Basics of Magnetics for Switching Power Webinar Series

Basics of Power Inductors

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Basics of Power Inductors

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Today’s outline

- What’s so important about inductors?
- The laws that govern magnetics
- Core materials and characteristics
- Energy storage and gaps
- Inductors in converters
- Saturation current
- Rated current
- Frequency
- Temperature
- Coupled inductors
- Flyback ‘transformers’
What’s so important about inductors?

3.7 V

![Battery](image1.png)

![Inductor](image2.png)

1.0 V

![Microchip](image3.png)

Diagram: Circuit components with labeled components:
- $S_1$ (Switch)
- $L_1$ (Inductor)
- $C_1$ (Capacitor)
- $D_1$ (Diode)
- $C_2$ (Capacitor)
What’s so important about inductors?

- Buck regulators make up the vast majority of switch mode power supplies.
- Therefore it is important to understand how they work and the impact of their characteristics on the power supply circuit.
- Most courses in electrical engineering give little time to magnetic devices.
- To be a good power supply designer, you must understand how all the key components work and interact with each other in the power system.
Key points about inductors

- Inductors oppose changes in current flow
- Current in an inductor cannot change instantaneously but changes with time however the voltage, including polarity can change instantly
- In switching circuits applying a rectangular wave voltage causes a linearly increasing current ramp called magnetizing current
- Magnetizing currents create magnetic fields
- Magnetic fields store energy
- Inductors are temporary energy storage devices
- Used in low pass filters with capacitors for current and voltage smoothing
- A saturated inductor acts like a piece of wire (dc resistance only)
## System of units

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name of Quantity</th>
<th>SI Units</th>
<th>CGS Units</th>
<th>CGS ► SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Φ</td>
<td>Total magnetic flux (V·s)</td>
<td>Weber (Wb)</td>
<td>Maxwell (Mx)</td>
<td>x10⁻⁸</td>
</tr>
<tr>
<td>B</td>
<td>Magnetic flux density (magnetic induction)</td>
<td>Tesla (T) Wb/m²</td>
<td>Gauss (G)</td>
<td>x10⁻⁴</td>
</tr>
<tr>
<td>F</td>
<td>Magnetomotive Force (MMF) Total Field</td>
<td>A·T</td>
<td>Gilbert (Gb)</td>
<td>x10/4π</td>
</tr>
<tr>
<td>H</td>
<td>Magnetic field intensity (strength)</td>
<td>A·T/m</td>
<td>Oersted (Oe)</td>
<td>x79.578</td>
</tr>
<tr>
<td>R</td>
<td>Reluctance (F/Φ)</td>
<td>A·T/Wb</td>
<td>Gb/Mx</td>
<td>x79.578x10⁶</td>
</tr>
<tr>
<td>L</td>
<td>Inductance</td>
<td>Henry (H)</td>
<td>Henry (H)</td>
<td>=</td>
</tr>
<tr>
<td>μ</td>
<td>Permeability (B/H)</td>
<td>4π·10⁻⁷</td>
<td>1</td>
<td>x1.257x10⁻⁶</td>
</tr>
<tr>
<td>W</td>
<td>Energy</td>
<td>Joule (J)</td>
<td>Erg</td>
<td>x10⁻⁷</td>
</tr>
</tbody>
</table>
The laws

- Biot-Savart law (1820)
  The magnetic field generated by a current varies directly with the current intensity and inversely to the distance from the conductor.

  \[ H = \frac{I}{2\pi r} \]

- Ampere’s law (1826)
  The net magnetomotive force (MMF) around a closed path is equal to the total current passing through the interior of the path.

  \[ F = \oint Hdl = NI \]
  \[ H = \frac{N \cdot I}{l_e} \]
More laws

- **Faraday’s law (1831)**
  The magnitude of the induced emf is proportional to the rate of change of the magnetic flux.

\[ V(t) = -N \frac{d\Phi}{dt} \quad B_{max} = \frac{E \cdot dt}{A \cdot N} \]

