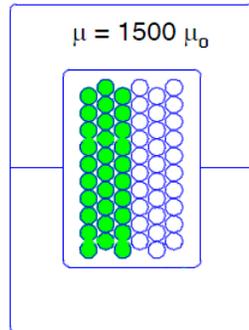


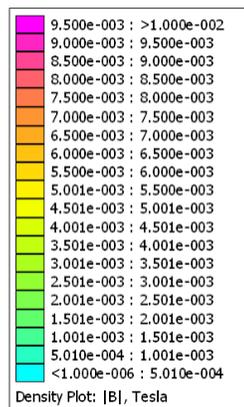
## Simulation Example



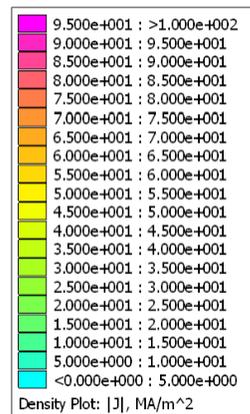
- AWG#30 copper wire
  - Diameter  $d = 0.294$  mm
  - $d = \delta$  at around 50 kHz
- 1:1 transformer
  - Primary and secondary are the same, 30 turns in 3 layers
- Sinusoidal currents,
 
$$I_{1rms} = I_{2rms} = 1 \text{ A}$$

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

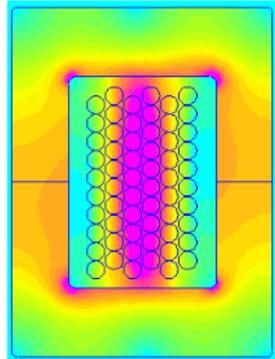


Current density magnitude

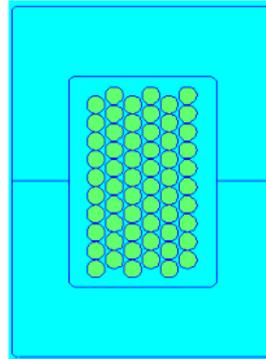


## Frequency: 1 kHz

Flux density

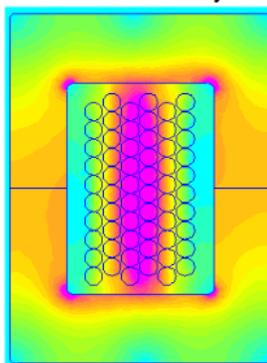


Current Density

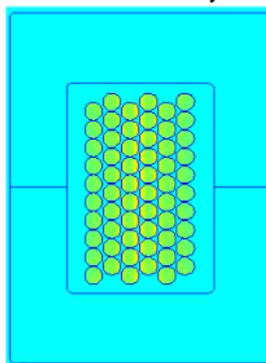


## Frequency: 100 kHz

Flux density



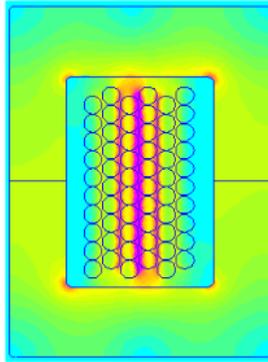
Current Density



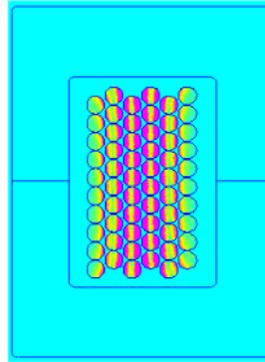
Total copper losses 1.8 larger than at 1 kHz

## Frequency: 1 MHz

Flux density



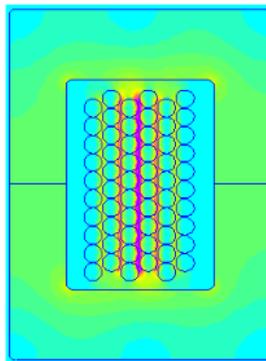
Current Density



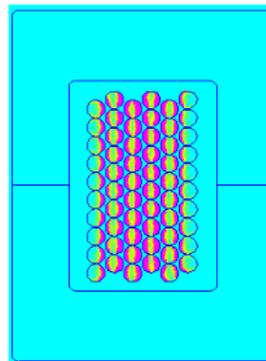
Total copper losses 20 times larger than at 1 kHz

