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Basics of Magnetics for Switching Power Webinar Series

Basics of Power Transformers

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Basics of Power Transformers

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Today's outline

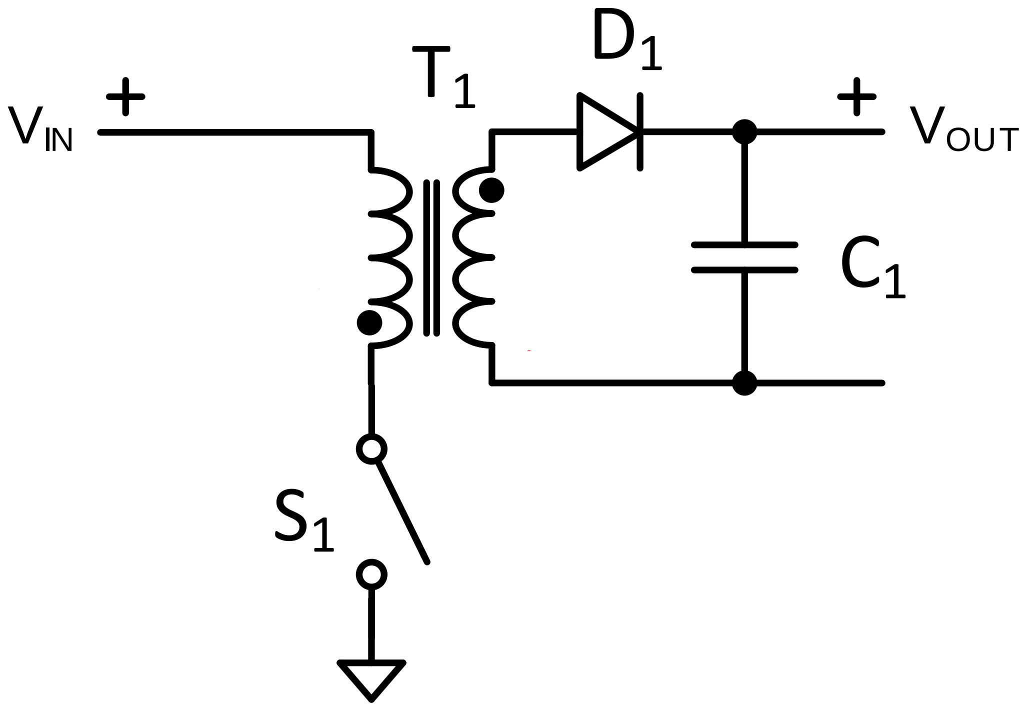
- Continue from flyback 'transformers'
- Magnetics everywhere
- Principle of transformer
- Equivalent circuit
- Leakage inductance – coupling
- Winding capacitance
- Core losses - ferrite
- Winding losses – R_{dc} - skin effect – proximity effect
- Forward – unipolar – half the core – two switch
- Push-pull – bipolar - extra windings
- Half / full bridge – bipolar – good usage of core and windings
- LLC – frequency regulation – almost ideal
- Safety agency requirements

Michael Faraday's original induction ring, 1831

Photo credit: Paul Wilkinson, Royal Institution

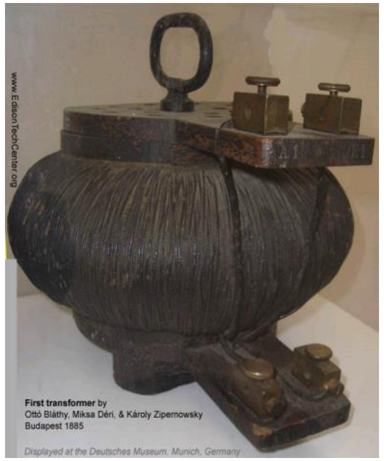
Flyback 'transformer'

- By definition, as an energy storage device it's an inductor
- The circuit operates this device as two separate inductors that use the same core to link them together.
- Because they are linked by the mutual flux, the voltages and currents have transformer like property of turns ratio
- Because the input and output use different windings it has the transformer property of galvanic isolation
- Transformer-choke

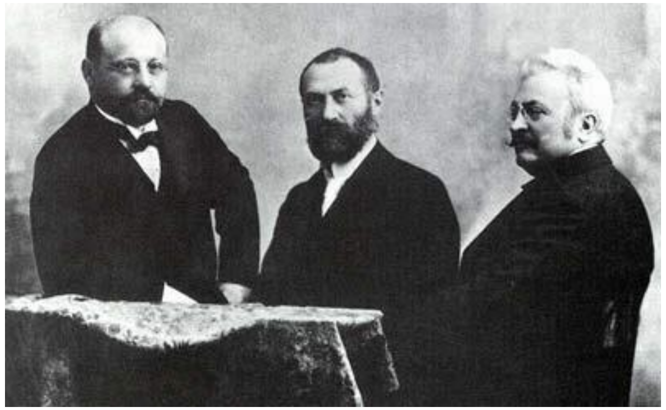


Crossroads

- Inductor:
  - An magnetic device that impedes the change in the flow of electric current by storing and releasing energy from its magnetic field.
- Transformer:
  - A magnetic device that transfers energy instantaneously through its magnetic field. Used to change the voltage or current and provides galvanic isolation.

