Magnetic Components Design

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Seminar Contents

- Basic Concepts
- Design
- Modeling
- Simulation
- Examples

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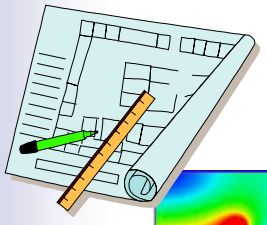
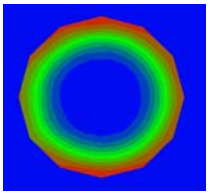
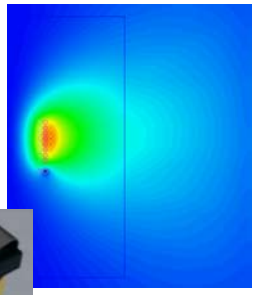
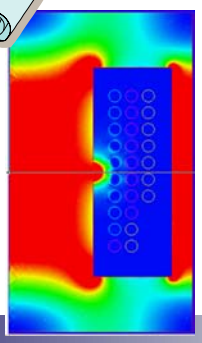
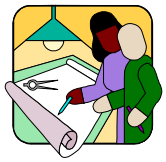
Basic Concepts



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Basic Magnetic Theory

AMPERE'S LAW

$$\oint H\,dl = ni$$

FARADAY'S LAW

$$V(t) = n\frac{d\Phi}{dt}$$

$B = \mu H$
$\Phi = BA$
$\mu = \mu_r \mu_o$

H:	Magnetic field
Φ:	Magnetic flux
B:	Magnetic flux density
A:	Area
V(t):	Voltage
i:	Current
dl:	Vector lenght
μ:	Permeability
μ_o:	Air permeability
μ_r:	Relative permeability
n:	Number of turns
F(t):	Electromagnetic force

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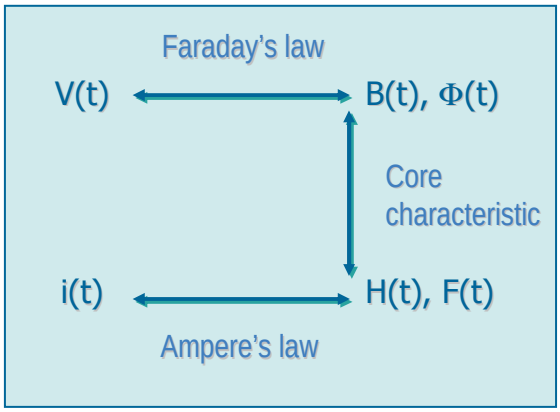
Basic Magnetic Theory



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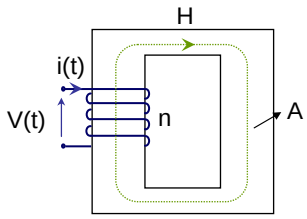
Basic Magnetic Theory



$$V(t) = nA\frac{dB(t)}{dt}$$

$$H(t)l = ni(t)$$

$$V(t) = nA\mu\frac{dH(t)}{dt}$$

$$V(t) = \frac{n^2A}{l}\mu\frac{di(t)}{dt}$$

$$L = \frac{\mu n^2 A}{l}$$

$$V(t) = L\frac{di(t)}{dt}$$

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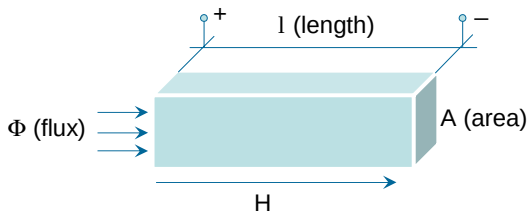
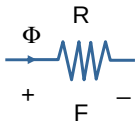
Basic Magnetic Theory

Magnetic Circuits



$$F = Hl = \frac{l}{\mu A}\Phi$$

$F = \Phi R$ ⇨ $R = \frac{l}{\mu A}$ (Reluctance)



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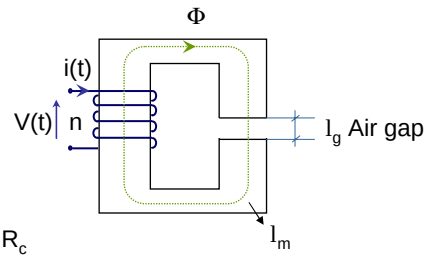
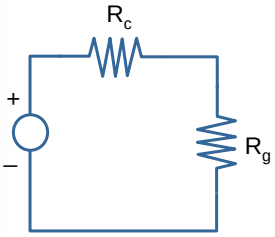
Basic Magnetic Theory





$$ni(t) = \Phi(R_c + R_g)$$

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Basic Magnetic Theory

$$\left.\begin{aligned} V(t) &= n\frac{d\Phi}{dt} \\ ni(t) &= \Phi(R_c + R_g) \end{aligned}\right\} V(t) = \frac{n^2}{R_c + R_g} d\frac{i(t)}{dt}$$

$$L = \frac{n^2}{R_c + R_g}$$

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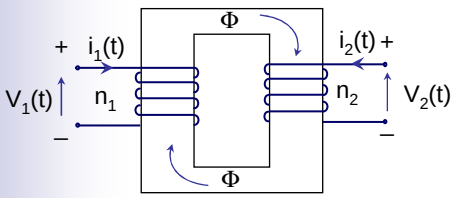
Basic Magnetic Theory

Transformer



$$R = \frac{l_m}{\mu A}$$

$$n_1 i_1 + n_2 i_2 = \Phi R$$

$$\left.\begin{aligned} V_1 &= n_1 \frac{d\Phi}{dt} \\ V_2 &= n_2 \frac{d\Phi}{dt} \end{aligned}\right\} \frac{d\Phi}{dt} = \frac{V_1}{n_1} = \frac{V_2}{n_2}$$

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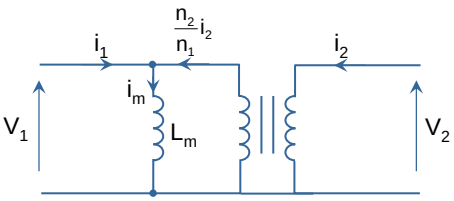
Basic Magnetic Theory

$$V_1 = \frac{n_1^2}{R}\frac{d}{dt}\left[i_1 + \frac{n_2}{n_1} i_2\right]$$

$$V_1 = L_m \frac{d\, i_m}{dt}$$



$$L_m = \frac{n_1^2}{R}; \qquad i_m = i_1 + \frac{n_2}{n_1} i_2$$

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Basic Concepts

- There are many Applications of Magnetic components
  - ✓ Galvanic Isolation
  - ✓ Adjust Voltage Levels
  - ✓ Filters
  - ✓ Resonant Inductors
  - ✓ Measurements for Feedback and Protections
  - ✓ Pulse Transformers
  - ✓ …
- But basically, they produce
  - ✓ Energy Storage
  - ✓ Energy Transfer
  - ✓ Losses

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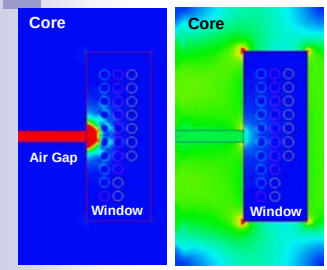
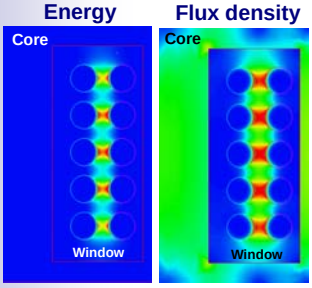
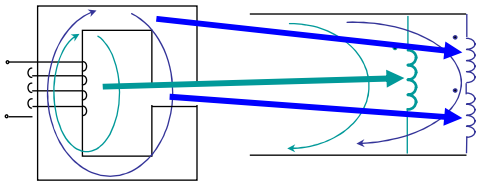
Magnetic Energy



Energy | Flux density

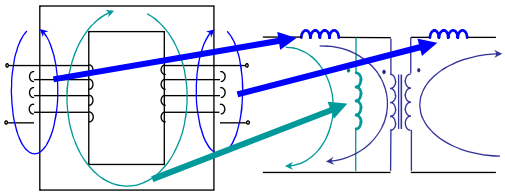


Inductors



Each inductance models the "magnetic energy storage" In each different zone

Transformers



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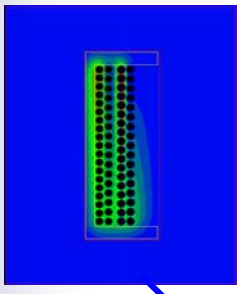
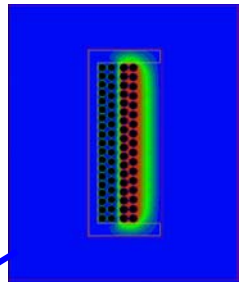
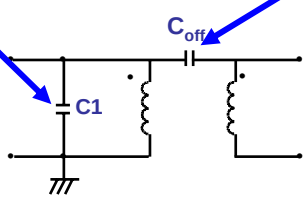
Electric Energy



Each capacitance models the "electric energy storage"





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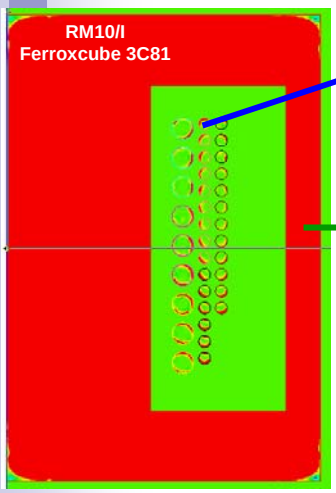
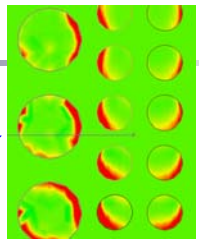
Losses



Losses @ 1MHz



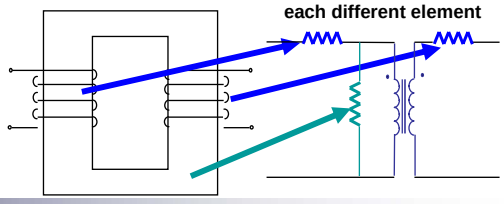
Winding Losses

Skin effect
Proximity effect
Gap effect
End effect

Core Losses

Eddy Current
Hysteretic
Residual

Each resistance models the "losses" in each different element



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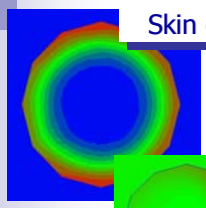
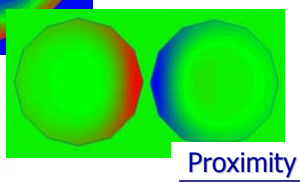
Winding Losses

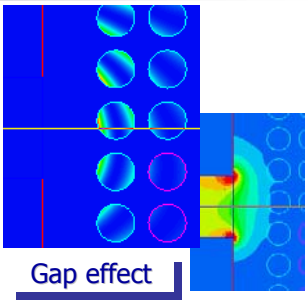
Skin effect



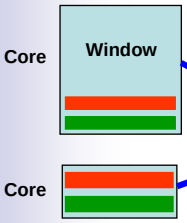
$$\delta = \frac{1}{\sqrt{\pi f \mu_0 \sigma}}$$



Proximity effect



Gap effect



Different Open Circuit Resistances — Same Short Circuit Resistance

	R_{open_prim} (mΩ)	R_{open_sec} (mΩ)	R_{short_prim} (mΩ)
A	3.5	3.65	5.74
B	6.32	6.33	5.74

Core Proximity effect

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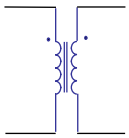
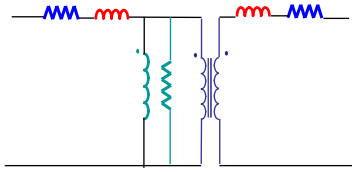
Ideal and Real Components





- Ideal transformer:

$$\frac{d\phi}{dt} = \frac{v_1}{n_1} = \frac{v_2}{n_2} = \ldots = \frac{v_p}{n_p}$$

$$n_1 \cdot i_1 = n_2 \cdot i_2$$

No energy storage !!

No losses !!

- Real transformer :
  - ✓ **Common energy:**

$$L_{mag,\,i} = \frac{n_i^2}{\Re}$$

$$\sum ni = \Phi \cdot \Re$$

From any winding

  - ✓ **Self energy**
  - ✓ **Conductor losses**

Notice the difference between "transferred" and "stored" energy

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Magnetic Component Elements

Core
- ☑ Flux Path
- ☑ Energy storage

Windings
- ☑ Electrical terminals
- ☑ Current path

Bobbin
- ☑ Windings holder

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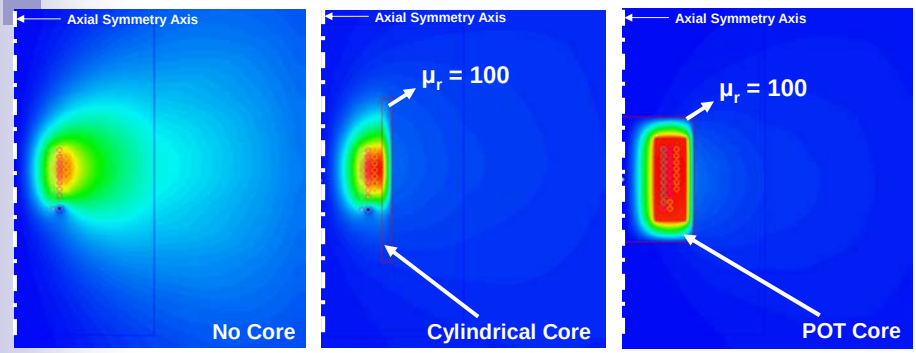
The Role of the Core I



Flux Lines

The Core helps to create a flux path

Additionally the core determines the energy and inductance

Unfortunately, the core also produces losses

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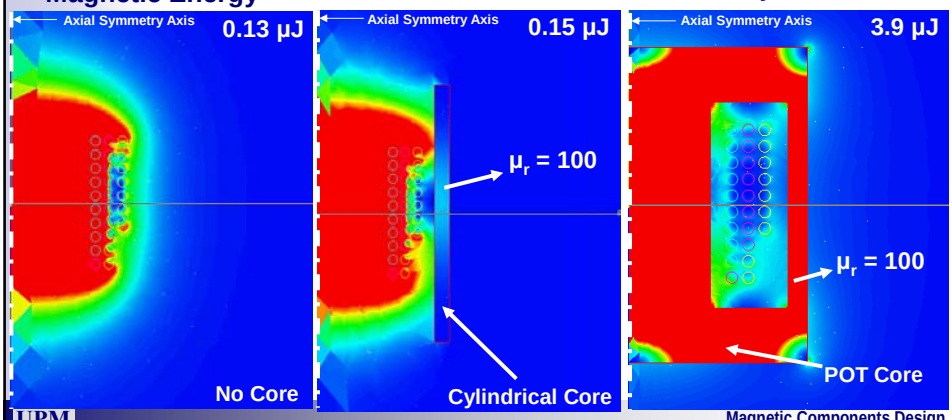
The Role of the Core II

Reluctance

$$\Re = \frac{1}{\mu} \cdot \frac{\text{length}}{Area}$$

$$L = \underbrace{\mu_o \cdot \mu_r}_{\text{Material}} \cdot \underbrace{\frac{Area}{Length}}_{\text{Geometry}} \cdot \underbrace{n^2}_{\text{Turns}}$$

Magnetic Energy



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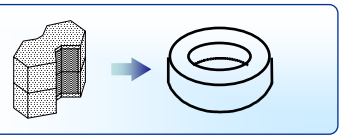
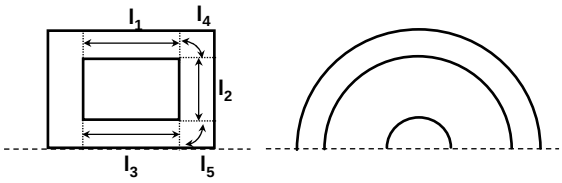
The Effective Values of the Core

Effective Values



Example: POT Core



$$L = \mu_o \cdot \mu_r \cdot \frac{\text{Area}}{\text{Length}} n^2$$

$$A_e = \frac{C_1}{C_2}; \quad V_e = \frac{C_1^3}{C_2^2}; \quad l_e = \frac{C_1^2}{C_2}$$

$$C_1 = \sum_1^5 \frac{l_i}{A_i} mm^{-1} \quad C_2 = \sum_1^5 \frac{l_i}{A_i^2} mm^{-3}$$

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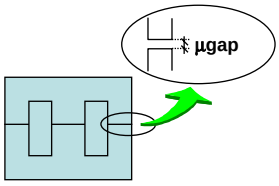
The Tolerances of the Core

GRADE	A_L (nH)	μ_e	AIR GAP (µm)
3B8 sup	160 ±3%	≈59	≈900
	250 ±3%	≈92	≈500
	315 ±3%	≈116	≈400
	400 ±3%	≈147	≈300
	630 ±3%	≈232	≈150
	4950 ±25%	≈1820	≈0



μ_e (and A_L) depends on the "micro-gap" (2.5 µm or 100 mils each union) because of mechanization process

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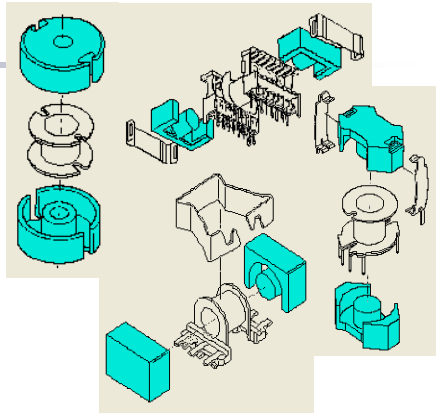
The Core Choices

Shapes
RM, POT, EE, EI, PQ, TOROIDS...

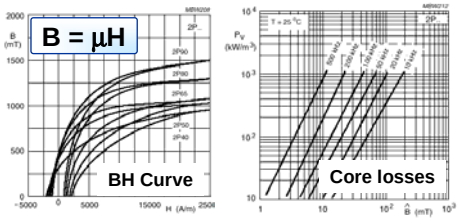
- ☑ Effective values
- ☑ Magnetic coupling
- ☑ Heat transfer
- ☑ Unit Cost
- ☑ Manufacturing Cost



Materials
3F3, 3C85, 3C90, N67, N47...

- ☑ Core losses
- ☑ Permeability and Reluctance
- ☑ Conductivity
- ☑ Saturation flux density

$$L = \mu_o \cdot \mu_r \cdot \frac{Area}{Length} \cdot n^2$$



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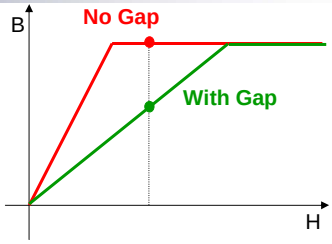
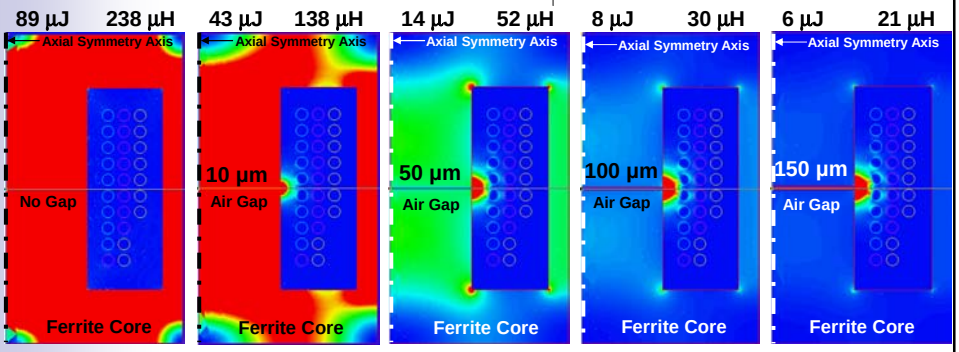
The Role of the Gap

- ☑ Adjust the reluctance value
- ☑ Adjust the energy storage
- ☑ Avoid saturation





