Designing power inductors,
Practical solutions

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I: Introduction

1) Core losses:
   - given only for sine wave by manufacturers.
   - bulk losses
2) Copper: eddy current important, transverse field is dominant
3) Simplified thermal aspects
4) Loss reduction and heat drain improvements
5) Rectangular coil formers on demand

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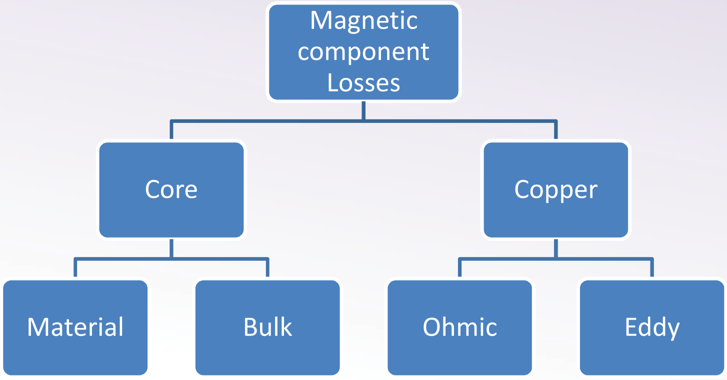
Losses in inductive components

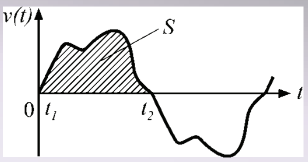


Magnetic component Losses

- Core
  - Material
  - Bulk
- Copper
  - Ohmic
  - Eddy

I: Core losses

-Core losses for sine wave induction [1,2]



$$\Psi_{pp} = S$$

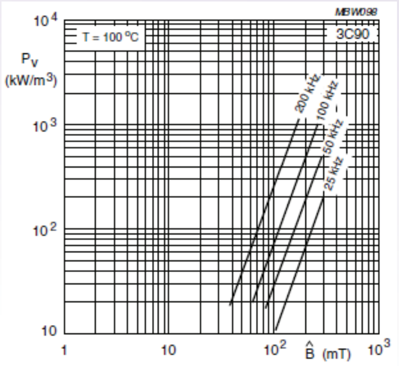
= peak-peak flux linkage [V s]

$$B_{pp} = \frac{\Psi_{pp}}{A_c\, N}$$

= peak-peak induction in the core [T]
N= number of turns [.]
A_c = core section [m^2]

$$\frac{B_{pp}}{2} = "\hat{B}"$$

= Peak of AC component is traditionally used to read losses in the manufacturer data
For example see →



Remarks:

- It is true for sine wave and for low frequency
- Unequal flux around the core results in somewhat higher losses
- The losses of magnetic materials may be much larger at heavily distorted waveform (extreme duty ratio)
- A flux with a DC component superposed may have up 2-3 times more losses

I: Core losses

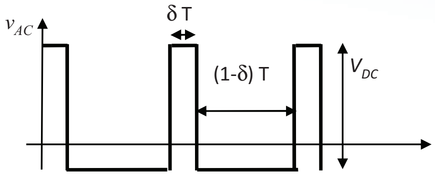
-Core losses for non sine waves (simplified)

The rms voltage can be calculated or measured with an oscilloscope.

$$\frac{B_{pp}}{2} \quad \text{Better replaced by} \quad \frac{V_{rms}\sqrt{2}}{2\pi f}$$

The ac component of V_{rms} for a square wave with duty ratio δ is:

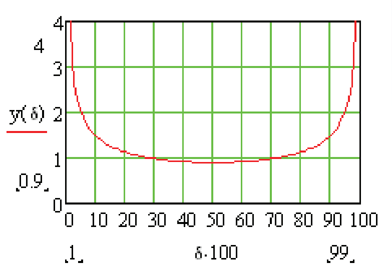
$$V_{rms} = V_{dc}\sqrt{(1-\delta)\,\delta}$$



More detailed models: [1]

Error of sine wave approach:
small at 50% large at 95%

Error



$$y(\delta) := \frac{\sqrt{\delta\cdot(1-\delta)}\cdot\frac{\sqrt{2}}{2\cdot\pi}}{\frac{\delta\cdot(1-\delta)}{2}}$$

