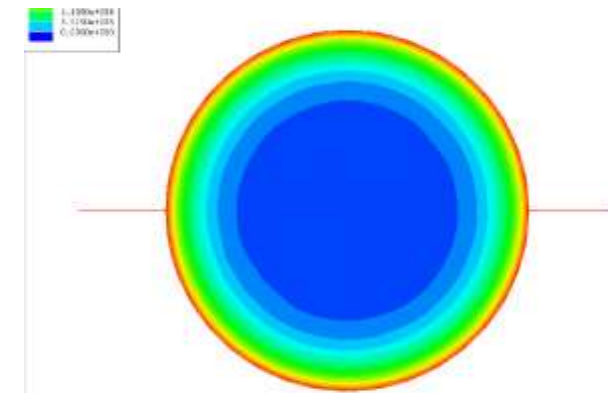
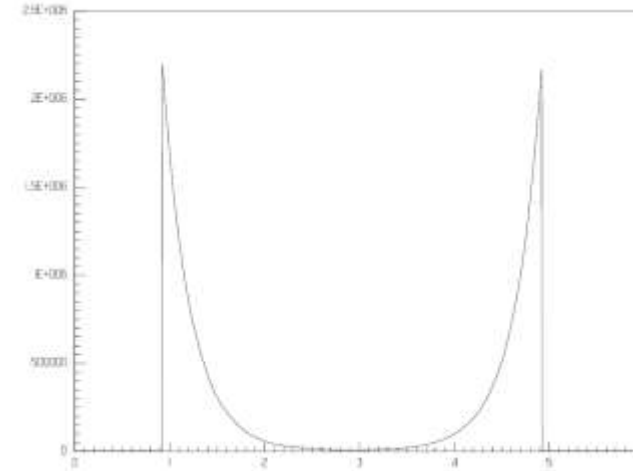
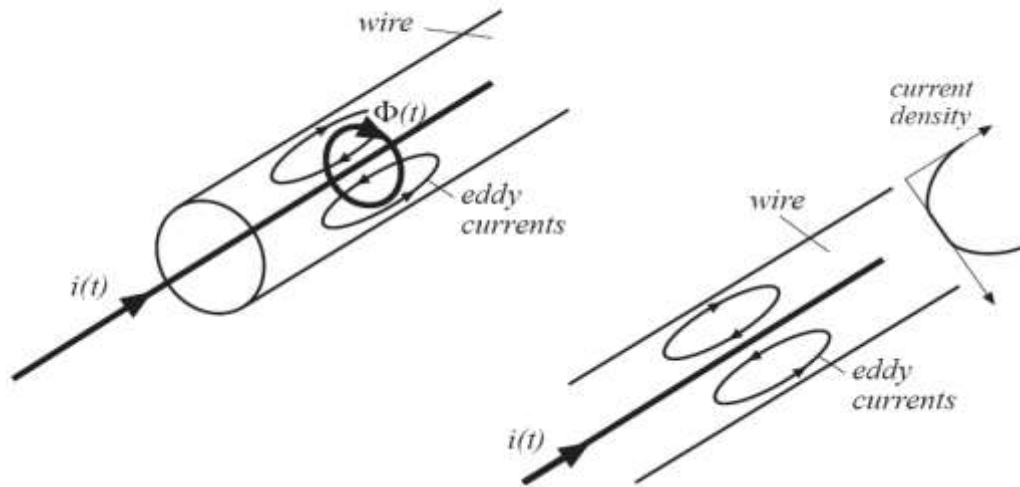


$$A = 4 \text{ mm}^2$$

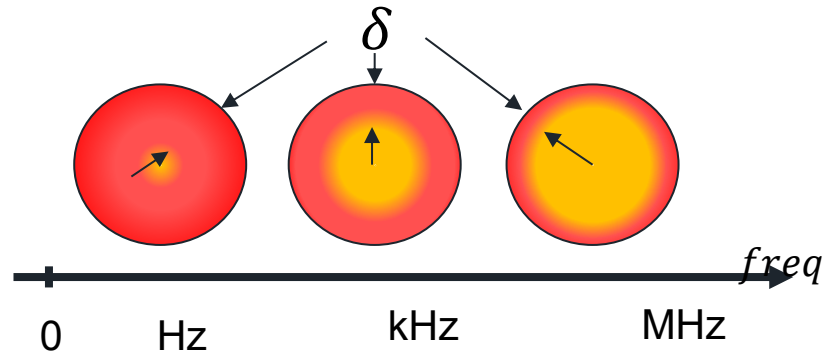
$$R_{DC} = 4,48 \text{ m}\Omega$$

INDUCTOR LOSSES : COPPER AC LOSSES

Eddy Currents in Wire



INDUCTOR LOSSES : COPPER AC LOSSES, SKIN EFFECT



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

δ = skin depth

ρ = resistivity

ω = angular frequency $2\pi f$

μ - permeability

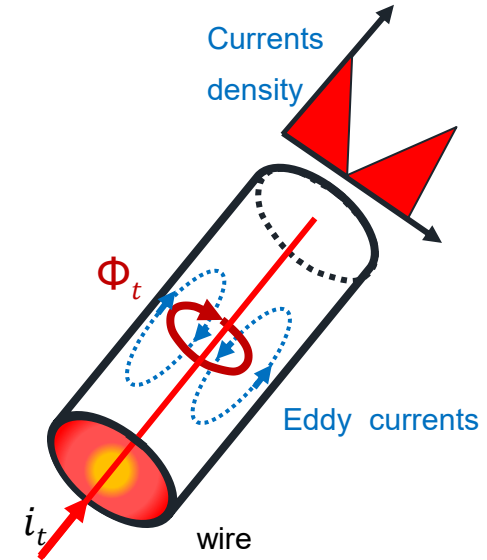
$$\delta = \frac{76}{\sqrt{f}} \text{ mm} \quad @ 100^\circ\text{C}$$

For Copper

$\delta @ 50\text{Hz} = 9.38 \text{ mm}$

$\delta @ 10\text{kHz} = 0.66 \text{ mm}$

$\delta @ 100\text{kHz} = 0.22 \text{ mm}$



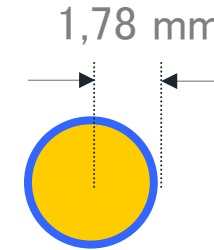
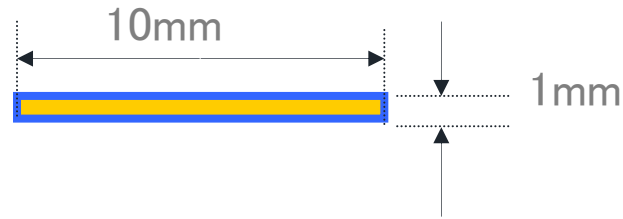
INDUCTOR LOSSES : COPPER AC LOSSES, SKIN EFFECT

Comparison:

flat wire

vs.

round wire



cross section of both wires is 10mm^2

BUT: flatwire has much more bigger surface

Flat wire surface : 22mm / round wire 11,18mm

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

AND: high frequency currents only use the surface

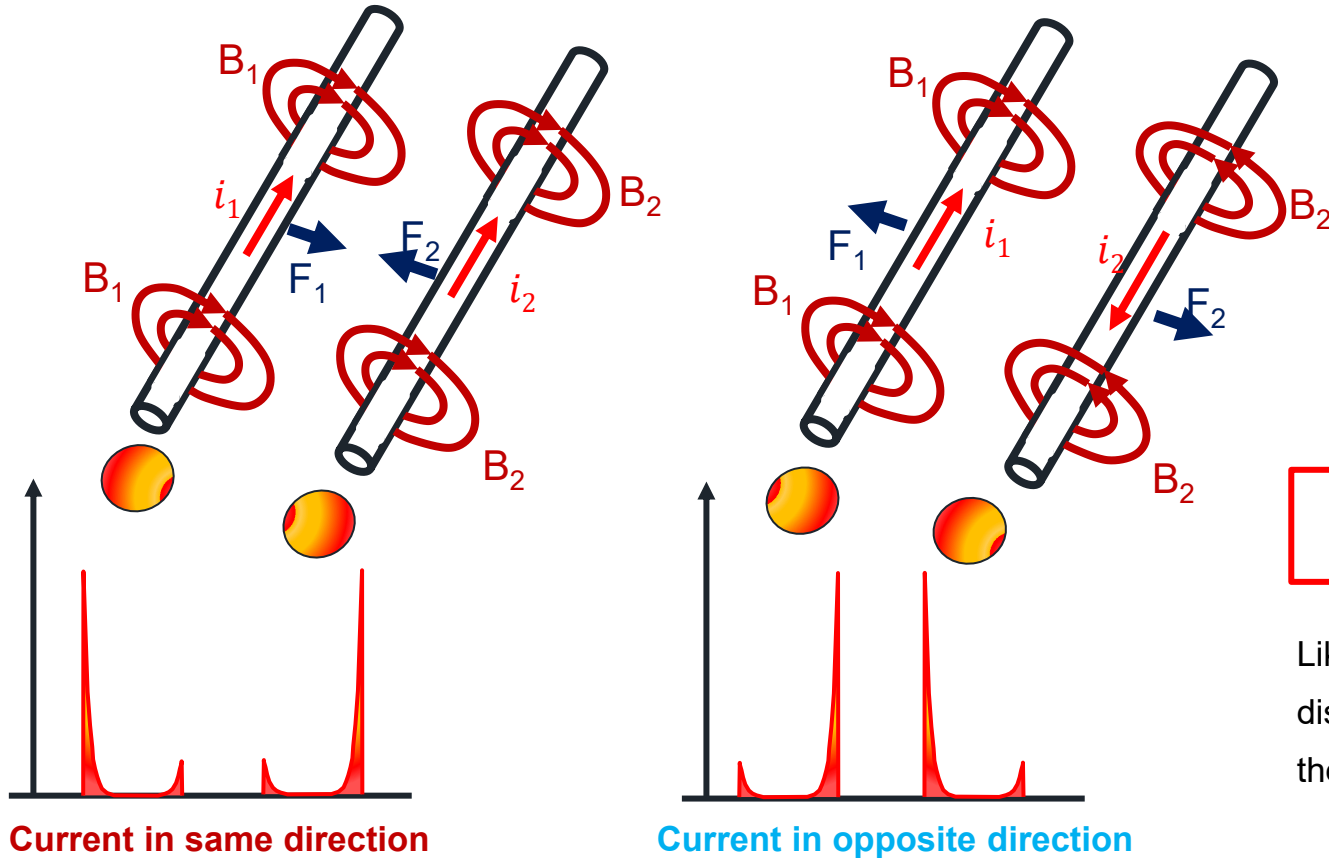
→ Skin effect



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



INDUCTOR LOSSES : COPPER AC LOSSES, PROXIMITY EFFECT



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

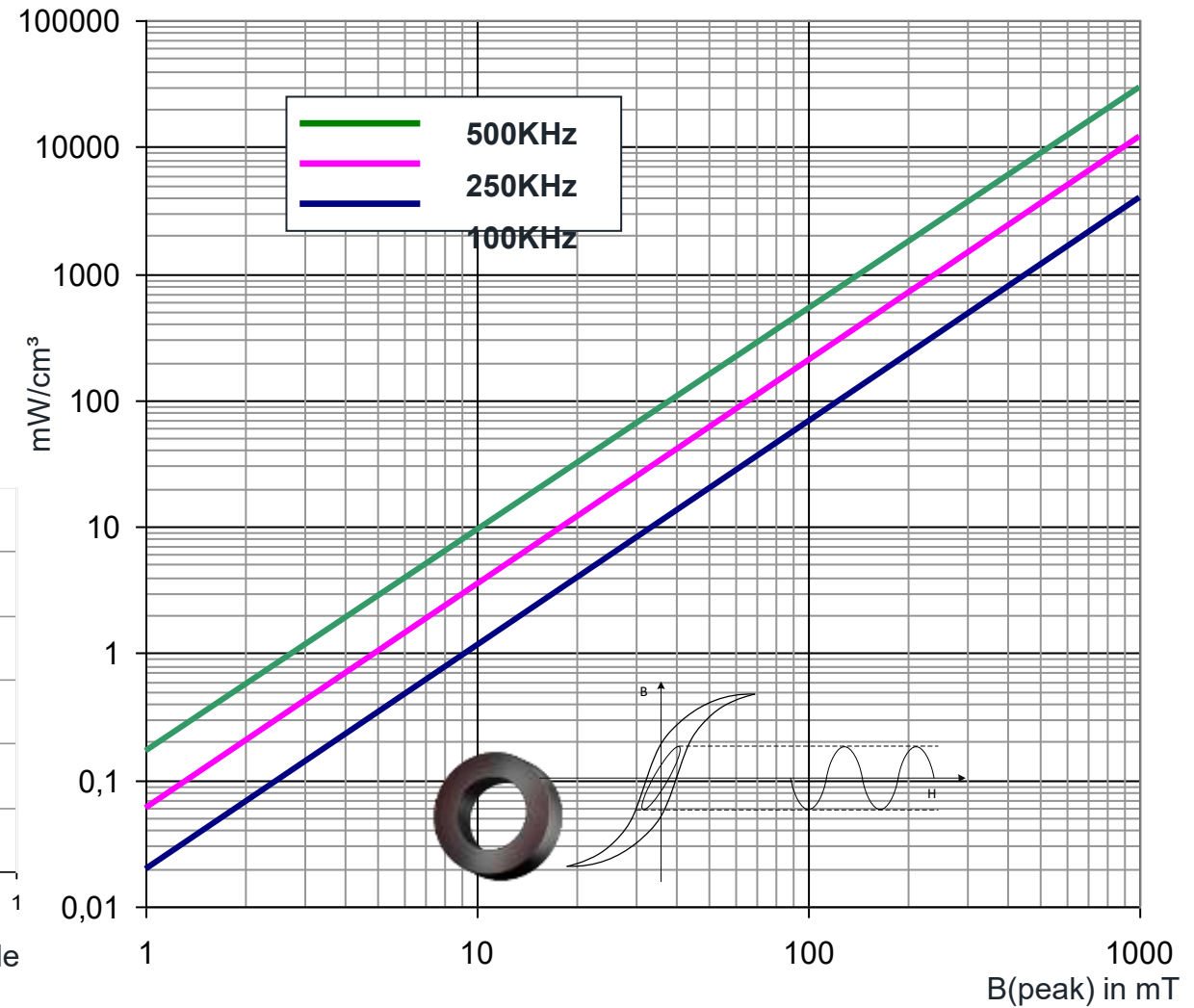
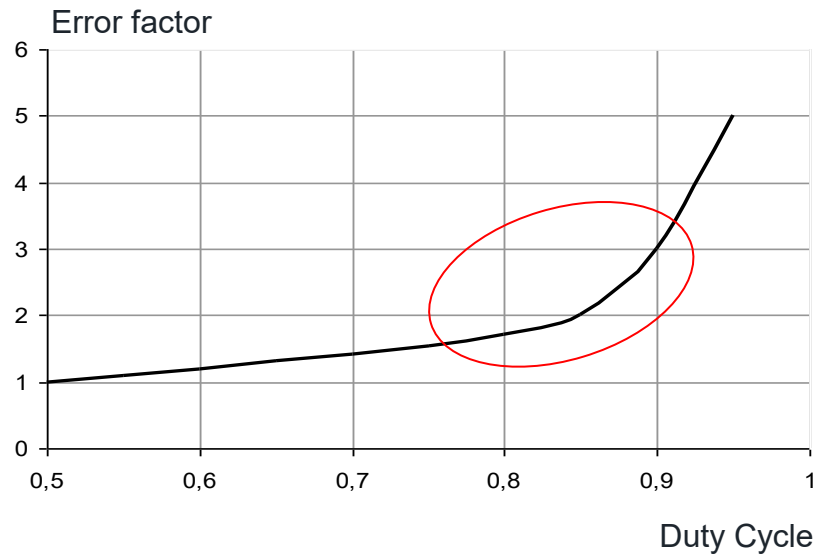
Like the skin effect, the distribution of current inside the wire is reduced