- **Lenz’s law (1834)**
  An induced electric current always flows in such a direction that it opposes the change producing it.
Connect the dots

Faraday's law

Terminal characteristics

$i(t)$ \quad Ampere's law

$H(t), \Phi(t)$

Core characteristics

$B(t), \Phi(t)$

$v(t)$

4.2 $\mu$H
30 A

PQ 2014
7 turns
Total flux ($\Phi$), flux density ($B$)

The total magnetic flux $\Phi$ passing through an area $A_e$ is related to the flux density $B$ according to

$$\Phi = \int B \cdot dA$$

$A_e$ – Cross-sectional Area

$l_e$ – magnetic path length

$\Phi$ – Total flux

$B$ – Flux density

surface

cross sectional area of core $A_c$

flux lines

Cross-sectional Area
Elemental magnetics

\[ B \rightarrow B_r \rightarrow B \]

Field Intensity vs. Flux Density

- \( B \): Flux Density
- \( B_r \): Remanent Flux Density
- \( H \): Field Intensity
- \( H_c \): Curie Point

Ordered vs. Unordered Structures

 ceremonia
B-H Curve Terms

- $\Delta B =$ total flux swing (pk to pk)
- $B =$ one half $\Delta B$
- $B_{pk}, B_{max} =$ flux swing from zero
- $B_{sat} =$ flux saturation level
- $B_r =$ remanence - flux at zero $H$
- $H_c =$ coercivity – field strength at zero $B$

The B-H curve shows flux density as a function of an applied magnetic force.
Inductor equivalent circuit

- $R_W$ – dc winding resistance + ac losses from skin & proximity effects
- $C_W$ – winding self capacitance
- $R_C$ – core losses
- $L_M$ – magnetizing inductance
Overview of core materials

- Soft magnetic materials
  - Ferromagnetic materials
    - Crystalline
      - Steel
    - Nano-crystalline
      - Fe-Ni alloy
  - Ferri-magnetic materials
    - Amorphous
      - 90’s
    - 70’s
      - 50’s

High frequency applications
## Core materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Trade names</th>
<th>Permeability</th>
<th>Bsat</th>
<th>Core Loss</th>
<th>DC Bias</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder</td>
<td>Ni Fe Mo</td>
<td>MPP</td>
<td>14-550</td>
<td>0.7</td>
<td>Lowest</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Fe SiB C</td>
<td>AmoFlux®,</td>
<td>60</td>
<td>1.0</td>
<td>Low</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Ni Fe</td>
<td>Hi-Flux™, High Flux</td>
<td>14-160</td>
<td>1.5</td>
<td>Moderate</td>
<td>Best</td>
</tr>
<tr>
<td></td>
<td>Fe Si Al</td>
<td>Kool Mµ®, Sendust</td>
<td>26-125</td>
<td>1.0</td>
<td>Low</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Fe Si Al Ni</td>
<td>Optilloy™</td>
<td>14-125</td>
<td>1.3</td>
<td>Good</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>Fe Si</td>
<td>XFlux®, Fluxsan™, MegaFlux®</td>
<td>26-90</td>
<td>1.6</td>
<td>High</td>
<td>Best</td>
</tr>
<tr>
<td></td>
<td>Fe</td>
<td>Iron</td>
<td>10-100</td>
<td>1.2</td>
<td>High</td>
<td>Poor</td>
</tr>
<tr>
<td>Lamination or strip</td>
<td>Fe Si</td>
<td>Oriented M-4</td>
<td>1,500-10,000</td>
<td>2.0</td>
<td>High</td>
<td>Best</td>
</tr>
<tr>
<td></td>
<td>Amorphous</td>
<td>Metglas 2605</td>
<td>10k-100,000</td>
<td>1.5</td>
<td>Low</td>
<td>Best</td>
</tr>
<tr>
<td></td>
<td>NanoCrystalline</td>
<td>Viroperm 500F</td>
<td>15k-100,000</td>
<td>1.2</td>
<td>Low</td>
<td>Best</td>
</tr>
<tr>
<td>Ceramic</td>
<td>Ferrite</td>
<td></td>
<td>15-20,000</td>
<td>0.45</td>
<td>Lowest</td>
<td>Poor</td>
</tr>
</tbody>
</table>