I: Core losses

-Core losses for superposed DC

For example ferrite,
losses for different bias levels,
3F3 material

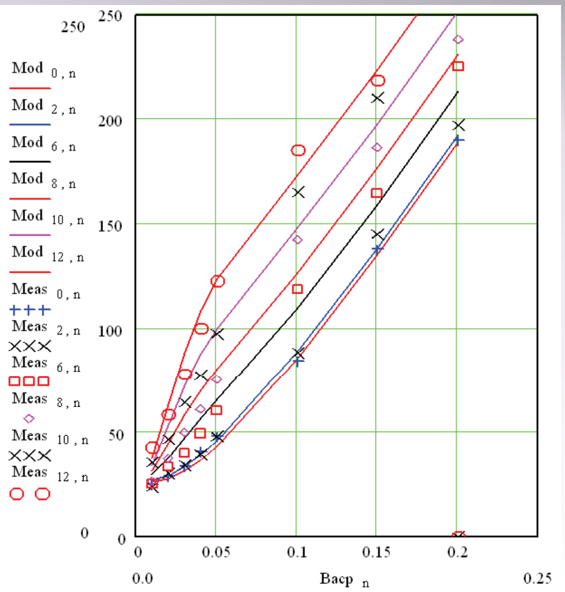


Fig. 5 P/B² [W/T²] at 100kHz for ETD 44.
From lower to upper curves and measuring points:
DC bias 0A; 0.2A; 0.6A; 0.8A; 1A; 1.2A

I: Core losses

-Bulk core losses

Ferrite:

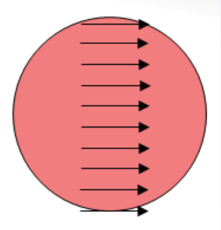
The resistivity Mn-Zn ferrites is high: 1-3 Ωm, but due to the capacitive-resistive impedance of ferrite, the bulk losses are not negligible.
At 50V/m in the ferrite it begins adding losses.
Large cores have more W/cm^3 for the same induction and frequency.
One better measures the losses of the real core and not the material on a small sample

Iron, amorphous and nanoX, iron powder:

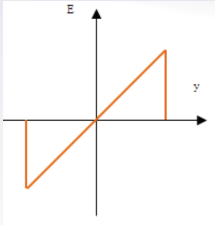
The iron contact should be kept low, one can measure it with an ohm-meter
Quality of insulation layers and burr removal are important
Significantly higher losses occur if the core is cut, this is a drawback for inductors
And cut cores

2: Eddy current, Low frequency

Eddy currents in round wires for low frequency, transverse field [1,3]



Homogenous transverse field



EMF in wire

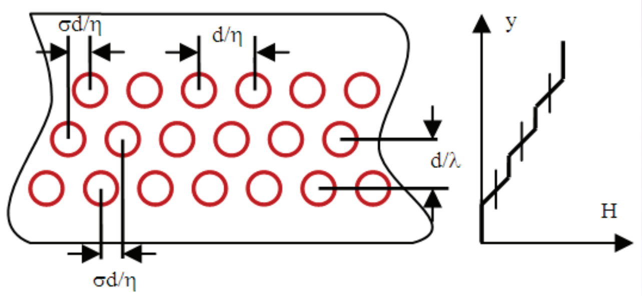
$$P_{eddy,LF} = l\frac{\pi R^4 \omega^2 \mu_0^2}{\rho}\frac{1}{4}H_{tr}^2$$

Other types of losses exist, but transverse field is responsible for 85%-98% of losses (for one layer or more)

When “Low frequency”? $d < 1.8\ \delta$ $\delta(f) = \sqrt{\frac{2\rho}{\omega\mu_0}}$

2: Eddy current, layers, low frequency

-Losses in layers of transformers (low frequency and transverse field only



$$R_{eddy,LF} = \frac{\zeta^4 R_o}{64}\left(\frac{4M^2-1}{3}\,\frac{1}{4}\,\eta^2\right)$$

M =number of layers
ζ = copper diameter/penetration depth $\qquad \zeta = d/\delta(f)$
R_0 = DC resistance

2: Eddy current, layers, wide frequency

Losses in transformers, extension to high frequency and also other losses included

