Modeling and Optimization of High Frequency Magnetic Components

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Outline

- Basic concepts and classical design
- High frequency effects
- Modeling review
- Advanced design and optimization process
- Application to converters
- Summary of design guidelines

1

Basic concepts and classical design

Basic concepts

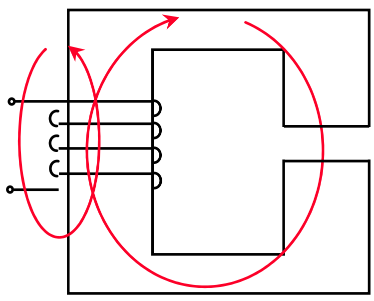
- Main applications of Magnetic components:
  - ✓Galvanic isolation
  - ✓Adjust voltage levels
  - ✓Filters
  - ✓Resonant inductors
  - ✓Measurement for feedback and protections
  - ✓Pulse transformers
  - ✓...

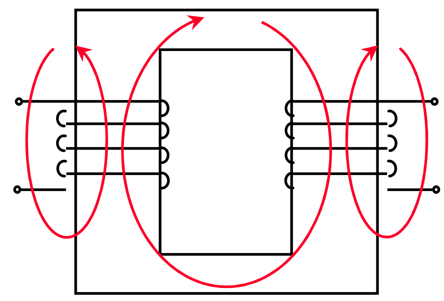
... but basically, they produce:

- ENERGY TRANSFER
- ENERGY STORAGE

... and unfortunately, also LOSSES

Inductor | **Transformer**



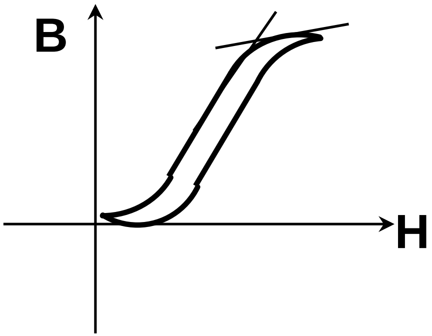


- Core:
  - ✓ **Flux: Energy link**
  - ✓ **Non-linearity and hysteresis**
  - ✓ **Losses:**
    - **Hysteresis**
    - **eddy currents**
    - **residual**

- Windings:
  - ✓ **Electrical terminals**
  - ✓ **Losses**
    - **DC losses**
    - **AC losses**
  - ✓ **Winding strategy affects strongly to performance**

PERMEABILITY

$$B = \mu H$$

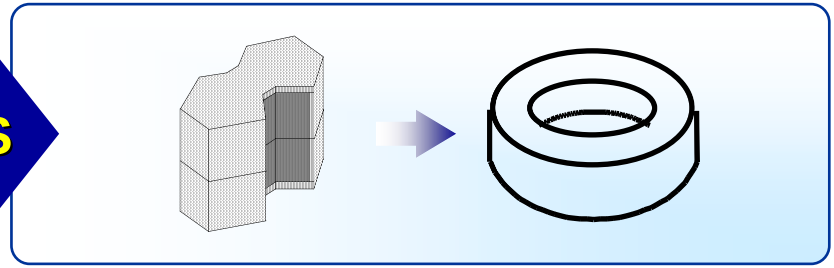


Permeability = Slope
NOT LINEAR

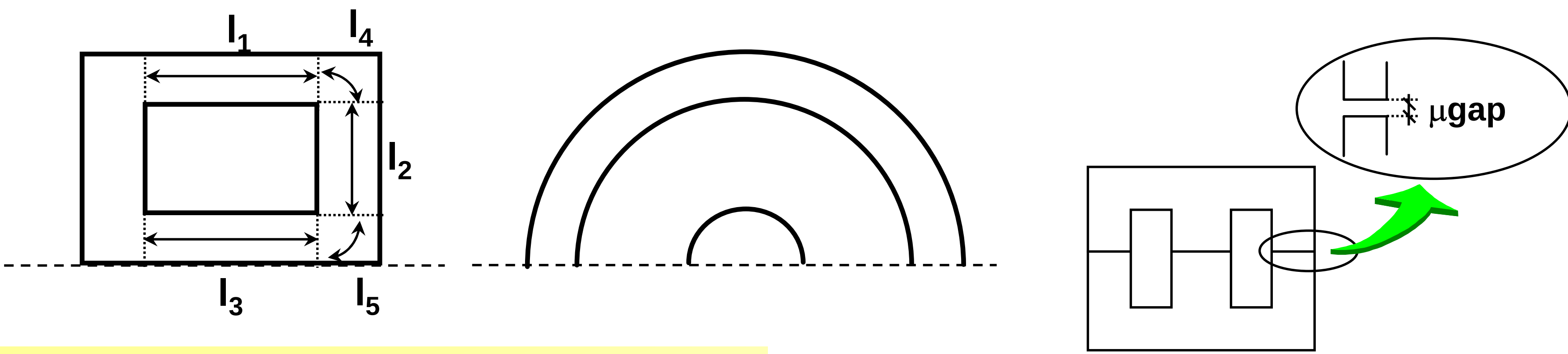
RELUCTANCE

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

EFFECTIVE VALUES



EXAMPLE: POT CORE



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

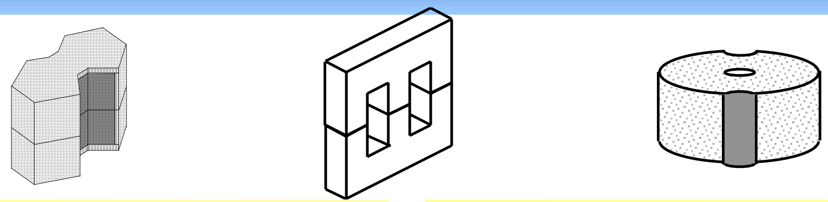
$$C_1 = \sum_1^5 \frac{l_i}{A_i} mm^{-1} \qquad C_2 = \sum_1^5 \frac{l_i}{A_i^2} mm^{-3}$$

μ_e depends on the "microgap" (2.5 μm) due to the mechanization procedure

Basic concepts

Types of cores and windings

CORES



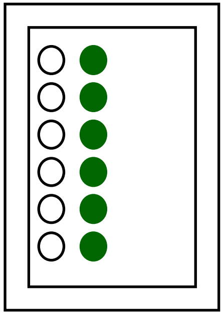
Shapes
RM, POT, EE, EI, PQ, TOROID...

- ☑ Effective values
- ☑ Magnetic coupling
- ☑ Thermal management

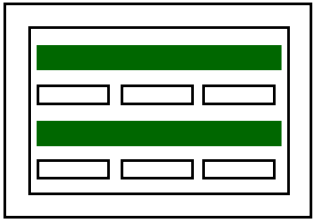
Materials
3F3, 3C85, 3C90, N67, N47...

- ☑ Core losses
- ☑ Reluctance and conductivity
- ☑ Maximum flux density

WINDINGS



Concentric

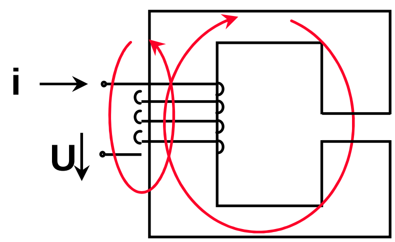


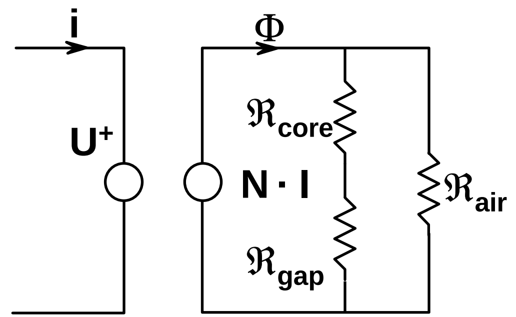
Top down

Interleaving techniques can be applied in both strategies

Basic concepts

Inductor





Some flux “leaks”, that affects to EMI, not to L

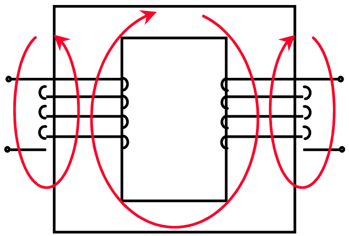
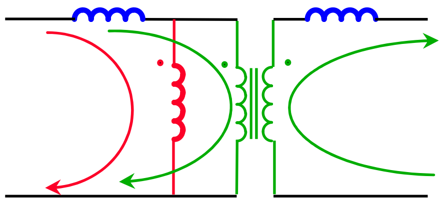
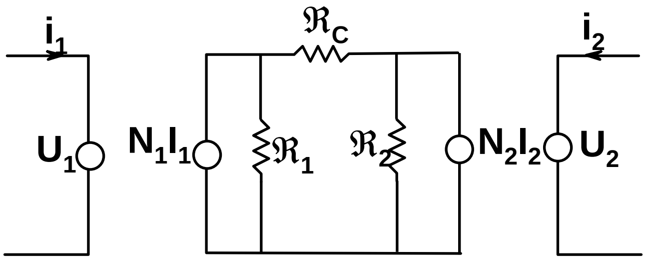
Duality principle

Electric	*Magnetic*
U	NI
I	Φ
R	$\Re$
ρ	$1/\mu$

Main relationships

$$U = L\frac{\Delta i}{\Delta t} = N\frac{\Delta \Phi}{\Delta t}$$

$$L = N^2 A_L$$

- **Ideal Transformer:**

$$\frac{d\phi}{dt} = \frac{u_1}{n_1} = \frac{u_2}{n_2} = ... = \frac{u_p}{n_p}$$

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

No Energy Storage !!
No Losses !!

- **Real Transformer:**
  - ✓ **Common Energy:**

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

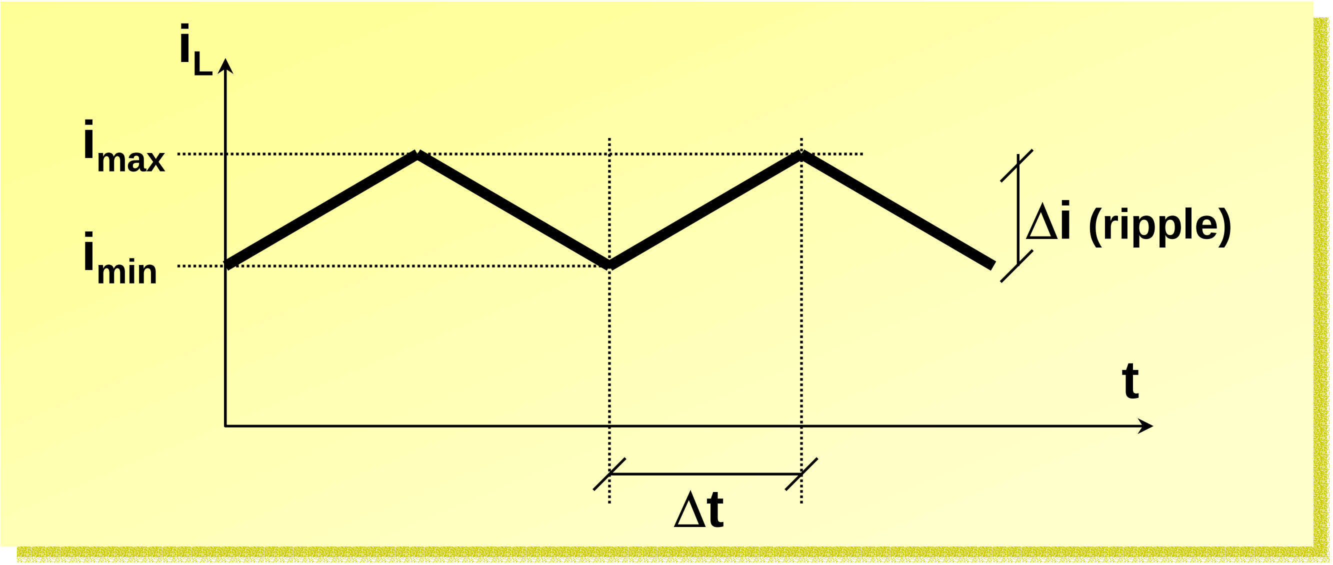
$$\sum ni = \Phi \cdot \Re$$

in any winding

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

Note difference between
"transferred energy" and "stored energy"

Calculation of the required inductance



$$U = L\,\frac{\Delta i}{\Delta t} \quad \Rightarrow \quad L = \frac{U \cdot \Delta t}{\Delta i}$$

U = Voltage applied to the inductor during Δt

1.	CORE SHAPE	Depends on the application (see data books)
2.	CORE SIZE	Depends on the power (see 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 required copper losses. The maximum current density should be fixed with the conductor area

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

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

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

This procedure guarantees that the inductor will not be saturated

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

$$\Re_T = \frac{N^2}{L}$$

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

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

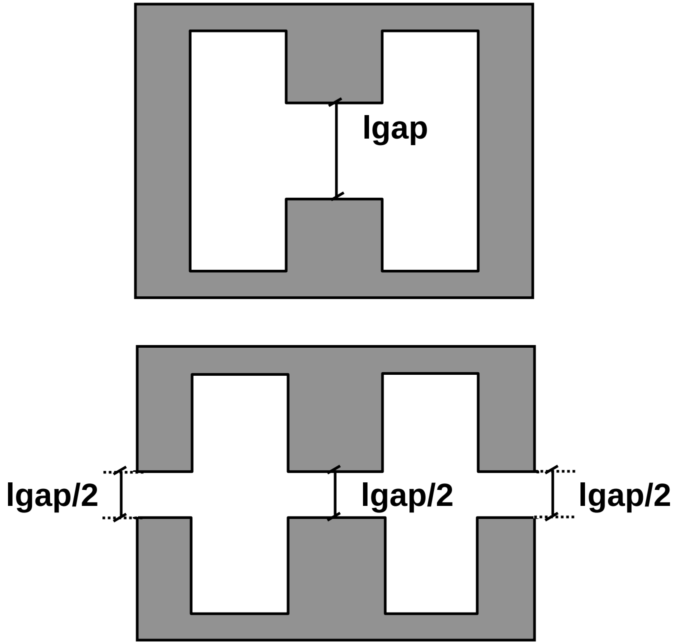
$$\Re_T = \Re_{ferrite} + \Re_{air} = \frac{1}{\mu_o \mu_e} \cdot \frac{l_e}{A_e} + \frac{1}{\mu_o} \cdot \frac{l_{gap}}{A_e}$$

$1/A_L$
(ferrite without gap)

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

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

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



1. CORE SHAPE — Depends on the application (see data books)

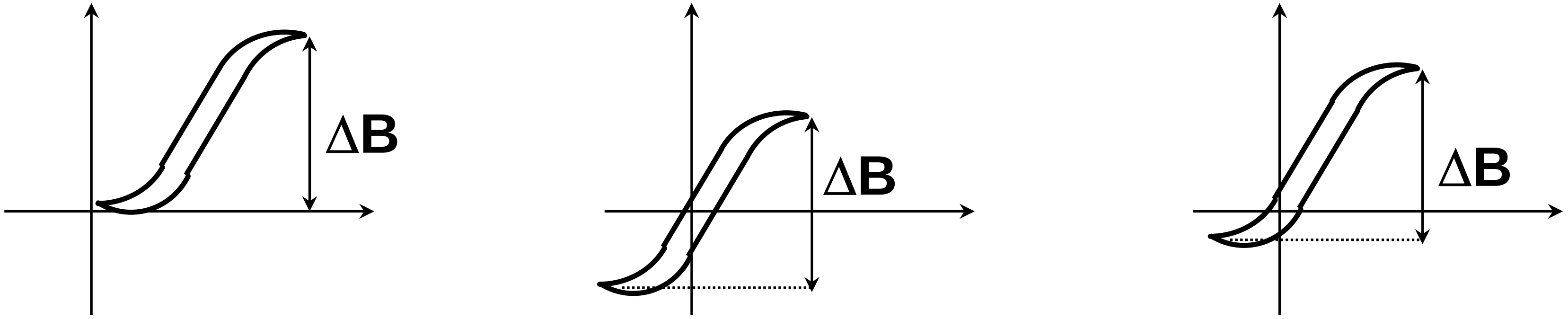
2. CORE SIZE — Depends on the power (see data books)

3. CORE MATERIAL — Depends on the frequency (see data books)

4. CONDUCTOR TYPE — Depends on the frequency (skin depth)
   - Solid wire: low frequency
   - Litz or foils wire: high frequency

5. CONDUCTOR AREA — In transformers: Copper losses = Core losses

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



$$U_1 = N_1 \cdot \frac{\Delta \Phi}{\Delta t} = N_1 \cdot A_e \cdot \frac{\Delta B}{\Delta t} \Rightarrow N_1 = \frac{U_1 \Delta t}{A_e \Delta B}$$

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

Magnetizing inductance

$$L_{m1} = \frac{N_1^2}{\Re} = N_1^2 \cdot A_L$$

→ ↑ L_m ↓ i_{mag}

Losses

CORE → **Data book abacus**

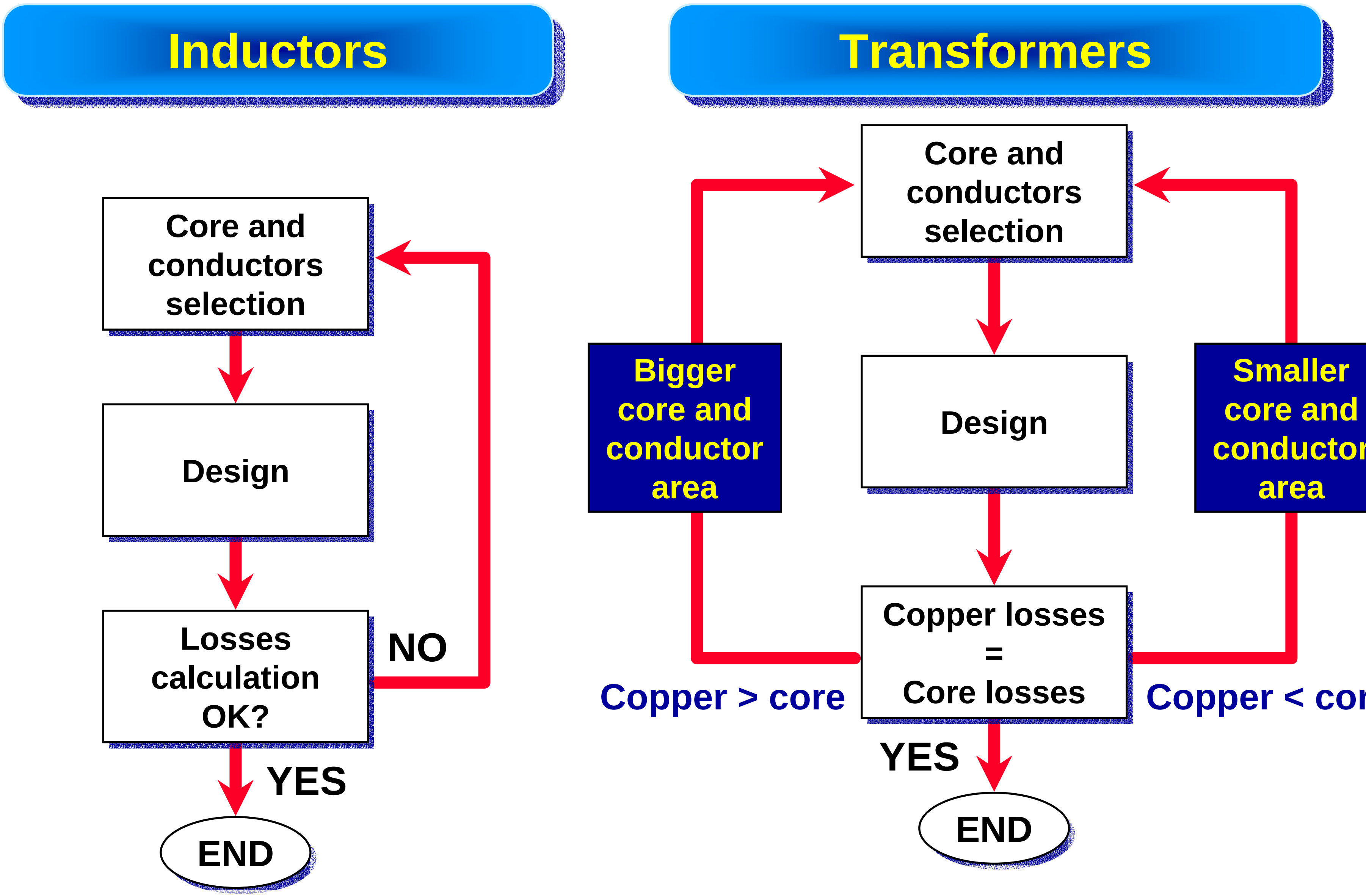
COPPER →

$$P = R \cdot I^2$$

$$R = \rho \frac{l}{s}$$

Losses in core and copper should be equal

Design procedure



Inductor

Keeping L constant

Increasing Core Size

- ↓ Number of turns
- ↓ Air gap
- ↓ Copper losses
- ↑ Core losses

Transformer

Keeping n1/n2 constant

Increasing Core Size

- ↓ Number of turns
- ↓ Copper losses
- ↓ L_{mag}
- ↑ Core losses

2

High Frequency effects

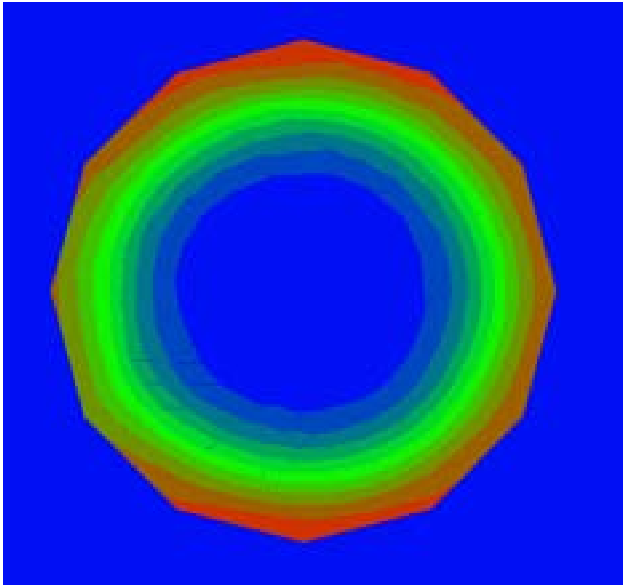
Skin

Proximity

Gap

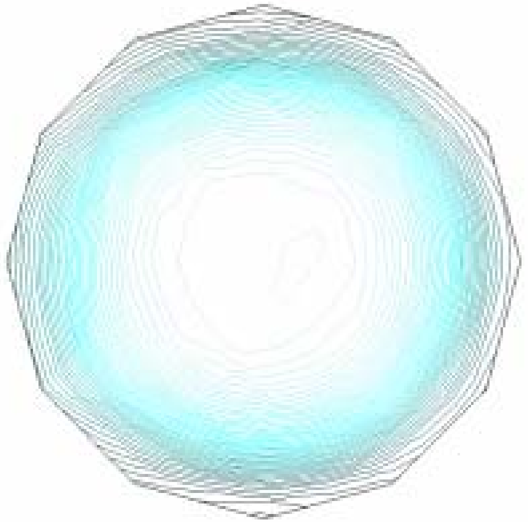
Interleaving

Skin effect



Shaded drawing

150kHz



Lined drawing

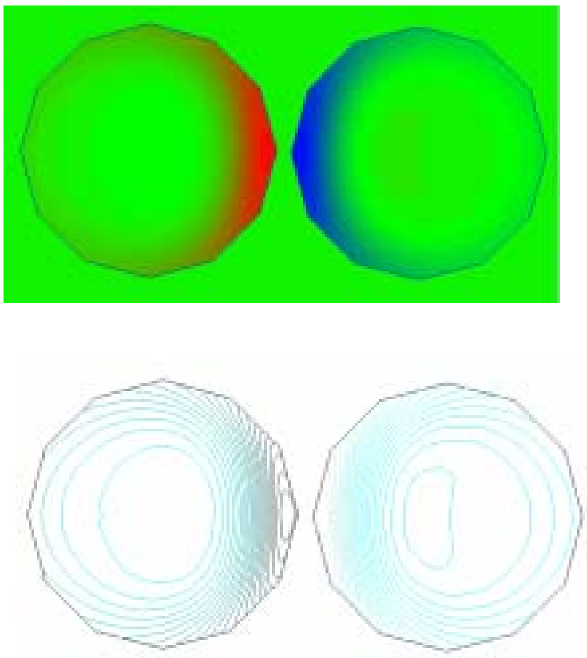
Skin depth

$$\delta = \frac{1}{\sqrt{2\pi f \mu_0 \sigma}}$$

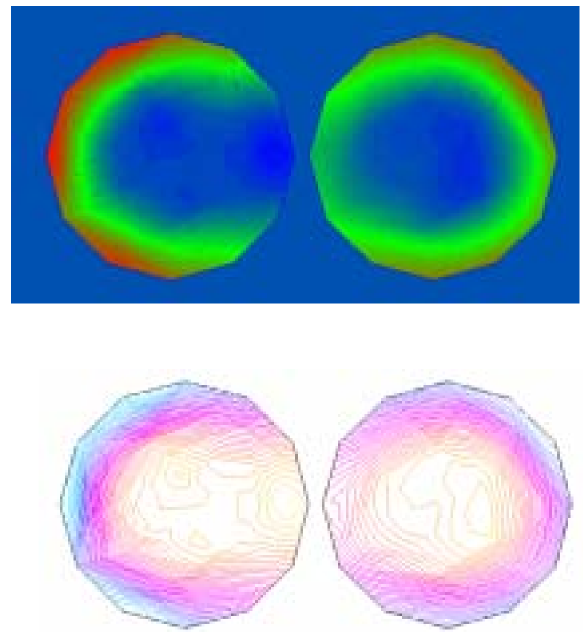
At high frequency, current tends to flow through the surface

Proximity effect

Opposite currents

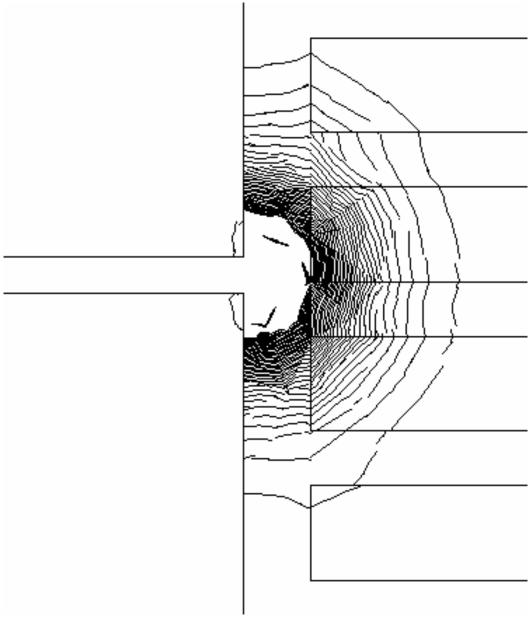


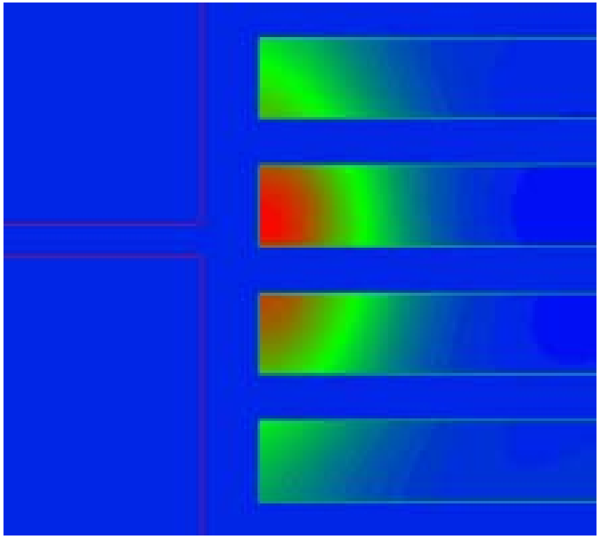
Parallel currents



- ✓ **Opposite currents tend to flow together**
- ✓ **Parallel currents tend to separate**

Gap effect

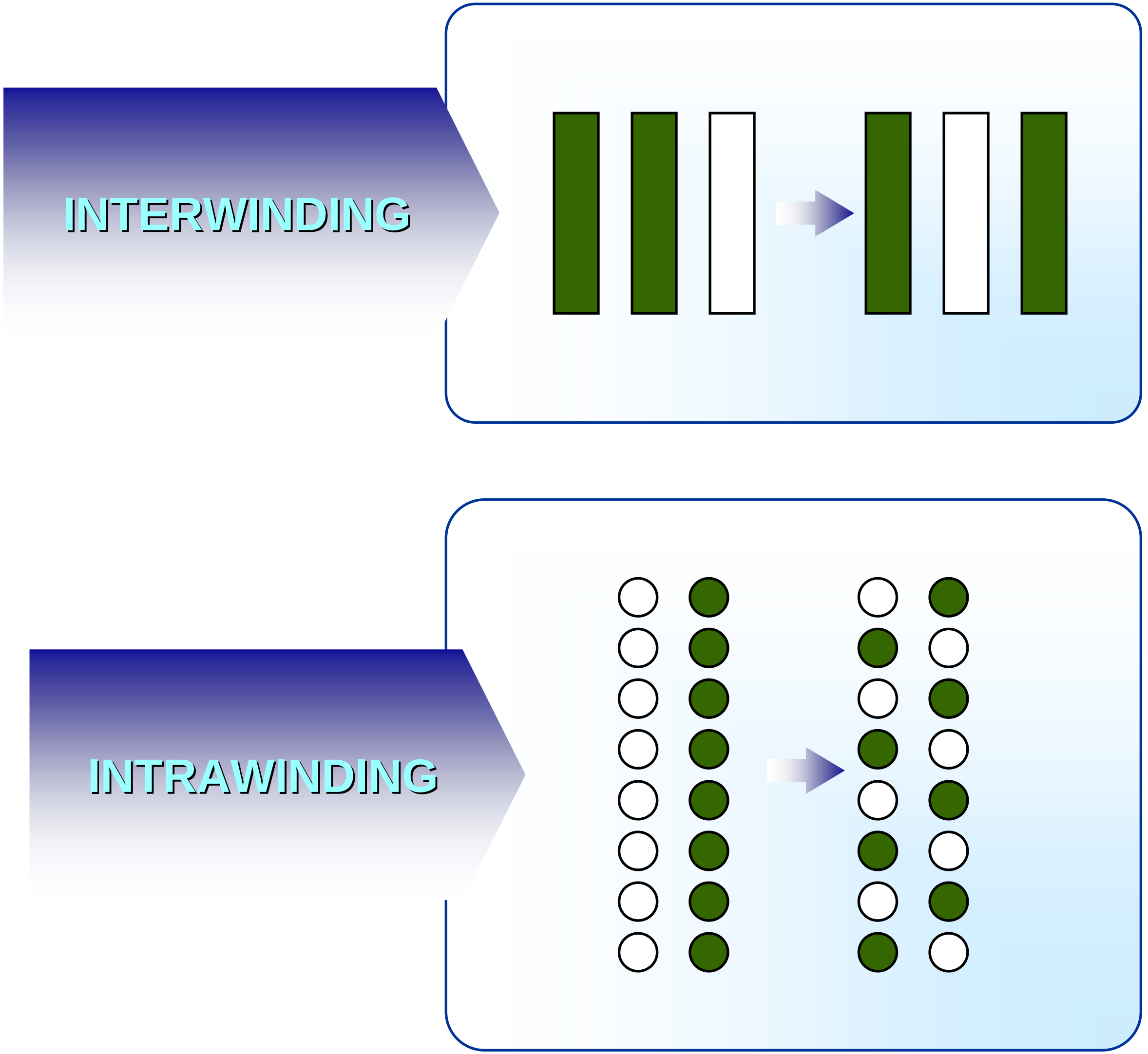




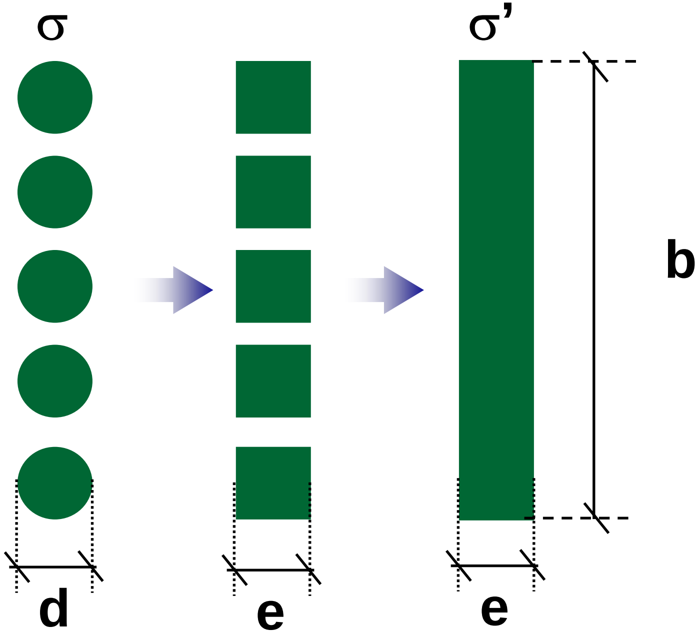
Fringing flux **Current density distribution**

Fringing flux affects to conduction losses

Interleaving



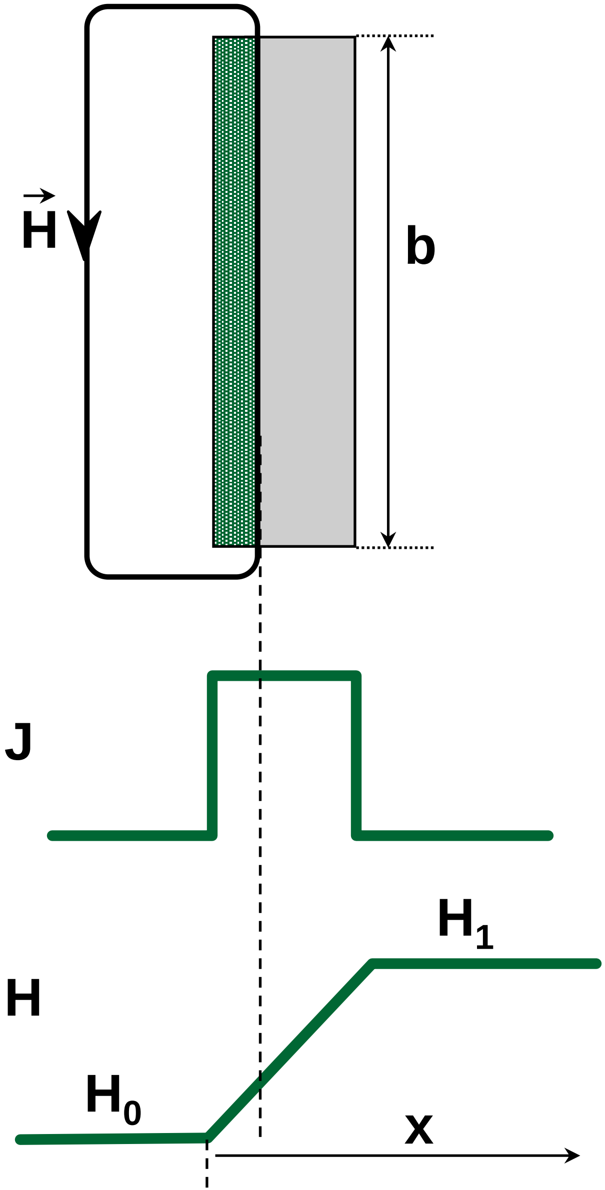
Current sheet



$$e = \sqrt{\frac{\pi}{4} \cdot d^2}$$

$$\eta = \frac{e \cdot N}{b} \qquad \sigma' = \sigma \cdot \eta$$

Current sheet with same equivalent resistance



$$\oint \vec{H} \cdot \vec{dl} = n \cdot I$$

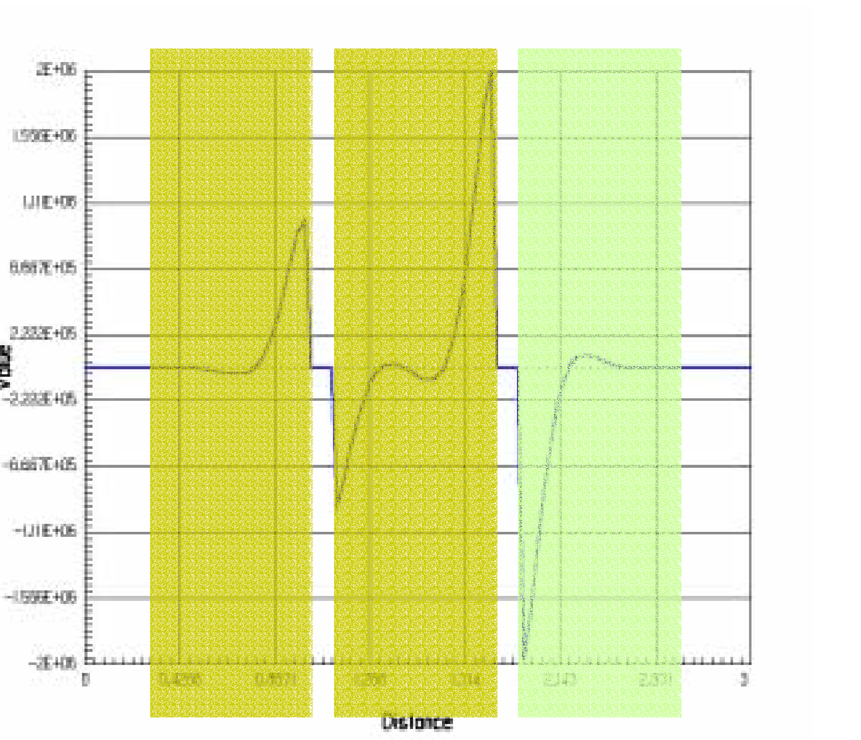
$$H(x) \cdot b = H_0 \cdot b + J \cdot x \cdot b$$

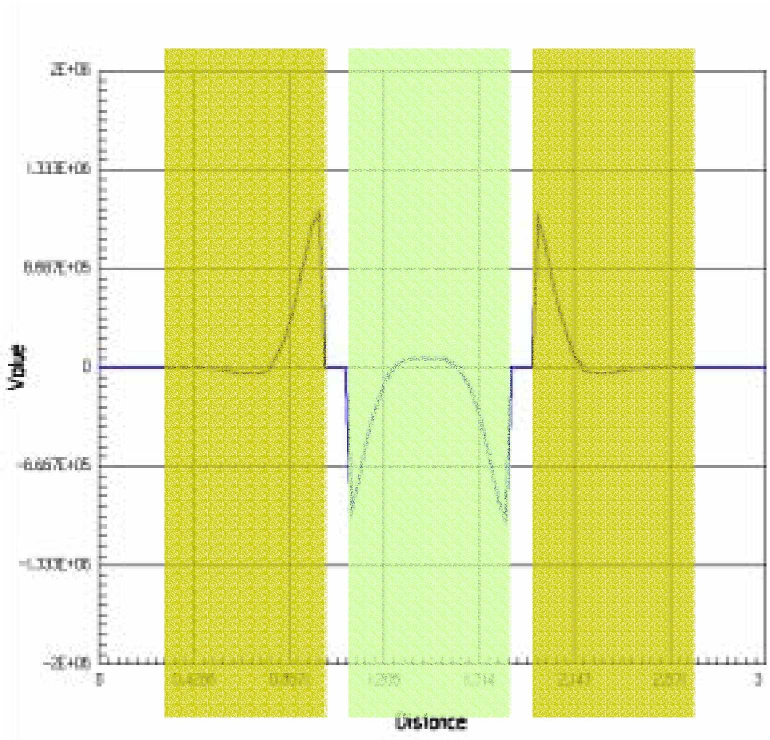
$$H(x) = H_0 + J \cdot x$$

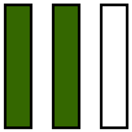
Interleaving

Reduction of the AC resistance
CURRENT DENSITY (J)

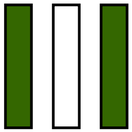
ONLY in AC







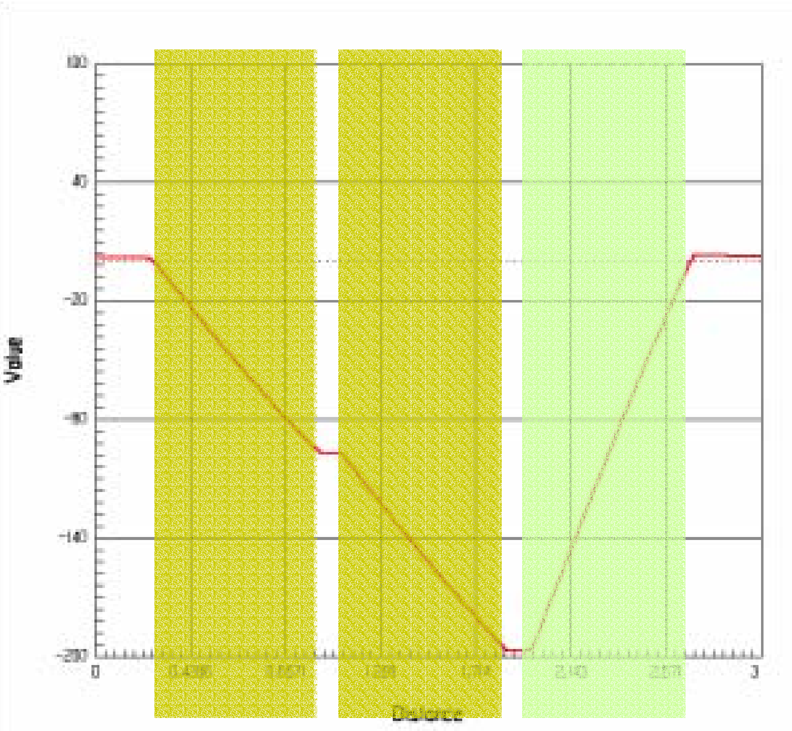
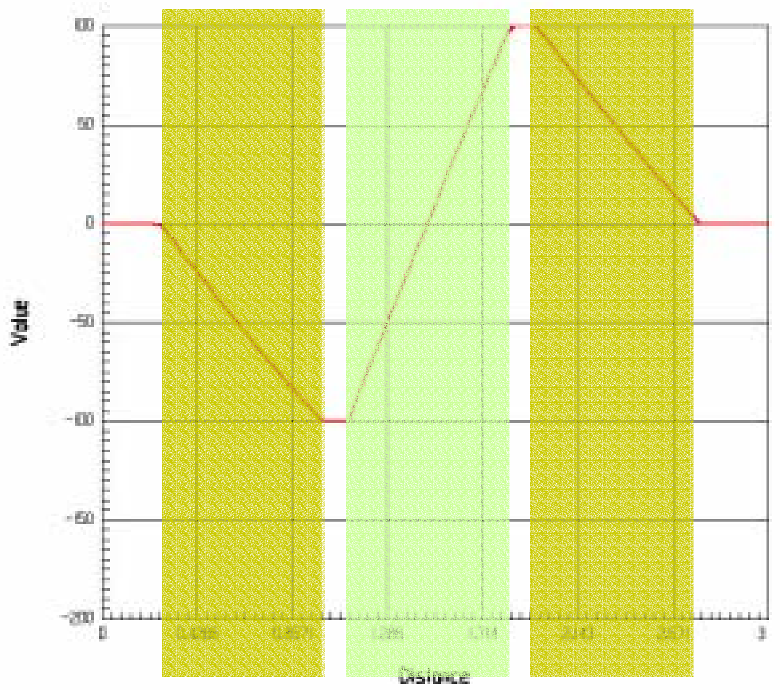
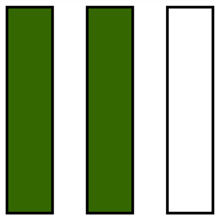
***J* distribution improves**



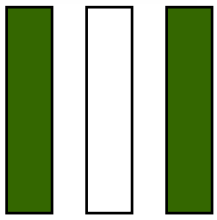
Interleaving

Reduction of the leakage inductance
MAGNETIC FIELD (H)