- 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

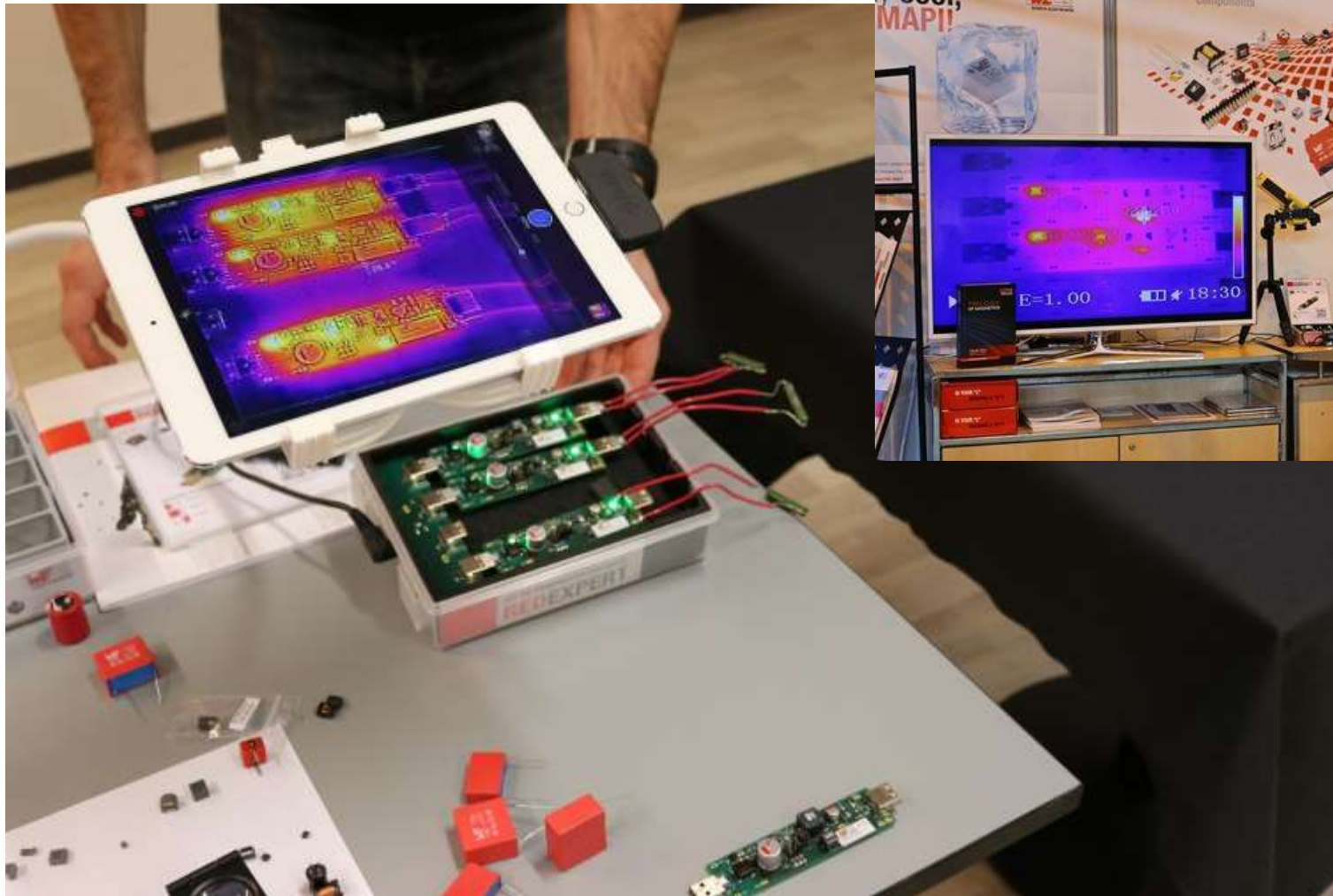
INDUCTOR LOSSES : CORE LOSSES

- Steinmetz formula

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



REDEXPERT – THE MISSING LINK

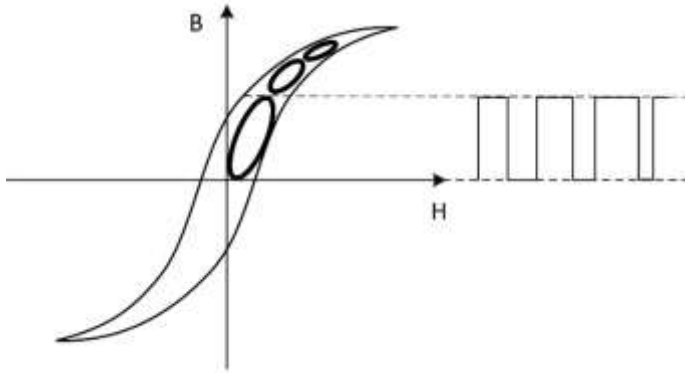


WORLD'S MOST ACCURATE AC LOSS MODEL

Wurth AC Loss Model

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

➔ Core Loss & AC Wire Loss



➔ Point of Operation Approach
triangular current form

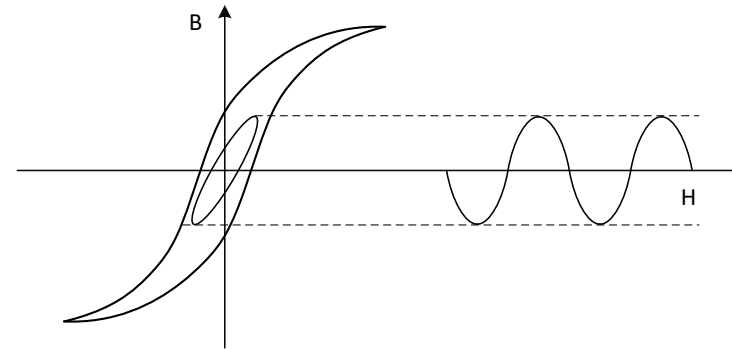
Steinmetz Models

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

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

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

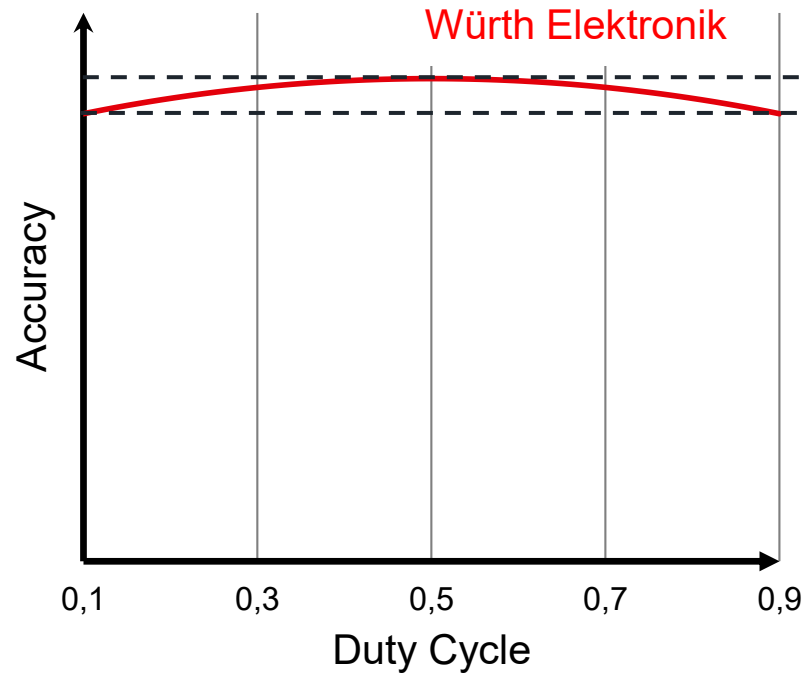
➔ Core Loss Only



➔ Major Loop Approach
only sine wave

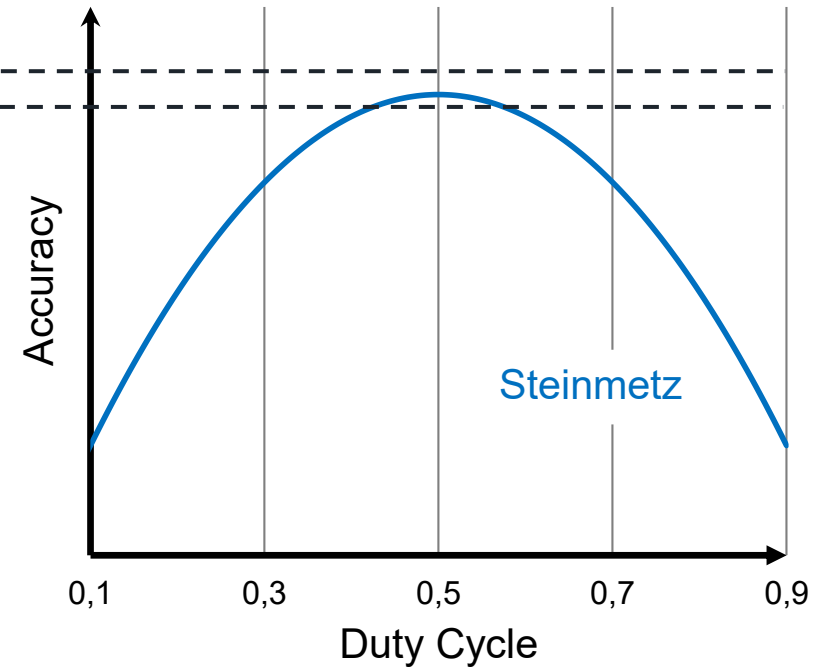
WORLD'S MOST ACCURATE AC LOSS MODEL

Würth AC Loss Model

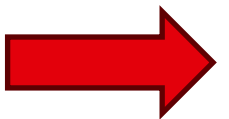


Highest Accuracy
over wide DC range

Steinmetz Models



Acceptable Accuracy at 50%,
even worse for other DC

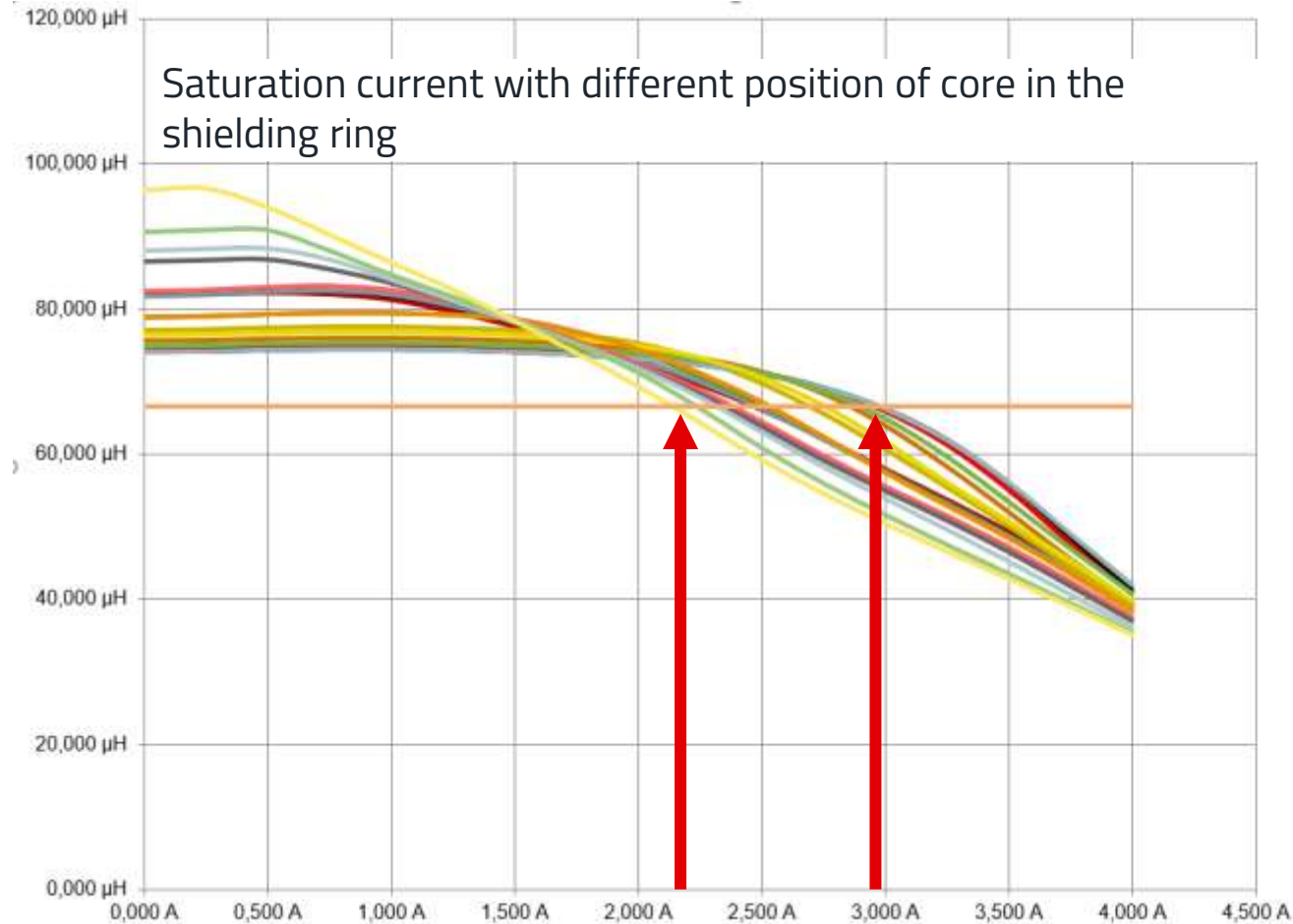


GOOD TO KNOW

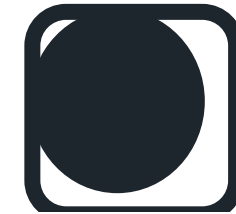
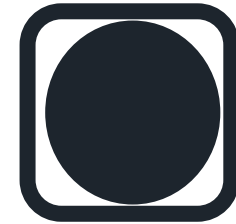


SATURATION CURRENT VS SHIELDING POSITION

If the production is not controlled the saturation current can change from one inductor to another.

