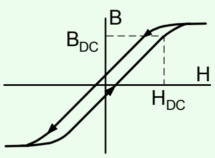
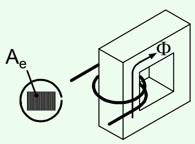
Magnetics Design

Faraday's law





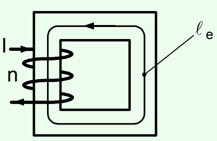
$$V = n\frac{d\Phi}{dt} = nA_e\frac{dB}{dt}; \quad \mu = \frac{\Delta B}{\Delta H}$$

Φ - magnetic flux Weber [Wb] V - voltage [V]

B - flux density $\frac{Wb}{m^2} = \text{Tesla}$ [T]

Also : Gauss [G] 1T = 10,000 G

Ampere's law



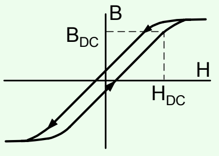
H - magnetic field [A/m]

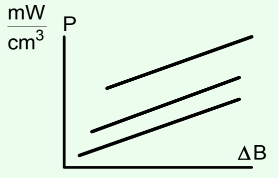
$$\oint H d\ell = n \cdot I$$

$$n \cdot I = H \cdot \ell_e$$

$$H = \frac{n \cdot I}{\ell_e} \text{ [A/m]}$$

Magnetic losses

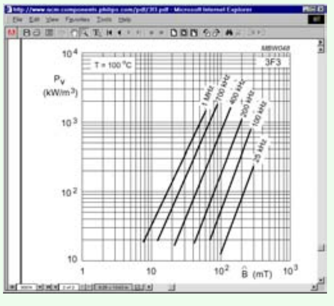




Magnetic losses ~ΔB

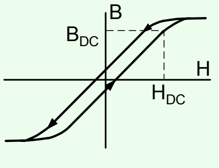
“Good number” = 100mW/cm^3 =100KW/m^3

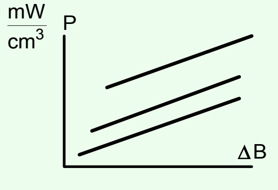
Magnetic Losses



- “Good number”=100mW/cm^3=100 kW/m^3

Magnetic losses





Magnetic losses ~ΔB

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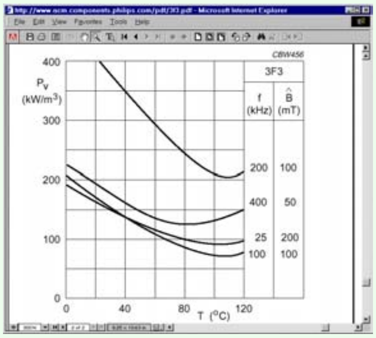
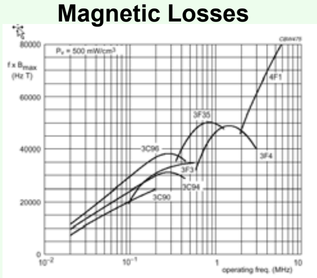
Magnetic Losses

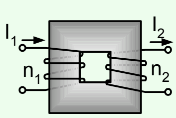


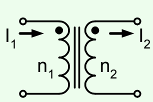
Magnetic Losses



- Curves for constant loss: 500mW/cm^3
- Figure of merit B*f
- Each material has optimum operating temperature (minimum loss)

Transformer currents





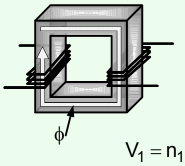
For ideal transformer $n_1 I_1 = n_2 I_2$ $\frac{I_1}{I_2} = \frac{n_2}{n_1}$

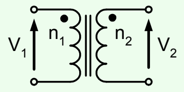
At any given moment $n_1 i_1 = n_2 i_2$

I_1, I_2 opposite direction.