Energy

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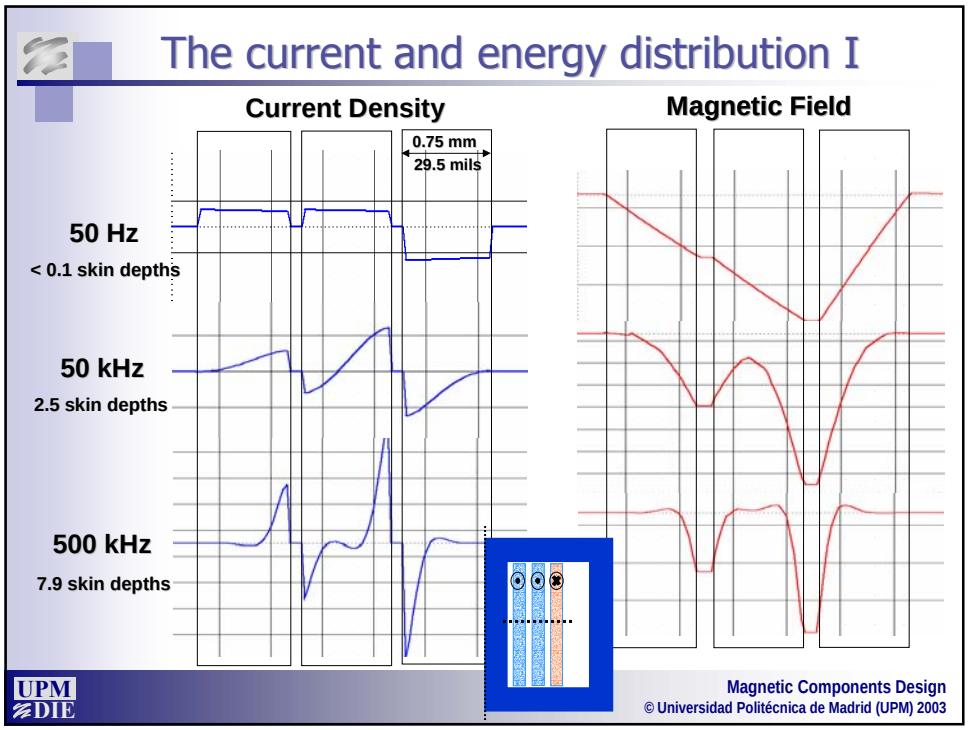
The current and energy distribution I
Current Density
Magnetic Field
0.75 mm
29.5 mils
50 Hz
< 0.1 skin depths
50 kHz
2.5 skin depths
500 kHz
7.9 skin depths
UPM
DIE
Magnetic Components Design
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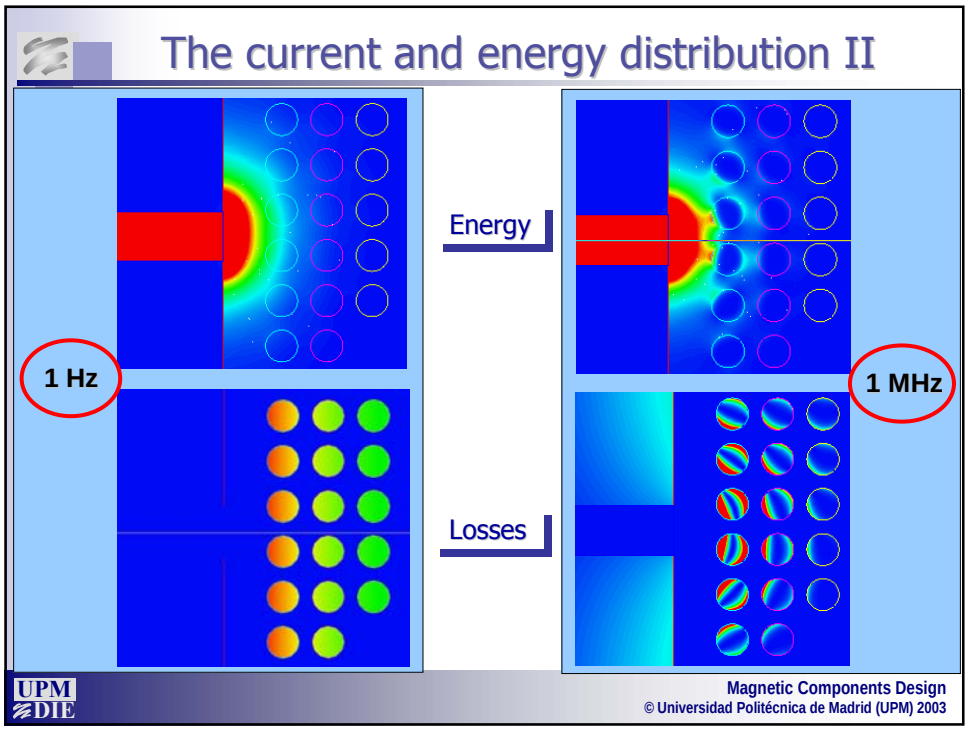
The current and energy distribution II
Energy
Losses
1 Hz
1 MHz
UPM
DIE
Magnetic Components Design
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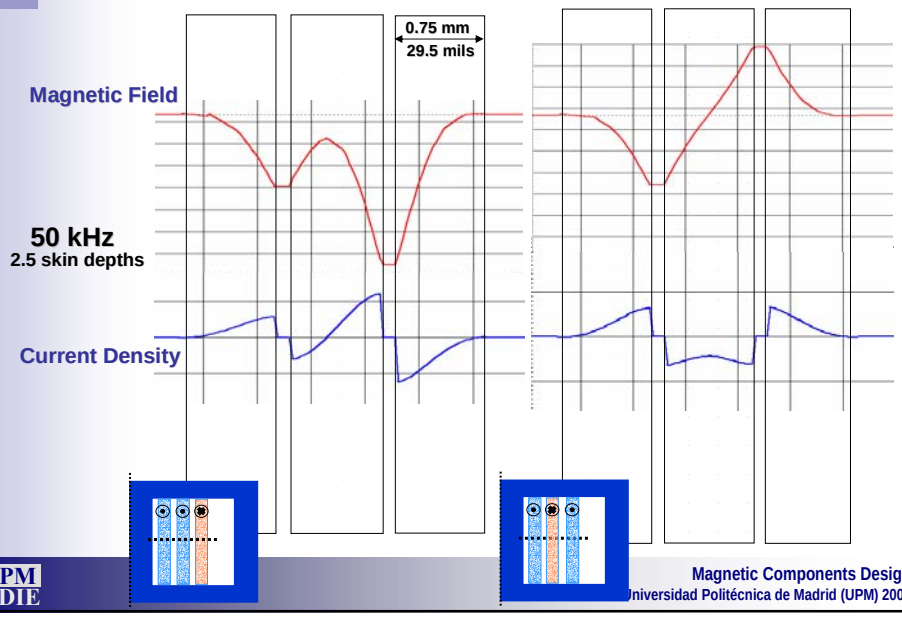
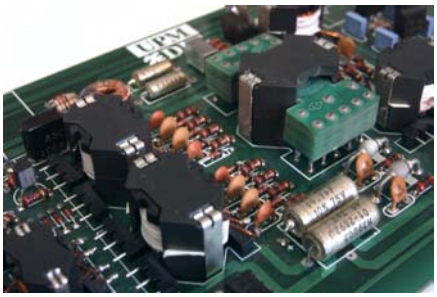
Interleaving Application



Design



Selection of Constructive Elements

1. CORE SHAPE — Depends on the application (see data books)
2. CORE SIZE — Depends on the power ("area product" or data books)
3. CORE MATERIAL — Depends on the "frequency" (see data books)
4. CONDUCTOR TYPE — Depends on the "frequency" (skin depth)
   - Solid wire: low frequency
   - Litz wire and foils: high frequency
5. CONDUCTOR AREA — Depends on the optimum losses

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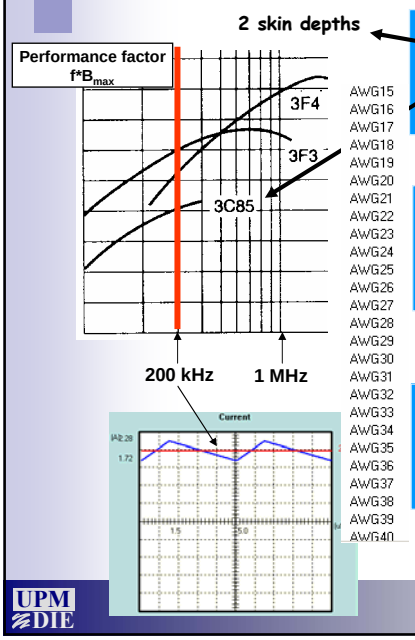
Example of selection of elements



AWG15 AWG16 AWG17 AWG18 AWG19 AWG20 AWG21 AWG22 AWG23 AWG24 AWG25 AWG26 AWG27 AWG28 AWG29 AWG30 AWG31 AWG32 AWG33 AWG34 AWG35 AWG36 AWG37 AWG38 AWG39 AWG40

RM4/I
AWG 30
Ferroxcube 3C85
L = 20 µH
f = 200kHz

Losses considering selected model

Core:	7.068 (mW)
Winding:	477.236 (mW)
Total:	484.304 (mW)

RM4/I
AWG ?
Ferroxcube 3C85
L = 20 µH
f = 200kHz

Losses considering selected model

Core:	7.068 (mW)
Winding:	132.385 (mW)
Total:	139.453 (mW)

AWG 24 ≅ 4 skin depths

RM4/I
AWG 24
Ferroxcube ?
L = 20 µH
f = 200kHz

Losses considering selected model

Core:	538.461 (uW)
Winding:	105.221 (mW)
Total:	105.759 (mW)

3F3

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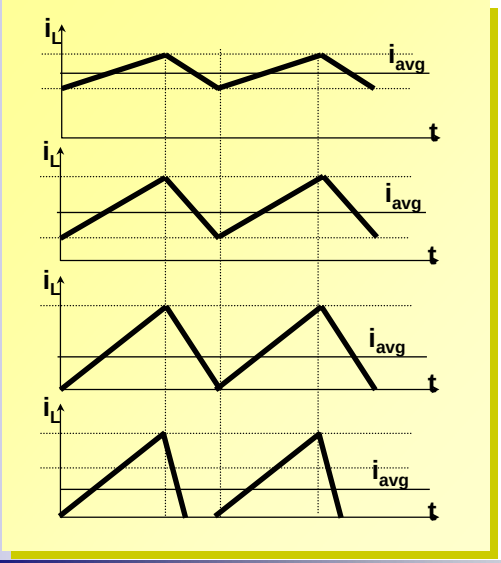
The "effective frequency" concept



Same frequency?
Yes

Same "effective frequency"?
No

Affects the selection of:

- CORE MATERIAL
- CONDUCTOR TYPE
- CONDUCTOR AREA

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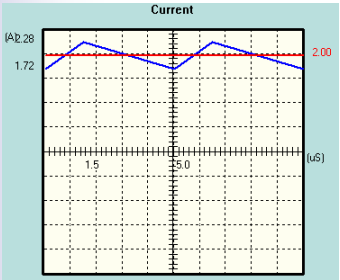
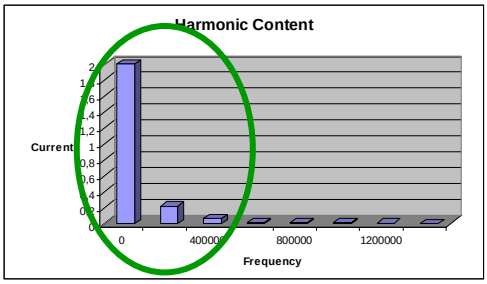
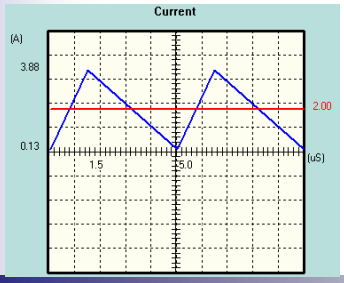
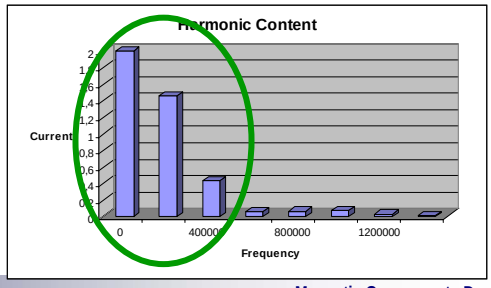
The "effective frequency" concept









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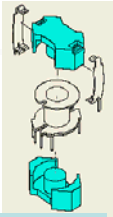
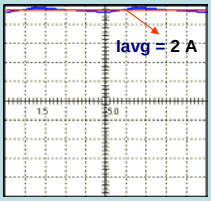
Example (Effective Frequency)



Vpos = 7.5 V; Vneg = 3.21 V; Switch. Freq = 200 kHz; Iavg = 2 A; Duty = 30%

Core shape and size: RM5/I
Wire gauge: AWG28 (370 µm or 14.5 mils diameter)

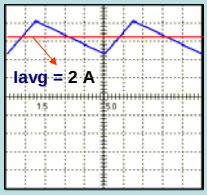


L = 100 µH;
Ripple = 112.5 mA

Ripple = 5.6% Iavg

Ferroxcube 3F35 (Ferrite)
Losses = 785 mW (32 turns)

Ferroxcube 2P90 (Iron Powder)
Losses = 577 mW (16 turns)



L = 10 µH;
Ripple = 1.125 A

Ripple = 56% Iavg

Ferroxcube 3F35 (Ferrite)
Losses = 89 mW (4 turns)

Ferroxcube 2P90 (Iron Powder)
Losses = 371 mW (16 turns)

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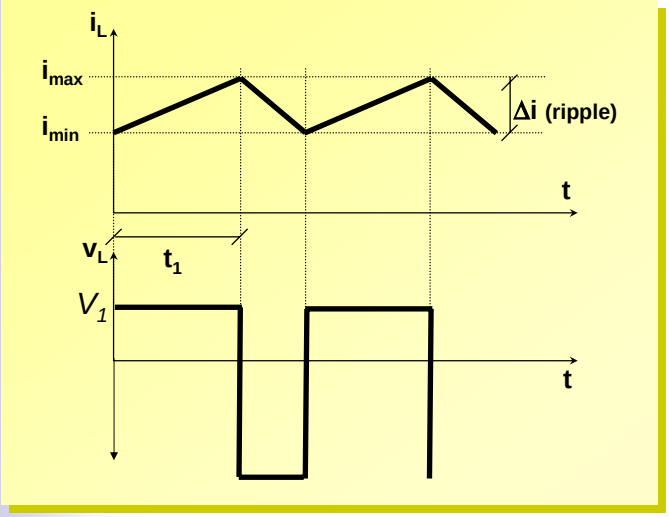
Inductors

Calculation of Inductance



$$V_1 = L\frac{\Delta i}{t_1}$$

$$L = \frac{V_1 \cdot t_1}{\Delta i}$$

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Inductors

Calculation of initial number of turns

The minimum number of turns should be calculated in order to keep flux density under the saturation value

$$L\frac{\Delta i}{\Delta t} = N\frac{\Delta \Phi}{\Delta t} \Rightarrow L\Delta i = N \cdot A_e \cdot \Delta B \Rightarrow$$

$$\Rightarrow L \cdot i_{max} = N \cdot A_e \cdot B_{max} \Rightarrow \boxed{N = \frac{L \cdot i_{max}}{A_e \cdot B_{max}}}$$

This number of turns ensures that the inductor will not be saturated

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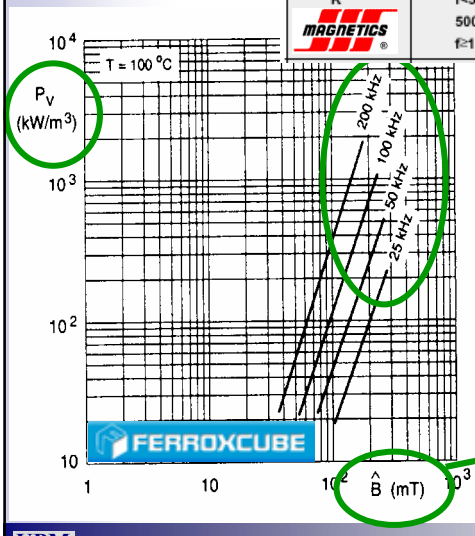
Core Losses Calculation

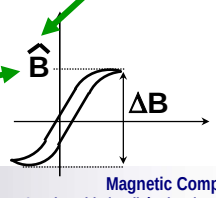
Material	Frequency	a	c	d
K	f<500 kHz	0.0530	1.60	3.15
	500 kHz≤f<1 MHz	0.00113	2.19	3.10
	f≥1 MHz	$1.77 \cdot 10^{-9}$	4.13	2.98



Steinmetz Equation

FORMAT: $P_L = af^c B^d$

P_L in mW/cm³, B in kG, f in kHz



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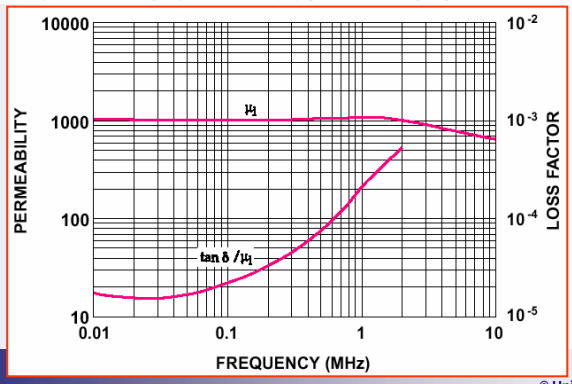
Core Losses Calculation

CORE LOSS vs PEAK AC FLUX DENSITY

$$\text{FORMULA: } CL(mW/cm^3) = \frac{f}{\frac{a}{B^3} + \frac{b}{B^{2.3}} + \frac{c}{B^{1.65}}} + (d\, f^2\, B^2)$$

Material	a	b	c	d
-2	4.0×10^9	3.0×10^8	2.7×10^6	8.0×10^{-15}
-8	1.9×10^9	2.0×10^8	9.0×10^5	2.5×10^{-14}
-14	4.0×10^9	3.0×10^8	2.7×10^6	1.6×10^{-14}
-18	8.0×10^8	1.7×10^8	9.0×10^5	3.1×10^{-14}
-26	1.0×10^9	1.1×10^8	1.9×10^6	1.9×10^{-13}



Steward

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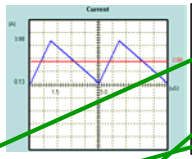
Winding Losses Calculation

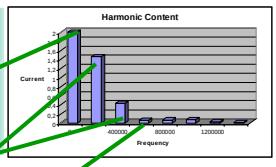
1. R_{DC}

$$P = I^2_{rms} * R_{DC}$$

$$R_{DC} = \rho \cdot \frac{\text{length}}{\text{Area}}$$

2. R_{AC}





$$P = I^2_{DC} * R_{DC} + I^2_{rms_1} * R_{AC_1} + I^2_{rms_2} * R_{AC_2} + I^2_{rms_3} * R_{AC_3} + \ldots$$

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Winding Losses Calculation

$$P = I^2_{DC} * R_{DC} + I^2_{rms_1} * R_{AC_1} + I^2_{rms_2} * R_{AC_2} + I^2_{rms_3} * R_{AC_3} + \ldots$$

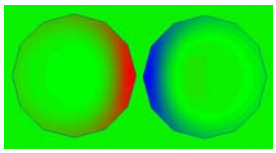
1. Only Skin

$$\delta = \frac{1}{\sqrt{\pi f \mu_0 \sigma}}$$

2. Analytical (i.e. Dowell)

$$K_r = \frac{R_{AC}}{R_{DC}} = 0.5y\left[M(y) + (2m-1)^2 \cdot D(y)\right]$$

3. FEA



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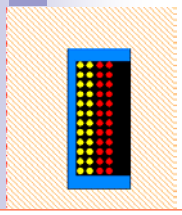
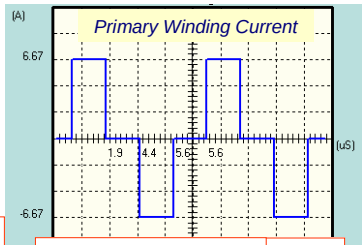
Winding Losses Calculation. Example 1.



RM7/I
AWG 26
(2 skin depths)
n1=n2=12 (2 parallel)



Frequency = 20 kHz | 25 W

$$P = I^2_{rms} * R_{DC}$$

R_{DC} → 1.506 W

$$P = I^2_{DC} * R_{DC} + I^2_{rms_1} * R_{AC_1} + I^2_{rms_2} * R_{AC_2} + I^2_{rms_3} * R_{AC_3} + \ldots$$

Skin → 1.529 W

Dowell → 1.527 W

128 harmonics

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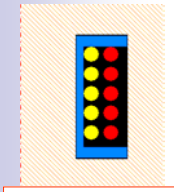
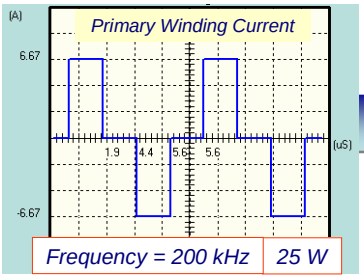
Winding Losses Calculation. Example 2.