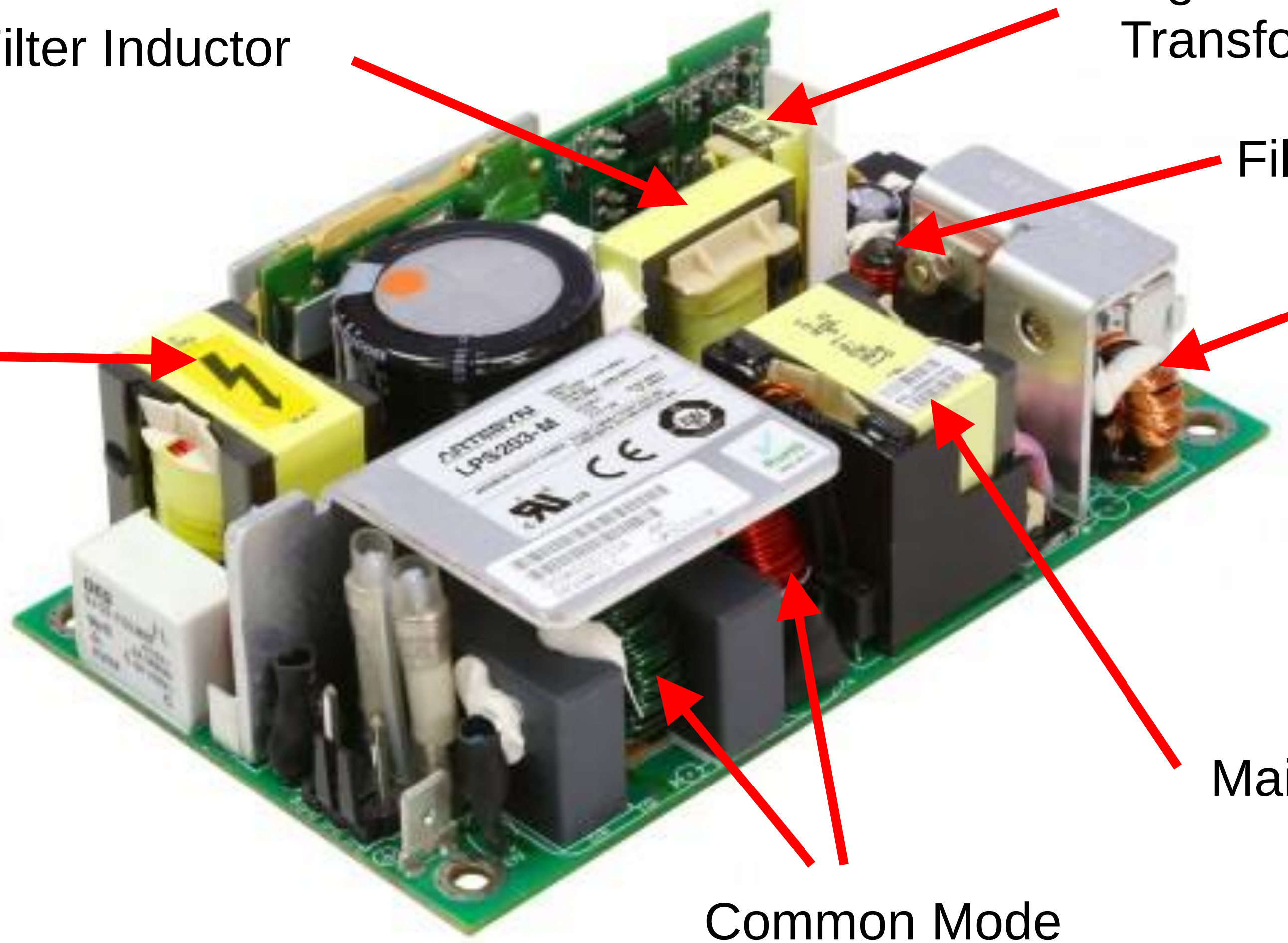


1885

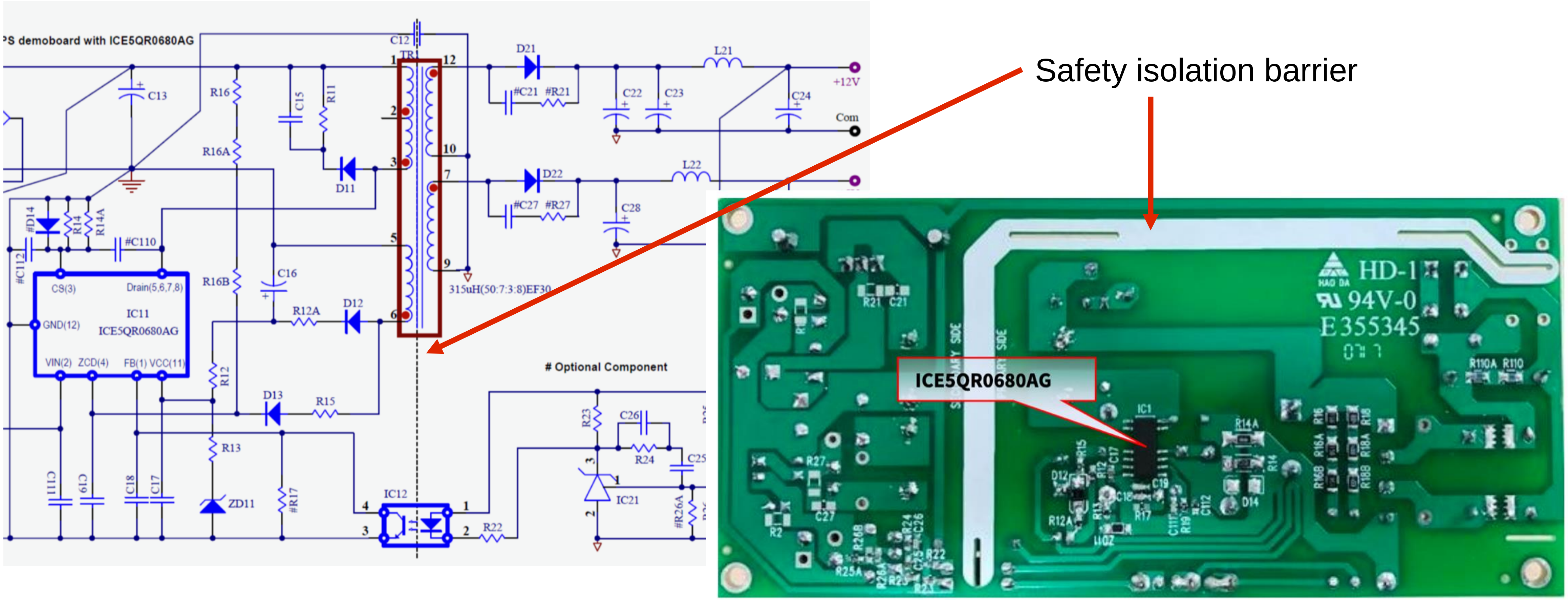


Ottó Bláthy, Miksa Déri, Károly Zipernowsky

Magnetics everywhere

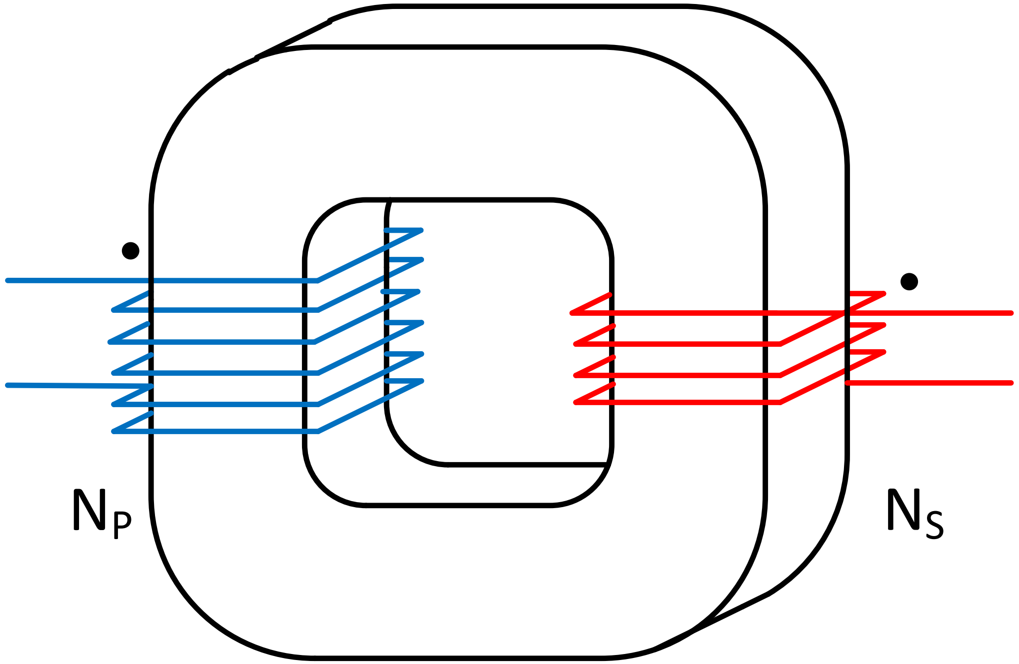


Galvanic isolation



Infineon app note AN_201702_PL83_007

Principle of a transformer



$$\frac{Vs}{Vp} = \frac{Ns}{Np}$$

$$\frac{Is}{Ip} = \frac{Np}{Ns}$$

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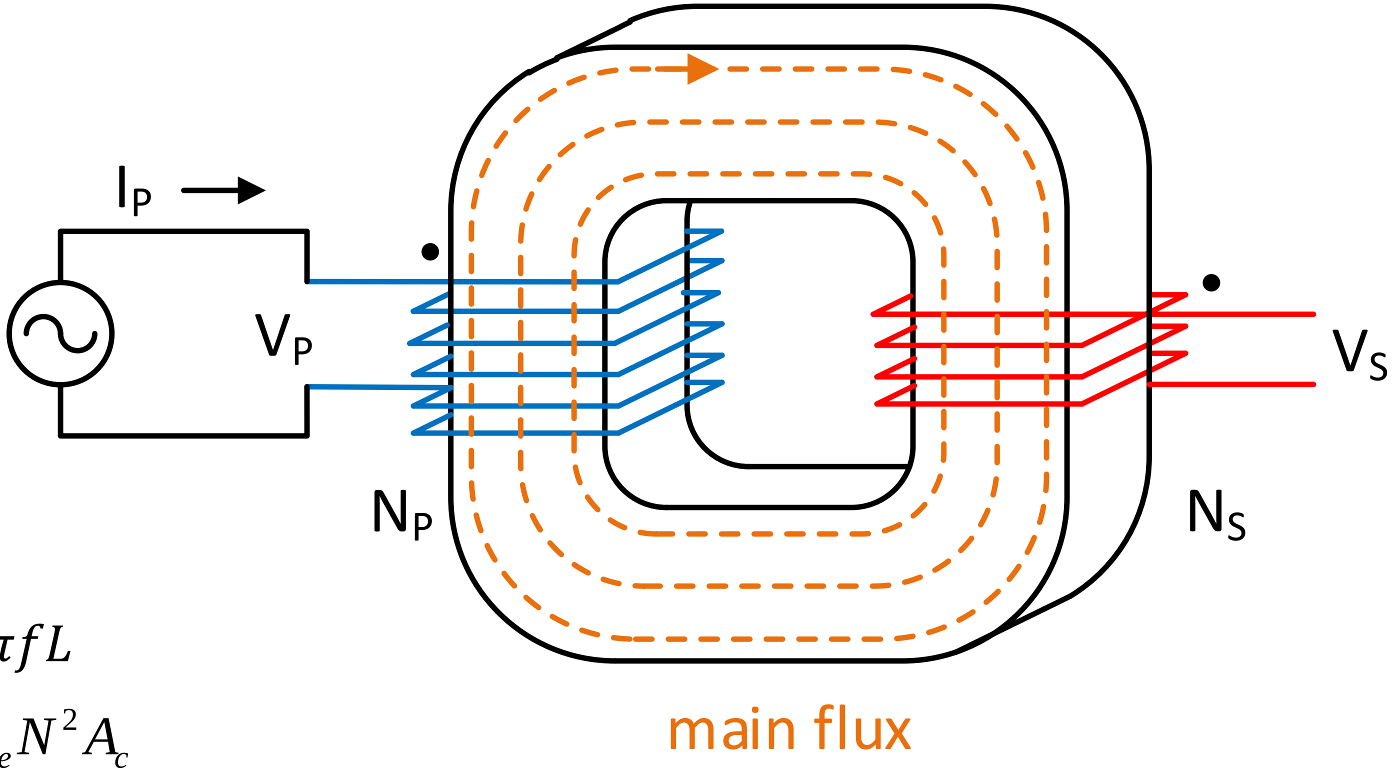
Add a source

$$V = -NA_c \frac{\Delta B}{\Delta t}$$

$$\frac{Vs}{Vp} = \frac{Ns}{Np}$$



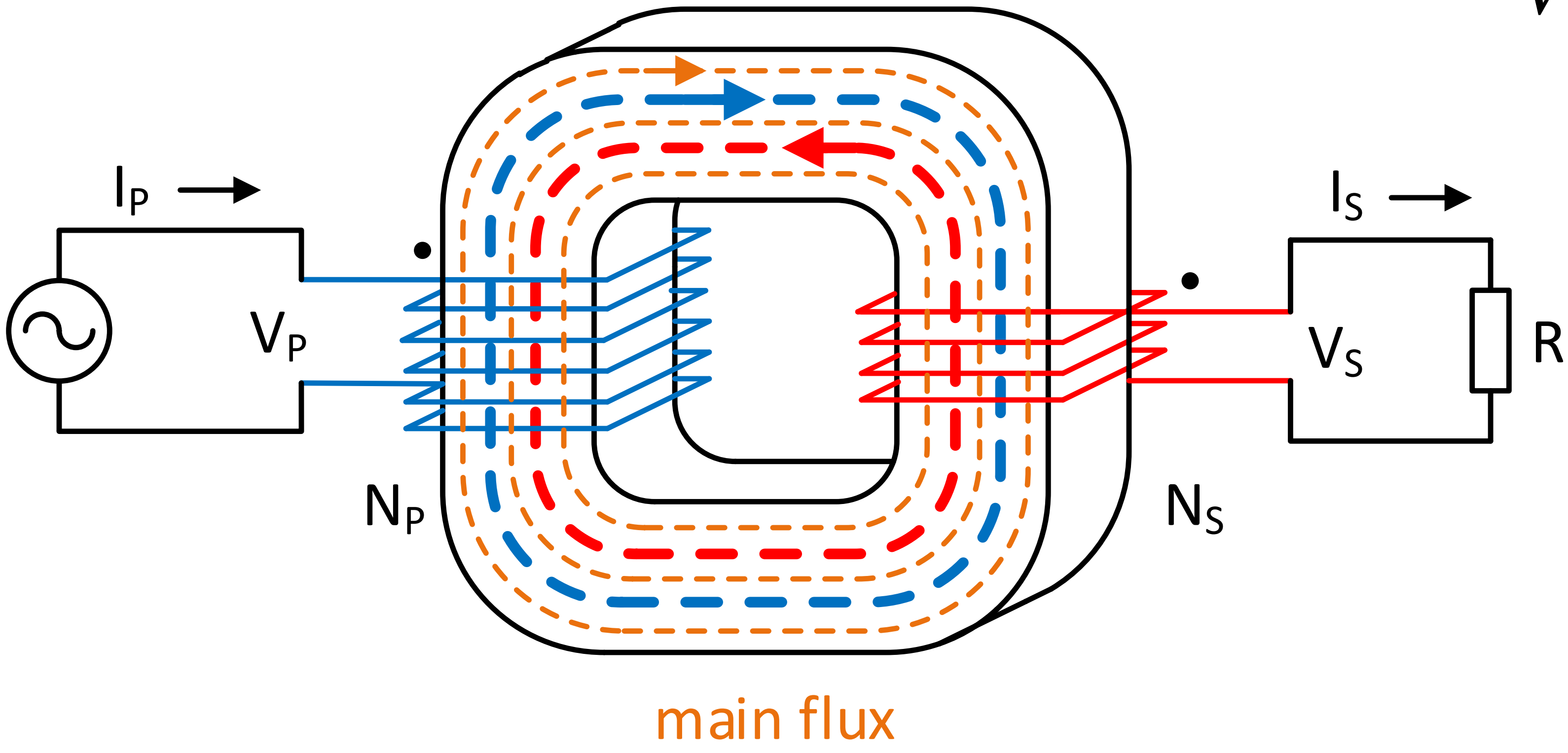
$$X_L = 2\pi f L$$

$$L = \frac{\mu_0 \mu_e N^2 A_c}{l_c}$$

$$B_{max} = \frac{V}{4NAef}$$ (Square wave)

Right hand rule determine flux direction

Add a load

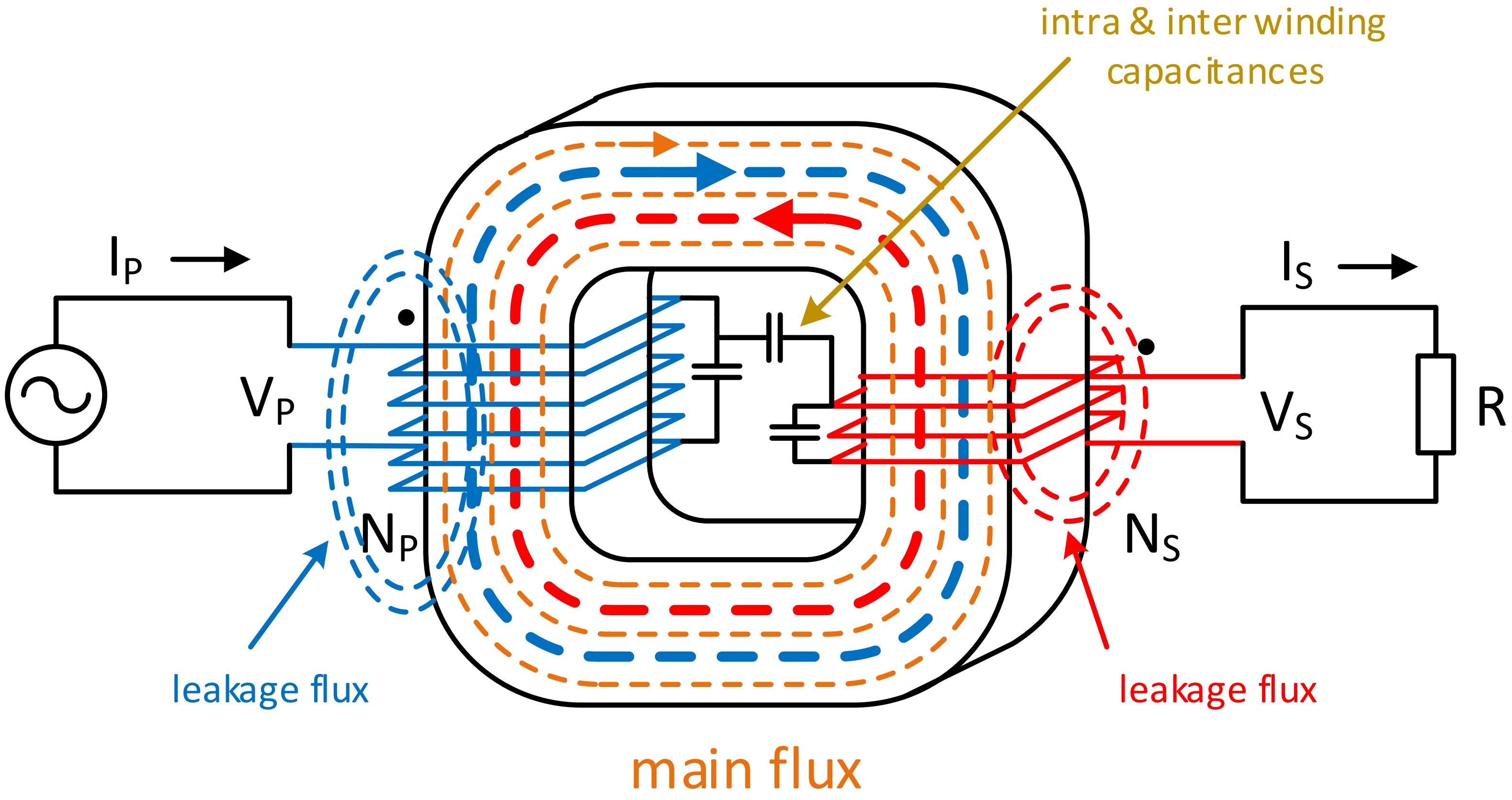


$$V = -NA_c \frac{\Delta B}{\Delta t}$$

$$\frac{Vs}{Vp} = \frac{Ns}{Np}$$

$$\frac{Is}{Ip} = \frac{Np}{Ns}$$

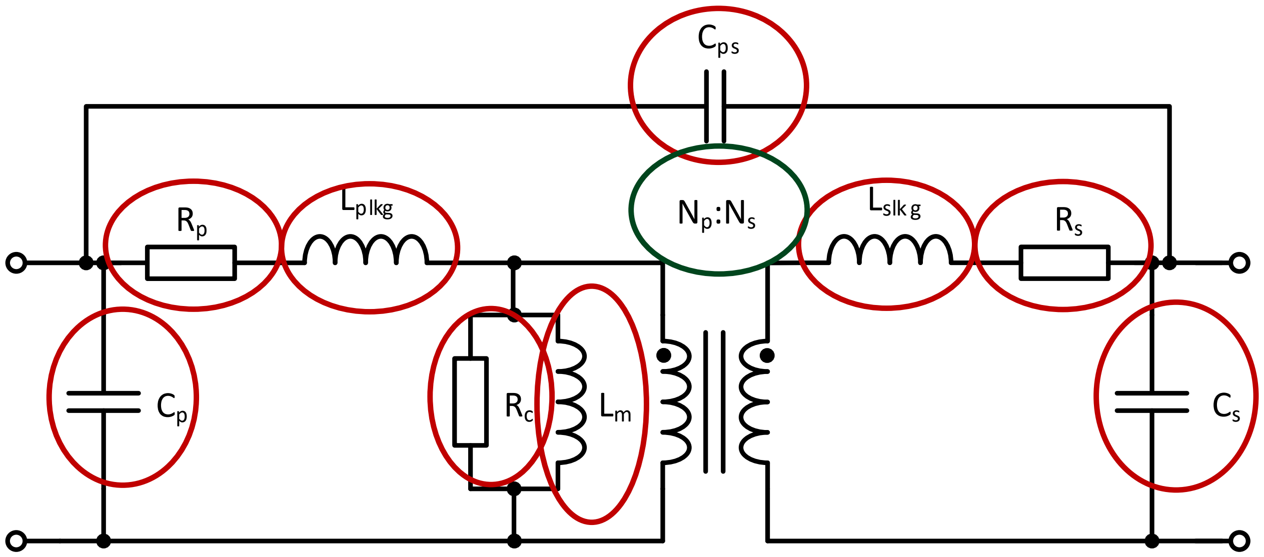
Add parasitics



$$k = \sqrt{1 - \frac{lkg}{L}}$$

Equivalent circuit (lumped)

- N_p:N_s – turns ratio (n)(note: either side can be the reference)
- L_m – magnetizing inductance
- R_c – core loss
- L_{plkg}, L_{slkg} – leakage inductance (usually combined into one)
- R_p, R_s – winding resistances – both ac and dc
- C_p, C_s – intra winding capacitance
- C_{ps} – interwinding capacitance
- Most element's characteristics are frequency dependent



The secondary side elements of leakage inductance, resistance and capacitance can be transferred to the primary by the square of the turns ratio.

