

Mor M. Peretz, Switch-Mode Power Supplies [3-1]

Magnetics

- Faraday's and Amper's laws
- Permeability
- Inductor
 - Reluctance model
 - Air gap
 - Current crowding
 - Inductor design
- Skin effect, proximity effect
- Losses
- Transformer
 - Ideal transformer
 - Real transformer
 - Transformer design

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Important relationships

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Magnetic quantities Analogies to electrical quantities

Magnetic field H

ℓ

MMF $F_M = H \cdot \ell$

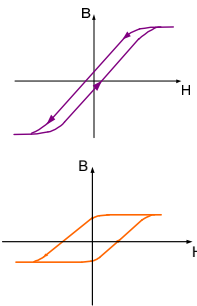
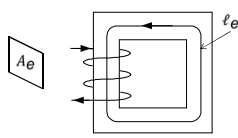
Electric field E

ℓ

Voltage $V = E \cdot \ell$

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Important relationships

Faraday's law

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

Amper's law

$$\oint H d\ell = n \cdot I \quad H = \frac{nI}{\ell_e}$$

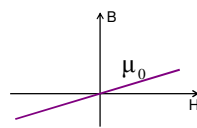
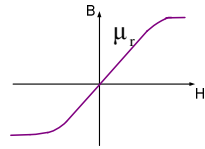
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Units

Φ - magnetic flux Weber [Wb] V - voltage [V]
 B - flux density $\frac{Wb}{m^2} =$ Tesla [T]
 Gauss [G] 1T = 10,000 G
 H - magnetic field [A/m]
 μ - magnetic permeability [H/m]

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Permeability


Free space permeability
 (Vacuum)
 $\mu_0 = 4\pi \cdot 10^{-7}$

Typical B_{sat}
 Ferrite: 0.2 – 0.5 T
 Iron powder: 0.5 – 1 T

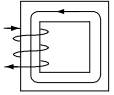
Typical magnetic material permeability
 $\mu_r = 10^3 - 10^5$

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What is inductance ?



$$V = n \frac{d\phi}{dt} \quad V = L \frac{di}{dt}$$



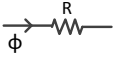
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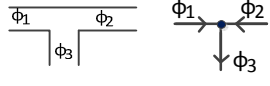
Reluctance model

$$F = H\ell_e$$

$$H = \frac{B}{\mu} \quad B = \frac{\phi}{A}$$

$$R = \frac{\ell_e}{\mu A} \quad [H^{-1}]$$

$$F = \phi R$$




$$\phi_3 = \phi_1 + \phi_2$$

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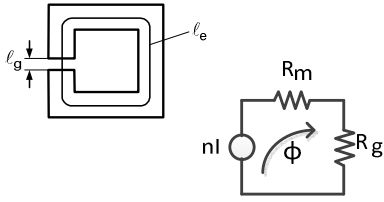
Inductance with gap

$$R_m = \frac{\ell_e}{\mu_r A_e}$$

$$R_g = \frac{\ell_g}{\mu_0 A_e}$$

$$nl = \phi(R_m + R_g)$$

$$v = n \frac{d\phi}{dt} = \frac{n^2}{\underbrace{R_m + R_g}_L} \frac{di}{dt}$$



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Current crowding

$$R_m = \frac{l_e}{\mu_r A_e}$$

$$R_g = \frac{l_g}{\mu_0 A_e}$$

$$\frac{nI R_g}{(R_m + R_g)} \xrightarrow{R_g \gg R_m} nI$$

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Inductor design Air gap

$$l_g \ll l_e$$

$$l_g + l_e \cong l_e$$

If $\frac{l_e}{l_g} < \mu_r$ $\mu_{re} \cong \left(\frac{l_e}{l_g}\right)$

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Inductor design Saturation - Ae

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

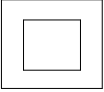
$$n A_e \int_0^{B_{max}} \left(\frac{dB}{dt}\right) dt = L \int_0^{I_{pk}} \left(\frac{dI}{dt}\right) dt$$

$$L I_{pk} = n A_e B_{max}$$

$$n = \frac{L I_{pk}}{B_{max} A_e}$$

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Inductor design
Aw



$$A_w = \frac{nW_a}{k}$$

$$W_a = \frac{I_{rms}}{J}$$

$$A_w = \frac{nI_{rms}}{Jk}$$

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Inductor design
Ap

$$A_p = A_e A_w = \frac{LI_{pk} I_{rms}}{B_{max} Jk}$$

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Inductor design
summary

- Calculate Ap
- Choose core
- Calculate n
- Calculate lg or adjust gap

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Inductor selection Off-shelf product

VISHAY **IHLP-1616BZ-11**
Vishay Dale

Low Profile,

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Inductor selection Off-shelf product