Graphical way for transformers
Recalculate from 0.5mm wires

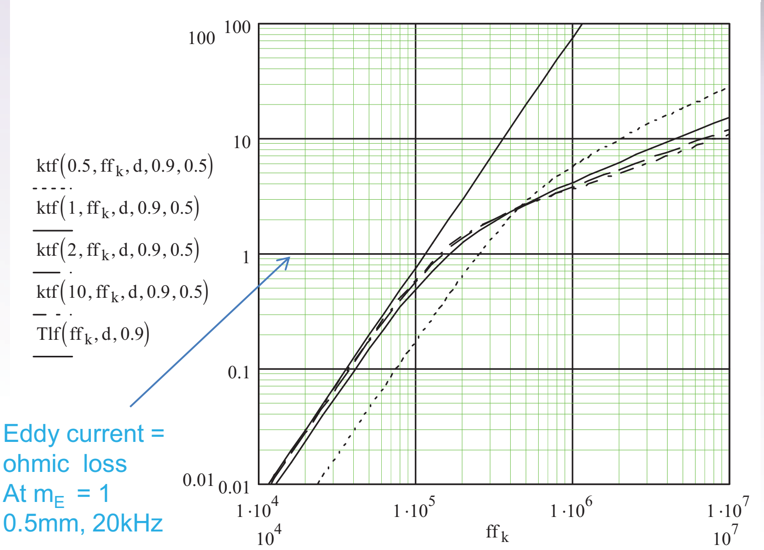
$$P_{loss,cu} \approx (1+k_{c,tr})\,I^2 R_{DC}$$

$$k_{c,tr} \approx m_E^2\; p\; k_{tf}$$

m_E is the equivalent number of layers
Note that
m_E = 0.5 for a half layer
(additional factor 4 in loss reduction)
p: parallel wires
(But f_{eq} increases with p)

recalculated frequency :

$$f_{eq} = f_{ap}\left(\frac{d_p}{0.5}\right)^2\left(\frac{20\times10^{-9}}{\rho_c}\right)$$



Eddy current =
ohmic loss
At m_E = 1
0.5mm, 20kHz

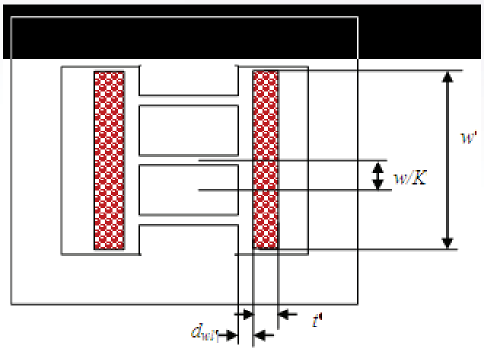
k_{tf} for transformers, for a horizontal filling factor 0.9 and a vertical of 0.5, for a wire of 0.5mm diameter of resistivity 20*10^{-9} Ωm, the full line is the low frequency model.

2: Eddy current, inductors

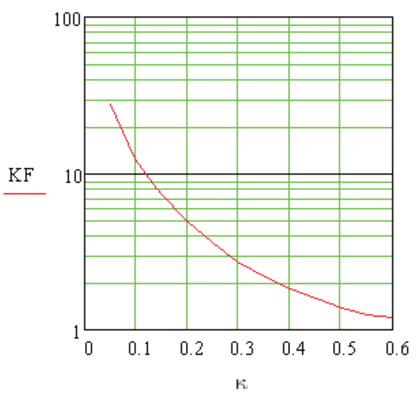
Graphical method for Inductors

Additional loss factor for air gap: KF
Much more losses than in transformers
Due to the air gap
Up to 10-20 times,
concentrated close to the air gap