RM10/I
AWG 15
(10 skin depths)
n1=n2=5



$P = I^2_{rms} * R_{DC}$

R_{DC} → 149.6 mW

$$P = I^2_{DC} * R_{DC} + I^2_{rms_1} * R_{AC_1} + I^2_{rms_2} * R_{AC_2} + I^2_{rms_3} * R_{AC_3} + \ldots$$

Skin → 464.9 mW

Dowell → 750.5 mW

128 harmonics

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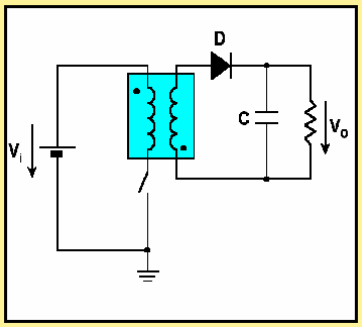
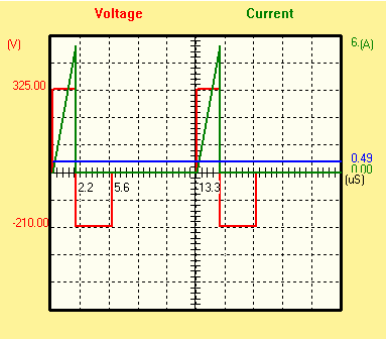
Winding Losses Calculation. Example 3

Input Voltage: 325 V

Switching Frequency: 75 kHz

Output Values
Voltage: 42 V
Current: 3.81 (A)
Power: 160 W
Load: 11.03 (ohm)





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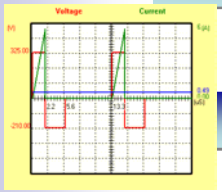
Winding Losses Calculation. Example 3



R_{DC}

Windings: 457.225 (mW)

Temperature Rise (ºC) 6.69

Skin

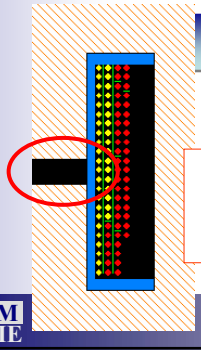
Windings: 777.438 (mW)

Temperature Rise (ºC) 10.19

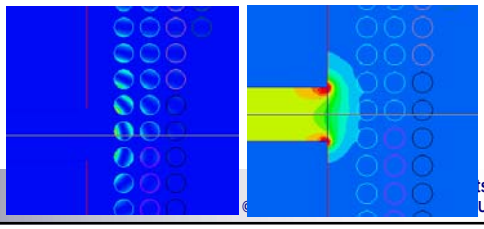
FEA

Windings: 38.375 (W)

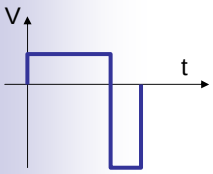
Temperature Rise (ºC) 423.14

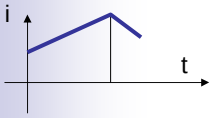


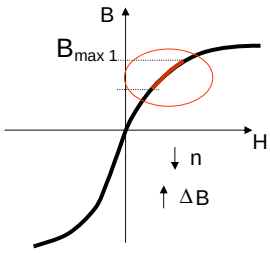
ETD39
AWG 20
n1= 40
n2=8

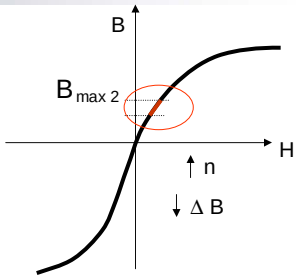


Optimization (I)









$$n \cdot \Delta B = \frac{V \cdot \Delta t}{Area} \Rightarrow n \cdot \Delta B = Constant$$

$$n \cdot B_{max} = \frac{L \cdot i_{max}}{Area} \Rightarrow n \cdot B_{max} = Constant$$

$$\uparrow B_{max} \Rightarrow \left\{ \begin{matrix} \downarrow n \\ \uparrow \Delta B \end{matrix} \right\} \Rightarrow \left\{ \begin{matrix} \downarrow \text{Copper Losses} \\ \uparrow \text{Core Losses} \end{matrix} \right.$$

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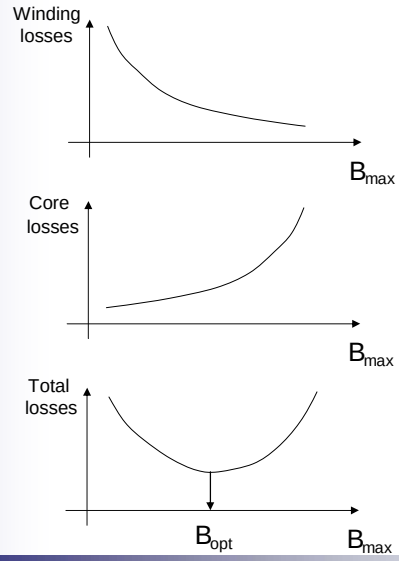
Optimization (II)

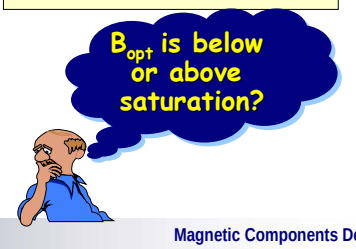


$\uparrow B_{max} \Rightarrow \downarrow n$

$$P = I^2_{rms} \cdot n \cdot \rho \cdot \frac{\text{length}}{\text{Area}}$$

$\uparrow B_{max} \Rightarrow \uparrow \Delta B$

$$P = V_e \cdot k \cdot f^{\alpha} \cdot \left(\frac{\Delta B}{2}\right)^{\beta}$$



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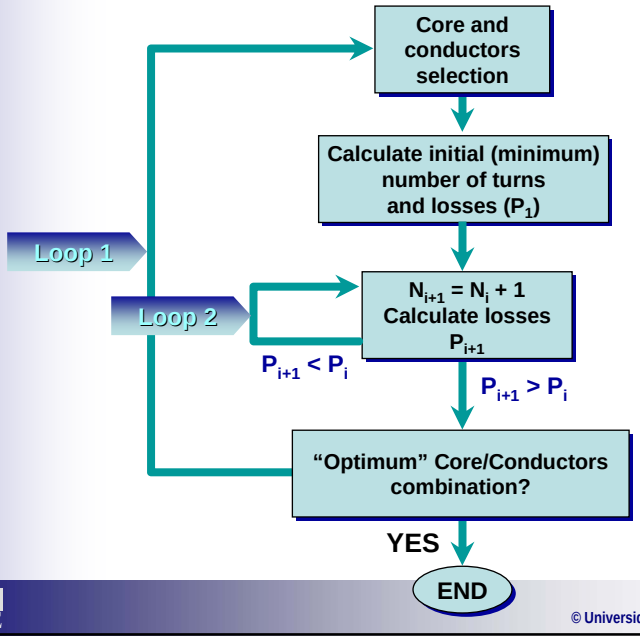
Optimization (III)



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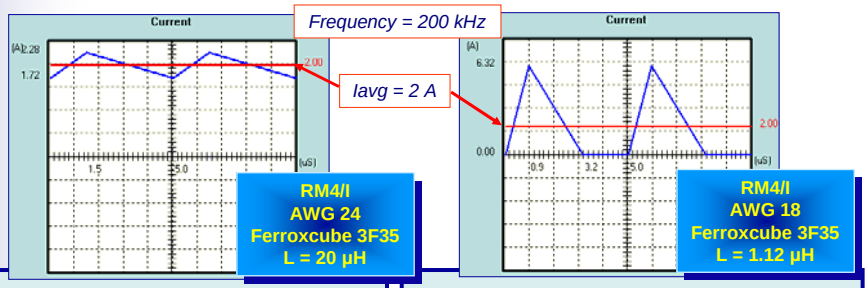
Optimization Example. Inductor



Bmax = 65% Bsat

Min n = 13

Core loss = 0.538 mW
Wire loss = 105.2 mW
Total loss = 105.76 mW

n = 14

Core loss = 0.444 mW
Wire loss = 114.1 mW
Total loss = 114.51 mW

Bmax = 65% Bsat

Min n = 2

Core loss = 21.3 mW
Wire loss = 12.7 mW
Total loss = 34 mW

n = 3

Core loss = 7.4 mW
Wire loss = 19.1 mW
Total loss = 26.5 mW

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Inductors

Calculation of the total reluctance

$$L = \frac{N^2}{\Re_T} = N^2 \cdot A_L \Rightarrow \Re_T = \frac{N^2}{L}$$

$$A_L = \frac{1}{\Re_T}$$

- $\Re_T$ is the total reluctance of the magnetic circuit.
- This reluctance may be obtained using:
  - ✓ Ferrite core + air gap
  - ✓ A material with distributed gap (low permeability) like iron powder

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Inductors

Calculation of the air gap length

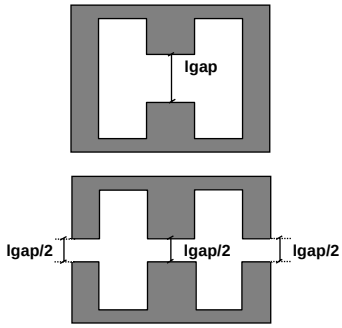
$$\Re_T = \Re_{ferrite} + \Re_{air} = \frac{1}{\mu_o \mu_e} \cdot \frac{l_e}{A_e} + \frac{1}{\mu_o} \cdot \frac{l_{gap}}{A_e}$$

$1/A_L$
(ferrite without gap)

$$\Re_T = \frac{1}{A_L} + \frac{1}{\mu_o} \cdot \frac{l_{gap}}{A_e}$$

$$\frac{1}{A_{L_T}} = \frac{1}{A_L} + \frac{l_{gap}}{\mu_o \times A_e}$$

$$l_{gap} = \mu_o A_e \left[\frac{1}{A_{L_T}} - \frac{1}{A_L} \right]$$



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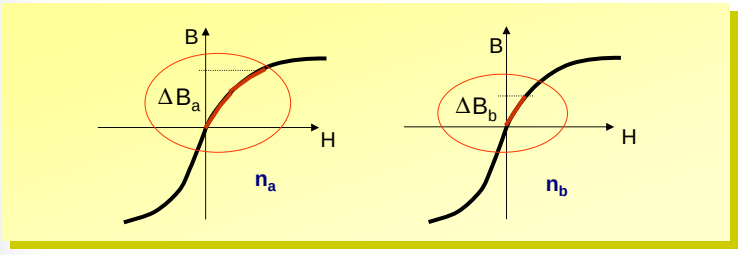
Transformers

Number of turns

Number of turns calculated to keep maximum flux density or core losses under an appropriate value



$$V_1 = N_1 \cdot \frac{\Delta \Phi}{\Delta t} = N_1 \cdot A_e \cdot \frac{\Delta B}{\Delta t} \Rightarrow N_1 = \frac{V_1 \Delta t}{A_e \Delta B}$$

$$a = \frac{N_1}{N_2} \Rightarrow N_2 = \frac{N_1}{a}$$

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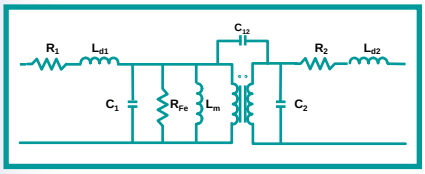
Modeling



$$\frac{\partial E(z,t)}{\partial z} = \mu \frac{\partial H(z,t)}{\partial t}$$

$$\frac{\partial H(z,t)}{\partial z} = \sigma \cdot E(z,t) + \varepsilon \frac{\partial E(z,t)}{\partial t}$$

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Modeling for Virtual Prototyping?

Do I make simulations?

Do I trust them?

if not, are magnetic component models the reason?

Model

...tool to obtain MY OWN design guidelines

...gate to simulation

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Modeling steps

Physical description (equations)

Equivalent Electrical model

Parameters extraction

Model solving

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Physics

Physical description (equations)

Maxwell equations

$$\nabla \cdot \boldsymbol{D} = \chi \qquad \nabla x \boldsymbol{E} = -\mu \frac{\partial \boldsymbol{H}}{\partial t}$$

$$\nabla \cdot \boldsymbol{B} = 0 \qquad \nabla x \boldsymbol{H} = \sigma \boldsymbol{E} + \varepsilon \frac{\partial \boldsymbol{E}}{\partial t}$$

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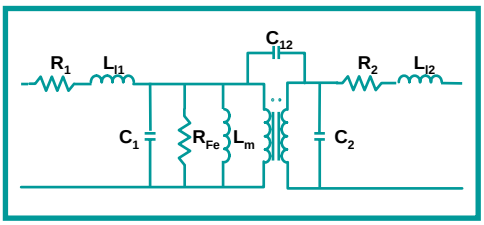
Equivalent Circuit (I)

Equivalent Electrical model

Discrete elements



Frequency Independent (only for sinusoidal waveforms)

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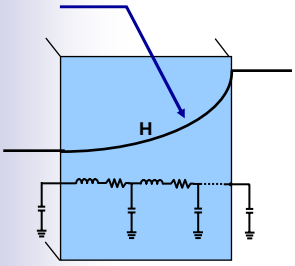
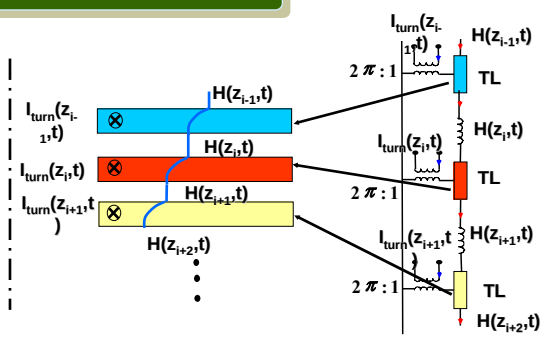
Equivalent Circuit (II)

Equivalent Electrical model

Transmission lines based

1D Maxwell equations





Transmission line equations

Frequency dependent
Magnetic/Electric Analogy based

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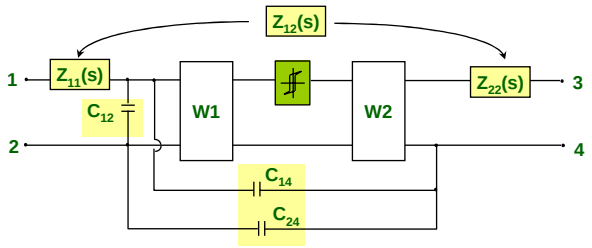
Equivalent Circuit (III)

Equivalent Electrical model

Behavioral



Frequency dependent
More Flexible behavior

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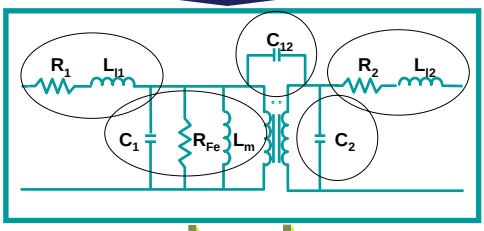
Parameters Extraction (I)

Parameters extraction



Analytical

Numerical

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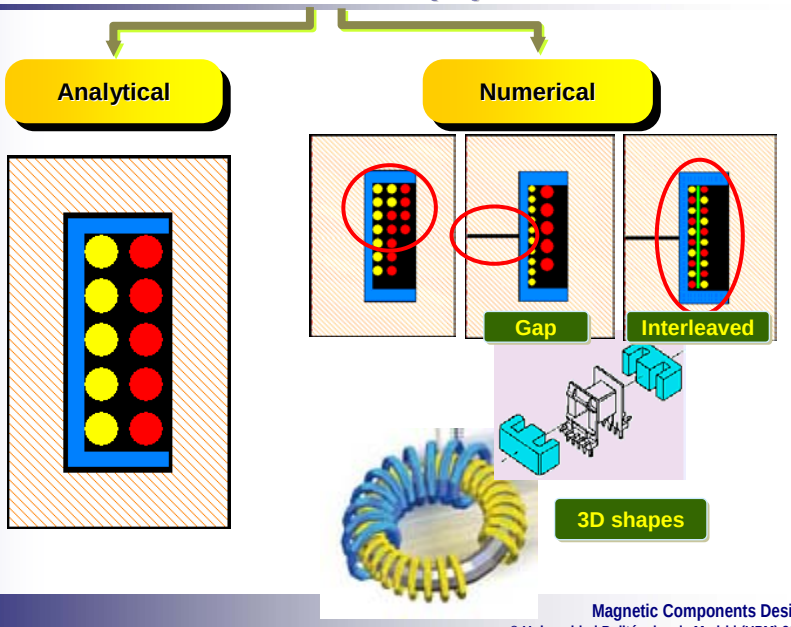
Parameters Extraction (II)



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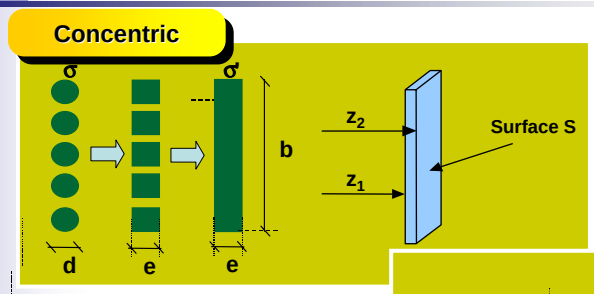
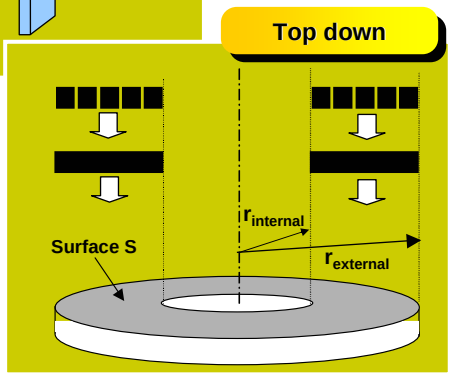
Analytical approach basis





Very useful to model 1D winding strategies

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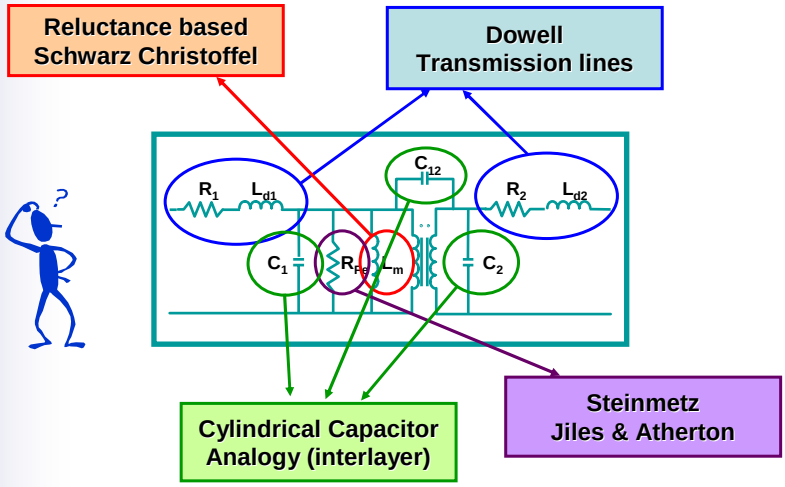
Analytical approach possibilities



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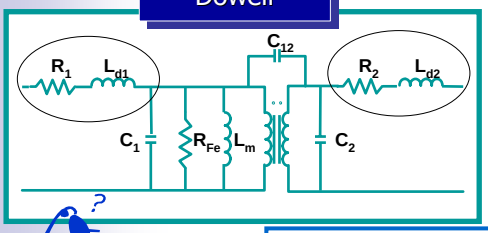
Analytical approach examples (I)

Dowell



$$K_r = \frac{R_{AC}}{R_{DC}} = 0.5y\left[M(y) + (2m-1)^2 \cdot D(y)\right]$$

$$y = \frac{h_C}{\delta}$$

h_C = Layer thickness
δ = Skin depth
m = Number of layers of the winding sector

$$M(y) = \frac{\sinh(y) + \sin(y)}{\cosh(y) - \cos(y)} \qquad D(y) = \frac{\sinh(y) - \sin(y)}{\cosh(y) + \cos(y)}$$

Calculation valid for a single frequency (sinusoidal)

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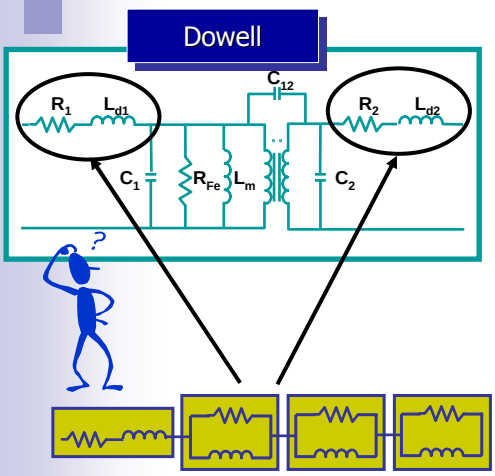
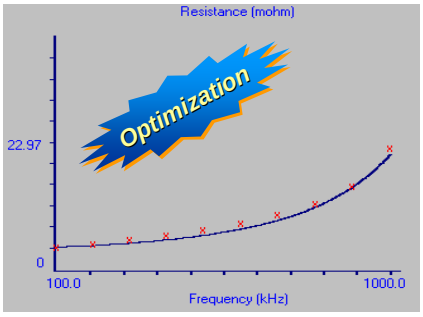
Analytical approach examples (II)



$$Z(s) = c_0 + c_1 s + \sum_{i=1}^{NPF} \frac{c_{2i} s}{s + c_{2i-1}}$$

Foster Network



Calculation valid for the whole frequency range

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Analytical approach examples (III)

Transmission line based parameters extraction

1D Maxwell equations

$$\frac{\partial E(z,t)}{\partial z} = \mu \frac{\partial H(z,t)}{\partial t}$$

$$\frac{\partial H(z,t)}{\partial z} = \sigma \cdot E(z,t) + \varepsilon \frac{\partial E(z,t)}{\partial t}$$

Transmission line equations

$$\frac{\partial V(z,t)}{\partial z} = \cancel{R} \cdot I(z,t) + L \frac{\partial I(z,t)}{dt}$$

$$\frac{\partial I(z,t)}{\partial z} = G \cdot V(z,t) + C \frac{\partial V(z,t)}{dt}$$

$$C = \varepsilon \cdot S$$

Electric energy

$$G = \sigma \cdot S$$

Losses

$$L = \frac{\mu}{S}$$

Magnetic energy

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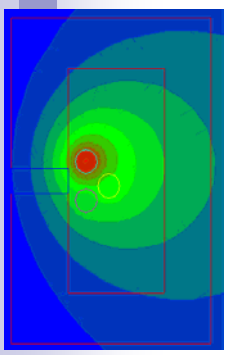
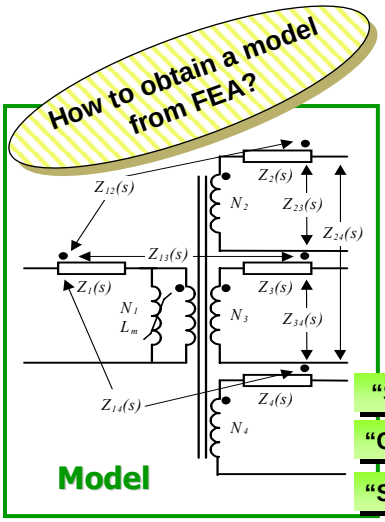
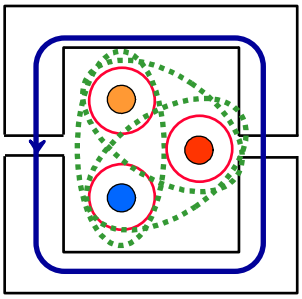
Numerical approach basis



How to obtain a model from FEA?