## Frequency: 10 MHz

Flux density

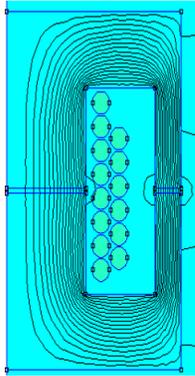


Current Density

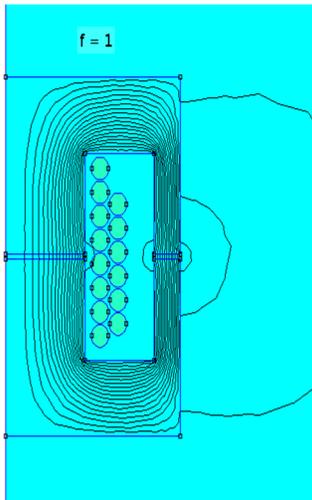


Very significant proximity effect  
Total copper losses = 65 times larger than at 1 KHz

## Fringing Flux



## 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

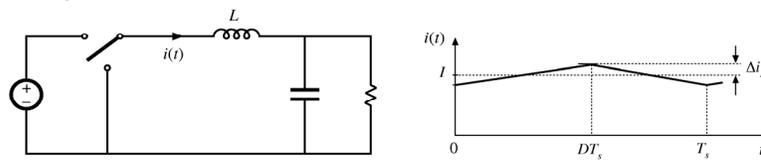
## Ch 14: Inductor Design

- 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

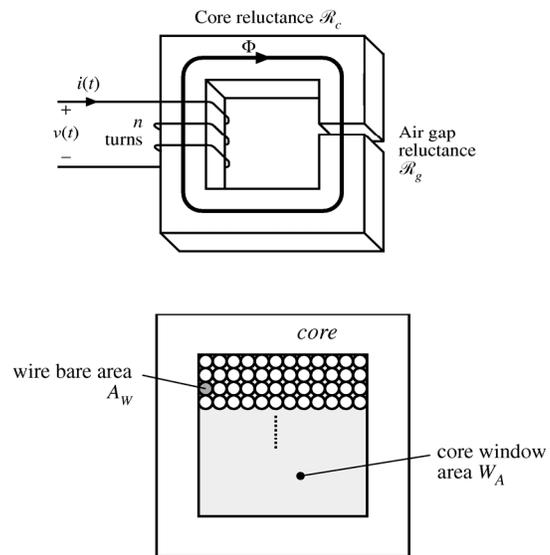
## Filter Inductor Design Constraints

## Design Goals

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



## Geometrical Parameters



## The $K_g$ Method

## 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

## 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  $B_{sat}$

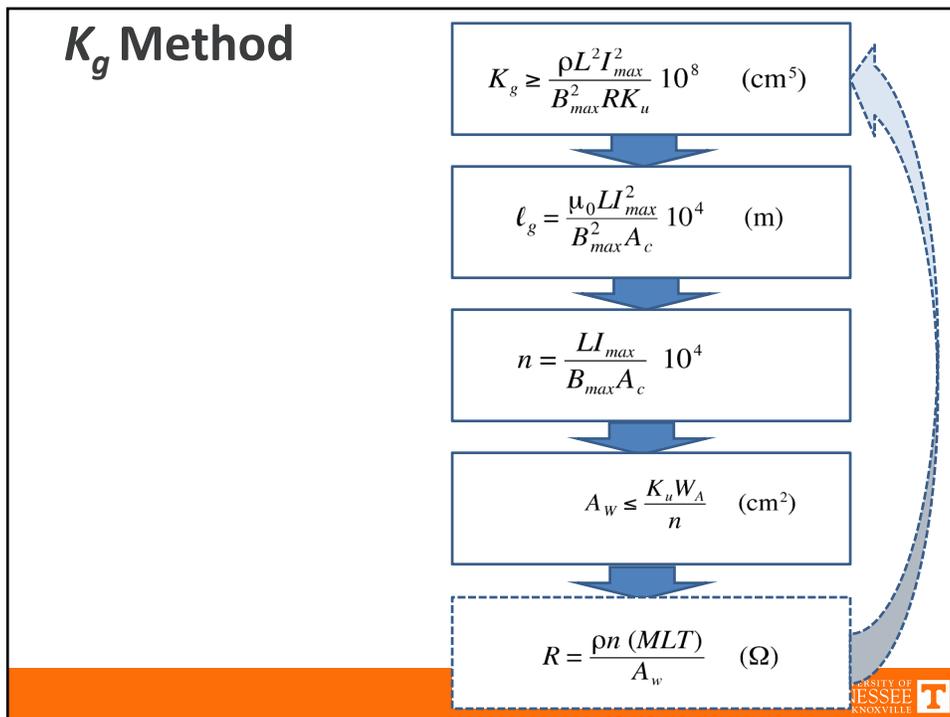
$R \Rightarrow$  allow more copper loss

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



## Alternate Applications

- Can be applied to multiple-winding magnetics as long as design goals apply
  - Core loss negligible
  - Saturation is limiting peak flux density
- 14.3 shows how the method changes

## Chapter 15: Transformer Design

- 15.1 Transformer design: Basic constraints
- 15.2 A step-by-step transformer design procedure
- 15.3 Examples
- 15.4 AC inductor design
- 15.5 Summary

*Fundamentals of Power Electronics*