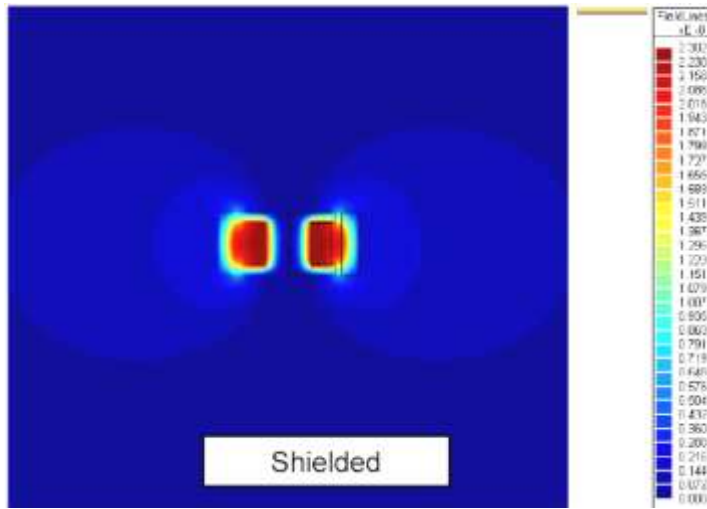


- Series1
- Series2
- Series3
- Series4
- Series5
- Series6
- Series7
- Series8
- Series9
- Series10
- Series11
- Series12
- Series13
- Series14
- Series15
- Series16
- Series17
- Series18



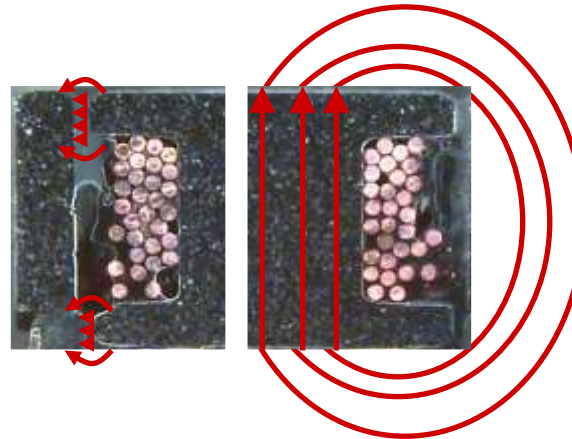
Special design helps to optimize the position of the core in order to reduce the tolerance of the inductance value.

INDUCTOR: SHIELDED VS UNSHIELDED



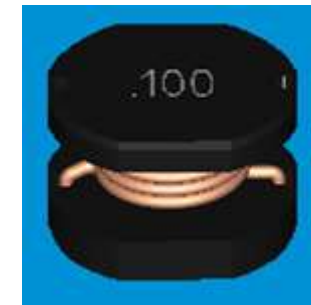
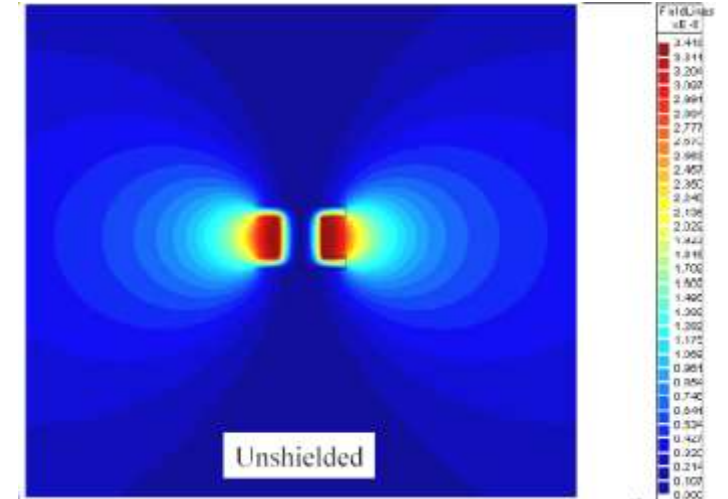
shielded

unshielded



smaller L_{eff}

bigger L_{eff}



With a shielded inductor the customer has a better chance to pass the EMC test

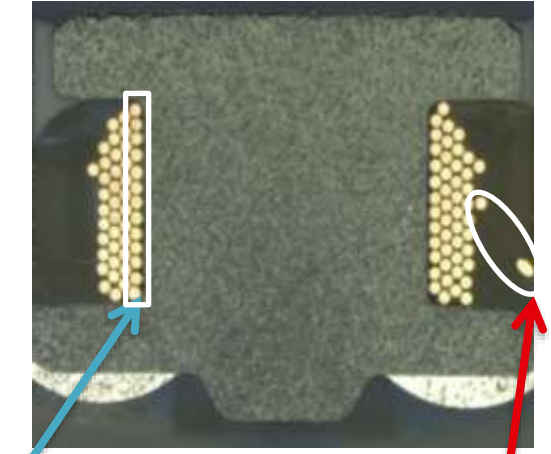
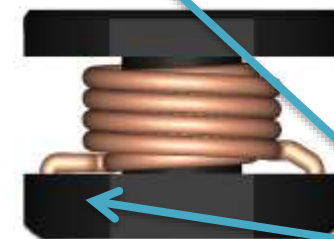
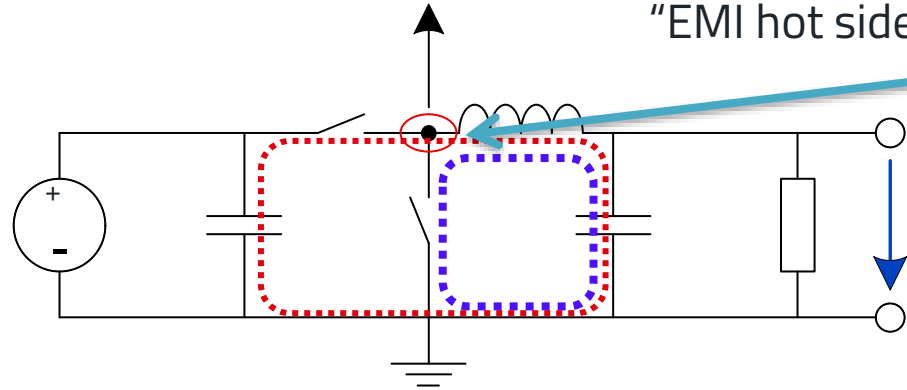


LAYOUT RECOMMENDATION

Start of winding : E shield !

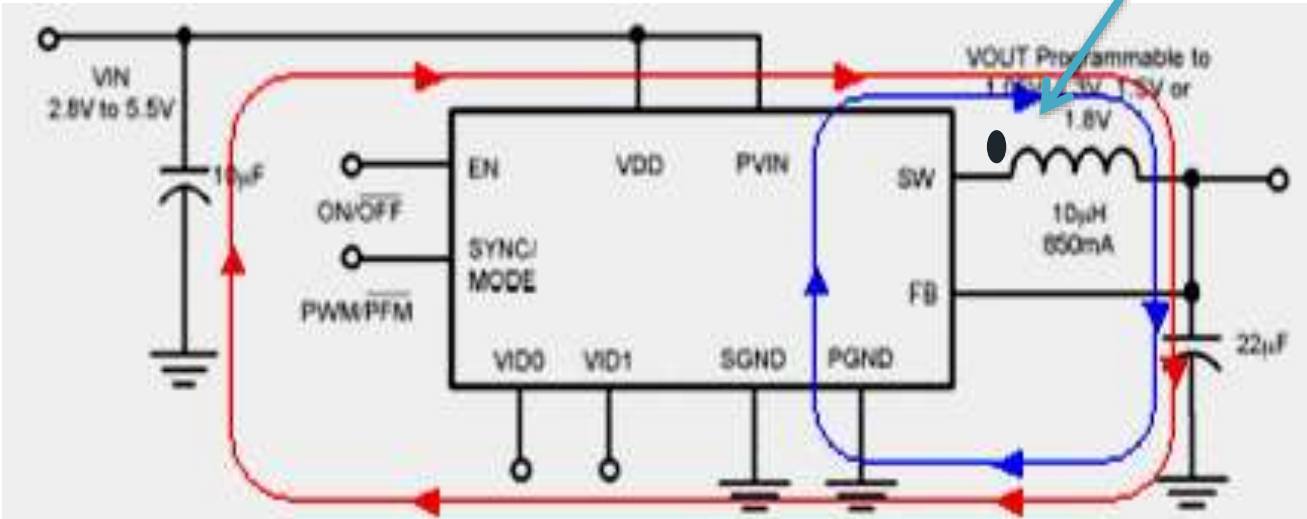
connection switch node

"EMI hot side"



Start Winding

End Winding

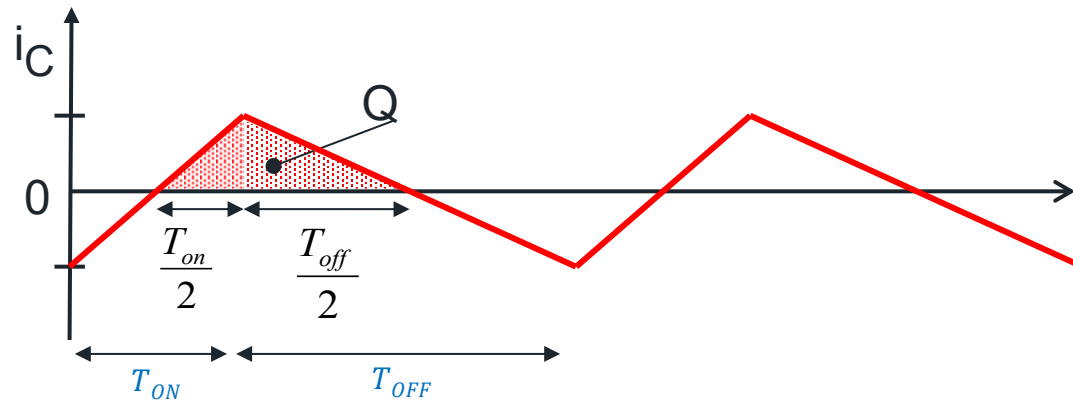


CAPACITOR SMART SELECTION

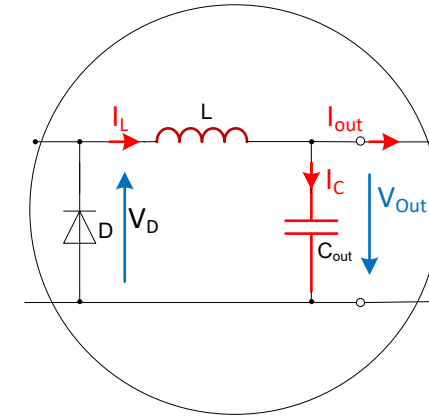


OUTPUT CAPACITOR: BASED ON RIPPLE VOLTAGE

Ideal



ΔI_L



$$\Delta Q = \frac{1}{2} \cdot \frac{\Delta I_L}{2} \cdot \frac{T_{on}}{2} + \frac{1}{2} \cdot \frac{\Delta I_L}{2} \cdot \frac{T_{off}}{2} = \frac{\Delta I_L (T_{on} + T_{off})}{8}$$

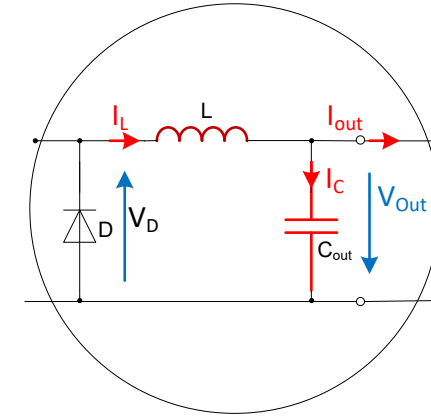
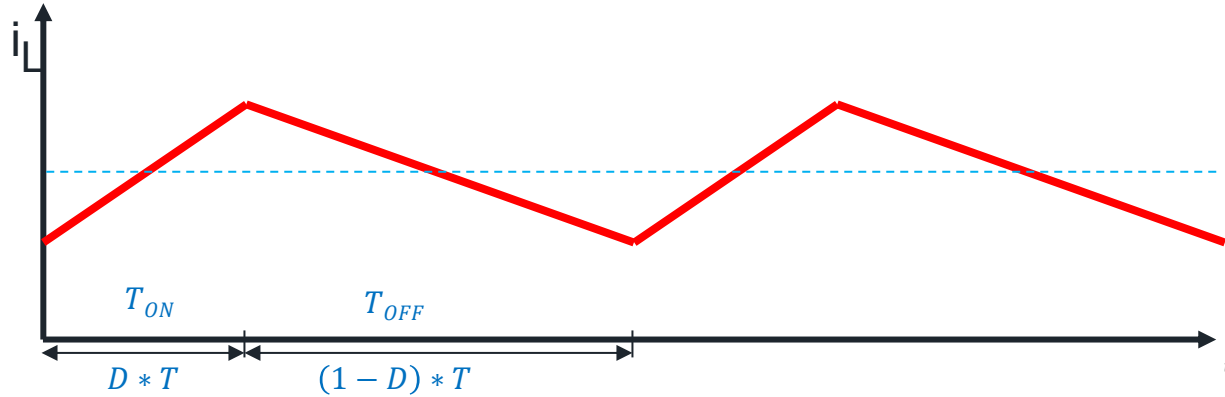
$$\Delta Q = C \Delta V$$

$$\Delta V = \frac{\Delta I_L * T_{switch}}{8C}$$

$$C = \frac{\Delta I_L * T_{switch}}{8\Delta V}$$

OUTPUT CAPACITOR: BASED ON RIPPLE VOLTAGE

Ideal



$$\Delta I_L = \frac{V_{in} - V_{out}}{L} * T_{on} = \frac{V_{out}}{L} * T_{off}$$

$$\Delta V = \frac{T_{switch} * V_{out}}{8LC} * T_{off}$$

$$\Delta V = \frac{T_{switch}^2 * V_{out}}{8LC} * (1 - D)$$

OUTPUT CAPACITOR: BASED ON RIPPLE VOLTAGE

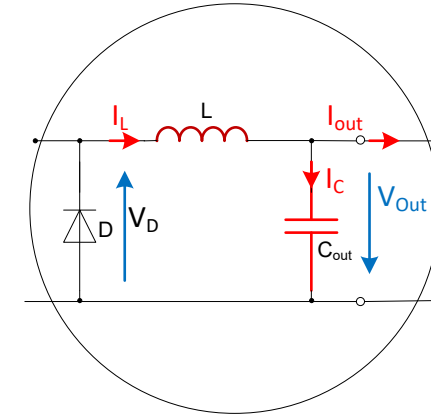
Ideal

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

$$\Delta V = \frac{T_{switch}^2 * V_{out}}{8LC} * (1 - D)$$

$$\Delta V = V_{out} * \frac{\pi^2}{2} * \left(\frac{f_0}{f_{switch}}\right)^2 * (1 - D)$$