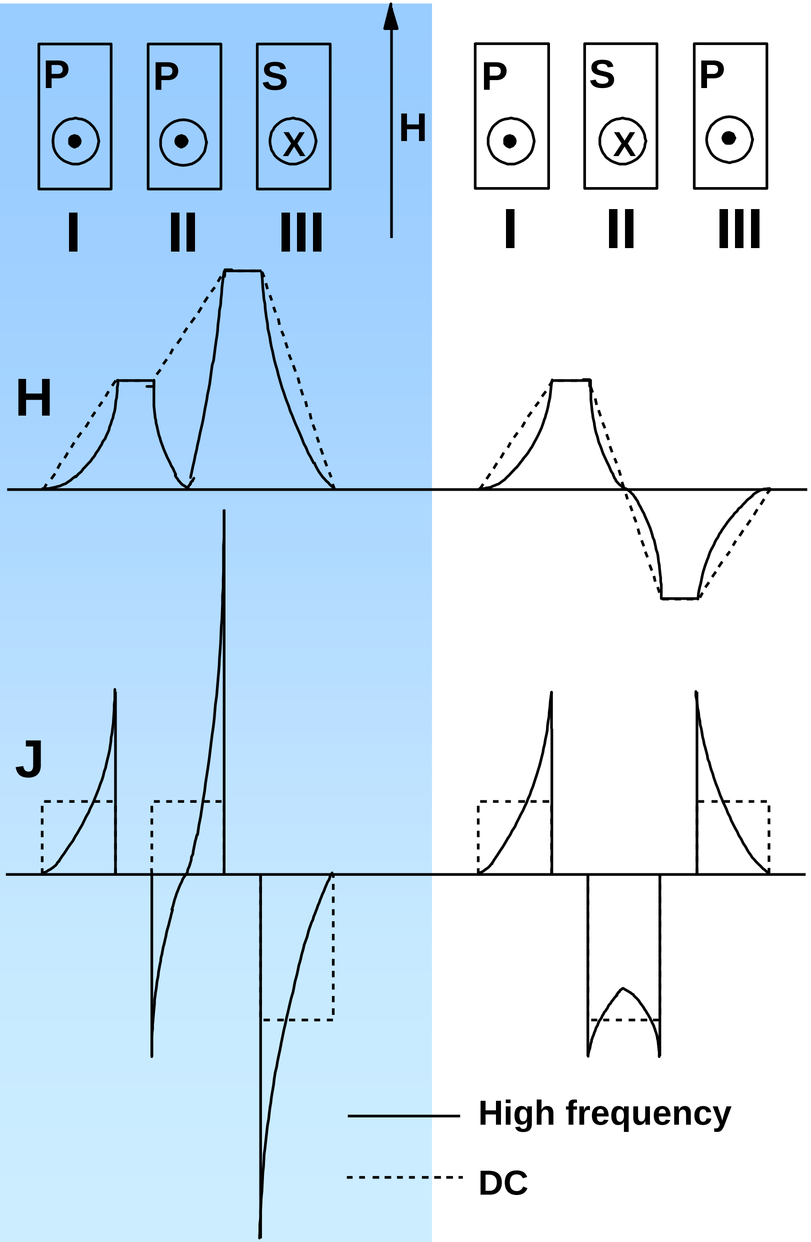
AC and DC

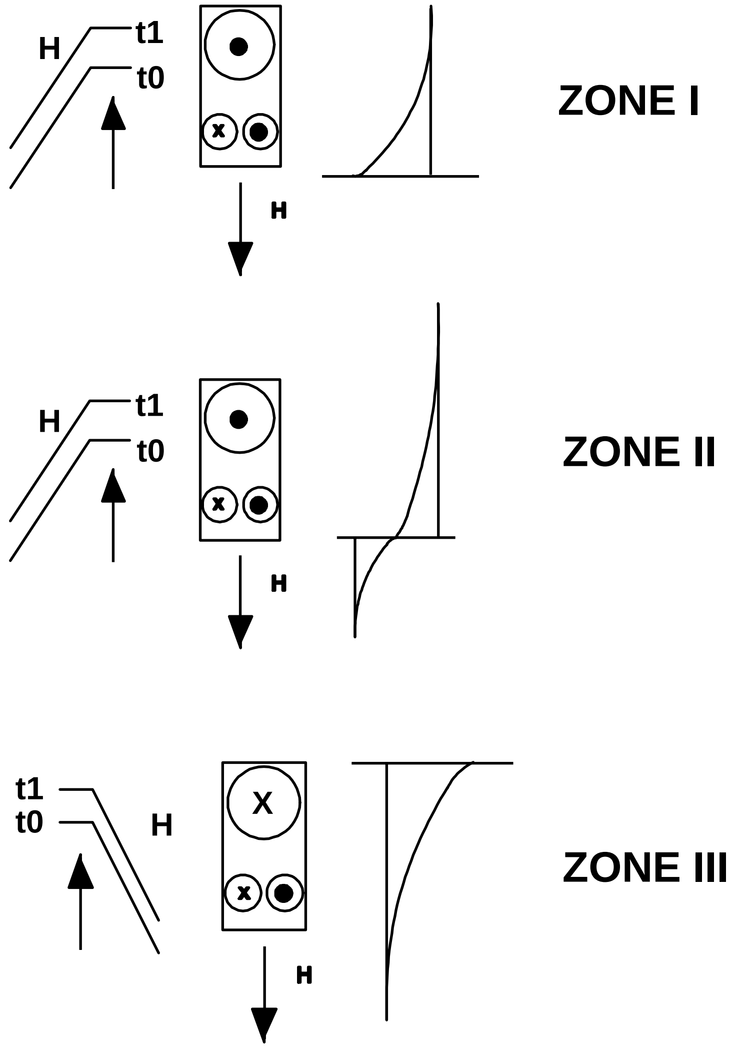




***H* distribution improves**



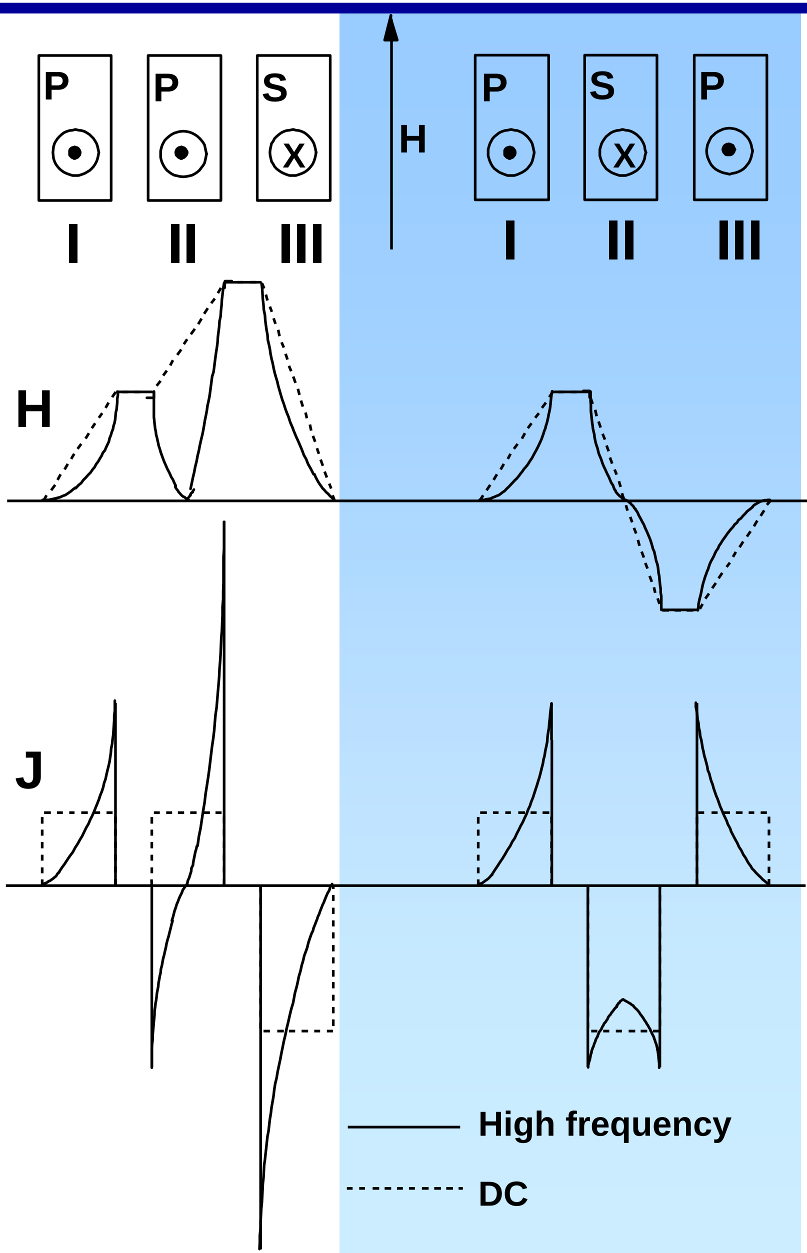
Interleaving

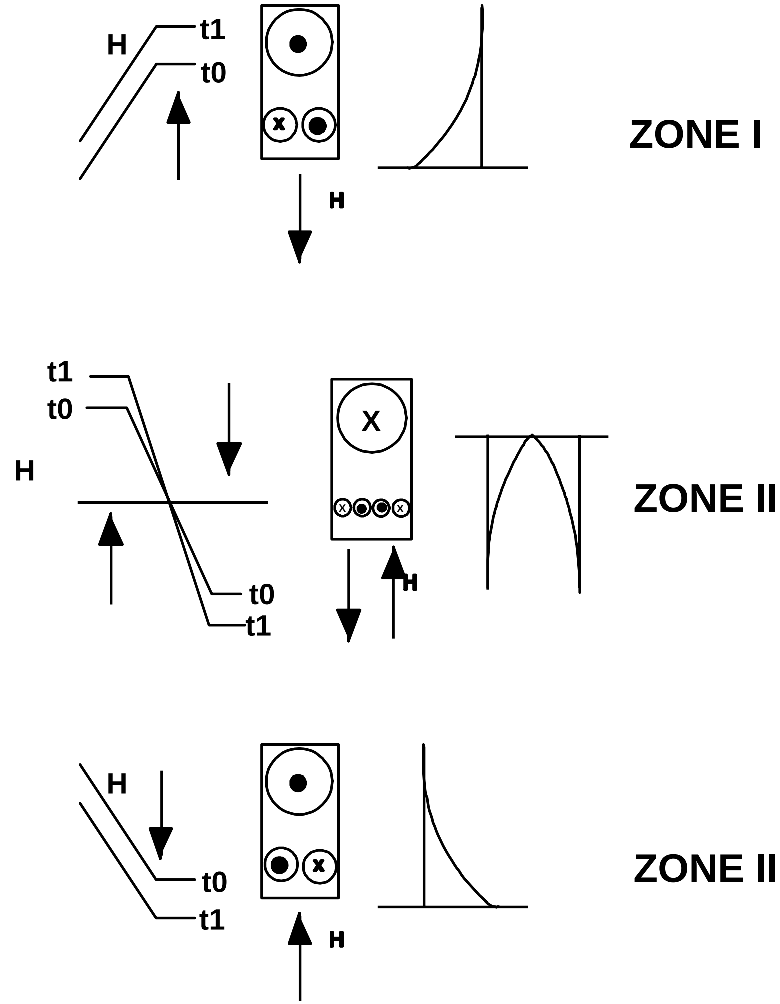




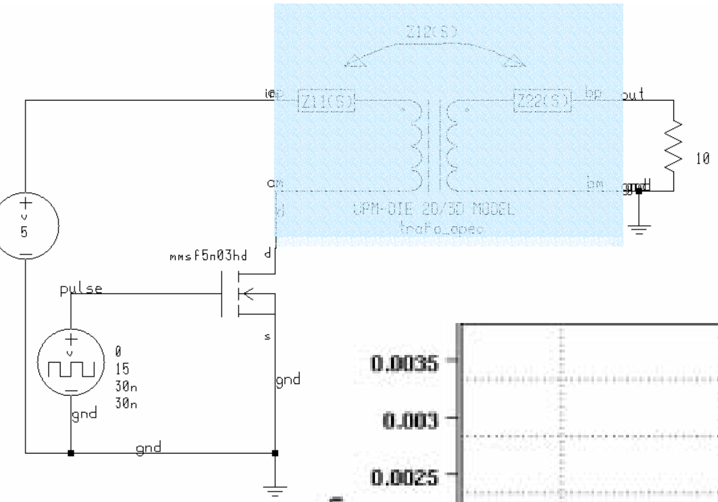
Without interleaving

Interleaving





With interleaving

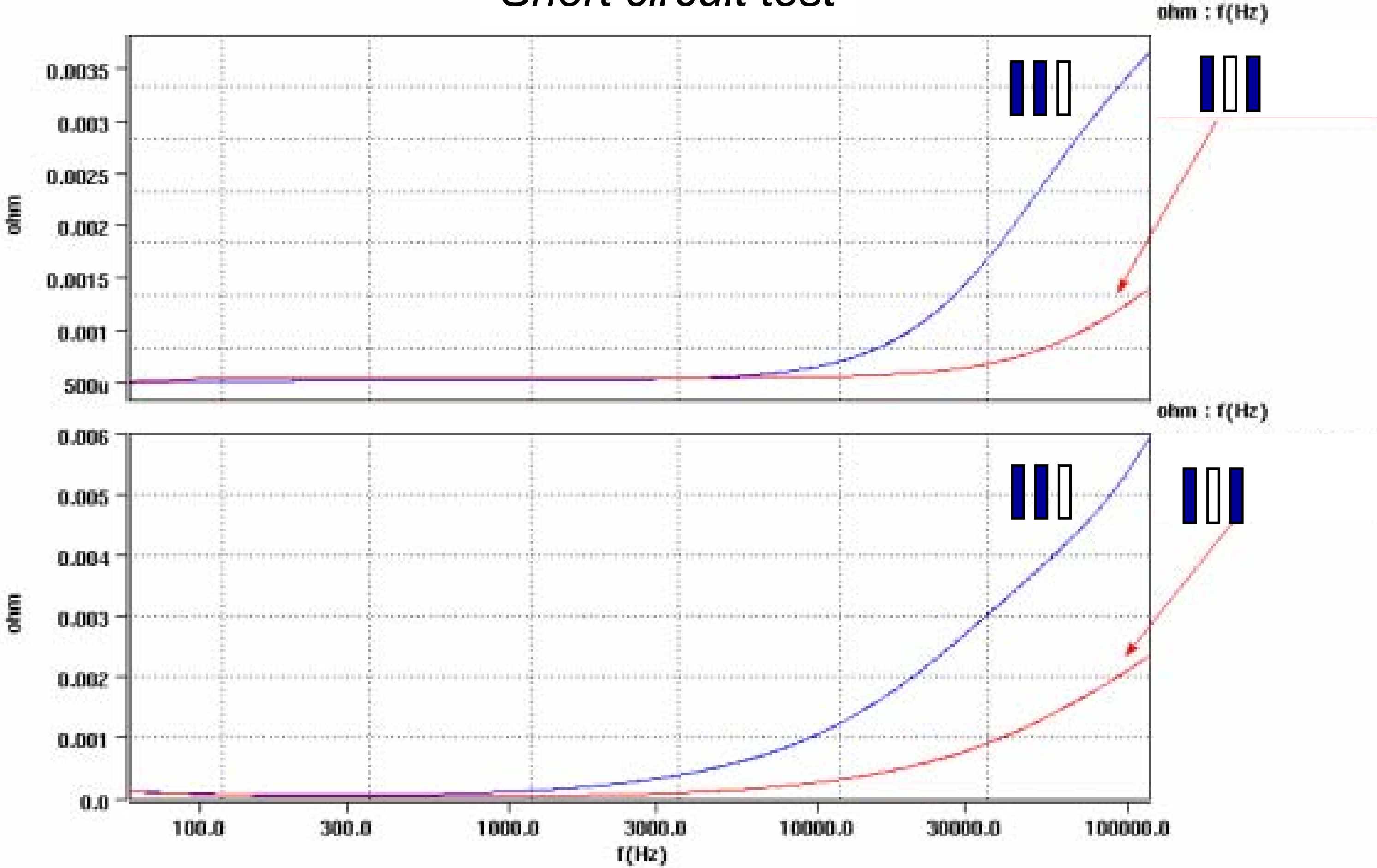


Frequency behavior

Short circuit test

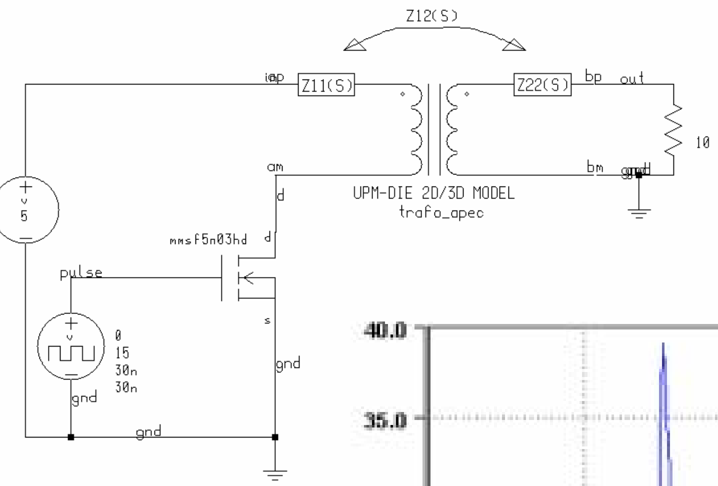
Resistance

Reactance

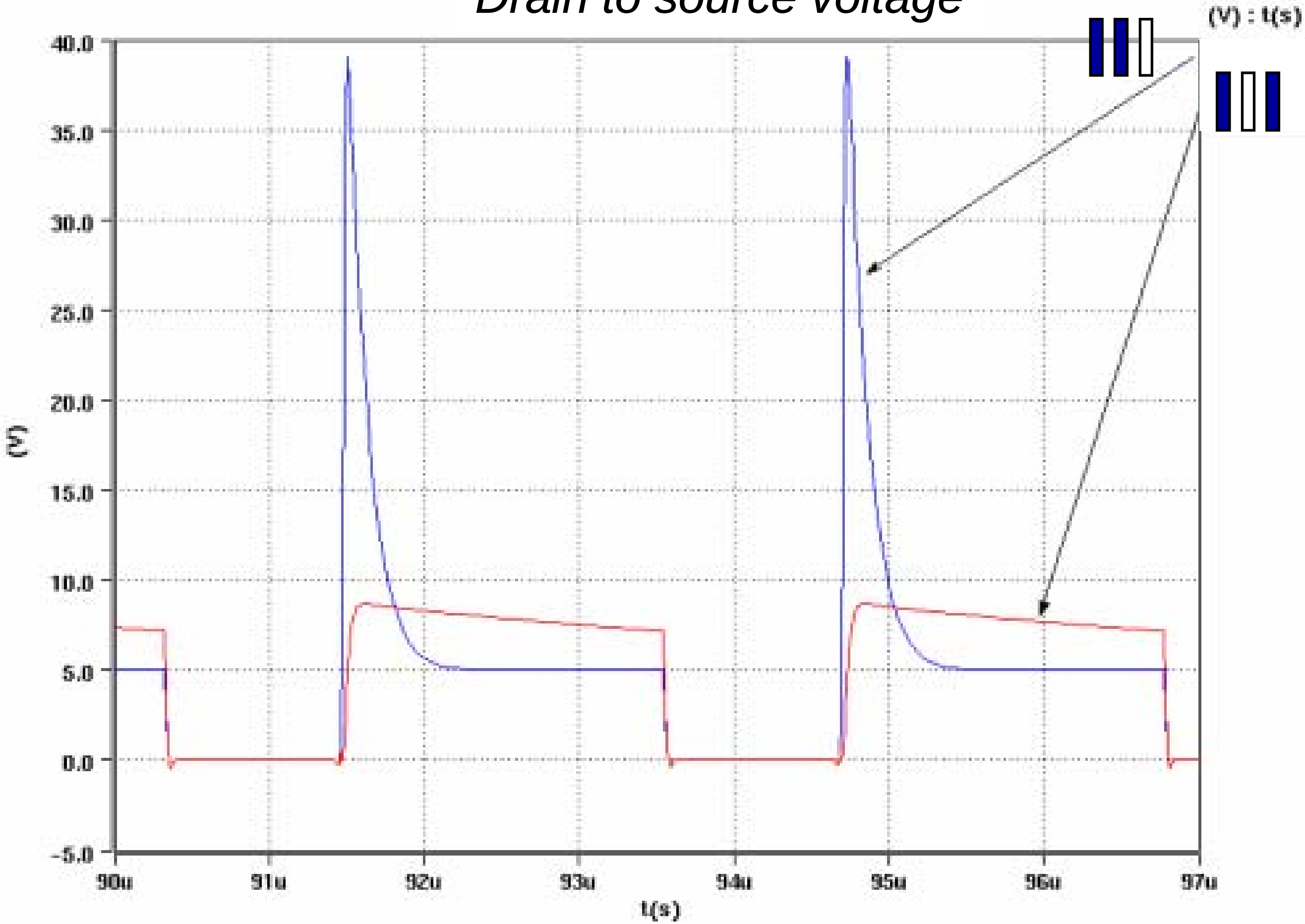


Interleaving

Voltage spikes due to leakage inductance

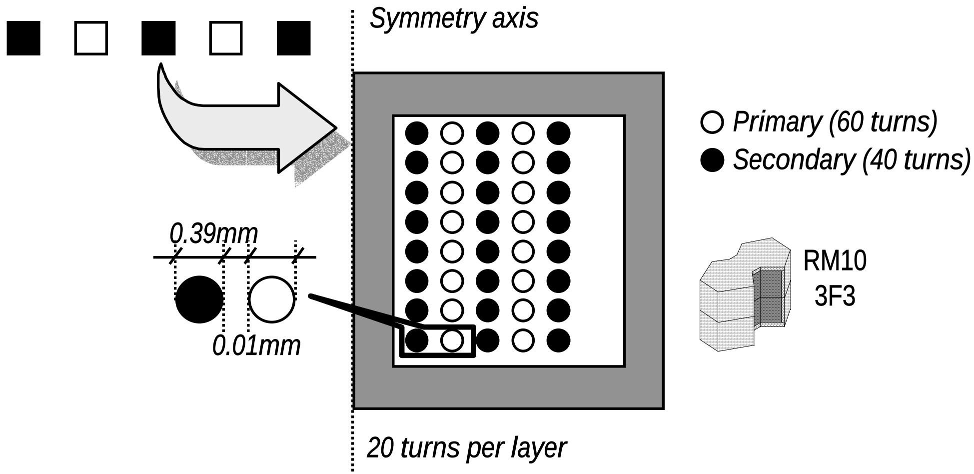


Drain to source voltage

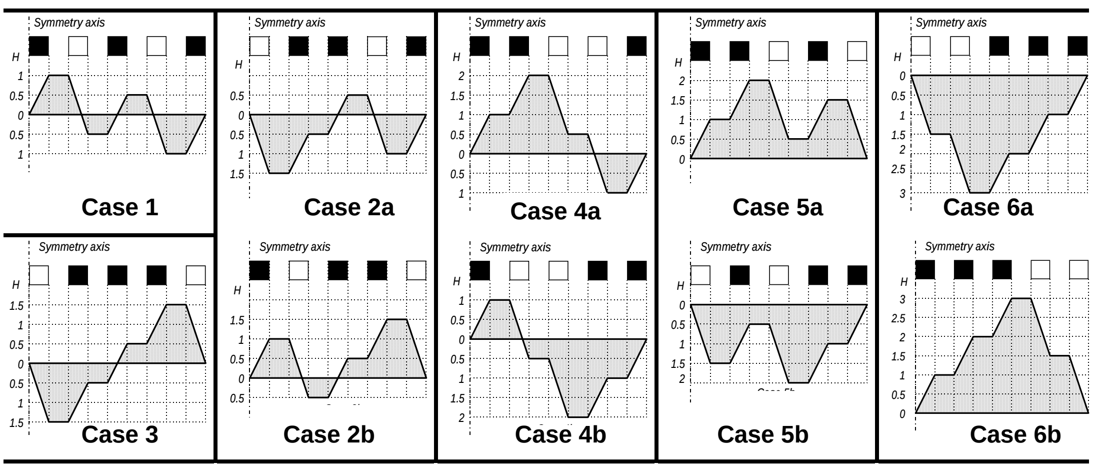


Interleaving

Comparison of winding strategies

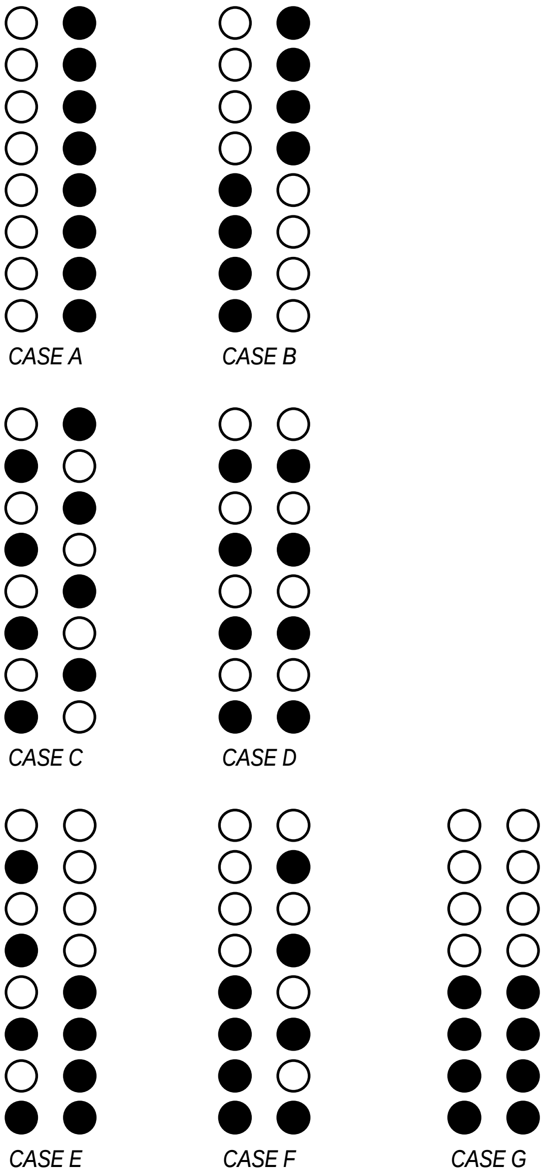


Case	R (Ω) @200kHz	$L_{leakage}$(μH) @200kHz
1	1.1	1.4
2a	1.5	1.9
2b	1.6	2.0
3	2.0	2.8
4a	2.4	3.5
4b	2.5	3.6
5a	2.8	4.2
5b	2.8	4.3
6a	5.7	9.5
6b	5.9	9.9



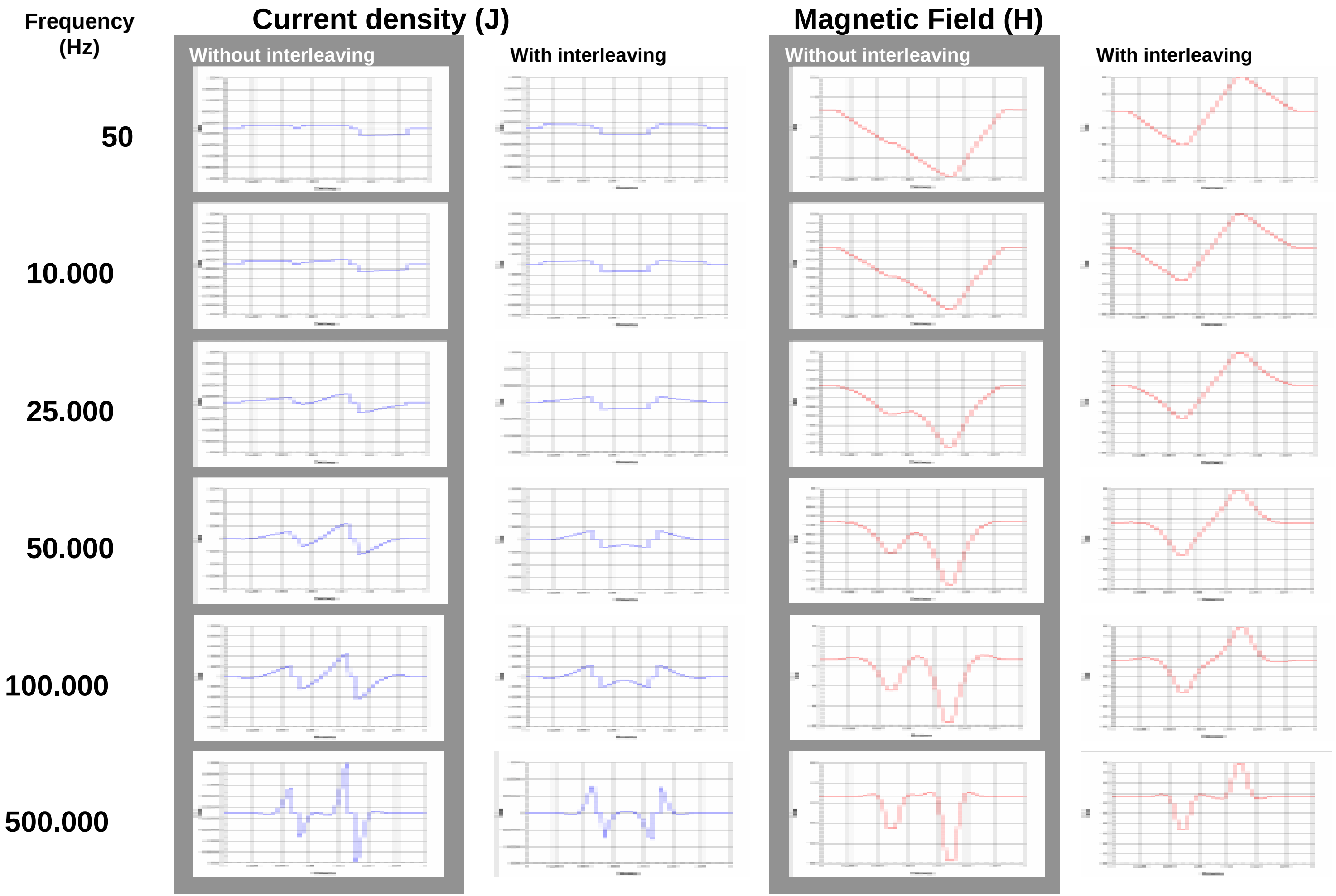
Interleaving

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

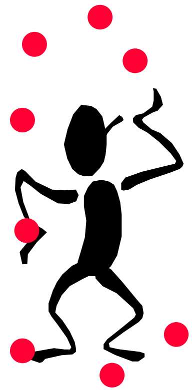
Interleaving



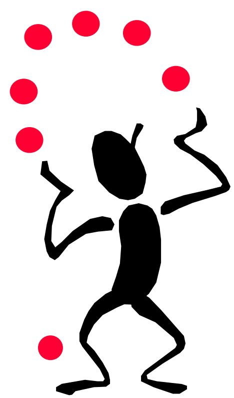
Official Outline

- Basic concepts
- High frequency effects
- **Modeling**
- Advanced design
- Application to converters

Mr Designer at UPM lab



before...



...after

Mr. Designer Outline

Mr Designer learns to design

Mr Designer has a problem

Mr Designer finds a solution

Mr Designer can use it !

Mr Designer succeeds !!

What is the real dimension of Modeling…?

Do I make simulations?

Do I trust them?

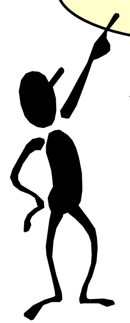
if not, are magnetic component models the reason?

Do I need a model...

...or just design guidelines?

Others or MY OWN design guidelines?

I need MY OWN QUANTIFICATION!!



What is the real dimension of Modeling…?

How many modeling works have I read?

How many of them am I using?

Do I wish to **IMPLEMENT**, or **just USE** them?

MODEL

…tool to obtain MY OWN design guidelines

…gate to simulation

3

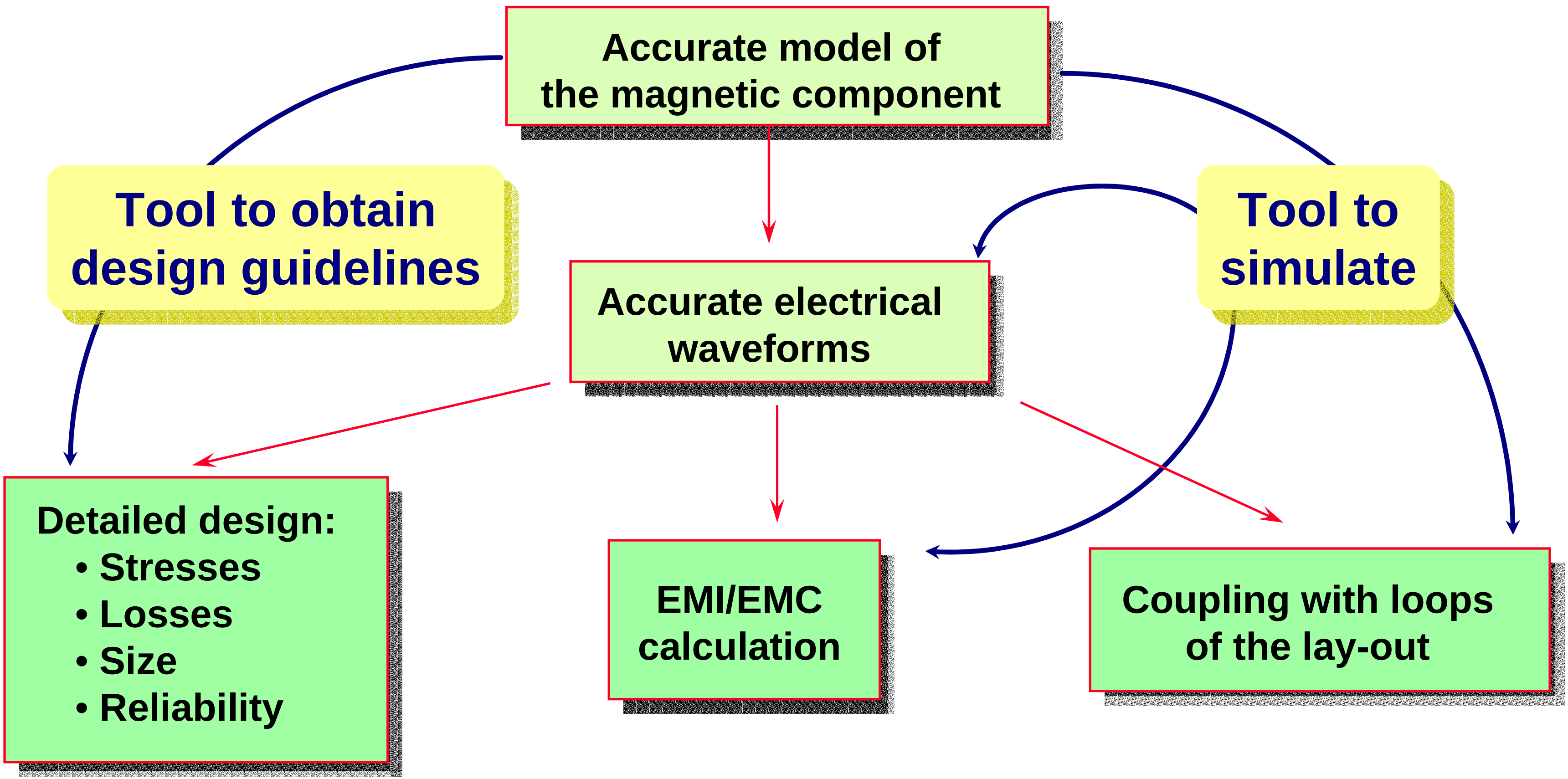
Modeling Review

Basic concepts

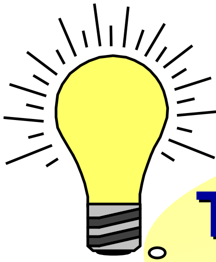
Analytical (1D effects)

FEA tools (2D/3D effects)

Basic concepts



Basic concepts



To obtain an accurate model, *physical effects* must be deeply analyzed

Distribution of

Magnetic fields
Electric fields
Current
Voltage

depend strongly on

Frequency
Waveform
(harmonic content, SMPS)
Geometry & Materials

Practical approach

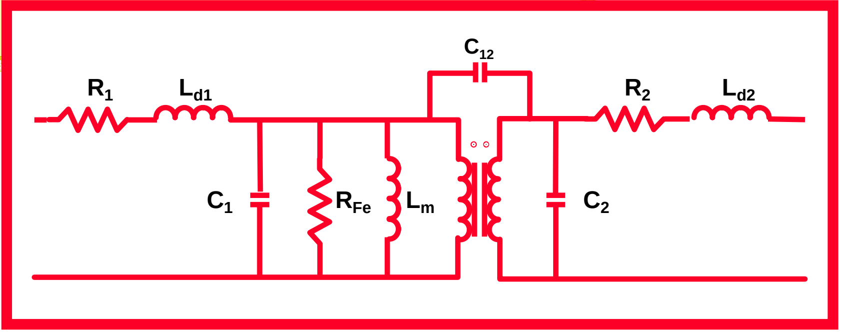
Maxwell equations → **1D problem: Analytical**
→ **2D/3D problem: FEA tool**

Non linear problem → **Windings are linear!!**

Basic concepts

CLASSICAL MODEL

- Frequency and geometry effects neglected (only for sinusoidal waveforms)
- Measurement needed to calculate parameters
- Dimensional effects neglected

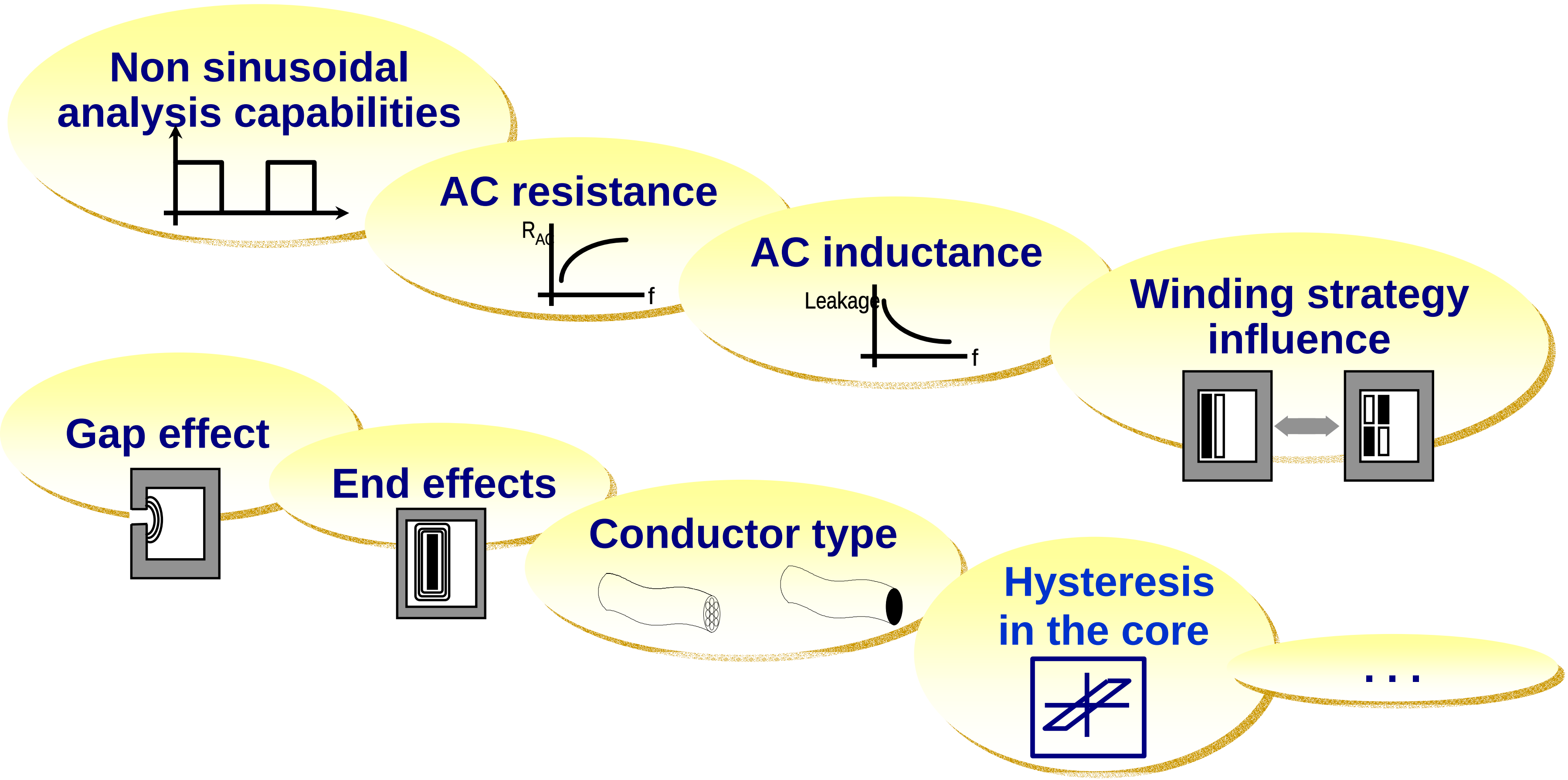


OTHER APPROACHES

- Analytical approaches in simple cases or using rough aproximations
- FEA is used do “see” the fields but no model is usually generated

Basic concepts

Main effects to be modeled

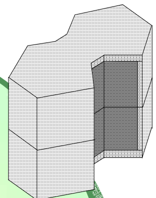


Basic concepts

Main effects to be modeled in the windings

Physical effects

Skin
Proximity
Gap effects
End effects



Produce

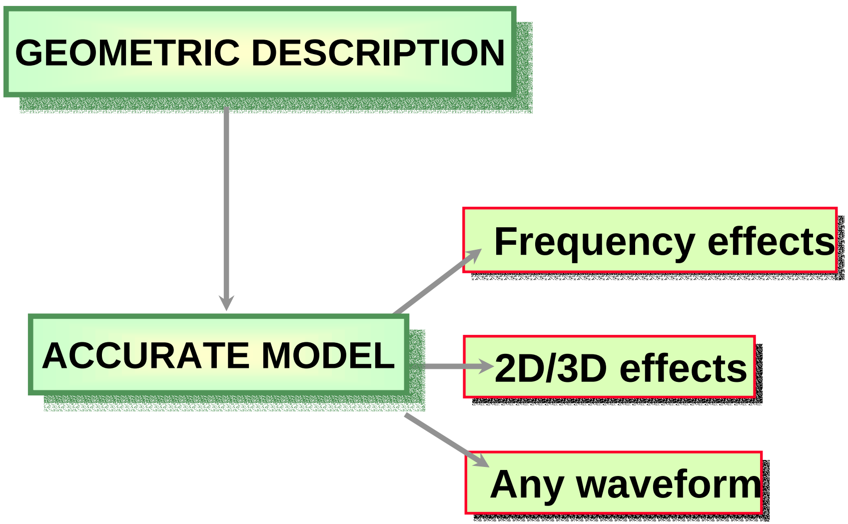
Energy storage
(electric+magnetic)
and
losses

Typically known as:

Leakage inductance
+
AC resistance
+
parasitic capacitances

Modeling Procedure

Objective

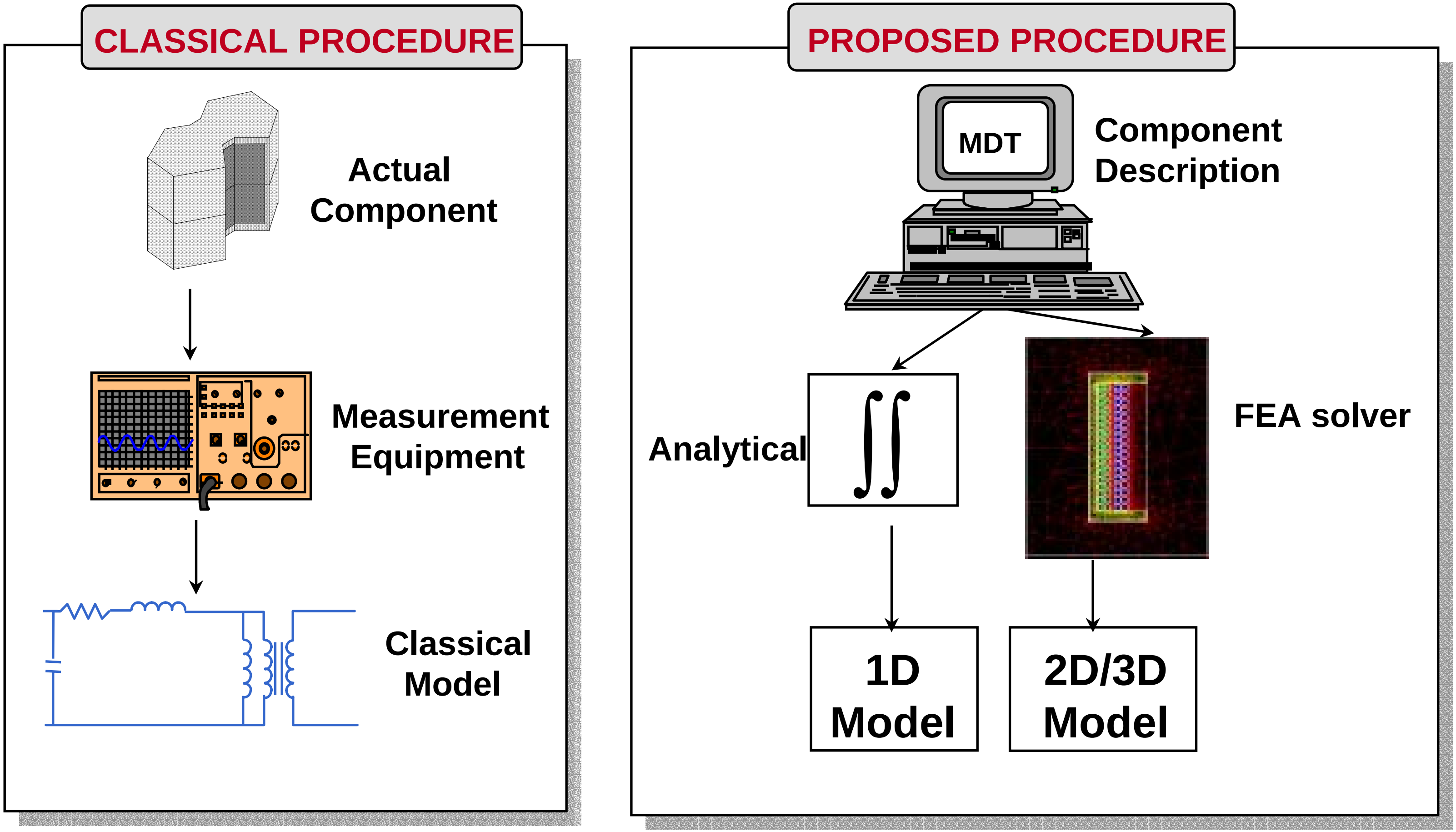


Avoid redesigns:
save time and money

Modeling strategy

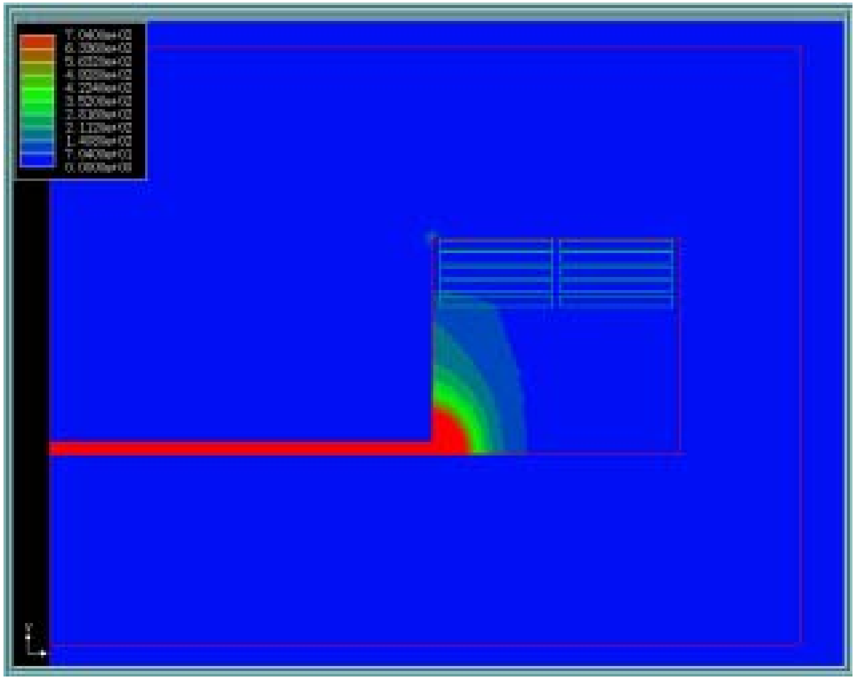
- **Use commercial models for the core**
- **Develop accurate models for the windings, using *Finite Element Analysis* (FEA) tool or analytical expressions**
- **Combine the core model and the winding model**