No magnetic energy stored due to useful currents I_1, I_2 (they cancel each other)

Transformer voltages





$$V_1 = n_1 \frac{d\phi_1}{dt} \qquad V_2 = n_2 \frac{d\phi_2}{dt}$$

Assuming $\phi_1 = \phi_2$

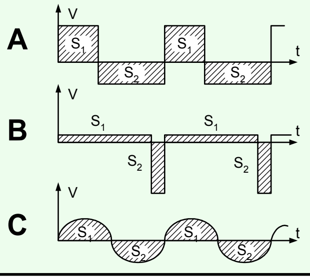
$$\frac{d\phi_1}{dt} = \frac{d\phi_2}{dt}$$

$$\frac{V_1}{V_2} = \frac{n_1}{n_2}$$

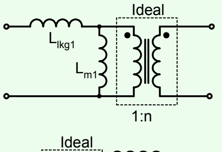
Voltages

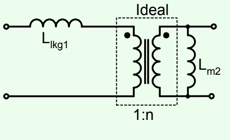
Since each winding also represents an inductance, therefore for any winding $\overline{V_n} = 0$

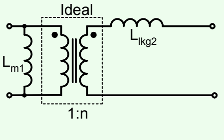
Permissible voltages: AC only on any winding



Equivalent circuit (preliminary)





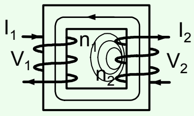


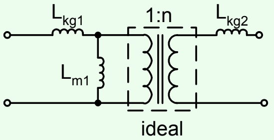
$$L_{m_2} = L_{m_1} n^2$$

Ideal transformer $L \to \infty$

Leakage

- Leakage inductance
- Leakage inductance is the uncoupled magnetic flux

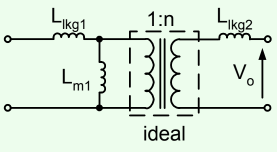


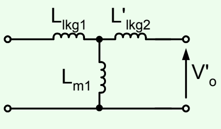


- Relationship between L_{lkg}, M and k (coupling coefficient).

$$M = k\sqrt{L_1 \cdot L_2}$$
$$L_{lkg1} \cong L_{m1}(1-k)$$
$$L_{lkg2} \cong L_{lkg1} \cdot n^2$$

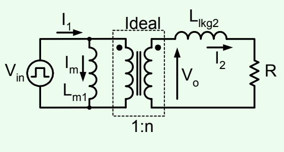
Leakage

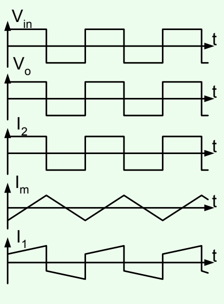




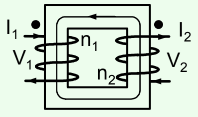
$$V'_o = \frac{V_o}{n^2}$$
$$L'_{lkg2} = \frac{L_{lkg2}}{n^2}$$

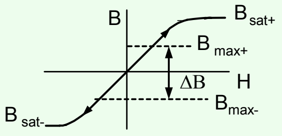
Magnetization Current





Transformer

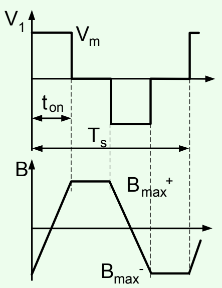




1. B_{max} (could be symmetrical or asymmetrical)
2. $B_{max} < B_{sat}$
3. In most case (high frequency) B_{max} limit by magnetic losses.

$$V_1 = n_1 \frac{d\Phi}{dt} = n_1 A_e \frac{dB}{dt}$$

Symmetrical operation



$$B = \frac{1}{n_1 A_e} \int V dt$$

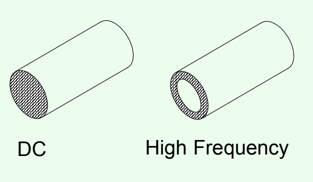
$$\left|B_{max}{}^{+}\right| = \left|B_{max}{}^{-}\right|$$