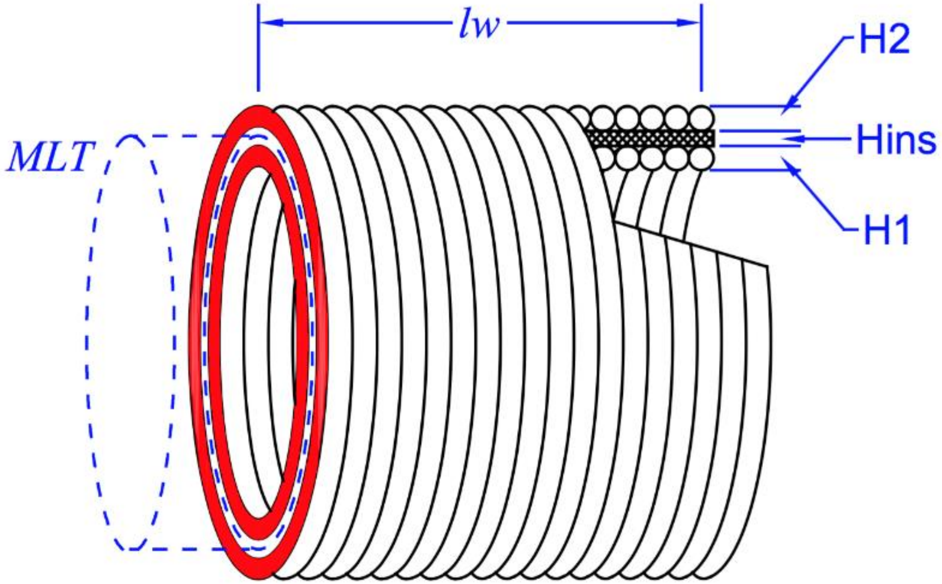
Leakage inductance

Solenoid

$$L = \frac{\mu_0 N^2 A}{l_w}$$

Leakage

$$L_{lkg} = \frac{\mu_0 N^2 A_{ins}}{l_w}$$



$$A_{ins} = MLT\left(H_{ins} + \frac{1}{3}H_1 + \frac{1}{3}H_2\right)$$

where

MLT = mean length turn

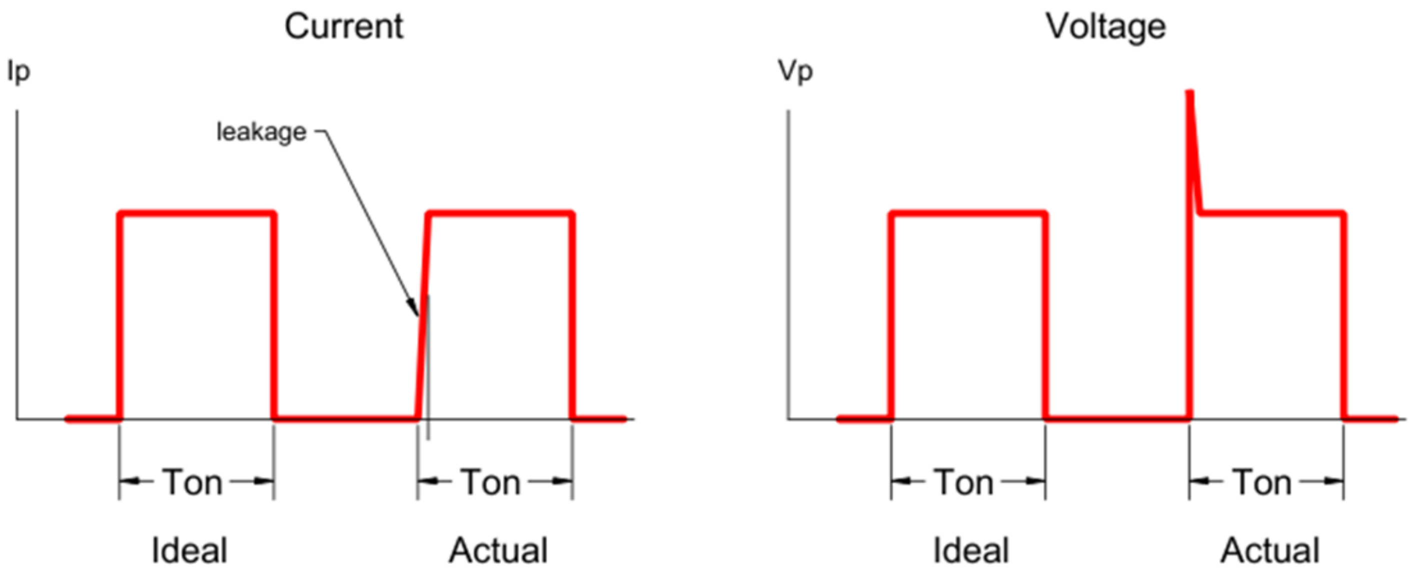
H_{ins} = *insulation thickness*

H_1 = *winding build*

H_2 = *winding build*

Effects of leakage inductance

- Delays power transfer
- Limits rate of rise of the current waveform at turn-on
- At turn-off causes voltage spike on drain of MOSFET
- Adds to secondary rectifier spikes



Reducing leakage inductance

- Only three soultions
- Reduce N^2 by minimizing turns – most effective
- Reduce A_{ins} by
  a) Keep the highest power windings next to each other
  b) Minimize insulation thickness between windings
  c) Avoid using shields
  d) Bifilar windings
- Increase l_w by
  a) Use long winding lengths with few layers
  b) Split and interleave the one winding – one is most effective
  c) Make winding lengths the same for all windings
  d) Two coil series construction on C or U cores

$$L_{lkg} = \frac{\mu_0 N^2 A_{ins}}{l_w}$$

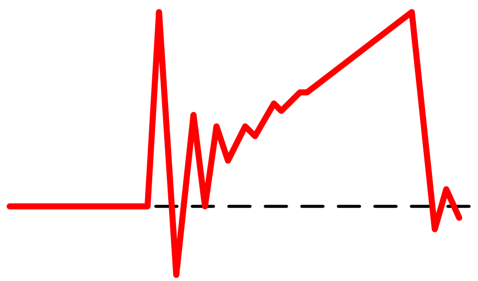
- Techniques to reduce leakage inductance usually increase winding to winding capacitance

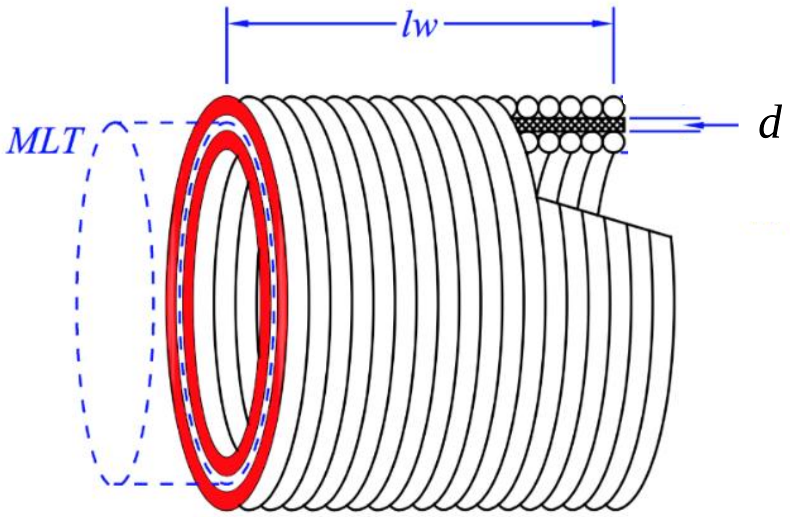
Capacitance everywhere

- When a transformer is energized, different voltage gradients arise almost everywhere
  - Between turns
  - Between layers
  - Between windings
  - Between terminals
  - Between core and end of layer
  - Between core and each terminal
- All these have capacitance which represents stored energy not used in the circuit

Effects of winding capacitance

- Slows the rise time of leading edge voltage
- Causes current spikes at turn on
- Conducts noise – EMI
- Limits operating frequency through self resonance





$$C = \epsilon_0 \varepsilon_r \frac{l_w \cdot MLT}{d}$$

$$\varepsilon_0 \approx 8.854 \times 10^{-12} \left(\frac{F}{m}\right)$$

w = width of winding
MLT = mean length turn
d = distance between plates
ε_r = relative permittivity

Reducing winding capacitance

- Reduce permittivity ε_r by careful material selection
- Reduce A by
  a) Reduce winding length
  b) Do not interleave windings
- Increase d by
  a) Increase dielectric thickness
  b) Use interlayer insulation
  c) Use heavier enamel insulation
  d) Do not wind bifilar
- Redistribute voltage and charge
  a) Use multiple section bobbins
  b) Use Z winding – changes voltage distribution
  c) Use a faraday shield – drains charge
- Techniques to reduce capacitance usually end up increasing leakage inductance

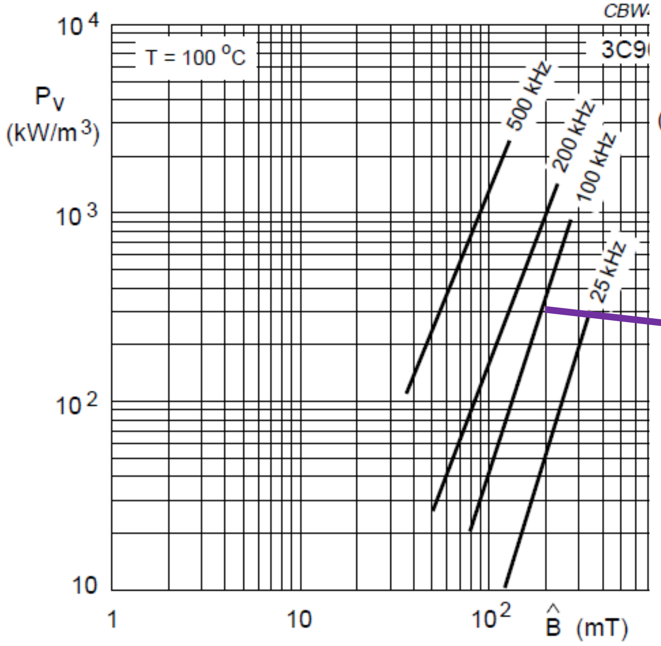
$$C = \epsilon_0 \varepsilon_r \frac{A}{d}$$

$$C = \frac{q}{V}$$

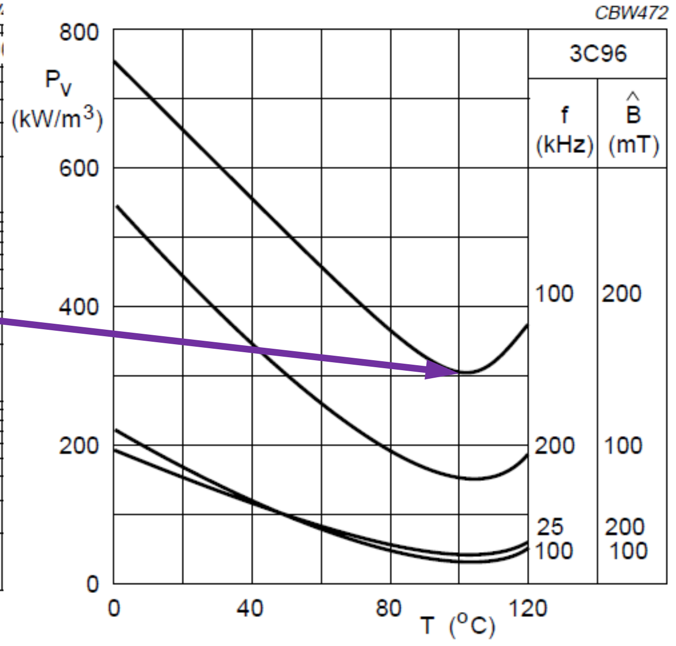
Core loss

- In applications it varies with
  - Frequency
  - Flux level
  - Temperature
  - Waveform (including duty cycle)
- Curves are empirical derived from measurement normally of a sine wave
- Slope changes with frequency
- Most models pick just one spot on the curves

Power Loss vs peak flux



Power Loss Freq-Flux-Temp



Steinmetz equation $P = kf^{\alpha}B^{\beta}$ Circa 1892

Ferrite core material

- First proposed by Hilpert in1909
- First invented by Kato & Takei in 1930
- First MnZn and NiZn by Sneok in 1945
- Core materials continue improve by tuning
- Material composition only affects Tc, Bs and crystalline anisotropy
- Structure sensitive properties are Hc, Br and permeability

Material optimization

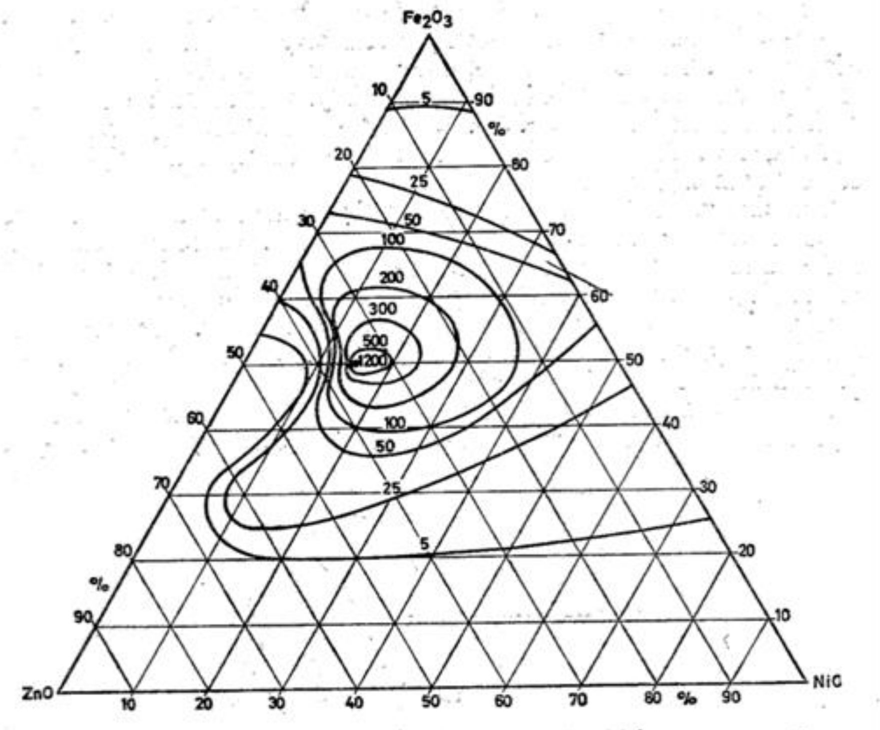


Figure 13.101. Loci of equal initial permeability displayed in a three-component diagram for NiO–ZnO–Fe_2O_3[50]