Modeling Procedure



- No actual magnetic component is built until expected performance is obtained
- Influence of the winding strategy can be tested

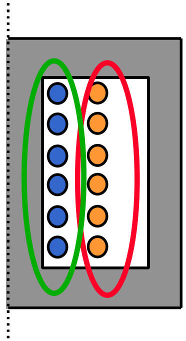
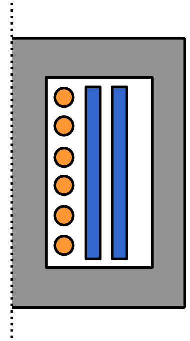
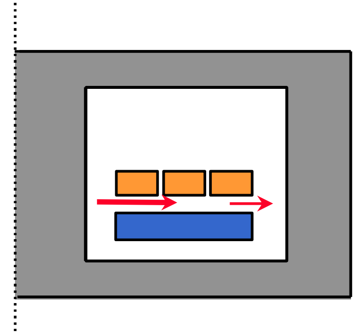
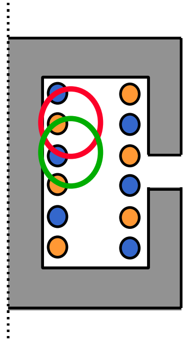
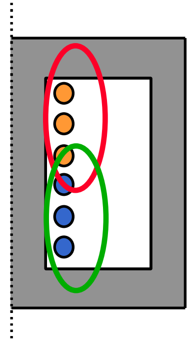
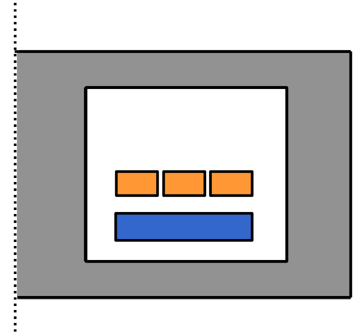
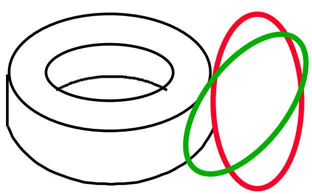
Modeling procedure



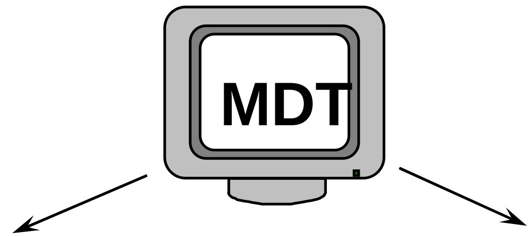
GOALS to model windings:

- **Energy and losses in the windings are the main goals**
- **Core properties that affect to windings are considered**
- **Energy in the core is also calculated**

Types of flux distribution

1D		**concentric**		**concentric**		**planar or PCB**
2D		**twisted and parallel**		**top/down**		**planar or PCB**
3D		**toroid**				

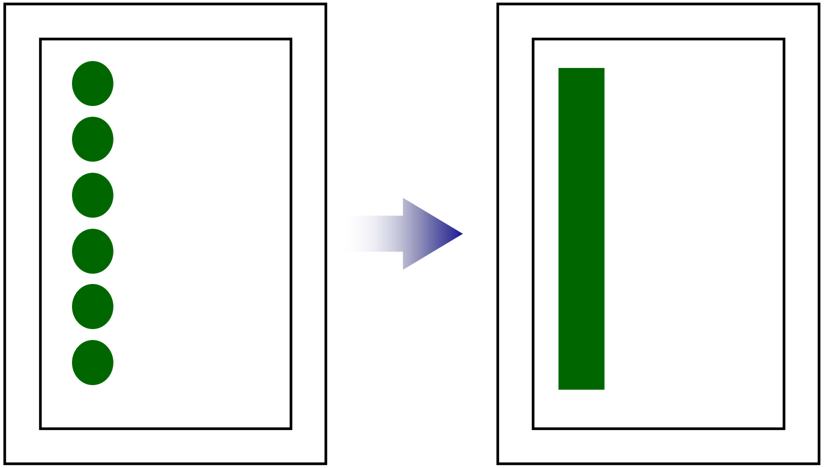
Basic features of the models



	1D MODEL	2D/3D MODEL
Flux & Field Distribution (Freq. effects)	**1D effects**	**2D/3D effects**
Geometries	**Most concentric and top-down**	**Any**
Capacitive effects	**Theoretical (interlayer)**	**FEA solver**
Generation time	**Instantaneous**	**FEA solver (2-3 hours)**

1D model features

Very useful to model 1D winding strategies



Advantages

- Fast model generation
- Easy to implement
- Frequency effects are taken into account

Disadvantages

- 2D effects neglected (gap, end...)
- Only valid in 1D winding strategies

1D model description

Maxwell equations (1D)

$$\frac{\partial E}{\partial x} = \mu_0 \frac{\partial H}{\partial t}$$

$$\frac{\partial H}{\partial x} = \sigma E z + \varepsilon \frac{\partial E}{\partial t}$$

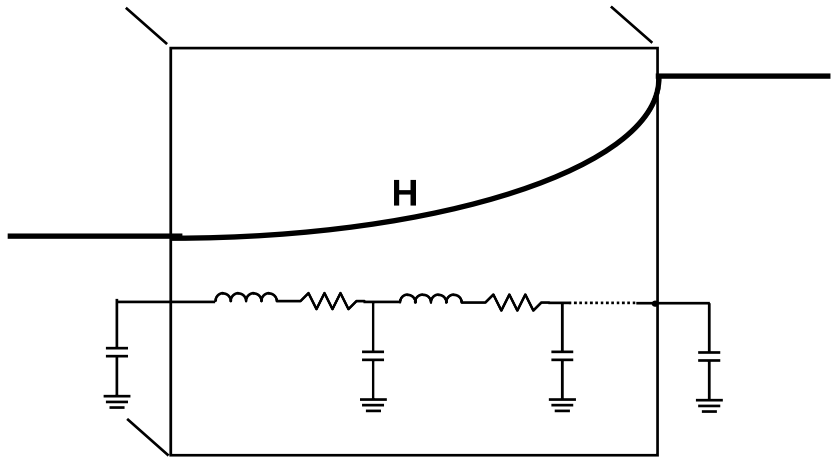
Transmission line equations

$$\frac{\partial i}{\partial x} = c \frac{\partial u}{\partial t}$$

$$\frac{\partial v}{\partial x} = R \cdot i + L \frac{\partial i}{\partial t}$$

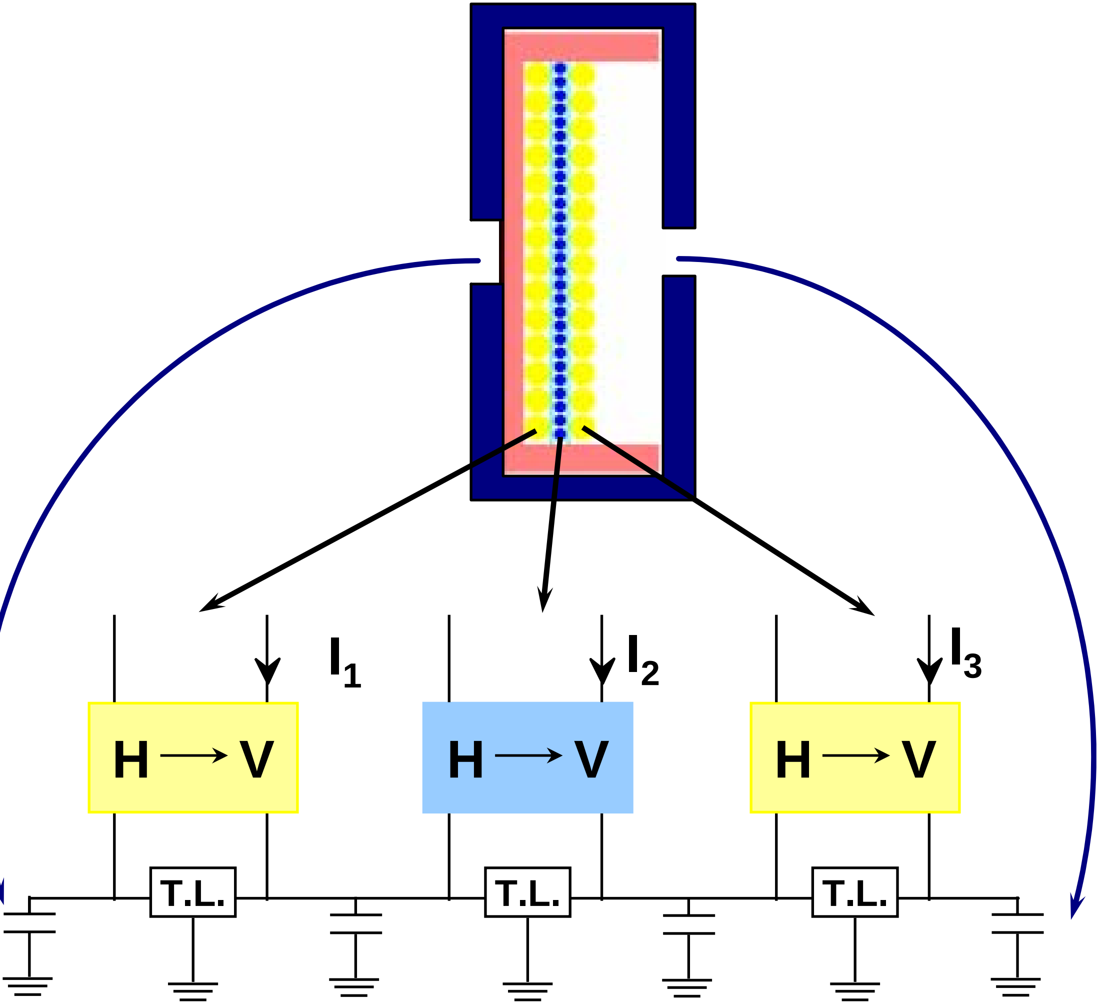
$$H = v; \quad E = \frac{i}{lb}$$

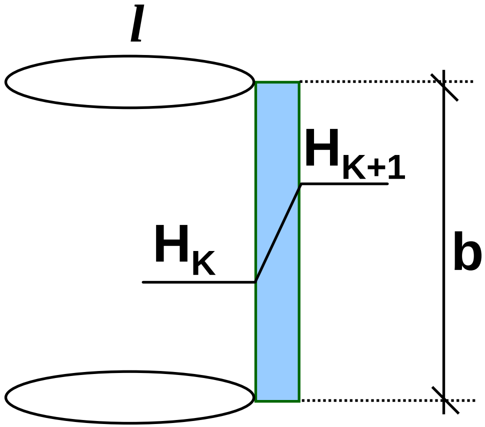
$$c = \mu_0 \cdot l \cdot b; \quad L = \frac{\varepsilon}{lb}; \quad R = \frac{\sigma}{lb}$$



Based on the analogy between transmission line and Maxwell equations for 1D

1D model description





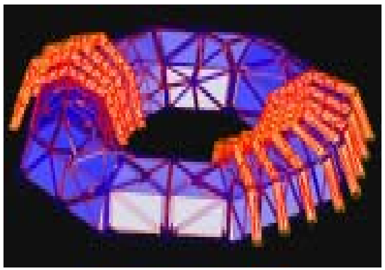
$$\oint H dl = ni$$

$$H_{K+1} - H_k = \frac{ni}{b}$$

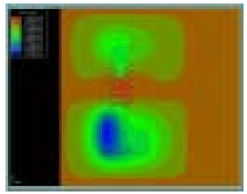
$$H \rightarrow V$$

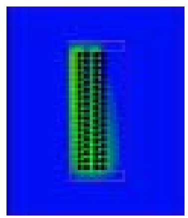
Magnetic Components Modeling (2D/3D model)

- Use FEA to compute the magnetic and electric behavior

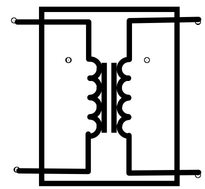


FEA tool
2D or 3D

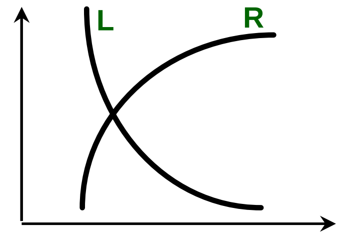




Magnetic and electric energies



Magnetic component model



Frequency behavior quantification

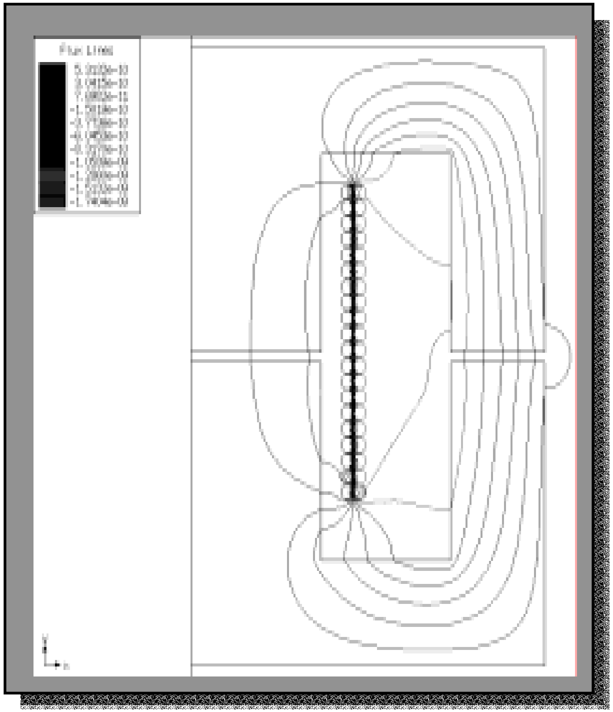
Frequency and geometry effects *in the windings* are taken into account

Magnetic Components Modeling (2D/3D model)

Why FEA?

- **Geometry and frequency effects**
  - Gap effect
  - End effect
  - Skin effect
  - Proximity effect

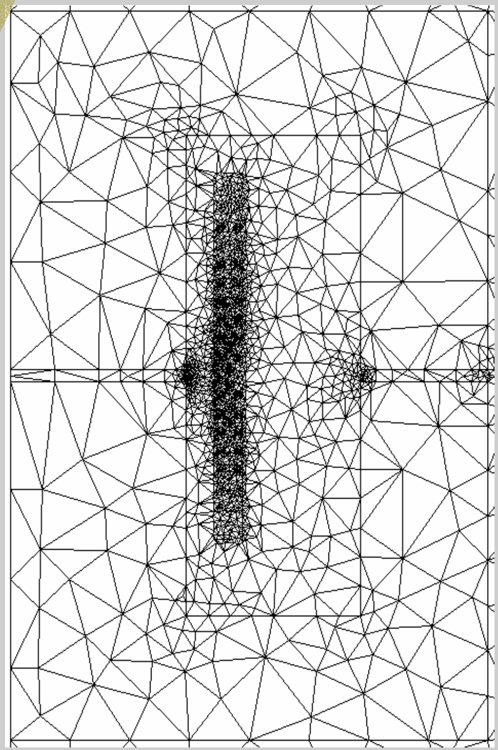
✓ **3D Effects**
  - Effect of the connections
  - Toroids

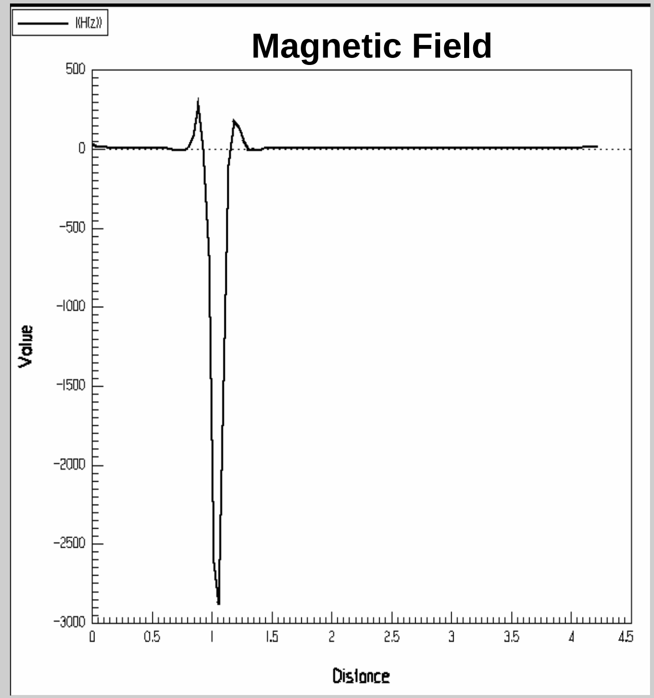


Dimensional effects for any structure are only taken into account by FEA

Finite Element Analysis (FEA) Solver

Additional advantages of FEA

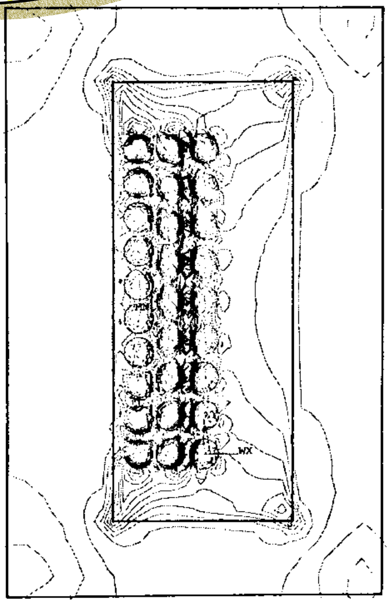


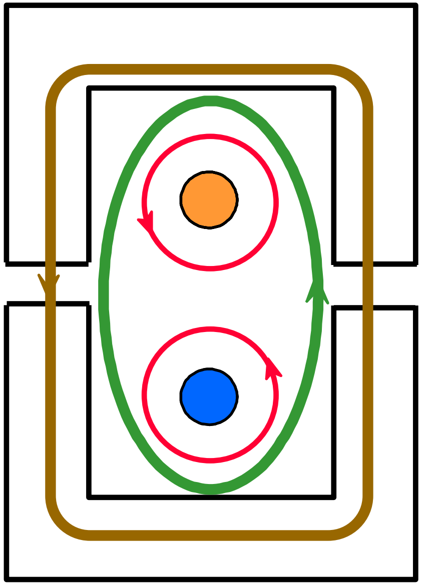


Insight in any physical quantity

Magnetic Components Modeling (2D/3D model)

How from FEA to the model?



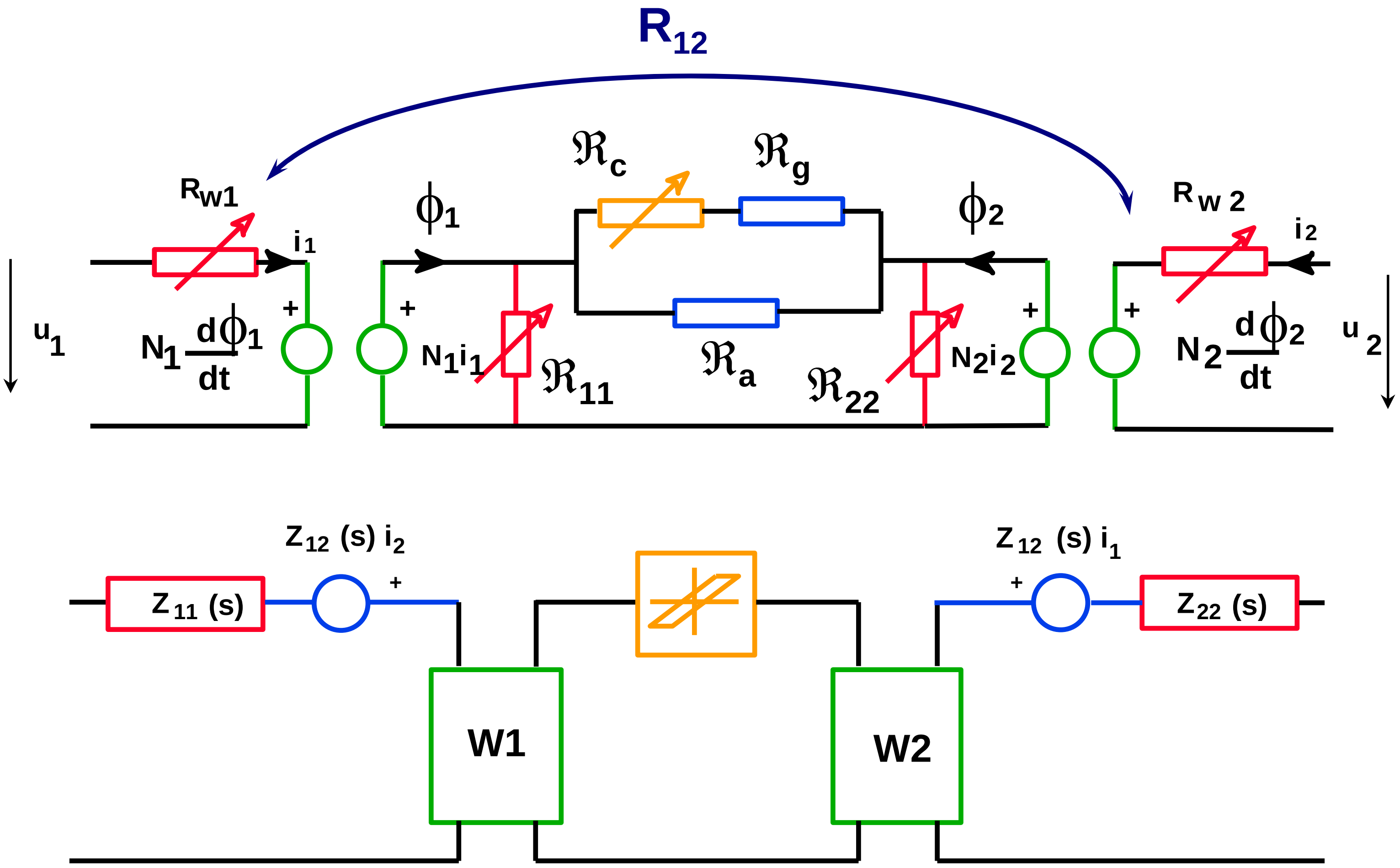


Energy tests (frequency sweep)

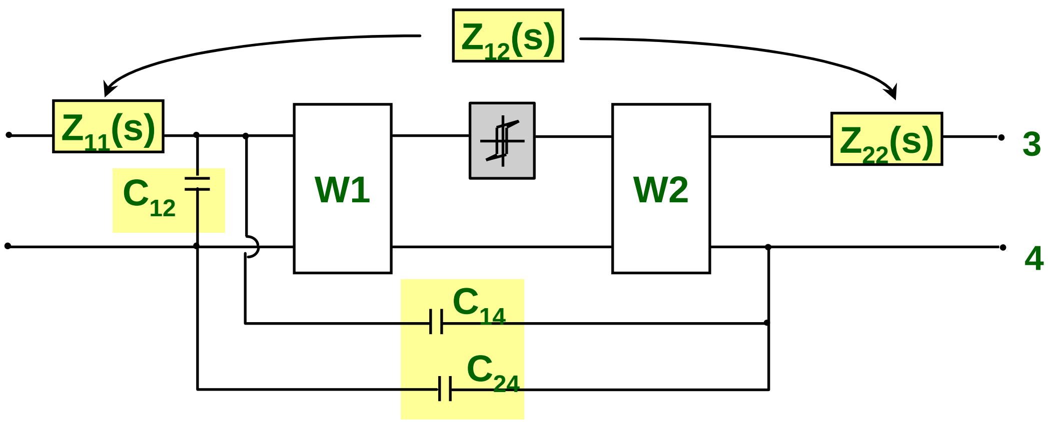
- Energy in the core
  - **Mainly common energy**
- Energy in the air
  - **Common energy**
  - **Self energy**
- Energy in the windings
- Losses in each winding
  - **Self losses**
  - **"Coupled" losses**

Magnetic Components Modeling (2D/3D model)

PRELIMINARY APPROACH



Magnetic Components Modeling (2D/3D model)



- ➢ Z_{11}, Z_{22}:
  - ✓ losses and energy due to I_1 OR I_2 INDEPENDENTLY
- ➢ Z_{12}:
  - ✓ losses and energy due to I_1 AND I_2 SIMULTANEOUSLY

UPM windings

- ➢ Geometry and frequency effects taken into account
- ➢ Distributed model
  - ✓ **Coupled inductors**
  - ✓ **Multiwinding transformers**

Commercial core model

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

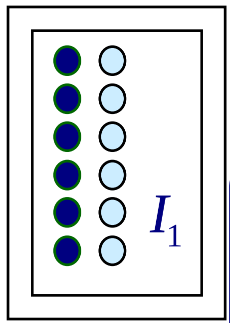
$$R(\omega) = c_o + \sum_{i=1}^{NPF} \frac{c_{2i}\omega^2}{\omega^2 + c_{2i-1}^2}$$

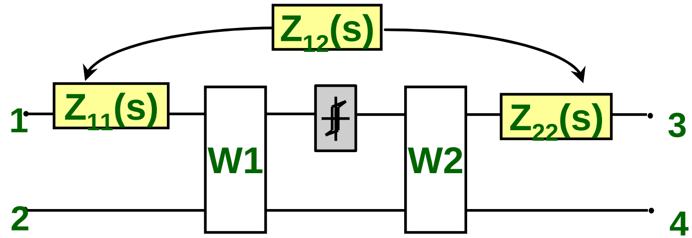
$$X(\omega) = \omega L(\omega) = \left[c_1 + \sum_{i=1}^{NPF} \frac{c_{2i}\omega^2}{\omega^2 + c_{2i-1}^2} \right]$$

Winding modeling using FEA

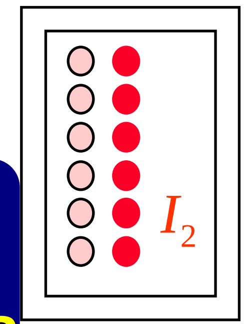
TEST 1

$\vec{J}_1$





TEST 2



$\vec{J}_2$

LINEAR PROBLEM!!
Superposition theorem applies for CURRENT, but not for LOSSES

FEA losses

$$P = \iiint \frac{1}{\sigma} \vec{J} \bullet \vec{J}^{\,*} dv =$$

$$= \iiint \frac{1}{\sigma} (\vec{J}_1 + \vec{J}_2) \bullet (\vec{J}_1^{\,*} + \vec{J}_2^{\,*})\, dv$$

$$\begin{cases} = \iiint \frac{1}{\sigma} \vec{J}_1 \bullet \vec{J}_1^{\,*}\, dv \\ + \iiint \frac{1}{\sigma} \vec{J}_2 \bullet \vec{J}_2^{\,*}\, dv \\ + \iiint \frac{1}{\sigma} (\vec{J}_1 \bullet \vec{J}_2^{\,*} + \vec{J}_2 \bullet \vec{J}_1^{\,*})\, dv \end{cases}$$

Model losses

$$P = R_1 I_1^2 + R_2 I_2^2 + 2 R_{12} I_1 I_2$$

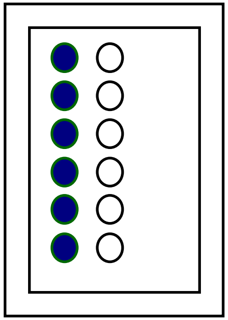
$$\begin{cases} R_1 I_1^2 \\ R_2 I_2^2 \\ 2 R_{12} I_1 I_2 \end{cases}$$

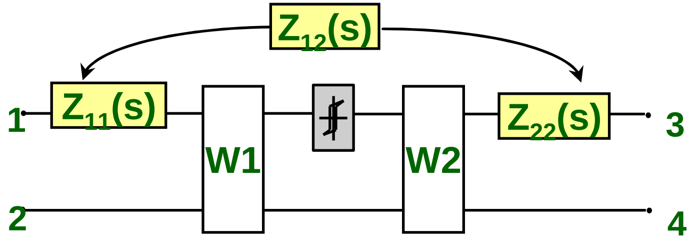
Winding modeling using FEA

$\vec{B}_1$

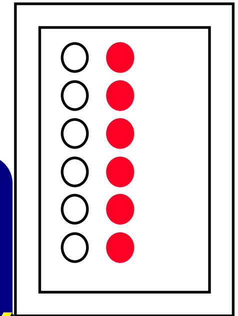
$\vec{H}_1$

TEST 1





TEST 2



$\vec{B}_2$

$\vec{H}_2$

LINEAR PROBLEM!!
Superposition theorem applies for CURRENT, but not for ENERGY

FEA magnetic energy

$$E = \frac{1}{2}\iiint \vec{B}\bullet\vec{H}^*\,dv$$

$$= \frac{1}{2}\iiint (\vec{B}_1+\vec{B}_2)\bullet(\vec{H}_1^*+\vec{H}_2^*)\,dv$$

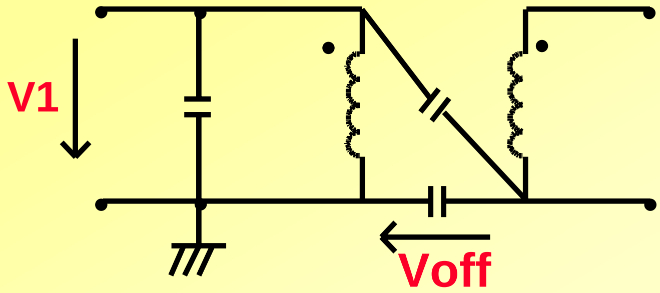
$$\begin{cases} = \dfrac{1}{2}\iiint \vec{B}_1\bullet\vec{H}_1^*\,dv \\ + \dfrac{1}{2}\iiint \vec{B}_2\bullet\vec{H}_2^*\,dv \\ + \dfrac{1}{2}\iiint (\vec{B}_1\bullet\vec{H}_2^* + \vec{B}_2\bullet\vec{H}_1^*)\,dv \end{cases}$$

Model magnetic energy

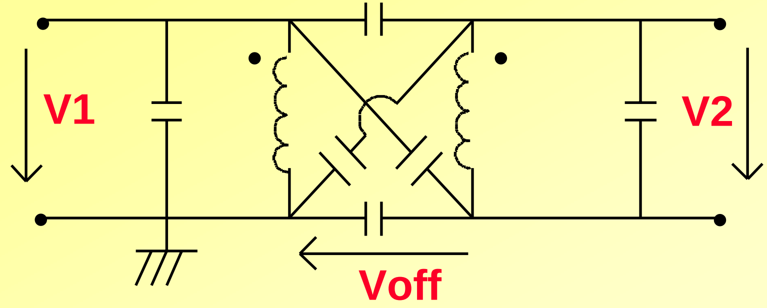
$$E = \frac{1}{2}L_1 I_1^2 + \frac{1}{2}L_2 I_2^2 + L_{12} I_1\, I_2$$

$$\begin{cases} = \dfrac{1}{2}L_1 I_1^2 \\ + \dfrac{1}{2}L_2 I_2^2 \\ + L_{12} I_1\, I_2 \end{cases}$$

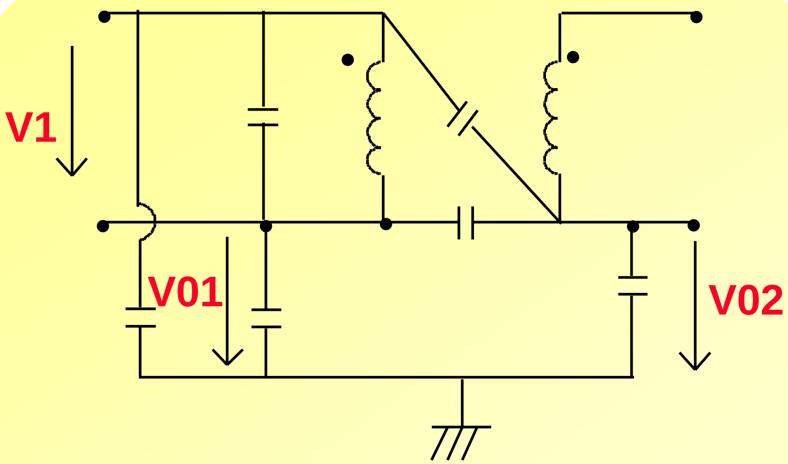
Proposed capacitive models
(two winding transformer)



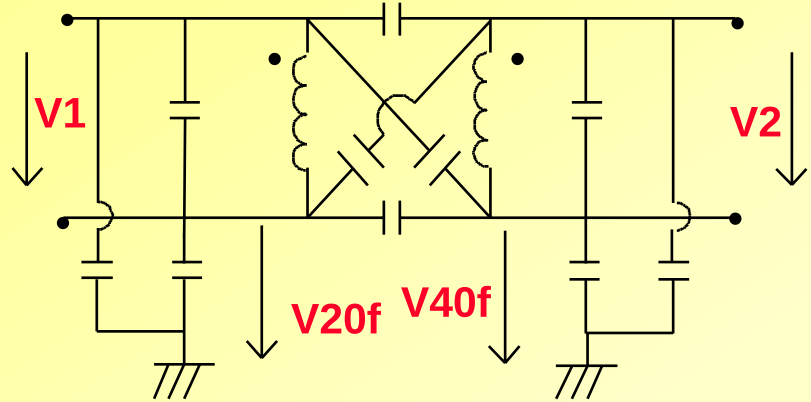
LEVEL 1



LEVEL 2

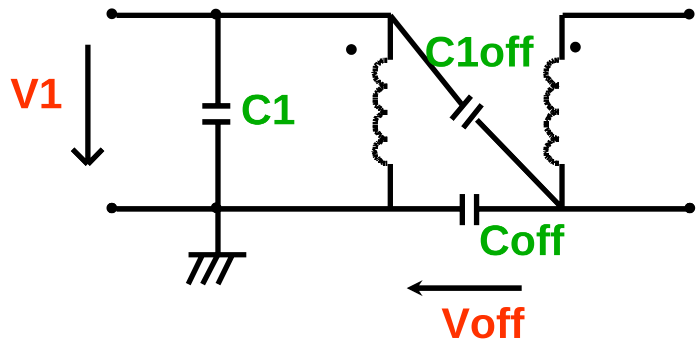


LEVEL 3



LEVEL 4

Level 1 Model. Two winding transformer



FEA Electric Energy

$$I=\frac{1}{2}\iiint_v \vec{D}\vec{E}d\,v=\frac{1}{2}\iiint_v(\vec{D}_1+\vec{D}_{off})(\vec{E}_{off}+\vec{E}_1)\,d\,v=$$

$$=\frac{1}{2}\iiint_v \vec{D}_1\vec{E}_1\,d\,v+$$

$$+\frac{1}{2}\iiint_v \vec{D}_{off}\vec{E}_{off}d\,v+$$

$$+\frac{1}{2}\iiint_v(\vec{D}_1\vec{E}_{off}+\vec{D}_{off}\vec{E}_1)\,d\,v$$

$$=I_1+I_{off}+I_{1off}$$

Model Electric Energy

$$I=\frac{1}{2}C_1V_1^2+\frac{1}{2}C_{off}V_{off}^2+\frac{1}{2}(V_1-V_{off})^2C_{1off}=$$

$$=\frac{1}{2}(C_1+C_{1off})V_1^2+$$

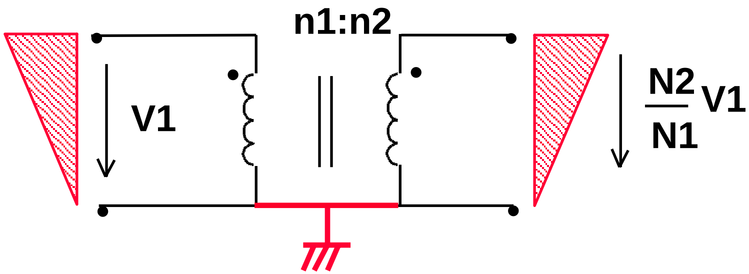
$$+\frac{1}{2}(C_{off}+C_{1off})V_{off}^2-$$

$$-C_{1off}V_1V_{off}=$$

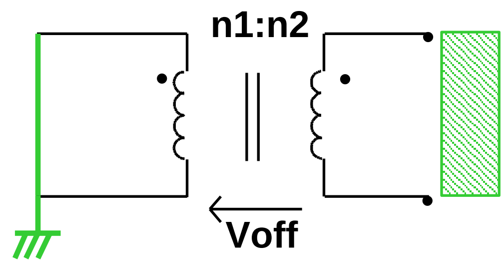
$$=I_1+I_{off}+I_{1off}$$

Finite Element Analysis Procedure for Capacitive Effects

ANALYSIS 1



ANALYSIS 2



ENERGY CALCULATION

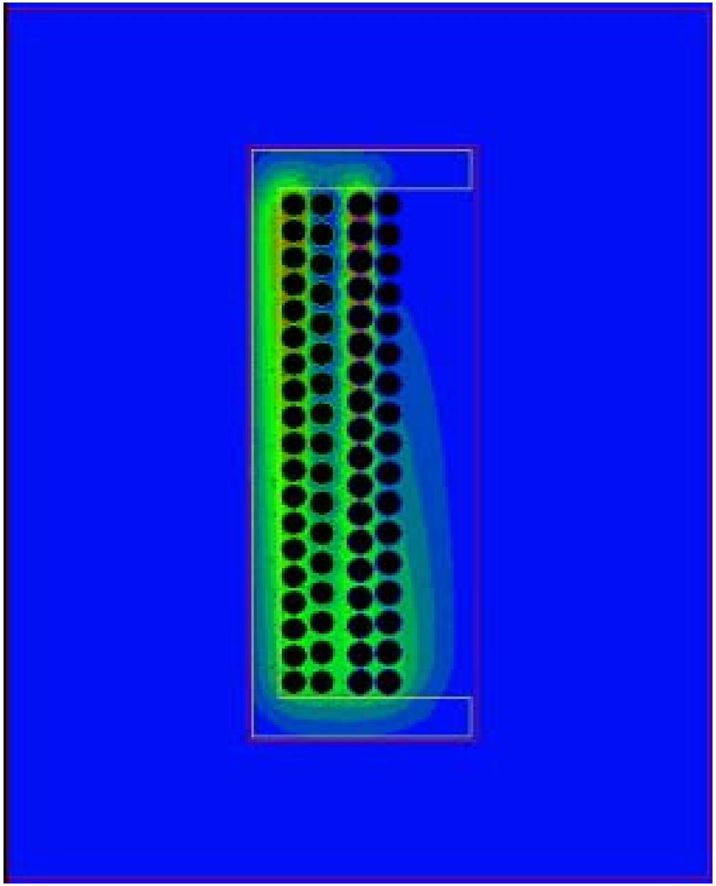
$$I_1 = \frac{1}{2}\iiint_v \vec{D}_1\vec{E}_1 \, dv$$

$$I_{off} = \frac{1}{2}\iiint_v \vec{D}_{off}\vec{E}_{off} \, dv$$

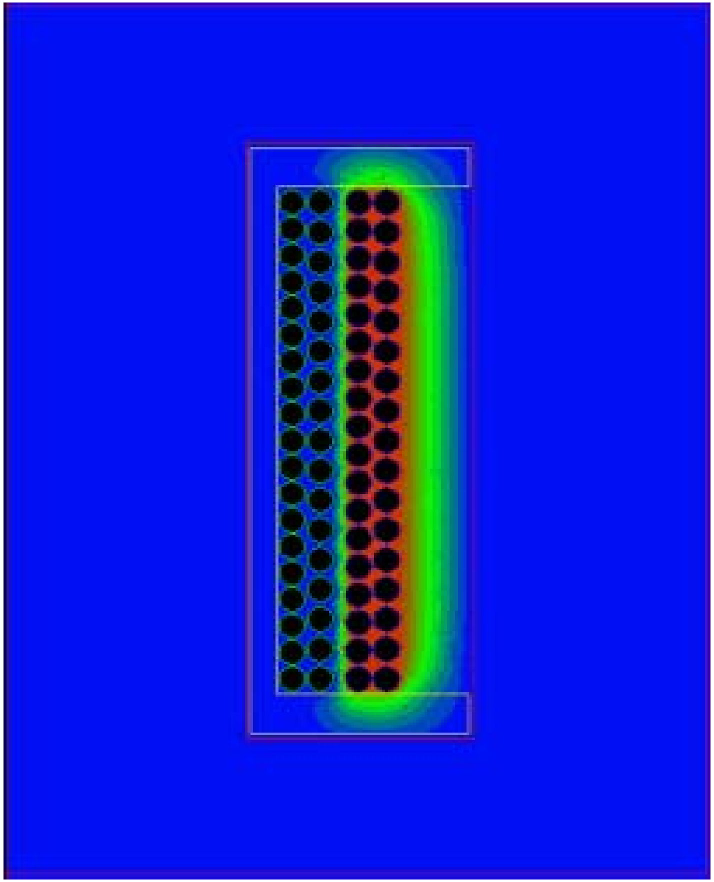
$$I_{1off} = \iiint_v (\vec{D}_1\vec{E}_{off} + \vec{D}_{off}\vec{E}_1) \, dv$$

Finite Element Analysis Procedure for Capacitive Effects

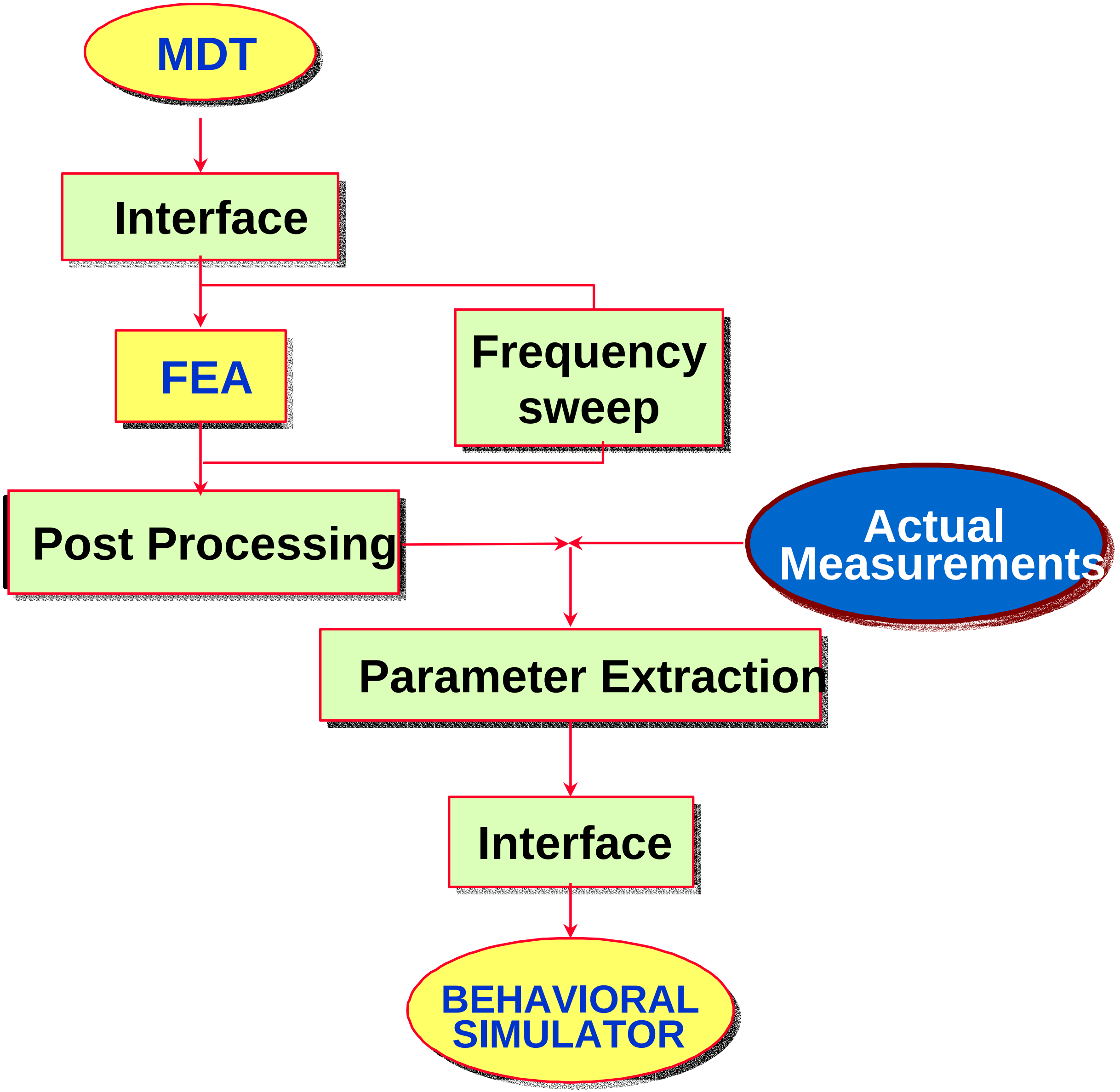
ANALYSIS 1



ANALYSIS 2

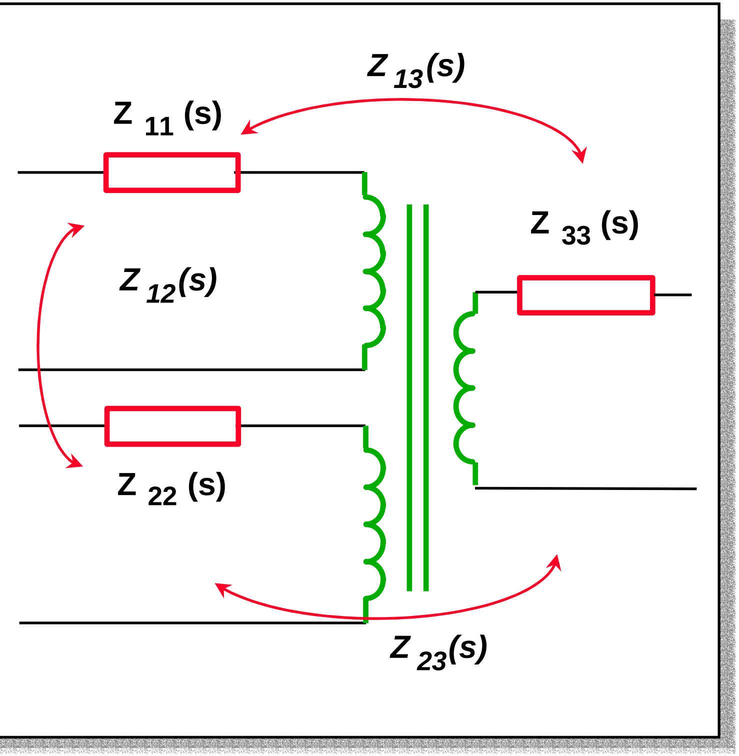


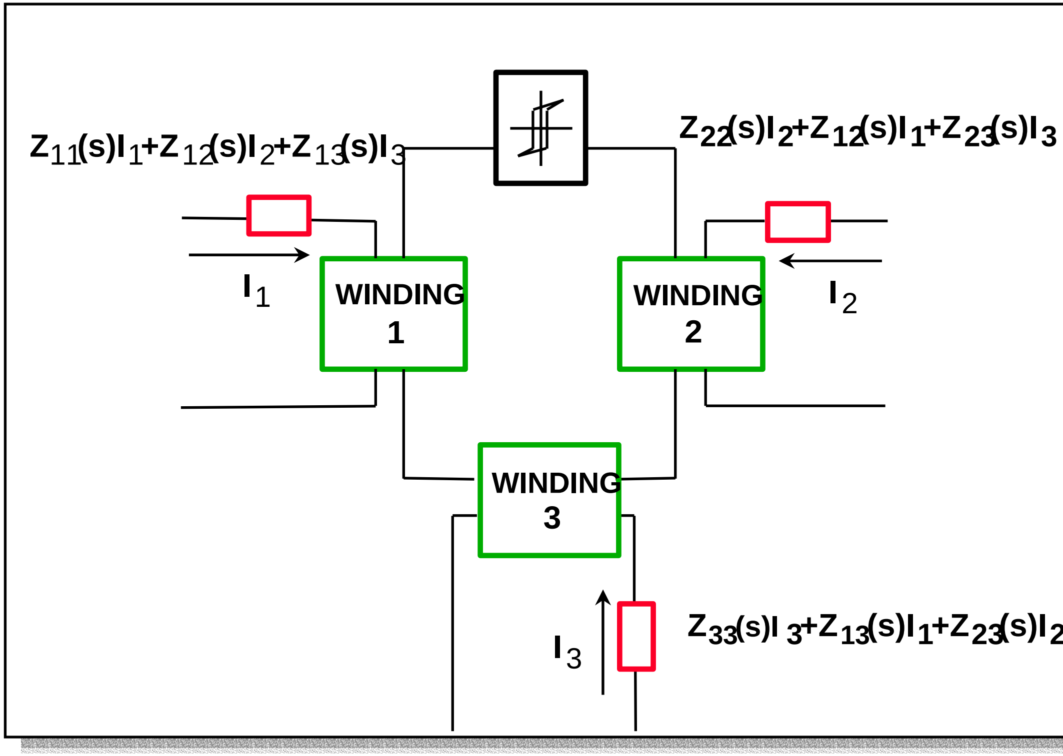
Magnetic Components Modeling (2D/3D model)