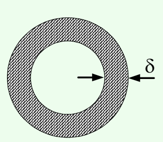
$$\Delta B = 2B_{max} = \frac{V_m t_{on}}{n_1 A_e}$$

$$n_1 = \frac{\{V_m, t_{on}\}}{2B_{max} A_e}$$

$$n_1 A_e \sim t_{on}\Big|_{t_{on} \to \frac{T_s}{2}} \sim \frac{1}{f_s}$$

Skin effect





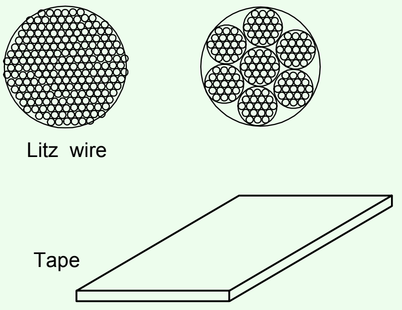
$$\frac{R_{AC}}{R_{DC}} > 1$$

δ – skin depth

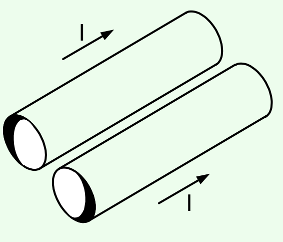
$$\delta\ (mm) = \frac{72}{\sqrt{f}}$$

f in Hz

Skin Effect Solutions

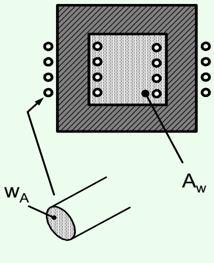


Proximity effect



Current crowding due to magnetic fields

Aw



A_w - winding area

$$A_w = \frac{\left[w_{A_1} \cdot n_1 + w_{A2} \cdot n_2\right]}{k}$$

k - filling factor k<1

$$w_{A_1} = \frac{I_{1\,rms}}{J}$$

J - current density A/m^2

$J \cong 4.5$ A/mm^2

$$I_2 = \frac{n_1}{n_2} I_1$$

Ap

$$A_w = \frac{n_1 I_{1rms}}{Jk}\cdot 2 \qquad n_1 = \frac{JkA_w}{2\cdot I_{1rms}}$$

$$n_1 = \frac{\{V_1, t_{on}\}}{2B_{max}A_e}$$

$$\rightarrow \frac{JkA_w}{I_{1rms}\cdot 2} = \frac{\{V_1, t_{on}\}}{2B_{max}A_e}$$

$$A_p = A_w A_e = \frac{\{V_1, t_{on}\}2\cdot I_{1rms}}{\{2B_{max}\}Jk}$$

$$A_p = \frac{\{V_1, t_{on}\}2\cdot I_{1rms}}{\Delta B\cdot Jk}$$

$$A_p = \frac{\{V_1, D_{on}\}2\cdot I_{1rms}}{f_s\cdot \Delta B\cdot Jk}$$

Transformer design stages

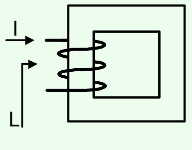
1. Calculate A_p $\qquad A_p = \frac{\{V_1, D_{on}\}2\cdot I_{1rms}}{f_s\cdot \Delta B\cdot Jk}$

In symmetrical operation
$\Delta B = B_{max}^{+} - B_{max}^{-}$

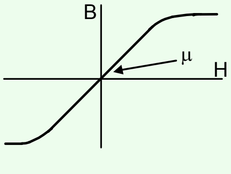
In asymmetrical operation
$\Delta B = B_{max} - 0$

2. Look for core
3. Calculate n_1 by: $\qquad n_1 = \frac{\{V_m, t_{on}\}}{2B_{max}A_e}$
4. Calculate n_2

Inductor design



Need to store energy
(in transformer $n_1\cdot I_1 = n_2\cdot I_2$)

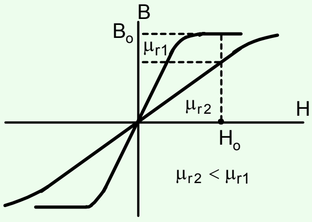


$\mu = \mu_o \mu_r$
μ_o - air (vacuum) permeability
μ_r - relative permeability

Permeability

$\mu_o = 1.26 \cdot 10^{-6} \frac{\text{Henry}}{\text{m}}$ μ_r of ferrites $\sim$ 2000 - 4000

$B = \mu H$

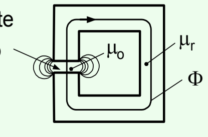


If μ is high B will reach quickly B_{sat}

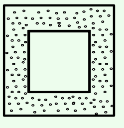
Need to slower μ

Gaps

Discrete air gap



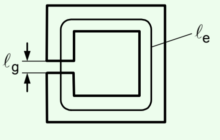
Distributed air gap



Same Φ magnetic lines in ferromagnetic material and in air.