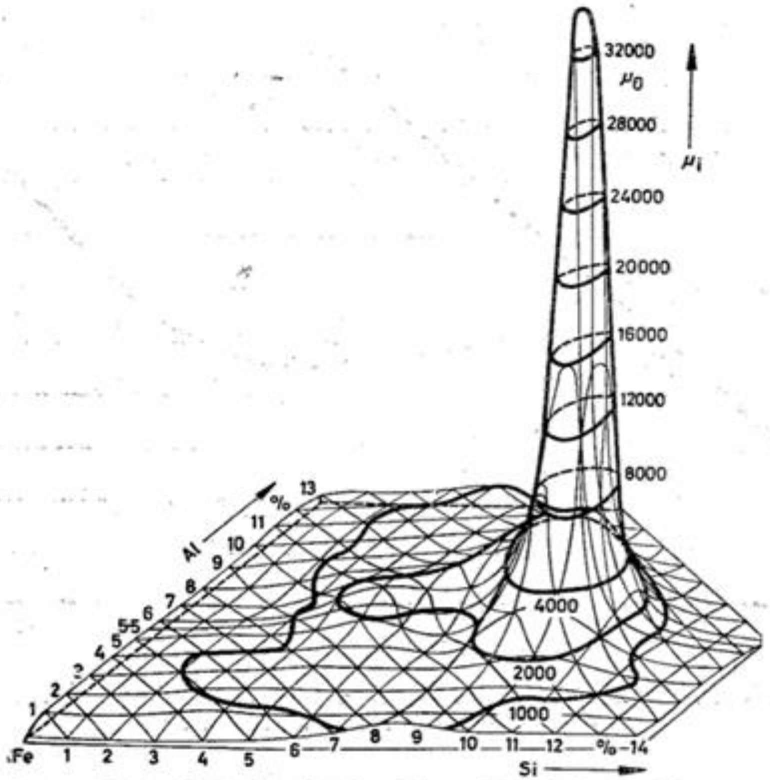
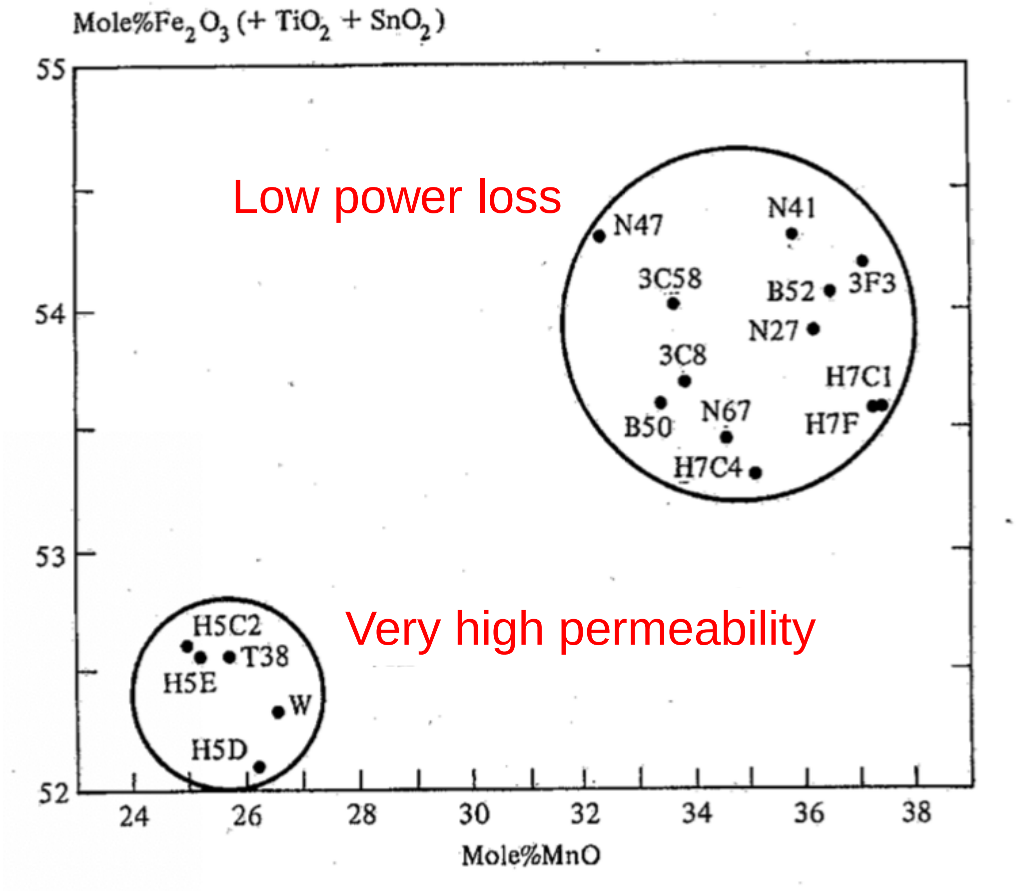


Figure 13.52. Initial permeability of Fe–Si–Al alloys[95]

Heck, C., Magnetic materials and their applications, Crane, Russak & Co., Inc., New York, 1974

You Pick Two®



A. Goldman, Modern Ferrite Technology, pg 101, from E. Roess, Advances in Ferrites, Vol 1

Low Power Loss	High Bsat
High Frequency	Wide Temperature

® Panera Bread

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Performance factor

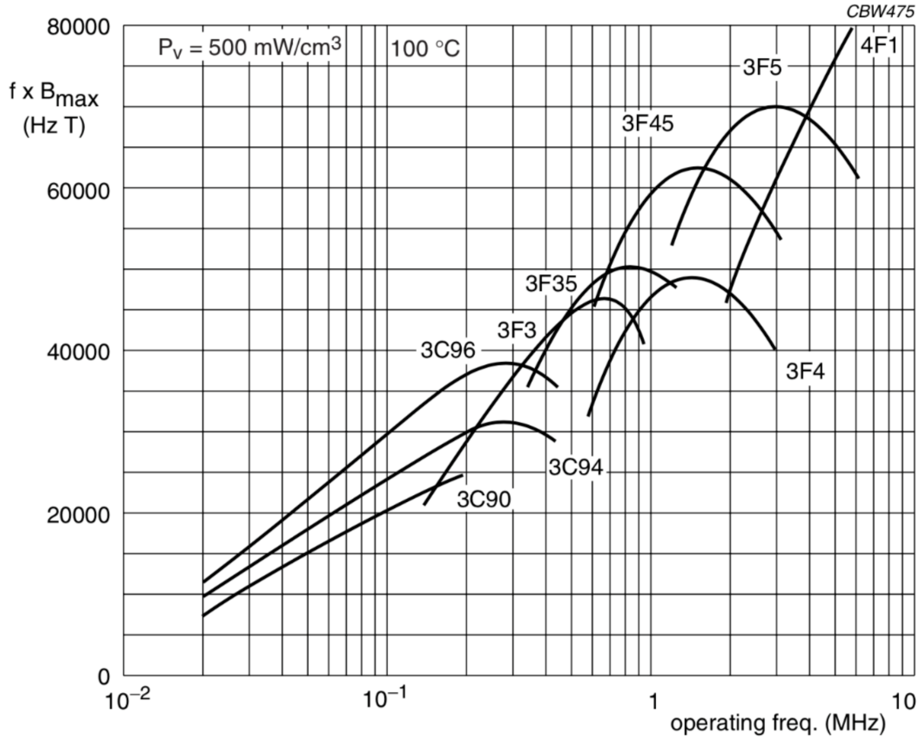


Fig.19 Performance factor ($f \times B_{max}$) at PV = 500 mW/cm^3 as a function of frequency for power ferrite materials.

(Ferroxcube)

Snoek's limit - 1947

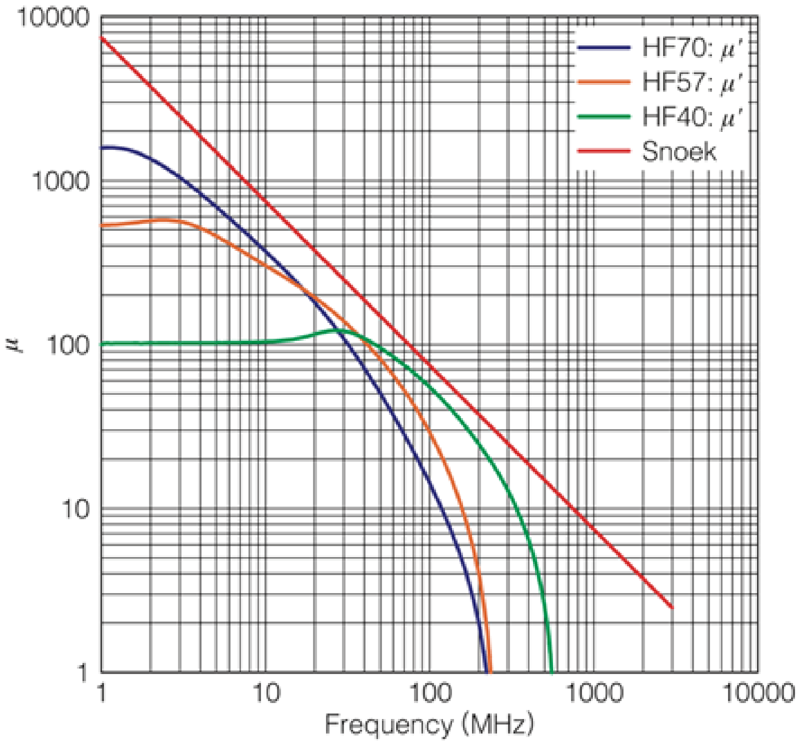


Fig. 3 Frequency characteristic of ferrite μ_i and Snoek's limit (TDK)

Winding losses

- Governed by conservation of energy
- DC losses
  - At low frequencies this is by minimizing I^2R losses.
- AC losses
  - At high frequencies it is by minimizing inductive energy - that is energy transferred to and from the magnetic field generated by the current flow even if that results in higher I^2R losses.
  - Eddy currents
  - Skin effect
  - Proximity effect

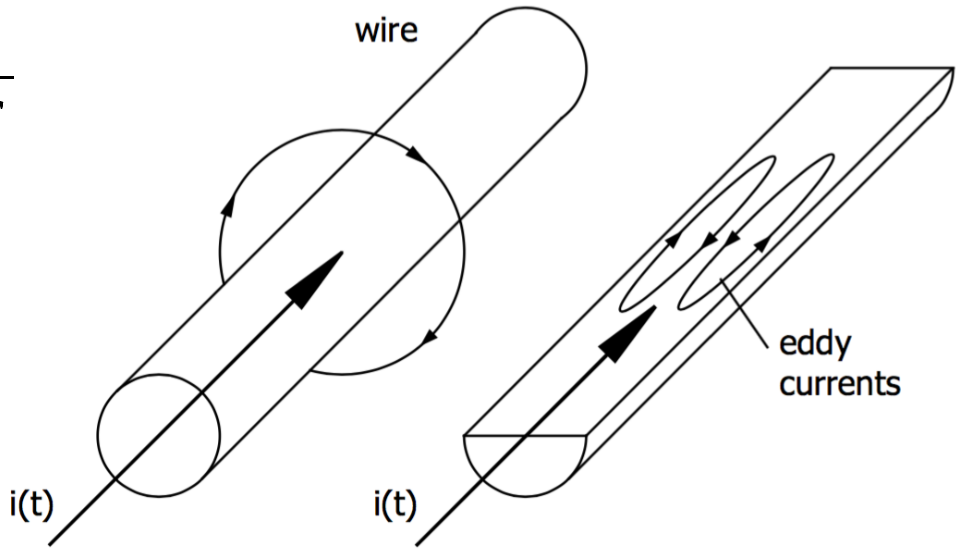
$$R_{dc} = \rho \frac{l}{A}$$

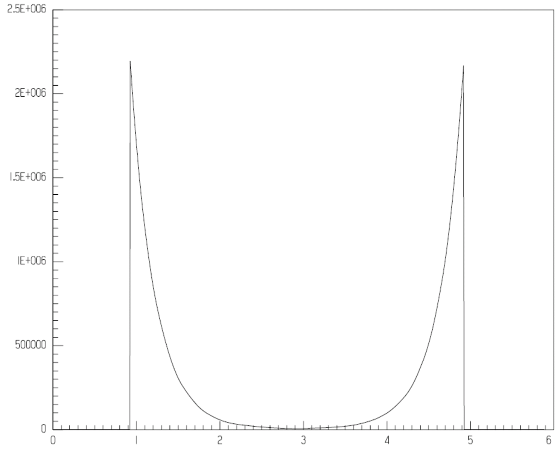
$$P_{cu} = I^2 R$$

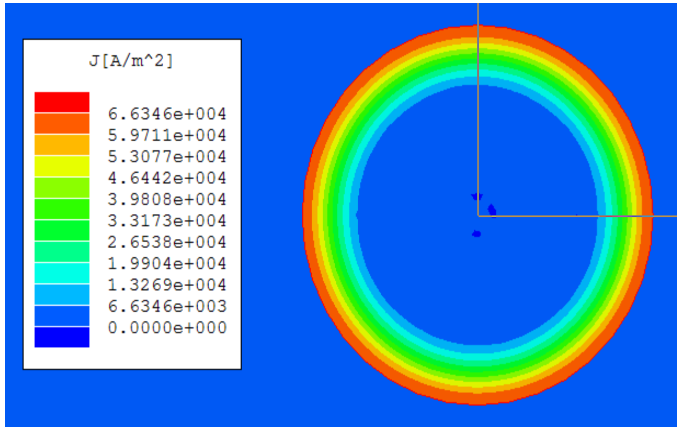
Skin effect

$$\delta = \sqrt{\frac{\rho}{\pi \bullet \mu_o \bullet \mu_r \bullet f}}$$

$$\delta = \frac{76}{\sqrt{f}} mm$$







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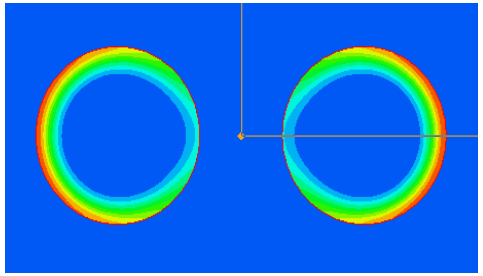
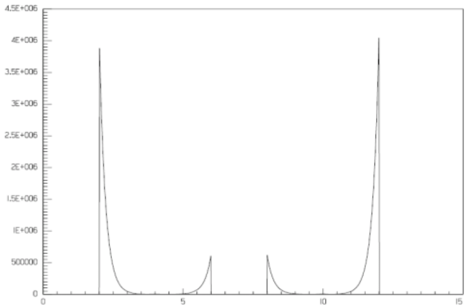
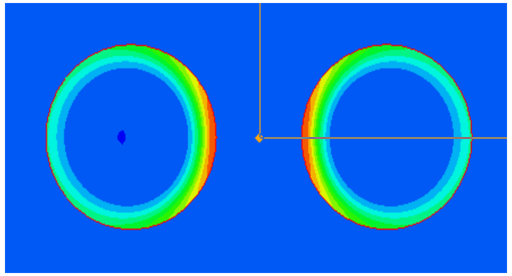
Promixity effect

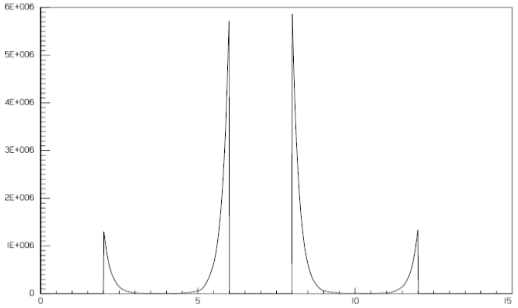
- The proximity effect plays a far greater role in transformers because the neighboring conductors of a winding and neighboring windings generate fields which displace the current.
- It's possible to calculate approximate eddy current losses for simple geometries using Dowell's curves.

Two wires with current in same direction









Two wires with current in opposite direction

Proximity effect

- For thick conductors h > δ
- Along a winding the current concentrates on the outer surfaces.
- Between primary and secondary the current concentrates on the facing surfaces.