STANDARD ELECTRICAL SPECIFICATIONS					
INDUCTANCE ± 20% AT 100kHz, 0.25 V, 0 A (µH)	DCR TYP. 25 °C (mΩ)	DCR MAX. 25 °C (mΩ)	HEAT RATING CURRENT DC TYP. (A) (3)	SATURATION CURRENT DC TYP. (A) (4)	
0.10	4.1	4.5	12.0	12.0	
0.22	6.5	7.0	9.0	9.0	
0.47	14.5	16	7.0	7.0	
1.0	24	27	4.5	5.0	
2.2	61	68	3.25	3.25	
4.7	95	105	1.7	1.75	

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Skin effect

DC High Frequency

δ – skin depth

$\frac{R_{AC}}{R_{DC}} > 1$ $\delta \text{ (mm)} = \frac{72}{\sqrt{f}}$

f in Hz

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Skin Effect Solutions

Litz wire

Foil/tape

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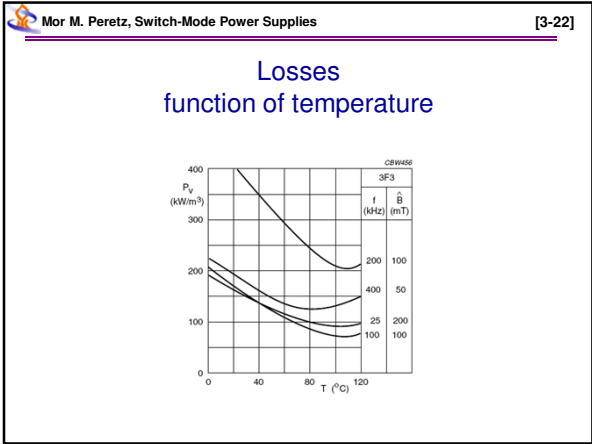
Proximity effect

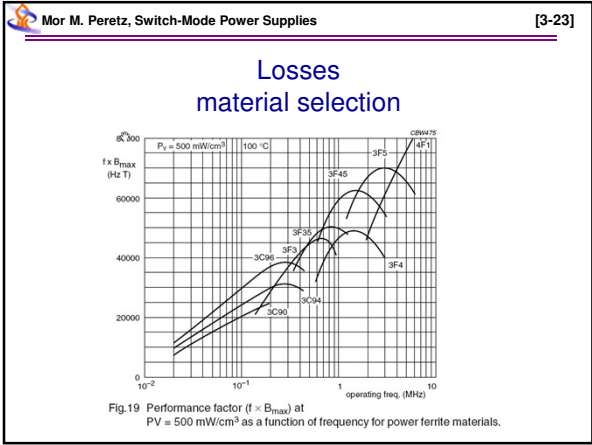
Current crowding due to magnetic fields

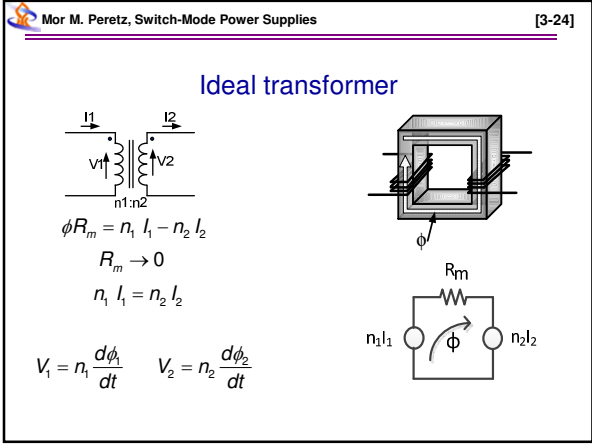
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Losses function of ΔB

$P_v \sim K \Delta B^i f^j$
 $i, j - \text{material dependent}$







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Transformer characteristics

- Current flow at the same time at primary and secondary
- Each winding represents inductance – Average voltage = 0
- AC only on any winding

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Magnetizing inductance

$\phi R_m = n_1 i_1 - n_2 i_2$
 $V_1 = n_1 \frac{d\phi}{dt}$
 $V_1 = \frac{n_1^2}{R_m} \frac{d}{dt} \left(i_1 + i_2 \frac{n_2}{n_1} \right)$

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Leakage inductance

- uncoupled magnetic flux

L_{kg} , M (mutual coupling) and k (coupling coefficient)
 $M = k \sqrt{L_1 \cdot L_2}$
 $L_{kg1} \cong L_m (1 - k)$
 $L_{kg2} \cong L_{kg1} \cdot n^2$

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Magnetizing and leakage inductances

The figure shows five waveforms on the left: V1 (square wave), V2 (square wave), I2 (square wave), Im (triangular wave), and I1 (square wave). To the right is a transformer equivalent circuit with primary current I1, leakage inductance Llk, magnetizing inductance Lm, primary voltage V1, secondary voltage V2, and turns ratio n1:n2. Secondary current I2 is also shown.

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Transformer design

Aw

$$A_w = \frac{n_1 W_{a1} + n_2 W_{a2}}{k}$$

$$W_a = \frac{I_{rms}}{J}$$

$$A_w = \frac{n_1 I_{1rms} + n_2 I_{2rms}}{Jk}$$

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

A diagram of a square core transformer with an inner square window.