2

*Chapter 15: Transformer design*

## Transformer Design Constraints

## Power Loss Tradeoffs

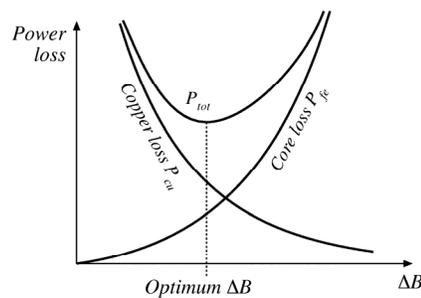
## Minimizing Total Loss

There is a value of  $\Delta B$  that minimizes the total power loss

$$P_{tot} = P_{fe} + P_{cu}$$

$$P_{fe} = K_{fe}(\Delta B)^{\beta} A_c \ell_m$$

$$P_{cu} = \left( \frac{\rho \lambda_1^2 I_{tot}^2}{4K_u} \right) \left( \frac{MLT}{W_A A_c^2} \right) \left( \frac{1}{\Delta B} \right)^2$$



## Calculation of Total Loss

Substitute optimum  $\Delta B$  into expressions for  $P_{cu}$  and  $P_{fe}$ . The total loss is:

$$P_{tot} = \left[ A_c \ell_m K_{fe} \right]^{\left( \frac{2}{\beta+2} \right)} \left[ \frac{\rho \lambda_1^2 I_{tot}^2}{4K_u} \frac{(MLT)}{W_A A_c^2} \right]^{\left( \frac{\beta}{\beta+2} \right)} \left[ \left( \frac{\beta}{2} \right)^{-\left( \frac{\beta}{\beta+2} \right)} + \left( \frac{\beta}{2} \right)^{\left( \frac{2}{\beta+2} \right)} \right]$$

Rearrange as follows:

$$\frac{W_A (A_c)^{2(\beta-1)\beta}}{(MLT) \ell_m^{(2/\beta)}} \left[ \left( \frac{\beta}{2} \right)^{-\left( \frac{\beta}{\beta+2} \right)} + \left( \frac{\beta}{2} \right)^{\left( \frac{2}{\beta+2} \right)} \right]^{-\left( \frac{\beta+2}{\beta} \right)} = \frac{\rho \lambda_1^2 I_{tot}^2 K_{fe}^{(2/\beta)}}{4K_u (P_{tot})^{((\beta+2)/\beta)}}$$