$$\kappa = \frac{d_{wl} + t/3}{w/K}$$



Relevant dimensions for κ



K_F air gap effect for inductors

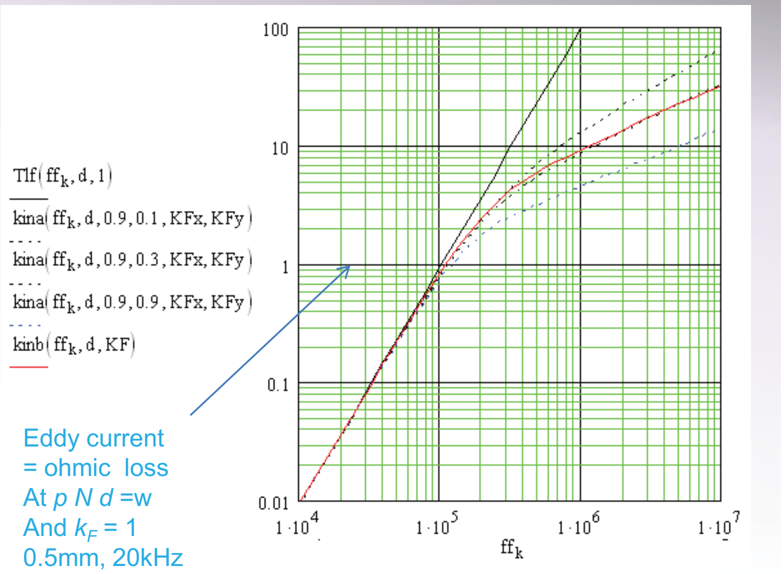
2: Eddy current, inductors

Graphical method for Inductors
Also fields not parallel to layers

$$k_{c,in} = \left(\frac{p\,N\,d}{w}\right)^2 k_F\; k_{in}\left(f_{eq}\right)$$

$$P_{eddy} = R_o\, I_{ac}^2\;\; k_{c,in}$$

Red line:
no layer effect
no local field
considered

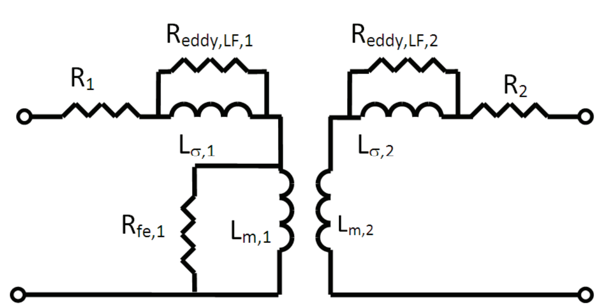


Eddy current
= ohmic loss
At *p N d* =w
And k_F = 1
0.5mm, 20kHz

Inductor cases, k_{in} as function of f_{eq} for λ=0.9, *d*=0.5mm, $\rho=23\times10^{-9}$, high m_E , Dotted line: η=0.1 0.3, 0.9; Red solid line simplified with F_T only

2: Transformer model

The resistors are constant for
- Low frequency eddy currents at leakage
- For a model with RMS voltages the resistor reflects more or less the waveform at a given frequency

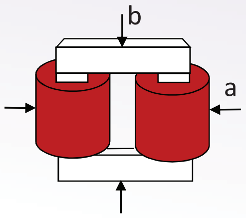


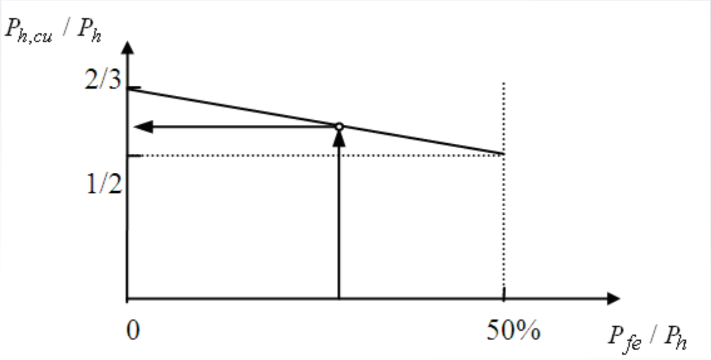
Equivalent loss resistance of the low frequency model for a transformer with eddy currents.

3: Simplified thermal aspects

Simplified heat transfer with natural convection

a and b: the largest outer dimensions of the component, including copper





$$P_h = k_A \, a \, b$$

k_A =2500 W/m^2

Allowed copper loss as a part of total heat transfer if copper loss is more than 50% of loss, the copper loss is about 2/3 of the normal allowed of P_h if there is no iron loss

4: Litz wire?

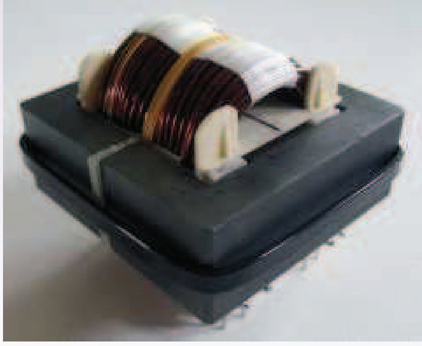
In low frequency eddy currents: losses inverse proportional with number of strands *p*

Litz wire optimized for transverse field

Advantage:
- Low losses by transverse field
- easy low frequency loss calculation