Magnetic Components Modeling (2D/3D model)

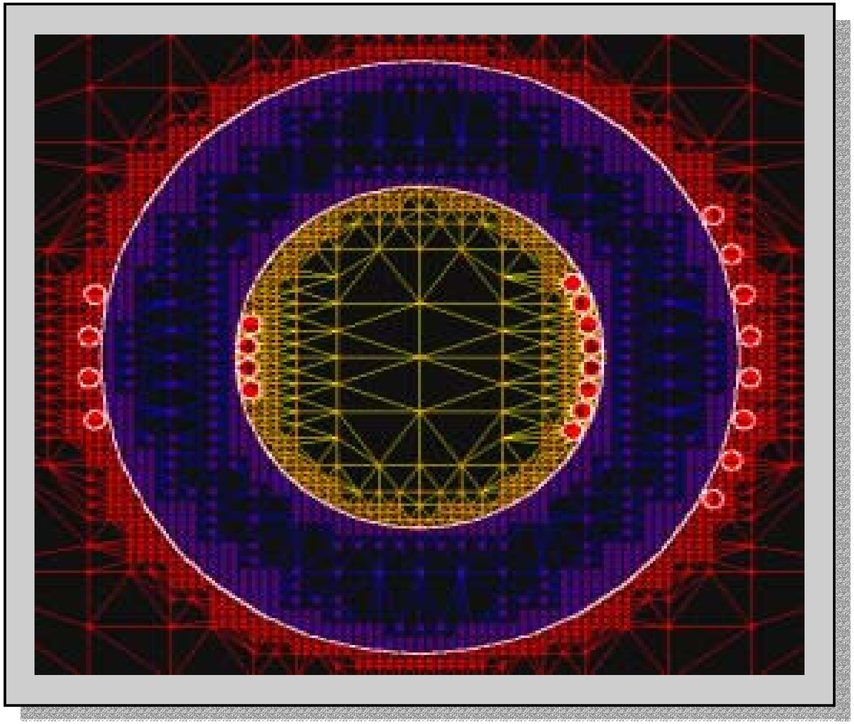
Behavioral model developed for ***multi-winding*** magnetic components

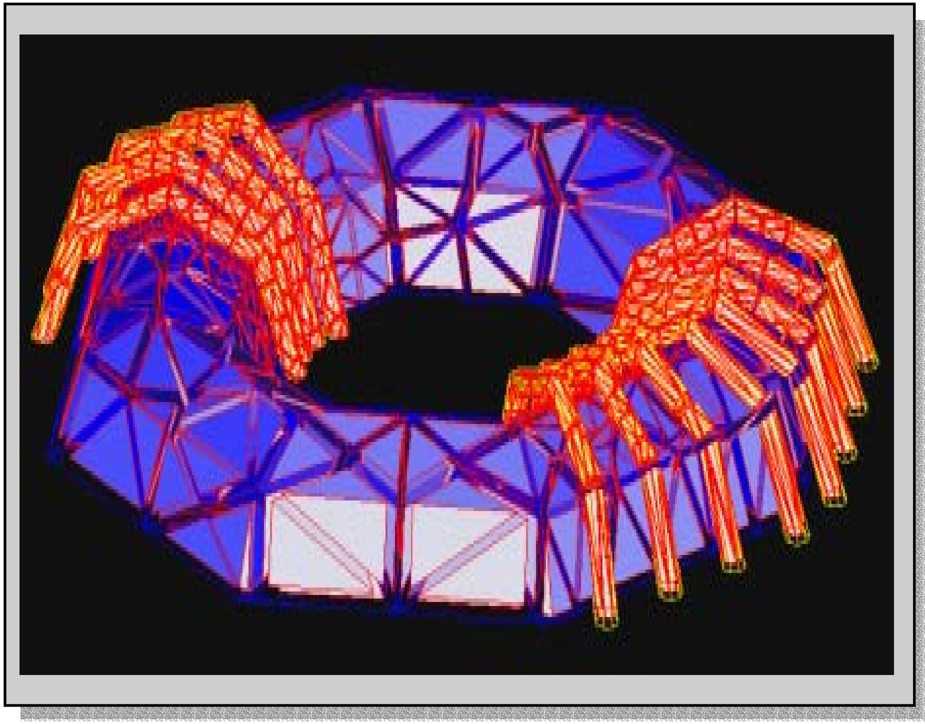




Magnetic Components Modeling (2D/3D model)

Procedure established for 2D and 3D simulations



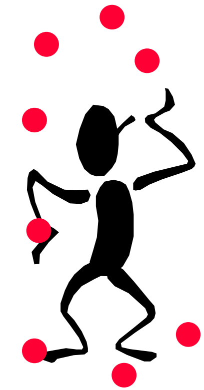


Official Outline

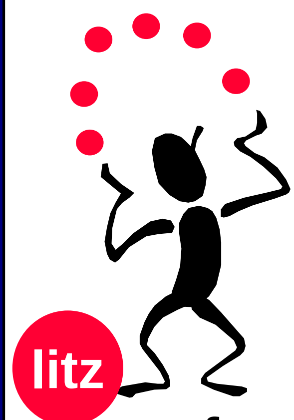
Mr. Designer Outline

- Basic concepts
- High frequency effects
- **Modeling**
- Advanced design
- Application to converters

Mr Designer at UPM lab

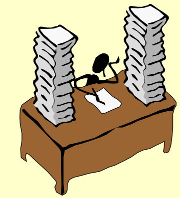


before...



...after

Mr Designer **learns to design**



Mr Designer **has a problem**

Mr Designer **finds a solution**

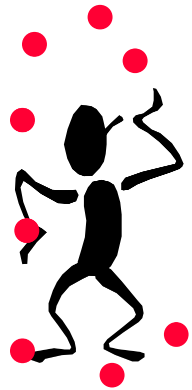
Mr Designer **can use it !**

Mr Designer **succeeds !!**

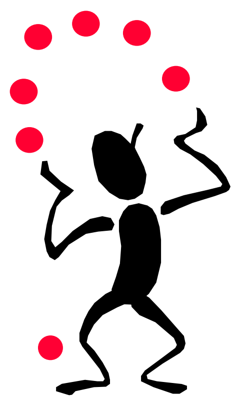
Official Outline

- Basic concepts
- High frequency effects
- Modeling
- Advanced design
- Application to converters

Mr Designer at UPM lab



before...



...after

Mr. Designer Outline

Mr Designer learns to design

Mr Designer has a problem

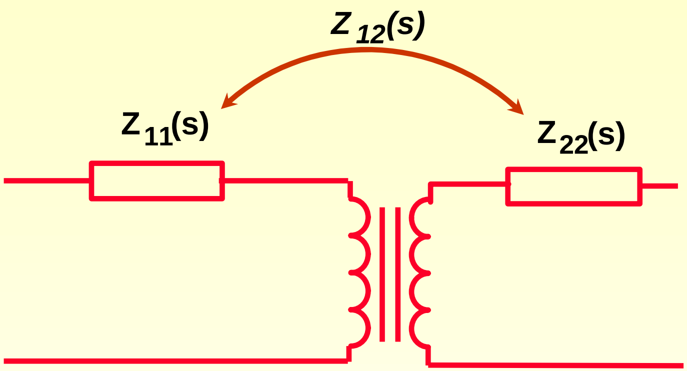
Mr Designer finds a solution

Mr Designer can use it !

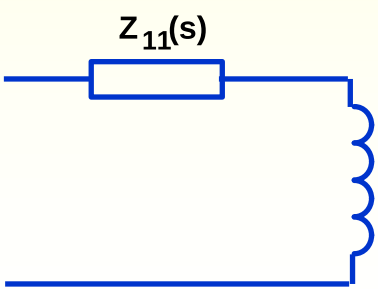
Mr Designer succeeds !!

Test strategy

Magnetic Components

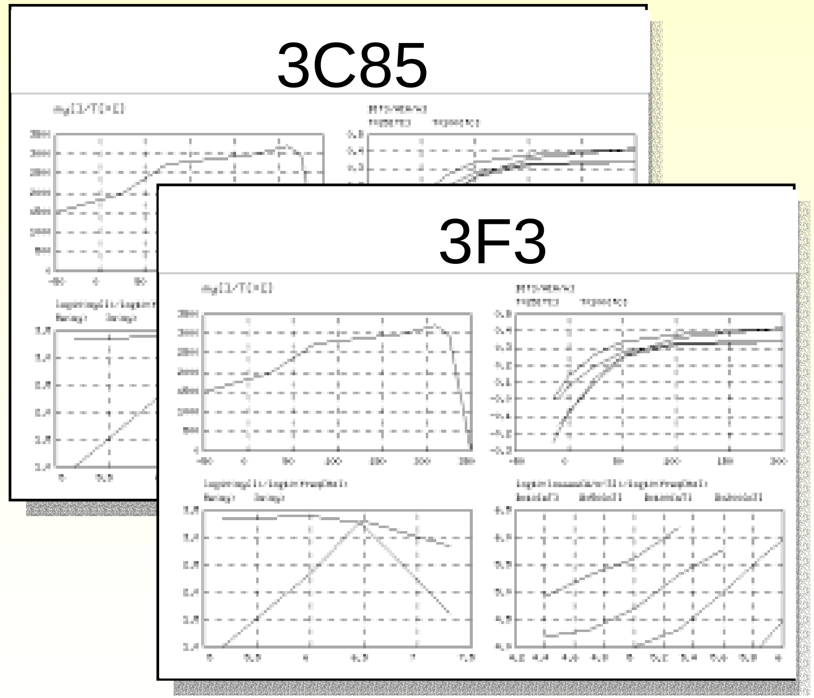


Transformers

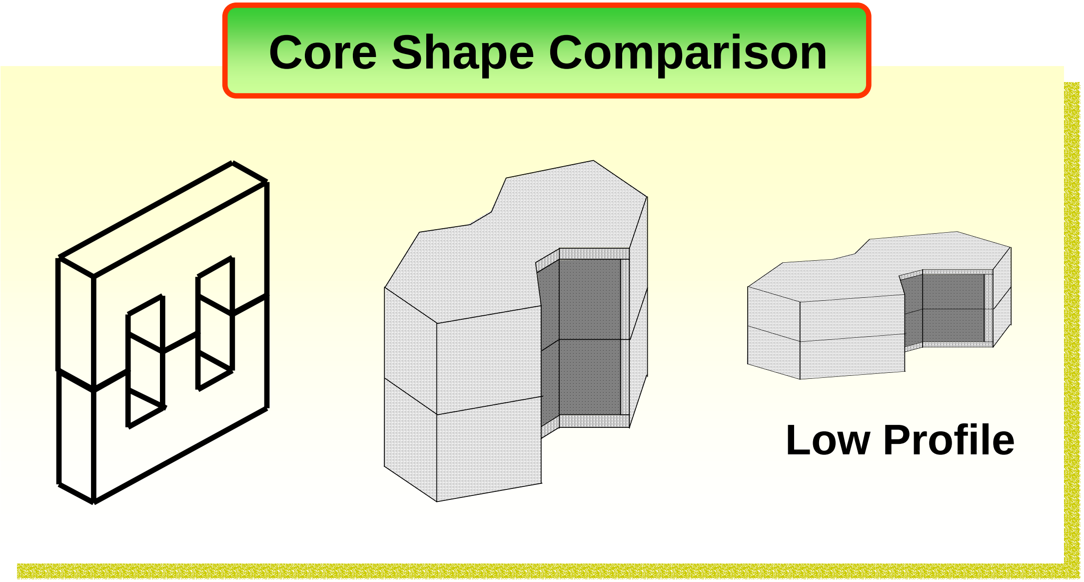


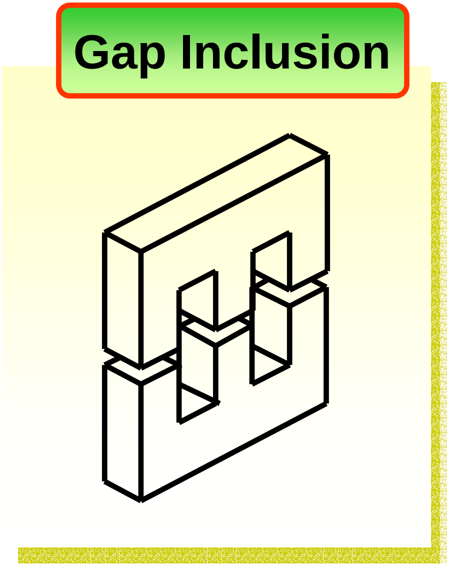
Inductors

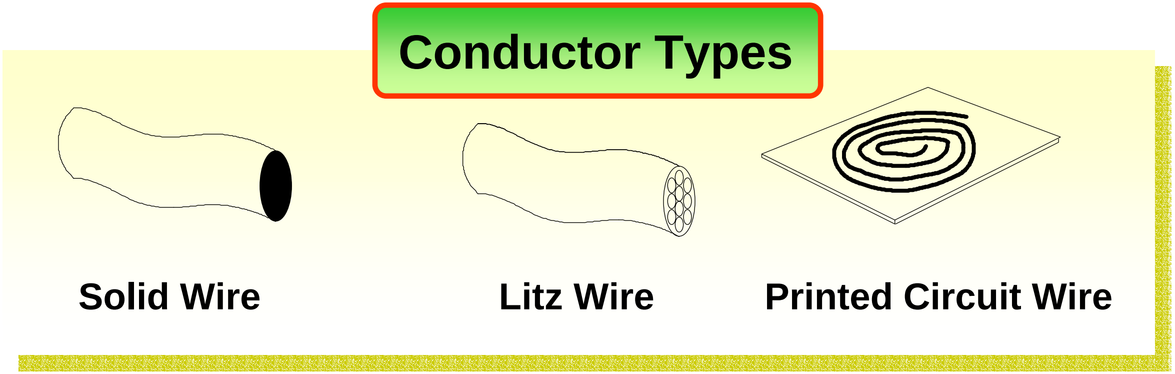
Materials



Test strategy







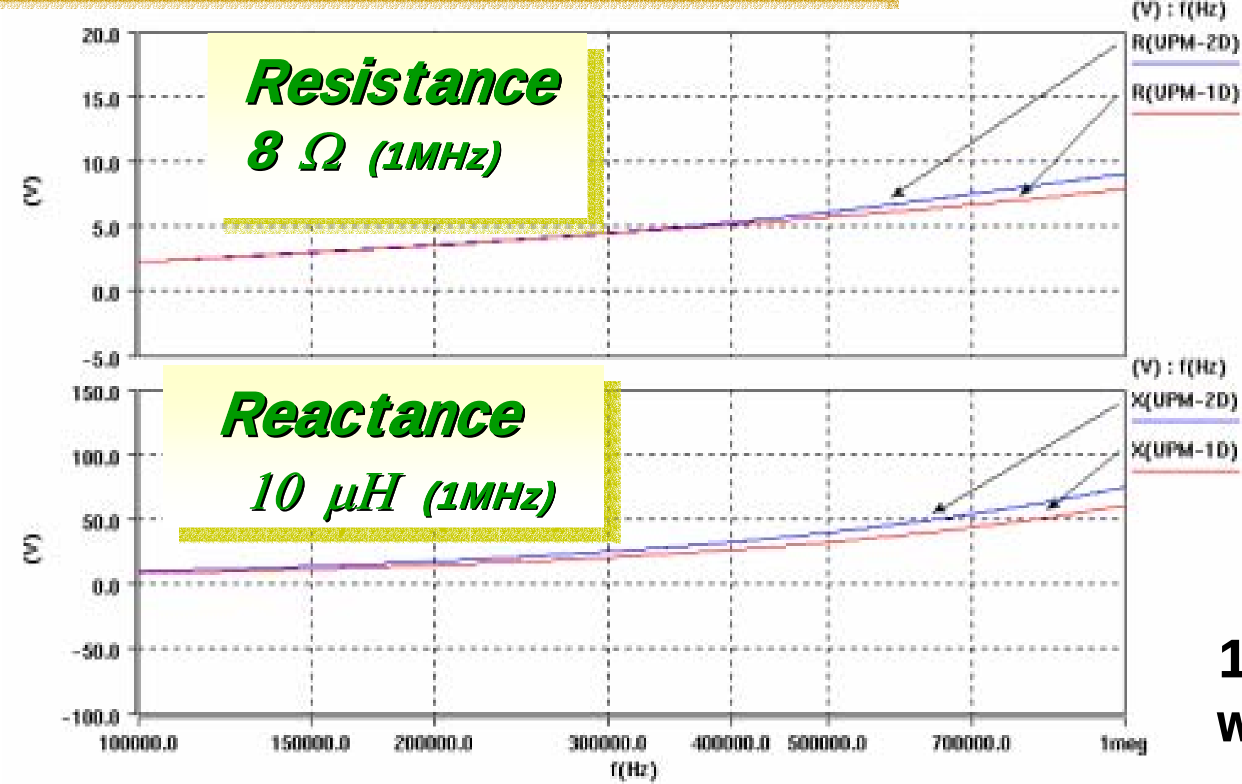
Experimental results

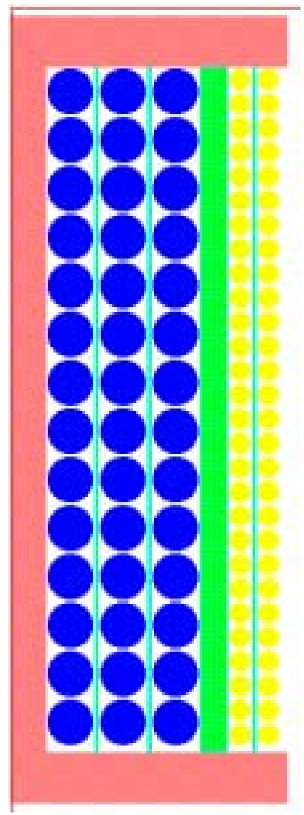
TRANSFORMER STUDIED

Geometric parameters

Core shape and size:................................ RM14
Core material:.. 3F3
Conductors:....... Solid, 1mm and 0.5mm diameter
Windings:............. Two in five layers (P:P:P:S:S)
Turns:.................... Primary: 42; Secondary: 56

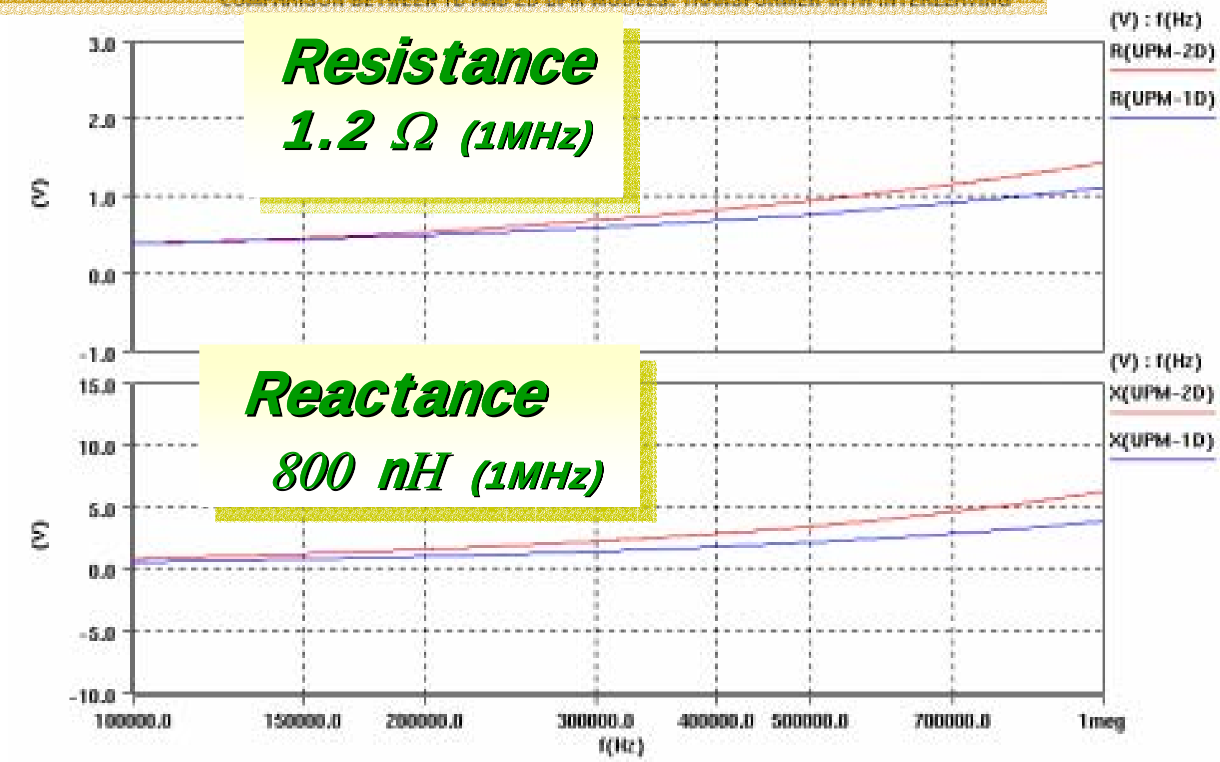
Short circuit test





1D transformer without interleaving

Experimental results

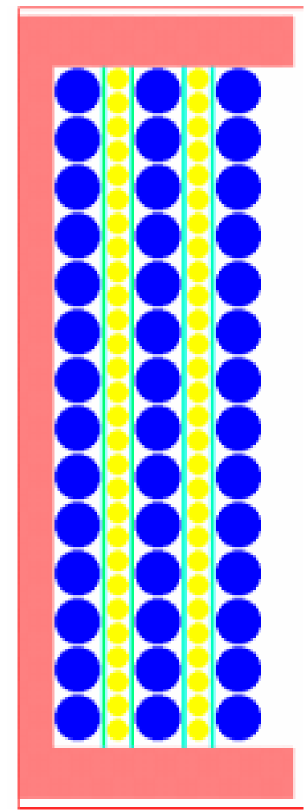


TRANSFORMER STUDIED

Geometric parameters

Core shape and size:................................ RM14
Core material:.. 3F3
Conductors:....... Solid, 1mm and 0.5mm diameter
Windings:.............. Two in five layers (P:S:P:S:P)
Turns:...................... Primary: 42; Secondary: 56

Short circuit test



1D transformer with interleaving

Experimental results

TRANSFORMER STUDIED

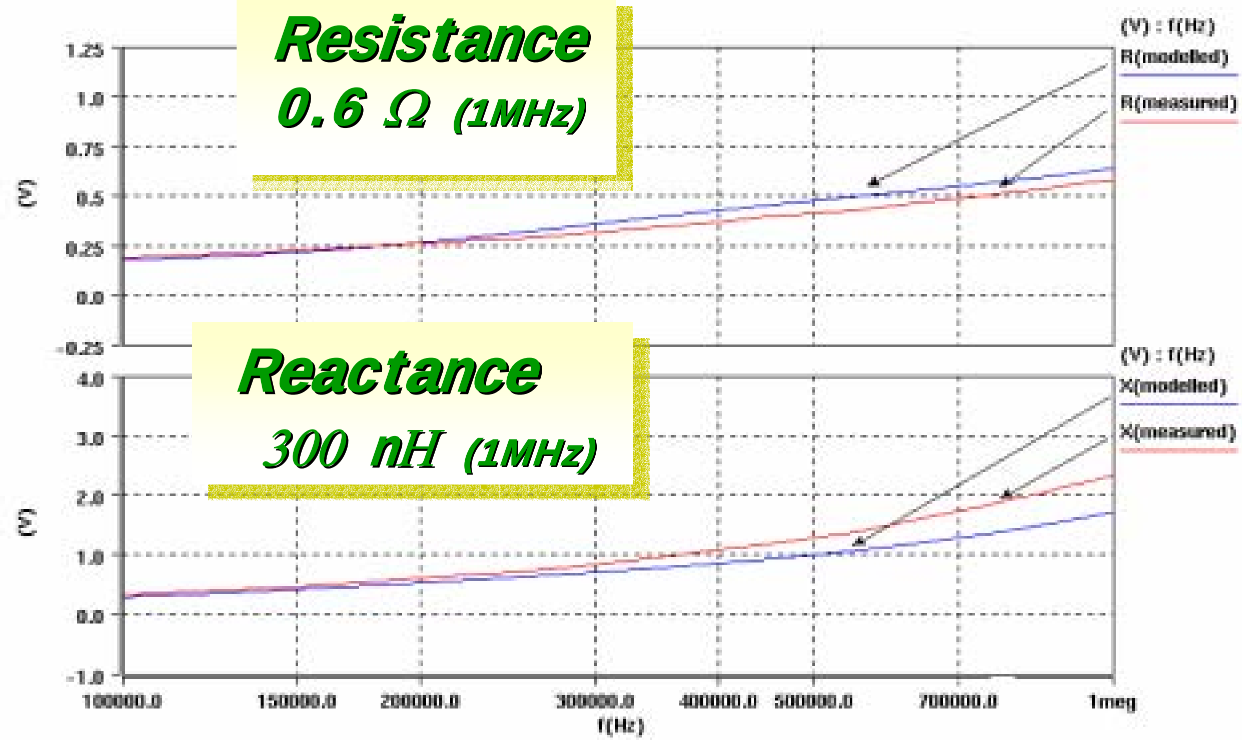
Geometric parameters

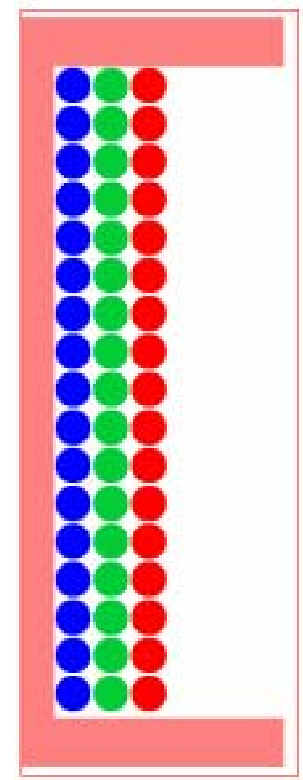
Core shape and size:.............................. RM12
Core material:....................................... 3F3
Conductors:............. Solid, 0.75mm diameter
Windings:........... Three in three layers (P:S:T)
Turns:.............. Primary: 17; Secondary: 17
Terciary: 17

Short circuit test

Resistance
0.6 Ω (1MHz)

Reactance
300 nH (1MHz)





1D transformer

Experimental results

TRANSFORMER STUDIED

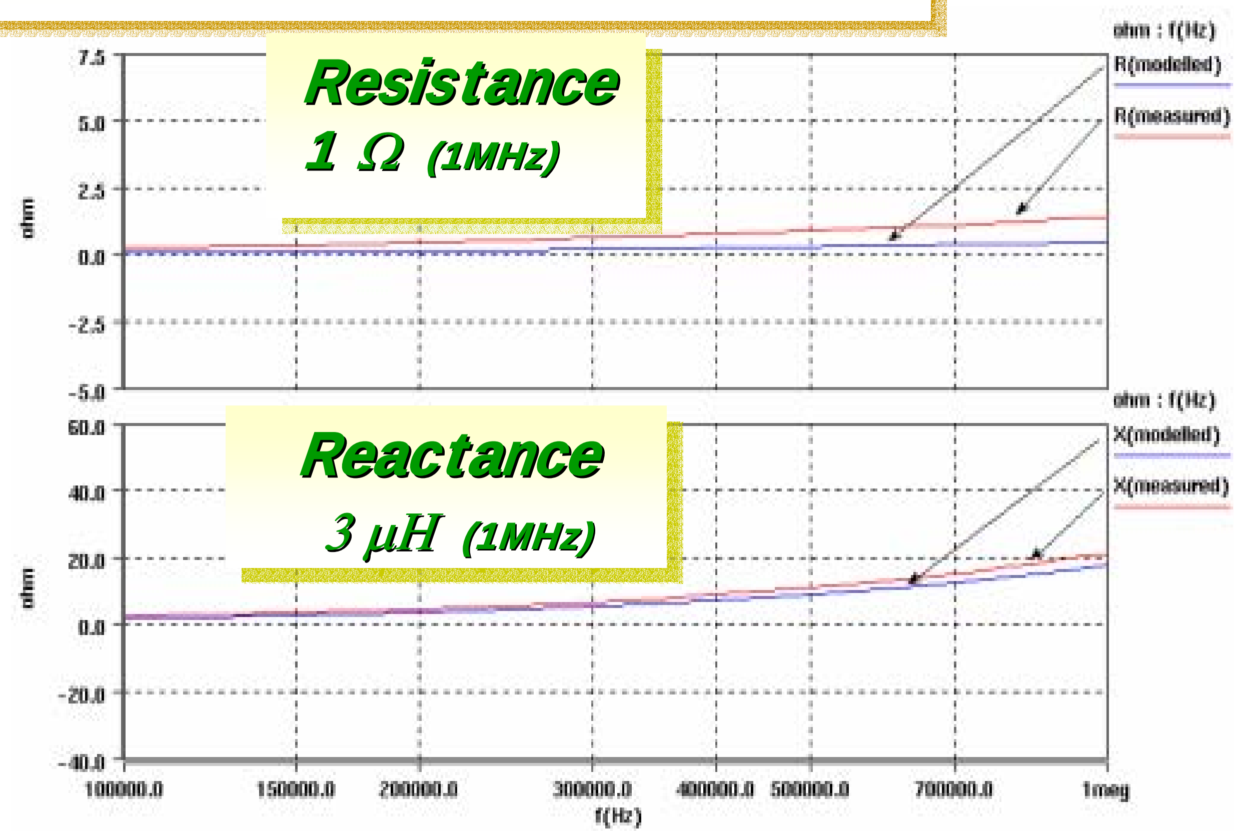
Geometric parameters

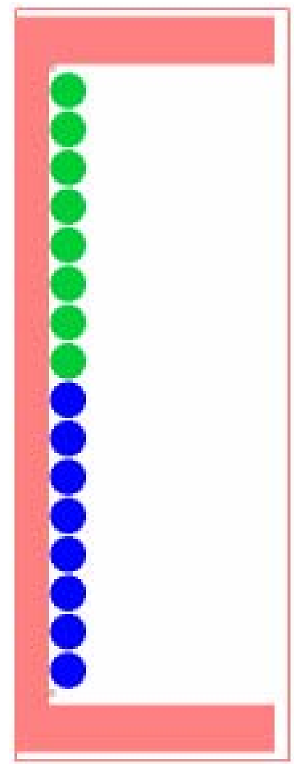
Core shape and size:............................ RM12
Core material:....................................... 3F3
Conductors:................ Solid, 0.7mm diameter
Windings:.................. Two in one layers (P:S)
Turns:.................. Primary: 8; Secondary: 8

Short circuit test

Resistance
1 Ω (1MHz)

Reactance
3 μH (1MHz)





2D transformer

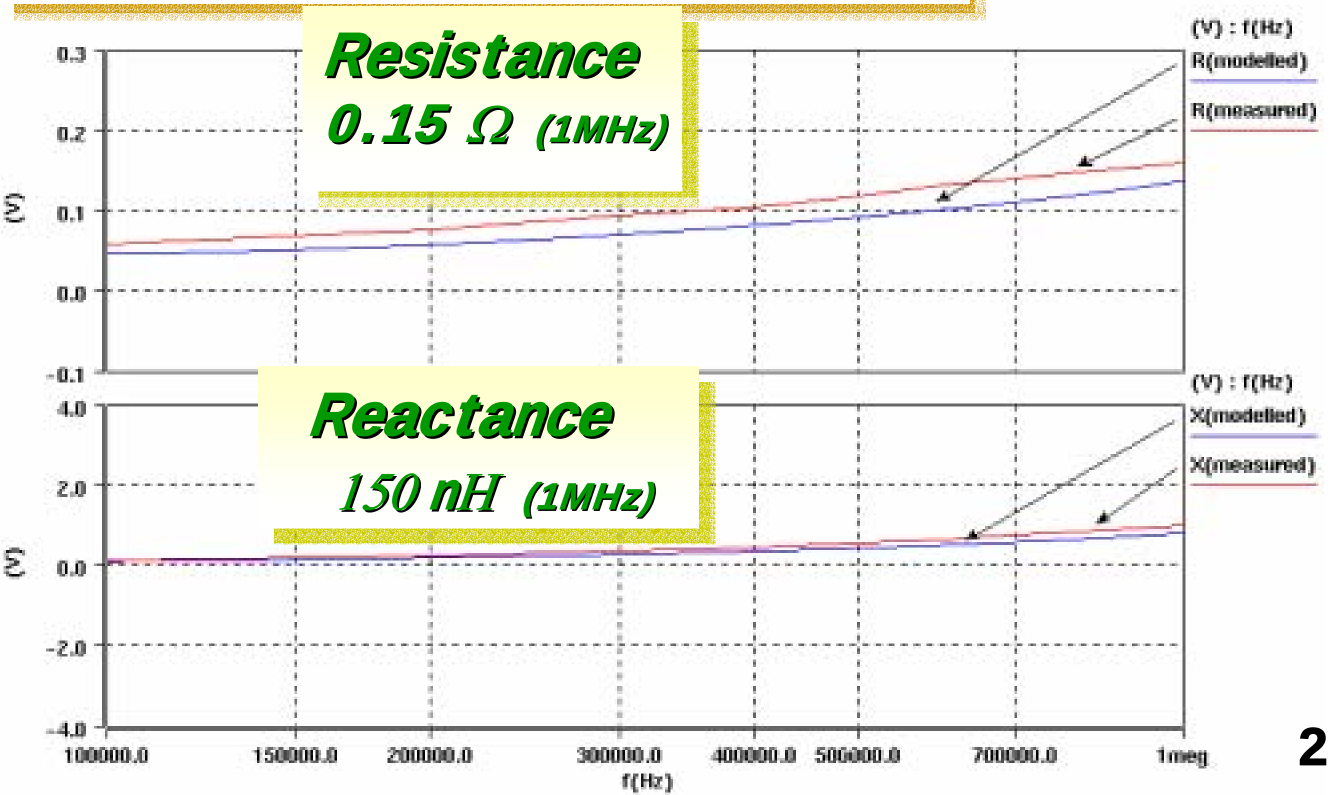
Experimental results

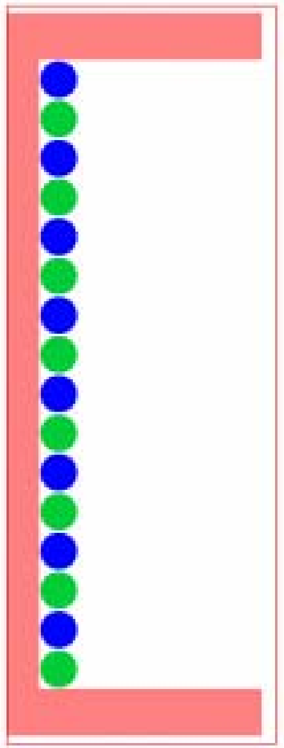
TRANSFORMER STUDIED

Geometric parameters

Core shape and size:............................ **RM12**
Core material:...................................... **3F3**
Conductors:................ **Solid, 0.7mm diameter**
Windings:.................. **Two in one layers (P:S)**
Turns:................... **Primary: 8; Secondary: 8**

Short circuit test





2D transformer

Experimental results

TRANSFORMER STUDIED

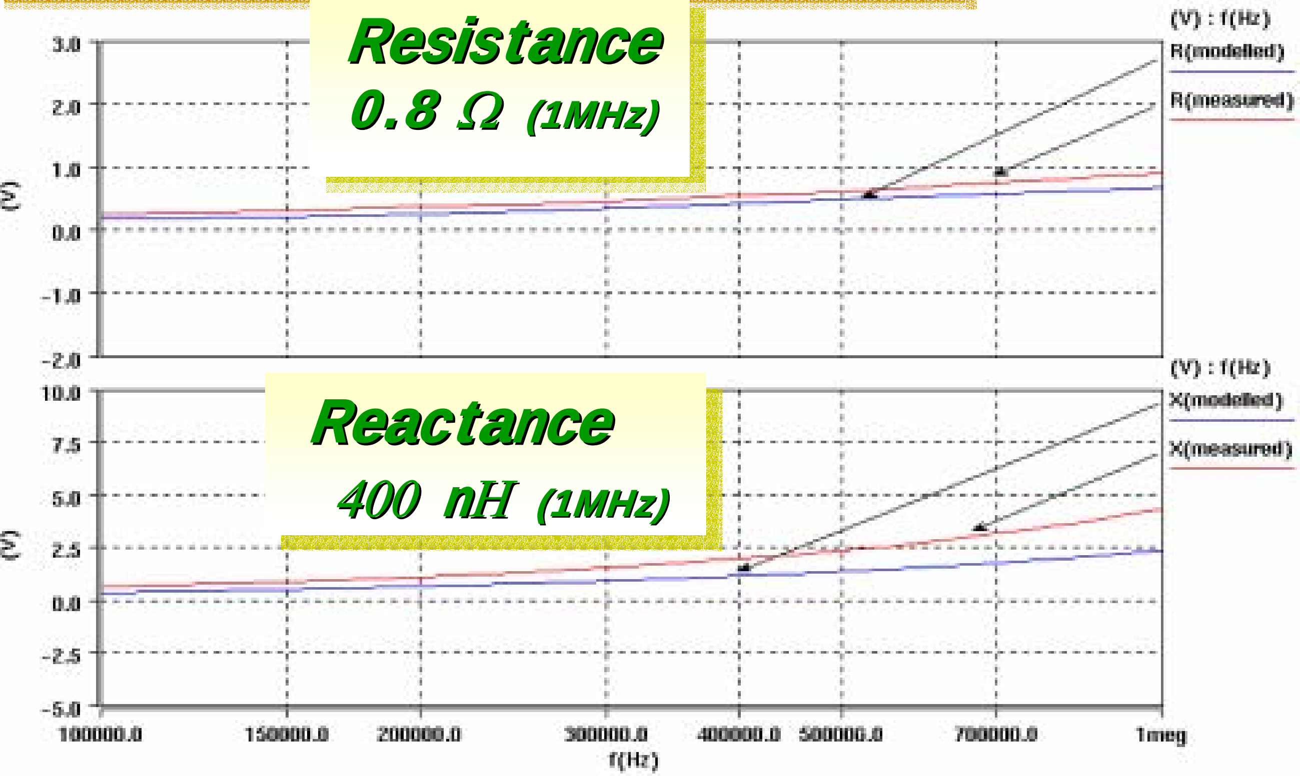
Geometric parameters:

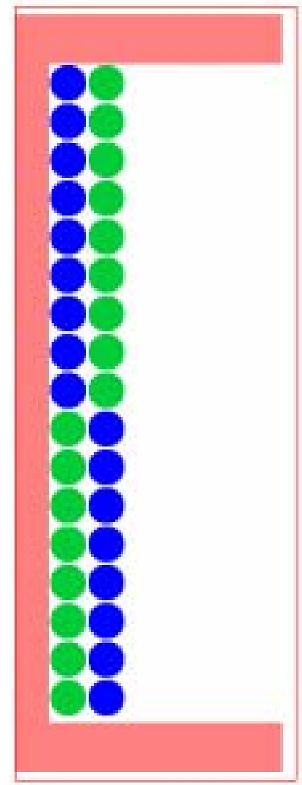
Core shape and size: **RM12**
Core material: **3F3**
Conductors: .... **Solid, 0.7mm diameter**
Windings: .... **Two in two layers**
Turns: ....**Primary: 17; Secondary: 17**

Short circuit test

Resistance
0.8 Ω (1MHz)

Reactance
400 nH (1MHz)





2D transformer

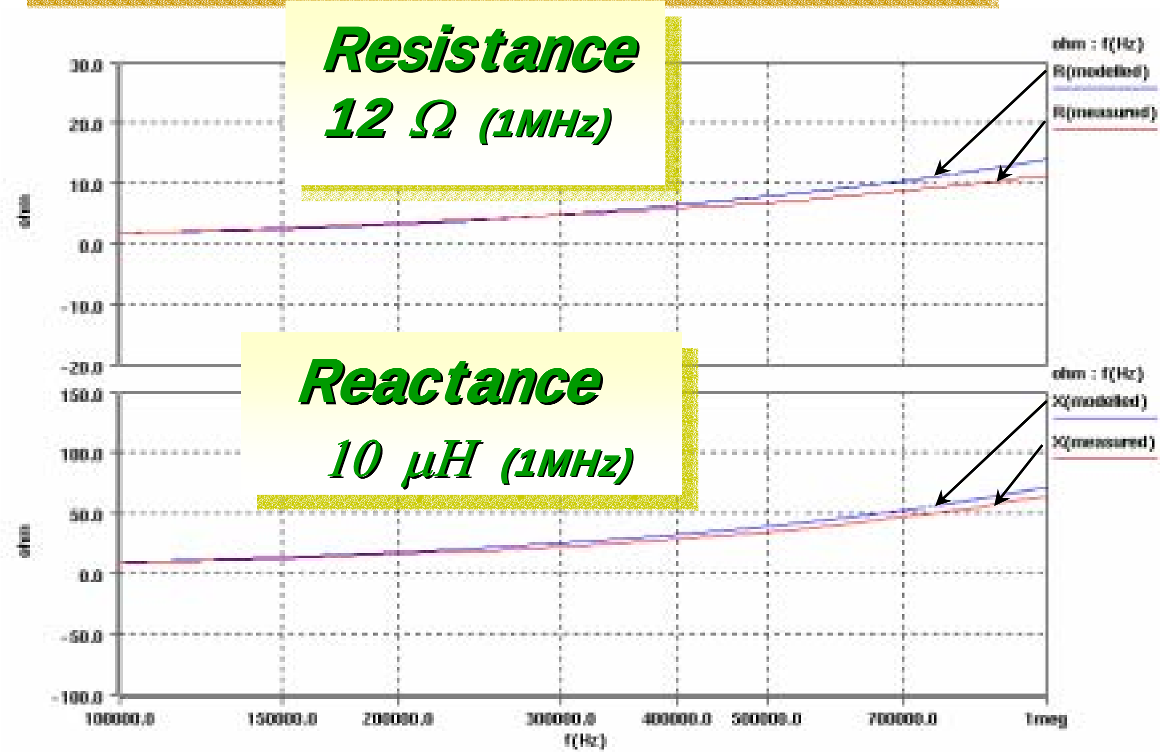
Experimental results

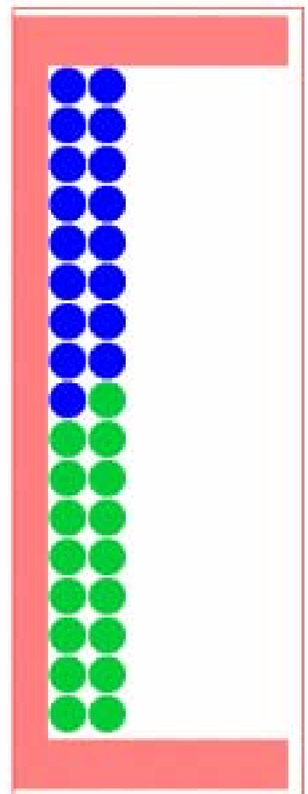
TRANSFORMER STUDIED

Geometric parameters:

Core shape and size:............................ RM12
Core material:....................................... 3F3
Conductors:............. Solid, 0.7mm diameter
Windings:........................... Two in two layers
Turns:.................Primary: 17; Secondary: 17

Short circuit test





2D transformer

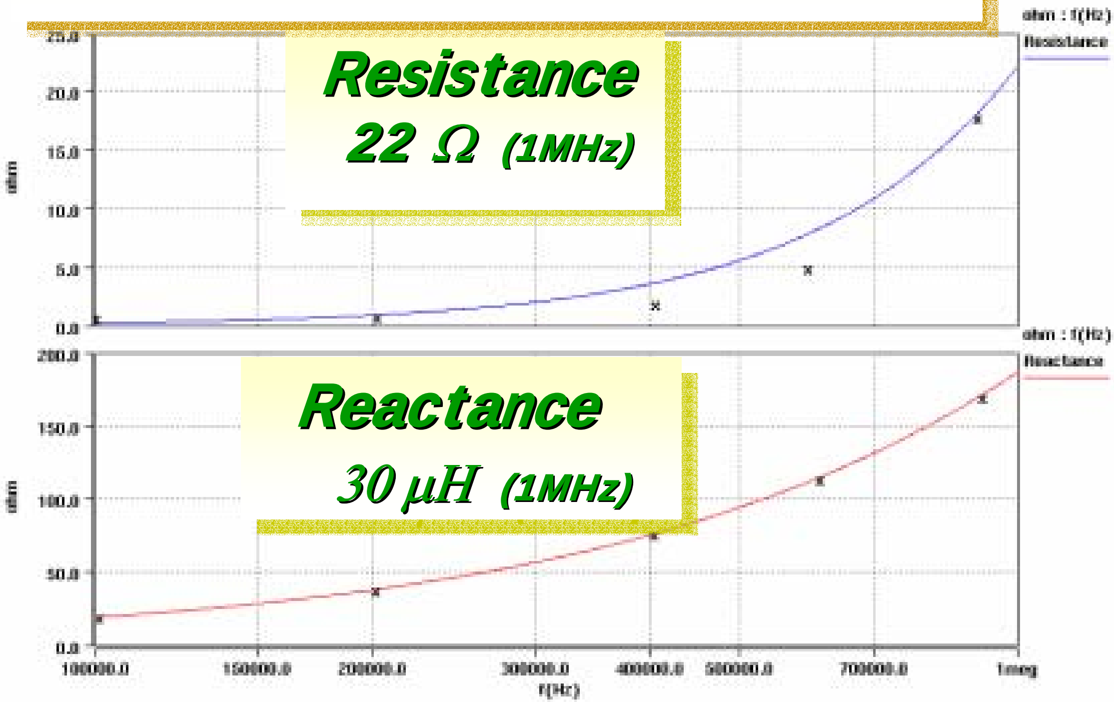
Experimental results

TRANSFORMER STUDIED

Geometric parameters:

Core shape and size:................**custom made**
Core material:....................................... **3F3**
Conductors:............. **foils, 70 μm thick**
Windings:........................... **Two in 11 layers**
Turns:........... **Primary: 5; Secondary: 11**

Open circuit test



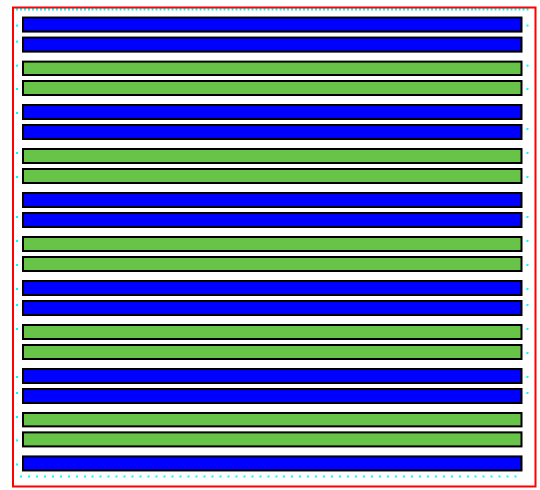
Experimental results

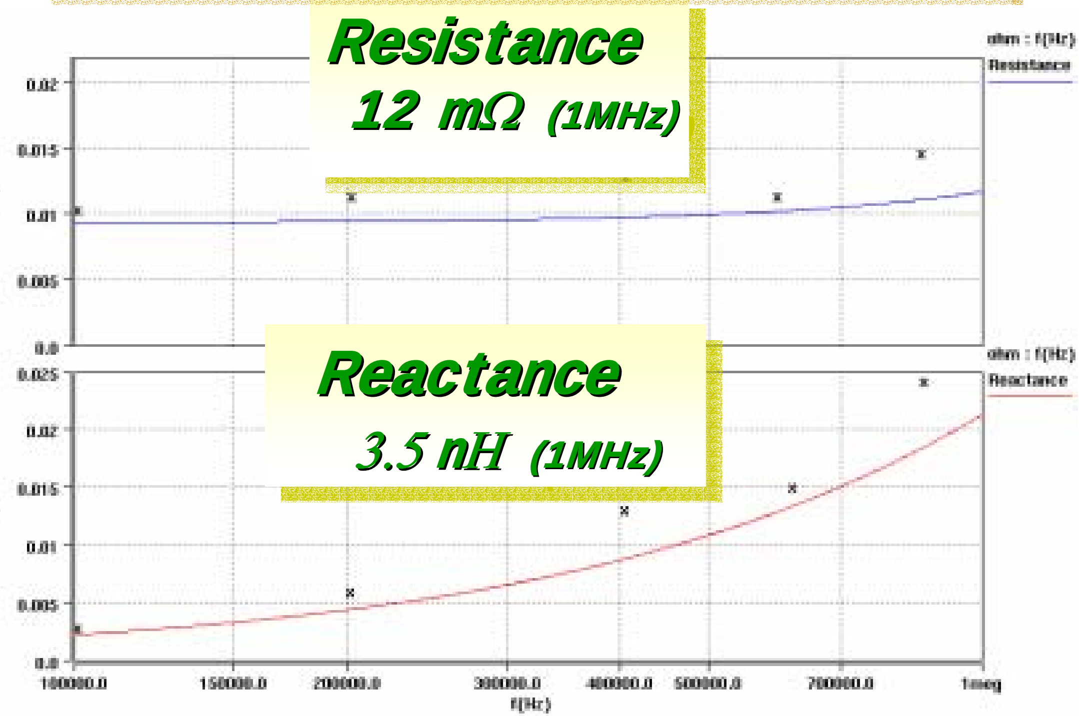
TRANSFORMER STUDIED

Geometric parameters

Core shape and size:................**custom made**
Core material:...................................... **3F3**
Conductors:............. **foils, 70 μm thick**
Windings:............................**Two in 11 layers**
Turns:............ **Primary: 5; Secondary: 11**

Short circuit test





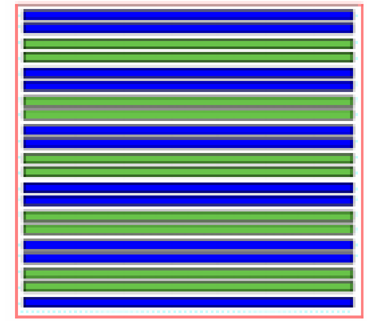
Experimental results

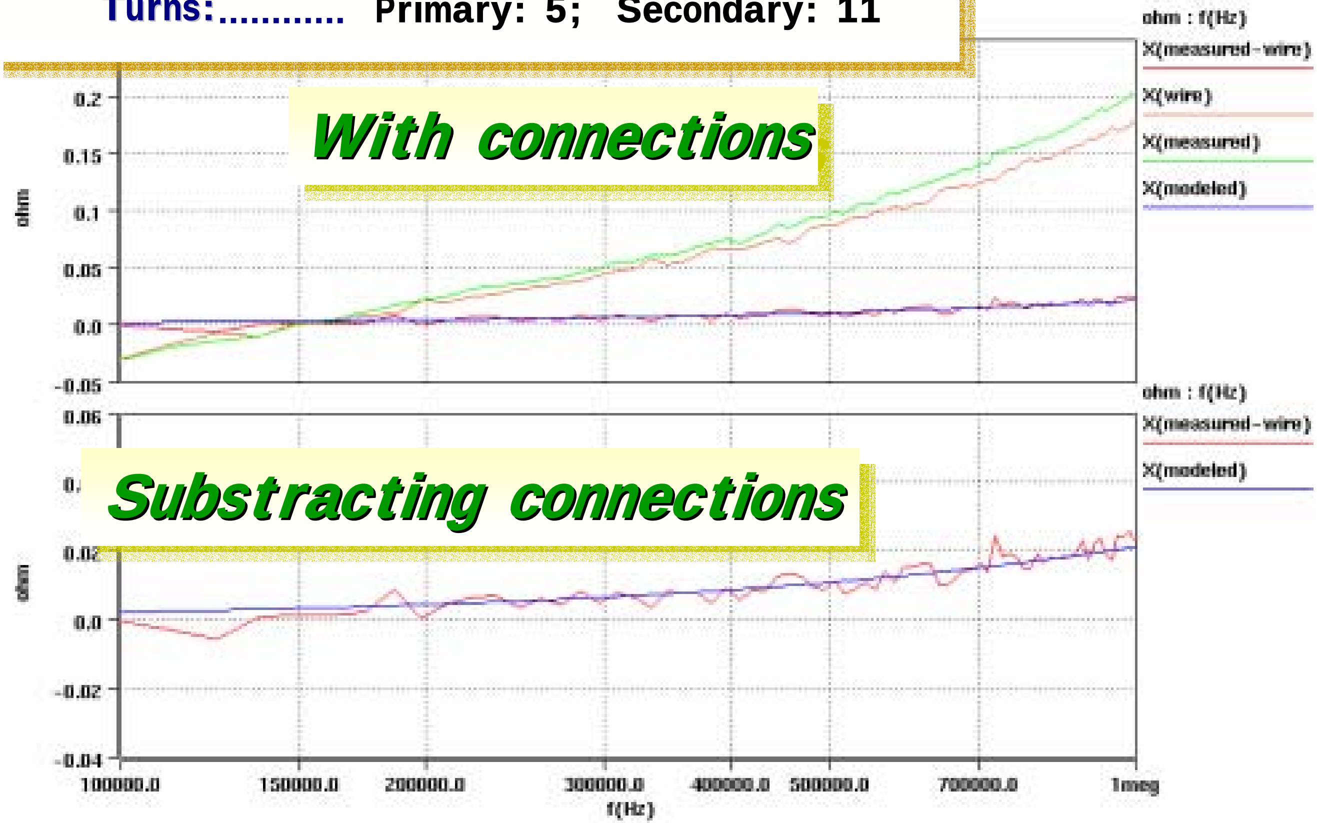
TRANSFORMER STUDIED

Geometric parameters

Core shape and size:................custom made
Core material:.. 3F3
Conductors:............. foils, 70 μm thick
Windings:........................... Two in 11 layers
Turns:........... Primary: 5; Secondary: 11

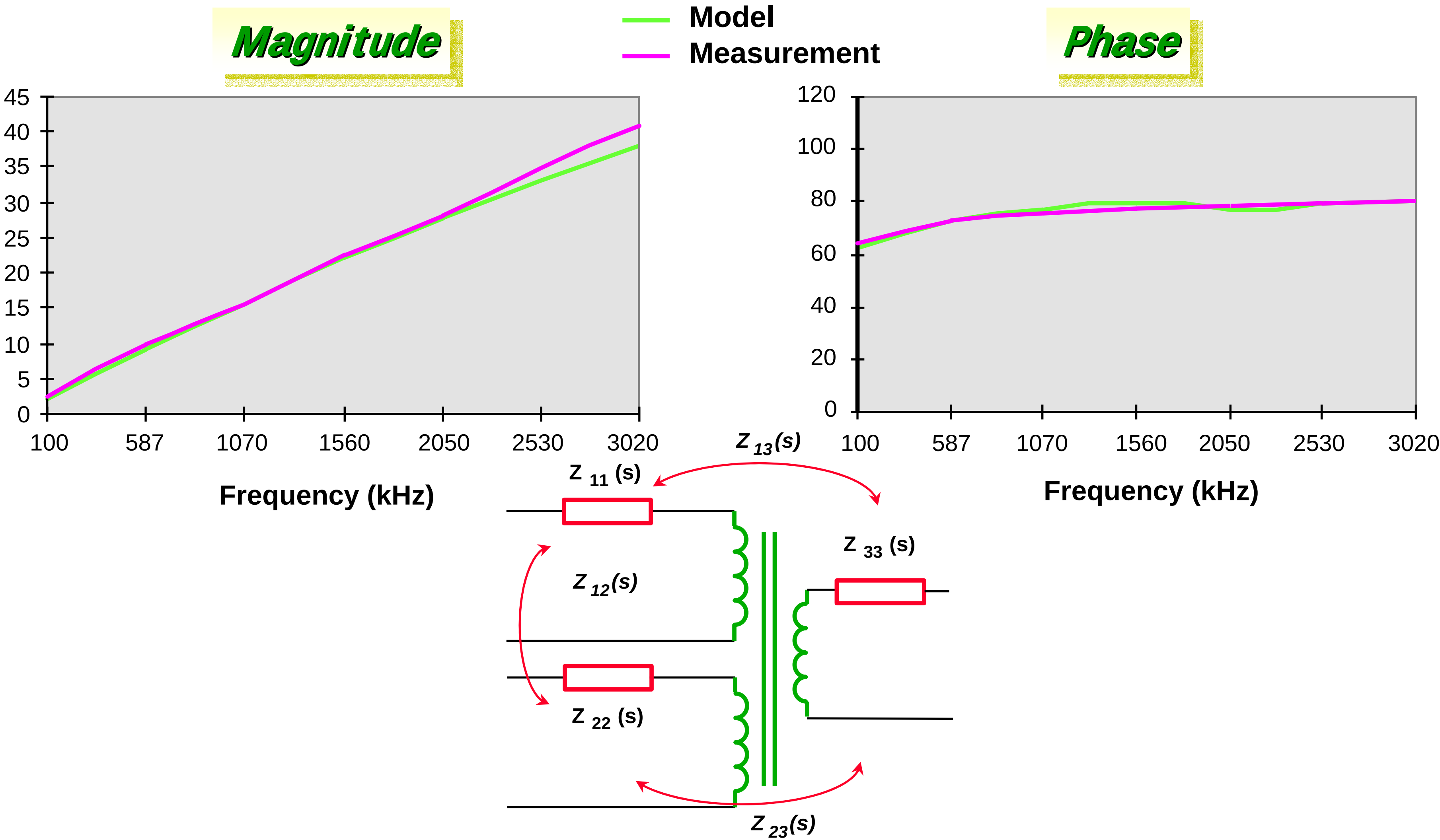
Effect of the connections





Using impedance analyzer instead of FEA

Short circuit test



Summary of magnetic component modeling

ADVANTAGES

- **Accurate model** for the windings, based on a **FEA tool or analytical expressions**
- All **high frequency and geometry effects** are taken into account
- Valid for **any electrical waveform** (not only sinusoidal)
- Valid for both **multi-winding** transformers and **coupled inductors**
- Valid for **behavioral simulator** and for electrical simulators

DRAWBACKS

- 1D model is only applicable when field distributions are uni-dimensional
- FEA solver needed for 2D/3D models
- Model generation time for 2D/3D models

Summary of magnetic component modeling

FEATURES

- **Several degrees of accuracy** have been established:

1D model
2D/3D model
→ depending →
- Stage in the design flow of the product
- Type of magnetic component
- Type of test to be performed
- Hardware & Software capabilities

- **Optimization of design process** of magnetic components, since models are generated from geometry and material descriptions
- Generate an accurate **model from an actual magnetic component**
- Check the **sensitivity** of magnetic components to winding strategies and material properties

4

Advanced design and optimization process

Sensitivity analysis

Flyback transformer

Low profile issues

4.1

Sensitivity Analysis

Sensitivity analysis

GOAL

Quantification of the influence of constructive parameters on the electrical peformance

CONSTRUCTIVE PARAMETERS

- **Interwinding distance**
- **Window height**
- **Airgap**
- **Conductors diameter**
- **Insulator permittivity**
- **Core permeability**

Their whole influence

Losses
Magnetic energy
Electric energy

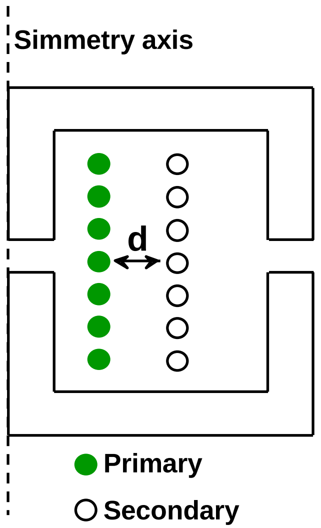
has to be analyzed

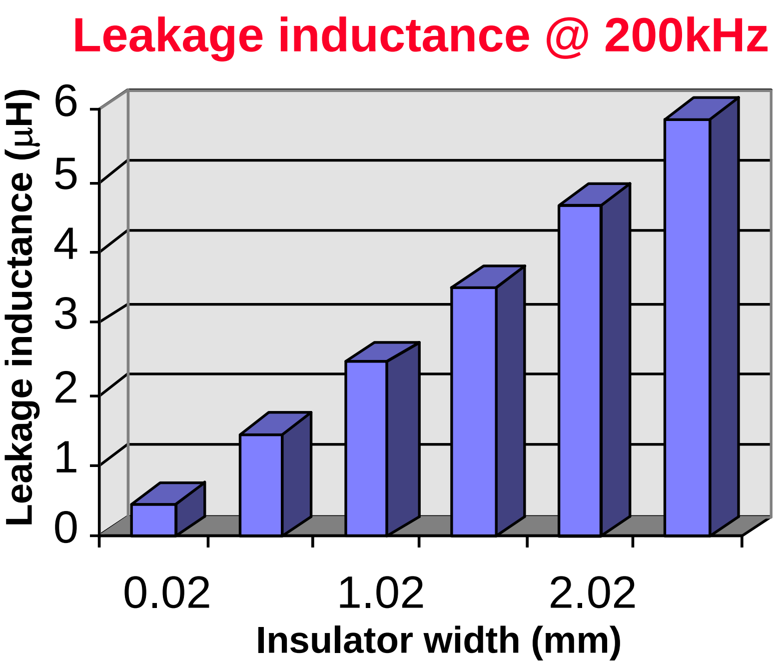
Influence of interwinding distance: *on leakage inductance*

TRANSFORMER STUDIED

Geometric parameters

Core shape and size: **RM8**
Core material: **3F3**
Conductors: .... **Solid, 0.38mm diameter**
Windings: .... **Two**
Turns: .... **Primary: 20; Secondary: 20**
Gap: **0.1mm**



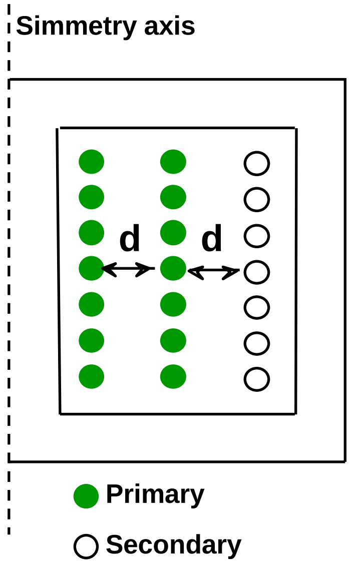


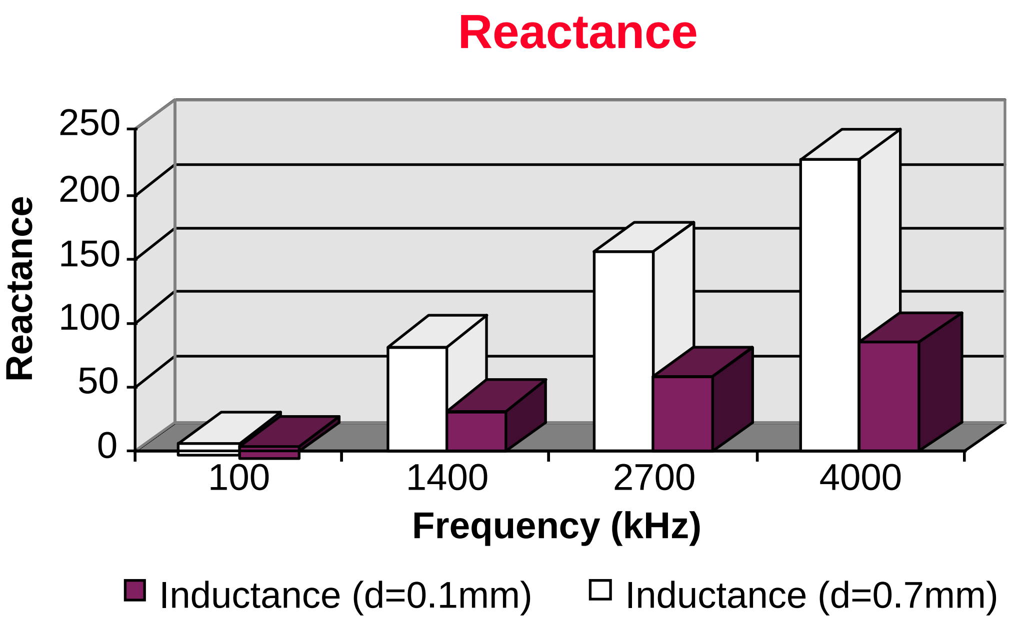
Influence of interwinding distance: *on leakage inductance*

TRANSFORMER STUDIED

Geometric parameters

Core shape and size:............................RM14
Core material:....................................... 3C85
Conductors:............. Solid, 0.8mm diameter
Windings:........... Two in three layers (P:P:S)
Turns:.............. Primary: 40; Secondary: 20



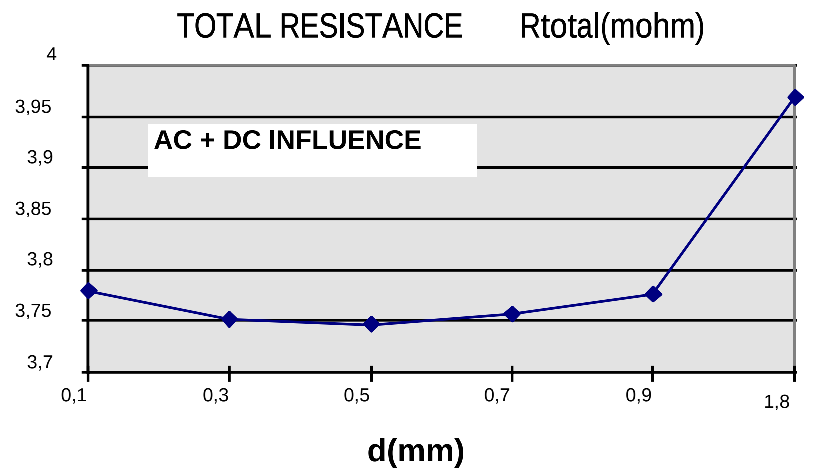


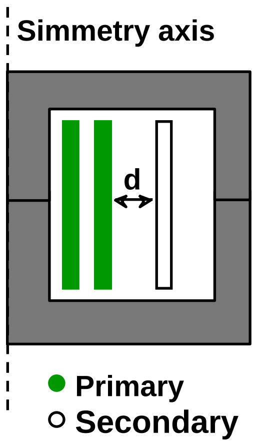
Influence of interwinding distance :
on AC resistance in concentric structures

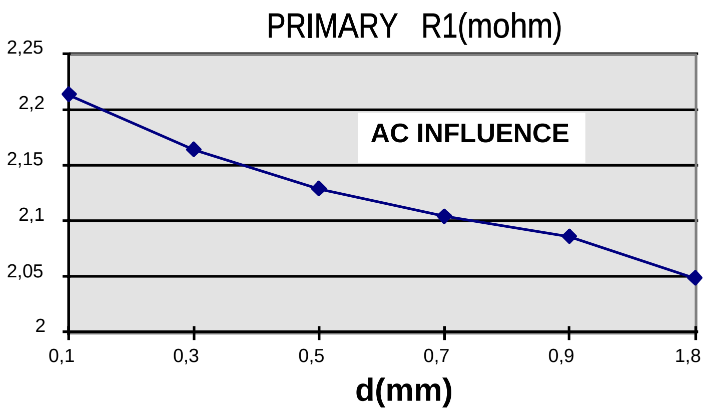
TRANSFORMER STUDIED

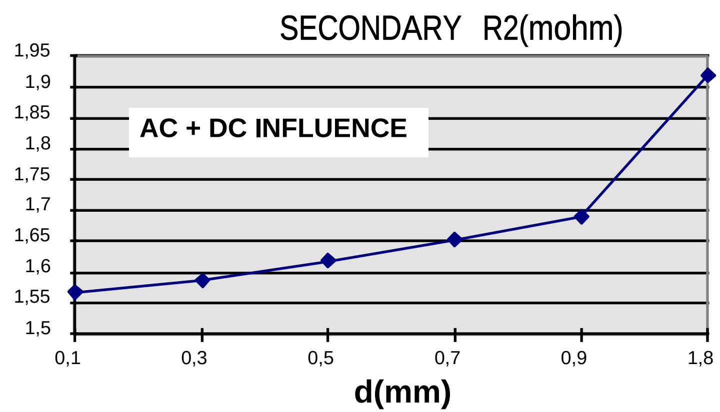
***Geometric parameters*:**

Core shape and size:...............................RM10
Core material:... 3F3
Conductors: ....Foils, 0.75 mm
Windings: ....Two
Turns:.....................Primary: 2; Secondary: 1
Frequency: 100kHz









Conductor length must be considered

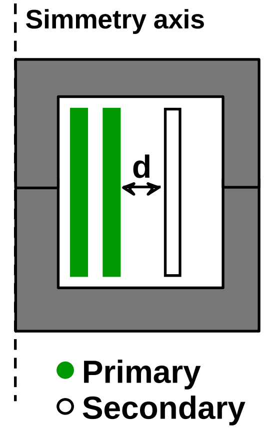
Influence of interwinding distance :

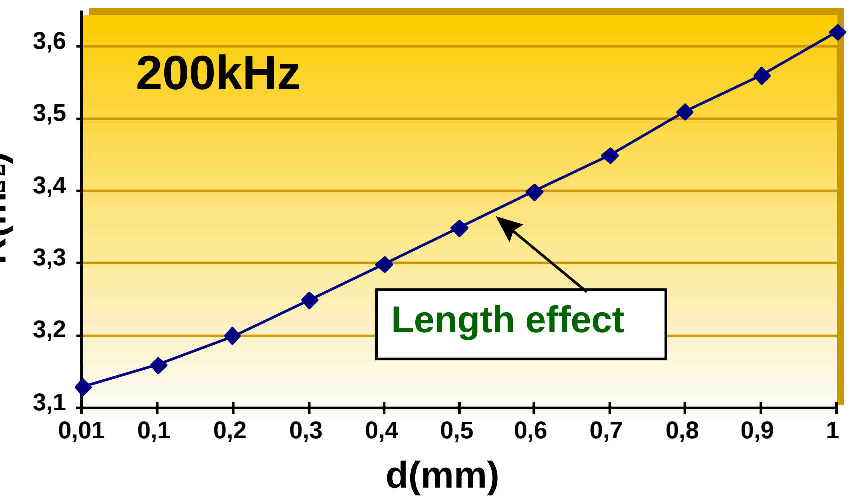
on AC resistance in concentric structures

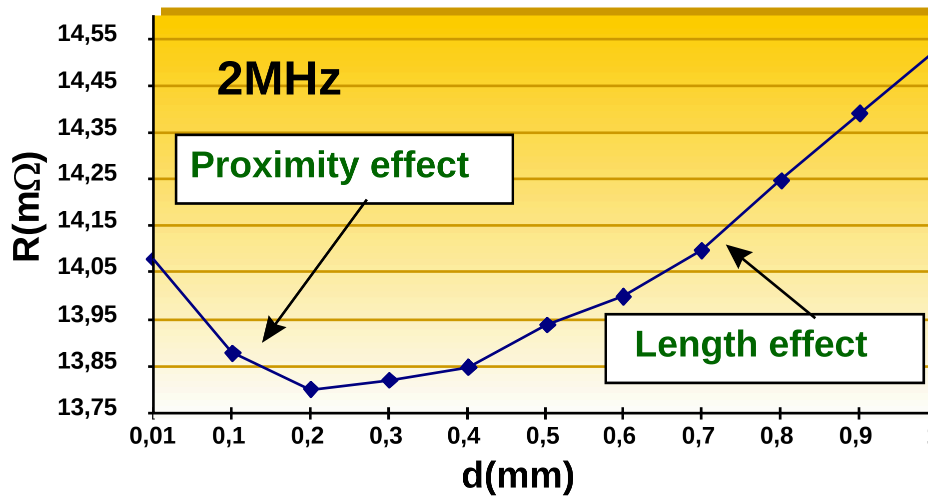
TRANSFORMER STUDIED

Geometric parameters

Core shape and size:.............................. RM6
Core material:.. 3F3
Conductors: .... Foils, 0.2 mm
Windings: .... Two
Turns:...................... Primary: 2; Secondary: 1







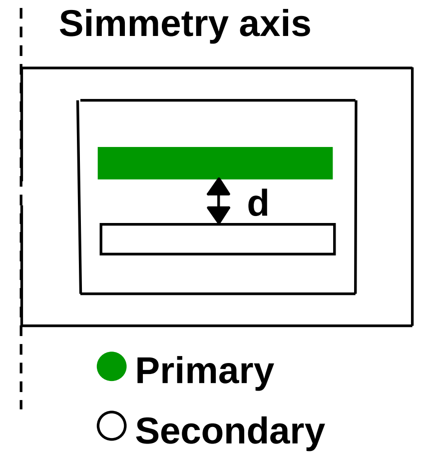
For the same structure, the optimum distance depends on the frequency

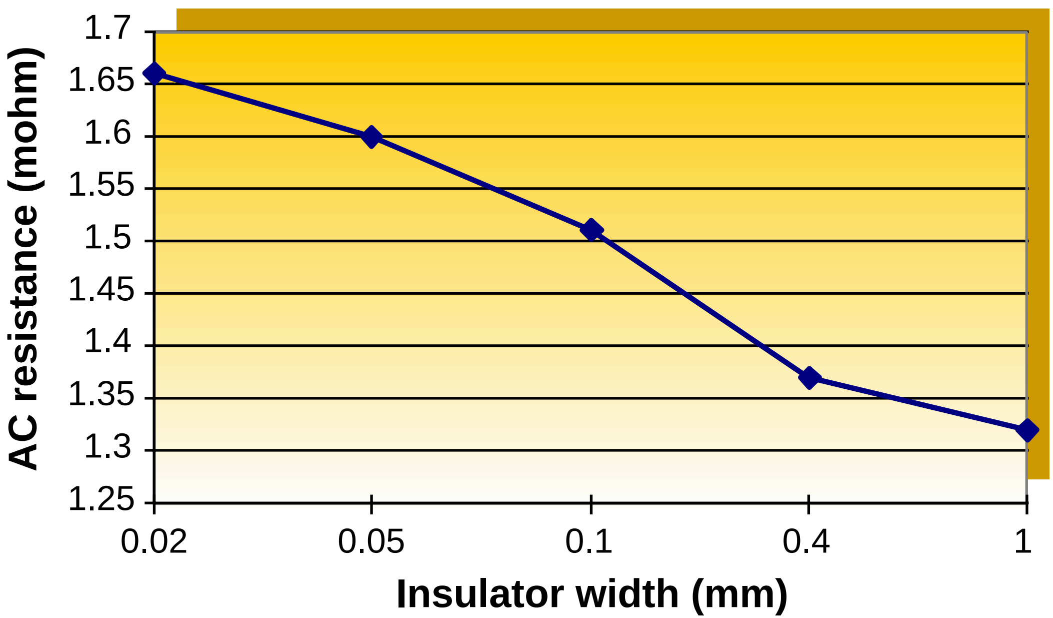
Influence of interwinding distance :
on AC resistance in top-down structures

TRANSFORMER STUDIED

Geometric parameters

Core shape and size:.................... RM8/LP
Core material:.................................... 3C85
Conductors:.............................Foils, 0.2mm
Windings: .... Two
Turns:................. Primary: 1; Secondary: 1





@500kHz

Influence of interwinding distance : *on electric energy*

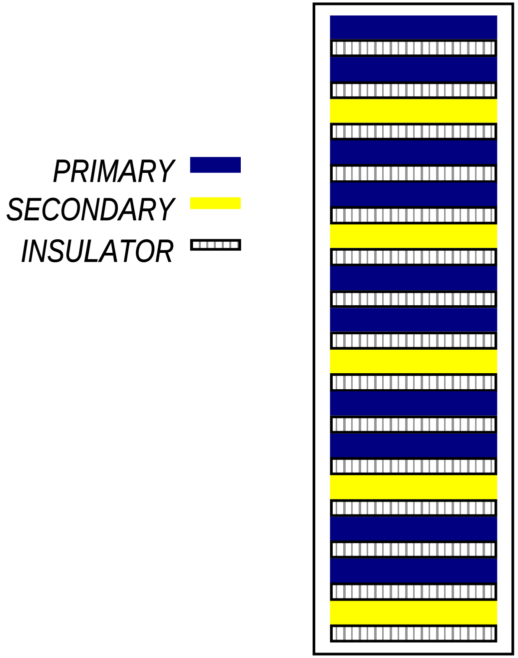
TRANSFORMER STUDIED

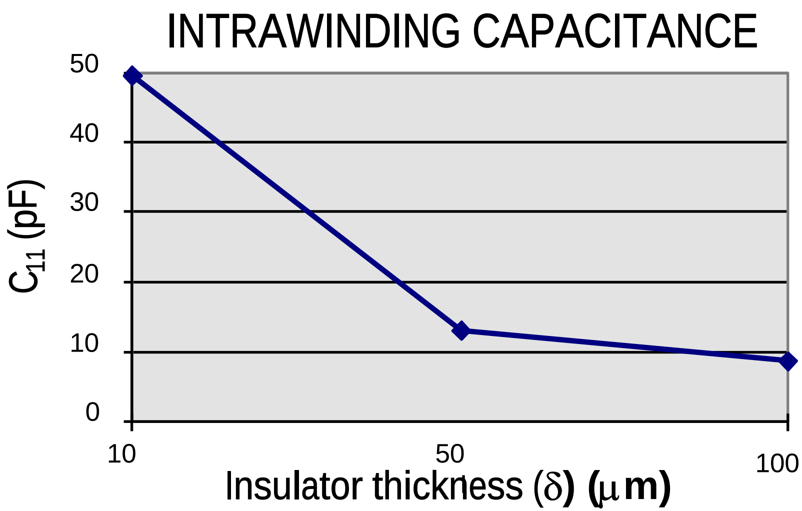
Geometric parameters

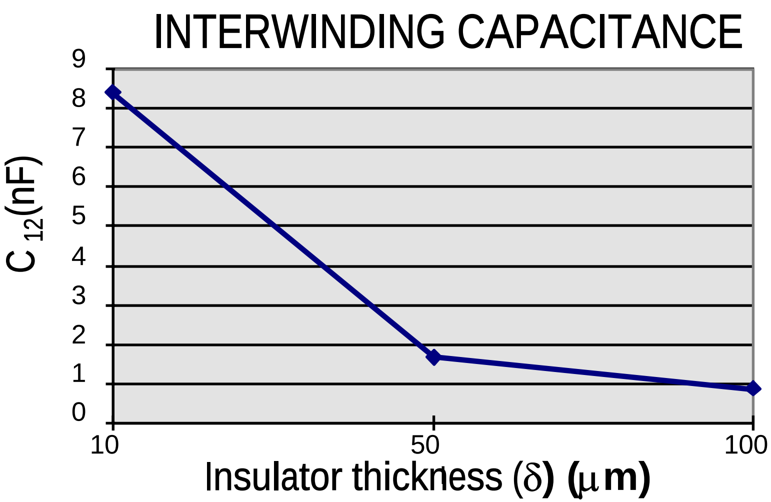
Core shape and size:.................... RM10
Core material:.................................. 3F3
Conductors:.........................Foils of 70μm
Windings:... Two
Turns:.........Primary: 10; Secondary: 5

Electric parameters

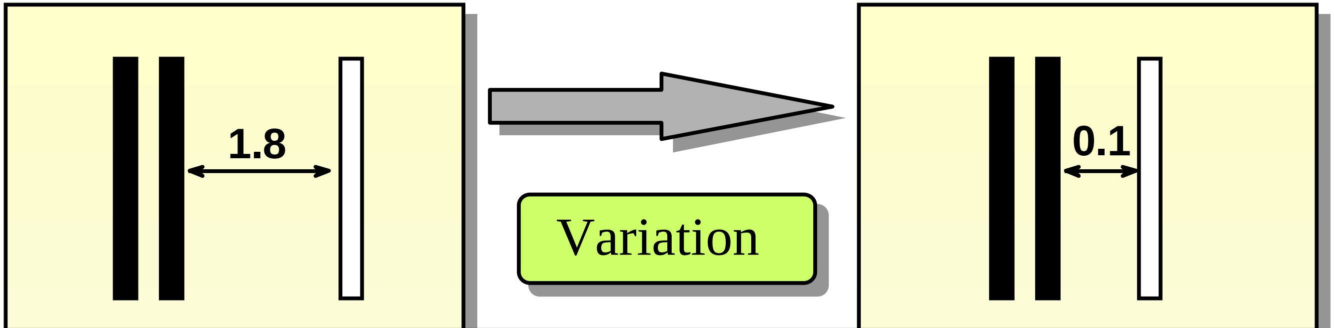
Insulator relative permittivity:......... 5
Core relative permittivity:............... 1e5





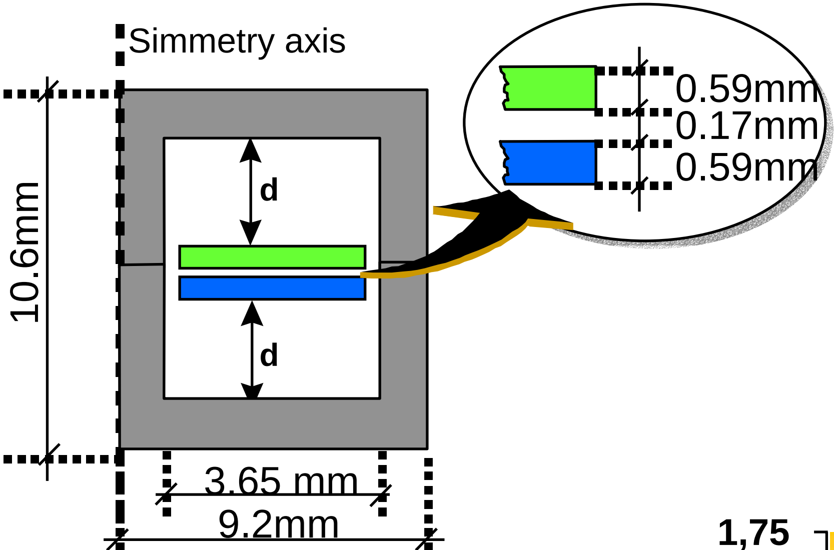


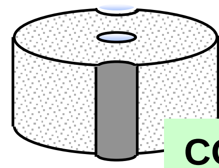
Influence of interwinding distance on R_{AC}, L_{leak} and C



R=3.97 mΩ	4%	R=3.78 mΩ
Lleak=50.27 nH	81%	Lleak=9.46 nH
C=42.80 pF	46%	C=79.44 pF

Influence of window height

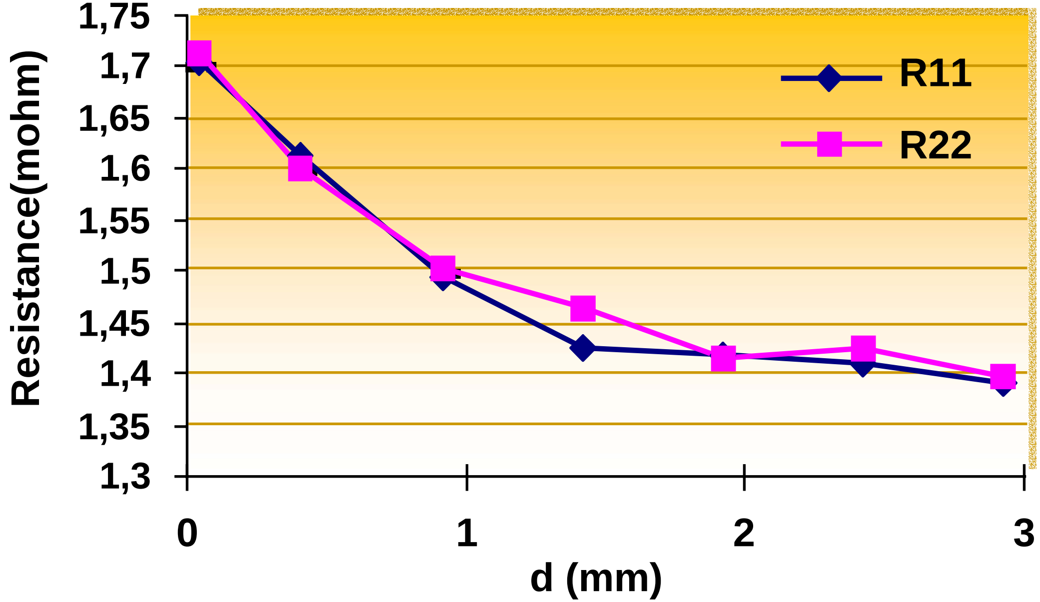




CORE SHAPE:	**POT**
CORE MATERIAL:	**3C85**

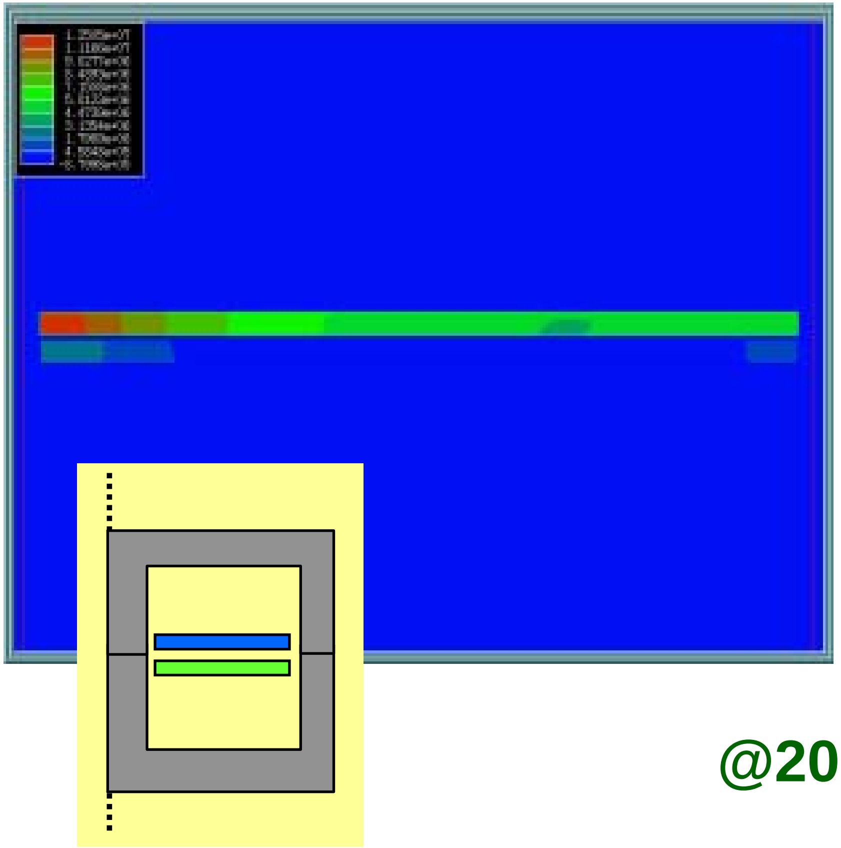
● **Primary**
● **Secondary**

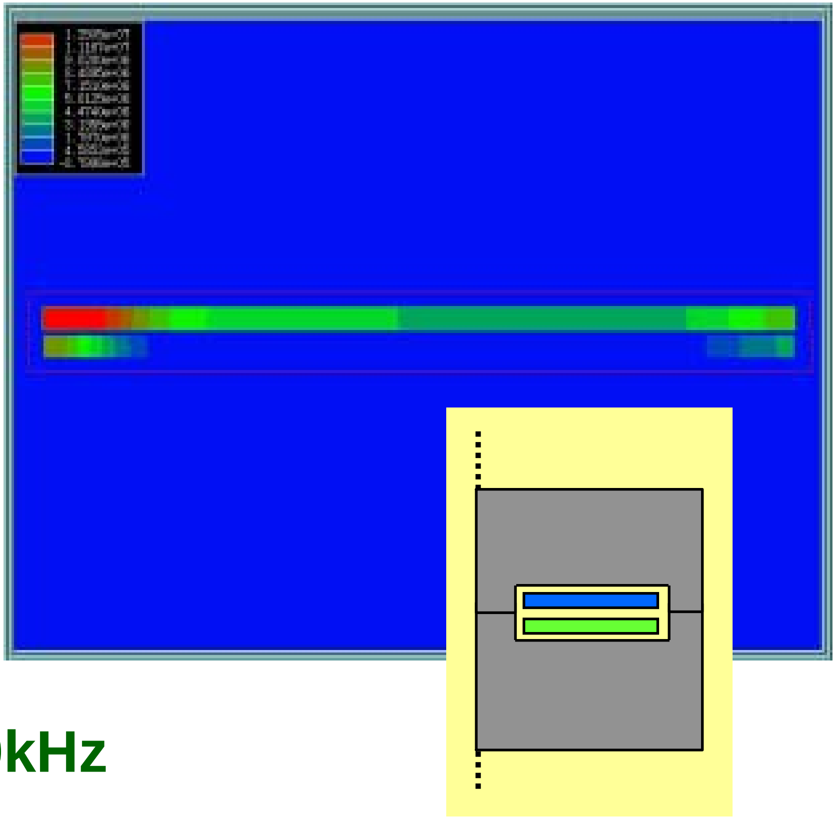
@150kHz



Influence of window height

Current distribution in primary winding

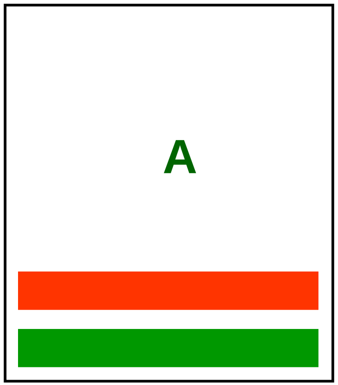


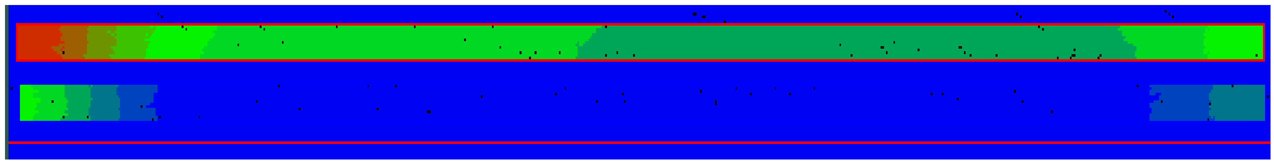


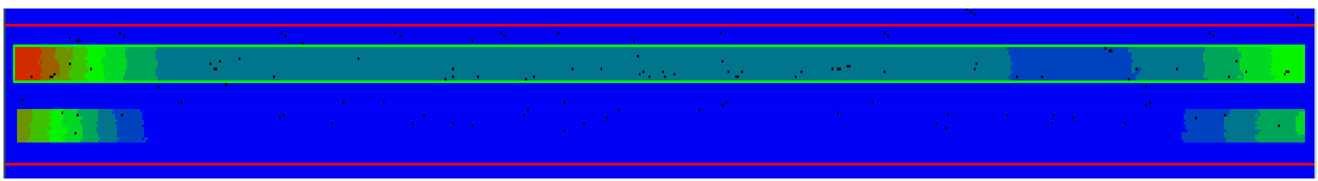
@200kHz

Influence of window height

@200kHz





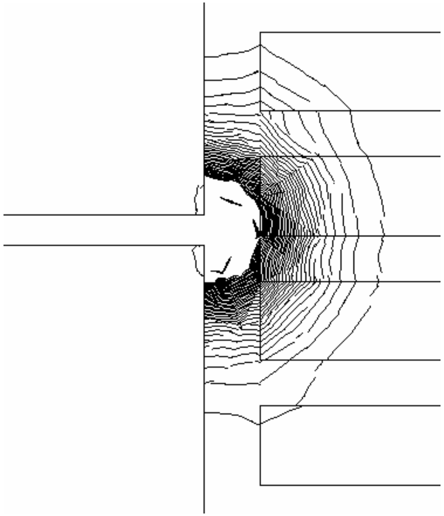


B

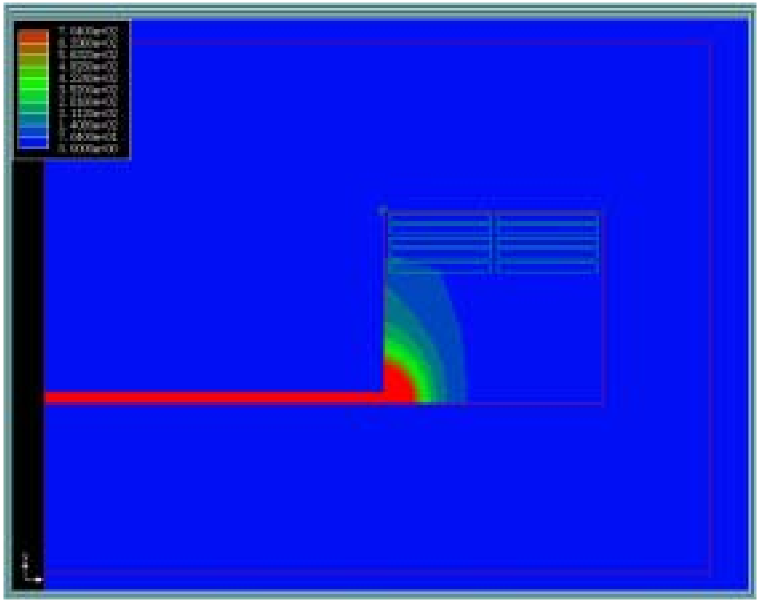
	R11 (mΩ)	R22 (mΩ)	R12 (mΩ)	Rprim (mΩ)	Lleak (nH)
A	3.5	3.65	0.72	5.74	1.69
B	6.32	6.33	3.45	5.74	1.71

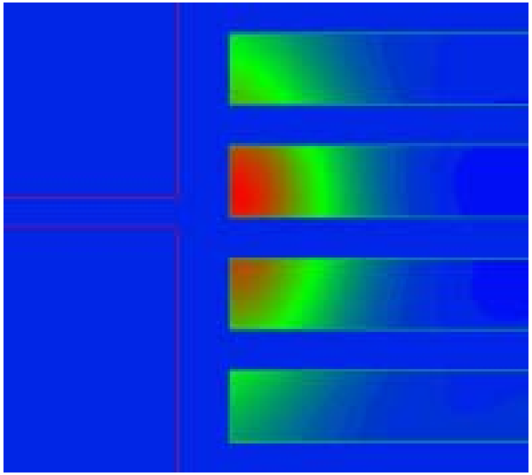
Flyback resistance is affected (R11,R22)
but not Forward resistance (Rprim) !!