- "Self" Energy
- "Common" Energy
- "Self" Losses
- "Induced" Losses

Based on Energy and Losses Calculations

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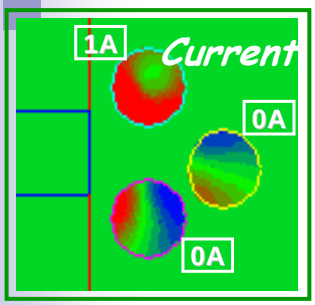
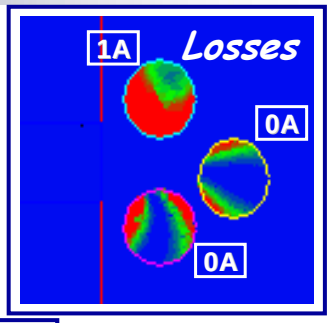
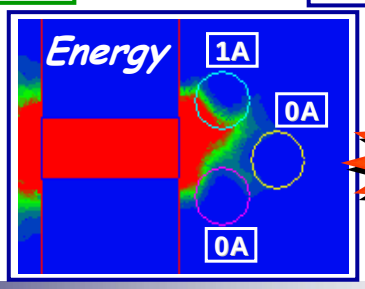
Numerical approach basis







Who owns the energy?

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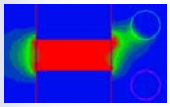
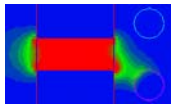
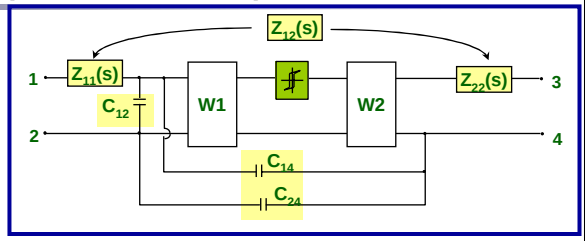
Numerical approach example



Test 1



Test 2



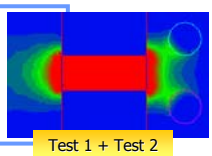
Z_{11}, Z_{22}:

✓Energy and losses due to I_1 OR I_2 INDEPENDENTLY

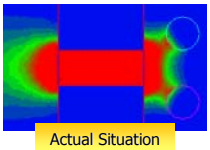
$$Z(s) = c_0 + c_1 s + \sum_{i=1}^{NPF} \frac{c_{2i} s}{s + c_{2i-1}}$$

Z_{12}: ← **Coupling?**

✓Energy and losses due to I_1 AND I_2 SIMULTANEOUSLY



Test 1 + Test 2



Actual Situation

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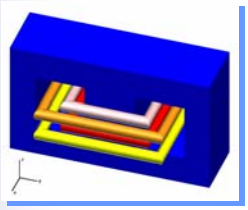
Numerical approach application (I)



Energy and losses should be the same

- **Energy in the core**
- **Energy in the window**
- **Energy in the air gap**
- **Losses in the core**
- **Losses in the conductors**

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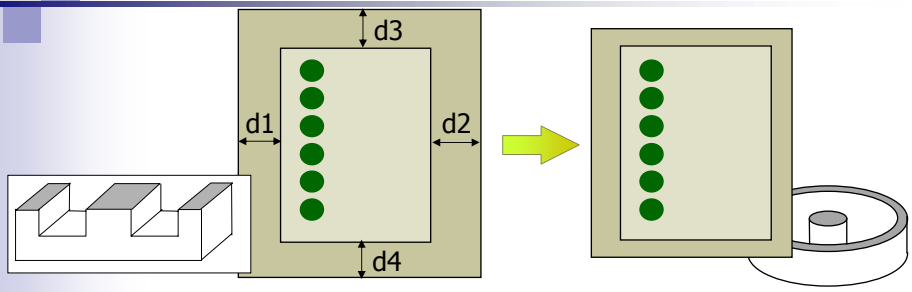
Numerical approach application (II)



- Window Height and Window Width are the same in both structures
- d1 is modified in order to obtain the same central leg area in both structures
- d2 is modified in order to obtain the same external leg area in both structures
- d3 is modified in order to obtain the same core volume in both structures

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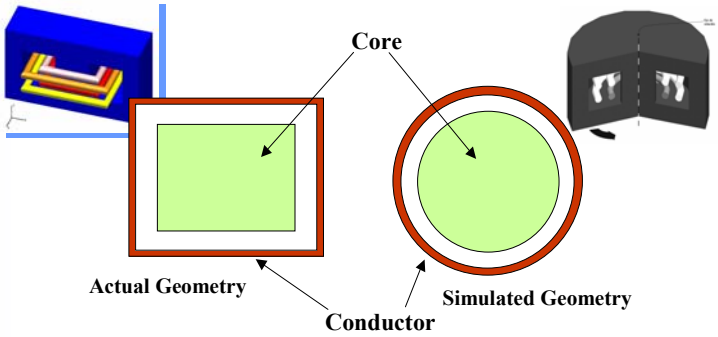
Numerical approach application (III)

Modification of properties: Conductors Resistance



$$R_{model} = \frac{length_{actual}}{length_{model}} R_{actual}$$

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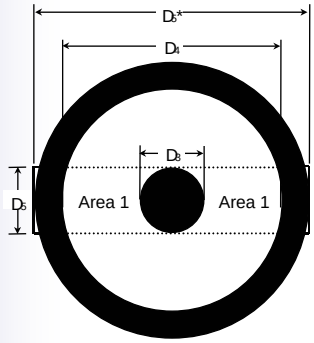
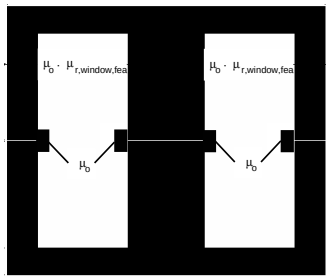
Numerical approach application (IV)

Modification of properties: Window Air Permeability





$$\mu_{r,window,fea} \cdot \mu_0 = \frac{Area\ 1}{Area\ 2} \cdot \mu_0$$

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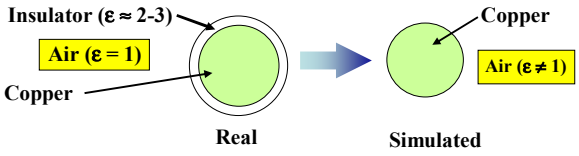
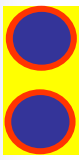
Numerical approach application (V)

Modification of properties: Window Air Permittivity



$$\varepsilon_{model} = \frac{\varepsilon_{isolator} \cdot Area_{wire\ insolator} + \varepsilon_{air} \cdot Area_{air}}{Area_{wire\ insolator} + Area_{air}}$$

$\varepsilon_{isolator} = 2.5$ **(Suggested)**



Air subwinding area

Isolator area

Considering each subwinding area

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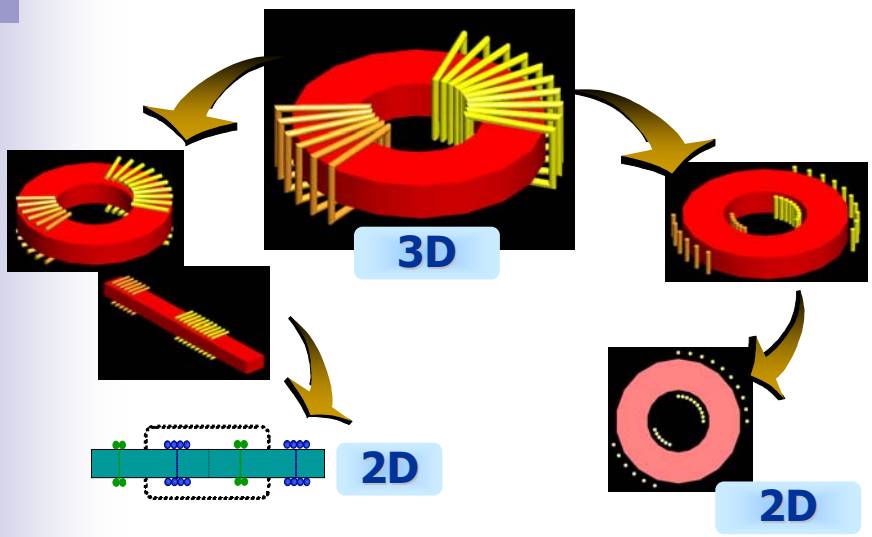
Double 2D concept: Application to Toroids



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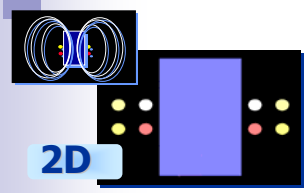
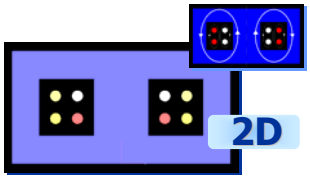
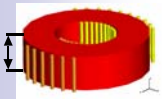
Double 2D concept



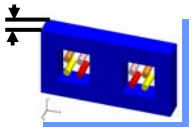
Magnetic Energy

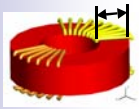
Losses





$$E_m = \frac{1}{2}\left[C_S \int B_S \cdot H_S^* dS + C_D \int B_D \cdot H_D^* dS\right]$$





$$P_d = C_S \int_{A_h} \frac{J_S \cdot J_S^*}{\sigma} dS + C_D \int_{A_h} \frac{J_D \cdot J_D^*}{\sigma} dS$$

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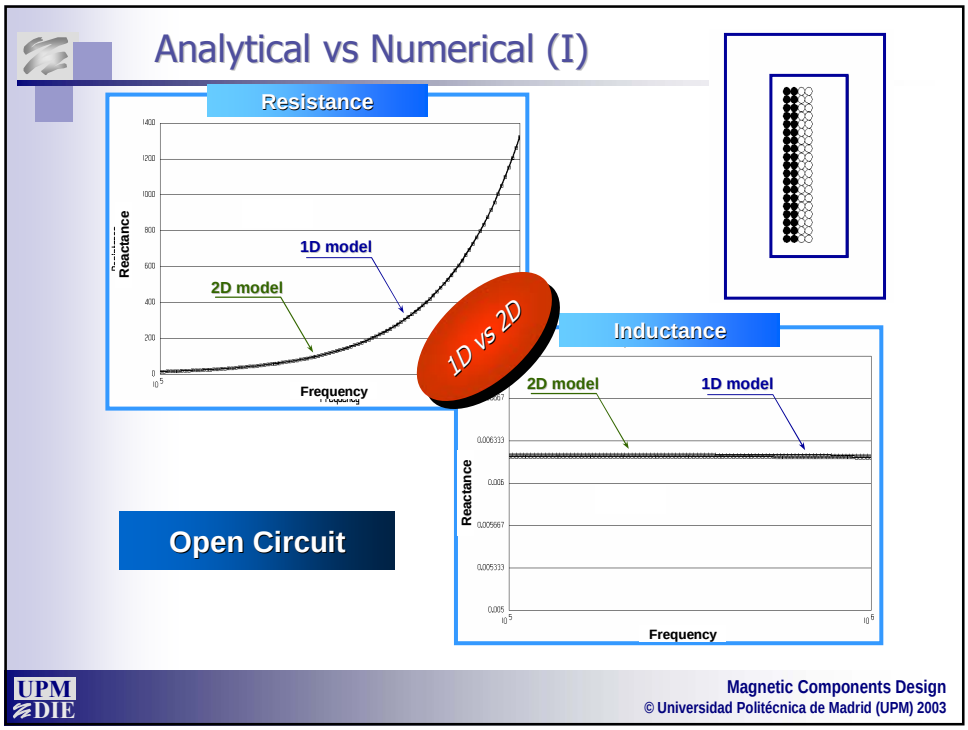
Analytical vs Numerical (I)
Resistance
Reactance
1D model
2D model
Frequency
1D vs 2D
Inductance
2D model
1D model
Reactance
Frequency
Open Circuit
UPM
DIE
Magnetic Components Design
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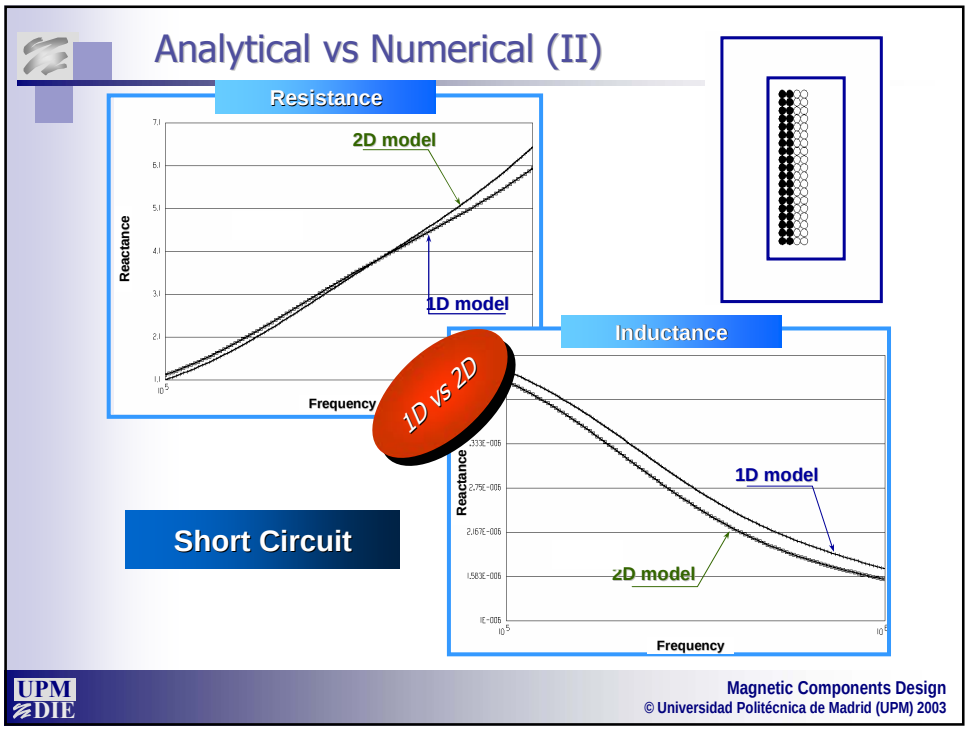
Analytical vs Numerical (II)
Resistance
2D model
Reactance
1D model
Frequency
1D vs 2D
Inductance
1D model
Reactance
2D model
Frequency
Short Circuit
UPM
DIE
Magnetic Components Design
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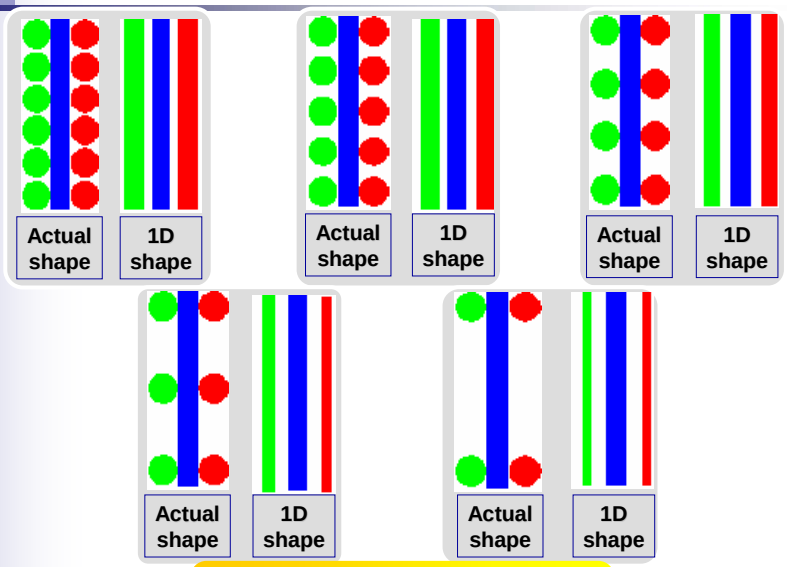
Analytical vs Numerical (III)



Window filling: turns spacing

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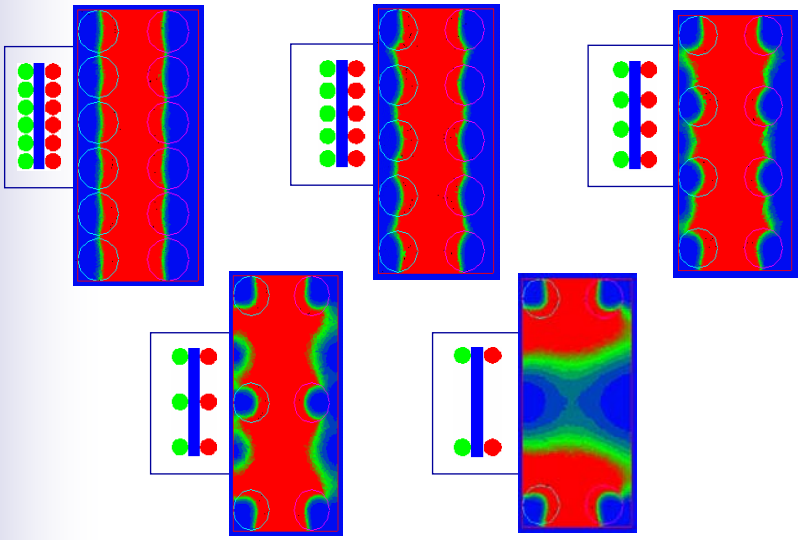
Analytical vs Numerical (IV)



Window filling: turns spacing

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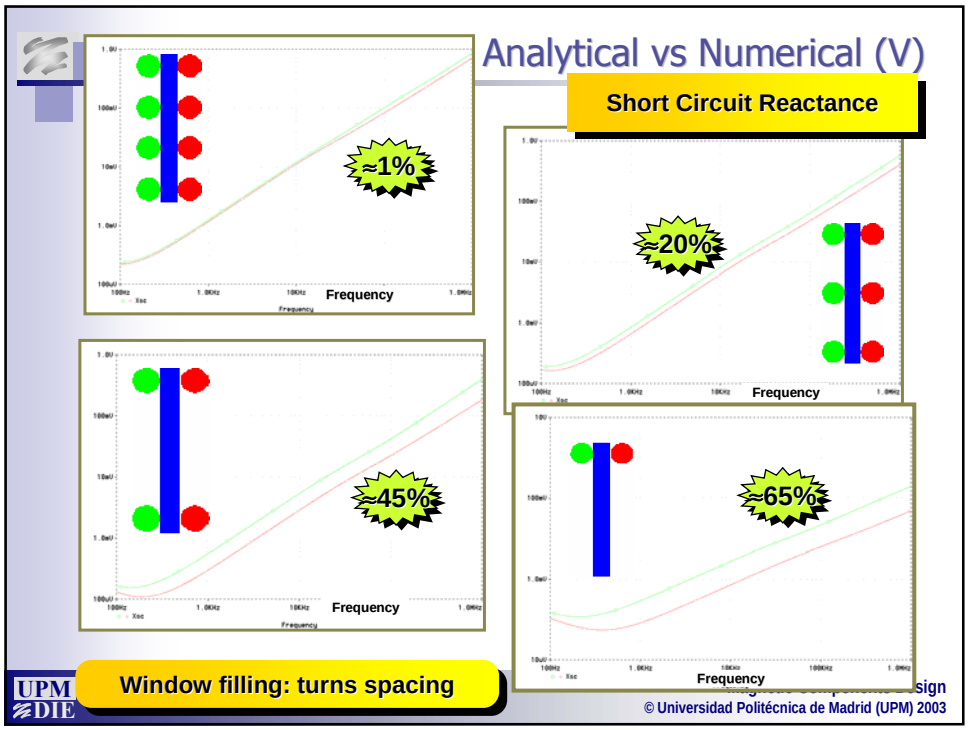
Analytical vs Numerical (V)
Short Circuit Reactance
≈1%
≈20%
≈45%
≈65%
Frequency
Window filling: turns spacing
UPM
DIE
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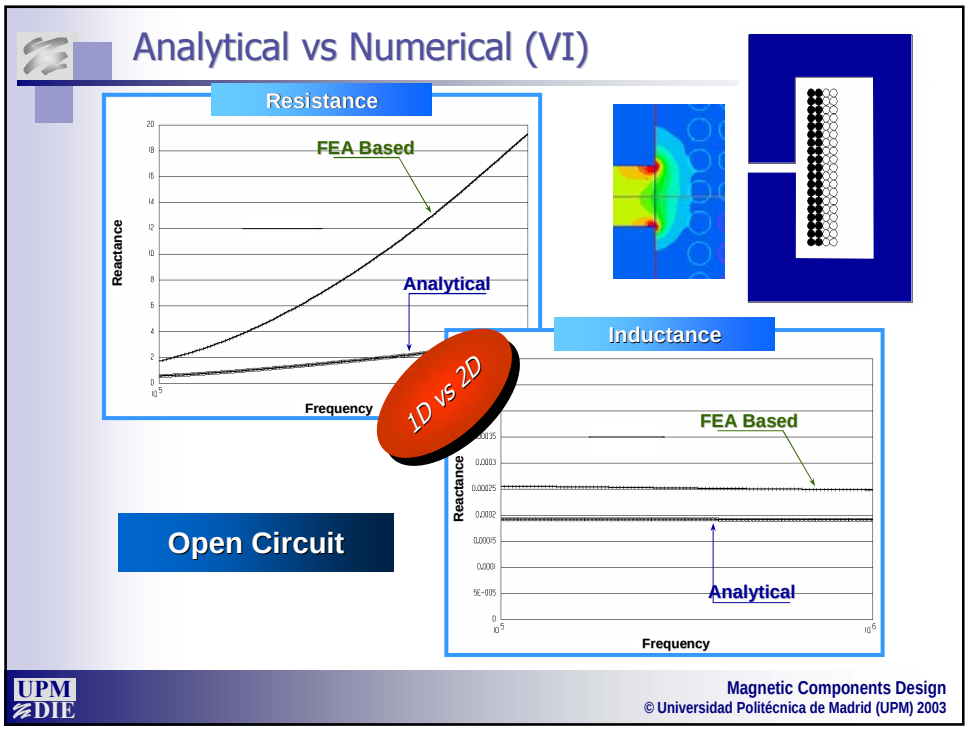
Analytical vs Numerical (VI)
Resistance
FEA Based
Analytical
Reactance
Frequency
1D vs 2D
Inductance
FEA Based
Analytical
Reactance
Frequency
Open Circuit
UPM
DIE
Magnetic Components Design
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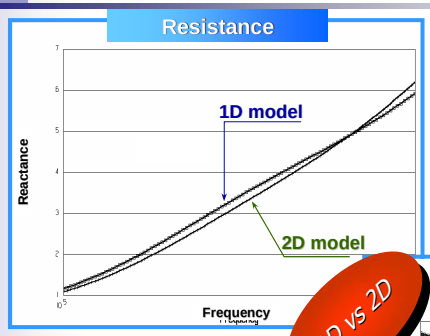
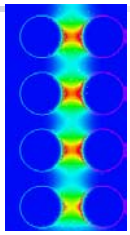
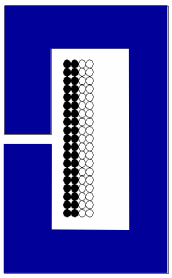
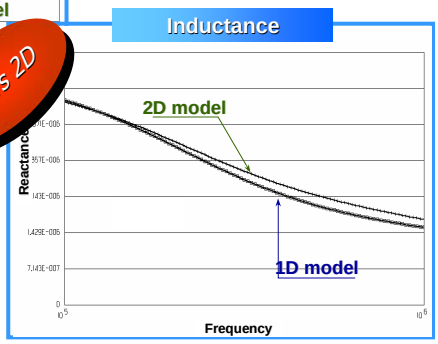
Analytical vs Numerical (VII)







1D vs 2D



Short Circuit

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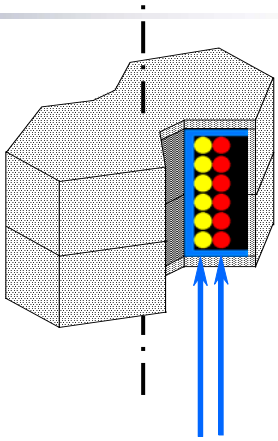
Parallel Windings: Introduction I



Two layers connected in parallel

How to calculate the resistance?

