Transformer and Inductor Design

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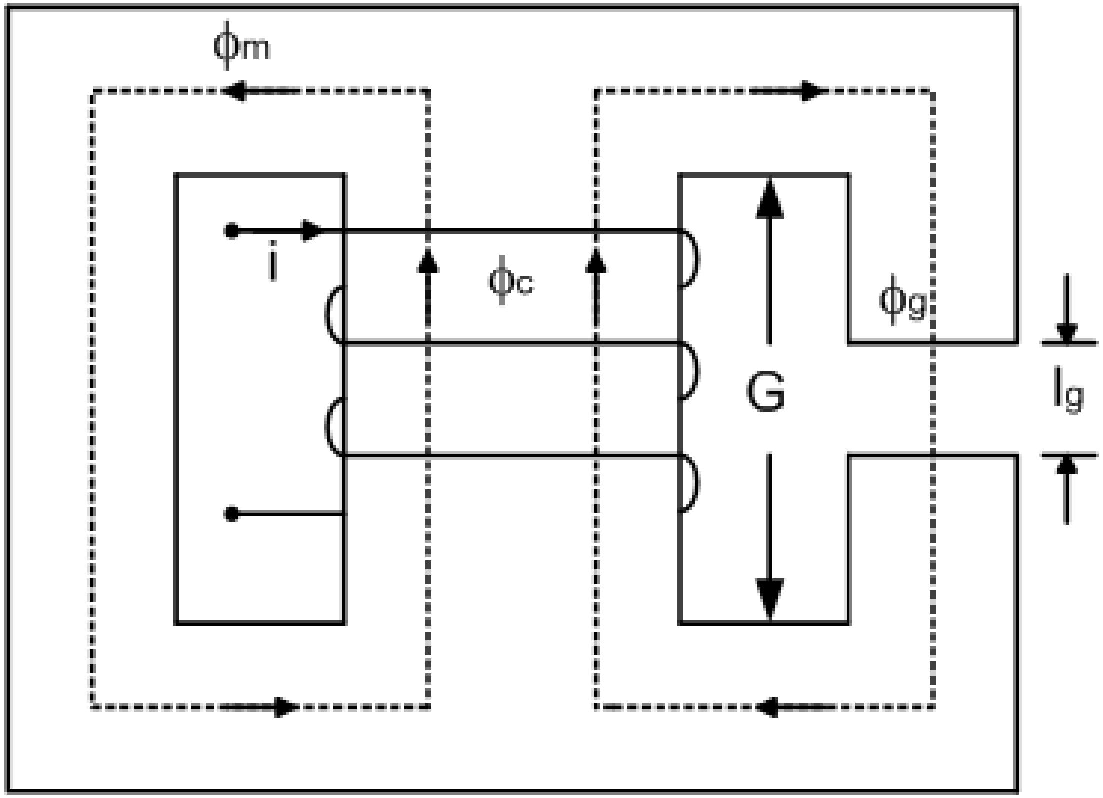
INDUCTOR DESIGN



$$R_c = \frac{l_c}{\mu_c S_c} = \frac{1}{P_c}$$

$$R_m = \frac{l_m}{\mu_m S_m} = \frac{1}{P_m}$$

$$R_g = \frac{l_g}{\mu_g S_g} = \frac{1}{P_g}$$

Design Considerations

Equipment Selection

1. Type, Structure, and size of magnetic
2. Type, figure, size and turn of copper wire
3. Type and characteristics of insulator
4. Case and heat sink
5. Other Electrical and mechanical properties

Specifications

1. Inductor value
2. Size, figure, frequency of current and voltage
3. Losses (Core loss, Copper loss) efficiency, Temperature rise (Trise)
4. Other Electrical and mechanical properties

Limitations

1. Saturation of Flux density in magnetic core
2. Power losses (Copper loss and Core loss)
3. Other properties : permeability (μ) , breakdown (Vb) , etc

Equation

- From limitation of magnetic core (Saturation or core loss),

$$B_{\max} = \frac{\phi_{\max}}{S} = \frac{\lambda_{\max}}{SN} = \frac{LI_{peak}}{SN}$$

$$\phi_{\max} = \frac{LI_{peak}}{N} \quad , \quad \phi \ \alpha \ \mathrm{I}$$

$$kW = NA_w \quad , \ \mathrm{k} = \text{window utilization factor} = 0.3 - 0.6$$

- From limitation of copper wire , we consider Copper loss (Pcu)

$$P_{cu} = I_{rms}^2 R$$

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

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

$$where \;\; J = 100 - 1000 \; A / cm^2$$

$$\rho = 1.724 * 10^{-8} \;\; \Omega - m$$

- From properties of magnetic circuit and inductor

$$L = N^2 P_c = N^2 / R_c$$

$$R_c = R_m + R_g \qquad ; \qquad R_g = \frac{l_g}{\mu_o S}$$

$$l_g = \frac{N^2 \mu_o S}{L}$$

Selection of Core size

(Slobodan Ćuk and R.D. Middlebrook, 1981)