Influence of the air gap: *on the AC resistance*



Fringing flux





Current density distribution

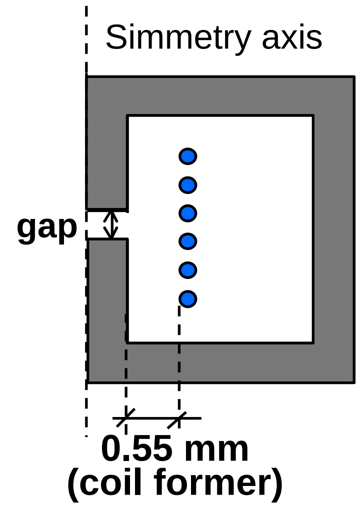
Fringing flux affects to current distribution and conduction losses

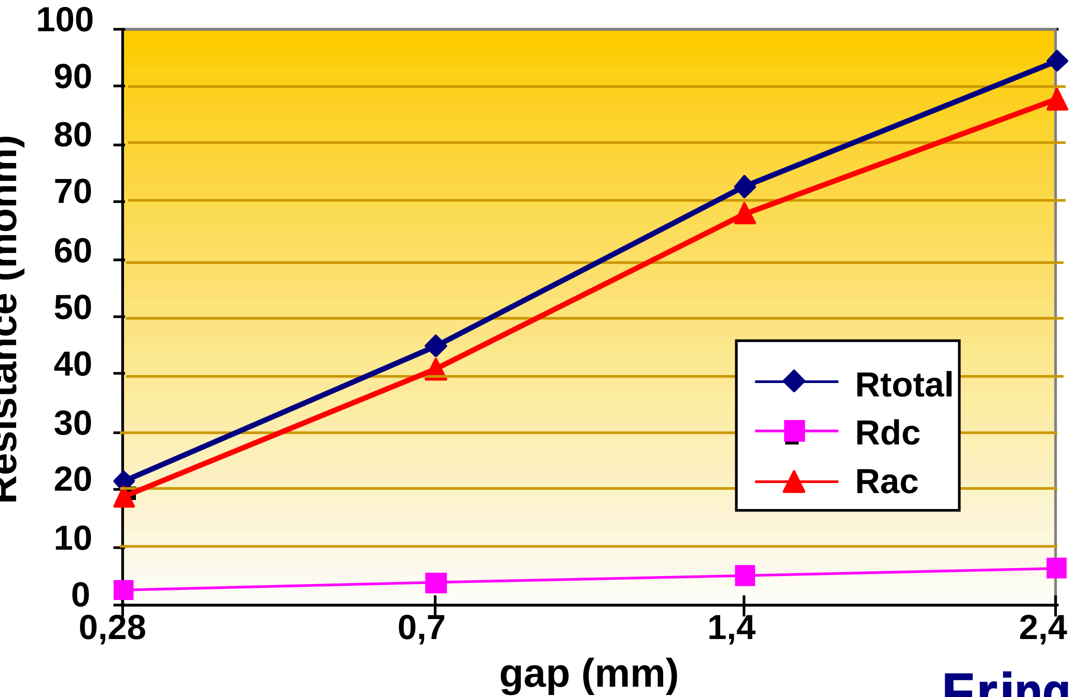
Influence of the air gap: *on the AC resistance*

TRANSFORMER STUDIED

Geometric parameters

Core shape and size:....................POT 22/13
Core material: 3C85
Conductors:............ Solid, 0.5mm diameter
Windings: .... One





@150kHz

Test conditions

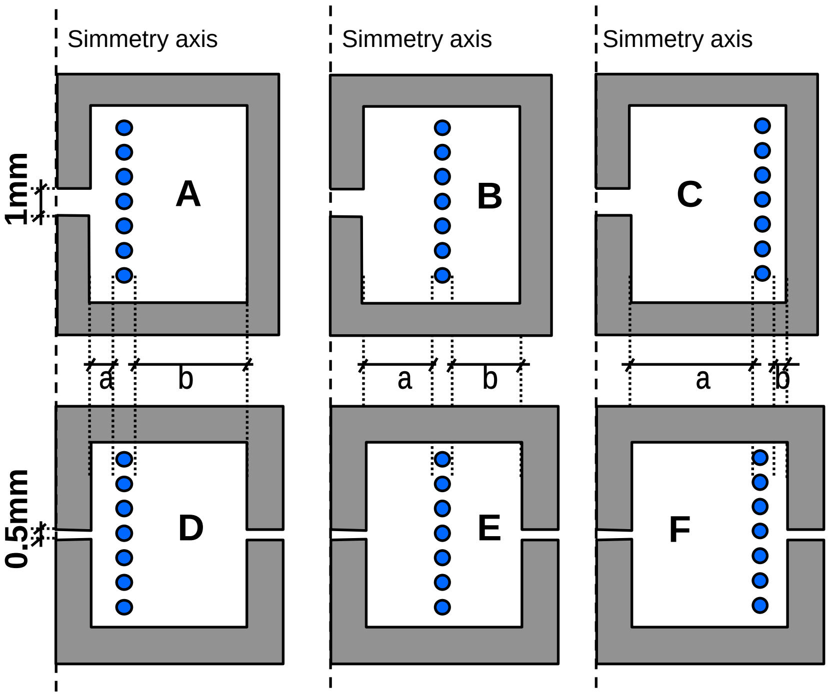
L_m = constant

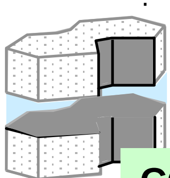
n ↑

R_{DC} ↑ (length effect)

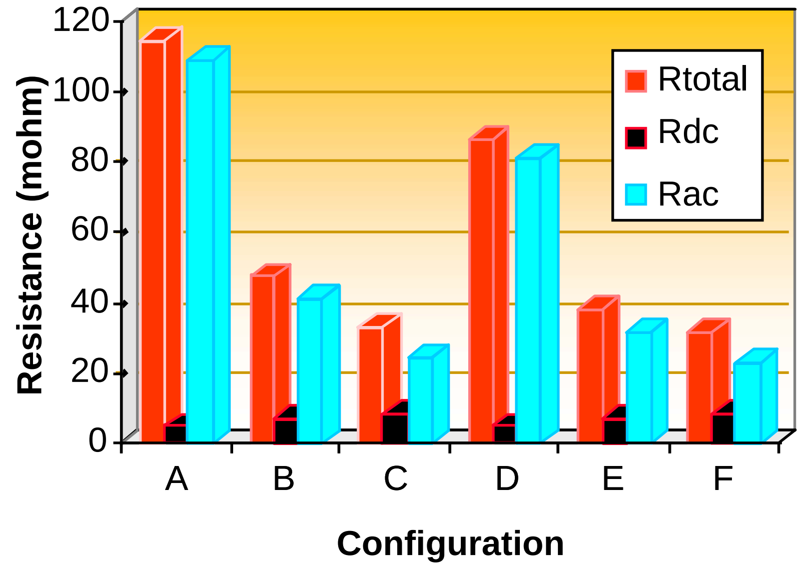
Fringing flux effect is much more important than length effect

Influence of the air gap: *on the AC resistance*





CORE SHAPE:	**RM12**
CORE MATERIAL:	**3F3**



@150kHz

Fringing flux affects to conduction losses

Influence of insulator permittivity

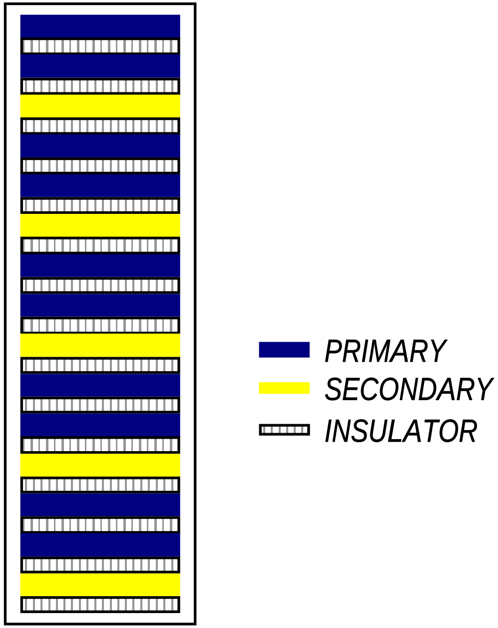
TRANSFORMER STUDIED

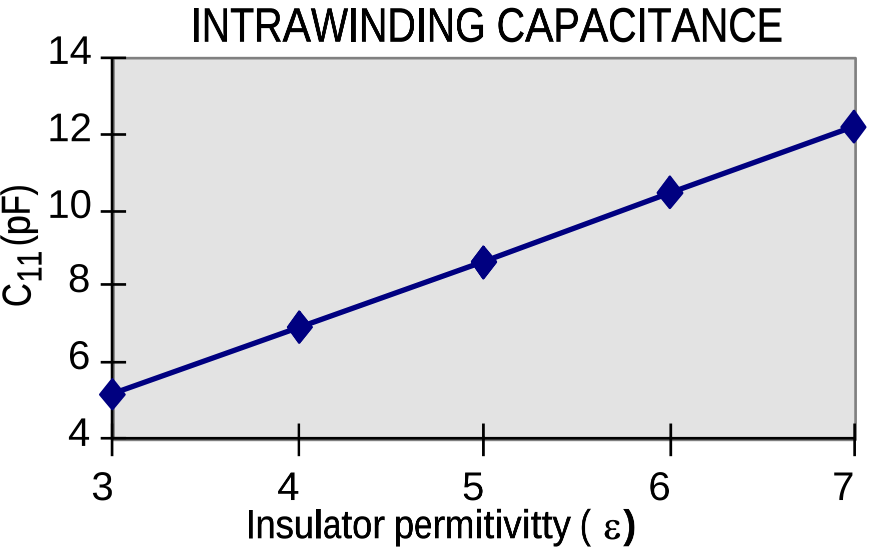
Geometric parameters

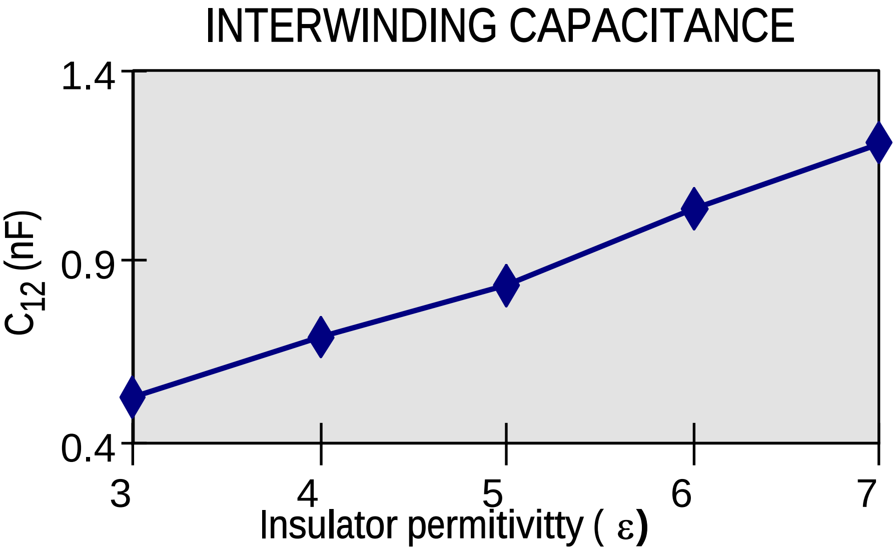
Core shape and size:...................... RM10
Core material:................................... 3F3
Conductors:...........................Foils of 70µm
Windings:... Two
Turns:.........   Primary: 10;   Secondary: 5
Insulator thickness...................... 100µm

Electric parameters

Core relative permittivity:.................. 1e5





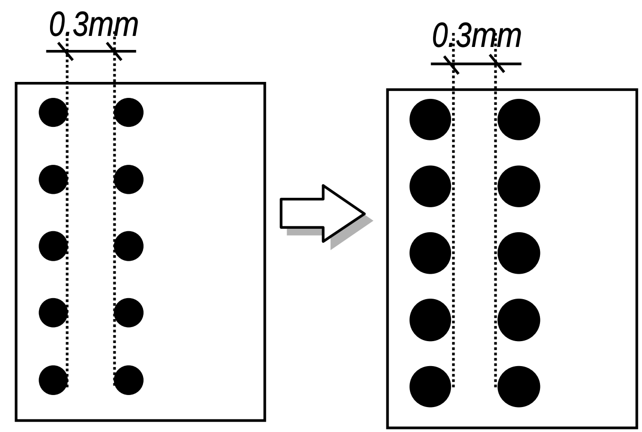


Influence of conductors diameter
on AC resistance and leakage inductance

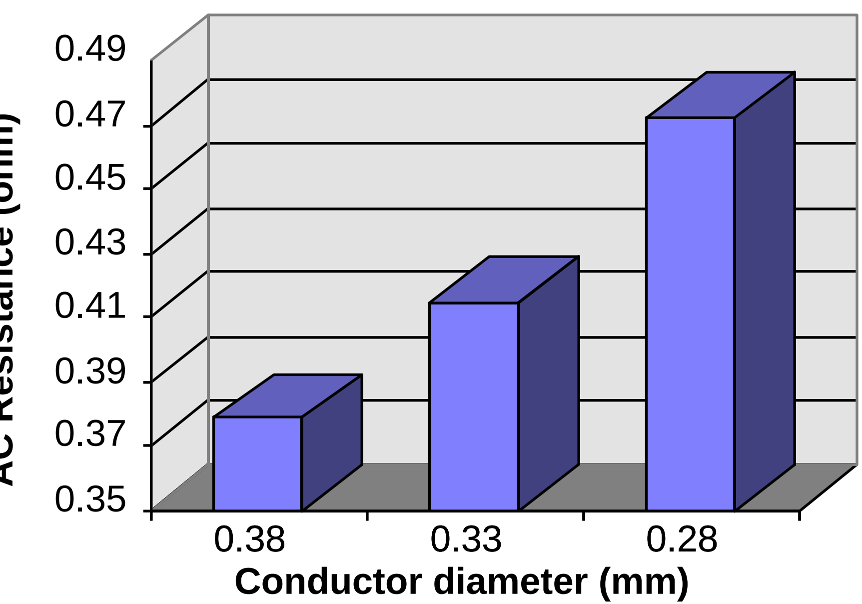
TRANSFORMER STUDIED

Geometric parameters

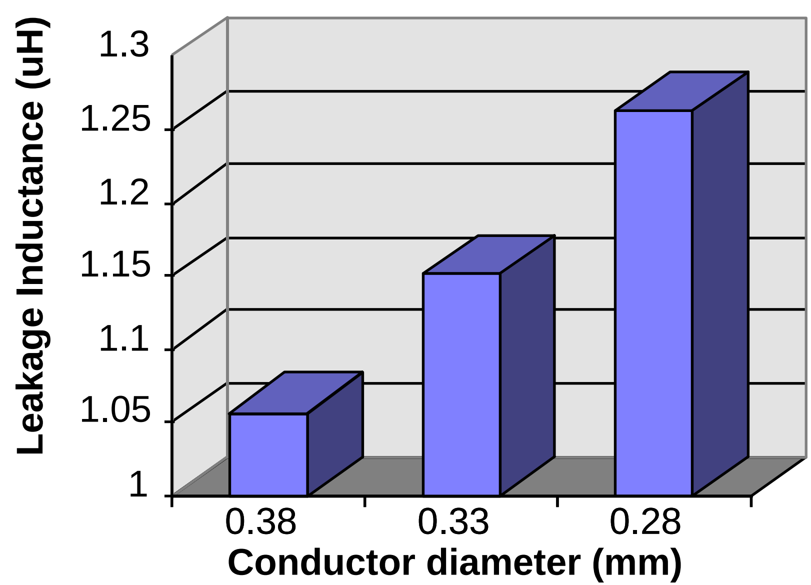
Core shape and size: **RM8**
Core material: **3F3**
Conductors: .... **Solid**
Windings: .... **Two**
Turns .... **Primary: 20; Secondary: 20**
Winding thickness .... **0.3 mm**



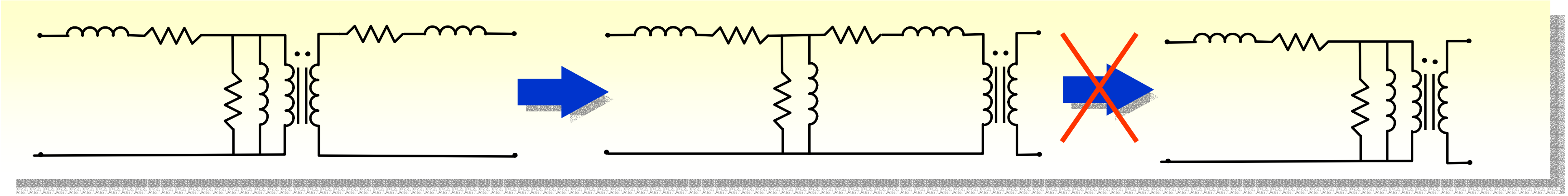
Resistance (ohm) @ 200kHz



Inductance (μH) @ 200kHz

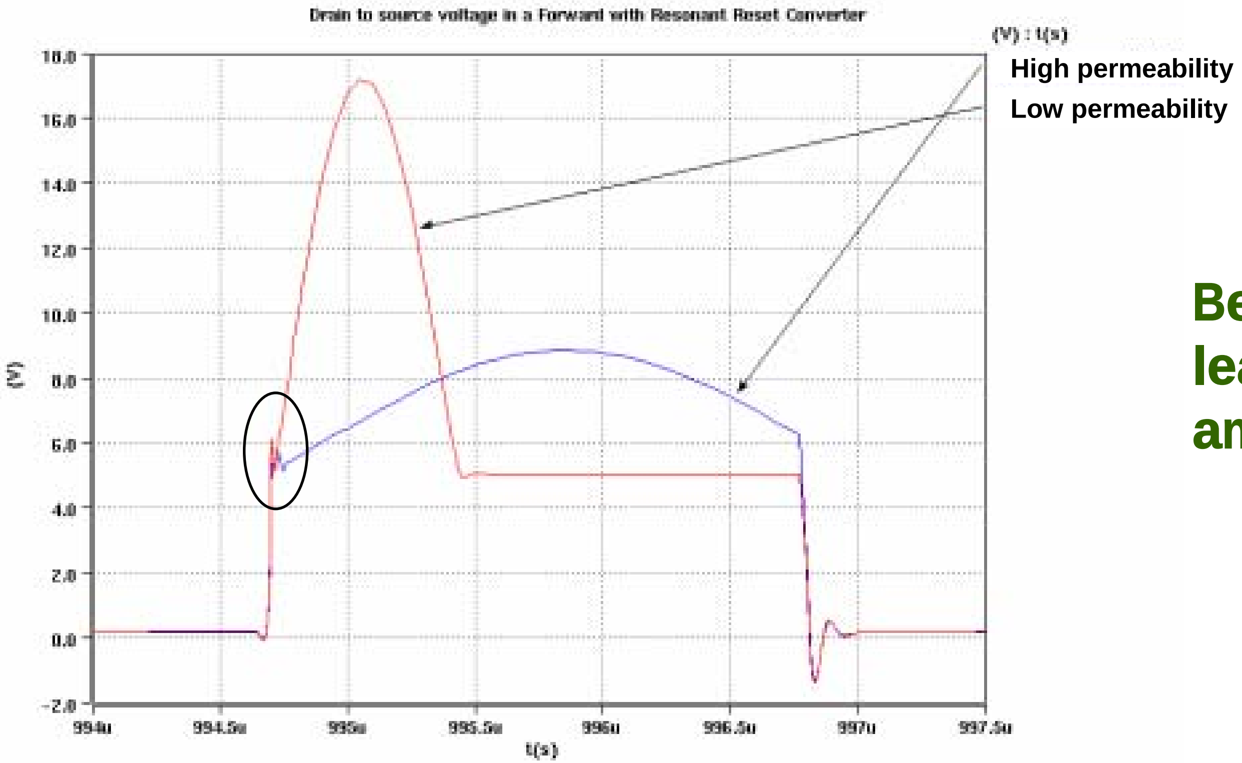


Influence of core permeability



A short circuit test and open circuit test do not account for L_{leak} and L_m if μ_{core} is too low

V_{DS} in main switch



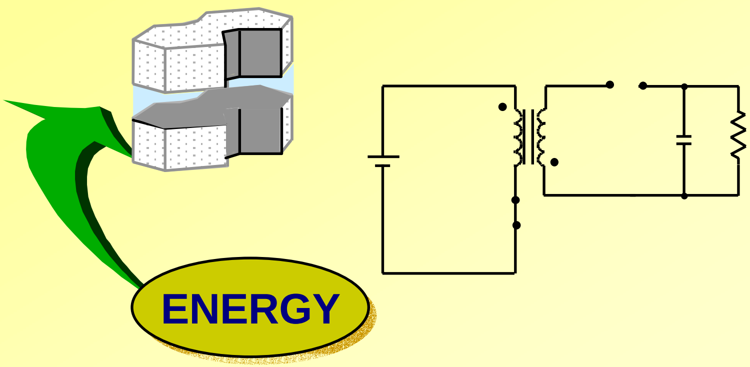
Better to quantify leakage energy on an actual converter

4.2

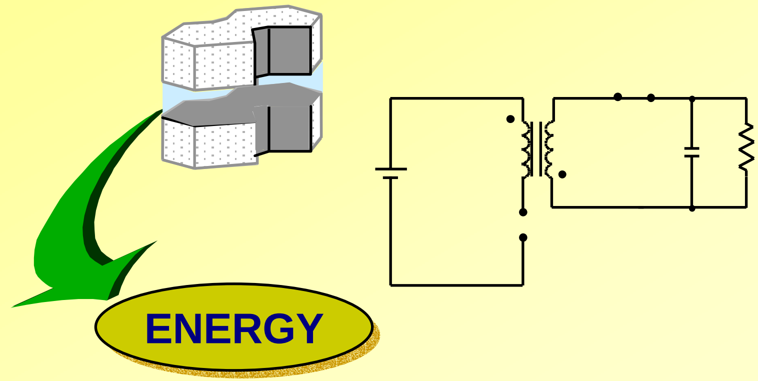
Flyback transformer

Electrical Description of Flyback Transformer

ON TIME



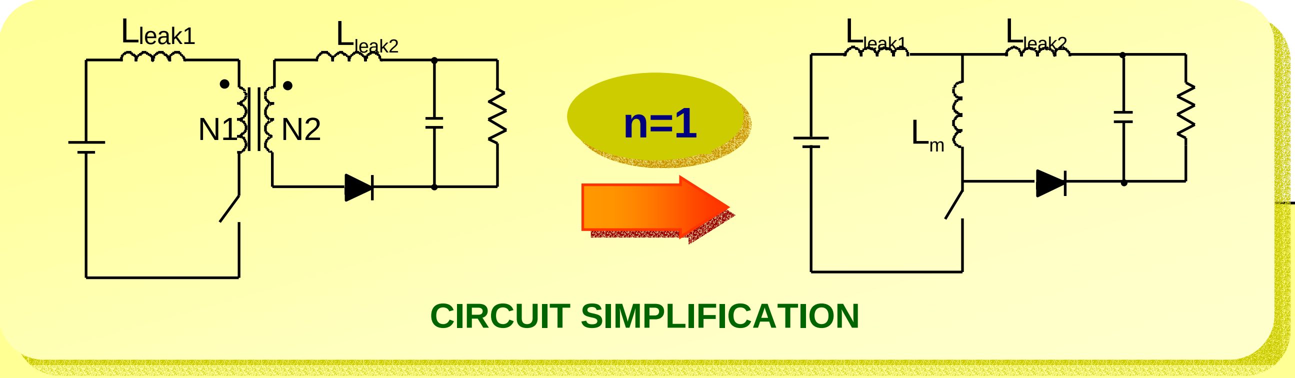
OFF TIME

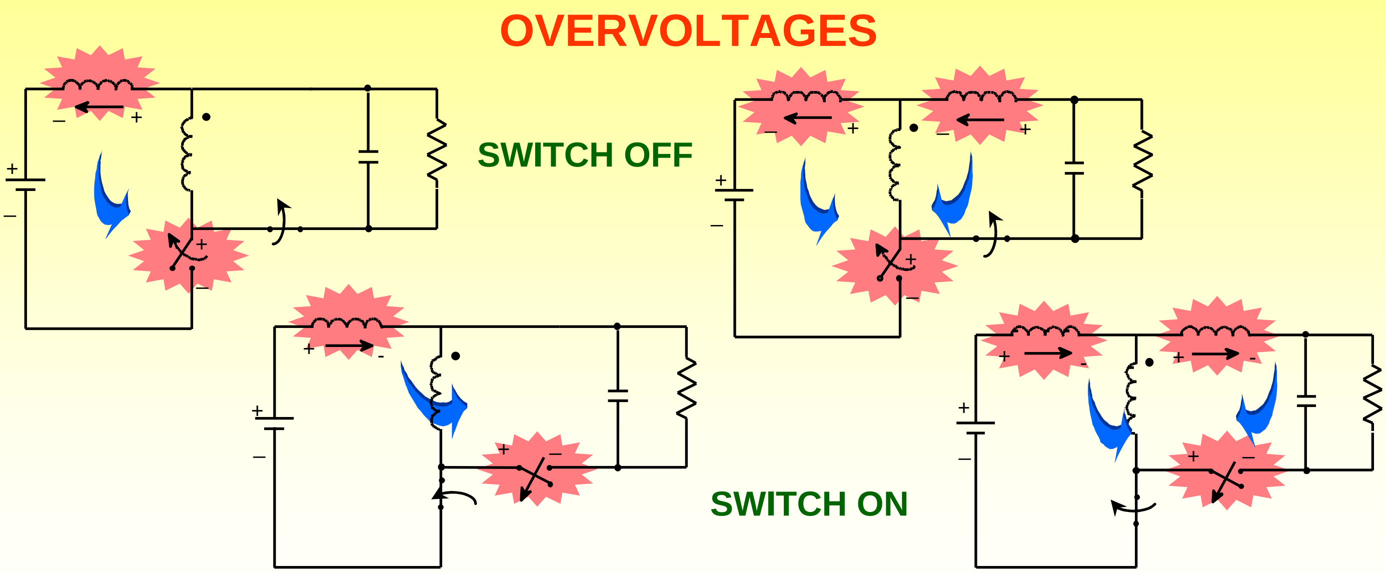


MAIN FEATURES

- 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

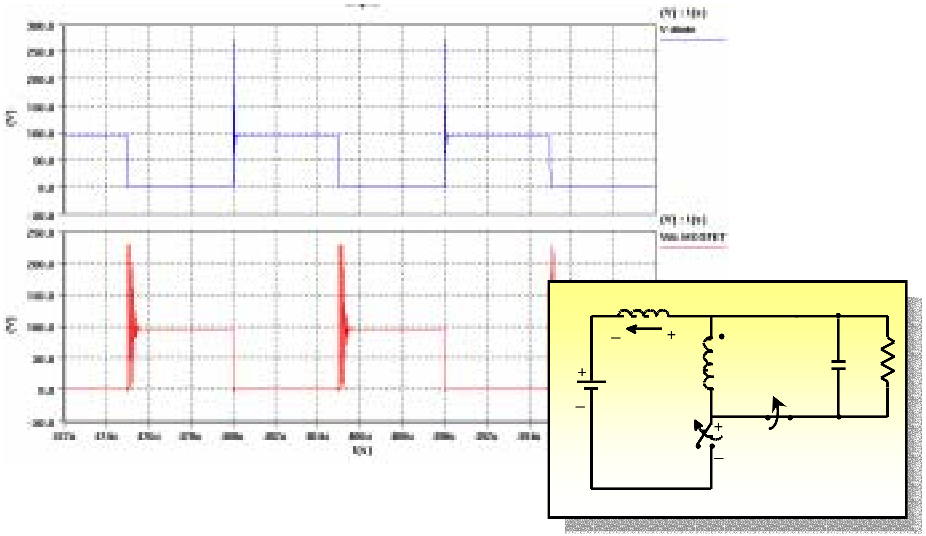
Electrical study of flyback topology

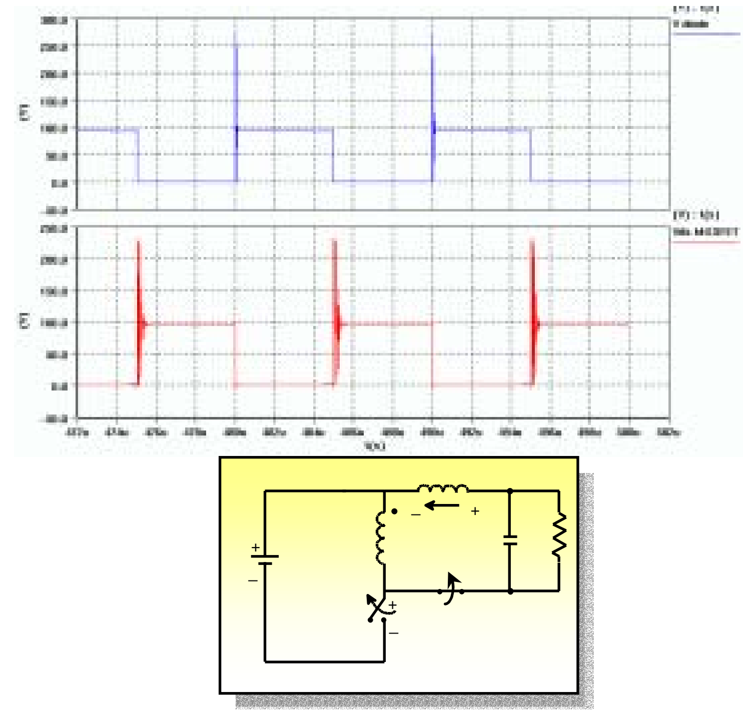


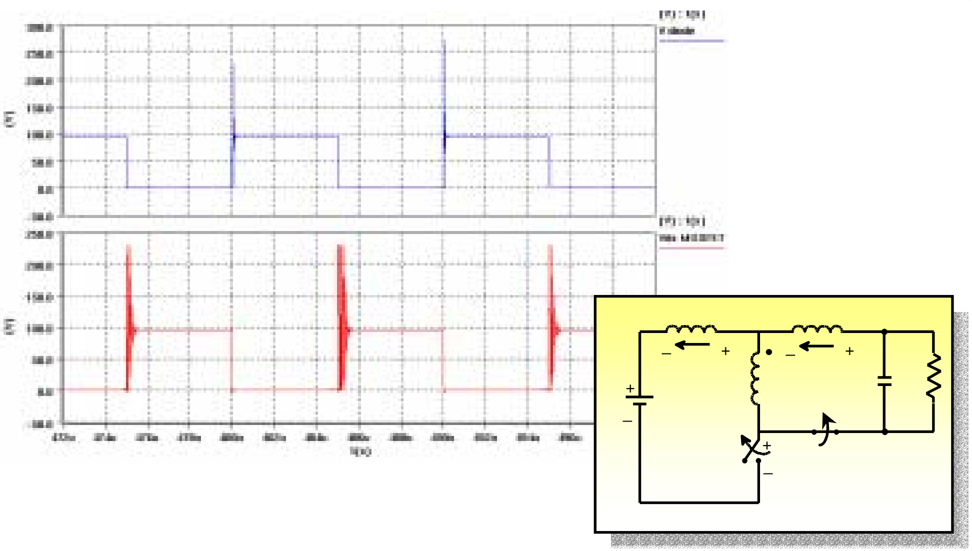


The leakage inductance of any winding has influence on MOSFET and diode voltages

Electrical study of flyback topology





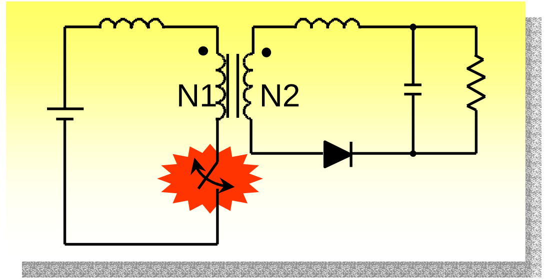


MAIN TARGET

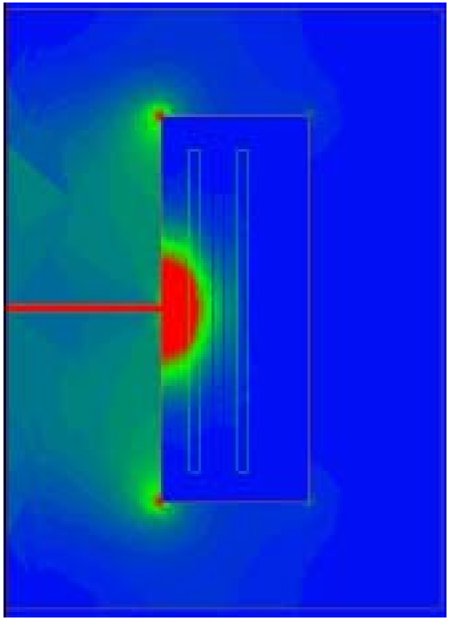
Reduced overall leakage inductance

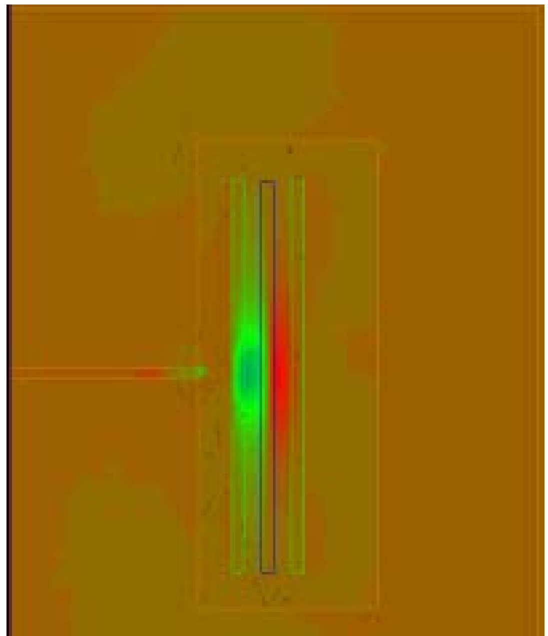
Study of the fields: leakage inductance

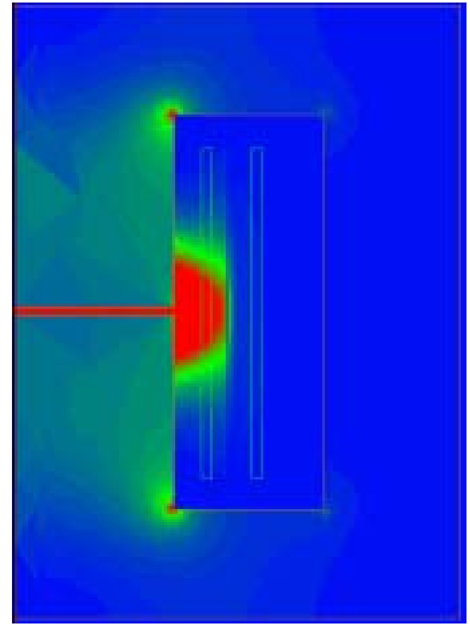
ENERGY 1

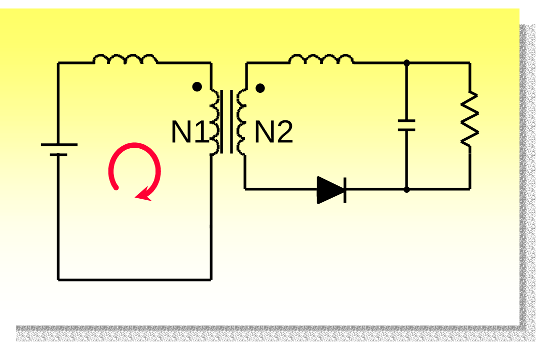


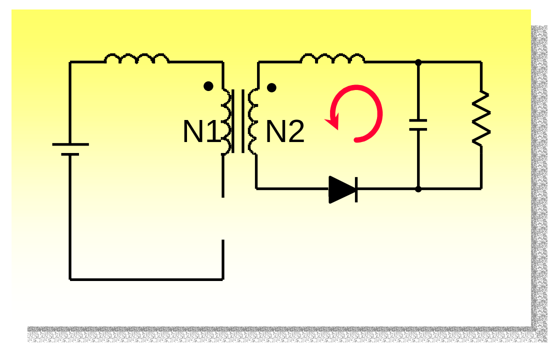
ENERGY 2









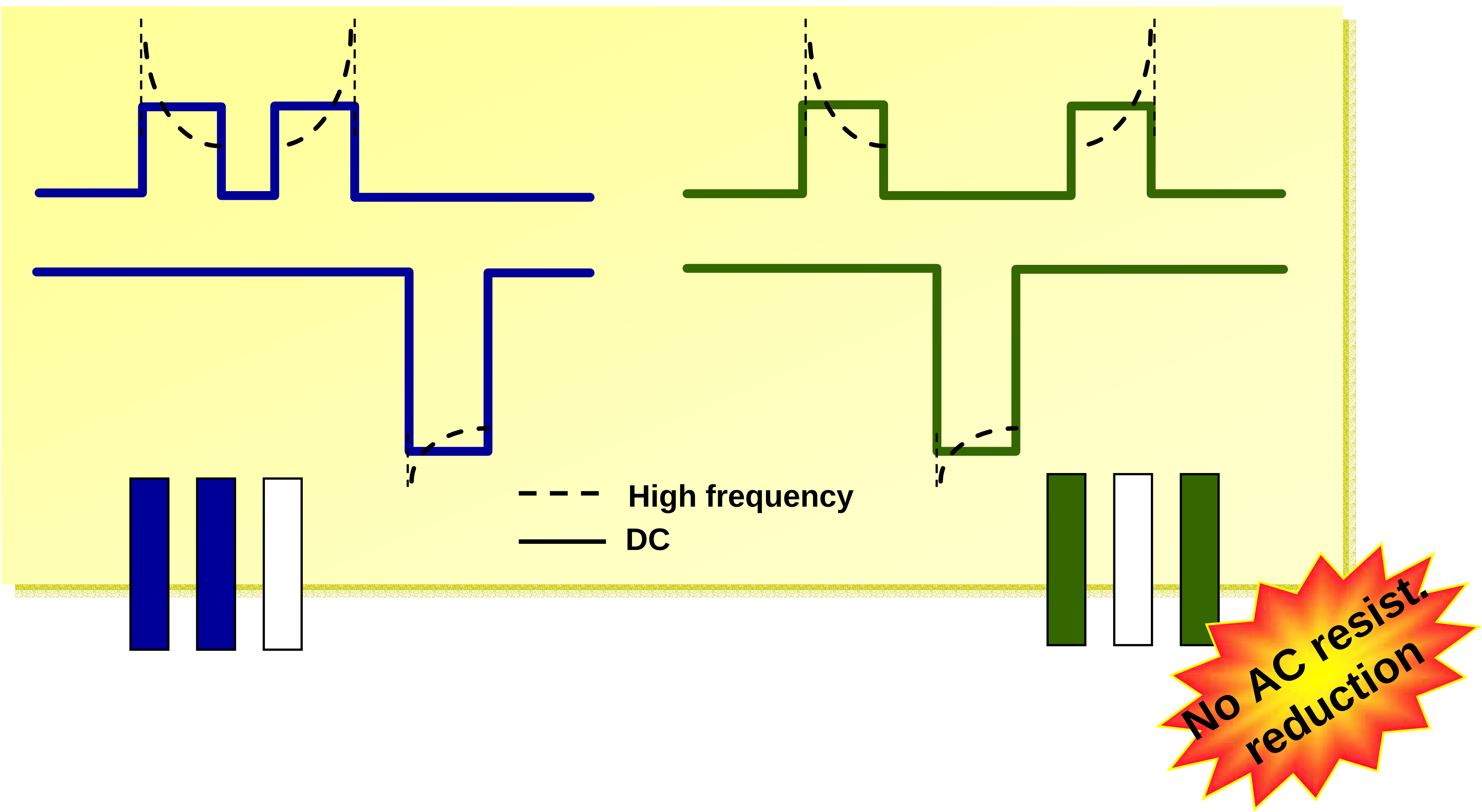


ENERGY 1 - ENERGY 2 =
LEAKAGE ENERGY

Goal: minimization of this energy

Interleaving in flyback type transformers

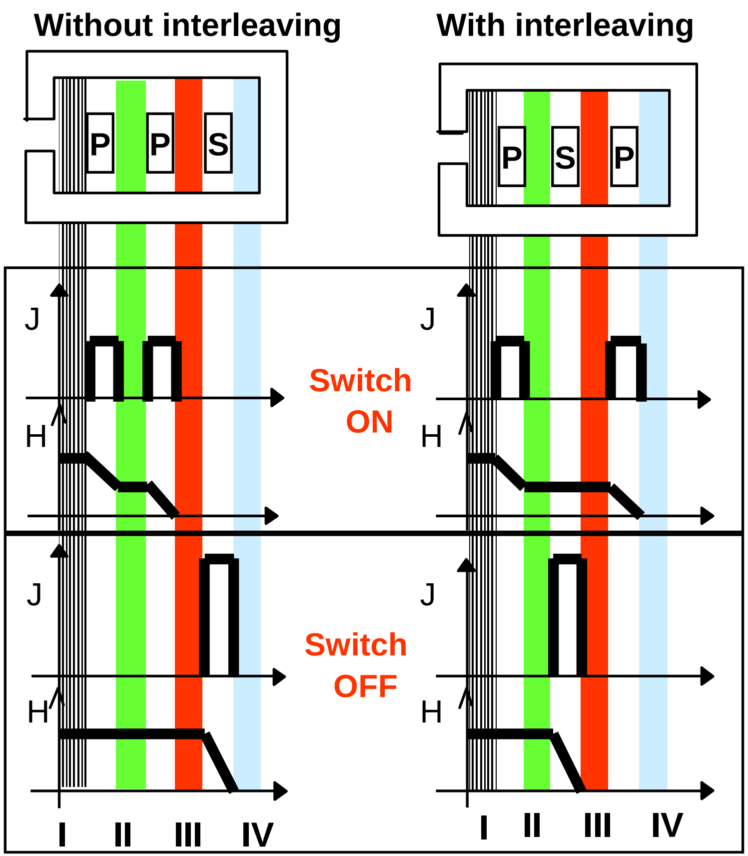
AC resistance

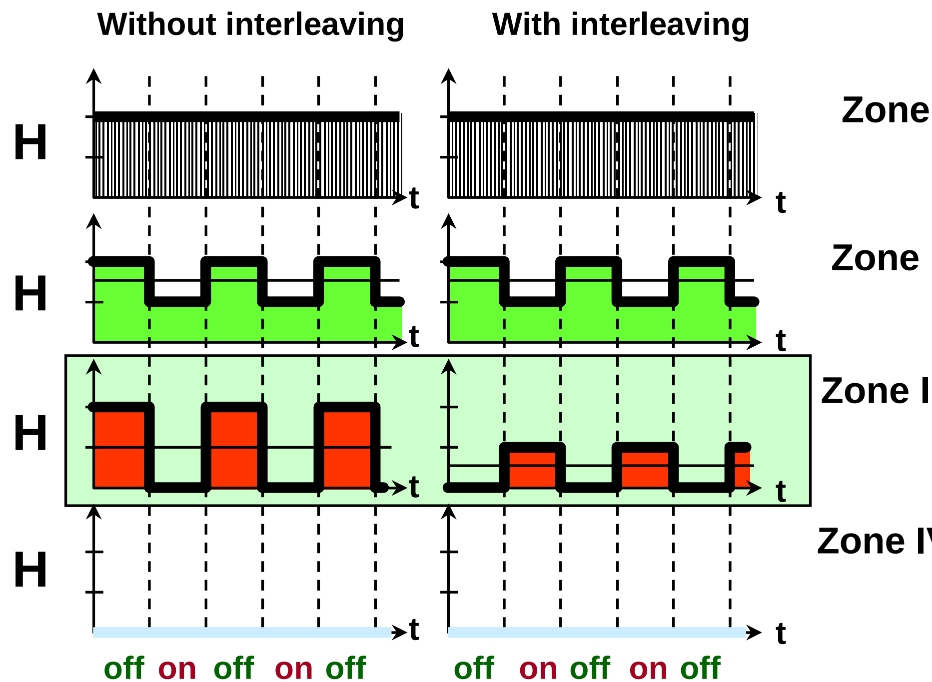


Interleaving in flyback type transformers

Leakage inductance

- **Magnetic field distribution**
  - ✓ **Low improvement during on and off states**
  - ✓ **High improvement in the switching times**





- Same current distribution
- *H* field distribution very similar (small differences in several parts of the window)

Interleaving in flyback type transformers

Forward type

- Energy transfer
- Interleaving
  - ✓ **Lower R_{AC}**
  - ✓ **Lower Energy in the window**
  - ✓ **Lower L_{LEAK}**

Flyback type

- Energy storage
- Interleaving
  - ✓ **Similar R_{AC}**
  - ✓ **Similar Energy in the window**
  - ✓ **Lower L_{LEAK}**

RECOMMENDED IN BOTH TYPES

- **Increase of cross regulation capabilities**
- **Reduction of size**

4.3

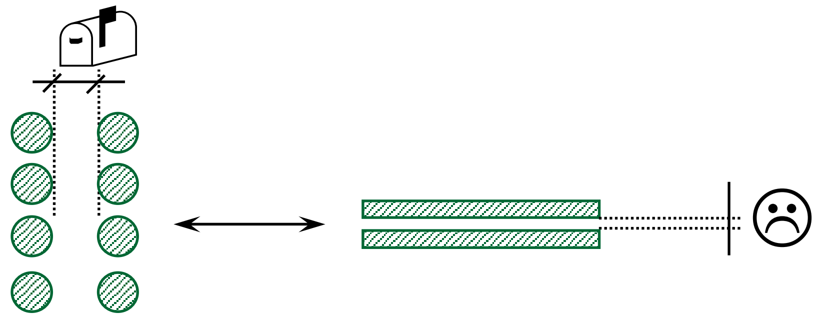
Low profile issues

Low profile

- The use of planar transformers is growing in the last years

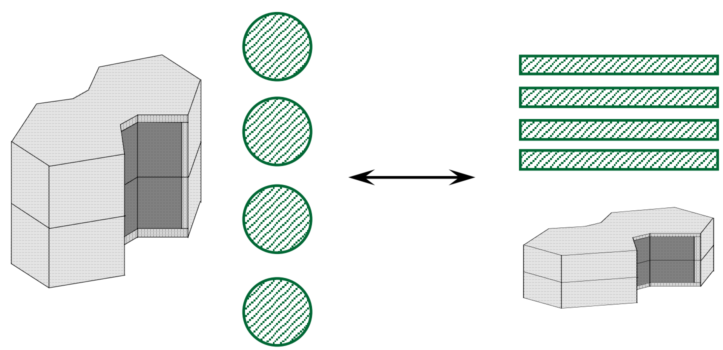
WHY?