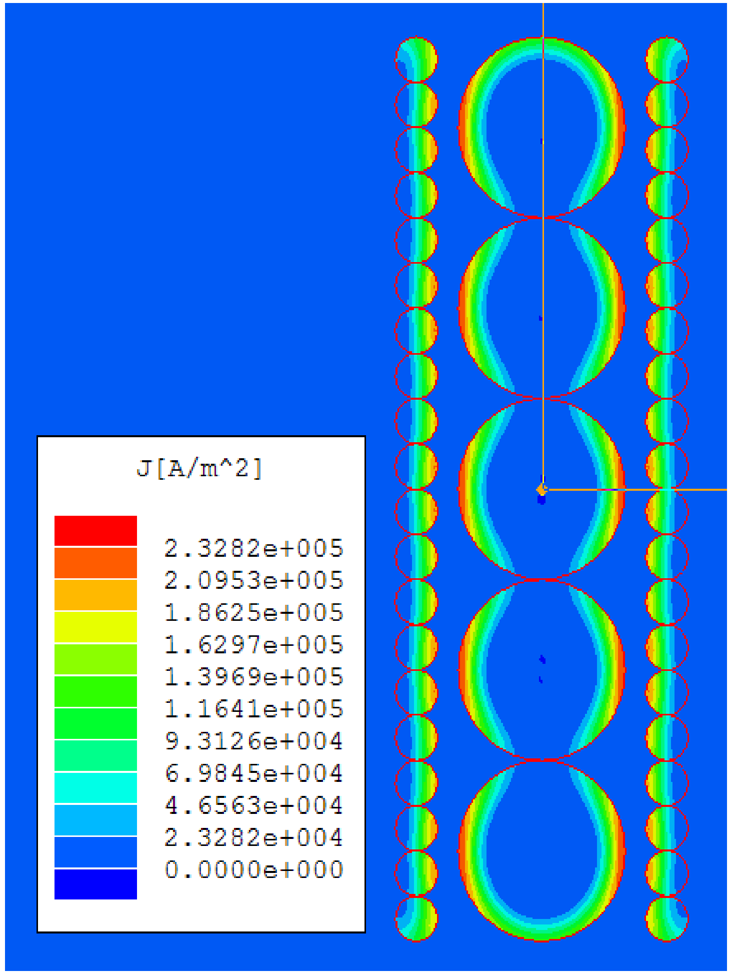
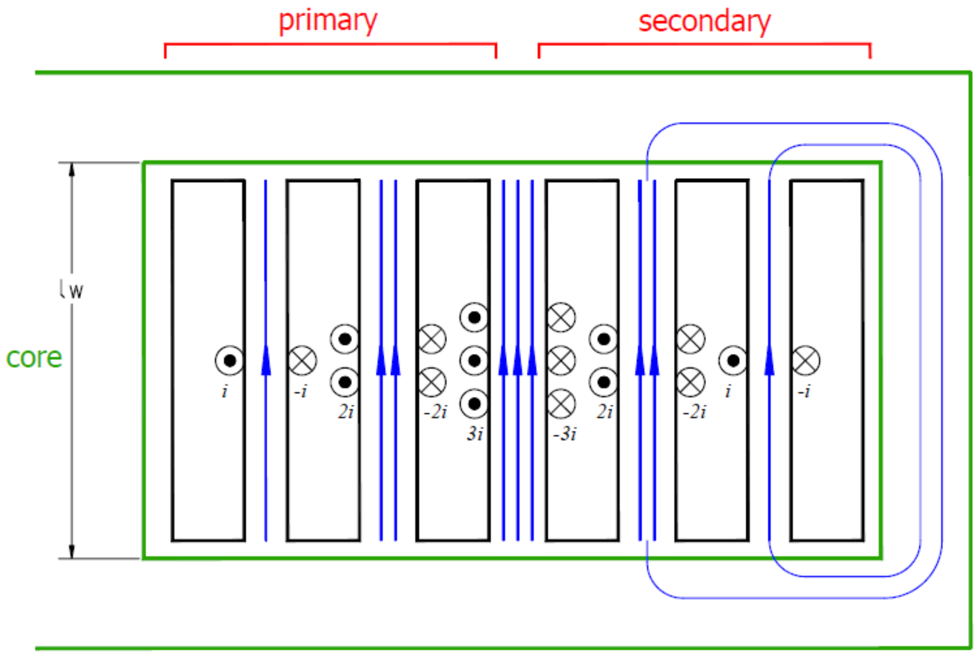


Image from en.wikipedia.org

Magnetic fields in windings

- The core provides a low reluctance path for flux so the concentration of force is between the turns (blue lines) and builds with each turn enclosed by the path loop. This force increases with each layer.



$$Ni = F$$

$$H = \frac{F}{l_w}$$

Power loss due to proximity effect

- Let P_1 be power loss in layer 1:

$$P_1 = I_{rms}^2 R$$

- Power loss P_2 in layer 2 is:

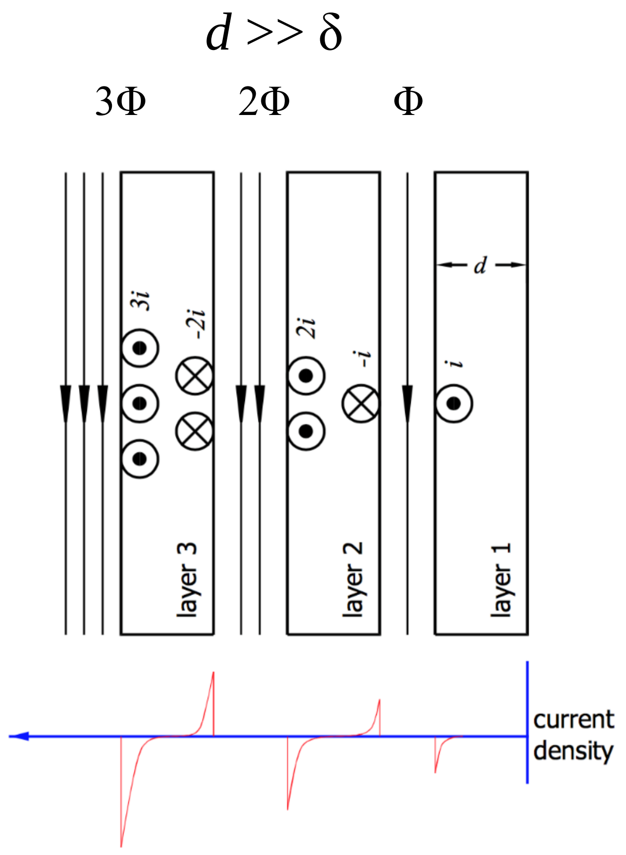
$$P_2 = I_{rms}^2 R + \left(2I_{rms}\right)^2 R = 1P_1 + 4P_1 = 5P_1$$

- Power loss P_3 in layer 3 is:

$$P_3 = \left(2I_{rms}\right)^2 R + \left(3I_{rms}\right)^2 R = 4P_1 + 9P_1 = 13P_1$$

- Power loss P_m in layer m is:

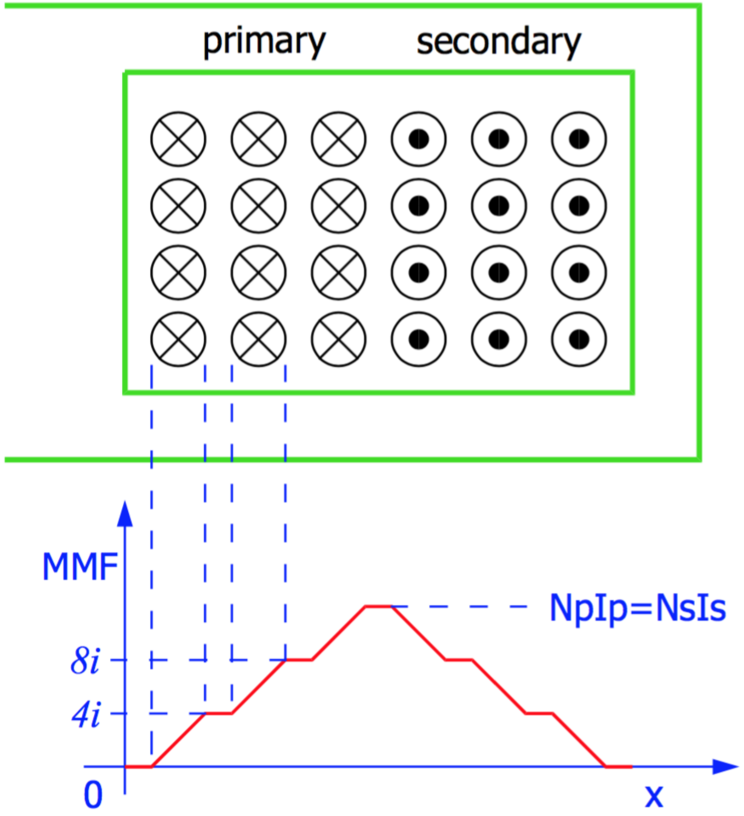
$$P_m = ((m-1)^2 + m^2)P_1$$



MMF diagram

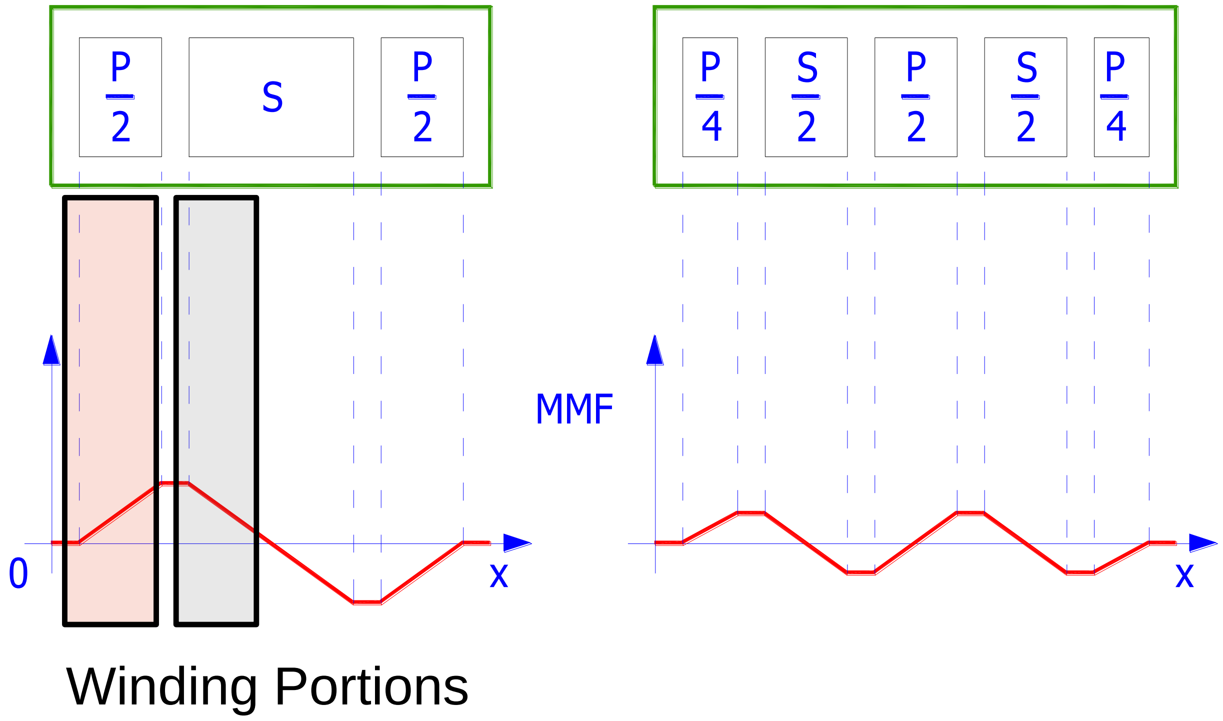
- The primary winding NI builds the MMF and the secondary winding NI reduces it back to zero.

$$Ni = F \qquad H = \frac{F}{l_w}$$

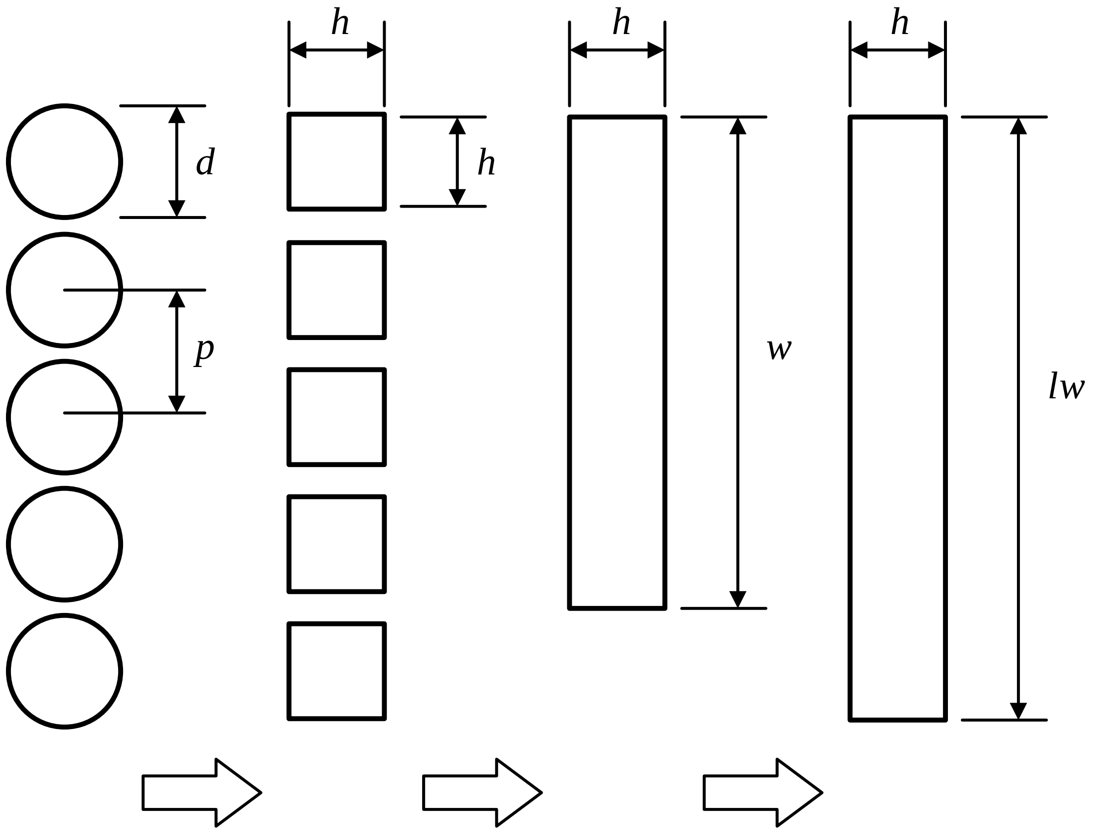


Interleaved windings

- Interleaving reduces MMF and hence eddy current losses. One interleave is the most practical for power transformers.