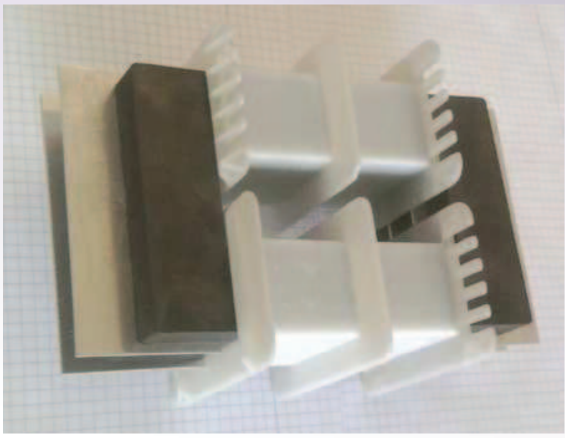
Disadvantages:
-Lower temperature class of isolation
-Low heat conduction
-5% more length and lowers the copper filling factor

4: Improved convection and reduced eddy current loss?



Inductor, EE55 shape, with a hole under the coil end for increased inner convection and lower eddy current losses.
1500W PFC choke for battery charging, natural convection.

4: Improved conduction?



Improved heat drain by aluminum plates between ferrites
Example: 6 UU 93/76/16 ferrite cores
No aluminium in the air gap itself.

4: Using ferrite discs and iron powder blocs.

Playing with “building blocks”, multiple air gap and versatile?

Fig. 20a. Ferrite disc with hole 50/15/10, low frequency high induction ferrite (unknown brand)

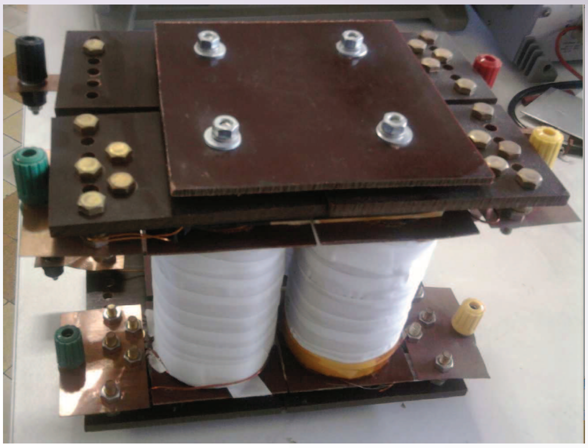
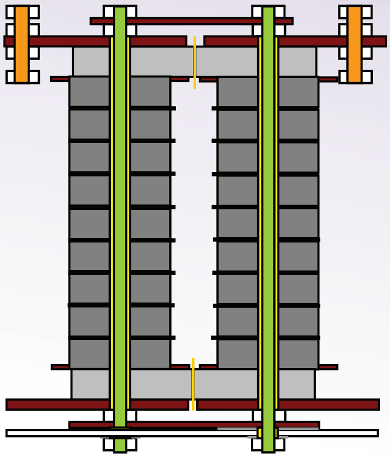


Fig. 20c. Four leg inductor using 50mm ferrite discs and iron powder yokes for
A 3-phase 10kVA filter 30kHz PWM, natural cooling

Fig. 20b. Iron powder yokes 60x30x15 mm bricks (Magnetics Spang)

4: Using ferrite discs and iron powder blocs.

Playing with “building blocks”, multiple air gap and versatile?



Cross section of multiple gap core
With ferrite discs and iron powder yokes

5: Rectangular coil formers on demand?

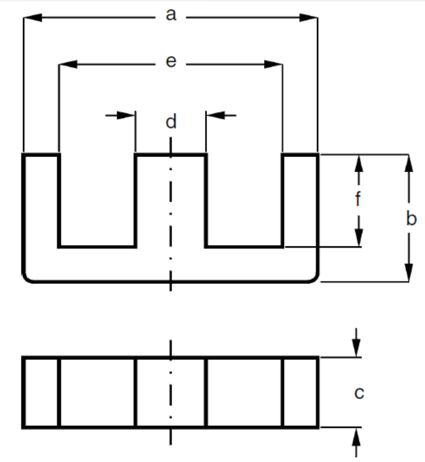
Coil formers on demand?

http://www.feryster.com.pl/polski
/podglad.php?lang=en&id=173

Coil formers on demand?
A lot of choice up to EE65
For large UU , stacked E, prolonged legs
No standard coil former exists
Make by hand?
Only a few dimensions of the core are relevant:

5: Rectangular coil formers on demand?

Coil formers on demand?