$$f_0 = f_{switch} * \frac{1}{\pi} * \sqrt{\frac{2\Delta V}{(1 - D)V_{out}}}$$

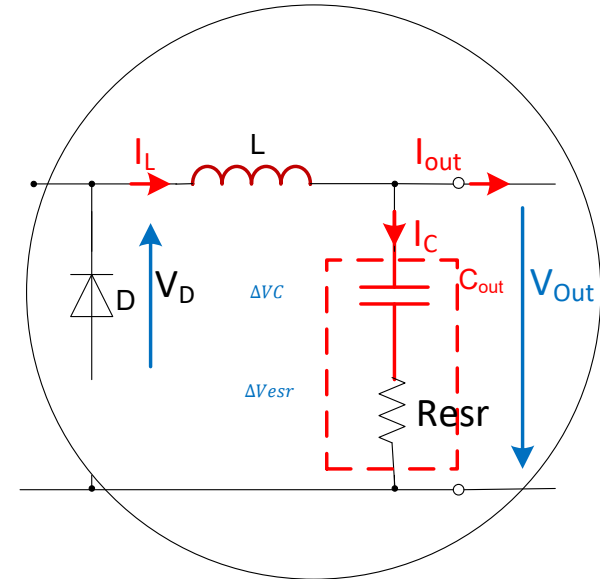


OUTPUT CAPACITOR: BASED ON RIPPLE VOLTAGE OF ESR

$$\Delta V_{Total} = \Delta V_C + \Delta V_{ESR}$$

$$\Delta V_{esr} = R_{esr} * \Delta I_L = R_{esr} * \frac{V_{out}}{L} * T_{off}$$

$$\Delta V_{esr} = R_{esr} * \frac{V_{out}}{L * f_{switch}} * (1 - D)$$



Real...ish

$$R_{esr} \leq \frac{\Delta V_{esr}}{V_{out}} * \frac{L * f_{switch}}{(1 - D)}$$

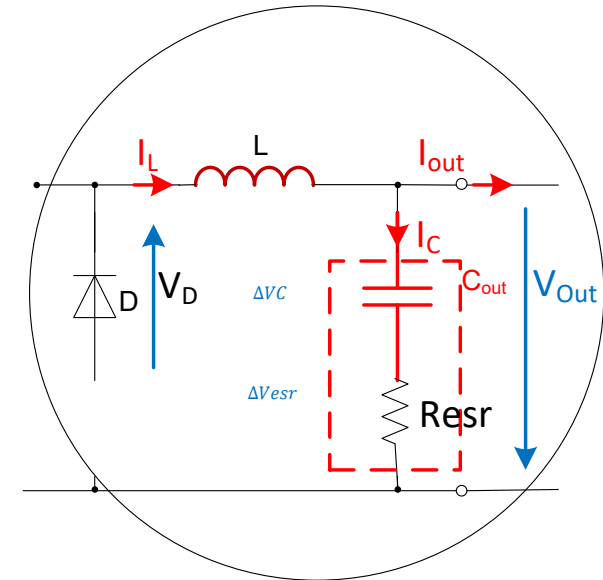
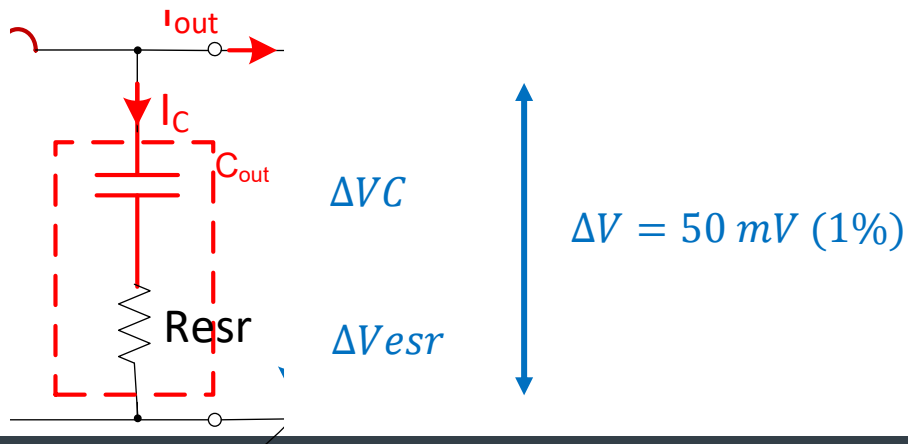
OUTPUT CAPACITOR: EXAMPLE OF CALCULATION

Max output ripple voltage 50 mV (1%)

$L = 10\mu\text{H}$ for 40% ripple

- $V_{in} = 24\text{V}$
- $V_{out} = 5\text{V}$
- $I_{out} = 2\text{A}$
- $F_{sw} = 535\text{ kHz}$

$$D = \frac{V_{out}}{V_{in}} = 0,208$$



Repartition of the ripple voltage

$$\Delta VC = 20\text{ mV} \quad 40\%$$

$$\Delta Vesr = 30\text{ mV} \quad 60\%$$

OUTPUT CAPACITOR: EXAMPLE OF CALCULATION

Max output ripple voltage 50 mV (1%) $L = 10\mu H$

- $V_{in} = 24V$
- $V_{out} = 5V$
- $I_{out} = 2A$
- $F_{sw} = 535\text{ kHz}$

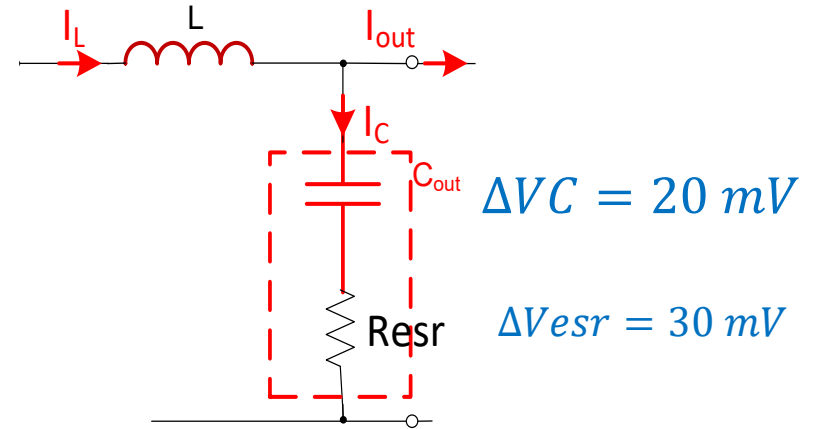
$$D = \frac{V_{out}}{V_{in}} = 0,208$$

$$f_0 = f_{switch} * \frac{1}{\pi} * \sqrt{\frac{2\Delta V_c}{(1-D)V_{out}}}$$

$$f_0 = 535\text{ kHz} * \frac{1}{\pi} * \sqrt{\frac{2 * 20\text{mV}}{(1-0,208) * 5}}$$

$$f_0 = 17,124\text{ kHz}$$

$$C_{out} = \frac{1}{(2\pi f_0)^2 L} = 8,64\mu F$$

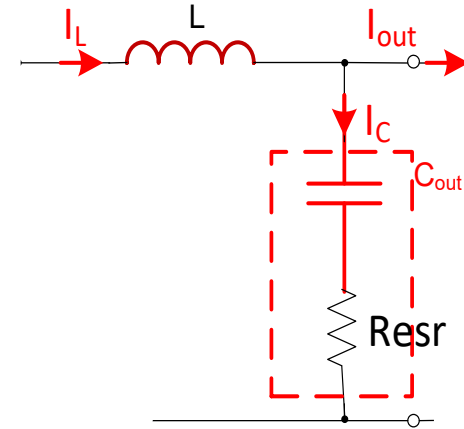
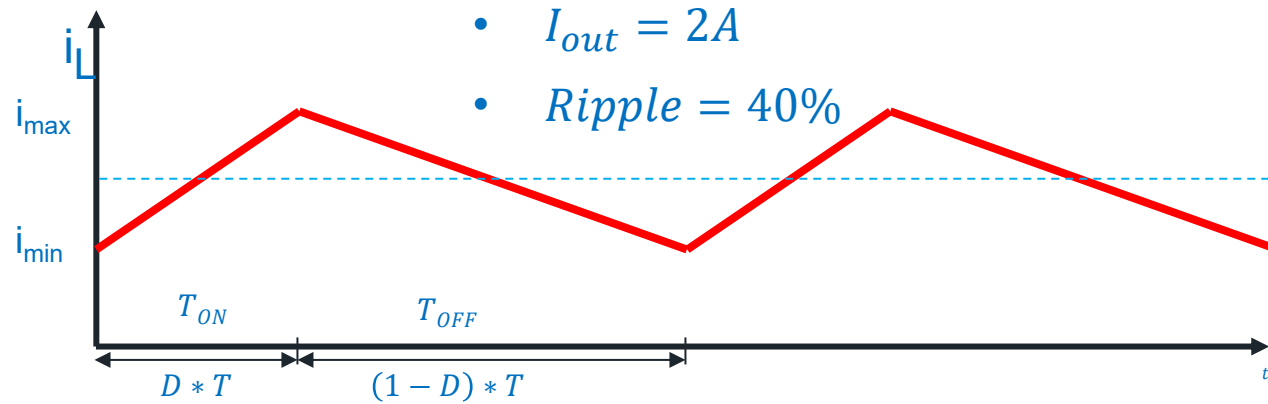


$$R_{esr} \leq \frac{\Delta V_{esr}}{V_{out}} * \frac{L * f_{switch}}{(1-D)}$$

$$R_{esr} \leq \frac{30\text{mV}}{5} * \frac{10\mu H * 535\text{ kHz}}{(1-0,208)}$$

$$R_{esr} \leq 40\text{m}\Omega$$

OUTPUT CAPACITOR: EXAMPLE OF CALCULATION



$$I_{Lmax} = I_{out} + \frac{\Delta I_L}{2}$$

$$I_{Lmin} = I_{out} - \frac{\Delta I_L}{2}$$

$$I_{L,rms} = \frac{\sqrt{12 \cdot I_{out}^2 + \Delta I^2}}{2\sqrt{3}} = 2,013A$$

$$I_{C,RMS} = \sqrt{I_{L,RMS}^2 - I_{out}^2}$$

$$I_{C,RMS} = 228 \text{ mA}$$

OUTPUT CAPACITOR: EXAMPLE OF CALCULATION

Max output ripple voltage 50 mV (1%)

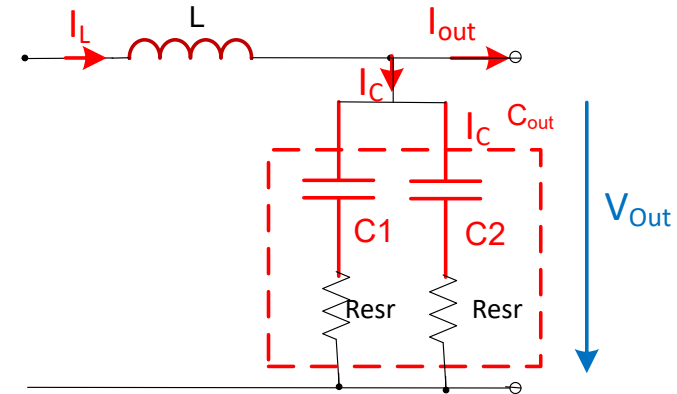
$L = 10\mu H$

- $V_{in} = 24V$
- $V_{out} = 5V$
- $I_{out} = 2A$
- $F_{sw} = 535 kHz$

$$C_{out} = 8,64\mu F$$

$$R_{esr} \leq 40m\Omega$$

$$I_{C,RMS} = 228 mA$$



$$C_{out} = 2 * 4,7\mu F$$

Capacitor : C1

$$C = 4,7\mu F$$

$$ESR @20^\circ C = 70m\Omega$$

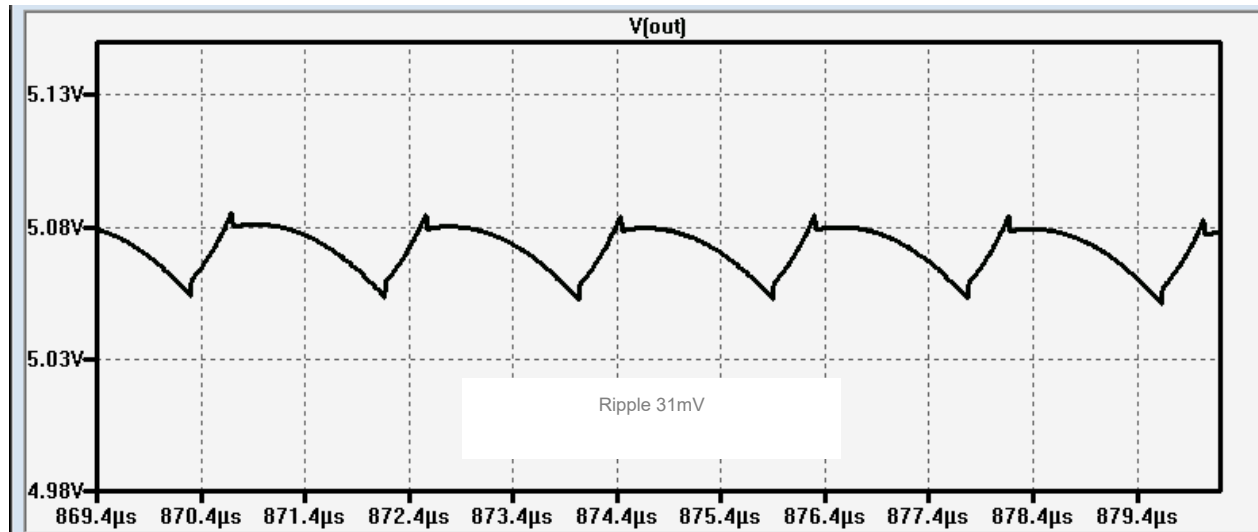
$$ESL = 5nH$$

OUTPUT CAPACITOR: EXAMPLE OF CALCULATION

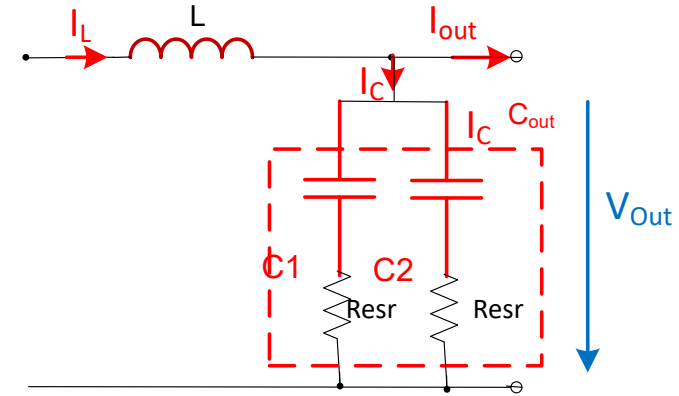
Max output ripple voltage 50 mV (1%)

$L = 10\mu H$

- $V_{in} = 24V$
- $V_{out} = 5V$
- $I_{out} = 2A$
- $F_{sw} = 535 kHz$



Is that all?