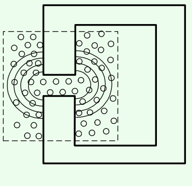
$\ell_g << \ell_e$

$\ell_g + \ell_e \cong \ell_e$



Current Crowding

Current crowding due to magnetic fields

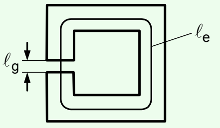


R_{AC} high around gap

Inductance with Gap

$\ell_g << \ell_e$

$\ell_g + \ell_e \cong \ell_e$



Φ = constant B $\cong$ constant

$$H_g = \frac{B}{\mu_o} \qquad H_m = \frac{B}{\mu_m}$$

$$nI = \ell_e H = H_m \ell_e + H_g \ell_g$$

$$\rightarrow \quad H\ell_e = \frac{B\ell_e}{\mu_m} + \frac{B\ell_g}{\mu_o}$$

Inductance with Gap

$$H\ell_e = \frac{B\ell_e}{\mu_m} + \frac{B\ell_g}{\mu_o}$$

- Dividing out l_e and defining $\mu_e = \frac{B}{H}$

$$H = \frac{B}{\mu_e} = \frac{B_m}{\mu_m} + \frac{B_a}{\mu_o \frac{\ell_e}{\ell_g}}$$

Gap Calculation

$$\frac{1}{\mu_e} = \frac{1}{\mu_m} + \frac{1}{\mu_o \left(\frac{\ell_e}{\ell_g}\right)}$$

$$\frac{1}{\mu_{re}\mu_o} = \frac{1}{\mu_{rm}\mu_o} + \frac{1}{\mu_o \left(\frac{\ell_e}{\ell_g}\right)}$$

$$\frac{1}{\mu_{re}} = \frac{1}{\mu_{rm}} + \frac{1}{\left(\frac{\ell_e}{\ell_g}\right)}$$

$$\frac{1}{\mu_{re}} = \frac{\left(\frac{\ell_e}{\ell_g}\right) + \mu_{rm}}{\mu_{rm}\left(\frac{\ell_e}{\ell_g}\right)}$$

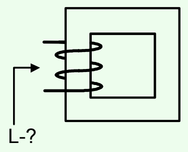
$$\mu_{re} = \frac{\mu_{rm}\left(\frac{\ell_e}{\ell_g}\right)}{\left(\frac{\ell_e}{\ell_g}\right) + \mu_{rm}}$$

If $\frac{\ell_e}{\ell_g} < \mu_{rm}$ $\mu_{re} \approx \left(\frac{\ell_e}{\ell_g}\right)$

Inductance

$$V = L\frac{dI}{dt} \qquad V = n\frac{d\Phi}{dt}$$

$$L\frac{dI}{dt} = n\frac{d\Phi}{dt}$$



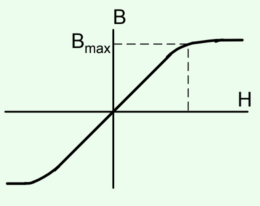
$$n\frac{d\Phi}{dt} = nA_e\frac{dB}{dt} = nA_e\mu\frac{dH}{dt} = nA_e\mu\frac{n}{\ell_e}\frac{dI}{dt}$$

$$L\frac{dI}{dt} = \frac{n^2A_e\mu}{\ell_e}\frac{dI}{dt} \qquad L = \frac{n^2A_e\mu}{\ell_e}$$