Trademarks owned by their respective companies
Core material selection

$X_L$ (Fe)  
$X_L$ (MnZn)  
$X_L$ (NiZn)

$f$ in MHz

Relative Reactance

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

0,01 0,1 1 10 100 1000
Powder core characteristics

Permeability vs. DC Bias

Permeability vs. Frequency

DC Magnetization

Magnetics MPP Cores
Powder core characteristics

Core Loss Density

Permeability vs. Temperature

(1 Telsa = 10,000 Gauss)

Micrometals-Arnold MPP Cores
## Ferrite core characteristics

<table>
<thead>
<tr>
<th>CONDITIONS</th>
<th>VALUE</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_i$</td>
<td>25 °C; ≤10 kHz; 0.25 mT</td>
<td>2000 ±20%</td>
</tr>
<tr>
<td>$\mu_a$</td>
<td>100 °C; 25 kHz; 200 mT</td>
<td>≈ 5500</td>
</tr>
<tr>
<td>B</td>
<td>25 °C; 10 kHz; 1200 A/m 100 °C; 10 kHz; 1200 A/m</td>
<td>≈ 500 mT  ≈ 440</td>
</tr>
<tr>
<td>$P_V$</td>
<td>100 °C; 100 kHz; 100 mT 100 °C; 100 kHz; 200 mT 100 °C; 500 kHz; 50 mT</td>
<td>≈ 40 kW/m³  ≈ 300  ≈ 250</td>
</tr>
<tr>
<td>$\rho$</td>
<td>DC; 25 °C</td>
<td>≈ 5 Ωm</td>
</tr>
<tr>
<td>$T_C$</td>
<td>≥ 240 °C</td>
<td></td>
</tr>
<tr>
<td>density</td>
<td>≈ 4800 kg/m³</td>
<td></td>
</tr>
</tbody>
</table>

Source: Ferroxcube Data Handbook 2013 – 3C96
Ferrite core characteristics

<table>
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<tr>
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<td>25 °C; 10 kHz; 1200 A/m; 100 °C; 10 kHz; 1200 A/m</td>
<td>≈ 500 mT; ≈ 440 mT</td>
</tr>
<tr>
<td>PV</td>
<td>100 °C; 100 kHz; 100 mT; 100 °C; 100 kHz; 200 mT; 100 °C; 500 kHz; 50 mT</td>
<td>≈ 40 kW/m³; ≈ 300 kW/m³; ≈ 250 kW/m³</td>
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<tr>
<td>$\rho$</td>
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<td>$T_C$</td>
<td></td>
<td>≥ 240 °C</td>
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<tr>
<td>density</td>
<td></td>
<td>≈ 4800 kg/m³</td>
</tr>
</tbody>
</table>