Conversion to equivalent foil



$$h = \sqrt{\frac{\pi}{4}} d$$

$$F_l = \frac{Nh}{l_w}$$

$$\varphi = \frac{h\sqrt{F_l}}{\delta}$$

Reference: P.L. Dowell, "Effects of eddy currents in transformer windings", Proc. Inst. Elect. Eng., vol. 113, no. 8, pp. 1387-1393, 1966

Basic equation

$$F_r = \frac{R_{ac}}{R_{dc}} = A\left[\frac{\sinh(2A)+\sin(2A)}{\cosh(2A)-\cos(2A)} + \frac{2(N^2-1)}{3}\frac{\sinh(A)-\sin(A)}{\cosh(A)+\cos(A)}\right]$$

$$A = \left(\frac{\pi}{4}\right)^{\frac{3}{4}}\left(\frac{d}{\delta}\right)\sqrt{\frac{d}{p}}$$

$d = bare\ wire\ diameter$

$p = wire\ pitch$

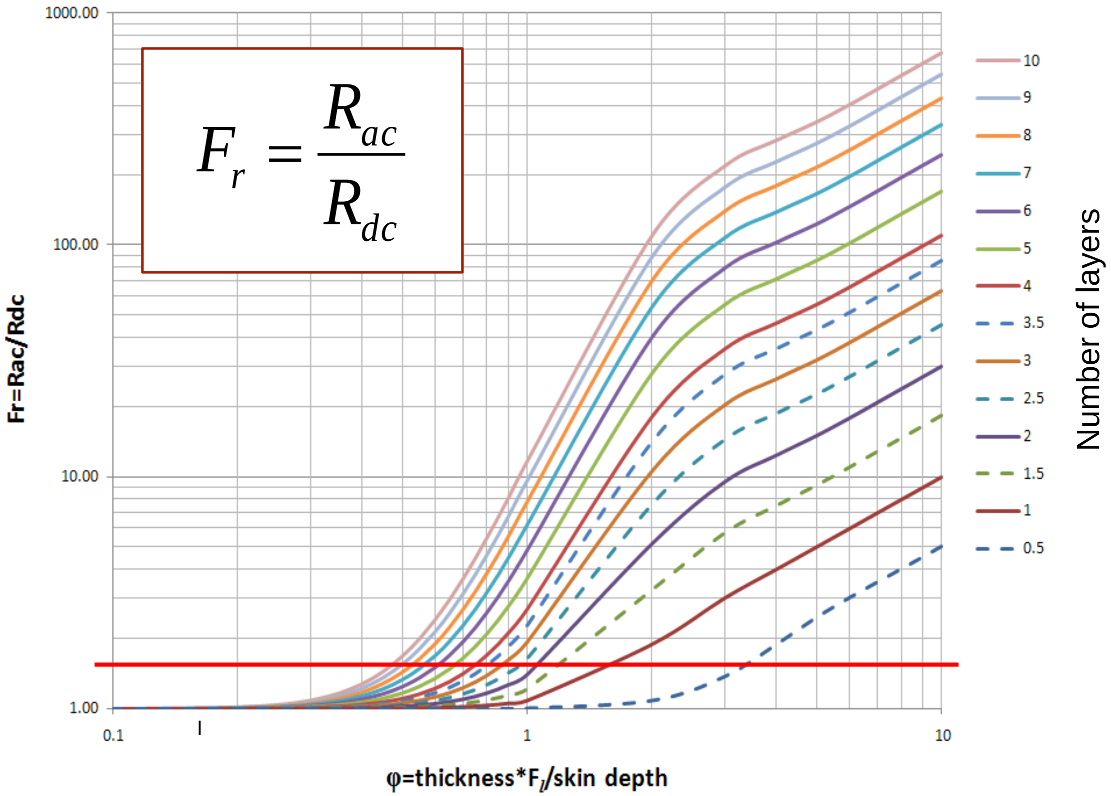
$\delta = skin\ depth$

$N = number\ of\ layers$

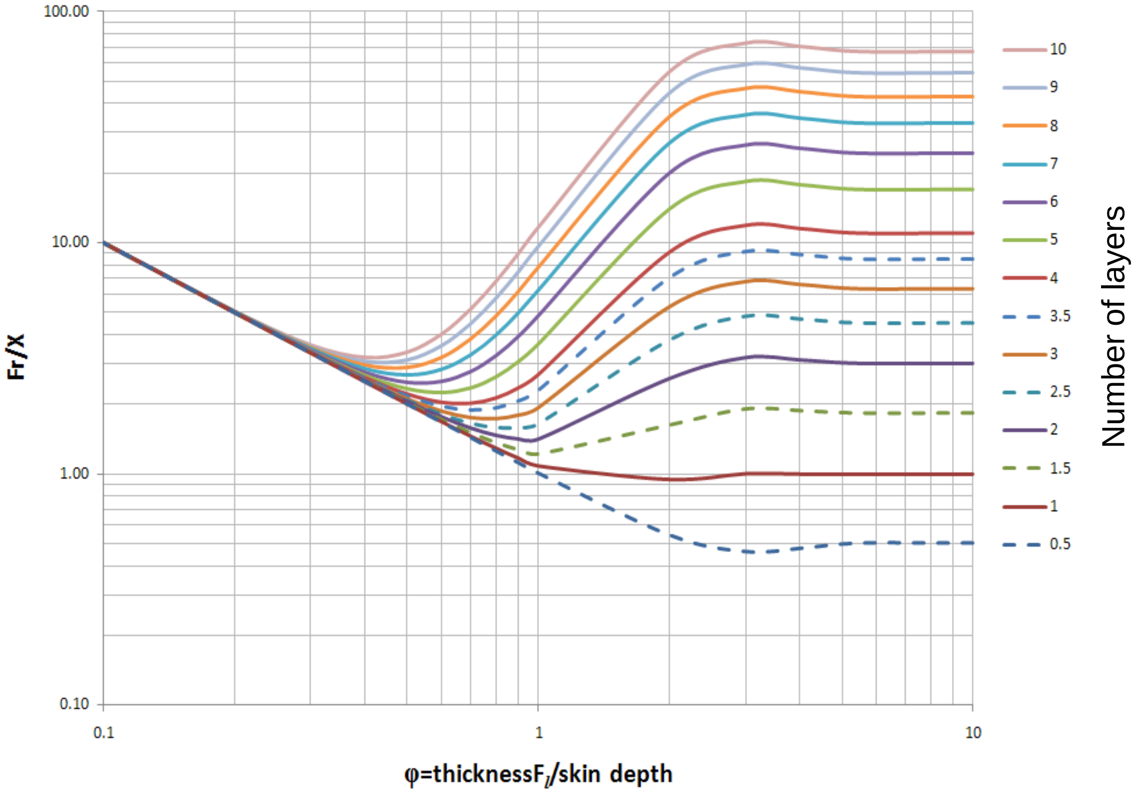
$$N_{litz} = N \cdot \sqrt{k},\ where\ k = number\ of\ strands$$

M. Kazimierczuk, *High-frequency magnetic components*, 2nd ed. Singapore: John Wiley & Sons, 2014, pp. 306-351.

Dowell's curves



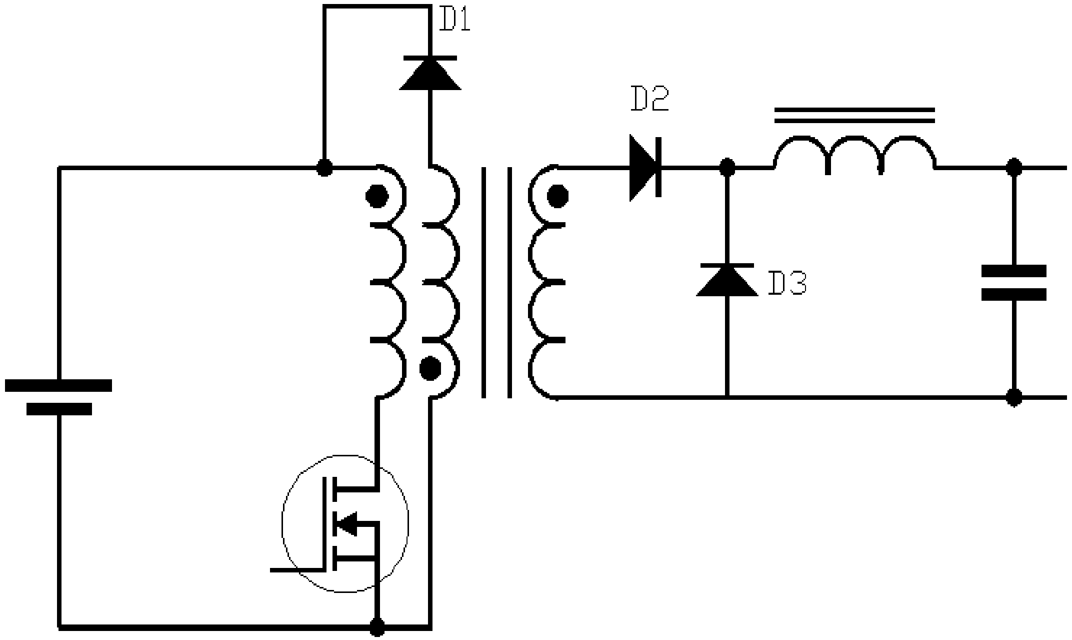
$$F_r = \frac{R_{ac}}{R_{dc}}$$

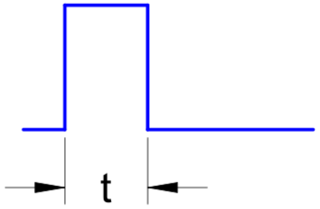


Normalized

Forward converter

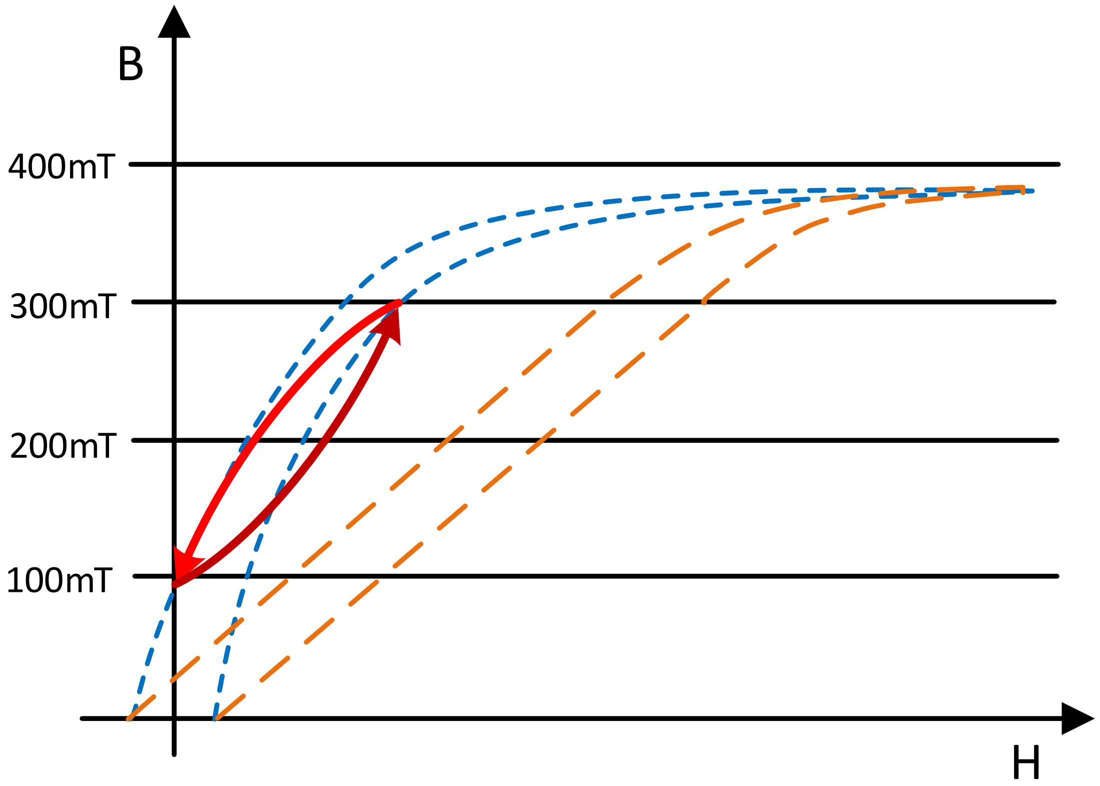
- True transformer
- Only uses half the capability of the core
- Uses a separate output filter inductor
- Usually limited to 50% duty because core must reset
- Separate reset winding
- High voltage on the switch – 2x Vin
- Limited by primary current to 100-200 W



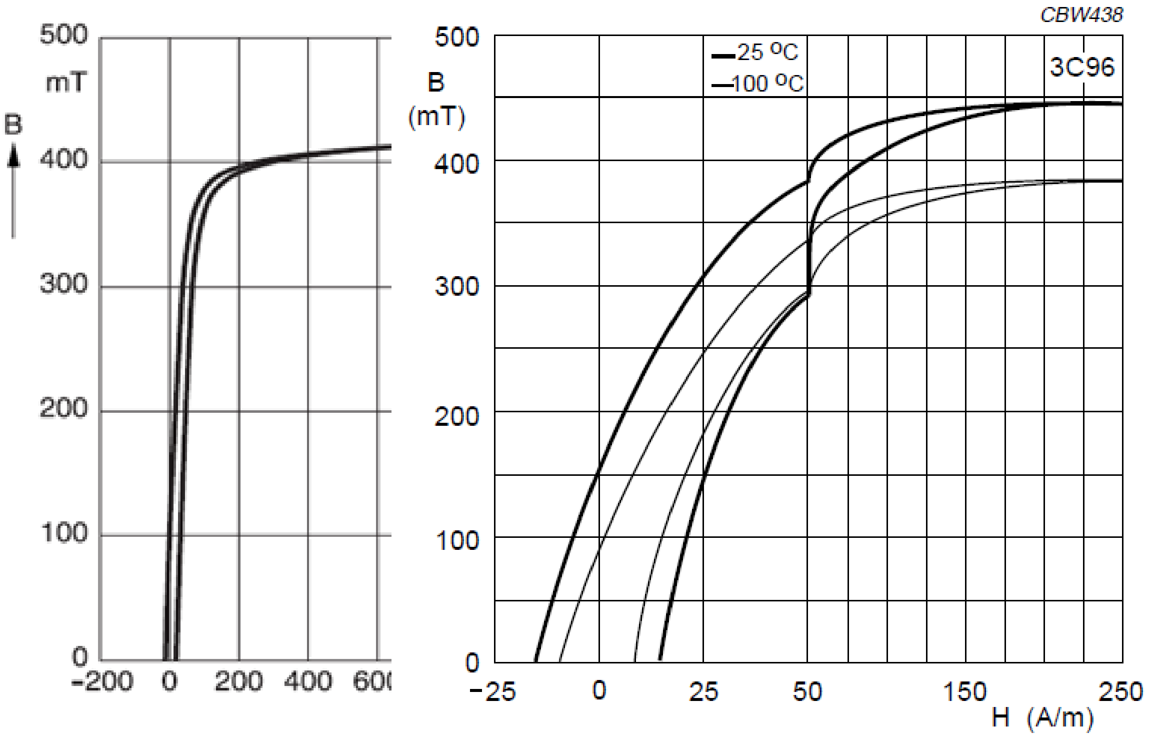


$$B_{max} = \frac{V_{pk} t_{on}}{N A_c}$$

Limited flux range – reset core



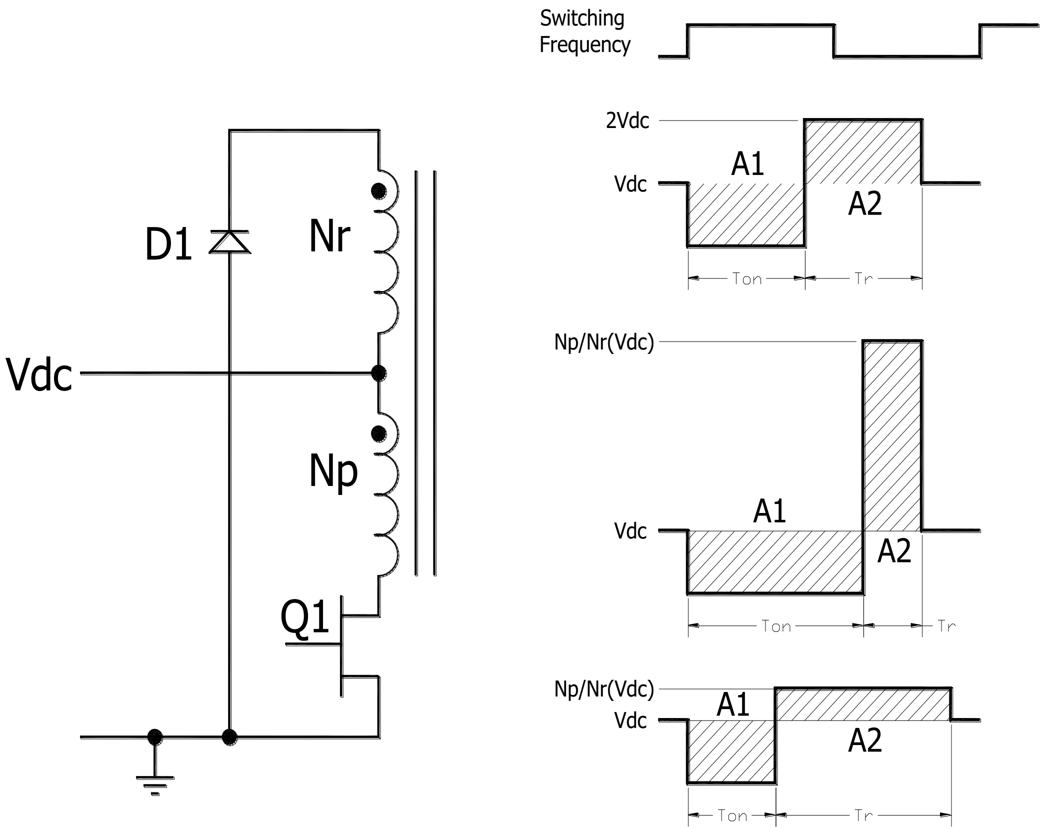
Dynamic magnetization curves
(typical values)
(f = 10 kHz, T = 100 °C)