$$C_{out} = 2 * 4,7\mu F$$

Capacitor : C1=C2

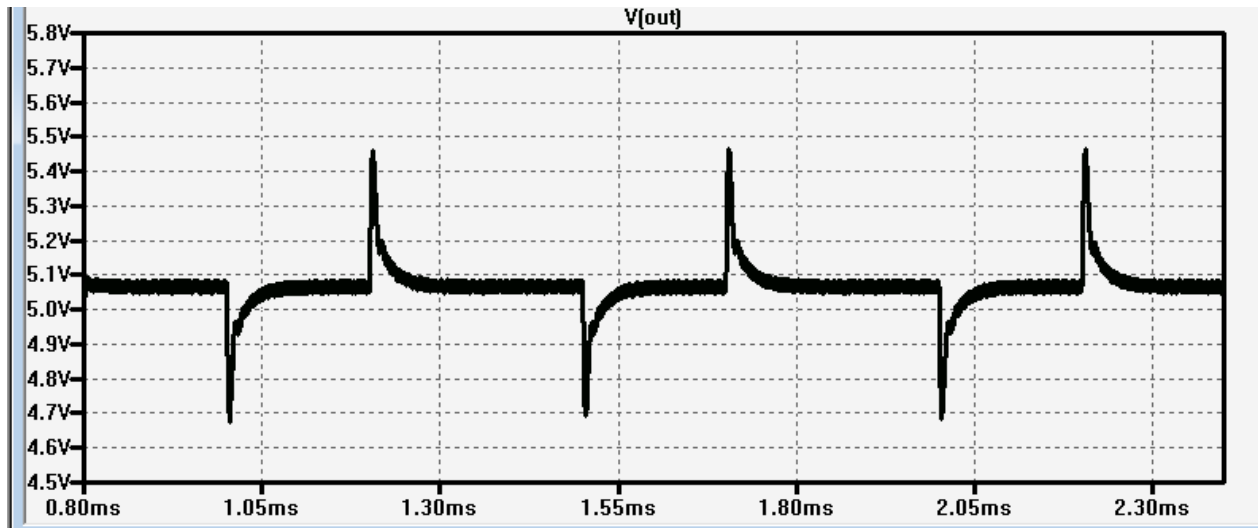
$$C = 4,7\mu F$$

$$ESR @20^{\circ}C = 70m\Omega$$

$$ESL = 5nH$$

OUTPUT CAPACITOR: TRANSIENT

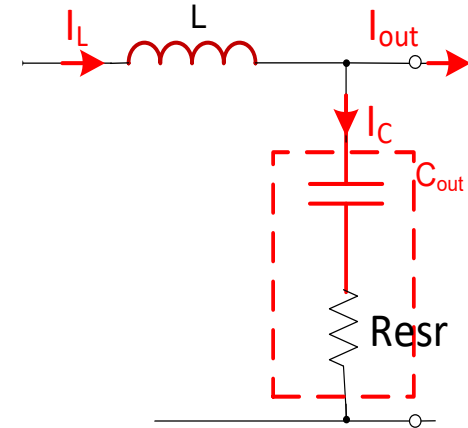
Not yet



Load transient : 0,5A to 2A in 1 μ s

Vdrop @ 400mV.....maybe to high

Only Vdrop @ 200mV, can be accepted



$$C_{out} = 9,4\mu F$$

$$= 2 * 4,7\mu F$$

Capacitor : C1=C2

$$C = 4,7\mu F$$

$$ESR @ 20^{\circ}C = 70m\Omega$$

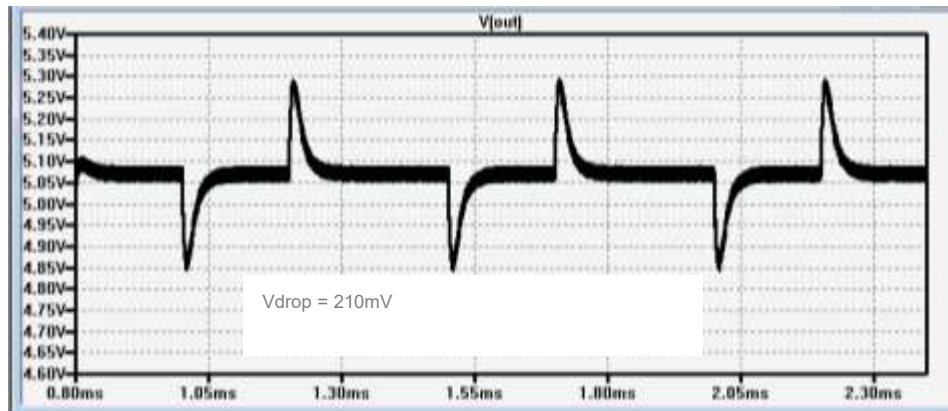
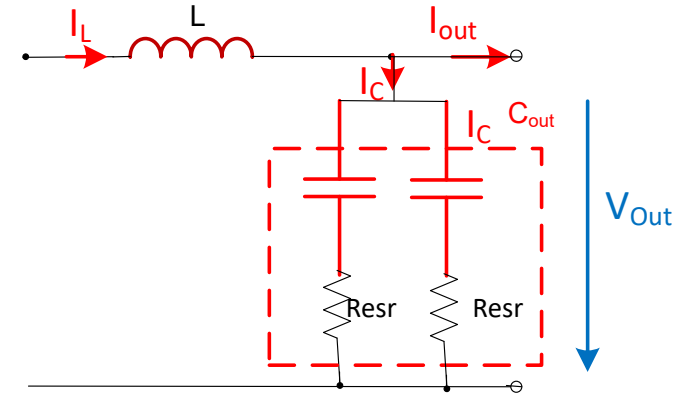
OUTPUT CAPACITOR: BASED ON TRANSIENT

Capacitor : $C1=C2$

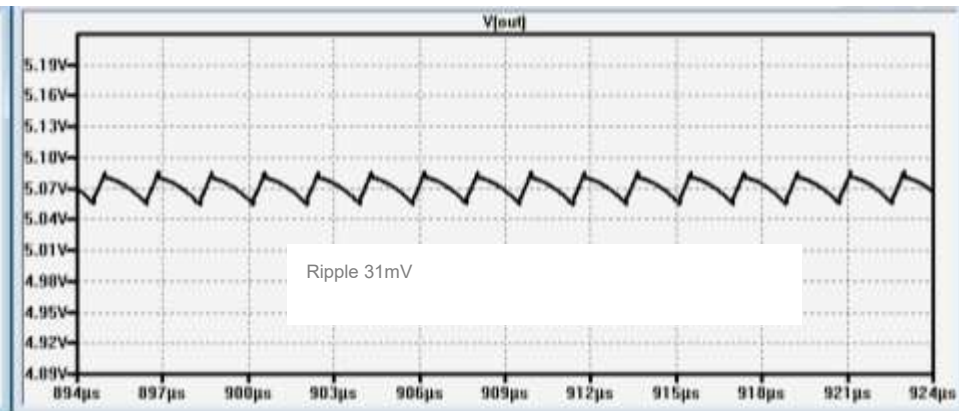
$C = 15\mu F$

$ESR @20^{\circ}C = 70m\Omega$

Is that all?



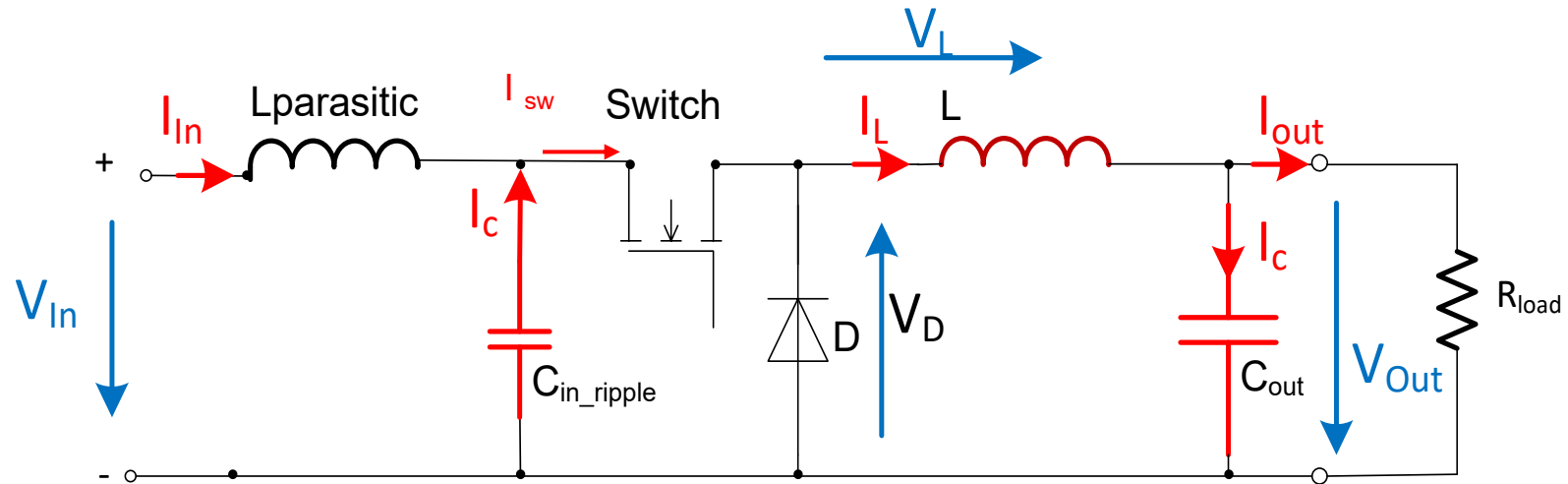
Transient



Steady state

INPUT CAPACITOR: RIPPLE AND TRANSIENT

Yes but need to consider Input capacitor



LT SPICE SIMULATIONS

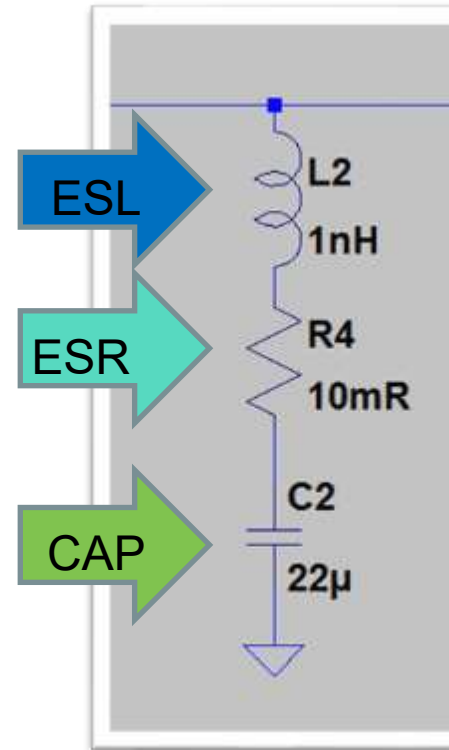
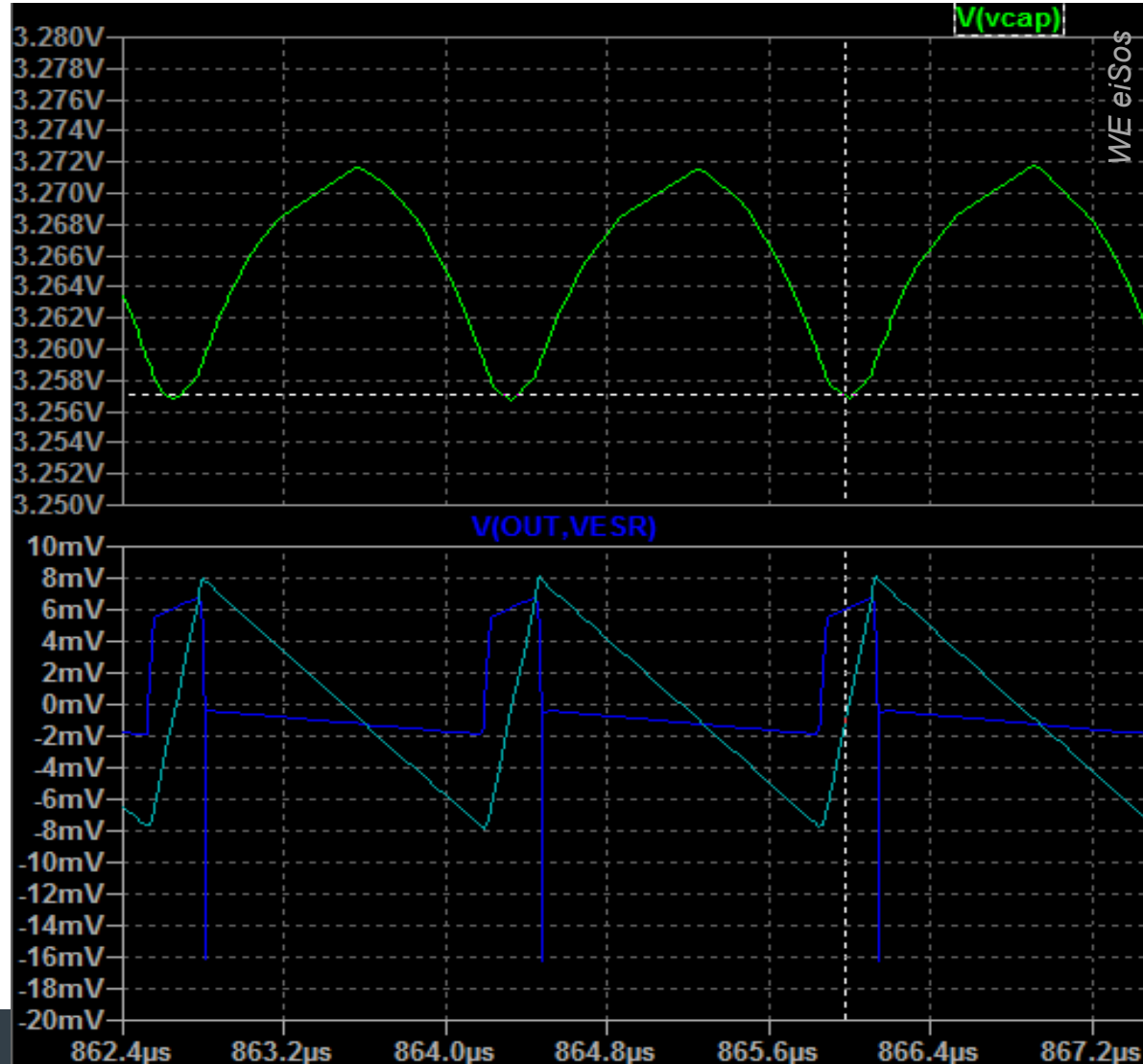
Take it to the next level