2 Methods:

1. Area Product : Ap Approach
2. Core Geometry : Kg Approach

Design

- Ap Approach

Trise is defined as current density

$$J = 100 - 1000\ A/cm^2$$

$$N = \frac{LI_{peak}}{B_{\max} S}$$

$$kW = \frac{NI_{rms}}{J}$$

$$replace\ \ N$$

$$kW = \frac{LI_{peak} I_{rms}}{B_{\max} SJ}$$

$$A_p = WS = \frac{LI_{peak} I_{rms}}{kB_{\max} J}$$

- If $I_{peak} = I_{rms}$, $Ap = WS = \dfrac{2E_{peak}}{kB_{\max} J}$

  $$where\ \ E_{peak} = \frac{1}{2} L I_{peak}^{2}$$

Procedures for Ap Approach

1. Specifications and Limitations , Calculate for Ap
2. Core Selection > Ap from 1
3. Calculate for turn (N)
4. Calculate for Wire Size (Aw)
5. Wire Size selection (Aw) > Aw from 4

Where radius of wire size < skin depth

$$\delta(m) = \sqrt{\frac{2\rho}{\mu\omega}}$$

6. Calculate $P_{cu} = I_{rms}^2 R$

7. Adjust J from procedure 1 to 6 again until Pcu is suitable.

8. Calculate air gap $l_g = \dfrac{N^2 \mu_o S}{L}$

9. Fringing Flux Correction Factor (F)

$$F = 1 + \left(\frac{l_g}{\sqrt{S}}\right)\left(\ln \frac{2G}{l_g}\right)$$

10. Adjust l_g until L is desirable.

2. **Core Geometry : Kg Approach**

This method uses Pcu

$$N = \frac{LI_{peak}}{B_{\max} S}$$

$$A_w = \frac{kW}{N}$$

$$l = Nt$$

$$R_w = \frac{\rho l}{A_w} = \frac{\rho N^2 t}{kW}$$

$$P_{cu} = I_{rms}^2 R_w$$

Replace many variables into Pcu,

$$P_{cu} = \frac{I_{rms}^2 \rho L^2 I_{peak}^2 t}{B_{\max}^2 S^2 k W}$$

Rearrange,

$$K_g = \frac{WS^2}{t} = \frac{4\rho \left[\frac{1}{2} L I_{rms}^2 \right] \left[\frac{1}{2} L I_{peak}^2 \right]}{k B_{\max}^2 Pcu}$$

- If $I_{peak} = I_{rms}$, $K_g = \frac{WS^2}{t} = \frac{4\rho E_{peak}^2}{kB_{\max}^2 P_{cu}}$

Where $E_{peak} = \frac{1}{2} LI_{peak}^2$

Procedures for Kg Approach

1. Specifications and Limitations , Calculate for Kg
2. Core Selection > Kg from 1
3. Calculate for turn (N)
4. Calculate for Wire Size (Aw)
5. Wire Size selection (Aw) > Aw from 4