Source: Ferroxcube Data Handbook 2013 – 3C96
## TDK N96

<table>
<thead>
<tr>
<th>Preferred application</th>
<th>Power transformers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>N96</td>
</tr>
<tr>
<td>Base material</td>
<td>MnZn</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_i$</td>
<td>2900±25%</td>
</tr>
<tr>
<td>$B_d$ (25 °C)</td>
<td>mT</td>
</tr>
<tr>
<td>$B_{gs}$ (100 °C)</td>
<td>mT</td>
</tr>
<tr>
<td>$B_{gs}$ (140 °C)</td>
<td>mT</td>
</tr>
<tr>
<td>$H_e$ (25 °C)</td>
<td>A/m</td>
</tr>
<tr>
<td>$H_e$ (100 °C)</td>
<td>A/m</td>
</tr>
<tr>
<td>$H_e$ (140 °C)</td>
<td>A/m</td>
</tr>
<tr>
<td>$f_{min}$</td>
<td>kHz</td>
</tr>
<tr>
<td>$f_{max}$</td>
<td>kHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hysteresis material constant</th>
<th>$H_B$</th>
<th>&lt;0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative loss factor at $f_{max}$</td>
<td>$\tan \delta_{f_{max}}$</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Curie temperature $T_C$</td>
<td>°C</td>
<td>&gt;240</td>
</tr>
<tr>
<td>Mean value of $\alpha_F$ at 25 °C</td>
<td>10^{-6}/K</td>
<td></td>
</tr>
<tr>
<td>Density (typical values)</td>
<td>kg/m³</td>
<td>4850</td>
</tr>
<tr>
<td>Relative core losses (typical values)</td>
<td>$P_V$</td>
<td>kW/m³</td>
</tr>
<tr>
<td>100 kHz, 200 mT, 25 °C</td>
<td>325</td>
<td></td>
</tr>
<tr>
<td>100 kHz, 200 mT, 60 °C</td>
<td>330</td>
<td></td>
</tr>
<tr>
<td>100 kHz, 200 mT, 100 °C</td>
<td>390</td>
<td></td>
</tr>
<tr>
<td>100 kHz, 200 mT, 140 °C</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>300 kHz, 100 mT, 100 °C</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Resistivity</td>
<td>$\rho$</td>
<td>Ωm</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: TDK Databook 2017
Where is the energy stored?

- Imagine MMF is like voltage, flux like current and reluctance (1/permeability) like resistance.
- Core is low reluctance, gap is high reluctance therefore MMF is greatest across gap.
Gaps store energy

\[ W = \frac{1}{2} \int HBdv \]

\[ W = \frac{1}{2} H_c B_c V_c + \frac{1}{2} H_g B_g V_g \]

\[ B = \frac{B}{o \ r H} \] therefore \[ H = \frac{B}{o \ r} \]

\[ W = \frac{1}{2} B_c^2 B_c l_c A_c + \frac{1}{2} B_g l_g A_c \]

\[ W = \frac{1}{2} B^2 A_c \left( \frac{l_c}{o \ r} + l_g \right) \]

Typically, \( \mu_r \) in power ferrite is 2300, therefore \( l_c/\mu_r \) is a very small number compared to \( l_g \)

\( V_c \) is the volume of the core where

\( V_c = l_c A_c \)

\( V_g \) is the volume of the air gap where

\( V_g = l_g A_c \)

Flux is uniform so \( B_c = B_g \)

neglecting fringing

Also \( A_c = A_g \)
Gaps cause fringing

Fringe factor

\[ F_F = 1 + \frac{l_g}{\sqrt{A_c}} \ln \left( \frac{2l_w}{l_g} \right) \]

- \( F_F \) = increase in inductance
- \( l_g \) = gap length
- \( l_w \) = window length
- \( A_c \) = core area
Gaps stabilize permeability

\[ \mu_e = \frac{\mu_r}{1 + \mu_r \left(\frac{l_g}{l_e}\right)} \]

\( \mu_e = \text{effective permeability} \)
Buck converter

\[
\frac{V_{out}}{V_{in}} = \left( \frac{t_{on}}{T} \right) = D
\]
Buck converter

\[ \frac{V_{\text{out}}}{V_{\text{in}}} = \left( \frac{t_{\text{on}}}{T} \right) = D \]
Effect of changing inductance value

- Effect of raising and lowering L while holding $V_{IN}$, $V_{OUT}$, $I_{OUT}$ and $f$ constant
- Lowering L increases $\Delta I$, raising L decreases $\Delta I$
- The choice of L is a trade off between the size, the copper losses and the core losses

\[ L = \frac{Edt}{di} \]
\[ di = \frac{Edt}{L} \]
**Important parameters of the inductor**

\[ I_{\text{AVG}}, I_{\text{OUT}}, I_{\text{DC}}, I_L \]

**ALL ARE THE SAME**, they refer to the average inductor current

Is the starting point of inductor current rating selection

Used to estimate DC copper losses

\[ I_{\text{MIN}}, I_{\text{PEAK}} \]

Determines the size of the inductor through the energy storage required

Used to determine minimum inductor saturation rating

\[ \Delta I \quad \text{Peak to peak ripple current} \]

- determined by inductance value

Used to estimate the core losses
Losses - Efficiency

![Chart showing efficiency at different load currents for Iron Powder and Ferrite cores. The chart highlights efficiency percentages and compares the performance of Iron Powder and Ferrite in terms of core and copper losses, with a focus on switching losses.]