Charge and discharge of cap

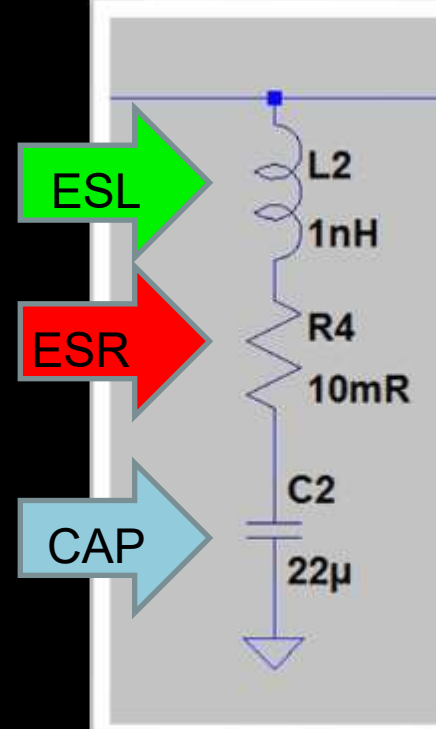
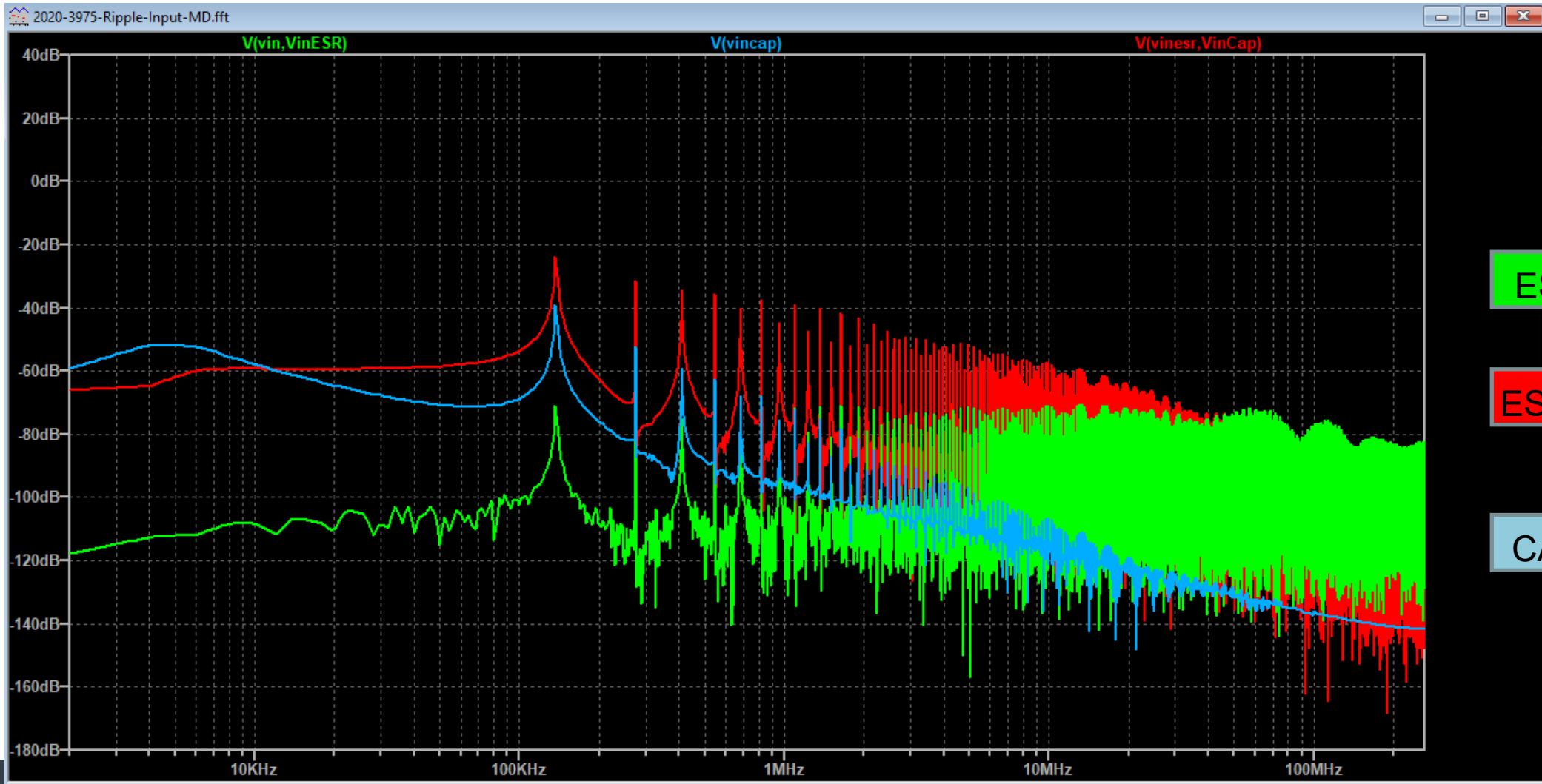
CAP → 14 mV_{p-p}

ESR → 16 mV_{p-p}

ESL → 10 mV_{p-p} at low frequencies
 25 mV_{p-p} at high frequencies



For another day



CAPACITORS

Aluminum: Electrolytic / Polymer / Hybrid polymer

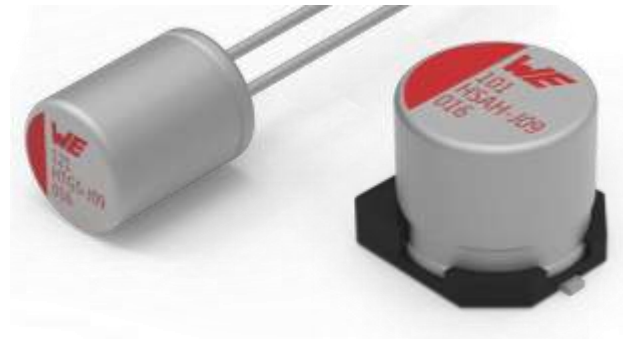
- Electrolytic
 - Wet electrolyte
 - Higher voltage / values
 - Voltage $\leq 450V$
 - Capacity up to $33000\mu F$
 - THT / SMT / Snap in mount



- Polymer
 - Solid electrolyte
 - Lower ESR / ESL
 - Voltage $\leq 100V$
 - Capacity up to $2000\mu F$
 - THT / SMT / H-Chip: Low profile & Low ESR versions
 - Lifetime

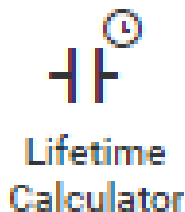


- Hybrid polymer
 - Low ESR & Low leakage current
 - High ripple current characteristics
 - High stability over the temperature range
 - High lifetime performance





CAPACITORS



Electrolytic : aging & lifetime with **REDEXPERT**

- Formula :
 - Aluminum electrolytic

$$L_X = L_{nom} \cdot 2^{\frac{T_{Max}-T_a}{10}}$$

- Aluminum Polymer

$$L_X = L_{nom} \cdot 10^{\frac{T_{Max}-T_a}{20}}$$

20

- Example: comparison of two 1000µF/35V 105 °C
 - ATG5 general purpose [WCAP-ATG5# 860020578018](#)
 - AT1H long life [WCAP-AT1H# 860240580011](#)
 - PTG5 Polymer [WCAP-PTG5# 870025175010](#)

Expected Lifetime

SELECTION

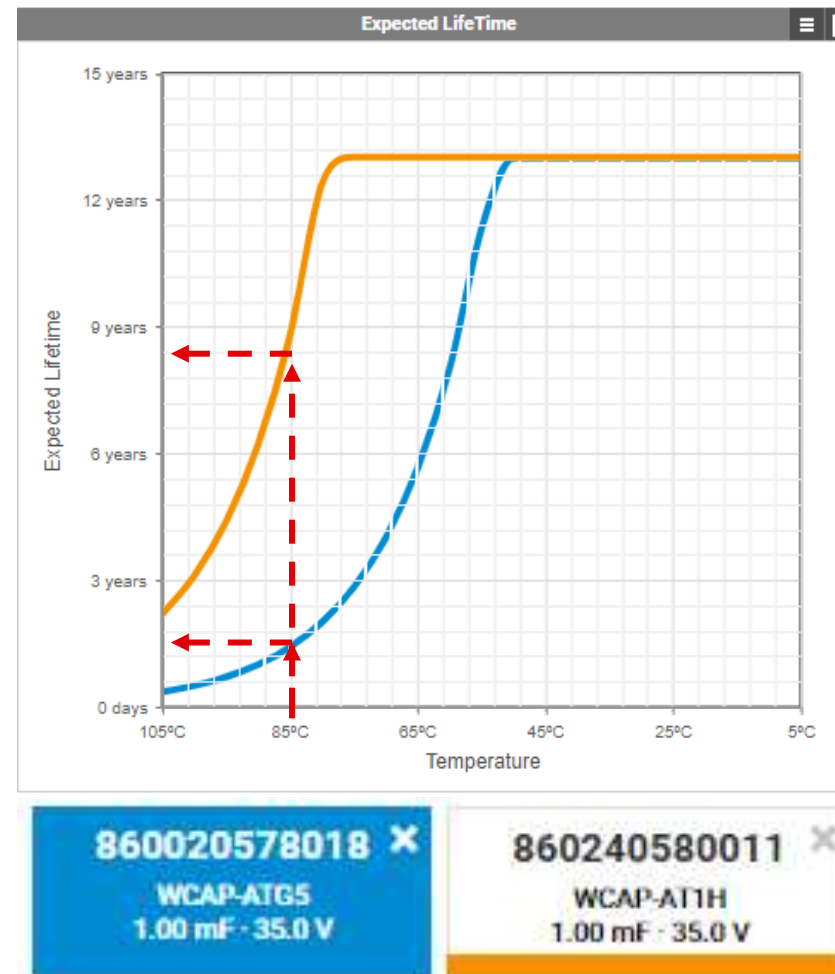
Actual Operating Temperature
T

Applied Frequency
f

Applied Voltage
V

Applied Ripple Current
I_r

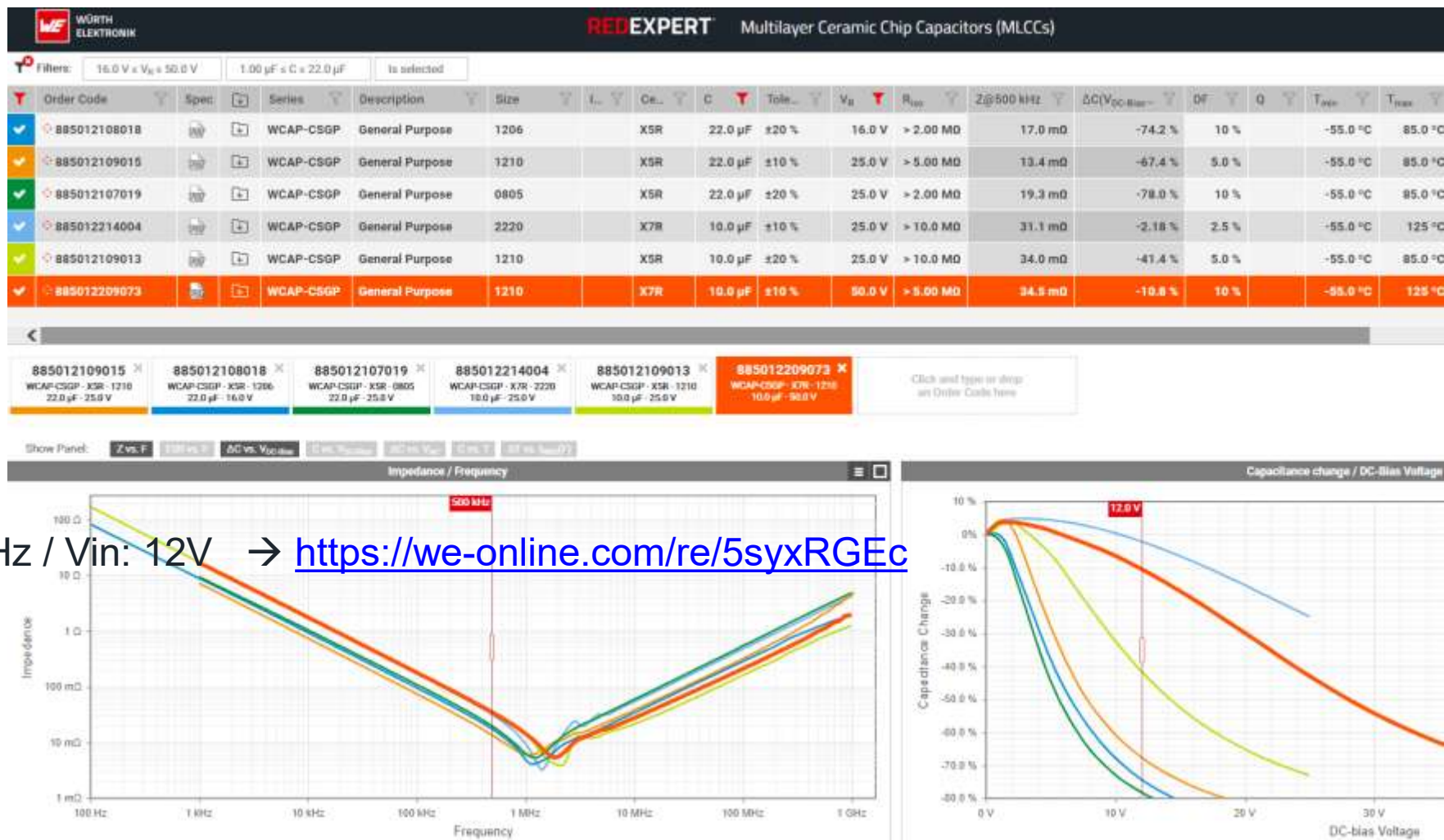
Do not apply Ripple Current filter





OK, BUT WHY NOT A MLCC?

Do you know Bias effect ? Two values two with two packages comparison



e.g. fsw: 500kHz / Vin: 12V → <https://we-online.com/re/5syxRGEc>

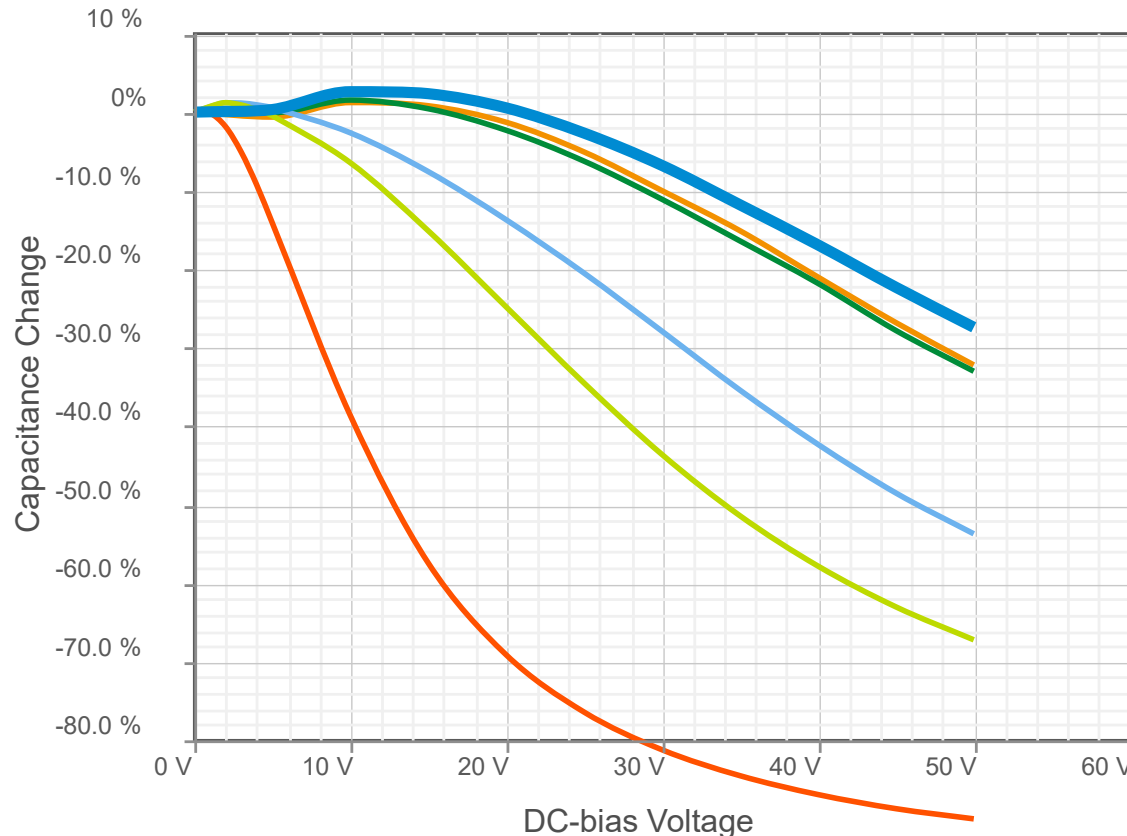


CAPACITORS : BIAS AND PACKAGE

MLCC DC Bias behavior : Size impact onto technology

885012210025 ✕ WCAP-CSGP - X7R - 1812 100 nF - 50.0 V	885012209041 ✕ WCAP-CSGP - X7R - 1210 100 nF - 50.0 V	885012208087 ✕ WCAP-CSGP - X7R - 1206 100 nF - 50.0 V	885012207098 ✕ WCAP-CSGP - X7R - 0805 100 nF - 50.0 V	885012206095 ✕ WCAP-CSGP - X7R - 0603 100 nF - 50.0 V	885012205086 ✕ WCAP-CSGP - X7R - 0402 100 nF - 50.0 V
--	--	--	--	--	--