- Where radius of wire size < skin depth

$$\delta(m) = \sqrt{\frac{2\rho}{\mu\omega}}$$

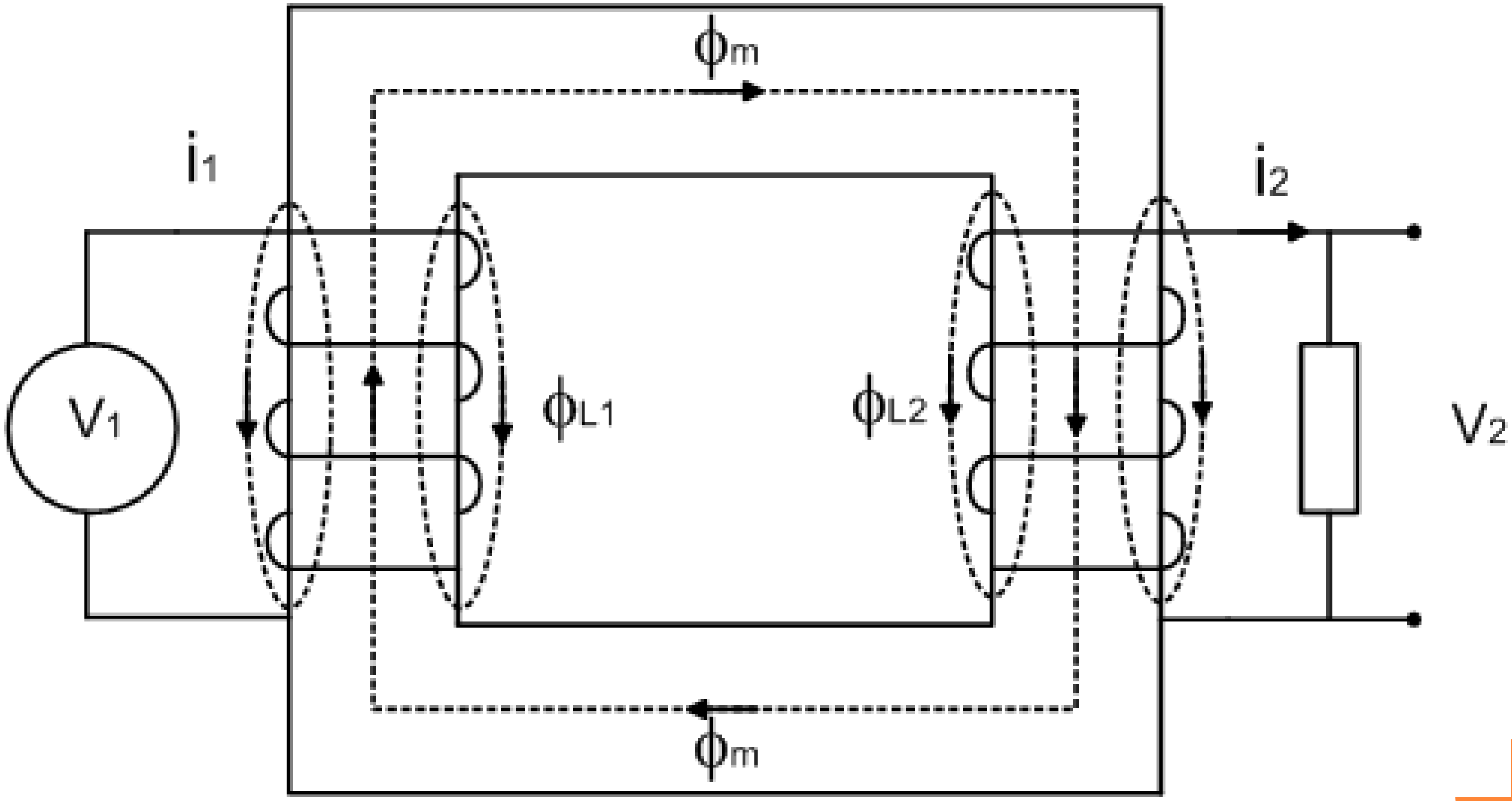
Calculate air gap $l_g = \frac{N^2 \mu_o S}{L}$

7. Fringing Flux Correction Factor (F)

$$F = 1 + \left(\frac{l_g}{\sqrt{S}} \right) \left(\ln \frac{2G}{l_g} \right)$$

8. Adjust l_g until L is desirable.

Transformer Design



Transformer Design

- **Consider for Transformer design**

Equipment Selection

1. Type, Structure, and size of magnetic
2. Type, figure, size and turn of copper wire N1, N2,N3,…, Nn
3. Type and characteristics of insulator
4. Case and heat sink
5. Other Electrical and mechanical properties

Limitations

1. Saturation of Flux density in magnetic core
2. Power losses (Copper loss and Core loss)
3. Other properties : permeability (μ) , breakdown (Vb) , etc

□ WAVE

Equation for Transformer Design

- From Core limitation (Saturation or Core loss)

□ wave ϕ V_e

$$\Delta\phi_m = \int \frac{v}{N}\,dt = \frac{V\,{T}/{2}}{N} = nB_{\max}S$$

$n = 1$ *when dc magnetizing current is there*

$n = 2$ *when no magnetizing current is there*

Calculate for turn

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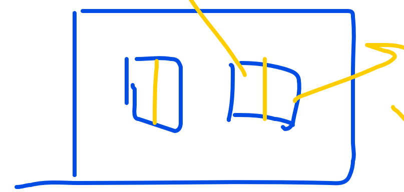
$$N_1 = \frac{V_1}{2nB_{\max}Sf}$$

½

$$N_2 = \frac{V_2}{2nB_{\max}Sf}$$

- When voltage is sinusoidal waveform,

$$kW = N_1 A_{w1} + N_2 A_{w2} \ ,$$



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$$Window\,Utilization\ Factor : k = 0.3 - 0.6$$

From the limitation of Copper loss (Pcu)

$$P_{cu} = I_{1rms}^2 R_1 + I_{2rms}^2 R_2$$

$$R = \frac{\rho l}{A_w} \quad , \quad J = \frac{I_{rms}}{A_w}$$

$$where \quad J = 100 - 1000 \ \ A/cm^2,$$

$$\rho = 1.724 * 10^{-8} \quad \Omega - m$$

- From magnetic circuit,

$$L = N^2 P_m = N^2 / R_m$$

$$L_{l1} = N_1^2 P_{l1}$$

$$L_{l2} = N_2^2 P_{l2}$$

$$P_m = \mu_m S_m / l_m$$

Selection of Core Size

(Slobodan Ćuk and R.D. Middlebrook, 1981)