Reset volt-second product

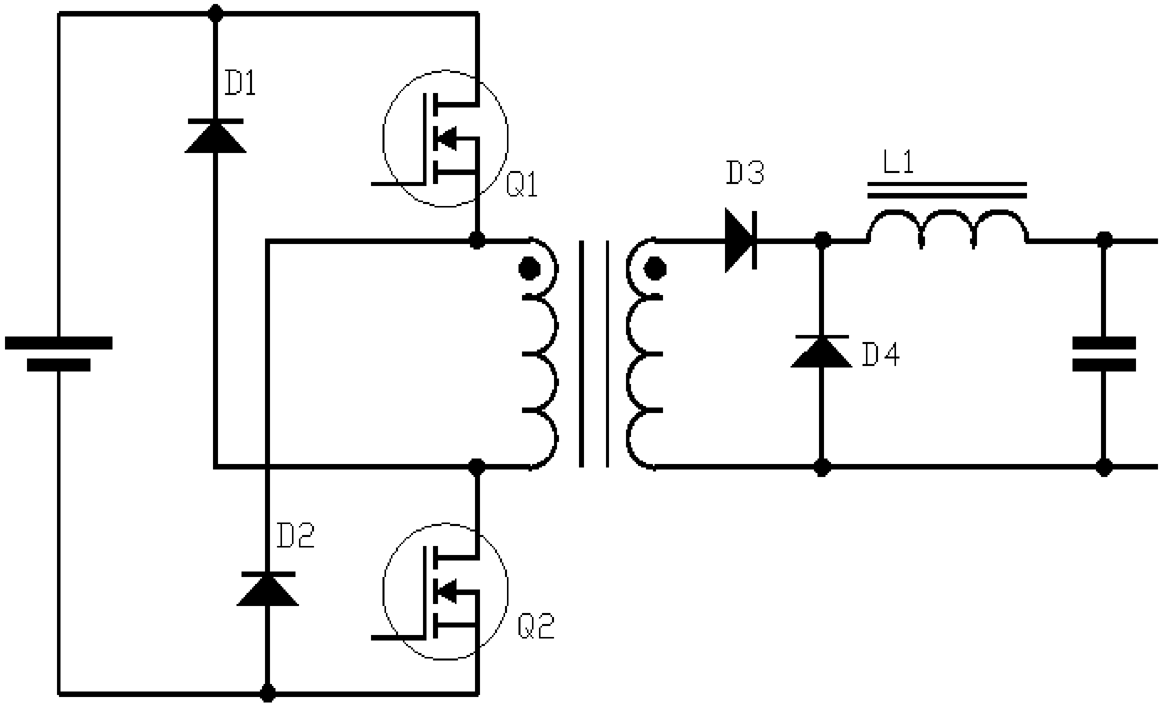
- Usually the reset turns are equal to the primary turns but this limits T_{on} to 50% max.
- By adjusting the turns ratio N_p/N_r the on time can be increased at the expense of higher reset voltage – V_{dss} on the switch.
- The reset voltage can be lower than V_{dc} but T_{on} is reduced
- In all cases the volt second areas must be equal, A1=A2.

$$V_{in}T_{on} = \frac{N_p}{N_r}V_{in}T_r$$



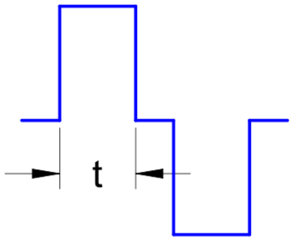
Two switch forward

- Adding the second switch and diodes reduces the voltage stress on the switch to Vin by clamping it and any leakage inductance spikes to the rail.
- Needs a high side drive
- Automatic reset – no extra winding
- Rugged circuit

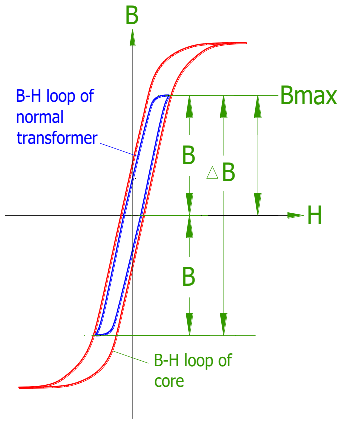


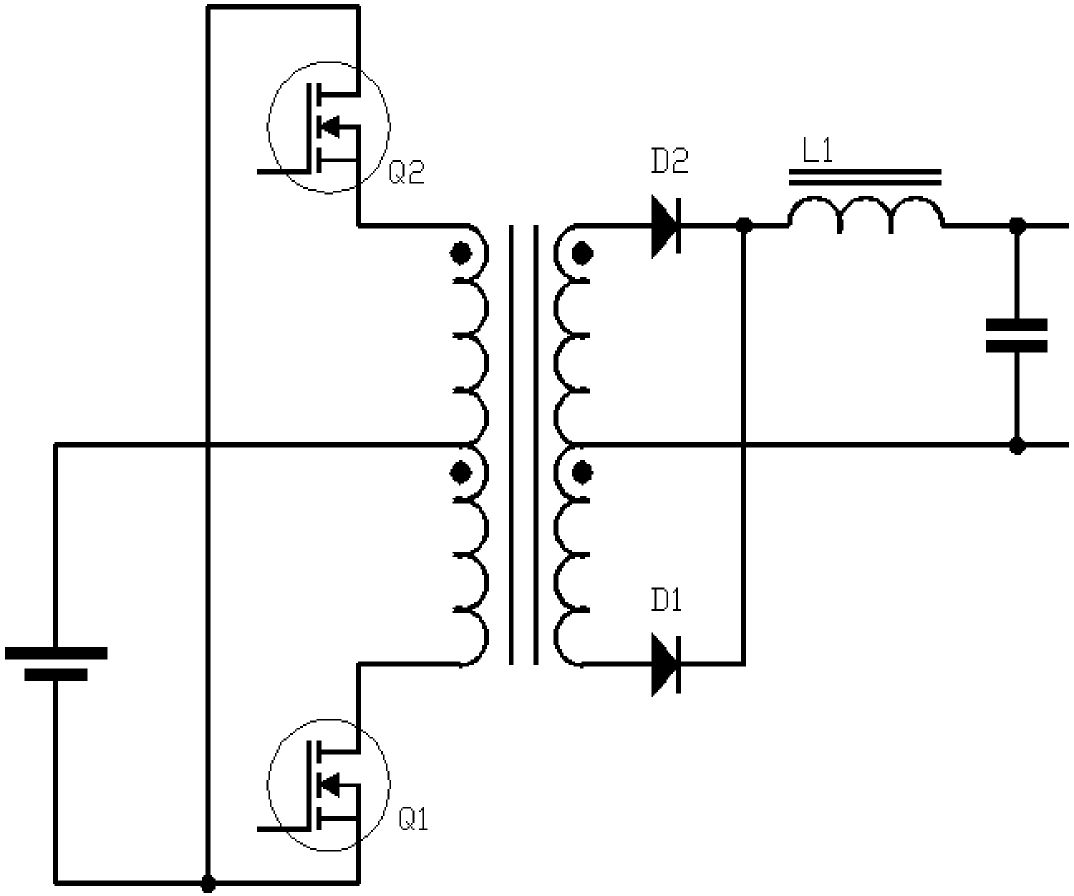
Push-pull

- Full usage of BH curve
- Poor utilization of winding area
- Only use half the windings at one time
- Each half needs to support full voltage



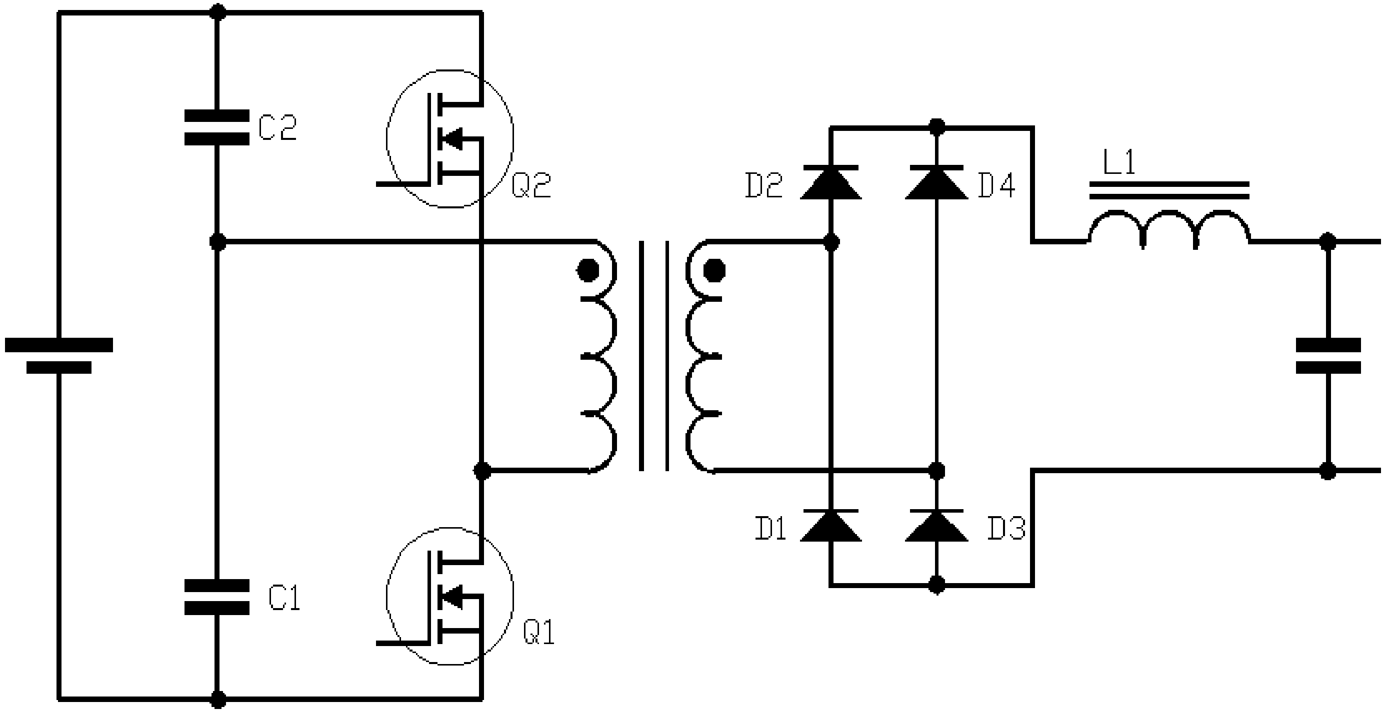
$$B_{max} = \frac{V_{pk} t_{on}}{2 N A_c}$$





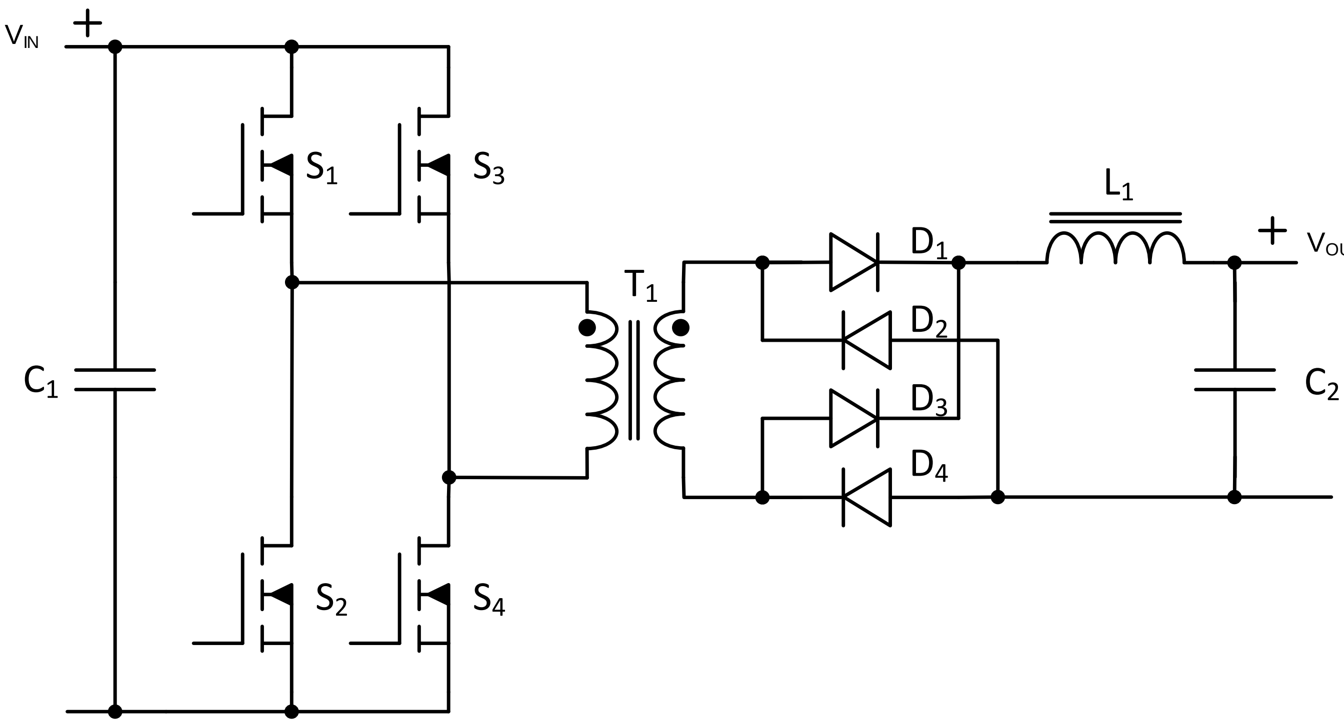
Half bridge

- Full use of BH curve
- Full use of winding area
- C1, C2 split the input voltage which reduces the primary turns count at the expense of higher current