Capacitance change / DC-Bias Voltage



<https://we-online.com/re/5t07mVB4>

- 885012209041
- 885012208087
- 885012207098
- 885012206095
- 885012205086
- 885012210025



CAPACITORS : ESR AND FREQUENCY

MLCC behavior : global impedance and ESR behavior

885012205086 ✕

WCAP-CSGP - X7R - 0402
100 nF - 50.0 V

885012206095R ✕

WCAP-CSGP - X7R - 0603
100 nF - 50.0 V

885012206095 ✕

WCAP-CSGP - X7R - 0603
100 nF - 50.0 V

885012208087 ✕

WCAP-CSGP - X7R - 1206
100 nF - 50.0 V

885012209041 ✕

WCAP-CSGP - X7R - 1210
100 nF - 50.0 V

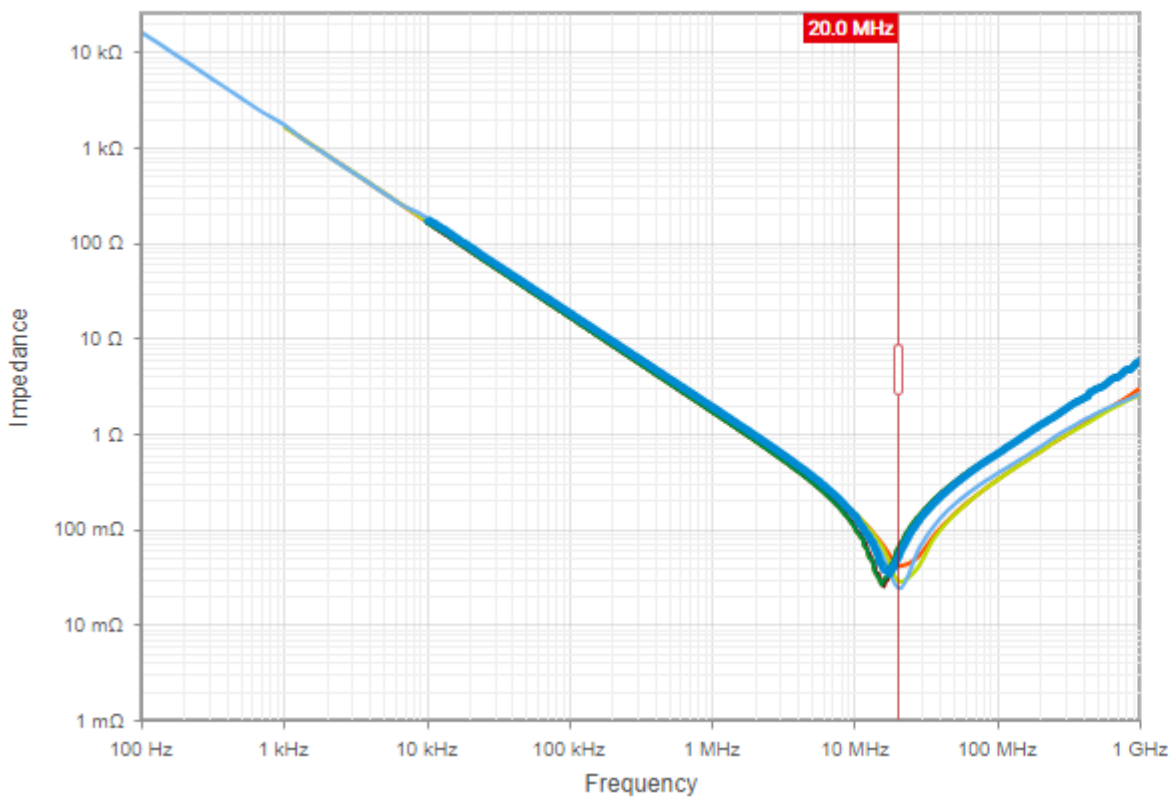
885012210025 ✕

WCAP-CSGP - X7R - 1812
100 nF - 50.0 V

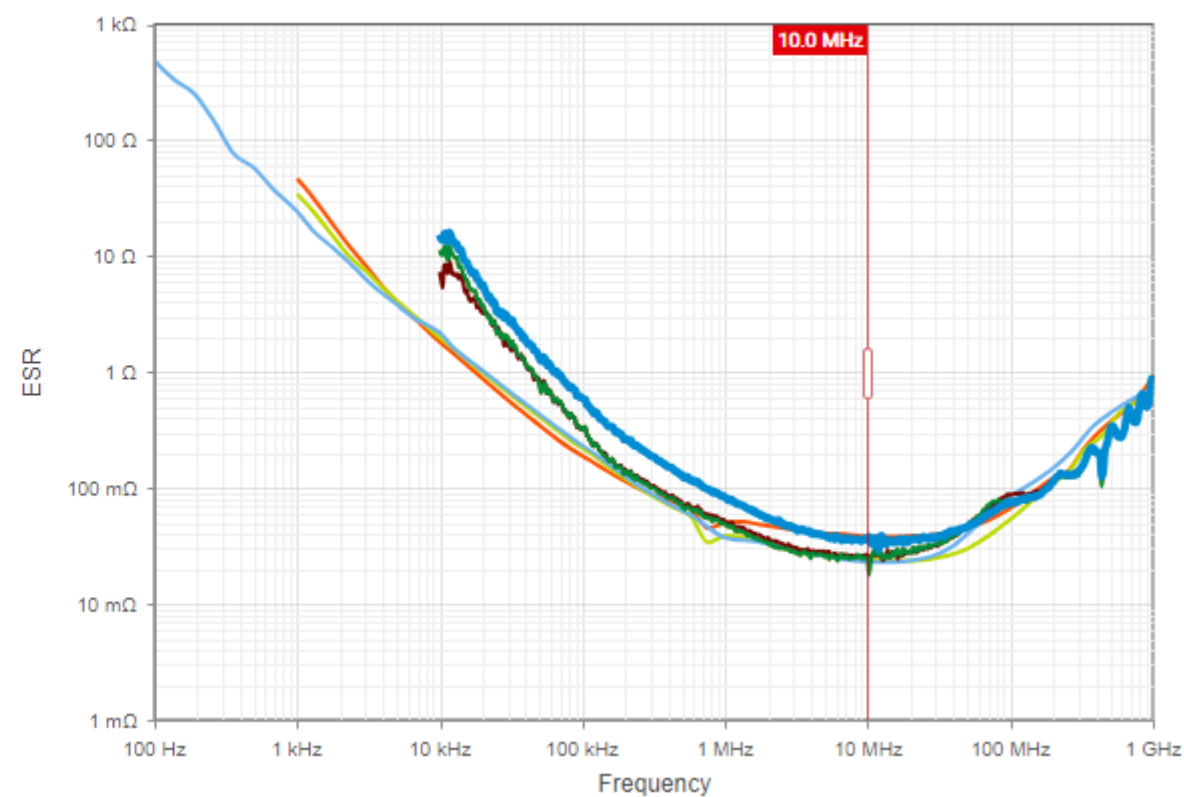
885012207098 ✕

WCAP-CSGP - X7R - 0805
100 nF - 50.0 V

Impedance / Frequency



ESR / Frequency

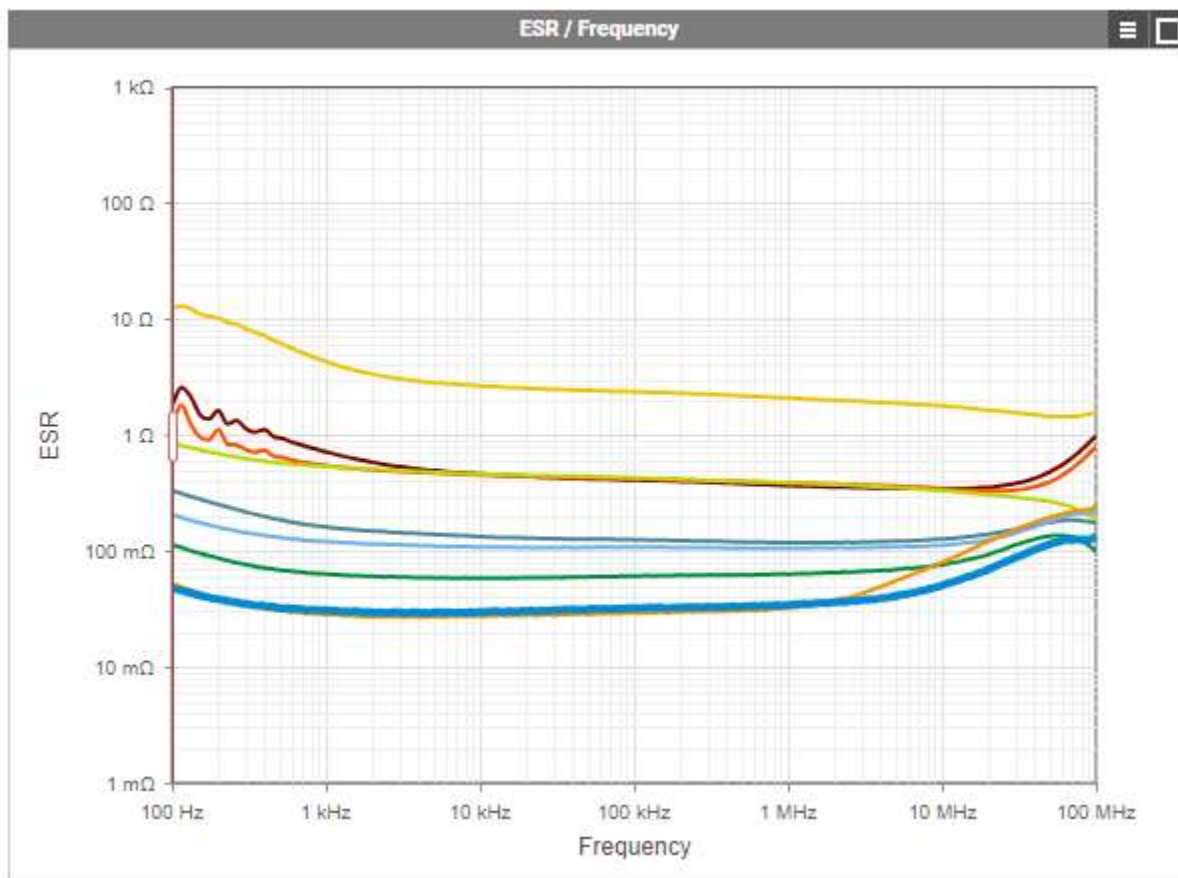
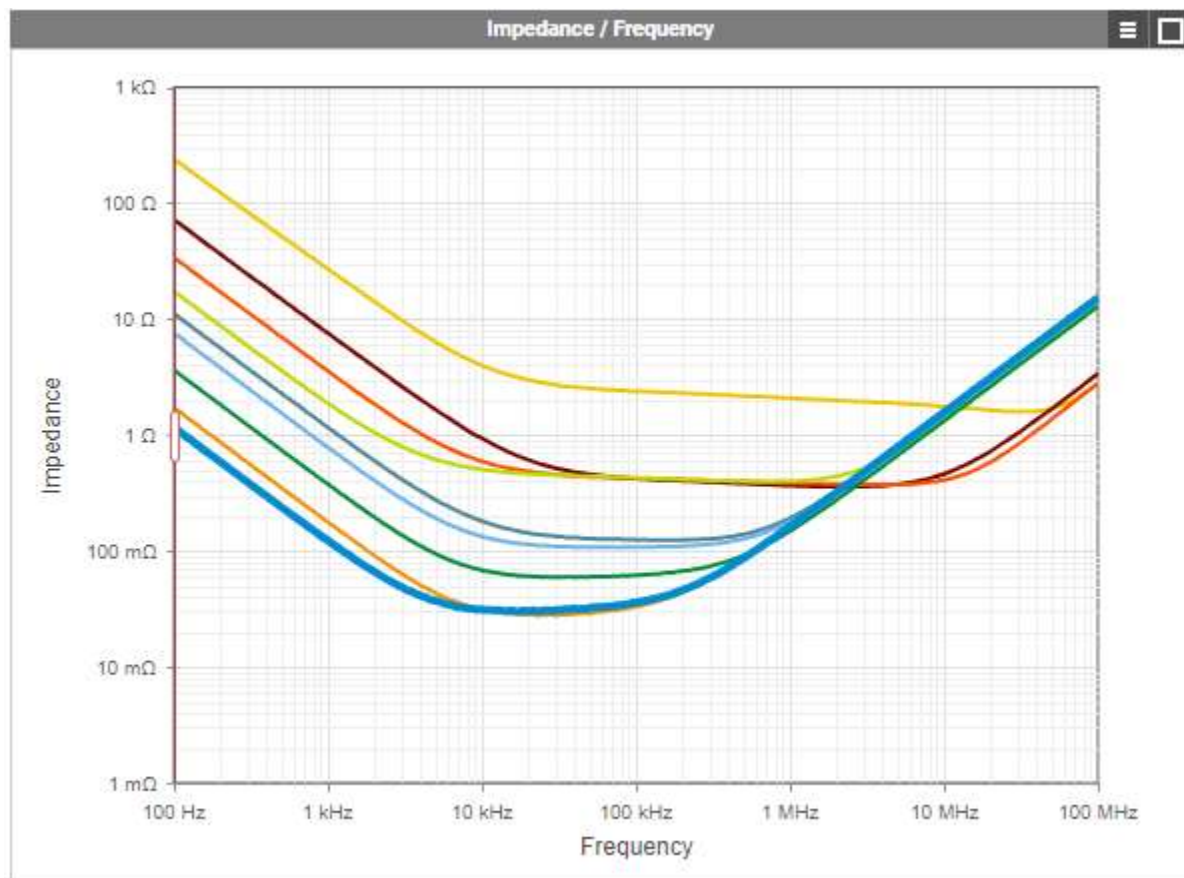




CAPACITORS : ESR AND FREQUENCY

Aluminum caps behavior : global impedance and ESR behavior

860020781027 ✕ WCAP-ATG5 1.50 mF · 63.0 V	860020780025 ✕ WCAP-ATG5 1.00 mF · 63.0 V	860020778021 ✕ WCAP-ATG5 470 µF · 63.0 V	860020775019 ✕ WCAP-ATG5 220 µF · 63.0 V	860020775015 ✕ WCAP-ATG5 100 µF · 63.0 V	860020773013 ✕ WCAP-ATG5 47.0 µF · 63.0 V	860020773011 ✕ WCAP-ATG5 22.0 µF · 63.0 V	860020772009 ✕ WCAP-ATG5 6.80 µF · 63.0 V	860020775017 ✕ WCAP-ATG5 150 µF · 63.0 V
---	---	--	--	--	---	---	---	--