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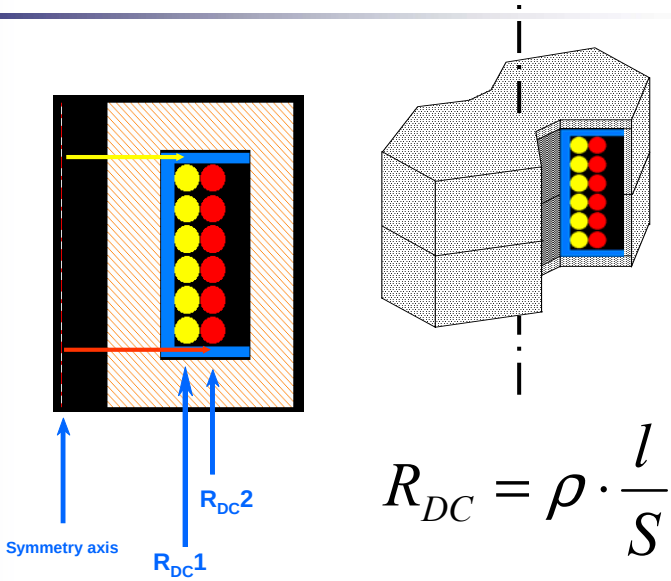
Parallel Windings: Introduction I



$$R_{DC} = \rho \cdot \frac{l}{S}$$

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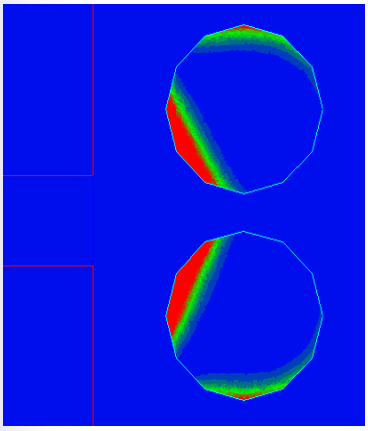
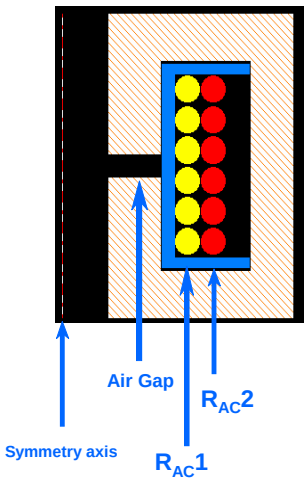
Parallel Windings: Introduction II



Current density



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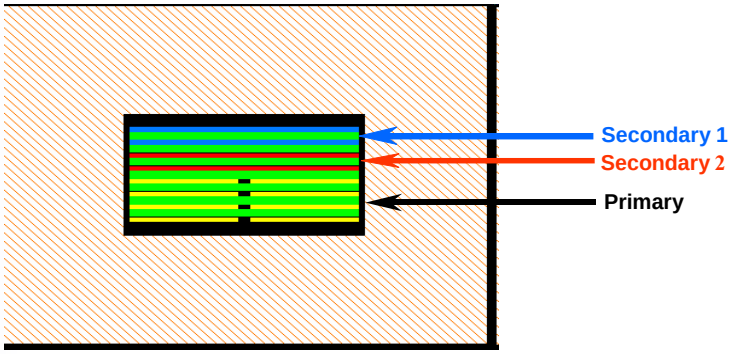
Parallel Windings: Introduction III



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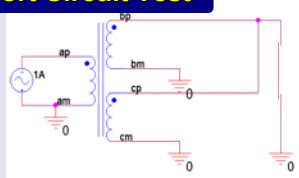
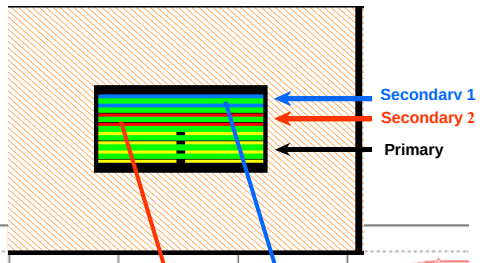
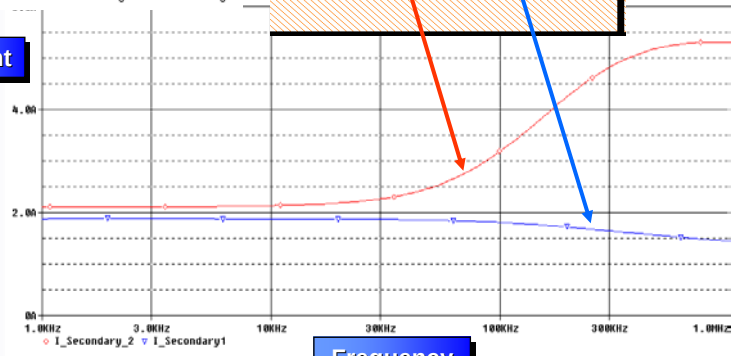
Parallel Windings: Introduction IV

Short Circuit Test





Current



Frequency

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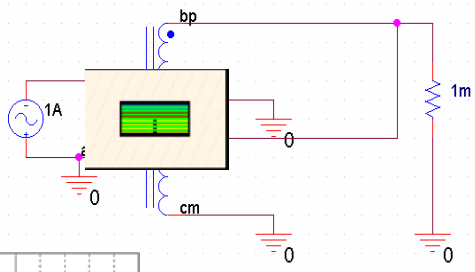
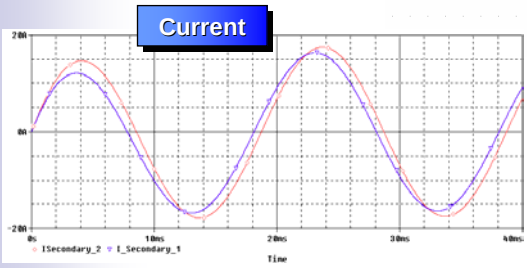
Parallel Windings: Introduction V

@50 Hz





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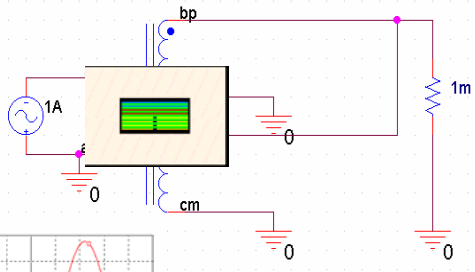
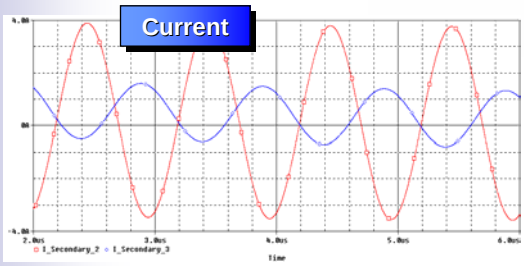
Parallel Windings: Introduction VI

@1 MHz





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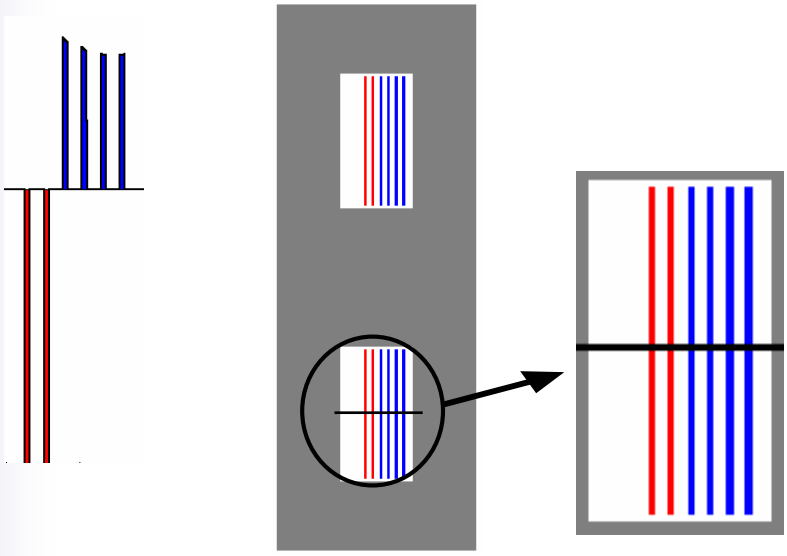
Analysis of different Winding Strategies



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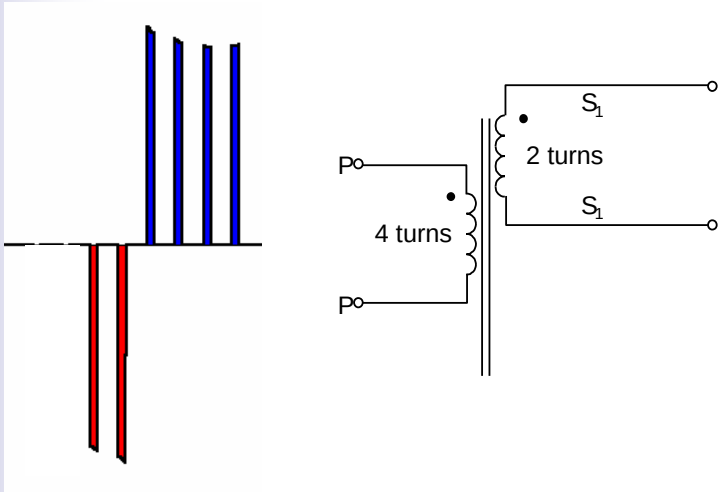
Two Windings in Parallel

LF (< 1 skin depth)



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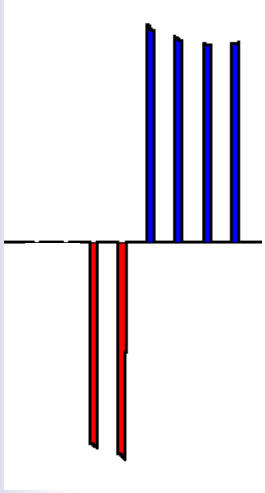
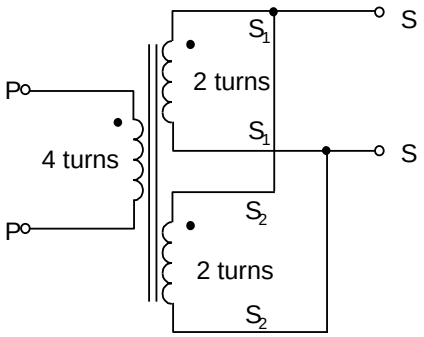
Two Windings in Parallel

LF (< 1 skin depth)





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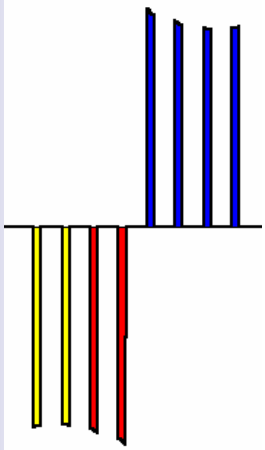
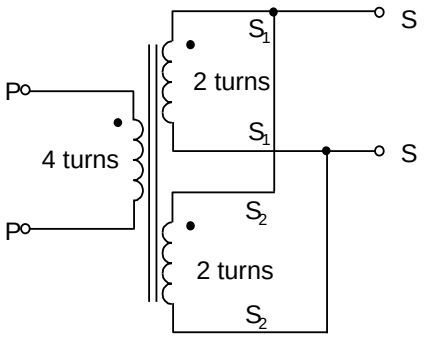
Two Windings in Parallel

LF (< 1 skin depth)





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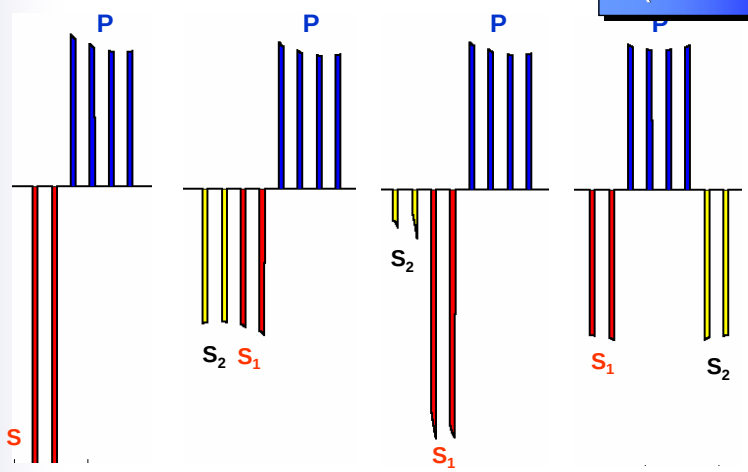
Two Windings in Parallel

LF (< 1 skin depth)



R=34.32 mΩ R=23.44 mΩ R=32.63 mΩ R=22.68 mΩ

"Balanced" distribution

"Real" distributions

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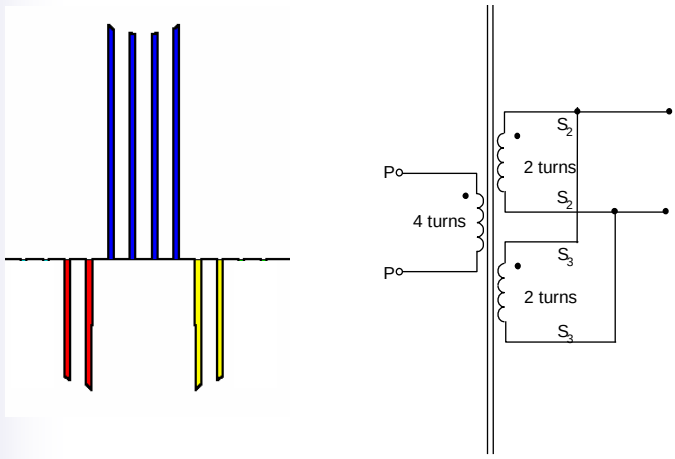
Four Windings in Parallel

LF (< 1 skin depth)



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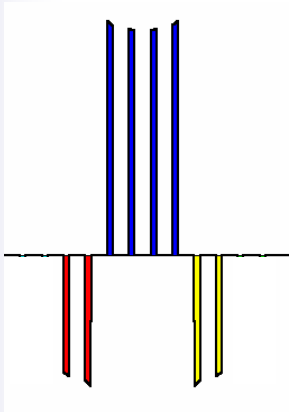
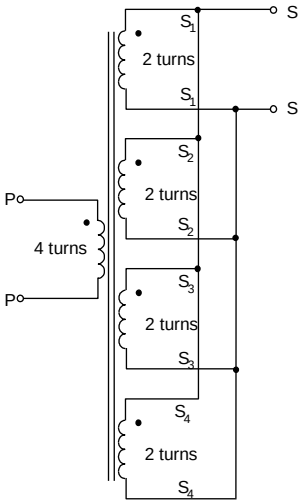
Four Windings in Parallel

LF (< 1 skin depth)





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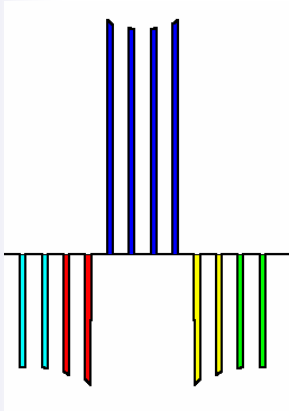
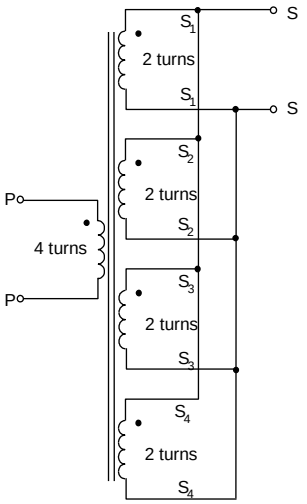
Four Windings in Parallel

LF (< 1 skin depth)





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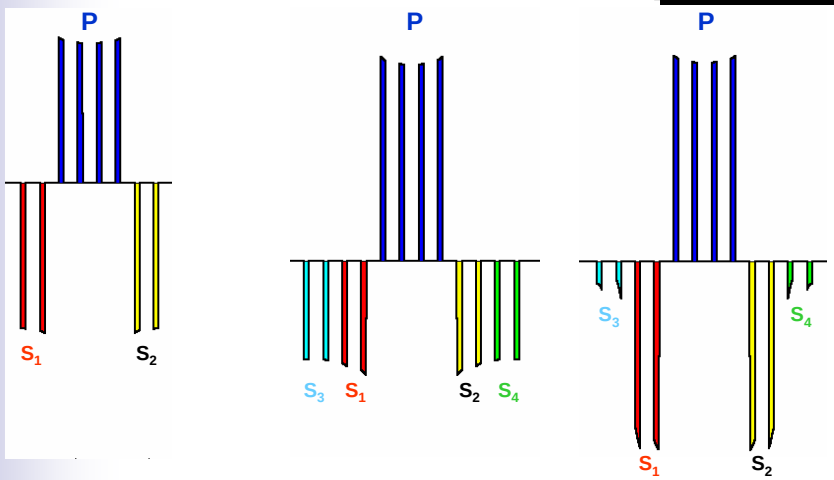
Four Windings in Parallel

LF (< 1 skin depth)



R=22.68 mΩ

R=17.32 mΩ

R=22.06 mΩ

"Balanced" distribution

"Real" distribution

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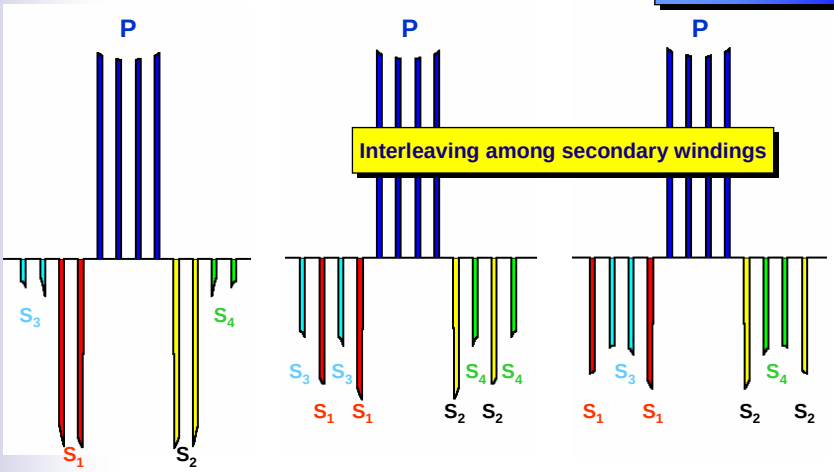
Four Windings in Parallel

LF (< 1 skin depth)