Two windings on same core

$$\frac{L_1}{L_2} = \left(\frac{n_1}{n_2}\right)^2$$

Inductor design



Saturation Limits

$$L\frac{dI}{dt} = n\frac{d\Phi}{dt}$$

$$L\int_0^{I_{pk}}\left(\frac{dI}{dt}\right)dt = nA_e\int_0^{B_{max}}\left(\frac{dB}{dt}\right)dt$$

$$L\,I_{pk} = nA_eB_{max}$$

$$n = \frac{LI_{pk}}{A_eB_{max}}$$ quick design and check

$$A_e = \frac{LI_{pk}}{nB_{max}} \qquad n = \frac{JkA_w}{I_{rms}}$$

Ap

$$A_p = A_e A_w = \frac{L I_{pk} I_{rms}}{B_{max} J k}$$

$$L I_{pk} I_{rms} \approx L I^2$$

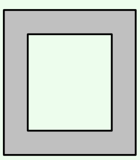
$$\text{Energy stored} = \frac{L I^2}{2}$$

Air gapped core Design

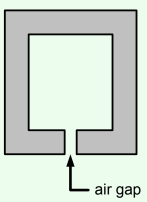
1. Calculate A_p
2. Choose a core
3. Iterate
4. Calculate ℓ_g (or increase gap until L is as required)

Cores

- Transformer core

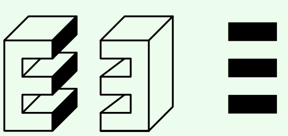


- Inductor core

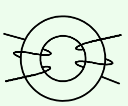


Cores

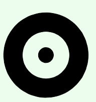
1. E - core



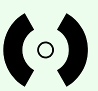
2. TOROID



3. ARENCO



4. POT



Commercial cores

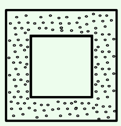
Distributed gap core

- **The concept of A_L**

$$A_L = \frac{H_y}{turn} \quad \left(\text{sometime } \frac{H_y}{1000\,turns}\right)$$

L for n turns: $L = n^2 \cdot A_L$

Distributed air gap



MAGNETICS Kool Mµ Powder Core Catalog - 2.0

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A_L and Inductance Considerations

The inductance of a wound core can be calculated from the core geometry by using the following equation:

$$L = \frac{.4\pi\mu N^2 A_e}{l_e \times 10^8}$$

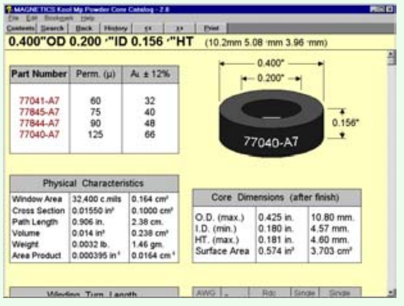
where: L = inductance (Henries)
µ = core permeability
N = number of turns
A_e = core cross-section (cm^2)
l_e = core magnetic path length (cm)

The inductance for a given number of turns is related to the nominal inductance (as listed in the catalog as mH/1000 turns) by the following:

$$L_n = \frac{L_{1000} N^2}{10^6}$$

where: L_n = inductance for N turns (mH)
L_{1000} = nominal inductance (mH/1000 turns),
or the A_L listed on the core pages.

Toroid Data

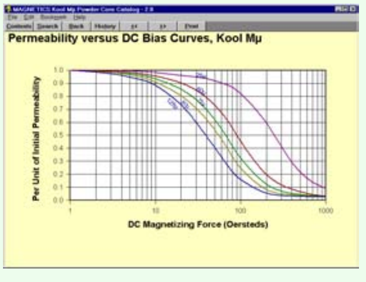

0.400"OD 0.200 "ID 0.156 "HT (10.2mm 5.08 mm 3.96 mm)

Part Number	Perm. (μ)	A_L ± 12%
77041-A7	60	32
77845-A7	75	40
77844-A7	90	48
77040-A7	125	66

Physical Characteristics		
Window Area	32,400 c.mils	0.164 cm²
Cross Section	0.01550 in²	0.1000 cm²
Path Length	0.906 in.	2.38 cm.
Volume	0.014 in³	0.238 cm³
Weight	0.0032 lb.	1.46 gm.
Area Product	0.000395 in⁴	0.0164 cm⁴

Core Dimensions (after finish)		
O.D. (max.)	0.425 in.	10.80 mm.
I.D. (min.)	0.180 in.	4.57 mm.
HT. (max.)	0.181 in.	4.60 mm.
Surface Area	0.574 in²	3.703 cm²

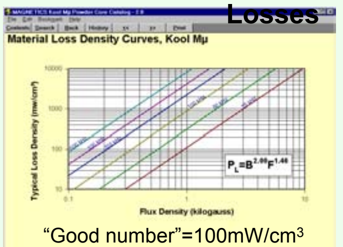
Permeability change



1 Amp/m =79.5 Oe

L decreases with DC current !