- **Iron Powder**
- **Ferrite**

Date: 2020.01.21  |  PSMA Magnetics Committee  |  Public  |  Topic: Basics of Power Inductors
AC Losses

Temperature Vs. AC loss - Ferrite Material (MnZn)

Inductor surface Temperature (°C)

AC Loss (mW)

6V, 200kHz

15V, 400kHz

11.5V, 400kHz

6V, 400KHz
Definition of Saturation current

- It's important to realize that every manufacturer uses a different value of percent drop.
- Also, different series of inductors may use different percentages – typically 10-30%
- Some definitions will go to 50%
Operation Area

Important when using inductors made out of ferrite

- safe operation area
- critical operating area
- total saturation area
Saturation: Ferrite vs. Iron Powder

WE-PD

WE-HCI

Inductance vs. Current

- Soft Saturation
- Hard Saturation
$B_{sat}$ vs. temperature
Saturation current – impact of gap

- defined air gap
- air gap > too small
- air gap > too big
Inductor selection

- Desired inductance value – know the minimum or maximum
- Tolerance and under what conditions (i.e. dc bias)
- Rated current to temperature
- Saturation current and applicable tolerance
- Mounting style
- If self shielding is required
- Sharp or soft roll-off
- Frequency of operation
Crossroads

- **Inductor:**
  - An magnetic device that impedes the change in the flow of electric current by storing and releasing energy from its magnetic field.

- **Coupled Inductor:**
  - A coupled inductor is an inductor with two or more windings on the same core which takes advantage of magnetic coupling to influence the behavior of each winding on the other.

- **Transformer:**
  - A magnetic device that transfers energy instantaneously through its magnetic field. Typically changes the voltage of current and can provide galvanic isolation.
Common Mode Inductors

- a.k.a current compensated chokes
- Windings are in the same direction
- Flux from common mode current add in the core
- Flux from differential currents cancel in core
- Allows use of high permeability cores which are sensitive to dc bias
- Reduces number of turns which reduce winding self capacitance which limits high frequency response
- This makes the filter smaller than using two cores
- When fluxes add, inductance increases
- Tight coupling desired

Flux from common currents add
Flux from differential currents cancel
SEPIC

- Non inverting
- Ground referenced
- Low ripple
- Can use individual or coupled inductors
Flyback ‘transformers’

- 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
Isolated Flyback

- Transformer-choke
- Transformer isolated version of a buck-boost
- Each circuit period has its own inductor but share the same core
- One coil builds the magnetic field
- The other harvests it
- Voltages exist on both coils giving it transformer like ratios
Isolated Flyback

- Transformer isolated version of a buck-boost
- Both step up and step down
- Multiple outputs
- Optimizes duty cycle for large voltage differences
- Wide input range

\[
\begin{align*}
V_{\text{IN}} & \quad V_{\text{OUT}} \\
D_1 & \\
S_1 & \\
C_1 & \\
T_1 & \\
\text{Current, } S_1 \text{ closed} & \\
\text{Current, } S_1 \text{ open}
\end{align*}
\]
Isolated Flyback

- Transformer isolated version of a buck-boost
- Both step up and step down
- Multiple outputs
- Optimizes duty cycle for large voltage differences
- Wide input range

![Isolated Flyback Diagram](image)
Conclusion

- Inductors play a key role in power electronics as energy storage devices for efficient power transfer.
- They must be properly rated to perform under all expected conditions.
- There is a wide selection of materials suitable for a wide variety of applications.
- Many resources are available from the many material suppliers, distributors, IC and magnetics manufacturers who are members of the PSMA.
Thank you