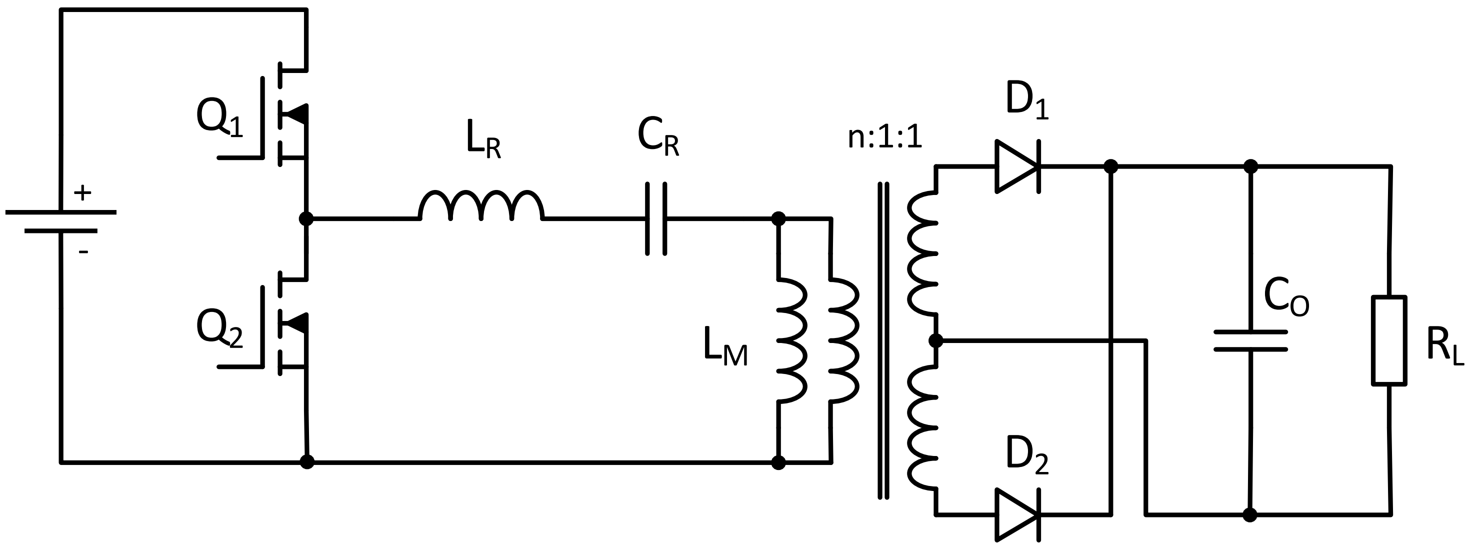
Full bridge

- Full use of BH curve
- Full use of winding area
- Used for highest power transfer



LLC converter

- Full use of BH curve
- Full use of winding area
- More sinusoidal waveforms
- Regulation by variable frequency



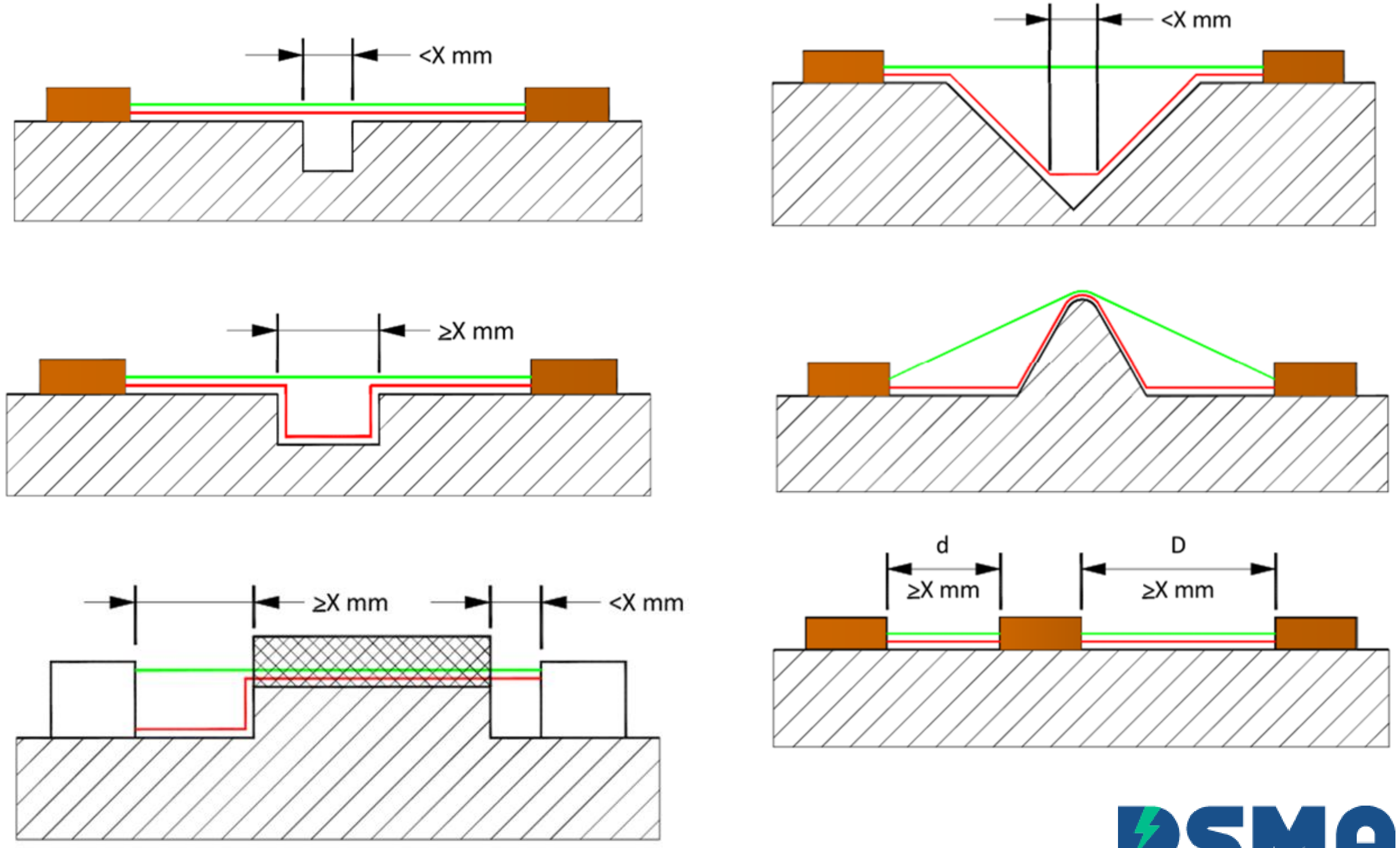
Safety considerations

- Most transformers are used for isolation
- Therefore they must meet safety agency requirements
- These standards, like IEC 62368-1 which replace IEC 60950-1 impose minimum requirements against defined hazards
  - Electrical safety, energy safety, mechanical safety,
  - heat – fire hazards, chemical hazards and radiation hazards

- Hazard based safety engineering – identify the source, the transfer mechanism and safeguard
- For electrical safety that means minimum insulation thicknesses/layers plus creepage and clearance distances
- The new standard goes from prescriptive to performance oriented solutions

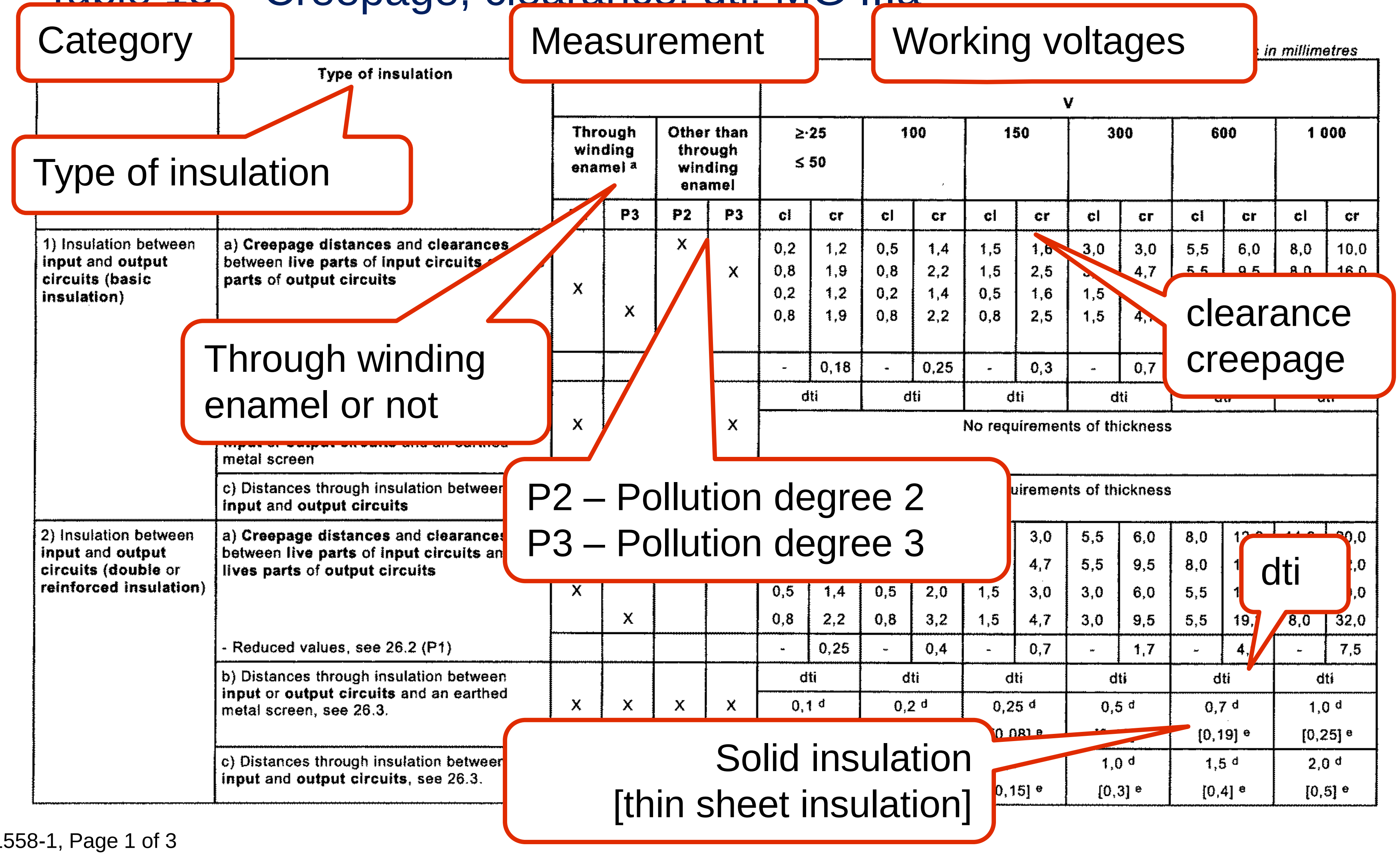
Creepage and Clearance

- Creepage and clearance are carefully defined in great detail
- The application depends on many factors which include required safety level, working voltages, insulation material and thickness, environment conditions, electrical environment, etc.



Application

Table 13 – Creepage, clearance, dti, MG IIIa



Source: IEC 61558-1, Page 1 of 3

Insulation systems

- Based on UL 1446 and IEC 61857
- Recognized component
- Covers materials for motors and transformers
  - Plastic and electrical insulation materials
  - Electrical insulation systems
  - Magnet wire and magnet wire coatings
  - Varnishes
- System of predefined lists of materials that can be used together to meet temperature classes.
- Under gone long-term thermal aging and sealed-tube testing.
- Usually sponsored by an insulation vendor.
- Can be adopted for a fee.

Winding Wire
- Recognized Component - Magnet wire (OBMW2), single build or greater, round or rectangular listed below or
- Recognized Component - Single and Multi-Layer Insulated Winding Wire (OBJT2) listed below or
- Recognized Component - Appliance Wiring Material (AVLV2) listed below

(unless otherwise noted, winding wire types listed below may be used in combination within a single product)

MW 79 or 155C Polyurethane
MW 80 or 155C Polyurethane (Polyamide)
MW 82 or 180C Polyurethane
MW 83 or 180C Polyurethane (Polyamide)

Furukawa	
TEX-F	3.9 mils (0.1 mm) triple insulated
Rubadue Wire Co. Inc.	
FEP wire	4.1 mils (0.1 mm) double or triple layer insulated
TCA3	4.1 mils (0.1 mm) double or triple layer insulated
Tefzel wire	3.6 mils (0.09 mm) double or triple layer insulated
Totoku Electric	
TIW-3	3.9 mils (0.1 mm) triple insulated
TIW-E	3.9 mils (0.1 mm) triple insulated

Ground & Interwinding Insulations

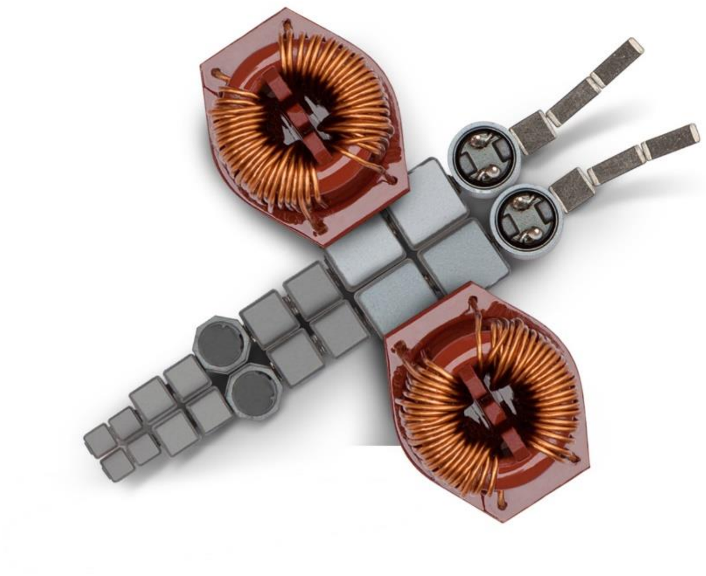
Any Recognized Component Plastic (QMFZ2), polyethylene terphthalate film (PET) 5 mils (0.13 mm) - various manufacturers

Designation (no.)	mils(mm)	comments
3M (Minnesota Mining & Mfg Co)		
56	5 (layers)	Recognized Component - Insulating Tape (OANZ2)
57	3 (layers)	Recognized Component - Insulating Tape (OANZ2)
58	3 (layers)	Recognized Component - Insulating Tape (OANZ2)
74	10 (layers)	Recognized Component - Insulating Tape (OANZ2)
Sumitomo Bakelite		
Sumikon AM-3200	11.8 (0.3)	DAP Molding Comopund
Sumikon PM-9630	11.8 (0.3)	Phenolic Molding Compound
Sumikon PM-9720	11.8 (0.3)	Phenolic Molding Compound
Sumikon PM-9750	11.8 (0.3)	Phenolic Molding Compound
Sumikon PM-9820	11.8 (0.3)	Phenolic Molding Compound

Varnishes (optional) Recognized Component - Varnishes (OBOR2)

Conclusion

- Transformers appear to be simple devices made from some copper, insulation and a core
- The reality is that there is a lot going on under the cover that makes it work properly in a given application
- Help, whether for components like cores and insulation, design or finish parts is available from many companies who are members of the PSMA



The art of magnetics

PSMA

Thank you