# High Frequency Estimation

Proximity effect

Interleaving

The current $i(t)$ having rms value $I$ is confined to thickness d on the surface of layer 1. Hence the effective "ac" resistance of layer 1 is:

$$R_{ac} = \frac{h}{\delta} R_{dc}$$

This induces copper loss $P_1$ in layer 1:

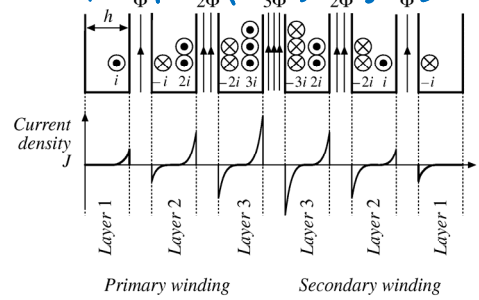
$$P_1 = I^2 R_{ac}$$

Power loss $P_2$ in layer 2 is:

$$P_2 = P_1 + 4P_1 = 5P_1$$

Power loss $P_3$ in layer 3 is:

$$P_3 = \left(2^2 + 3^2\right)P_1 = 13P_1$$




Power loss $P_m$ in layer $m$ is:

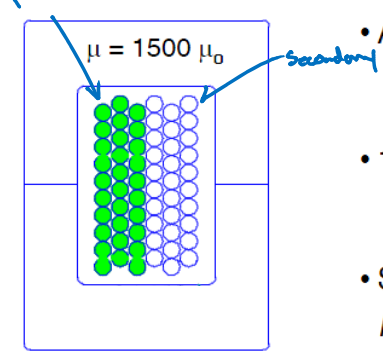
$$P_m = I^2\left[\left(m-1\right)^2 + m^2\right]\left(\frac{h}{\delta} R_{dc}\right)$$



# Simulation Example

30:30

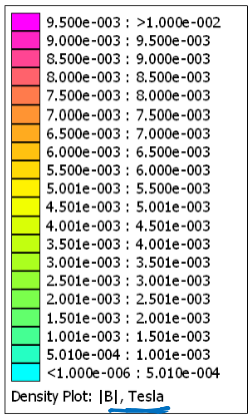
1A 1A



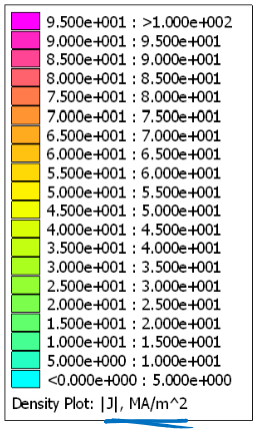

- AWG#30 copper wire
  - Diameter $d$ = 0.294 mm
  - $d = \delta$ at around 50 kHz
- 1:1 transformer
  - Primary and secondary are the same, 30 turns in 3 layers
- Sinusoidal currents, $I_{1rms} = I_{2rms} = 1$ A

Numerical field and current density solutions using FEMM (Finite Element Method Magnetics), a free 2D solver, http://www.femm.info/wiki/HomePage