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Transformer design

Saturation - Ae

The figure shows a triangular flux density waveform on the left. In the center is a core diagram with a winding. To the right is the equation $B = \frac{1}{nA_e} \int V dt$. Below the waveforms is the equation $|B_{max}^+| = |B_{max}^-|$ and a boxed equation $n = \frac{V_m T_{on}}{2 B_{max} A_e}$.

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Transformer design

A_p

$$A_p = A_w A_b = \frac{\{V_1 \cdot T_{on}\} 2 \cdot I_{rms}}{\{2B_{max}\} Jk}$$

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

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

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Transformer design summary

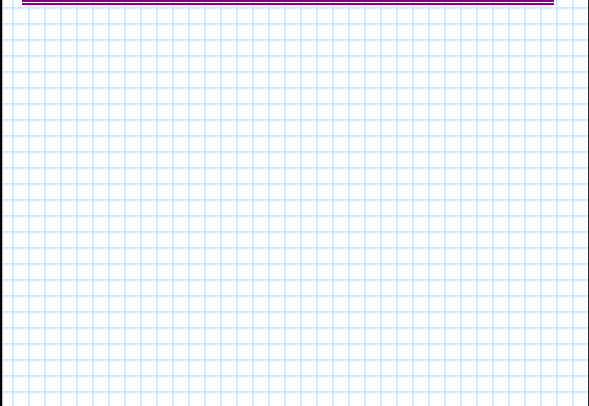
- Calculate A_p
- Choose core
- Calculate n_1
- Calculate n_2


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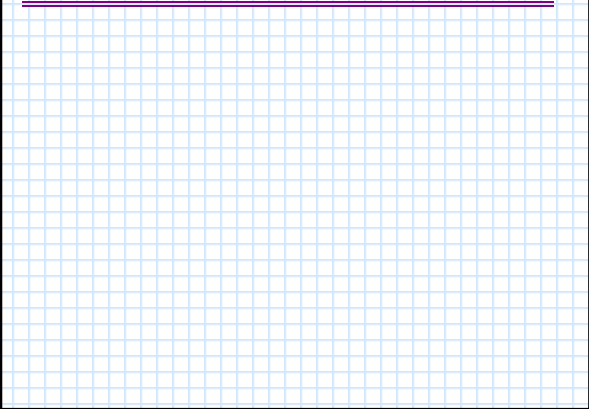
Magnetic design Example


- Boost converter: $P=100W$, $V_{in}=10V$, $V_o=50V$, $\Delta I_L=0.1I_{Lav}$
- Calculate L
- Calculate A_p

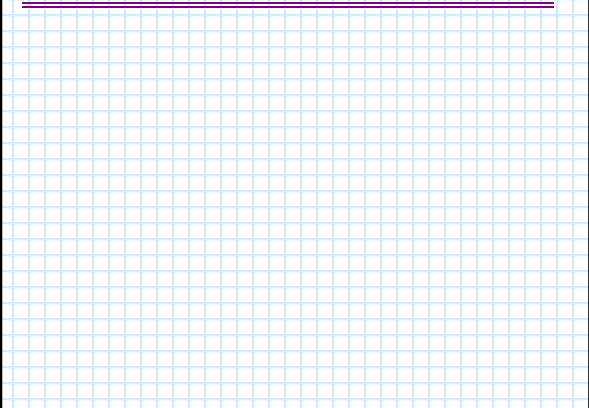
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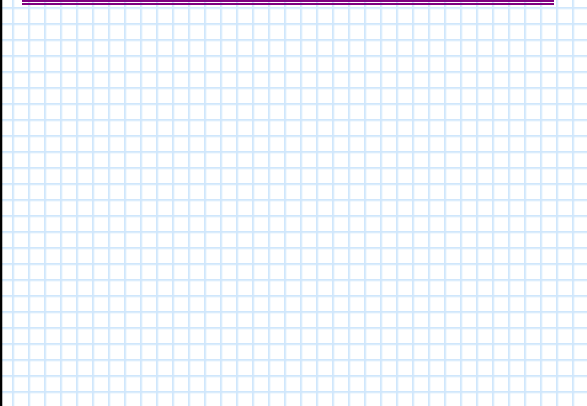
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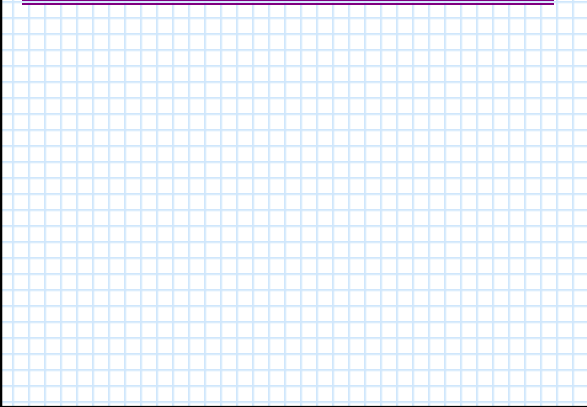
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