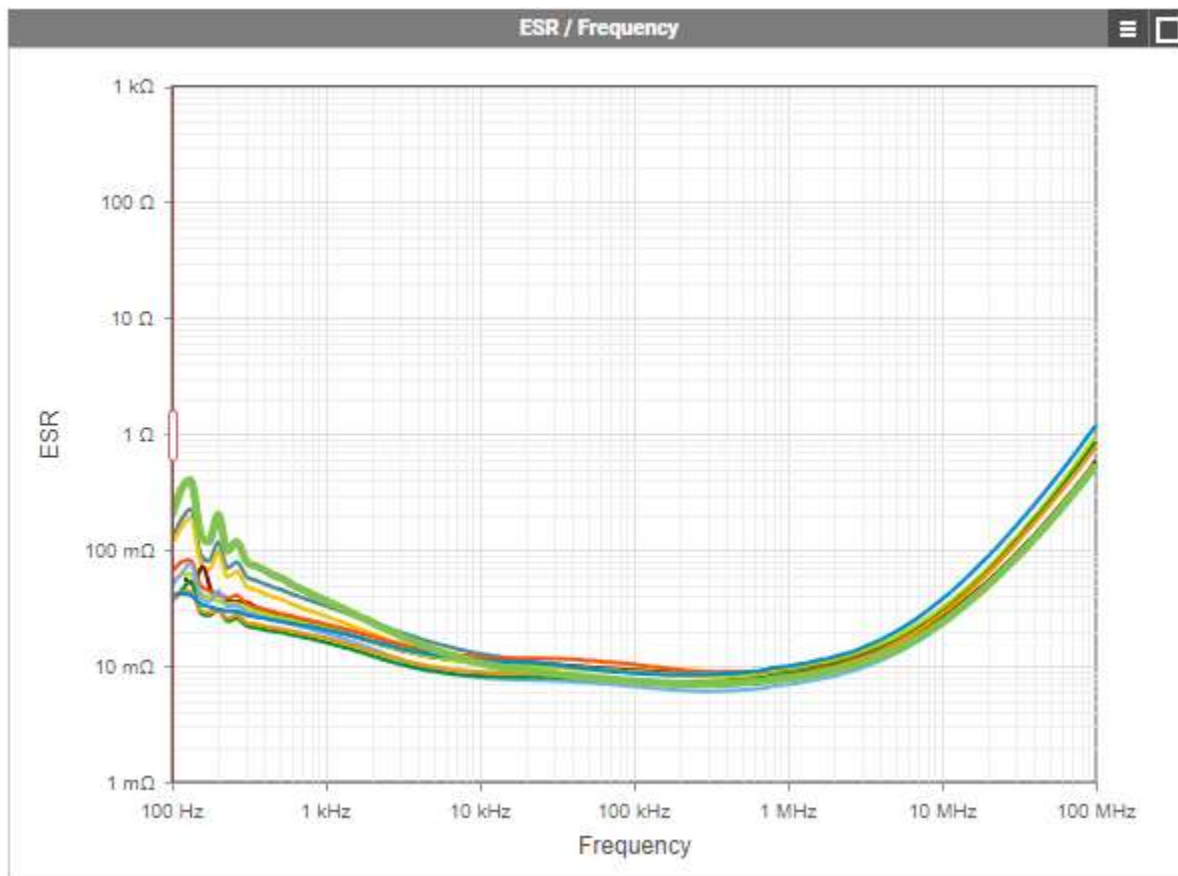
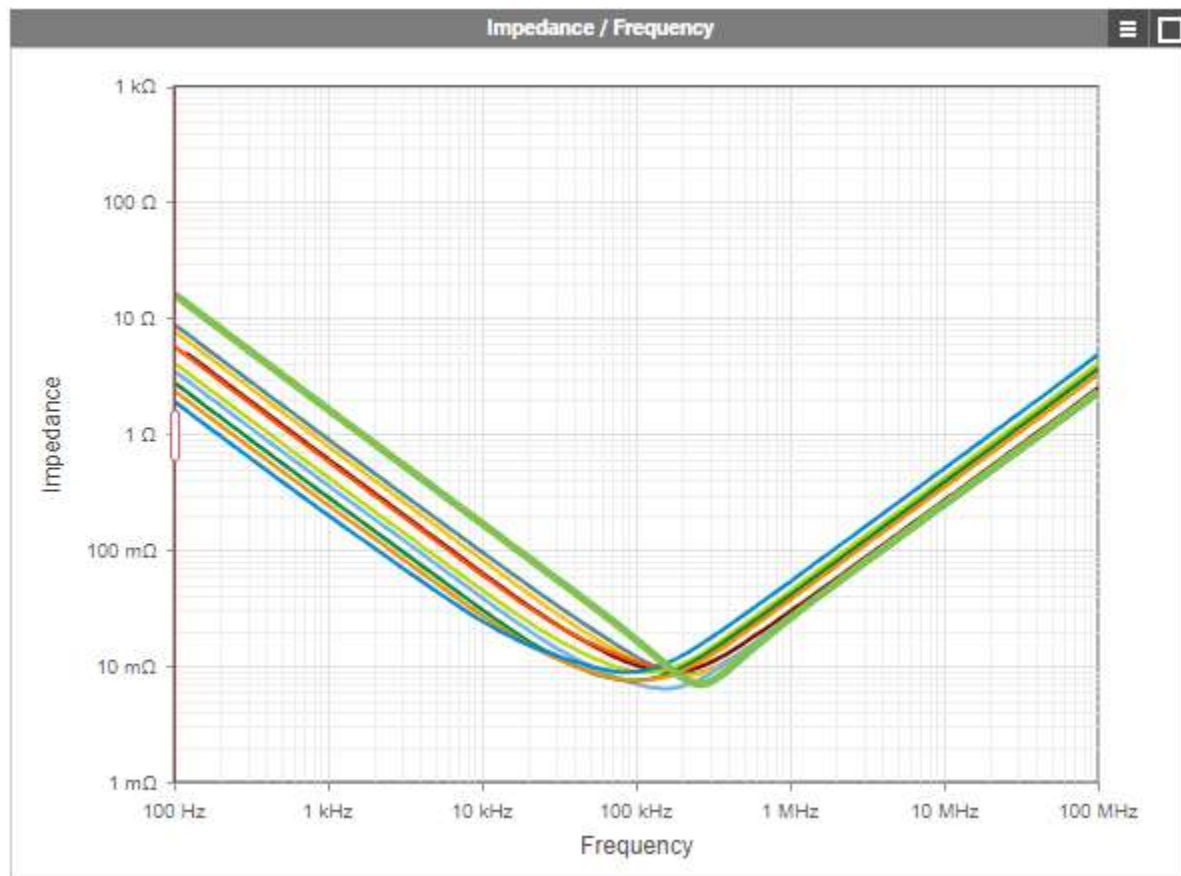




CAPACITORS : ESR AND FREQUENCY

Aluminum Polymer caps behavior : global impedance and ESR behavior

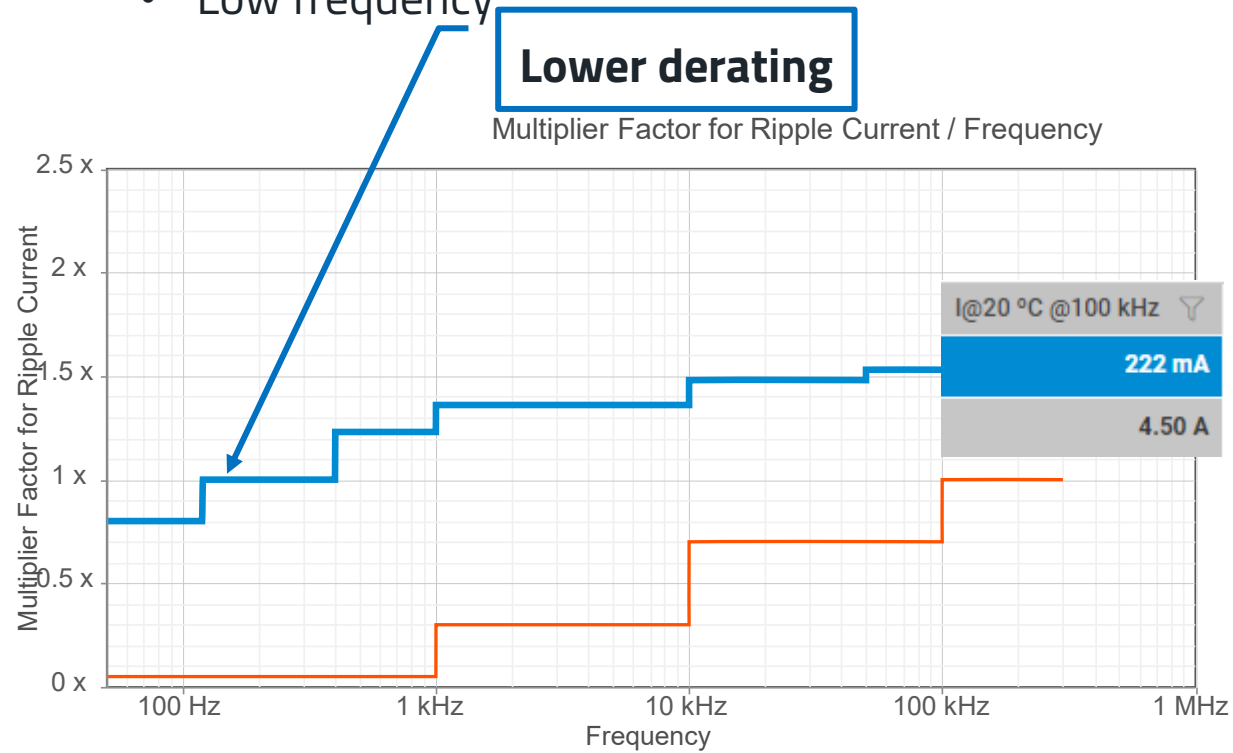
870025375010 ✕ WCAP-PTG5 820 μ F · 16.0 V	870025375009 ✕ WCAP-PTG5 680 μ F · 16.0 V	870025375008 ✕ WCAP-PTG5 560 μ F · 16.0 V	870025374007 ✕ WCAP-PTG5 470 μ F · 16.0 V	870025374006 ✕ WCAP-PTG5 390 μ F · 16.0 V	870025374005 ✕ WCAP-PTG5 330 μ F · 16.0 V	870025374004 ✕ WCAP-PTG5 270 μ F · 16.0 V	870025374003 ✕ WCAP-PTG5 220 μ F · 16.0 V	870025374002 ✕ WCAP-PTG5 180 μ F · 16.0 V	870025374001 ✕ WCAP-PTG5 100 μ F · 16.0 V
---	---	---	---	---	---	---	---	---	---



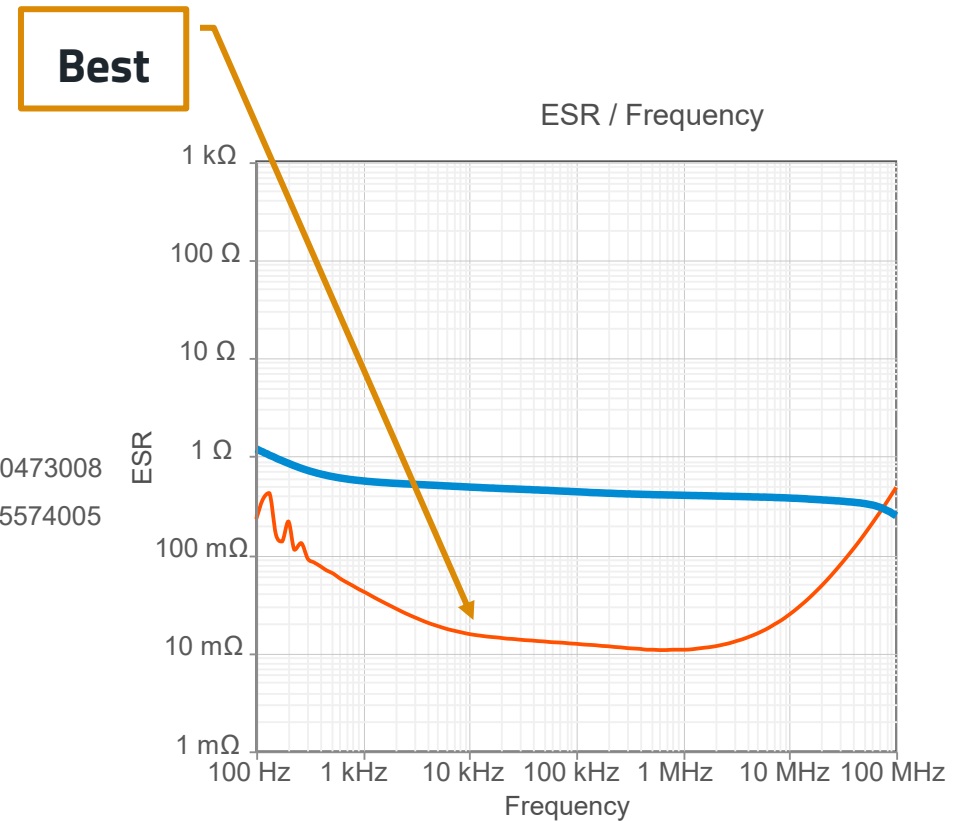
RIPPLE CURRENT

Order Code	Series	Spec	Technology	Series Description	C	To...	V _R	DF
860020473008	WCAP-ATG5		Alum. Electrolytic	THT - General Purpose +105°C	100 µF	±20%	25.0 V	< 14 %
870025574005	WCAP-PTG5		Alum. Polymer	THT - General Purpose +105°C	100 µF	±20%	25.0 V	< 8.0 %

- Aluminum Electrolytic Capacitors
 - Recommended for mains rectification / filtering
 - Low frequency



- Aluminum Polymer Capacitors
 - Lower ESR and high frequency dedicated



GOOD TO KNOW



CAPACITORS

Some other technologies and structure

- Snap-in and screw...

https://www.we-online.com/en/components/products/pbs/capacitors/aluminium_electrolytic_capacitors/aluminium_electrolytic_snap-in_capacitors

https://www.we-online.com/en/components/products/pbs/capacitors/aluminium_electrolytic_capacitors/wcap_screw_capacitors

- Non polar

<https://www.we-online.com/en/components/products/WCAP-ASNP>



CAPACITOR

Vibration-proof Aluminum Electrolytic- and Aluminum Hybrid Polymer Capacitors!

- Capacitors with high base plates are available on request for Aluminum Electrolytic- and Aluminum Hybrid Polymer Capacitors, as project parts.
- What are the benefits? - The SMT capacitor is surrounded by a high base plate that also has larger soldering pads, due to that, the results in vibration tests improve and the parts can withstand up to 30G.
- Ask eiCap BU for more information « High Baseplate »





ÇOK TEŞEKKÜR EDERİM

Mohamed Alalami
Technical Specialist

WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