Left side: terms depend on core geometry

Right side: terms depend on specifications of the application

## The $K_{gfe}$ Method

$$\text{Define } K_{gfe} = \frac{W_A (A_c)^{2(\beta-1)\beta}}{(MLT) \ell_m^{(2/\beta)}} \left[ \left( \frac{\beta}{2} \right)^{-\left( \frac{\beta}{\beta+2} \right)} + \left( \frac{\beta}{2} \right)^{\left( \frac{2}{\beta+2} \right)} \right]^{-\left( \frac{\beta+2}{\beta} \right)}$$

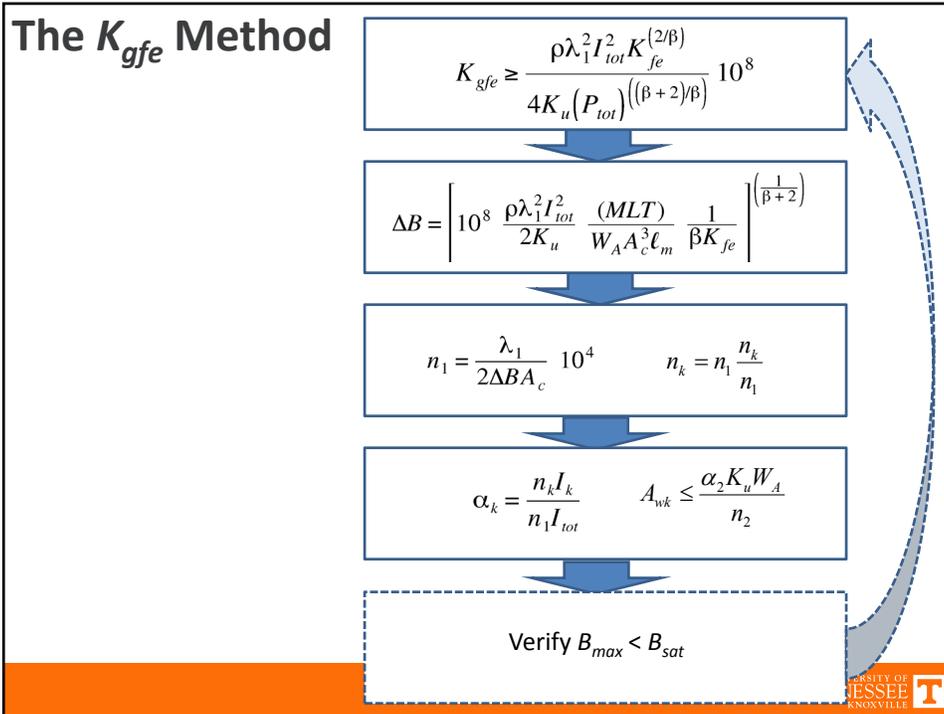
Design procedure: select a core that satisfies

$$K_{gfe} \geq \frac{\rho \lambda_1^2 I_{tot}^2 K_{fe}^{(2/\beta)}}{4K_u (P_{tot})^{((\beta+2)/\beta)}}$$

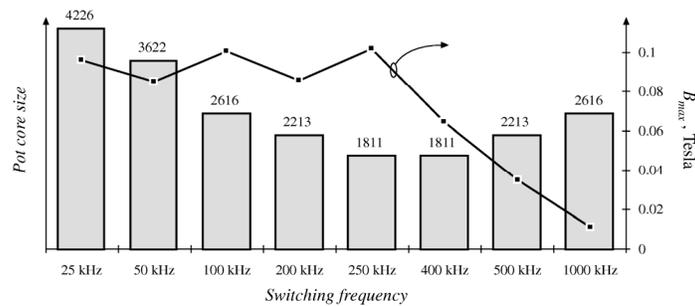
Appendix D lists the values of  $K_{gfe}$  for common ferrite cores

$K_{gfe}$  is similar to the  $K_g$  geometrical constant used in Chapter 14:

- $K_g$  is used when  $B_{max}$  is specified
- $K_{gfe}$  is used when  $\Delta B$  is to be chosen to minimize total loss



## Switching Frequency Vs. XF Size



- As switching frequency is increased from 25 kHz to 250 kHz, core size is dramatically reduced
- As switching frequency is increased from 400 kHz to 1 MHz, core size increases