Interleaving among secondary windings

R=22.06 mΩ

R=19.93 mΩ

R= 17.95mΩ

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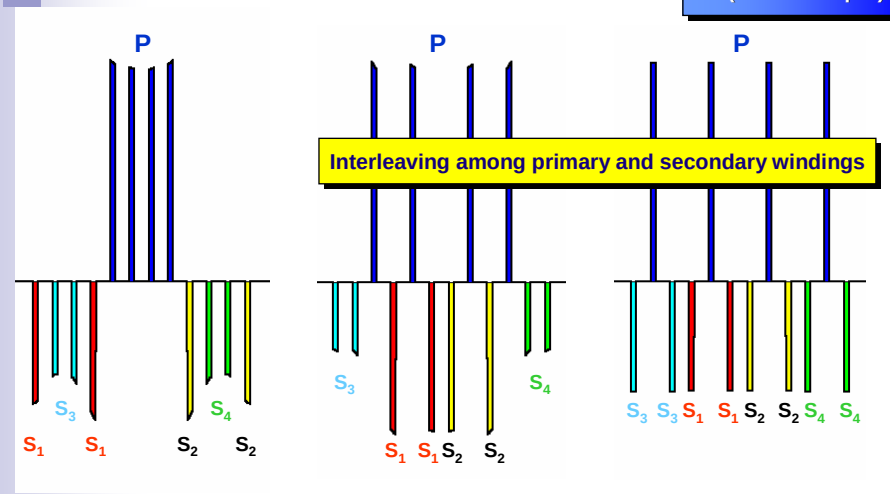
Four Windings in Parallel

LF (< 1 skin depth)



R= 17.95mΩ

R= 17.68mΩ

R= 16.77mΩ

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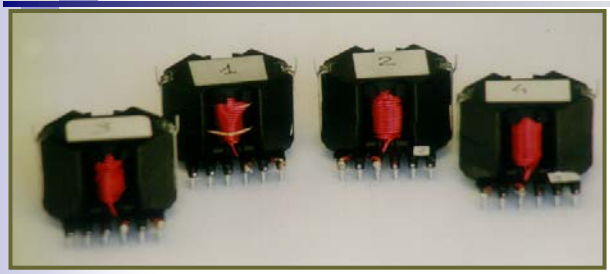
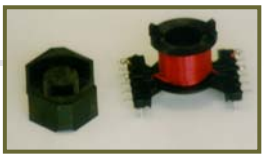
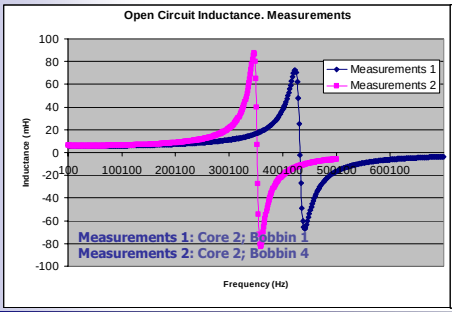
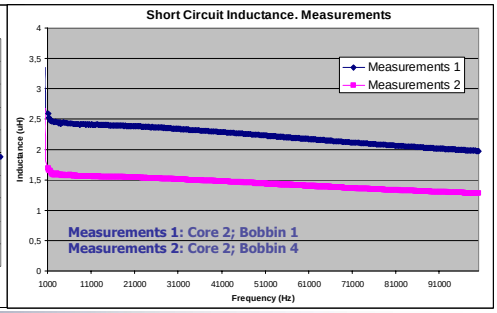
Measuring several samples





Four samples
Four cores and four bobbins
yields 16 possible combinations





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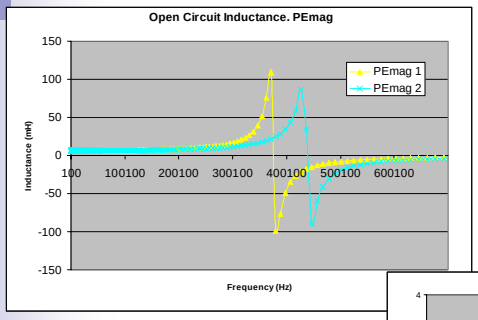
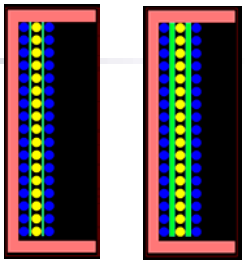
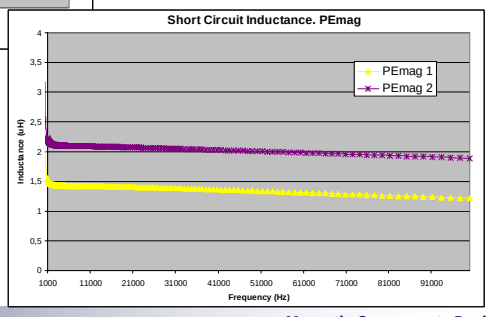
Generating the model





Case 1: separation 125 µm
Case 2: separation 375 µm



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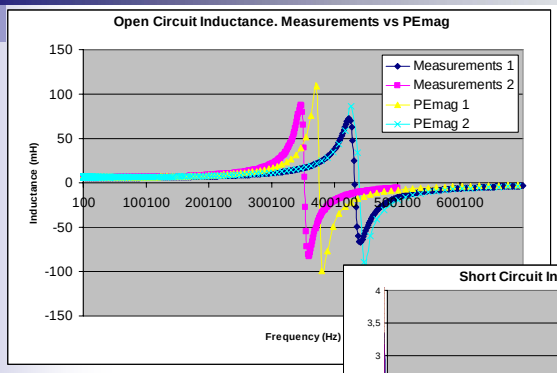
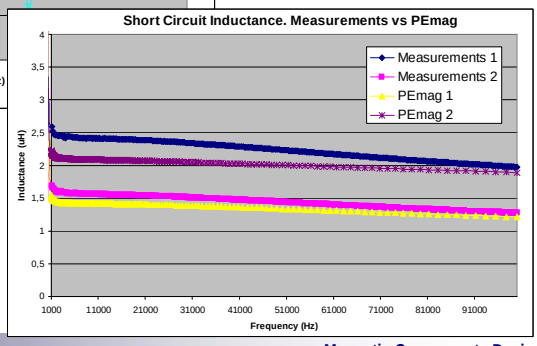
Comparing results





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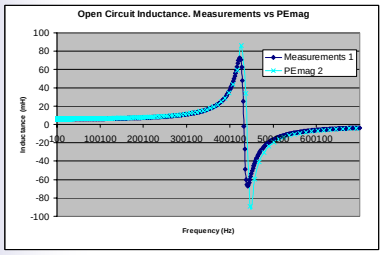
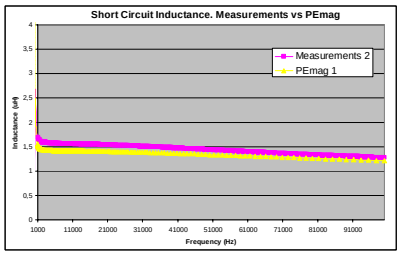
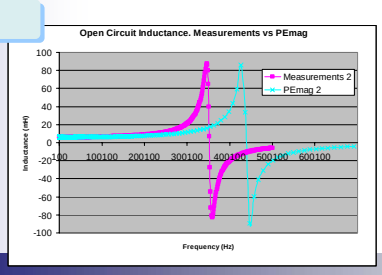
Comparing results

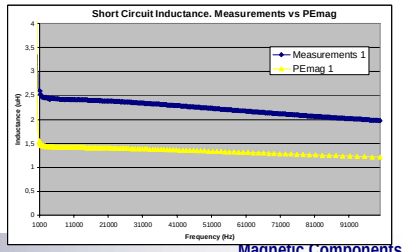
If only one real sample and only one model case are compared, results could be....





or....





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Seminar Contents

- Introduction
- Basic Concepts
- Design
- Modeling
- **Simulation**
- **Virtual Prototyping Examples**

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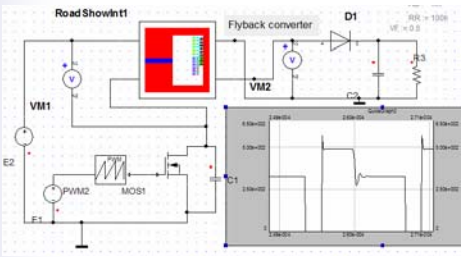
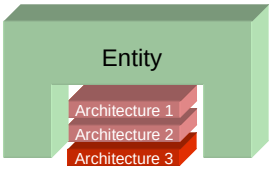
Simulation






```
package electrical_system IS
        SUBTYPE voltage IS real;
        SUBTYPE current IS real;

        NATURE electrical IS
                voltage ACROSS
                current THROUGH
                ground  REFERENCE;
end package electrical_system;
```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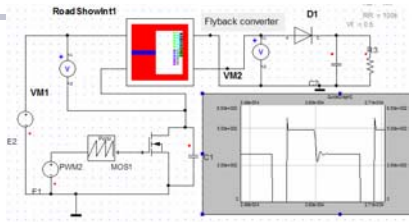
Simulation features



Simulation Goals

- Validation of the circuit operation
- Exploration of the waveforms
- Quantification of magnitudes (losses, stresses,…)
- Better understanding of the circuit operation

Simulation Challenges

- Lack of “accurate enough” models **(Magnetic, Semiconductors, Layout…)**
- Convergence problems (many “mathematical” parameters)
- Learning curve
- “Hard” transition from the design stage

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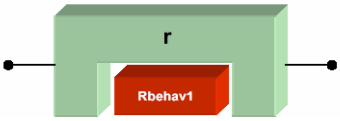
Simulator types

- Circuit simulation (i.e. SPICE based)
- System simulation (VHDL-AMS, MAST, SMD,...)

VHDL-AMS Code for a Resistor

```
ENTITY Resistor IS
 PORT (
   QUANTITY r : REAL := 1.0e+03; -- Default = 1 K
   TERMINAL p,m  : ELECTRICAL);
END ENTITY Resistor;

ARCHITECTURE Rbehav1 OF Resistor IS
   QUANTITY voltage ACROSS current THROUGH p TO m;
BEGIN
   current == voltage/r;
END behav;
```



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Seminar Contents

- Introduction
- Basic Concepts
- Design
- Modeling
- Simulation
- **Examples**
  - ✓ **Example 1: Coupling in Flyback transformer**
  - ✓ **Example 2: Coupling in Multi-winding transformers**
  - ✓ **Example 3: Multiphase Buck Inductors**
  - ✓ **Example 4: Flyback transformer**

Model + Simulation

Analytical vs Numerical

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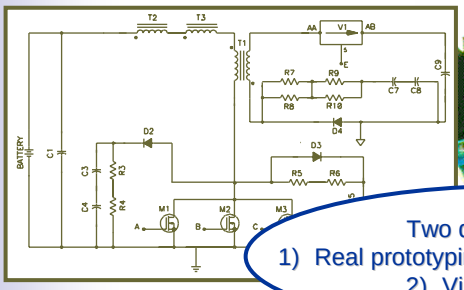
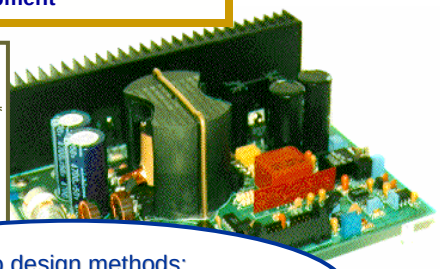
Example 1: Coupling in Flyback Transformer

FLYBACK With Hysteretic Control

Capacitive Load: 0.5 F
Output Voltage: 0 to 340 V
Output Power: up to 1kW
Input Voltage: 16 to 32 V
Switching Frequency: 1kHz to 40 kHz
Application: X ray equipment





Two design methods:
1) Real prototyping: Design + Measurements
2) Virtual prototyping

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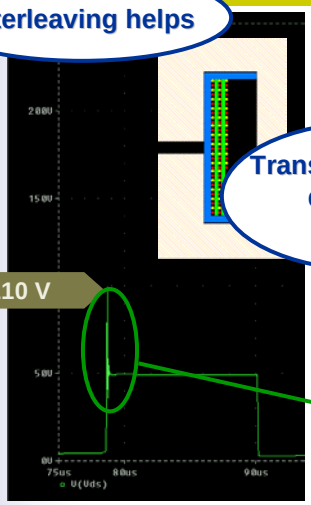
Example 1: Flyback Converter

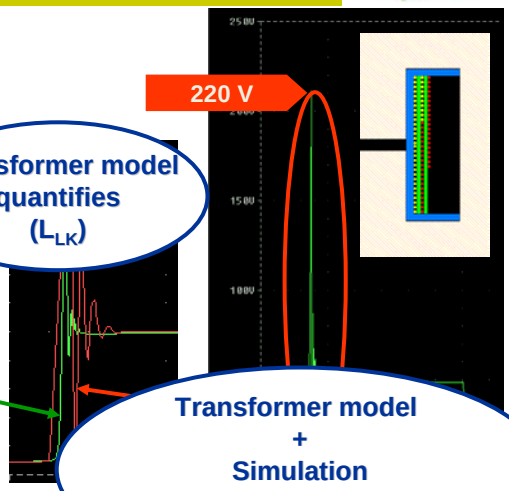
Vds in MOSFET

Interleaving helps



110 V

Transformer model quantifies (L_{LK})



220 V

Transformer model + Simulation provides the impact on the converter

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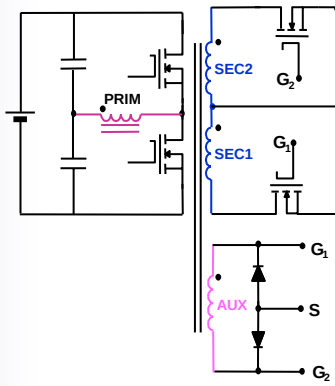
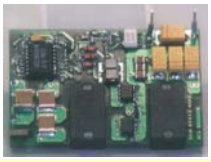
Example 2: Coupling in Multi-winding transformers



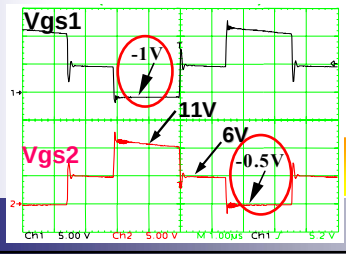


HB with SDSR

Input voltage:	**36 to 72 V**
Switching Frequency:	**150 kHz**
Output Power:	**15 W**
Output Voltage:	**1.5 V, 10 A**

Two design methods:
1) Real prototyping
2) Virtual prototyping

How to model?



Gate voltages with a proper coupling

UPM DIE

Magnetic Components Design
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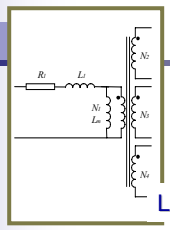
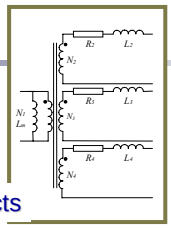
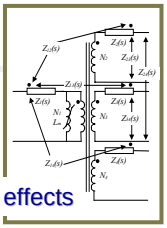
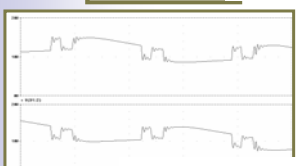


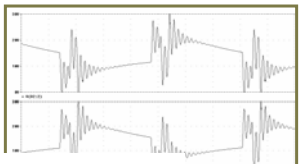
Lumped effects



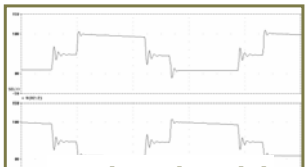


Distributed effects



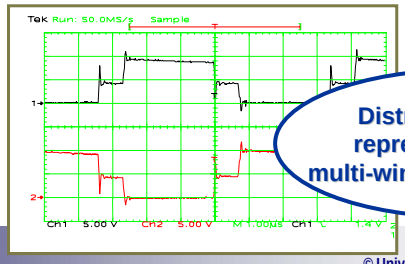


Measurements based Models



FEA based Model

Measurements



Distributed models represent better the multi-winding transformers

UPM DIE

Magnetic Components Design
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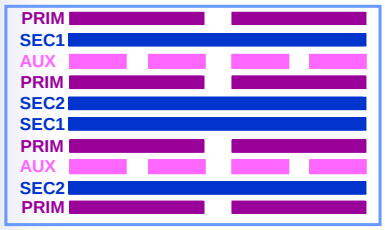
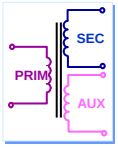
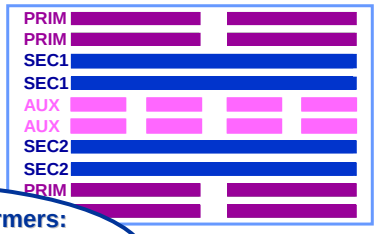
How to select the proper winding Strategy ?







Multi-winding transformers:
Full Bridge
Push-Pull
Multi-output converters…

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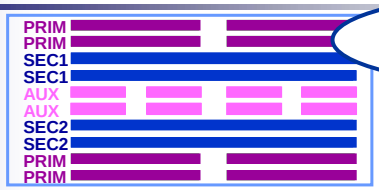
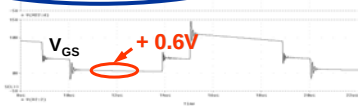
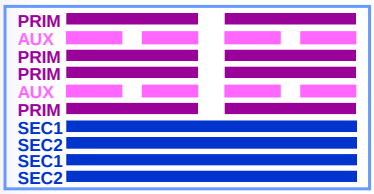
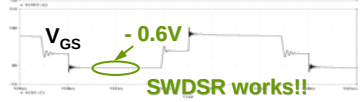
Using numeric (FEA) models

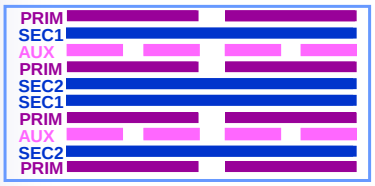
Auxiliary should be well coupled with primary











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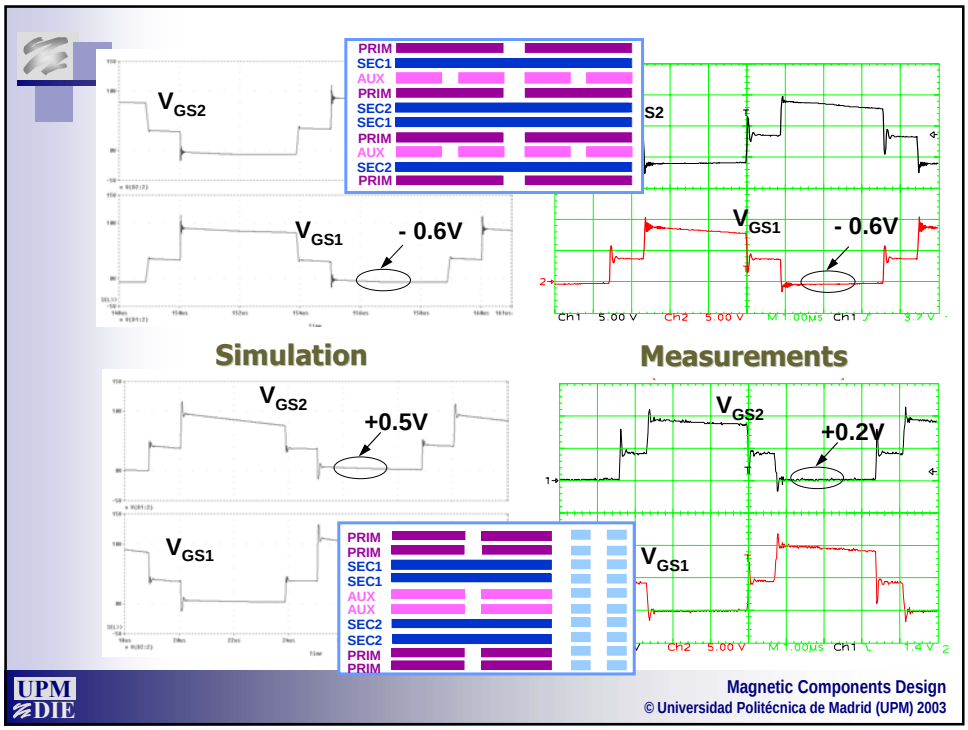
PRIM
SEC1
AUX
PRIM
SEC2
SEC1
PRIM
AUX
SEC2
PRIM
V_{GS2}
V_{GS1}
- 0.6V
Simulation
Measurements
V_{GS2}
+0.5V
V_{GS1}
V_{GS2}
+0.2V
V_{GS1}
PRIM
PRIM
SEC1
SEC1
AUX
AUX
SEC2
SEC2
PRIM
PRIM
UPM
DIE
Magnetic Components Design
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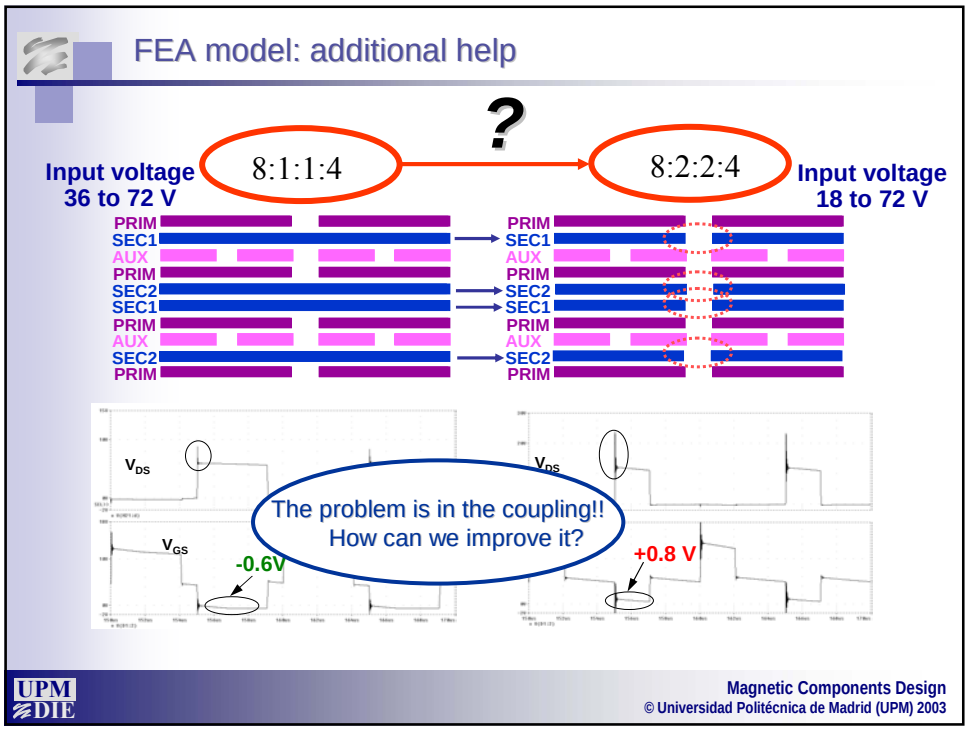
FEA model: additional help
?
Input voltage
36 to 72 V
8:1:1:4
8:2:2:4
Input voltage
18 to 72 V
PRIM
SEC1
AUX
PRIM
SEC2
SEC1
PRIM
AUX
SEC2
PRIM
V_{DS}
V_{GS}
-0.6V
V_{DS}
+0.8 V
The problem is in the coupling!!
How can we improve it?
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DIE
Magnetic Components Design
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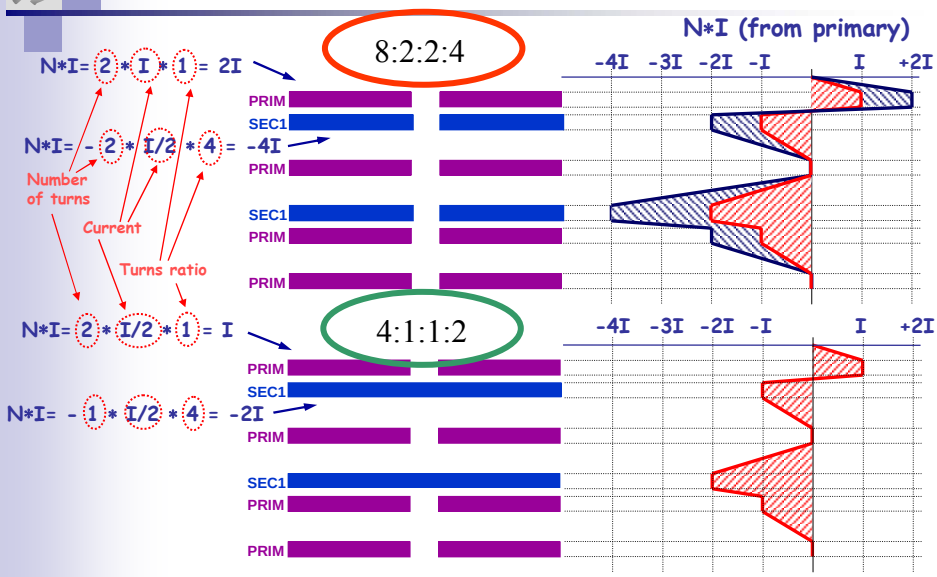
Studying the problem: DC energy