Flux density magnitude



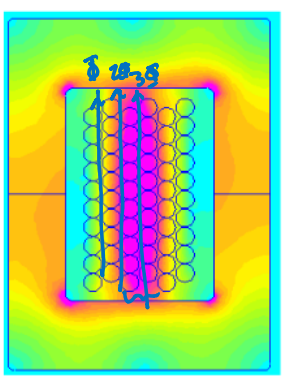

Current density magnitude



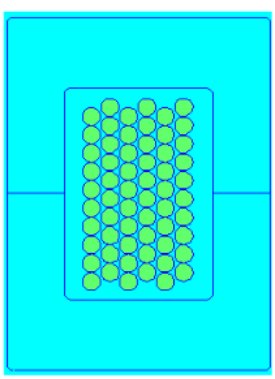



# Frequency: 1 kHz

Flux density

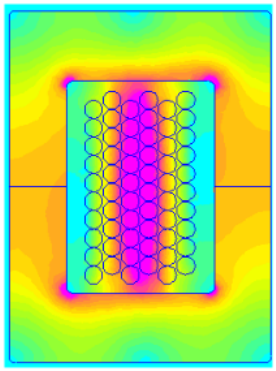


Current Density

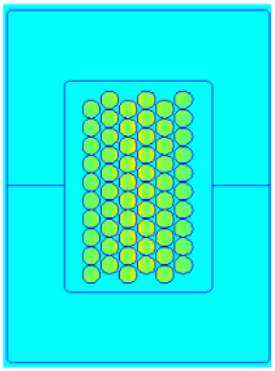


# Frequency: 100 kHz

Flux density



Current Density

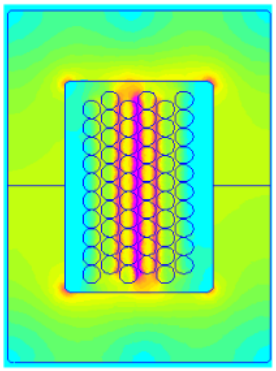


Total copper losses 1.8 larger than at 1 kHz

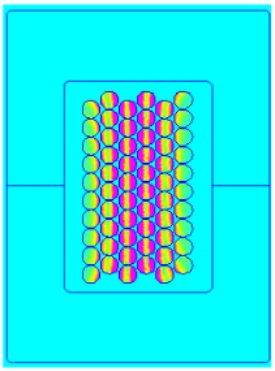


# Frequency: 1 MHz

Flux density



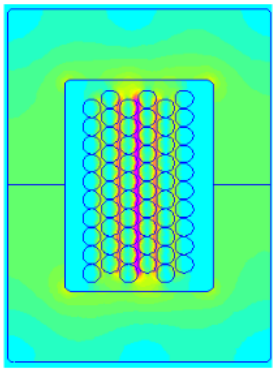
Current Density



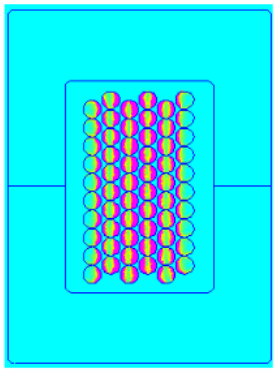
Total copper losses 20 times larger than at 1 kHz

# Frequency: 10 MHz

Flux density



Current Density



Very significant proximity effect
Total copper losses = 65 times larger than at 1 KHz

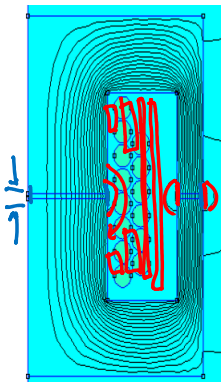


# Fringing Flux

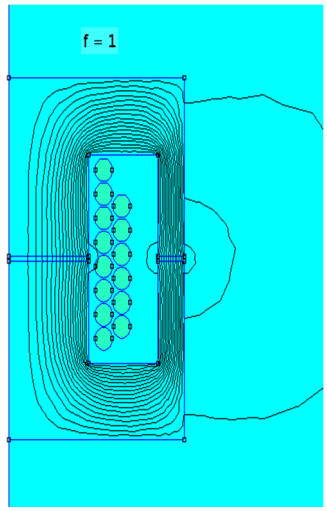
Proximity Effect

Fringing:

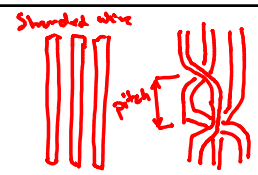
Air gap $l_g$



# Fringing Flux Simulation




# Litz Wire




- A way to increase conductor area while maintaining low proximity losses
- Many strands of small-gauge wire are bundled together and are externally connected in parallel
- Strands are twisted, or transposed, so that each strand passes equally through each position on inside and outside of bundle. This prevents circulation of currents between strands.
- Strand diameter should be sufficiently smaller than skin depth
- The Litz wire bundle itself is composed of multiple layers
- Advantage: when properly sized, can significantly reduce proximity loss
- Disadvantage: increased cost and decreased amount of copper within core window

# Ch 14: Inductor Design


14.1 Filter inductor design constraints

14.2 A step-by-step design procedure

14.3 Multiple-winding magnetics design using the $K_g$ method

14.4 Examples

14.5 Summary of key points

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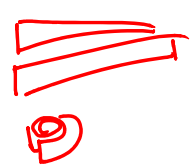
# Filter Inductor Design Constraints

→ ① Want to get desired L

→ ② Need to prevent saturation ($I_{max} < I_{sat}$)

③ Need to be able to fit windings in the core



④ Want to limit Power loss
- Dominated by $R_{DC}$

Design parameters

① Core { Geometry: $A_c$, $l_m$, MLT

② n

③ $l_g$

④ AWG of winding

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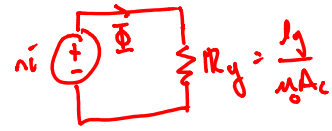
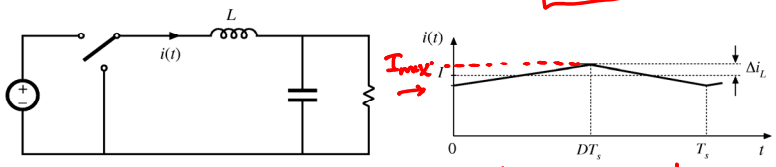
# Design Goals