Losses



"Good number"=100mW/cm³

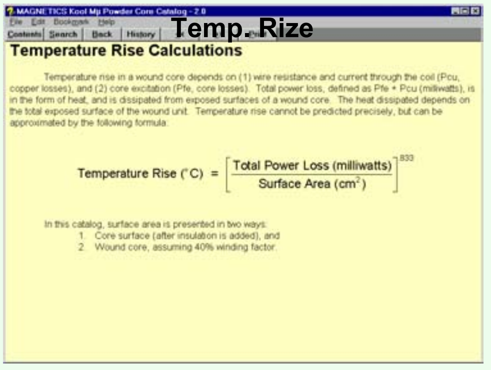
Misleading notations !
ΔB NOT B

These curves are measured by feeding ac signals.

If the current is composed of DC + ripple, core loss is due only to ripple component !

DC bias tend to increase loss

Temp. Rize


MAGNETICS Kool Mμ Powder Core Catalog - 2.0

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Temperature Rise Calculations

Temperature rise in a wound core depends on (1) wire resistance and current through the coil (Pcu, copper losses), and (2) core excitation (Pfe, core losses). Total power loss, defined as Pfe + Pcu (milliwatts), is in the form of heat, and is dissipated from exposed surfaces of a wound core. The heat dissipated depends on the total exposed surface of the wound unit. Temperature rise cannot be predicted precisely, but can be approximated by the following formula:

$$\text{Temperature Rise } (^\circ C) = \left[\frac{\text{Total Power Loss (milliwatts)}}{\text{Surface Area } (cm^2)}\right]^{.833}$$

In this catalog, surface area is presented in two ways:

1. Core surface (after insulation is added), and
2. Wound core, assuming 40% winding factor.

- "Hot Spot" - Critical parameter

Hanna Curve

$$n = \frac{LI_{pk}}{A_e B_{max}}$$

$$Hn = \frac{HLI_{pk}}{A_e B_{max}}$$

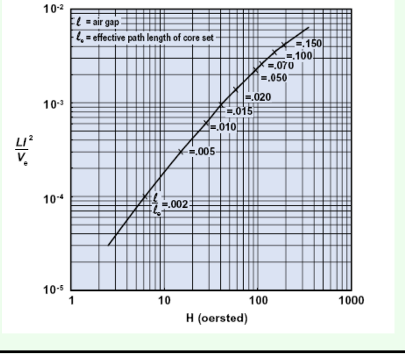
$$Hn = \frac{nI \ LI}{l_e \ A_e B_{max}}$$

$$H = \frac{LI^2}{V_e} \frac{1}{B_{max}}$$

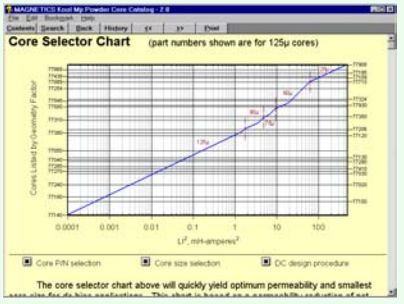
$$HB_{max} = \frac{LI^2}{V_e}$$

$$\frac{B_{max}}{H} = \mu = \mu_r \mu_o$$

Hanna Curve



Core Size Selection



Basic Design of Distributed Gap Core

1. Calculate LI^2
2. Look up manufacturer data
3. Select Core
4. Calculate $\mathbf{n} = 1000\sqrt{\frac{\mathbf{L}}{\mathbf{A_{L(1000)}}}}$
5. Check L_{min}
6. Calculate losses. Temp rise and and $\mu = f(\frac{nI}{\ell_e})$
7. Iterate