☺ **Leakage inductance Reduction**



☺ **AC Resistance Reduction**

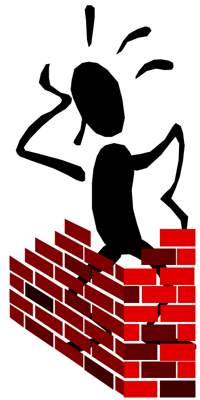
☺ **Size Reduction**



Low profile

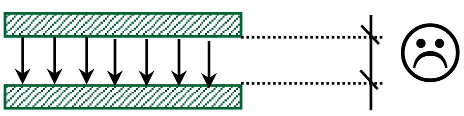
WHY NOT?

☹ **Technological step**



☹ **Thermal management**

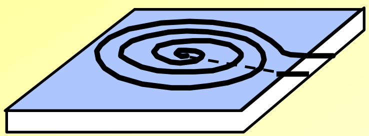
☹ **High capacitive effects**



Parasitic effects

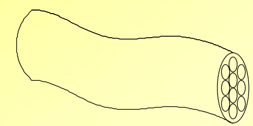
Planar structures vs Traditional structures

Planar transformer

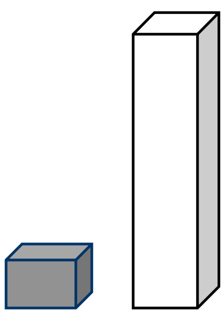


Qualitative comparison
(based on actual measurements)

Litz wire

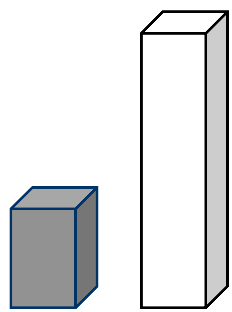


Lower leakage inductance



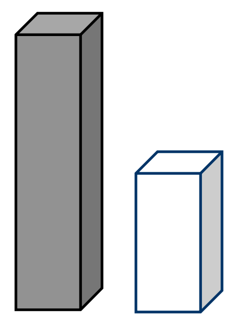
Reduction: 1:5

Lower AC Resistance



Reduction: 1:3

Higher capacitance



Increase: 2:1

Example

Transformer description
Core size: RM10

_PRIMARY: 12 turns
SECONDARY: 2 turns: Center tapped (Half-Bridge)

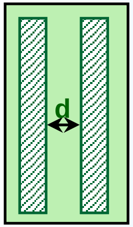
Comparison criteria: maximum current density (7.5A/mm^2)

LITZ WIRE		PLANAR
Primary: Litz wire (80x0.07 mm) Secondary: Litz wire (800x0.07 mm)		Primary: 0.276 mm^2 Secondary: 3.08 mm^2
2380 nH		480 nH
360 mΩ		119 mΩ
19pF		42pF
79%	Occupied window area 	30%

Layers separation

RESISTANCE

CONCENTRIC TRANSFORMERS

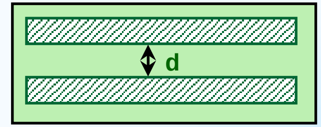


$\uparrow d \Rightarrow$

$\uparrow R_{DC}$ and $\downarrow R_{AC}$

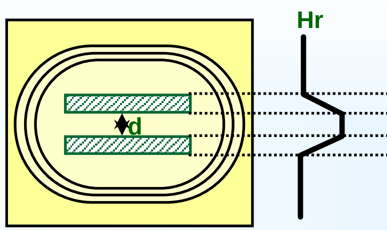
$\Rightarrow$ R = ??

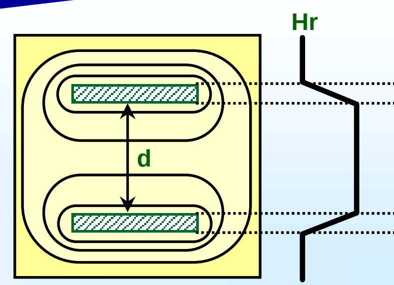
TOP-DOWN TRANSFORMERS (planar)



$\uparrow d \Rightarrow \downarrow R_{AC}$ and $R_{DC} \approx \Rightarrow \downarrow R$

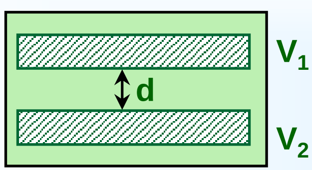
LEAKAGE INDUCTANCE





$\uparrow d \Rightarrow \uparrow$ Energy in the window $\Rightarrow \uparrow$ Leakage inductance

ELECTRIC ENERGY



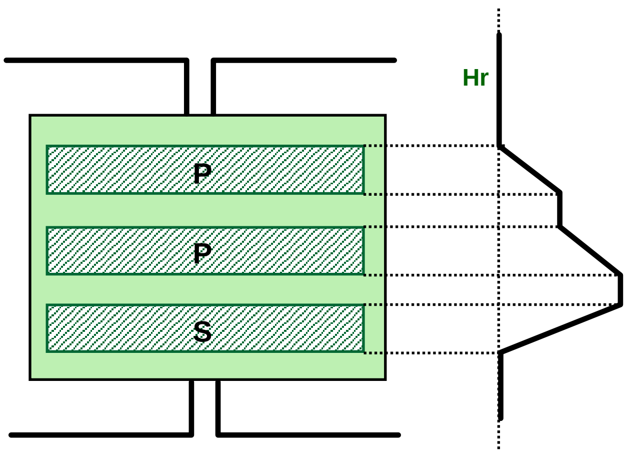
$\uparrow d \Rightarrow \downarrow C$

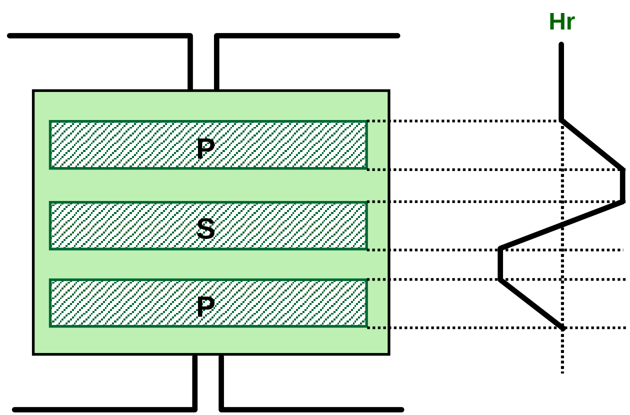
$$C \approx \frac{S}{d}$$

Interleaving in low profile transformers

Interleaving improvements

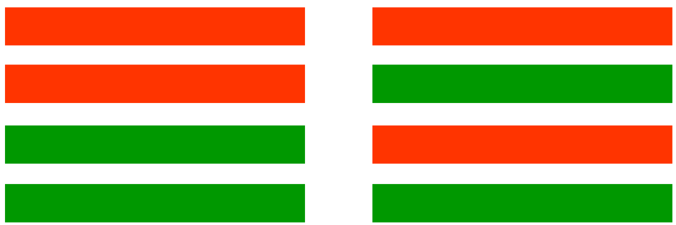
- ➢ Reduction of leakage inductance due to:
  - ✓ **Lower energy in the window**
- ➢ Reduction of AC resistance due to:
  - ✓ **Optimization of current distribution in the conductors (NOT IN FLYBACK TYPE TRANSFORMERS!!)**





Comparison of different winding strategies

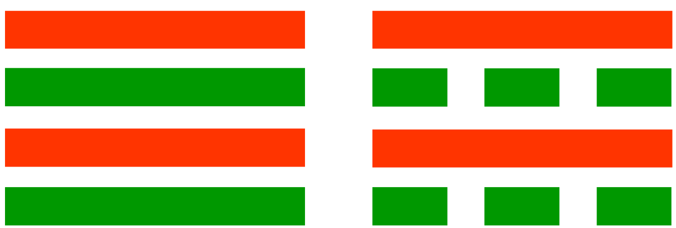
@200kHz



A B

	R (mΩ)	Lleak (nH)
A	3.44	2.63
B	3.07	0.59

Do interleaving!!
(but care about insulator thickness)



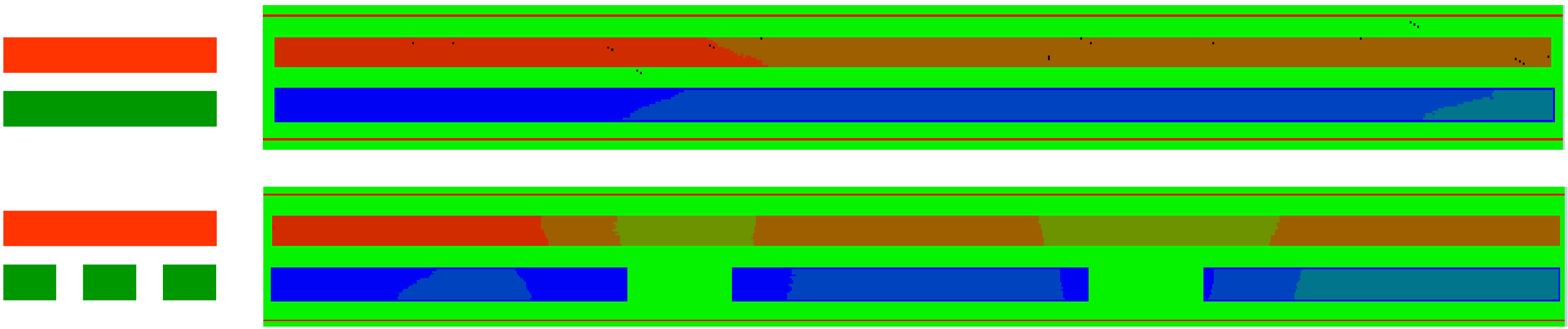
B C

	R (mΩ)	Lleak (nH)
B	3.07	0.59
C	3.43	0.7

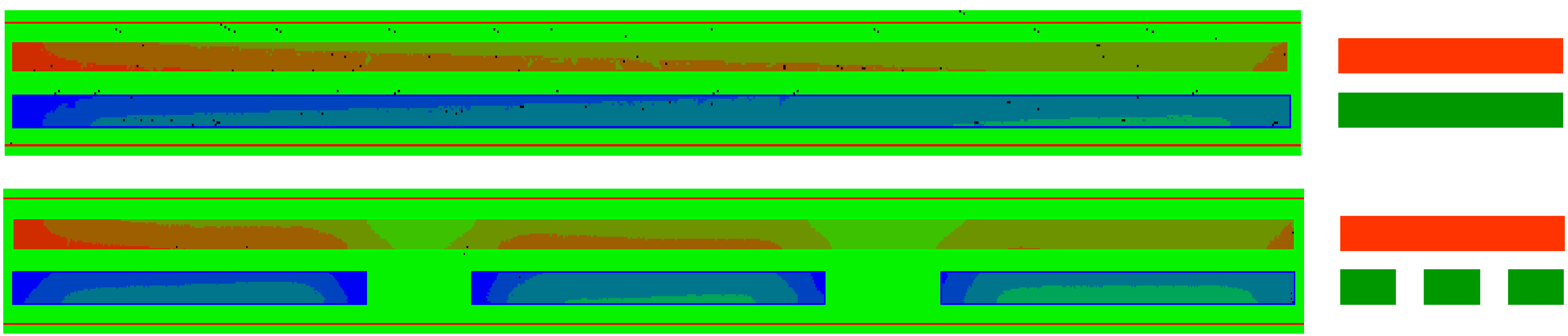
Do not split the track!

Comparison of different winding strategies

Splitting the tracks
Opposite currents tend to come closer

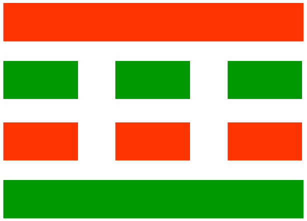


Current density distribution @250kHz



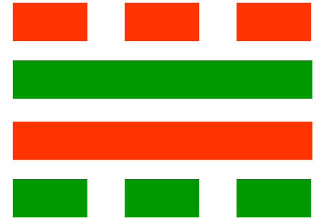
Current density distribution @1MHz

Comparison of different winding strategies



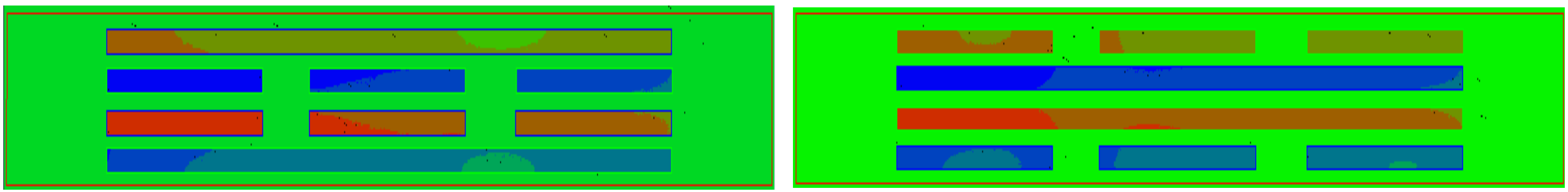
A

	R (mΩ)	Lleak (nH)
A	3.4	0.73
B	3.25	0.58

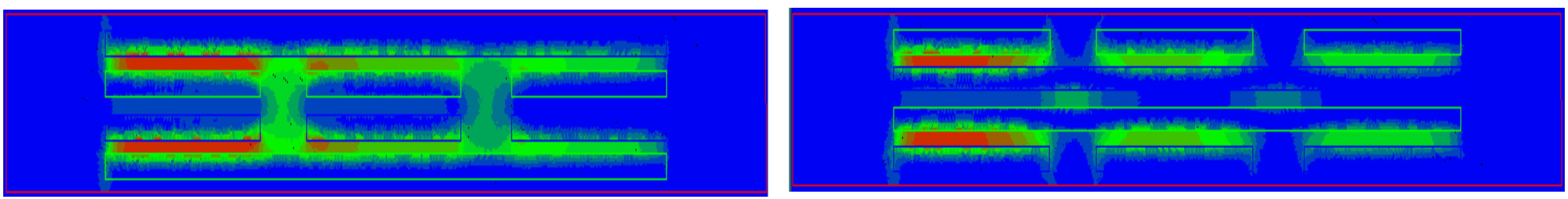


B

Current density Distribution



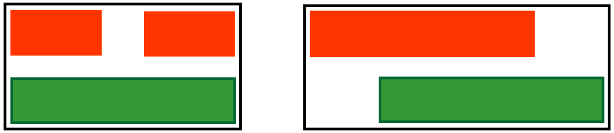
Magnetic Energy Distribution



@200kHz

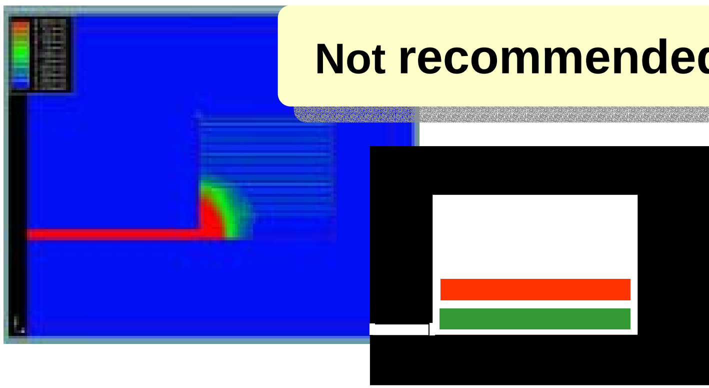
Place splitted tracks outside!!

Design guidelines

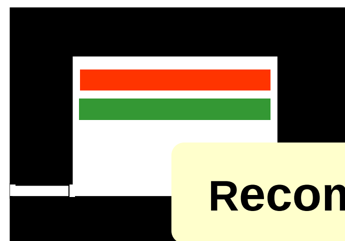


Not recommended

Recommended



Not recommended



Recommended

<2δ (skin depth)

Lower current density criteria

5

Application to converters

Charger of capacitors

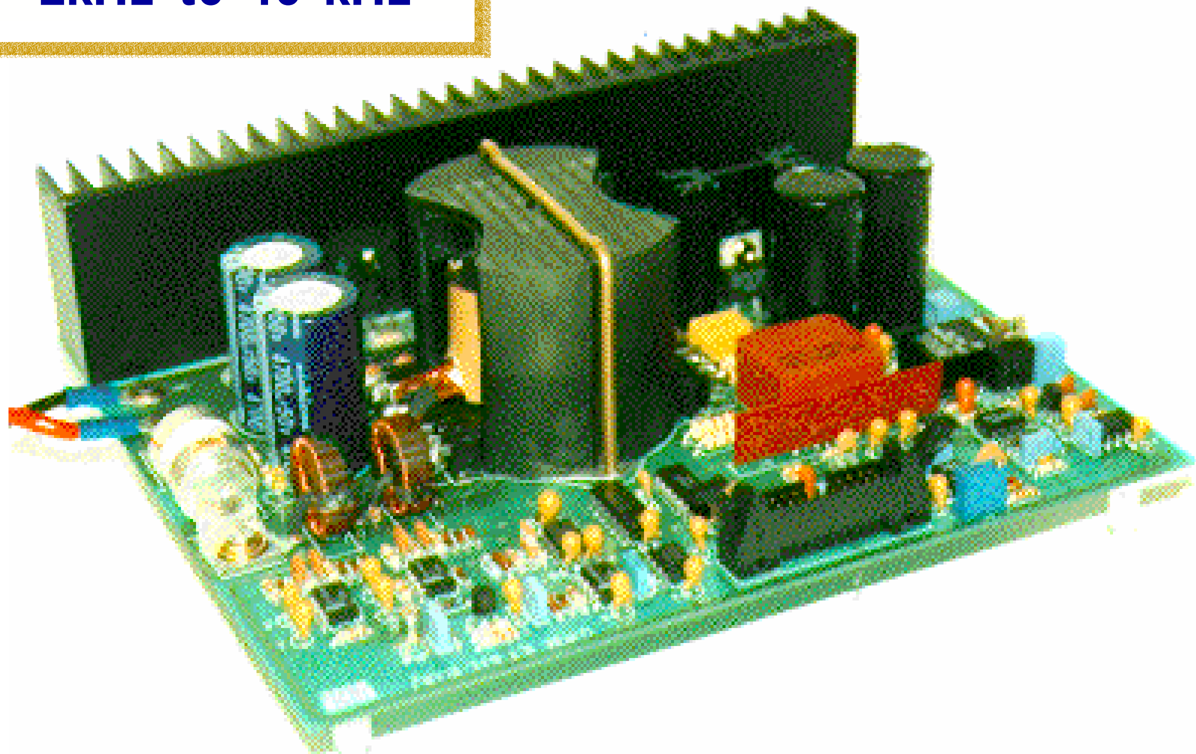
Multioutput converter

Low profile converter

Flyback converter for capacitor charger

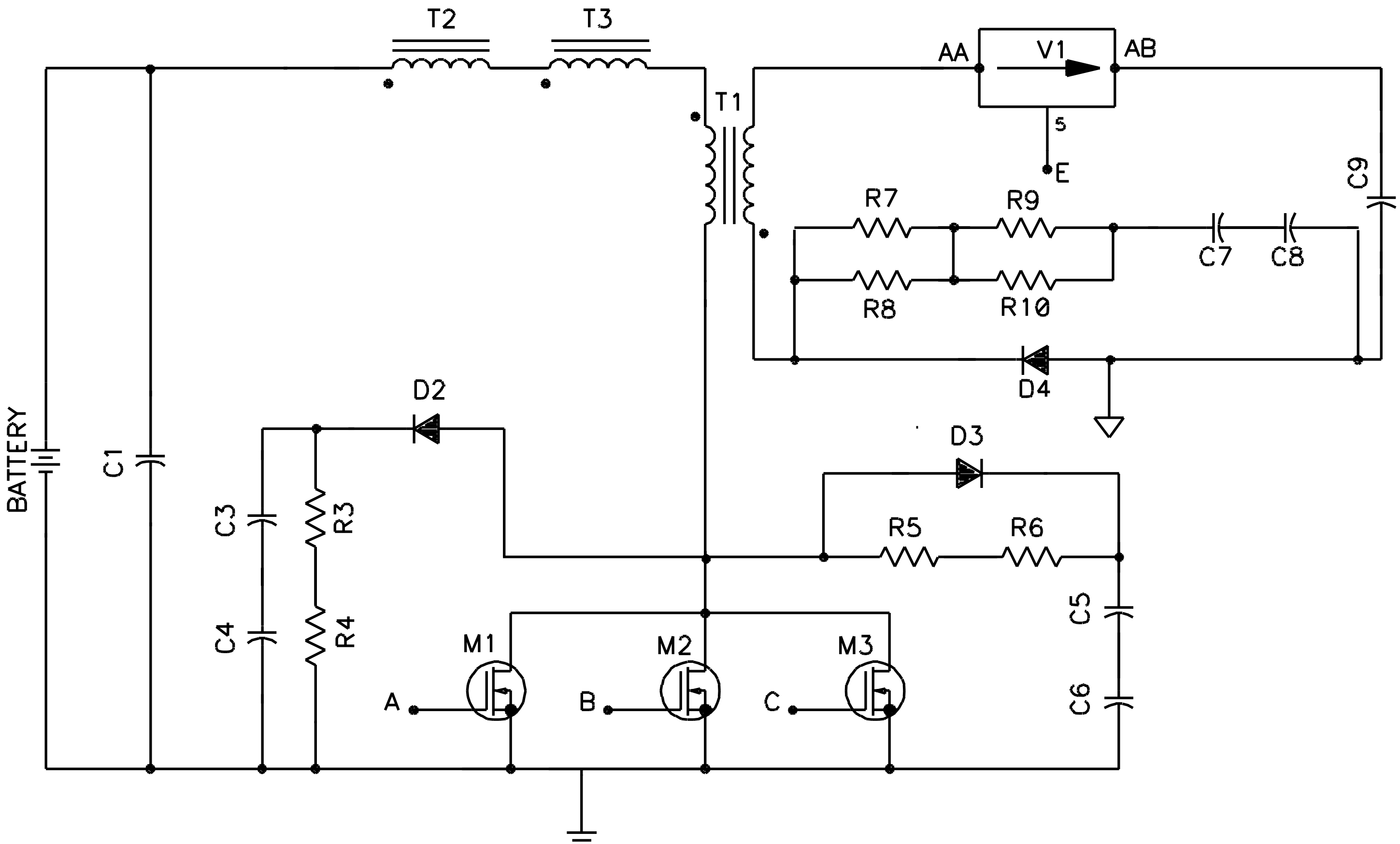
FLYBACK WITH HYSTERETIC CONTROL

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**



Flyback converter for capacitor charger

SCHEMATIC



Medical safety protections

Flyback converter for capacitor charger

Design of the power transformer

Core: PM62
- N27

Windings
- Solid wires
  - Primary 8 x 0.7mm
  - Secondary 1 x 0.7mm

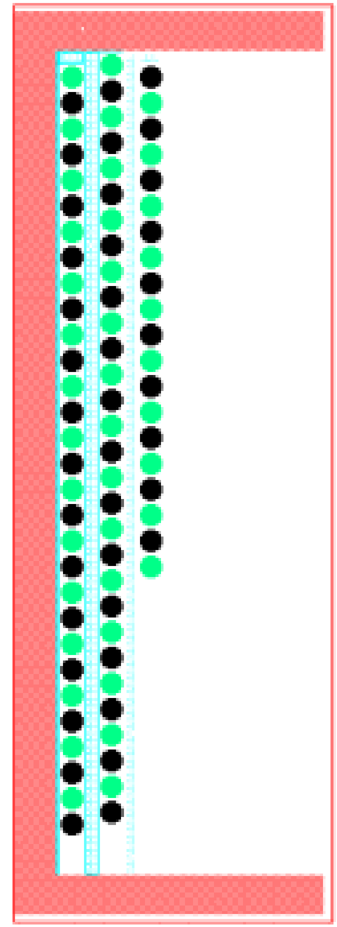
Turns ratio
- Primary: 5
- Secondary: 40

Max. Switching frequency: 40 kHz

$L_M = 8\mu H$

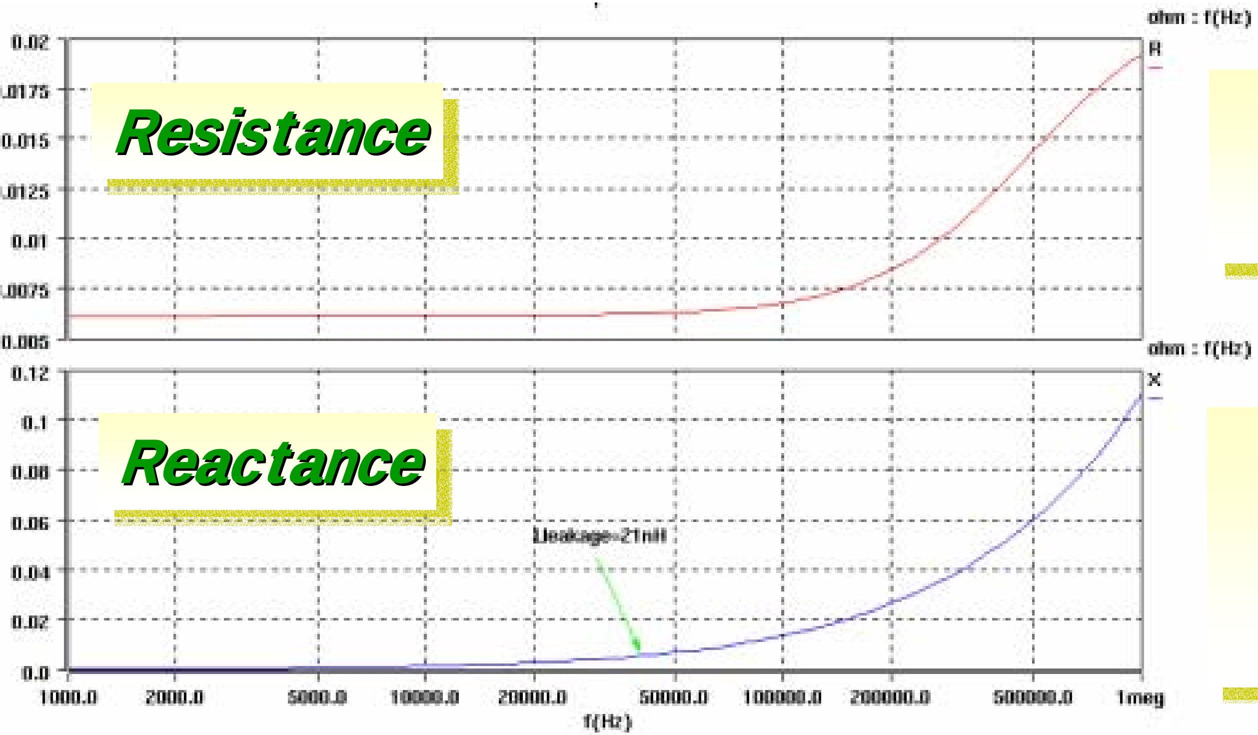
ΔB
- B_{max} 250mT
- B_{min} 70mT

I_{rms} primary = 46A



Flyback converter for capacitor charger

Transformer model



Open circuit test

Lm = 8μH

Short circuit test

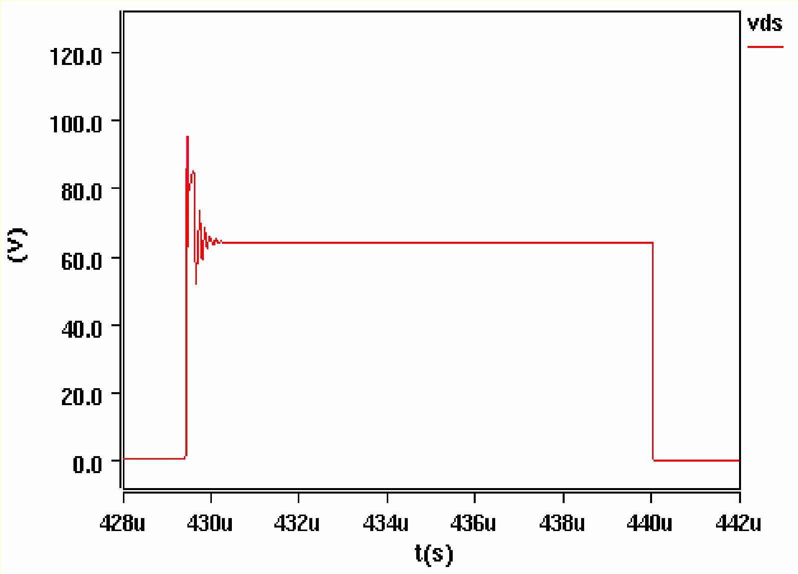
L_{leak} = 21nH (40kHz)

R_{AC} = 6mΩ (40kHz)

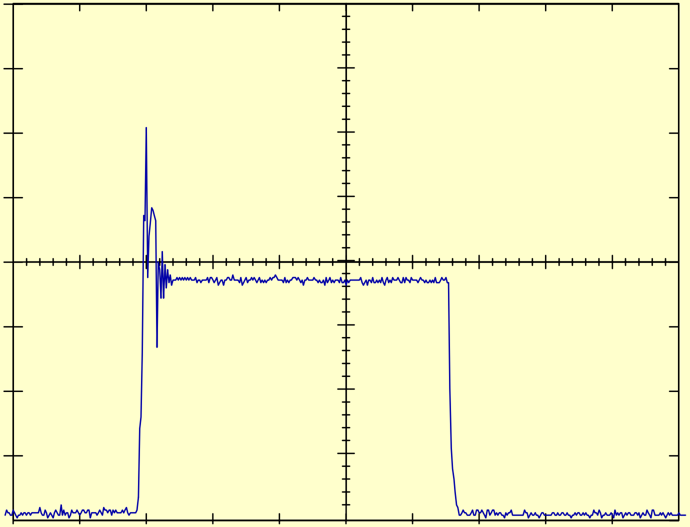
Flyback converter for capacitor charger

Experimental Results

SIMULATION



MEASUREMENT

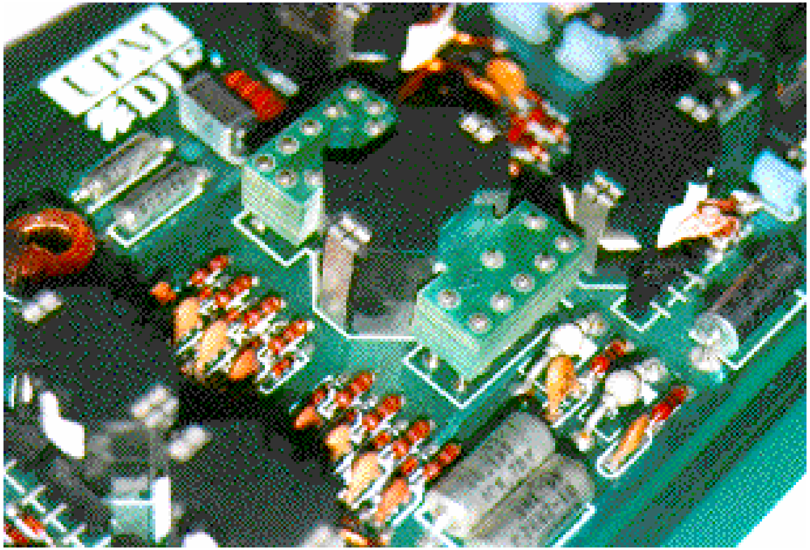


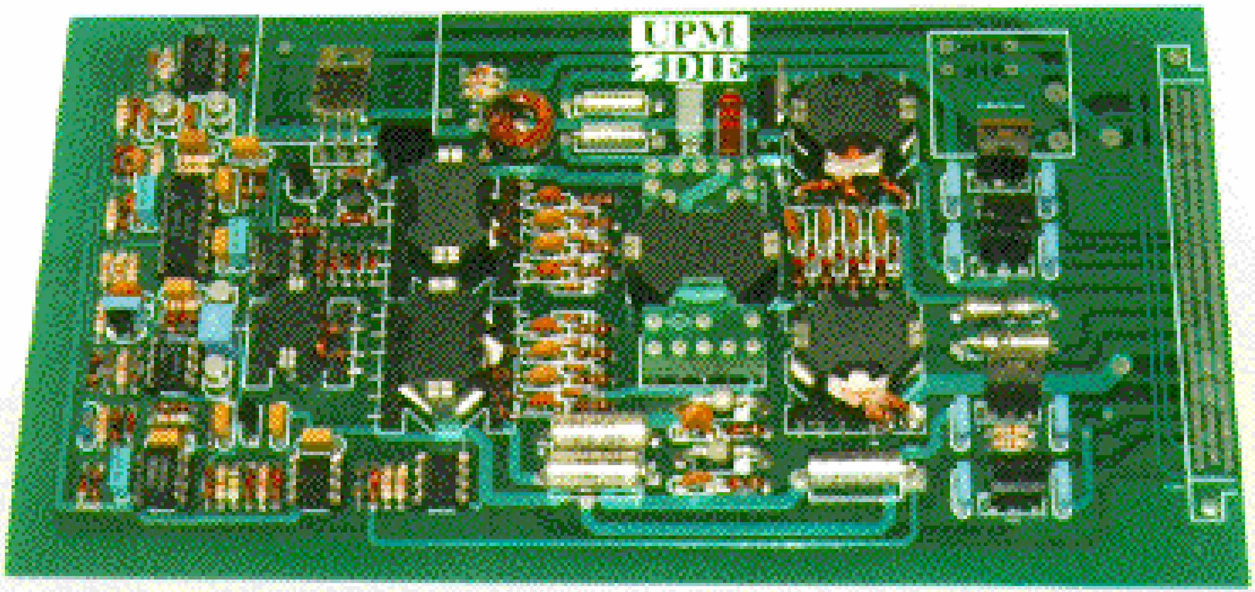
Vds in main switch at nominal conditions (Vo = 300V, Ids = 25-90A)

Multioutput forward RCD converter

FORWARD RCD

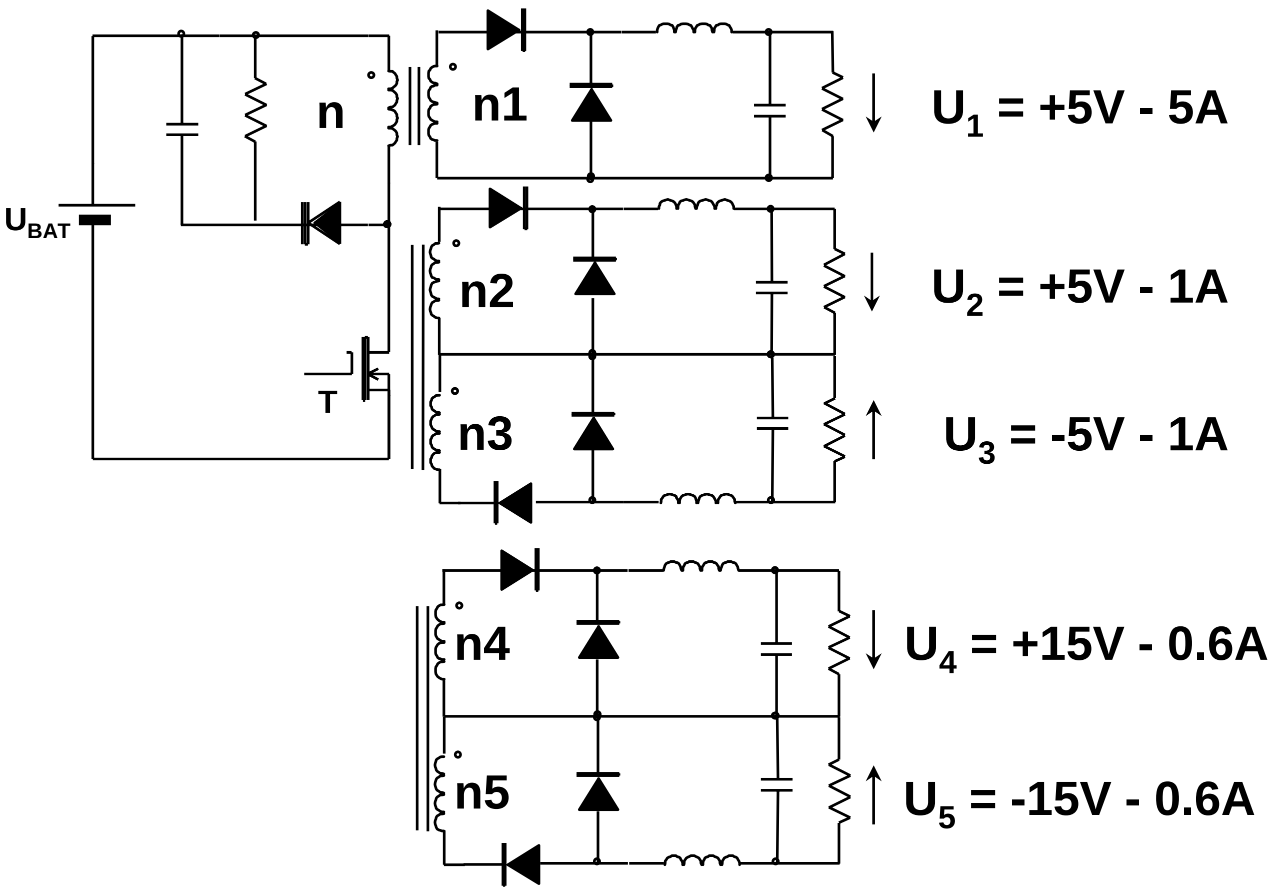
Input voltage:	**18 to 32 V**
Output Power:	**60 W**
Switching Frequency:	**300 kHz**
Output 1:	**5 V, 5 A**
Outputs 2,3:	**5 V, 1 A**
Outputs 4,5:	**15 V, 0.6 A**





Multioutput forward RCD converter

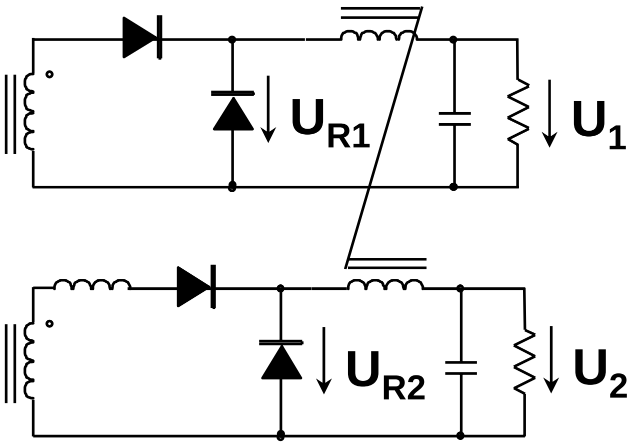
Schematic



WARNING: Transformer is the *heart* of a multi-output converte

Transformer and output inductors affect to cross regulation

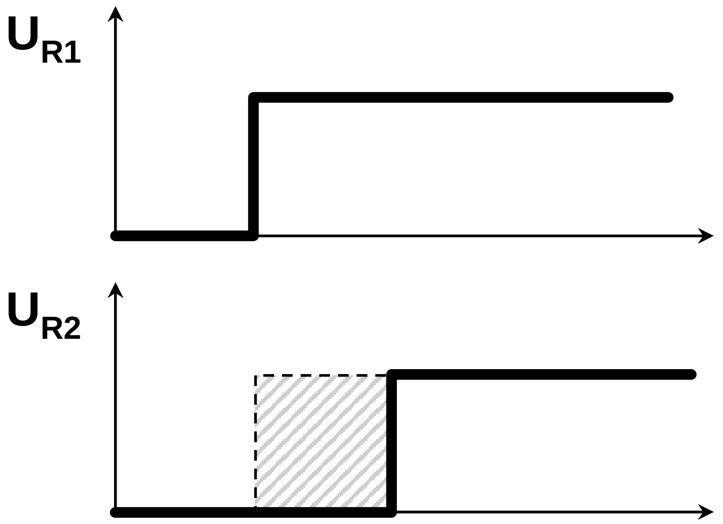
Dynamic cross regulation



Output inductors

(coupled inductors)

Static cross regulation



Transformer

(leakage between secondaries)

(leakage in primary does not affect to cross regulation)