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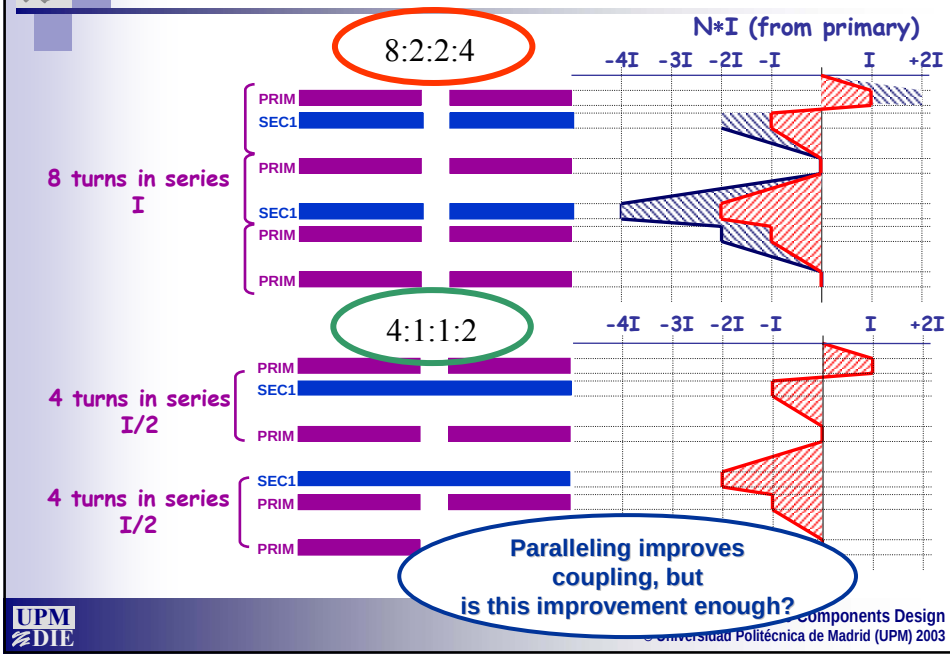
Studying the problem: DC energy



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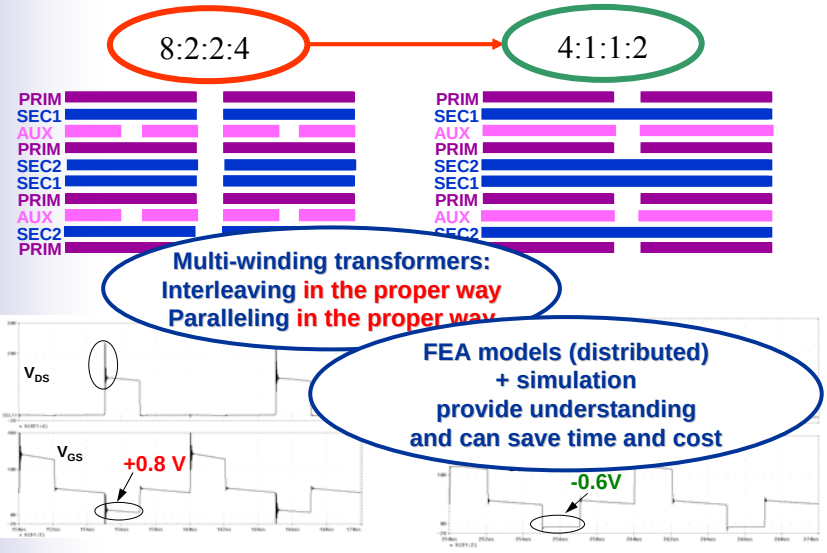
FEA model + simulation: additional help



Multi-winding transformers:
Interleaving in the proper way
Paralleling in the proper way

FEA models (distributed)
+ simulation
provide understanding
and can save time and cost

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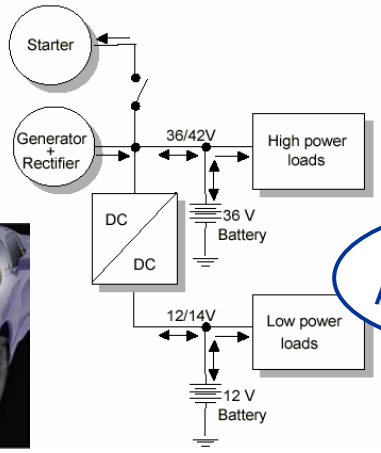
Example 3: Multiphase Buck Inductors Automotive Application



Magnetic design:
Analytical models fail!!!

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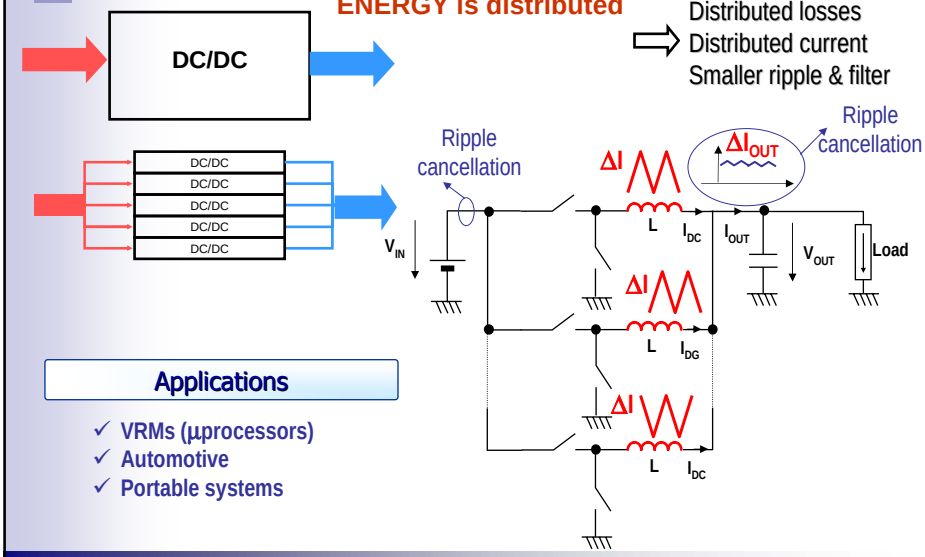
Multiphase converters



Applications

- ✓ VRMs (µprocessors)
- ✓ Automotive
- ✓ Portable systems

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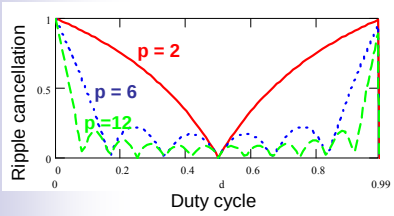
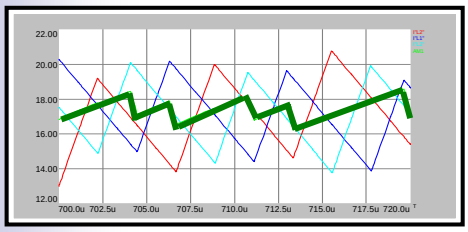
Multiphase converters



Ripple cancellation is determined by:

1. Number of phases: p
2. V_{OUT}/V_{IN} ratio (duty cycle): d

Low current ripple: small filter



Design

- ✓ Number of phases: p
- ✓ Switching frequency: f_{SW}
- ✓ Inductance per phase: L
  - ✓ Current ripple

Complex design with
a big number of combinations
(p inductors)

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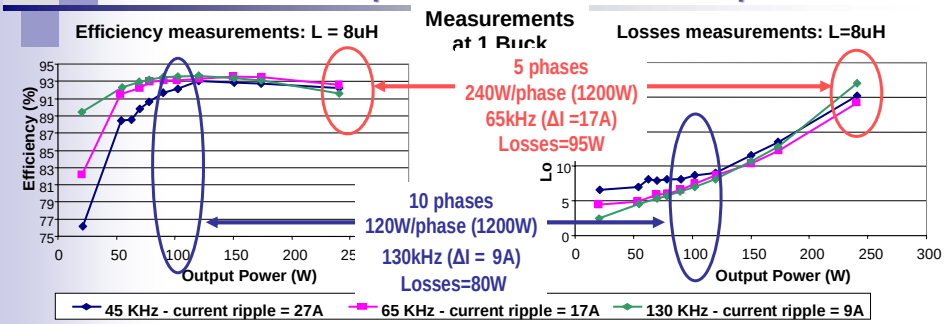
Which is the optimum number of phases?



- Depending on
  I_{DC}/phase, or Power/phase, or Number of phases
  the minimum losses are obtained at very different f_{sw}
- A high number of phases allows for a high f_{sw} with lower losses
  Smaller inductor size per phase but high number of phases ⇒ Size?

Trade-off: size - efficiency

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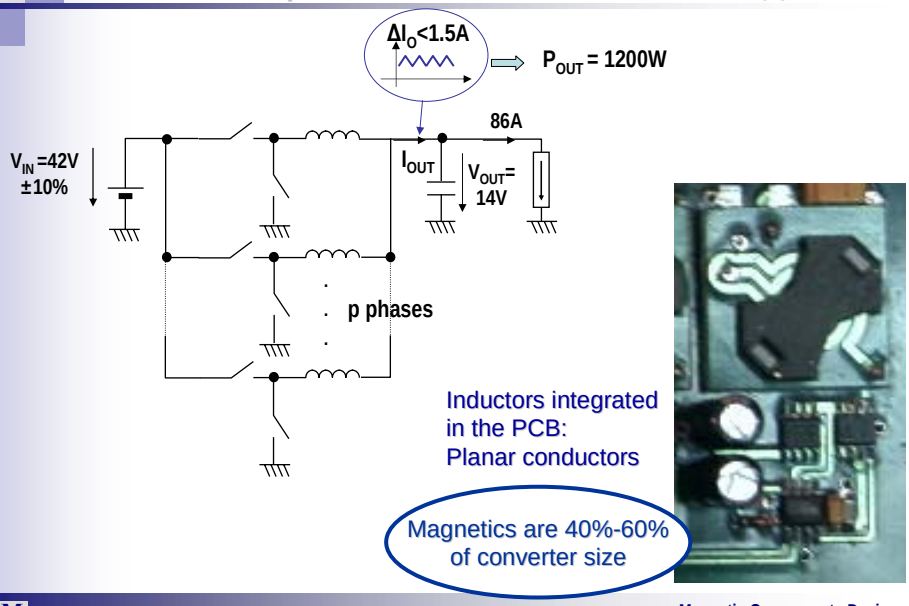
Converter specifications

Automotive application



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Design of inductors: analytical

- **Losses calculation accounts for:**
  - ✓ DC resistance
  - ✓ Skin effect
  - ✓ Core losses ($P=kf^{\alpha}B^{\beta}$)

  DC resistance + Skin effect → Winding losses; Core losses → Steinmetz
- Gap effect (2D) is not considered

Considered design options

Nº of phases	f_{sw} (kHz)	Cores	Material
6	100	RM6LP	3C90
10	200	RM7LP RM8LP RM10LP	3F3
16		RM12LP	3F4

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Designs of inductors: 16 phases, L=5μH

Core	DC losses / inductor (mW)	AC losses / inductor (mW)	Overall Losses (W)	Overall Area (mm^2)	Overall Height (mm)	Overall Volume (mm^3)

Total losses per inductor without considering AC effects

Total losses per inductor considering AC effects (AC + DC effects)

All inductors' total losses

All inductors' total dimensions

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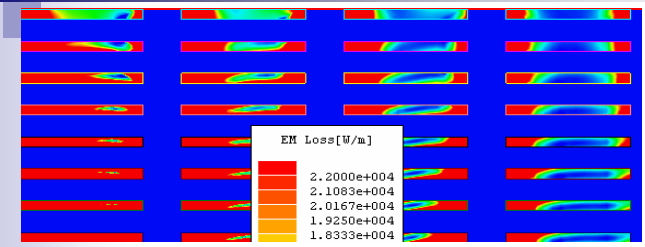
AC current distribution in planar conductors



4 turns
4 turns/layer
20 layers in parallel

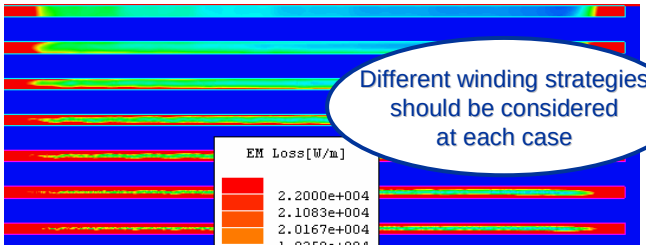
P_{DC} = 160mW

P_{AC} = 210mW

4 turns
1 turn/layer
5 layers in parallel

P_{DC} = 150mW

P_{AC} = 425mW



Different winding strategies should be considered at each case

Skin and proximity effects are stronger in wide planar conductors than in narrow ones

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Designs of inductors: 16 phases, L=5µH

Core	DC losses / inductor (mW)	AC losses / inductor (mW)	Overall Losses (W)	Overall Area (mm²)	Overall Height (mm)	Overall Volume (mm³)
100kHz, I_{DC} = 5.4A, ΔI = 19A						
16*RM7LP	420	425	6.8	5,010	9.8	49,000
16*RM8LP	275	285	4.5	6,300	11.6	73,125
16*RM10LP	90	155	2.4	9,660	13	125,600
200kHz, I_{DC} = 5.4A, ΔI = 9.5A						
16*RM6LP	250	300	4.9	3,550	9	31,970
16*RM7LP	215	235	3.7	5,010	9.8	49,000
16*RM8LP	130	150	2.4	6,300	11.6	73,125

Material
Turns
Winding strategy
Gap

Hundreds of combinations!!

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Designs of inductors: 10 phases, L=8μH

Core	DC losses / inductor (mW)	AC losses / inductor (mW)	Overall Losses (W)	Overall Area (mm²)	Overall Height (mm)	Overall Volume (mm³)
100kHz, I_{DC} = 8.6A, ΔI = 11.5A						
10*RM7LP	Too many losses					
10*RM8LP	740	790	7.9	3,940	11.6	45,700
10*RM10LP	250	325	3.2	6,040	13	78,520
200kHz, I_{DC} = 8.6A, ΔI = 5.8A						
10*RM7LP	950mW (100ºC) Too many losses					
10*RM8LP	300	350	3.5	3,940	11.6	45,700
10*RM10LP	190	200	2	6,040	13	78,520

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Designs of inductors: 6 phases, L=9.5μH

Core	DC losses / inductor (mW)	AC losses / inductor (mW)	Overall Losses (W)	Overall Area (mm²)	Overall Height (mm)	Overall Volume (mm³)
100kHz, I_{DC} = 14.4A, ΔI = 9.8A						
6*RM10LP	Too many losses					
6*RM12LP	680	710	4.3	5,610	16.8	94,298
200kHz, I_{DC} = 14.4A, ΔI = 4.9A						
6*RM10LP	735	760	4.5	3,625	13	47,110

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Selected solutions based on analytical model

Solution	Overall Losses (w)	A (mm^2)	h (mm)	V (mm^3)
16 x RM7LP, 100kHz	6.8	5,010	9.8	49,000
16 x RM6LP, 200kHz	4.9	3,550	9	31,970
10 x RM8LP, 200kHz	3.5	3,940	11.6	45,700
6 x RM12LP, 100kHz	4.3	5,610	16.8	94,298
6 x RM10LP, 200kHz	4.5	3,625	13	47,110

- **Final selection depends on:**
  - ✓ Losses of the whole converter
  - ✓ Size of the whole converter.
    Inductor size has a strong influence on overall size.
  - ✓ Height requirements

Is the analytical model good enough for this case?

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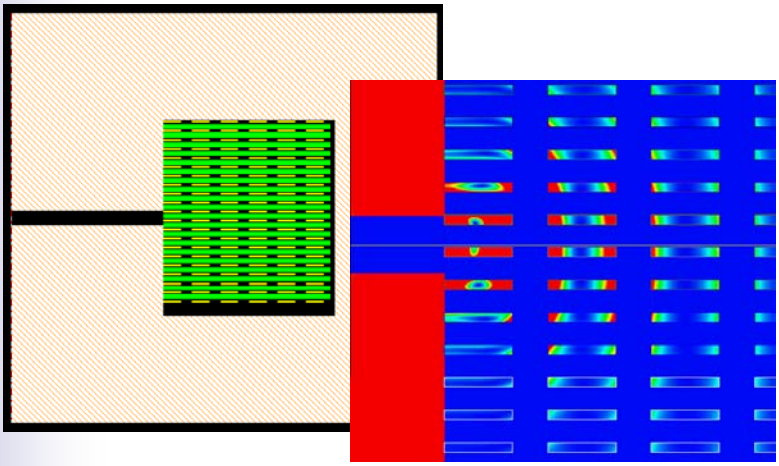
Automotive application: gap effect

How does the gap affect the current distribution and the losses of the selected solutions?



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Automotive application: gap effect

Solution	Gap (µm)	ΔI /inductor (A)	Analytical model Losses /inductor (W)	Analytical model ΔT in inductor (ºC)	FEA model Losses /inductor (W)	FEA model ΔT in inductor (ºC)
16*RM7LP, 100kHz	380	19	0.32	45	1.7	180
16*RM6LP, 200kHz	200	9.5	0.3	40	0.87	135
10*RM8LP, 200kHz	310	6	0.35	39	1.5	175
6*RM12LP, 100kHz	410	10	0.71	40	1.9	115
6*RM10LP, 200kHz	440	5	0.35	39	1.5	175

All the selected solutions based on analytical models are NOT FEASIBLE due to the gap effect!!!

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Design of inductors: numerical (FEA) model

- It accounts for:
  - ✓ DC resistance
  - ✓ Skin effect
  - ✓ Proximity effect
  - ✓ Gap effect
  - ✓ Core losses

Considered design options

Nº of phases	f_{sw} (kHz)	Cores	Material
6 10 16	100 125 150 200	RM6LP RM7LP RM8LP RM10LP RM12LP	3C90 3F3 3F4

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Design of inductor: 16 phases, 200kHz, RM7LP

Material

Turns

Winding strategy

L (µH)	ΔI / inductor (A)	ΔI_{OUT} (A)	Gap (µm)	Analytical Losses / inductor (W)	Numerical Losses / inductor (W)
2.5	19	1.2	170	0.28	2.2
3.6	13	0.8	215	0.22	2.0
6.2	7.4	0.5	190	0.21	0.85
9.4	4.9	0.3	260	0.33	0.63
12.6	3.7	0.2	250	0.33	0.76

In this case, the optimum gap-ΔI combination is obtained for a small ΔI_{OUT} (0.3A)

The analytical model gives a very high ΔI = 13A

This analysis is repeated for each selected case…

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Feasible solutions: Numerical Model

5000 combinations analyzed!!!