2 Methods:

1. Area Product : Ap Approach
2. Core Geometry : Kg Approach

1. Ap Approach

- This method uses Trise which is form of Current density : J= 100-1000 A/cm^2
- For square wave, no dc magnetizing current is appeared.

$$N_1 = \frac{V_1}{4B_{\max}Sf} \qquad , B_{\max} \lim it$$

$$N_2 = \frac{V_2}{4B_{\max}Sf} \qquad , B_{\max} \lim it$$

$$kW = N_1A_{w1} + N_2A_{w2} \qquad , Window\, area \lim it$$

$$kW = N_1\frac{I_{1rms}}{J} + N_2\frac{I_{2rms}}{J} \qquad , Window\, area \lim it$$

- Replacement with N1, N2,

$$kW = \frac{V_1 I_{1rms}}{4B_{\max} SfJ} + \frac{V_2 I_{2rms}}{4B_{\max} SfJ}$$

$$kW = \frac{V_1 I_{1rms} + V_2 I_{2rms}}{4B_{\max} SfJ}$$

Rearrange

$$A_{p=} WS = \frac{V_1 I_{1rms} + V_2 I_{2rms}}{4kB_{\max} fJ}$$

- Generally, $V_1 I_{1rms} = V_2 I_{2rms} = Pout$

$$A_p = WS = \frac{P_{out}}{2kB_{\max} fJ}$$

Procedures for Ap Approach

1. Specifications and Limitations , Calculate for Ap
2. Core Selection > Ap from 1
3. Calculate for turn (N1, N2)
4. Calculate for Wire Size (Aw) where $N_1 A_{w1} = N_2 A_{w2}$
5. Wire Size selection (Aw) > Aw from 4

Where radius of wire size < skin depth

$$\delta(m) = \sqrt{\frac{2\rho}{\mu\omega}}$$

6. Calculate $P_{cu} = I_{1rms}^2 R_1 + I_{2rms}^2 R_2$ #

7. Adjust J from procedure 1 to 6 again until Pcu is suitable.

8. Calculate Lm from

$$L_m = N^2 \mu_m S_m / l_m$$

9. Calculate im from

$$i_m = i_1 - \left(\frac{N_2}{N_1} \right) i_2$$

2. Core Geometry: Kg Approach

- This method uses copper loss (Pcu) for design.

$$N_1 = \frac{V_1}{4B_{\max} Sf} \quad , \quad N_2 = \frac{V_2}{4B_{\max} Sf}$$

$$N_1 A_{w1} = N_2 A_{w2} = \frac{kW}{2}$$

$$l = nt \quad , \quad t = length\ per\ turn$$

$$R = \frac{\rho l}{A_w} \quad , A_w = \frac{kW}{2N}$$

$$R_1 = \frac{\rho N_1 t}{\left(kW \big/ 2N_1 \right)} = \frac{2\rho t N_1^2}{kW}$$

$$R_2 = \frac{2\rho t N_2^2}{kW}$$

$$P_{cu} = I_{1rms}^2 R_1 + I_{2rms}^2 R_2$$

replace R_1 *and* R_2

$$P_{cu} = \frac{2\rho t}{kW}\left(N_1^2 I_{1rms}^2 + N_2^2 I_{2rms}^2 \right)$$

- Replace N1 and N2

$$P_{cu} = \frac{2\rho t}{kW\left(4B\max Sf\right)^2}\left(V_1^2 I_{1rms}^2 + V_2^2 I_{2rms}^2\right)$$

In general , $V_1 I_{1rms} = V_2 I_{2rms} = P_{out}$

$$P_{cu} = \frac{\rho t P_{out}^2}{4kWB_{\max}^2 S^2 f^2}$$

- Rearrange

$$K_g = \frac{WS^2}{t} = \frac{\rho P_{out}^2}{4kB_{\max}^2 f^2 P_{cu}}$$

Procedures for Kg Approach

1. Specifications and Limitations , Calculate for Kg
2. Core Selection > Kg from 1
3. Calculate for turn (N)
4. Calculate for Wire Size (Aw)
5. Wire Size selection (Aw) > Aw from 4

- Where radius of wire size < skin depth

6. Calculate number of wires
7. Calculate total wire length
8. Calculate Core Bmax
9. Calculate total wire resistance
10. Calculate total copper loss
11. Calculate core loss per weight

$$P_{core/weight} = 9.562x10^{-6} B_{\max}^{2.22} f^{1.192}$$

12. Calculate Core loss