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
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.

Ottó Bláthy, Miksa Déri, Károly Zipernowsky

1885
Magnetics everywhere

- Filter Inductor
- Signal Isolation Transformer
- Filter Inductor
- Filter Inductor
- Main Transformer
- Common Mode Filter Inductors
- Power Factor Correction Inductor
Galvanic isolation

Infineon app note AN_201702_PL83_007

Safety isolation barrier
Principle of a transformer

\[
\frac{V_s}{V_p} = \frac{N_s}{N_p} \quad \quad \frac{I_s}{I_p} = \frac{N_p}{N_s}
\]
Add a source

\[ V = -NA_c \frac{\Delta B}{\Delta t} \]

\[ \frac{V_S}{V_P} = \frac{N_S}{N_P} \]

\[ X_L = 2\pi fL \]

\[ L = \frac{\mu_0 \mu_e N^2 A_c}{I_c} \]

\[ B_{\text{max}} = \frac{V}{4NAef} \quad \text{(Square wave)} \]

Right hand rule determine flux direction
Add a load

\[ V = -NA_c \frac{\Delta B}{\Delta t} \]

\[ \frac{V_s}{V_p} = \frac{N_s}{N_p} \]

\[ \frac{I_s}{I_p} = \frac{N_p}{N_s} \]
Add parasitics

\[ k = \sqrt{1 - \frac{lk_g}{L}} \]
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
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 solutions
- 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

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

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

\[ C = \varepsilon_0 \varepsilon_r \frac{l_w \cdot MLT}{d} \]

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

- \( w \) = width of winding
- \( MLT \) = mean length turn
- \( d \) = distance between plates
- \( \varepsilon_r \) = relative permittivity
Reducing winding capacitance

- Reduce permittivity $\varepsilon_r$ 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

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

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

Steinmetz equation \[ P = k f^\alpha B^\beta \]  Circa 1892
Ferrite core material

- First proposed by Hilpert in 1909
- 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

You Pick Two®

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

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**Performance factor**

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

Snoek’s limit - 1947

Fig. 3 Frequency characteristic of ferrite \(\mu_i\) 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

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

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

\[ \delta = \sqrt{\frac{\rho}{\pi \cdot \mu_o \cdot \mu_r \cdot f}} \]

\[ \delta = \frac{76}{\sqrt{f}} \text{ mm} \]
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.
Proximity effect

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

\[
N_i = F
\]

\[
H = \frac{F}{l_w}
\]
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:
  \[ P_2 = I_{rms}^2 R + (2I_{rms})^2 R = 1P_1 + 4P_1 = 5P_1 \]

- Power loss $P_3$ in layer 3 is:
  \[ P_3 = (2I_{rms})^2 R + (3I_{rms})^2 R = 4P_1 + 9P_1 = 13P_1 \]

- 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.

$$NI = F \quad H = \frac{F}{l_w}$$
Interleaved windings

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


\[ h = \sqrt{\frac{\pi}{4}} d \]

\[ F_l = \frac{Nh}{l_w} \]

\[ \phi = \frac{h\sqrt{F_l}}{\delta} \]
Basic equation

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

\[ A = \left( \frac{3}{4} \right)^4 \left( \frac{d}{4} \right) \sqrt{\frac{d}{p}} \]

\[ d = \text{bare wire diameter} \]
\[ p = \text{wire pitch} \]
\[ = \text{skin depth} \]
\[ N = \text{number of layers} \]
\[ N_{litz} = N \sqrt{k}, \text{ where } k = \text{number of strands} \]

Dowell's curves

\[ F_r = \frac{R_{ac}}{R_{dc}} \]

Number of layers

Normalized

Number of layers
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

\[ B_{\text{max}} = \frac{V_{pk} t_{on}}{NA_c} \]
Limited flux range – reset core
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 $V_{in}$ by clamping it and any leakage inductance spikes to the rail.
- Needs a high side drive
- Automatic reset – no extra winding
- Rugged circuit

![Two switch forward circuit diagram]
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

\[ B_{\text{max}} = \frac{V_{pk} t_{on}}{2NA_c} \]
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**

<table>
<thead>
<tr>
<th>Type of insulation</th>
<th>Measurement</th>
<th>Working voltages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Through winding enamel or not</td>
<td>Through winding enamel</td>
<td>≤ 25 ≥ 25 100 150 300 600 1000</td>
</tr>
<tr>
<td>P2 – Pollution degree 2</td>
<td>a) Creepage distances and clearances between live parts of input circuits and parts of output circuits</td>
<td>5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5</td>
</tr>
<tr>
<td>P3 – Pollution degree 3</td>
<td>b) Distances through insulation between input or output circuits and an earthed metal screen, see 25.3.</td>
<td>5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0</td>
</tr>
<tr>
<td></td>
<td>c) Distances through insulation between input and output circuits, see 25.3.</td>
<td>1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0</td>
</tr>
</tbody>
</table>

| Solid insulation | [thin sheet insulation] |

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.
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
Thank you