From the point of view of the inductors:

Solution	ΔI_{OUT} (A)	Overall Losses (W)	Overall Area (mm²)	Overall Height (mm)	Overall Volume (mm³)
16 phases, RM7LP, 200kHz	0.3	10.1	5,010	9.8	49,000
16 phases, RM8LP, 125kHz	0.3	7.5	6,340	11.6	73,125
10 phases, RM10LP, 150kHz	1.2	6.9	6,040	13	78,520
6 phases, RM12LP, 125kHz	0.8	9	5,610	16.8	94,298

$\Delta I_{OUT} < 1.5A$

- **Virtual prototyping has allowed:**
  - ✓ To study 5000 cases, learning what is happening
  - ✓ To obtain design rules
  - ✓ To quantify and optimize

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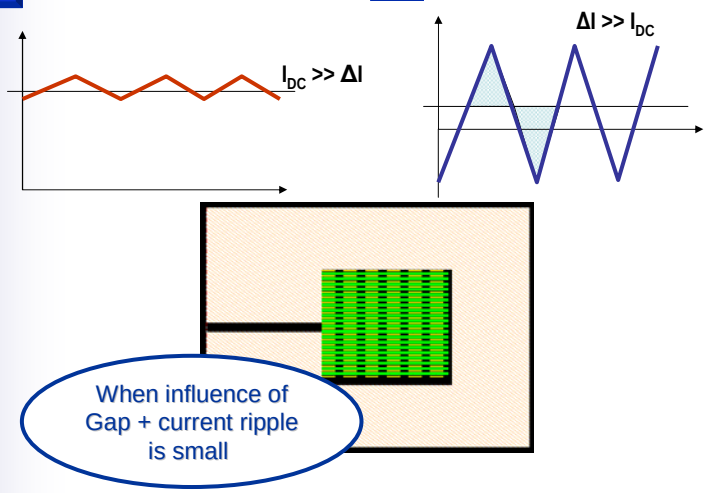
When are Analytical models useful?

A I_{DC} is predominant

B ΔI is predominant



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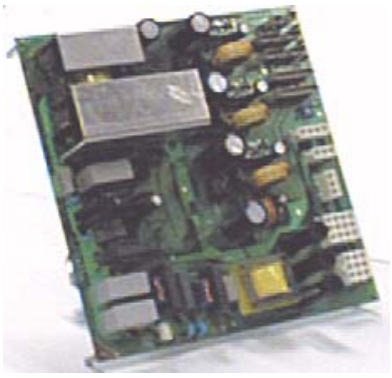
Example 4: Flyback Transformer



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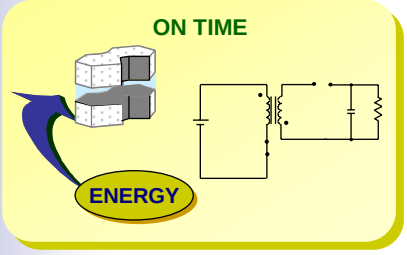
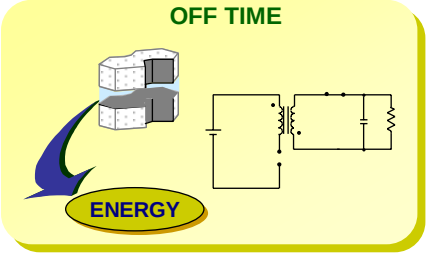
Electrical Description of Flyback Transformer





MAIN FEATURES

- Design in order to store energy
- Gap is usually needed
- Energy storage mainly in the gap
- Current is not flowing in both windings at the same time

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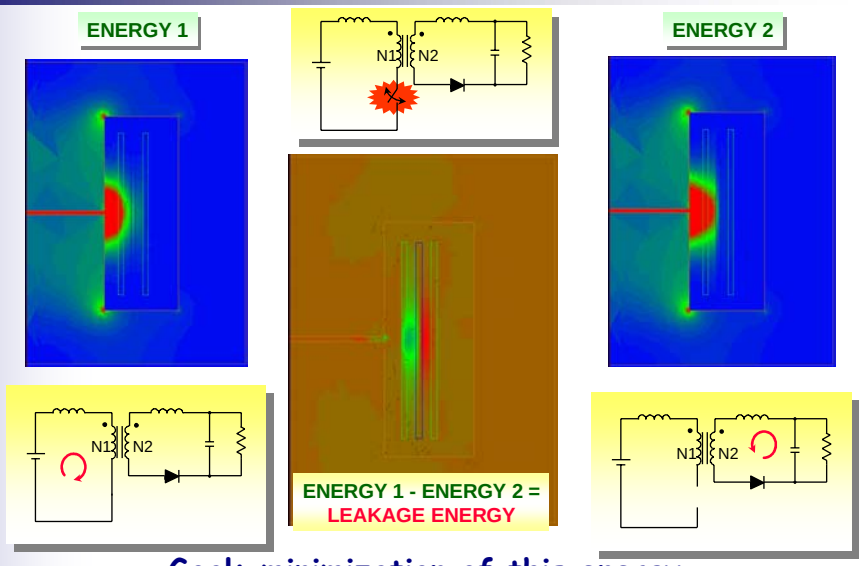
Study of the fields: leakage inductance



Goal: minimization of this energy

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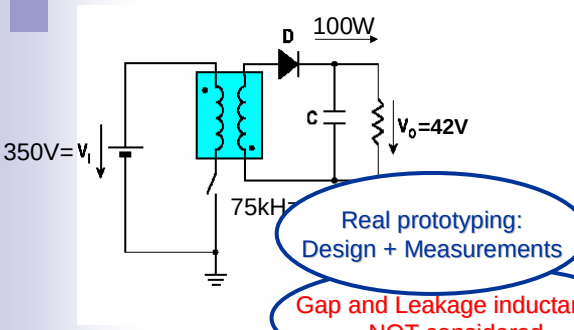
Design example: Flyback



Real prototyping:
Design + Measurements

Gap and Leakage inductance
NOT considered

Transformer A
Analytical design

ETD 39, 3F3

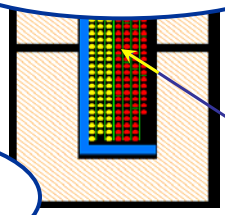
Air Gap 2.2mm (86.6mils)

Primary
- # turns: 30
- Wire Gauge: AWG22 (0.7mm, 27mils, 3 x skin depth)
- Parallel: 3

Secondary
- # turns: 6
- Wire Gauge: AWG22 (0.7mm, 27mils, 3 x skin depth)
- Parallel: 18

Analytical results

- ✓ Core losses: 450mW
- ✓ Winding losses: 200mW
- ✓ ΔT =7ºC



High window filling

DC resistance
Skin effect
Core losses

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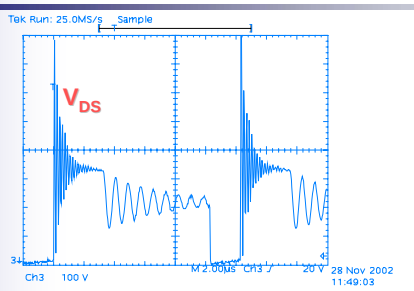
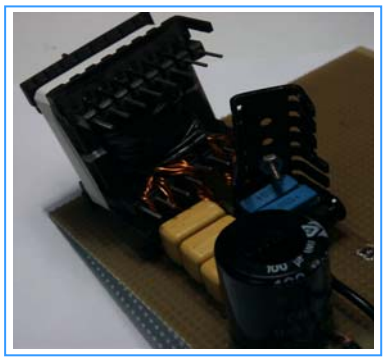
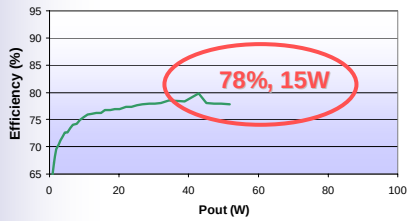
Transformer A: Measurements on Flyback prototype





Flyback efficiency



Too many losses
What is happening???

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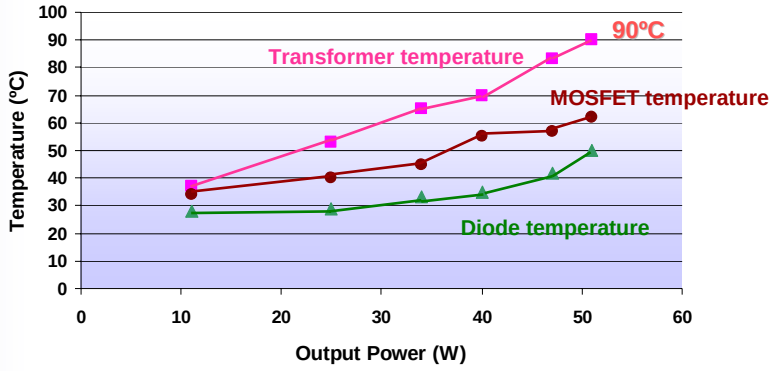
Transformer A: Measurements on Flyback prototype



The hottest component is the transformer, full power (100W) can not be achieved due to the transformer losses

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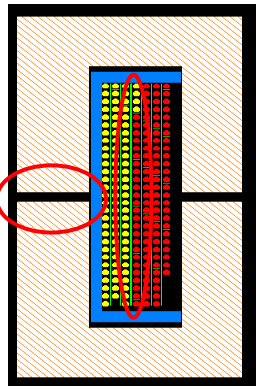
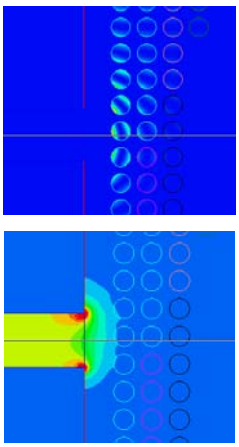
What can we do?

Impact of the air gap effect?
Impact of the leakage inductance?

Virtual prototyping: Numerical Model (FEA)

Core losses: 460mW
Winding losses: 11W!!!
ΔT = 140ºC





Current density

Energy density

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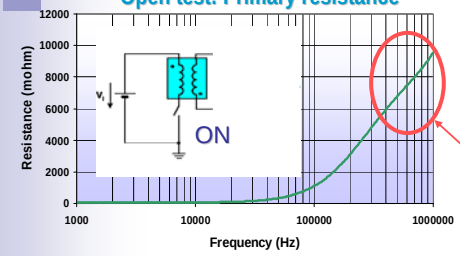
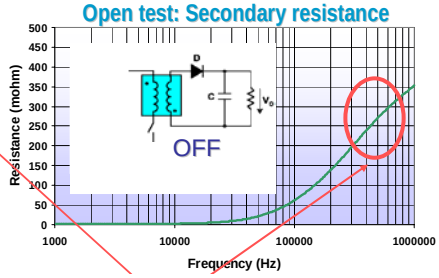
Transformer A: Numerical (FEA) model

Open test: Primary resistance

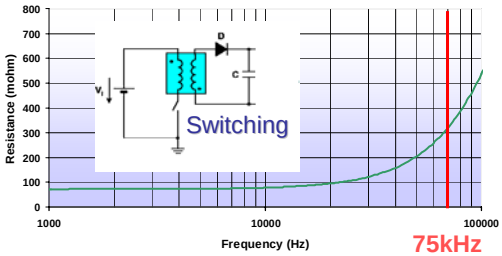


Open test: Secondary resistance



Gap effect!!

Short-circuit test
Primary resistance
(Numerical model)



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Design based on numerical model (FEA)

Transformer B

ETD 44, 3F3

Air Gap 2.2mm

Primary

turns: 30
Wire Gauge: AWG22
(0.7 mm, 27mils, 3 x skin depth)
Parallel: 1

Secondary

turns: 6
Wire Gauge: AWG22
(0.7 mm, 27mils, 3 x skin depth)
Parallel: 6

Compared with Tr.
Reduces gap effect
Improves coupling
Increases DC resistance

Compared with Tr. A:
Reduces gap effect
Similar coupling
Increases DC resistance

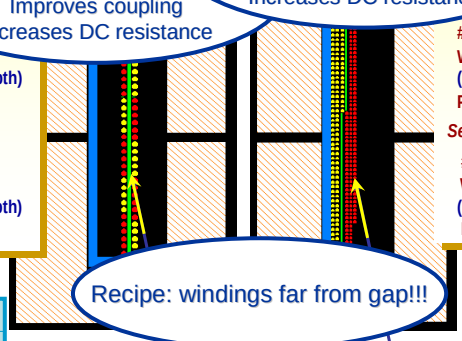
Transformer C

mm (86.6mils)

turns: 30
Wire Gauge: AWG25
(0.5mm, 19.7mils, 2 x skin depth)
Parallel: 4

Secondary

turns: 6
Wire Gauge: AWG25
(0.5mm, 19.7mils, 2 x skin depth)
Parallel: 24



Recipe: windings far from gap!!!

RESULTS	
Core losses:	720mW
Winding losses:	6.2W
ΔT =	60ºC

Low window filling

Medium window filling

RESULTS	
Core losses:	710mW
Winding losses:	9.8W
ΔT =	85ºC

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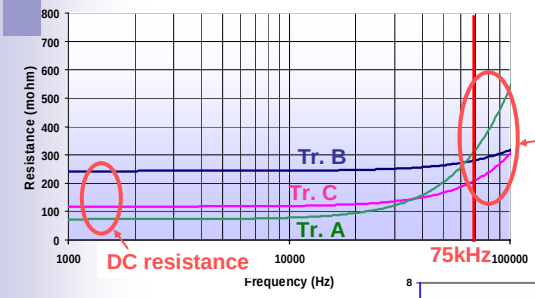
Numerical (FEA) models: short-circuit test

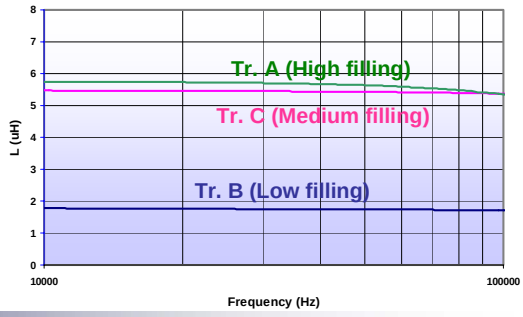


Resistance seen from primary

High frequency effects skin + proximity

Leakage inductance seen from primary

Transformer A and C has similar leakage inductance



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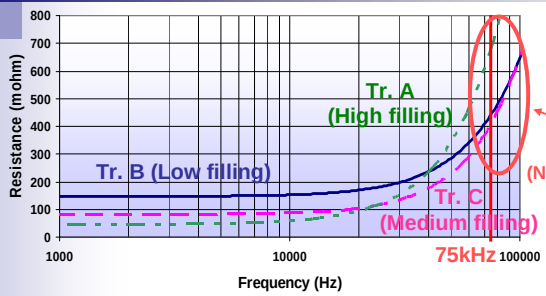
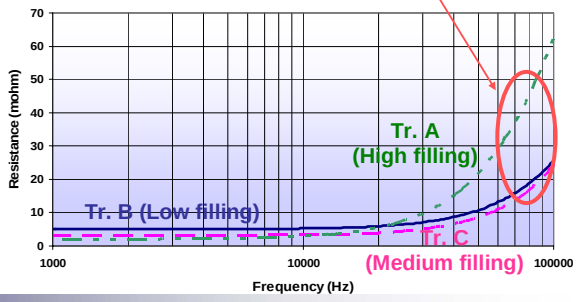
Numerical (FEA) models: Open test



Primary resistance

GAP effect
(No resonance effect, since transformer capacitances have been eliminated from the model)

Secondary resistance



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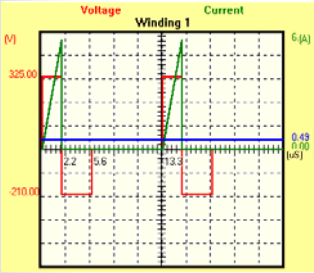
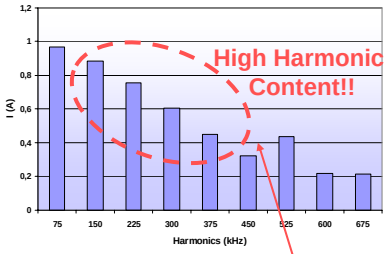
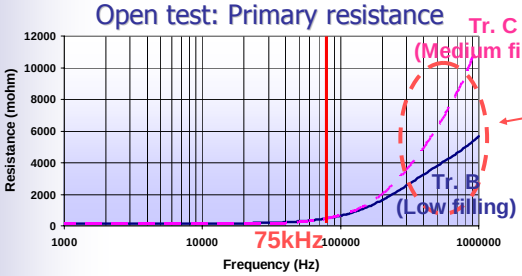
Studying the problem



Primary current: Harmonic content



Open test: Primary resistance



Similar resistance at 75kHz, but Tr. C is more sensitive at gap effect

Tr. B should be more efficient than Tr. C in the converter

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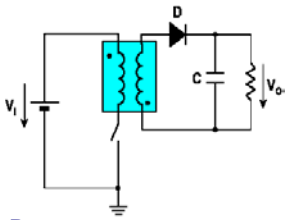
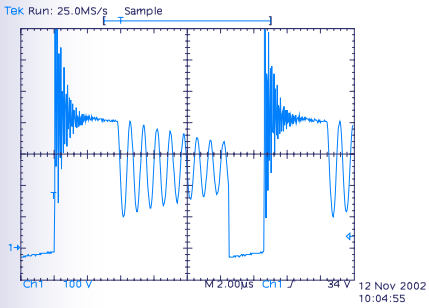
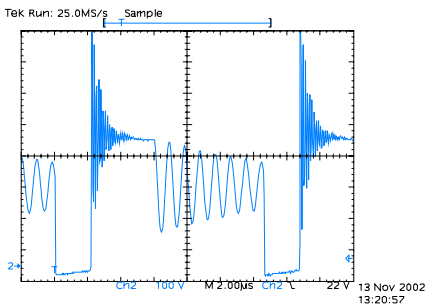
Flyback prototype: Measurements



Transformer B



Transformer C



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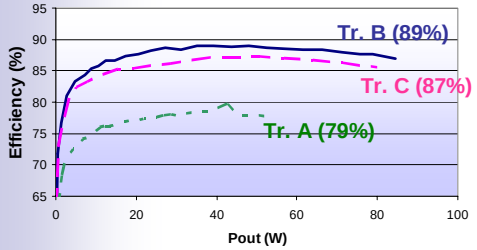
Flyback prototype: Measurements

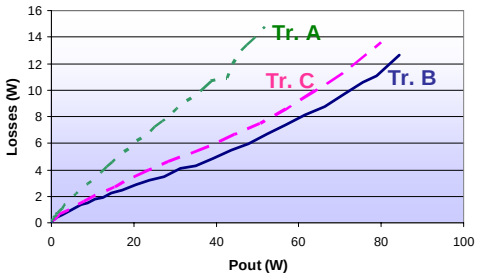
Flyback efficiency



Transformer A and C has similar inductance, however converter losses are very different ⇨GAP effect!!

Losses with Transformer C are 27% higher (3W higher) than with Transformer B

Flyback losses



Virtual prototyping accounts for 2D effects:

- ✓ problems can be properly understood
- ✓ optimum designs can be proposed:
  - ✓Not too many wires but properly placed and winded

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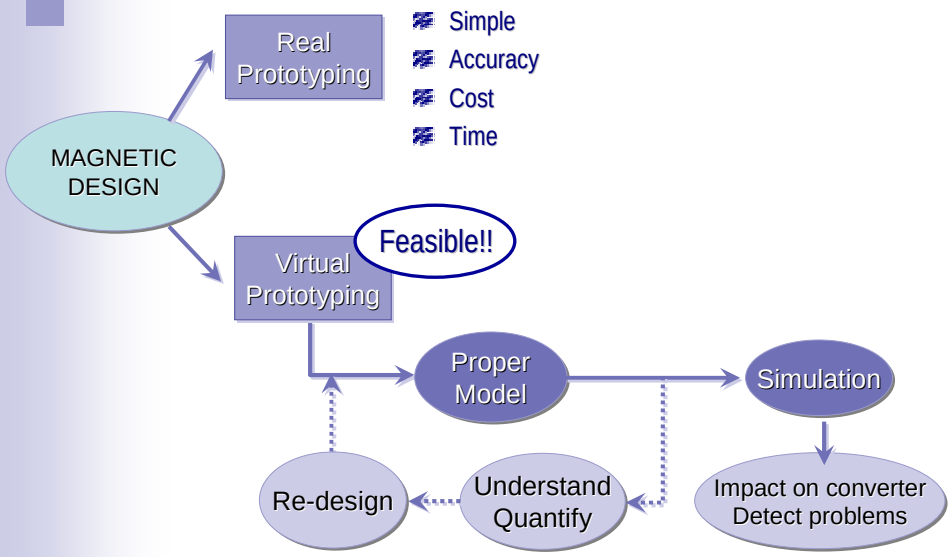

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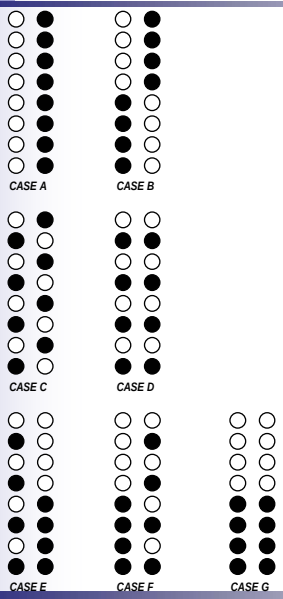
Interleaving

Comparison of winding strategies



Case	$L_{leakage}$ (μH) @200kHz	$L_{leakage}$ (μH) @2MHz
A	0.475	0.248
B	0.432	0.231
C	0.130	0.087
D	0.276	0.185
E	4.144	2.827
F	4.239	2.857
G	13.979	9.496

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