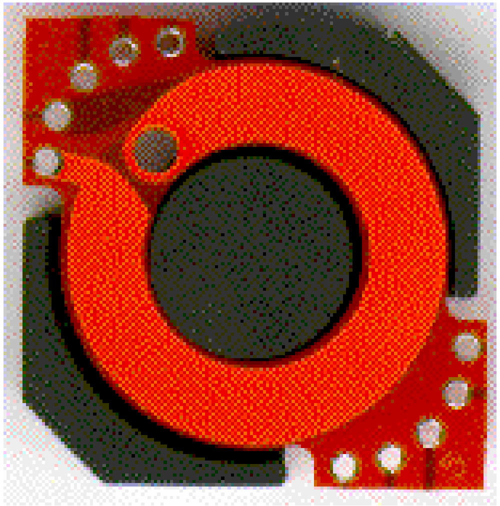
Multioutput forward RCD converter

Technological Characteristics

Copper thickness: $100\mu m$

Substrate thickness: $50\mu m$

Insulator thickness: $10\mu m$



Multioutput forward RCD converter

Design of the power transformer

Turns ratio

Primary	3
Secondary 1	2
Secondaries 2, 3	2
Secondaries 4, 5	6

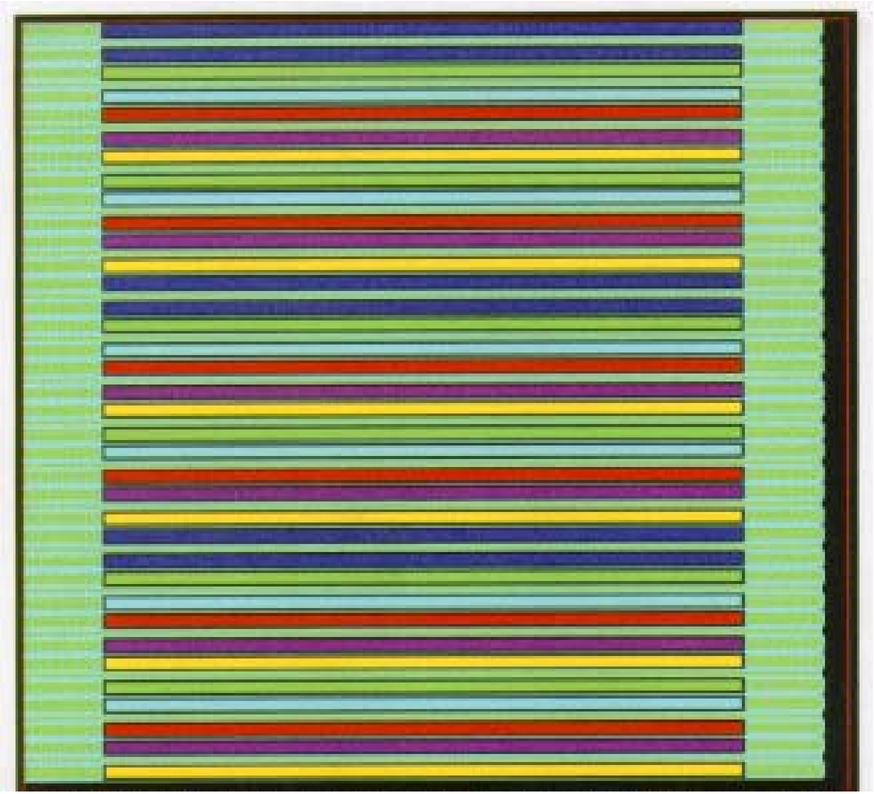
Switching frequency: 300kHz

Core: RM10 Low Profile

Material: 3F3

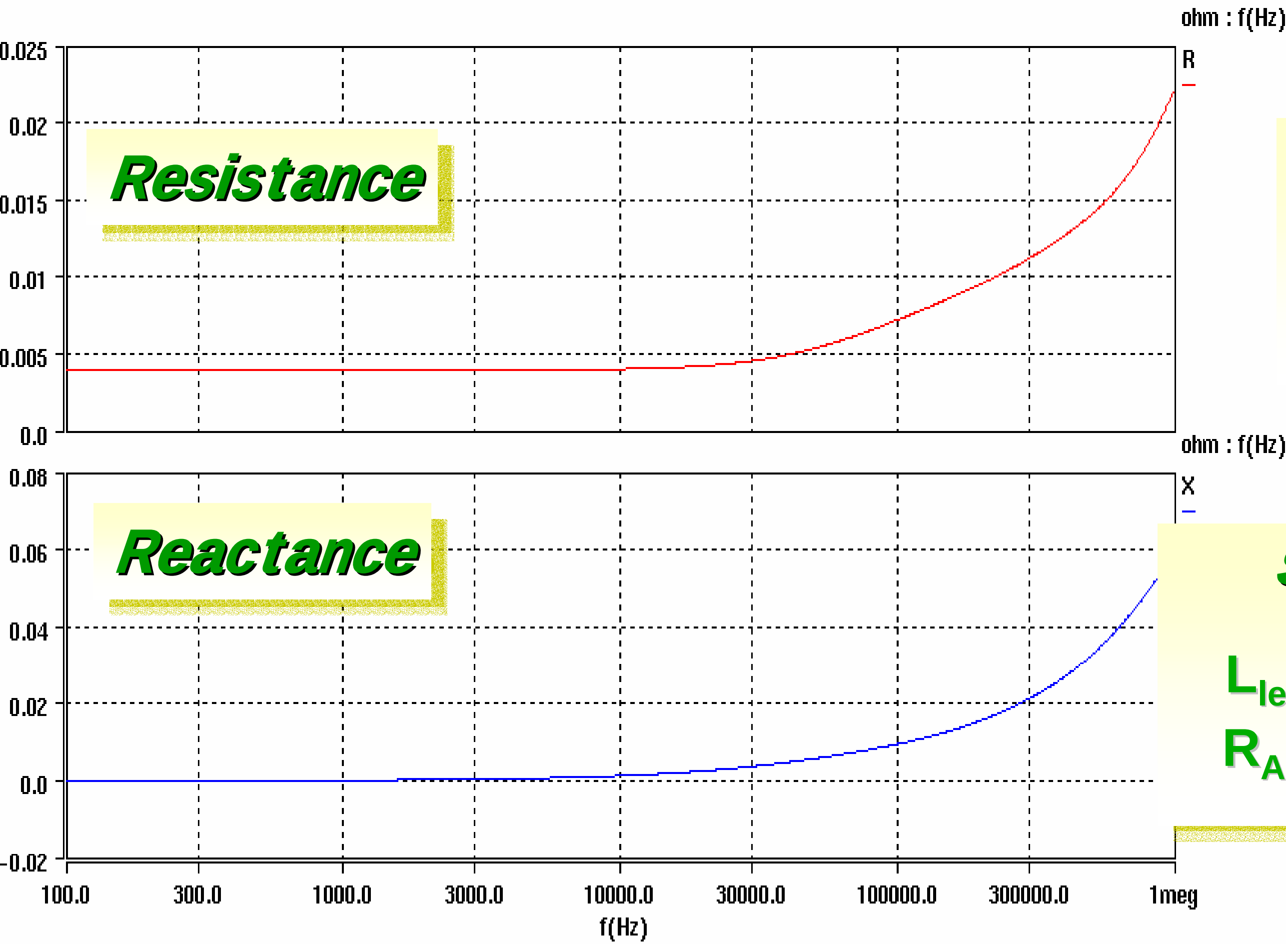
Windings: 36 copper layers

Cross section



Multioutput forward RCD converter

Transformer model



Open circuit test

Lm = 46 μH

Short circuit test

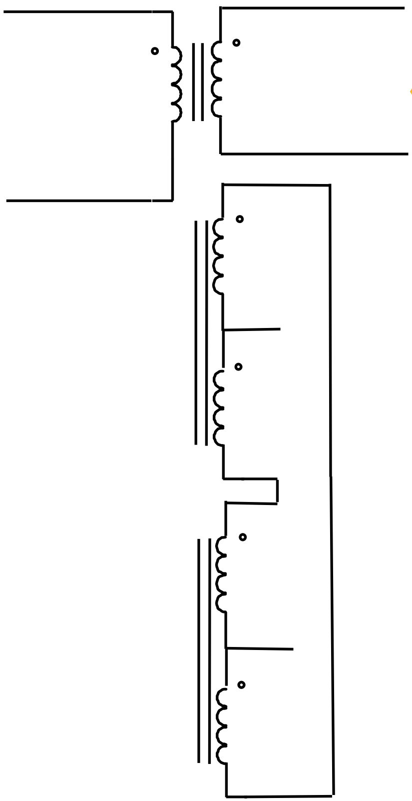
L_{leak} = 11nH (300kHz)

R_{AC} = 11mΩ (300kHz)

Multioutput forward RCD converter

Test of secondaries coupling

2 transformers have been tested



L_1 (300kHz)

TRANSF. 1	TRANSF. 2
Secondaries bad coupled	Secondaries well coupled
L_1 = 220nH	L_1 = 6.6nH

Multioutput forward RCD converter

Comparison of the static cross regulation

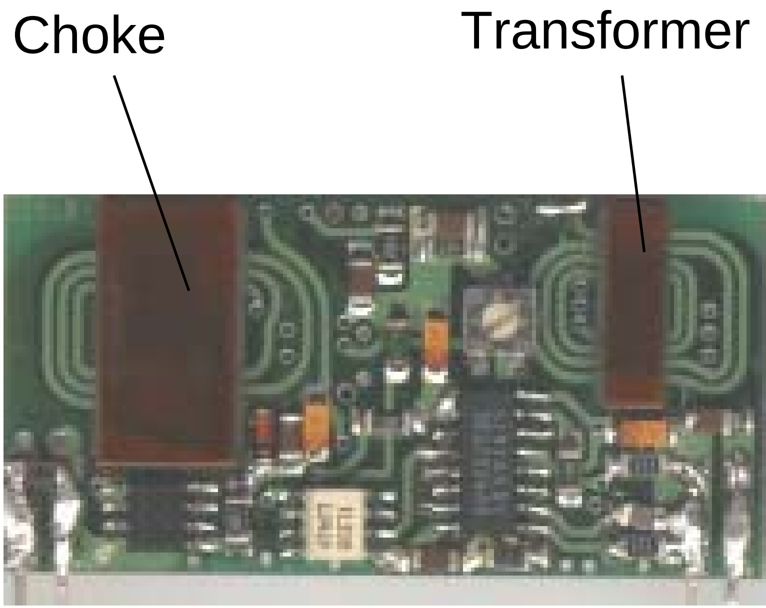
ΔU(mV)	TRANSFORMER 1	TRANSFORMER 2
U1	0	0
U2	176	106
U3	177	109
U4	673	338
U5	609	291

TEST CONDITION — Output current in main output: $I_1 = 5A$ / $I_1 = 0.5A$

Low profile on board converter (multilayer PCB)

FORWARD WITH RESONANT RESET

Output:	**1.5 V / 3 A**
Output Power:	**5W**
Input Voltage:	**3 to 6 V**
Switching Frequency:	**300 kHz**
Max. overall efficiency:	**85% (82%typ.)**

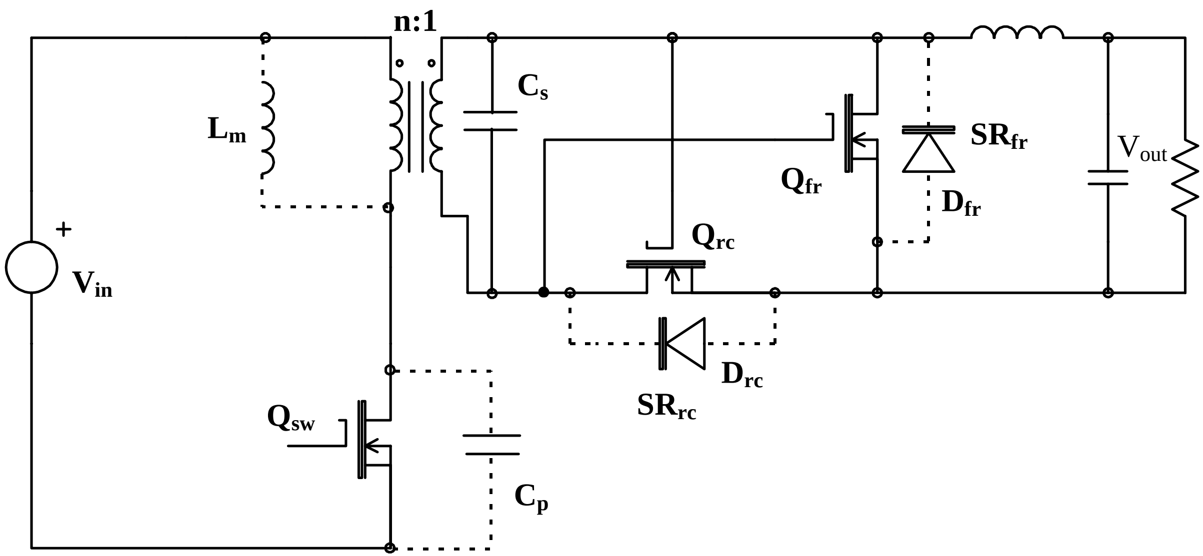


GOALS

- ✓ **Efficiency and size**
- ✓ **Magnetic components integrated in a multi-layer PCB**

Low profile on board converter (multilayer PCB)

Forward with Resonant Reset



FEATURES

- ✓ **Simplicity**
- ✓ **Self driven synchronous rectification**
- ✓ **WARNING: Performance depends on parasitics (transformer and semiconductors)**

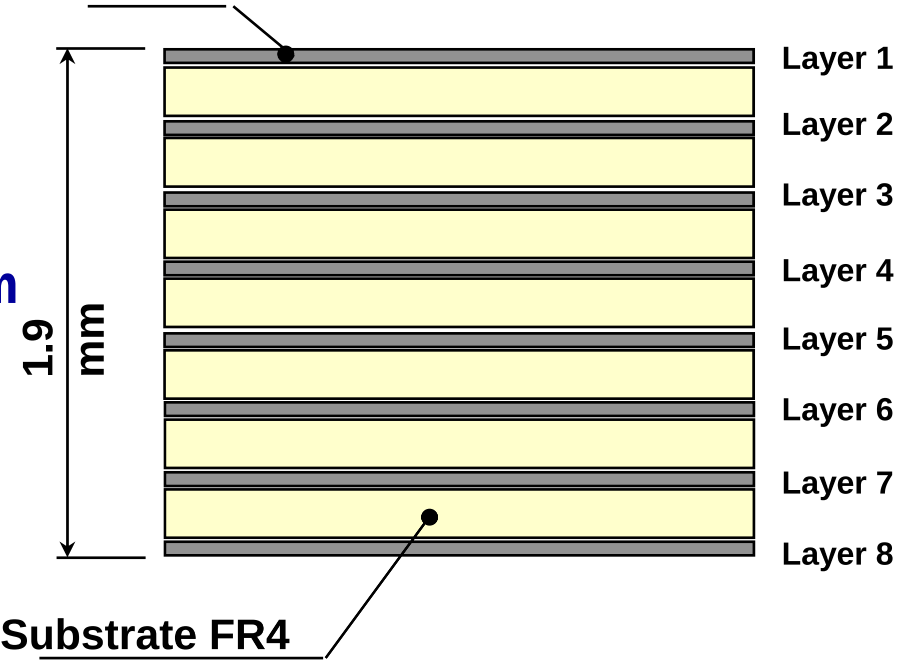
Low profile on board converter (multilayer PCB)

Technological Characteristics

8 layers

Copper thickness: 70 mm

Substrate thickness: 190 mm



Overall design is subjected to the PCB characteristics

Low profile on board converter (multilayer PCB)

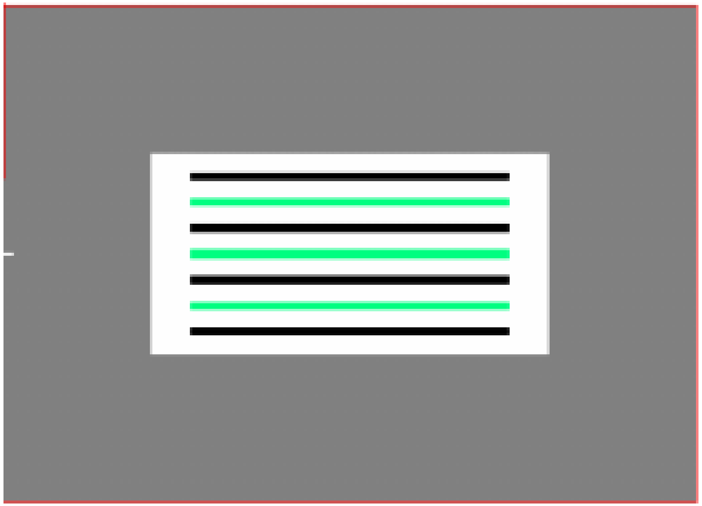
Design of the power transformer

Turns ratio 4 : 3

Switching frequency: 300 kHz

Resonant freq / Switching freq = 0.85

Parasitic capacitances of the switches



Turns ratio 4 : 3

Core

- Planar E core (E 14 / 3.5 / 5)
- Plate: PLT 14 / 5 / 1.5 3F3

Windings

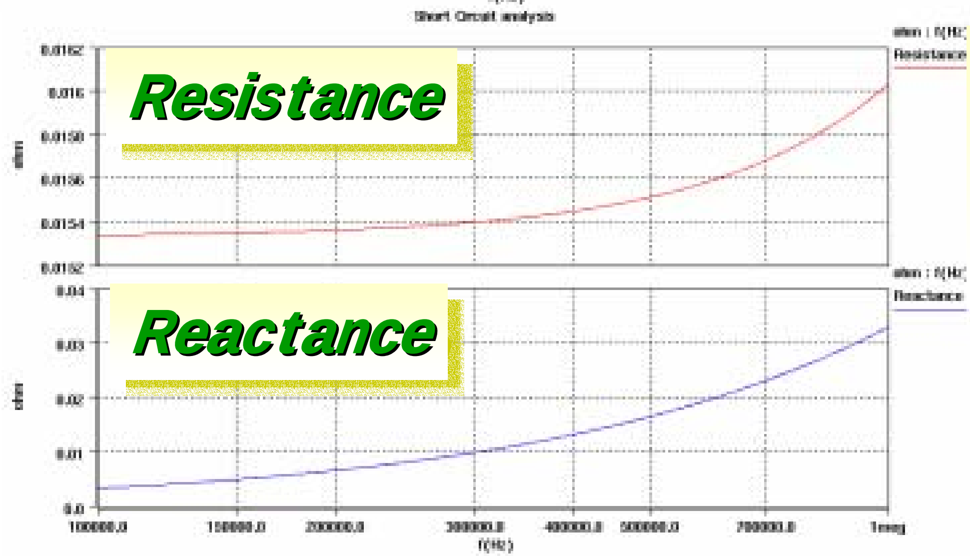
- 1 turn per layer
- n1 = 4 ; n2 = 3

Low profile on board converter (multilayer PCB)

Transformer model

Open circuit test

Lm = 19.3μH



Short circuit test

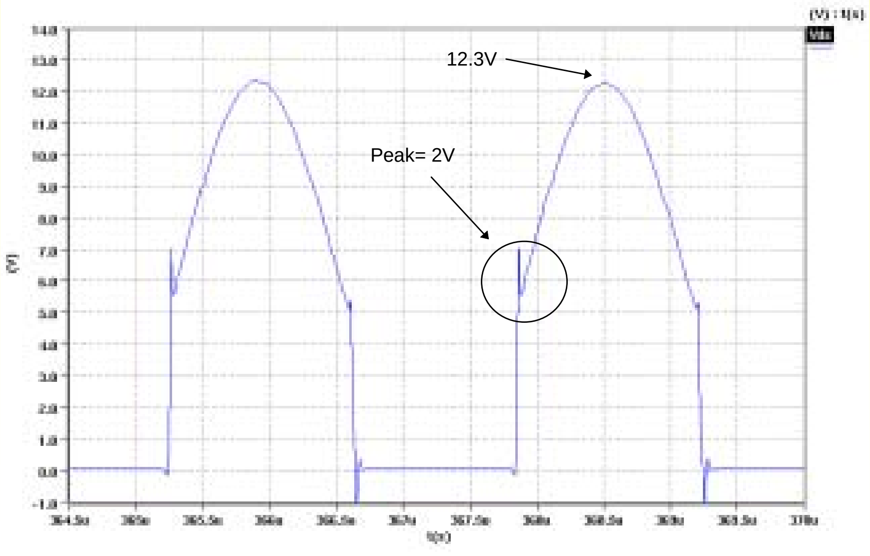
L_{leak} = 5.2 nH (300kHz)

R_{AC} = 15.4 mΩ (300kHz)

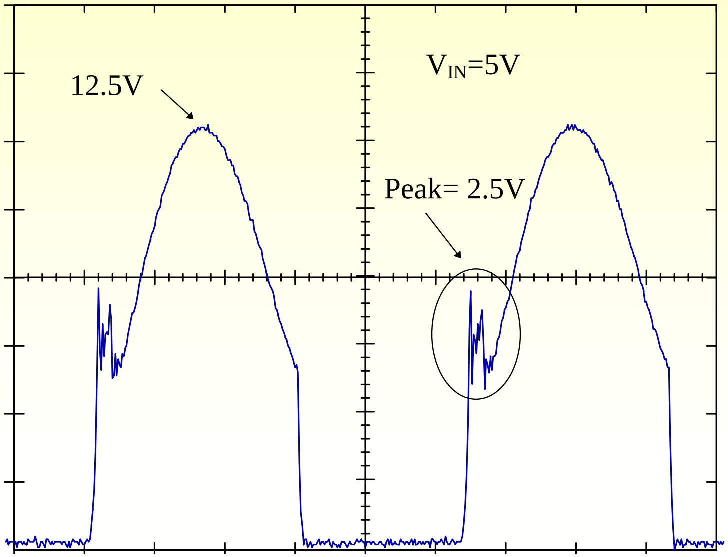
Low profile on board converter (multilayer PCB)

Experimental Results

SIMULATION



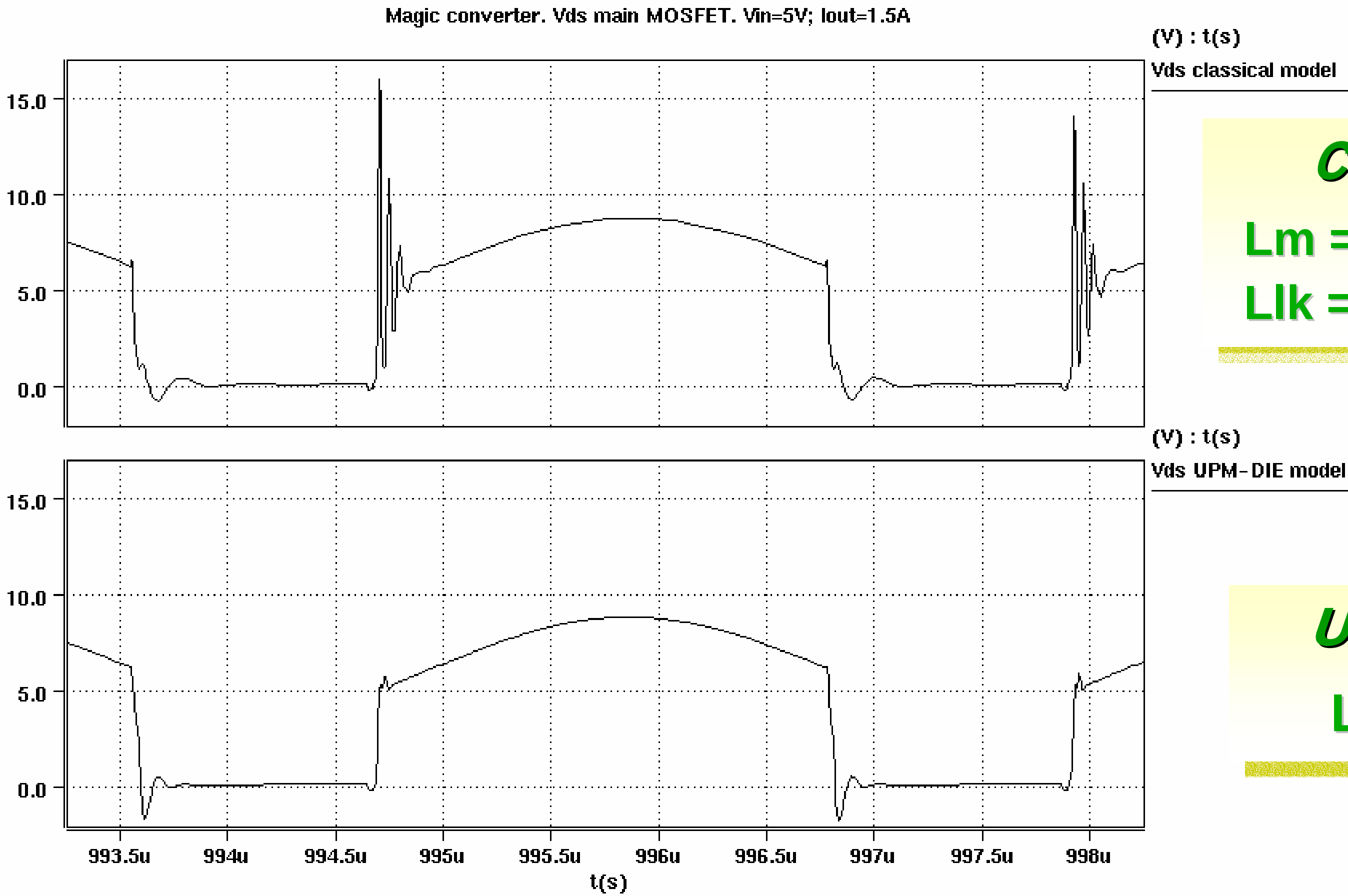
MEASUREMENT



Vds in main switch at nominal conditions (Vin=5V, Io= 3A)

Low profile on board converter (multilayer PCB)

If you just estimate leakage on a thick film transforme



Classical model

Lm = 30 μH

Llk = 30nH (estimated)

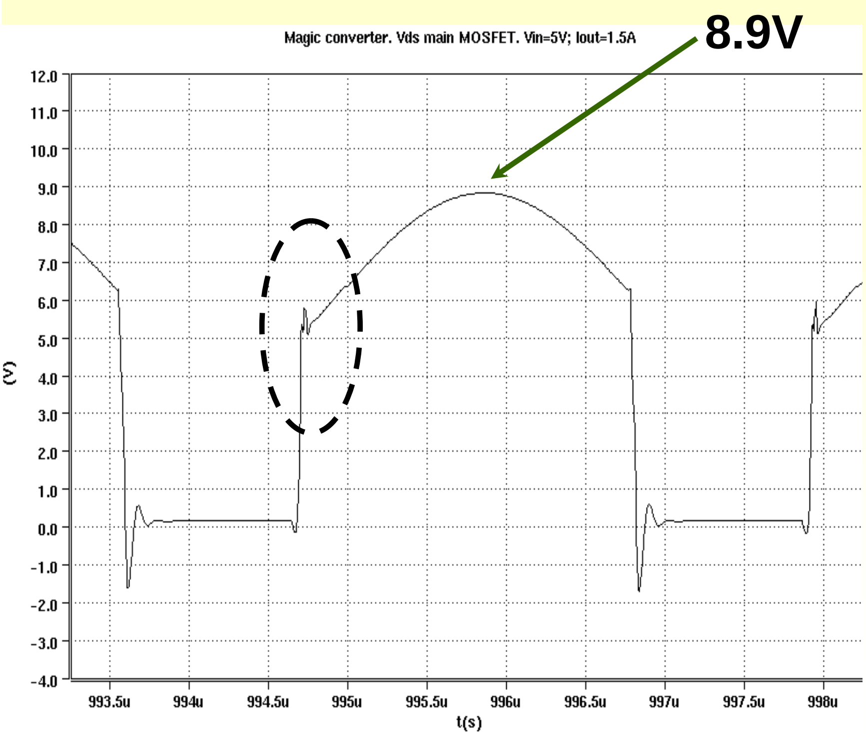
UPM model

Llk = 4nH

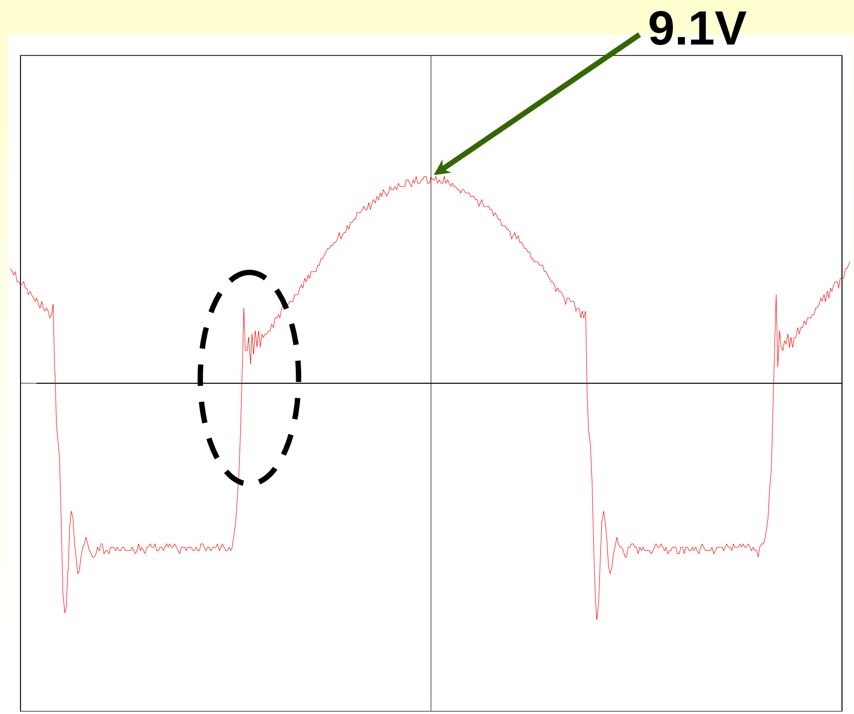
Low profile on board converter (multilayer PCB)

Experimental Results using thick film technology

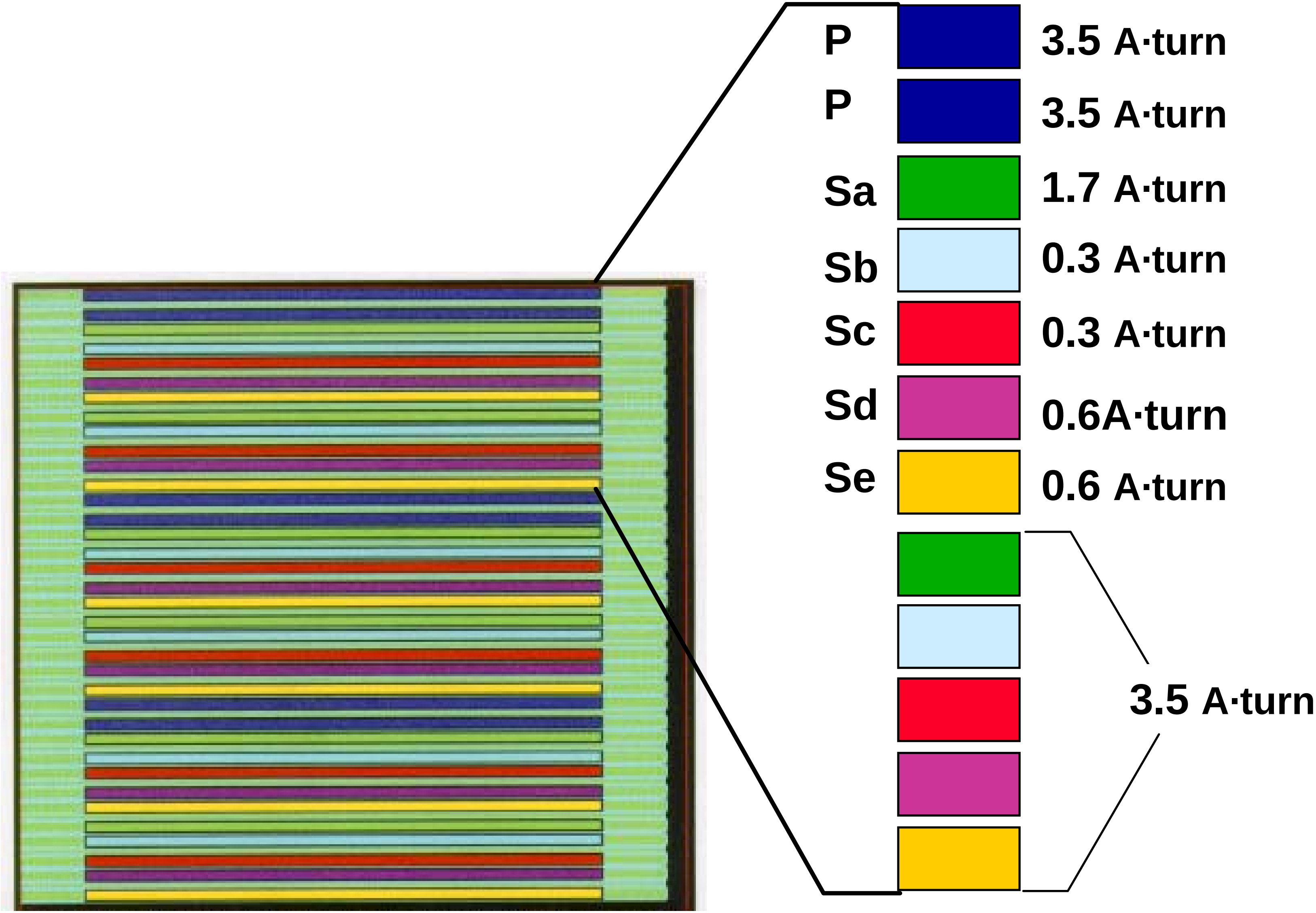
SIMULATION



MEASUREMENT



Small value of leakage inductance predicted by the Mod

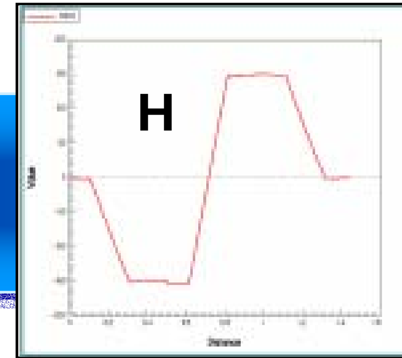

P
3.5 A·turn
P
3.5 A·turn
Sa
1.7 A·turn
Sb
0.3 A·turn
Sc
0.3 A·turn
Sd
0.6A·turn
Se
0.6 A·turn
3.5 A·turn

6

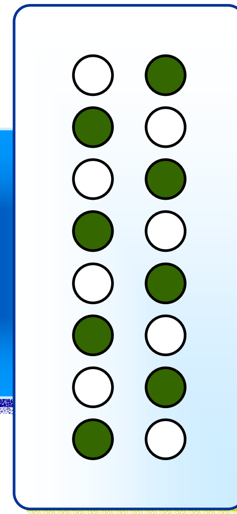
Summary of design guidelines

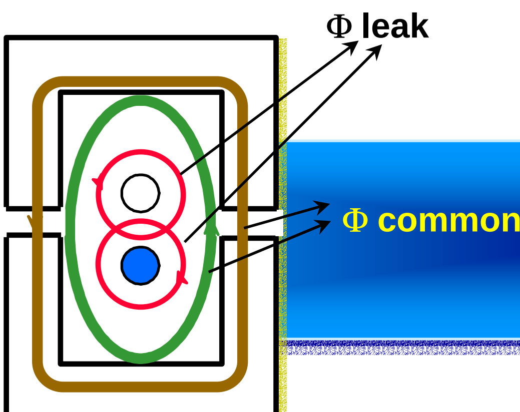
Interleaving

Reduces	Increases
L_{leak} R_{AC} $C_{intrawinding}$	$C_{interwinding}$



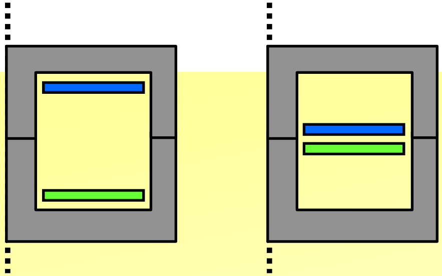
Conductors with opposite current should be placed as close as possible

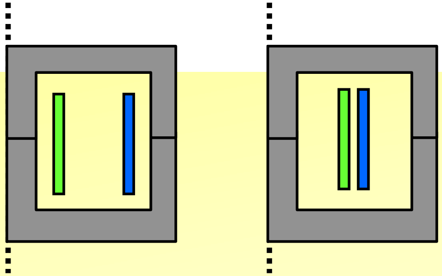




Energy in the air is not necessarily "leakage"

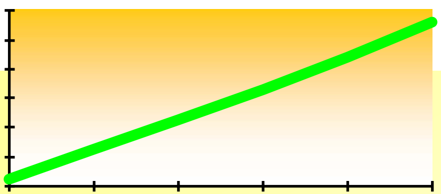
Windings separation





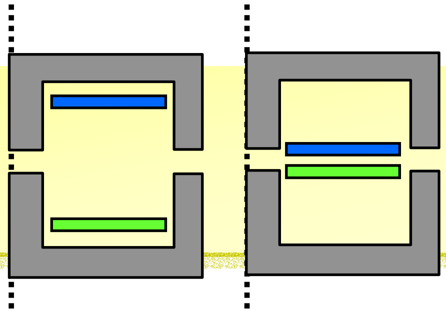
In top-down structures, R_{AC} decreases

In concentric structures, R_{AC} may increase or decrease

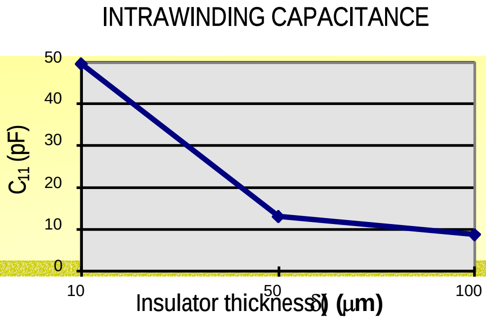


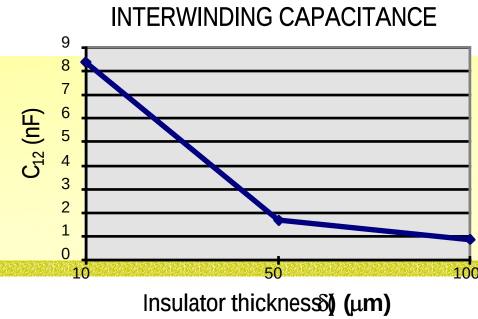
L_{leak} linearly dependent on winding separation

End effect reduced if conductors are far from the core



Interwinding and intrawinding capacitance decrease with layer separation





Air gap

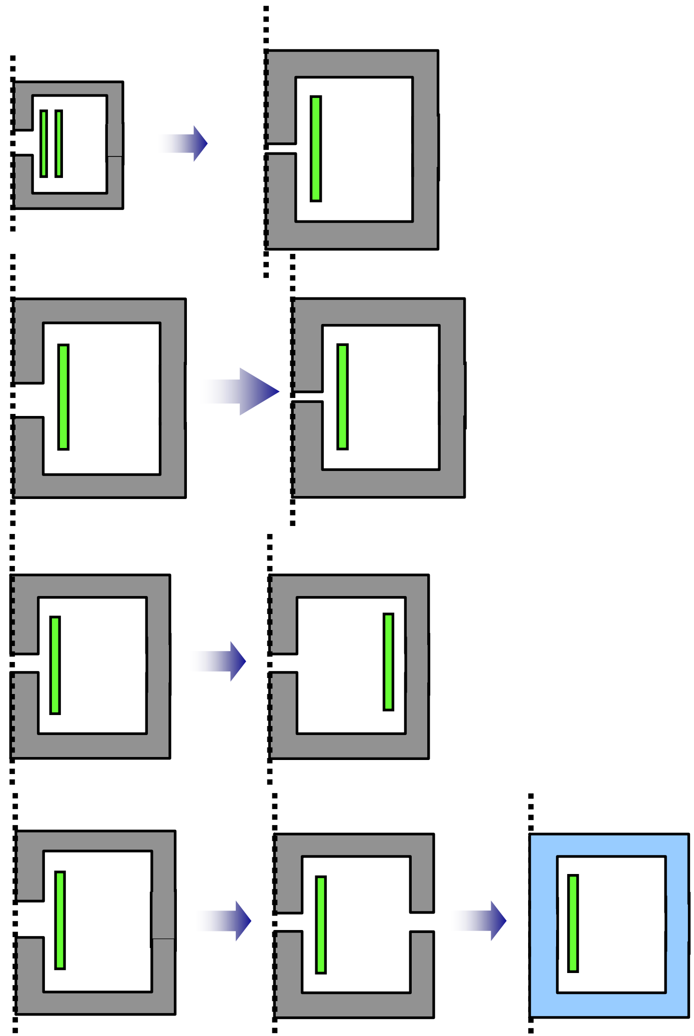
TO REDUCE R_{AC}

AIR GAP THICKNESS

AIR GAP THICKNESS

RELATIVE POSITION GAP-WINDINGS

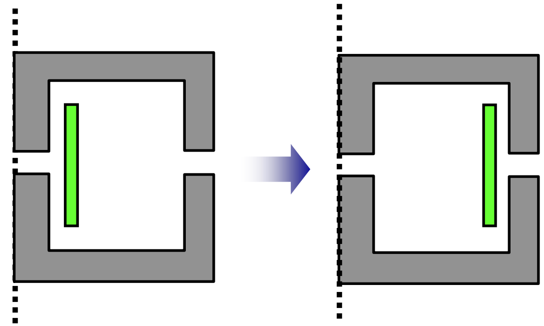
DISTRIBUTED GAP



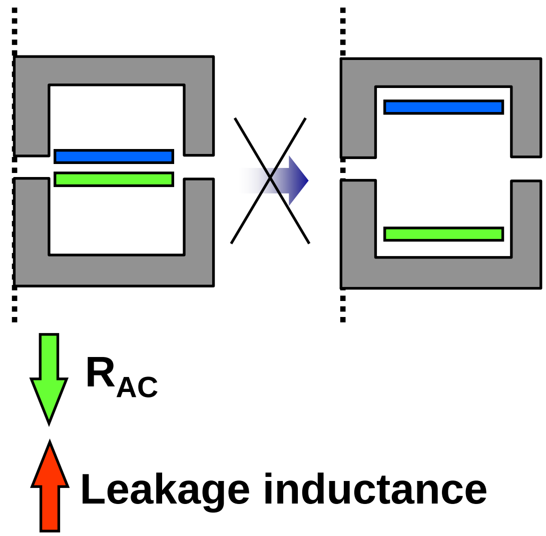
Air gap

TO REDUCE R_{AC}

CENTER-OUTER LEG

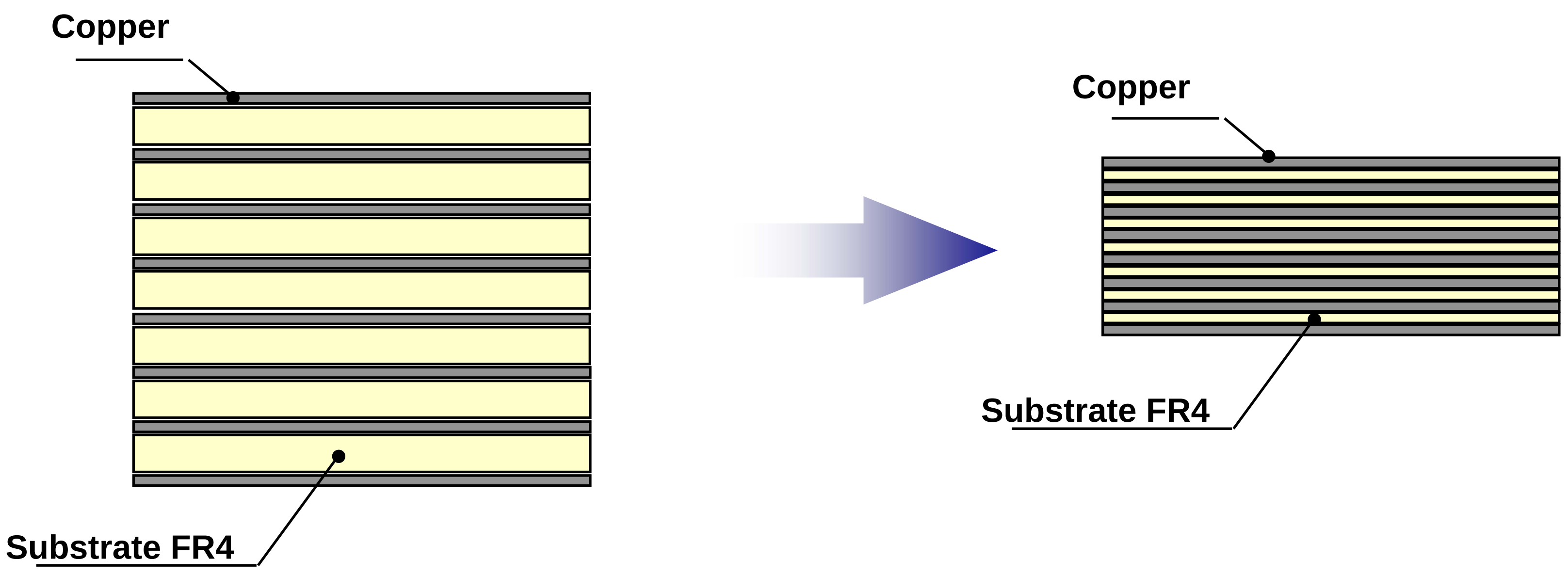


WINDINGS SEPARATION VS GAP INFLUENCE



Substrate thickness reduction

Substrate thickness reduction is limited by technological constraints, but also take into account that...



- ✓ R_{AC} slightly increases, but more blocks can be connected in parallel !!
- ✓ Leakage inductance drastically decreases
- ✓ Capacitance increases
- ✓ Isolation requirements to accomplish regulations

Summary

Modeling:

- It is possible to generate **accurate models** for high frequency magnetic components, based on a **FEA tool** or **analytical expressions**
- All **high frequency and geometry effects** are taken into account
- Valid for **any electrical waveform** (not only sinusoidal)
- Valid for both **multi-winding** transformers and **coupled inductors**
- Valid for **behavioral simulator** and for electrical simulators

Design guidelines:

- **Geometry** equivalent to **performance**
- **Low profile magnetics** and **standard winding construction** techniques are current trends
- Care about **all physical effects** together (Electric energy, Magnetic energy and losses)
- Care about **regulations**