Coil formers on demand?
A lot of choice up to EE65
For large UU , stacked E or U, prolonged legs (multigap)
No standard coil former exists, and is not worthwhile for small series.
Who starts automised sample/small series production?
Only a few dimensions of the core are relevant:

d: leg width
c: thickness
w= 2*f: winding space width
e: coil former width

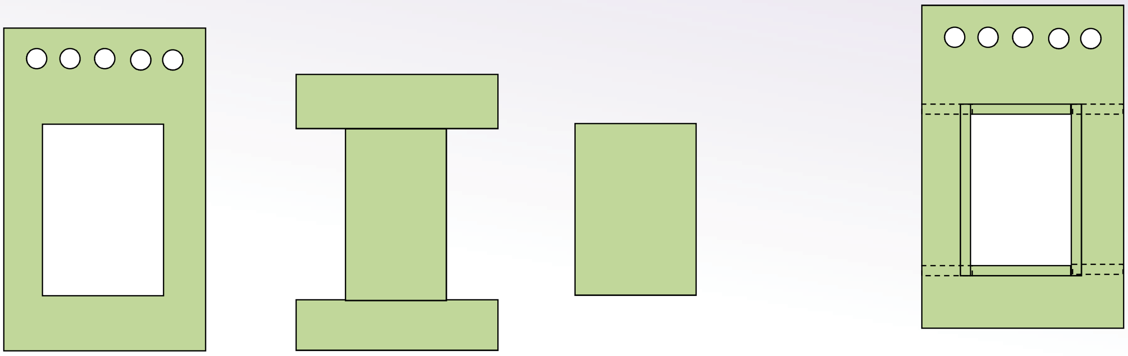
s: space to ferrite, for example 0.2mm
(coil former shrinks by the pressure of the wires)

Material?
Fiber glass with epoxy?
Advantage: high temperature, can be glued
Glue: 150℃ grade glue or better, allows impregnation of coil

5: Rectangular coil formers on demand?

6 plates, 2 of each make the coil former
Shown for hypothetic EE60, 30mm stack

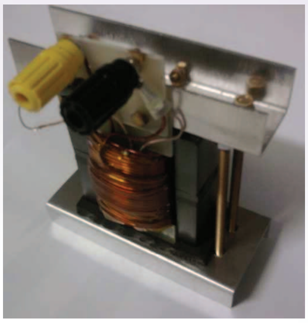
Glued assembly ?



A) flanges B) side core plates C) inner core plates

5: Rectangular coil formers on demand?

Examples showing the need of it:



Inductor with increased cooling of yokes,
Coil former epoxy without flanges.

Detail of a glued coil formers,
large UU inductor with iron core,
adjustable air gap

5: Rectangular coil formers on demand?

Laser cutting? No: it can make material conductive
Water jet? could de
Simply milling? like PCB

Glue:
High temperature cyano-acrylate?
Epoxy?
Impregnating varnish?

Holes?
For solder tags, fixing?

The core itself is normally fixed, it can help heat transfer

High voltage test?

Conclusion

❑ Magnetic component losses

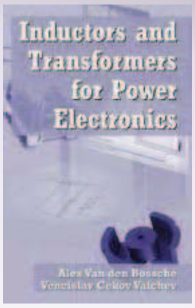
❖ Non sine may have more core losses than sine

❖ Bulk losses get also non-negligible

❖ DC-bias results in more mosses than without

❖ Eddy current losses always important in larger cores.

❖ Air gaps induce more losses in inductors compared to transformers



❑ Larger power components, still with natural convection?

❖ Litz wire?

❖ A hole under the coil end for better copper cooling

❖ Multiple gap.

❖ Ferrite discs $\phi = 50\text{mm}$ as building blocs?

❖ More heat drain: alu plates in parallel with ferrite

❑ Coil formers on demand?

❖ Only a few dimensions relevant, x-y epoxy – glass fiber?

References

1. Alex Van den Bossche, Vencislav Chechov Valchev, “Inductors and Transformers for Power Electronics”, February 23, 2005, CRC-press, Boca Raton USA, ISBN 1574446797, hardcover, 480 pages.
2. Vencislav C. Valchev, Alex P. Van den Bossche, David M. Van de Sype “Ferrite losses of cores with square wave voltage and DC bias” IEEE 31th Annual conference of the Industrial Electronics Society, IECON, November 6-10 2005, Raleigh, NC, USA, pp. 837-841
3. Alex Van den Bossche, “Inductive Components in Power Electronics”, keynote paper, 33th International Telecommunications Energy Conference, IEEE-Intelec 2011, 9-13 October 2011, USB-stick, 11pp.

Thank you
for
your attention!

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