***Example***: filter inductor in CCM buck converter




$I_{max}$ : max instantaneous current during operation

① $\boxed{L = \frac{\mu_0 n^2 A_c}{l_g}}$

② $\Phi = \frac{ni}{\mathcal{R}_g} = BA_c \rightarrow i = \frac{\mathcal{R}_g}{n} BA_c = \frac{l_g}{n\mu_0} B$

$\boxed{I_{max} = \frac{l_g}{\mu_0 n} B_{max}}$

$B_{max} < B_{sat}$ by about (~10%)



# Geometrical Parameters

③ $\boxed{n A_W \le W_A K_u}$

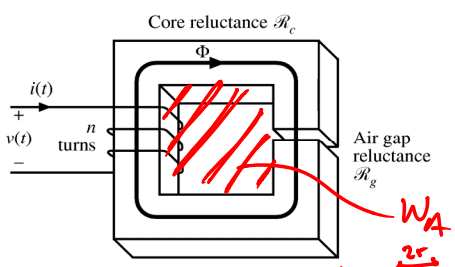
$K_u$ = "fill factor"

$0 \le K_u \le 1$

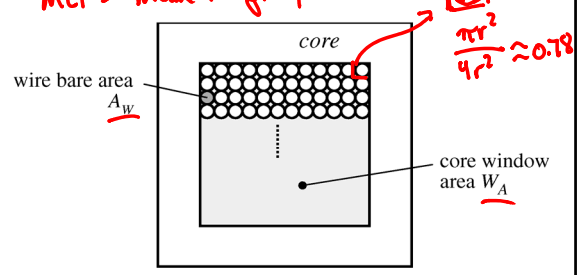
④ $P_{cu} \approx I_{rms}^2 R_{DC}$

$R_{DC} = \rho \frac{l_{winding}}{A_{wire}}$

$\boxed{R_{DC} = \rho \frac{n(MLT)}{A_W}}$




MLT = "Mean length per turn"




$\frac{\pi r^2}{4r^2} \approx 0.78$

# The $K_g$ Method

① $L = \frac{\mu_0 n^2 A_c}{l_g}$

② $I_{max} = \frac{B_{max} l_g}{n \mu_0}$

③ $A_w n \le K_u W_A$

④ $R = \rho \frac{n MLT}{A_w}$

① & ② eliminate $l_g$

$I_{max} = \frac{B_{max}}{n \mu_0} \left( \frac{\mu_0 n^2 A_c}{L} \right) = \frac{B_{max} n A_c}{L}$

③ & ④ eliminate $A_w$

$R = \rho \frac{n^2 MLT}{K_u W_A}$

core geometry

$I_{max}^2 = \frac{B_{max}^2 A_c^2}{L^2} \frac{R K_u W_A}{\rho MLT}$

constants & circuit parameters

$$\boxed{\frac{I_{max}^2 L^2 \rho}{B_{max}^2 R K_u} \le \frac{W_A A_c^2}{MLT} = K_g}$$

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# Window Utilization $K_u$ – "fill factor"

$K_u$ is the fraction of the core window area that is filled by copper

Mechanisms that cause $K_u$ to be less than 1:

- Round wire does not pack perfectly, which reduces $K_u$ by a factor of 0.7 to 0.55 depending on winding technique
- Insulation reduces $K_u$ by a factor of 0.95 to 0.65, depending on wire size and type of insulation
- Bobbin uses some window area
- Additional insulation may be required between windings

Typical values of $K_u$:

0.5 for simple low-voltage inductor

0.25 to 0.3 for off-line transformer

0.05 to 0.2 for high-voltage transformer (multiple kV)

0.65 for low-voltage foil-winding inductor



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# Discussion

$$K_g = \frac{A_c^2 W_A}{(MLT)} \geq \frac{\rho L^2 I_{max}^2}{B_{max}^2 R K_u}$$

$K_g$ is a figure-of-merit that describes the effective electrical size of magnetic cores, in applications where the following quantities are specified:

- Copper loss
- Maximum flux density

How specifications affect the core size:

A smaller core can be used by increasing

$B_{max} \Rightarrow$ use core material having higher $B_{sat}$

$R \Rightarrow$ allow more copper loss

How the core geometry affects electrical capabilities:

A larger $K_g$ can be obtained by increase of

$A_c \Rightarrow$ more iron core material, or

$W_A \Rightarrow$ larger window and more copper



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# $K_g$ Method

pick a core

$$K_g \geq \frac{\rho L^2 I_{max}^2}{B_{max}^2 R K_u} 10^8 \quad (\text{cm}^5)$$

$$\ell_g = \frac{\mu_0 L I_{max}^2}{B_{max}^2 A_c} 10^4 \quad (\text{m})$$

$$n = \frac{L I_{max}}{B_{max} A_c} 10^4$$

$$A_W \leq \frac{K_u W_A}{n} \quad (\text{cm}^2)$$

$$R = \frac{\rho n (MLT)}{A_w} \quad (\Omega)$$

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