Impact of Current-Compensated Choke Design on EMI Filter Performance

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Goal of Presentation

- Current-compensated choke in EMI filter
- Comparison of different current-compensated choke designs concepts
- Parameters impact on current-compensated choke properties
- Comparison of core shapes
- Magnetic material impact on current-compensated choke properties:
  - Comparison of ferrite cores with different permeability
  - Comparison of nanocrystalline cores with different permeability
  - Comparison of nanocrystalline vs. ferrite cores
  - Comparison of nanocrystalline and ferrite saturation properties
- Impact of winding method on current-compensated choke properties
- Conclusion
Current-Compensated Choke in EMI Filter

HF Model EMI Filter

Equivalent scheme of EMI filter for Common Mode

Equivalent scheme of EMI filter for Differential Mode
Current-Compensated Choke Design Examples

- U Core
- Edge Windings
- Coper foil Windings
- Core
Properties of current-compensated choke vs. frequency depends on:

- Dimension and type of core, (cross section of core $A_e$, magnetic length of core $l_e$)
- Properties of magnetic material (permeability $\mu'$, $\mu''$, magnetic flux $B_s$)
- Saturation properties
- Number of turns and method of winding (parasitic capacitance)

$$L_s = \frac{\mu' \mu_o A_e N^2}{l_e}$$

$$R_s = 2\pi f \frac{\mu'' \mu_o A_e N^2}{l_e}$$
Comparison of Core Shape

No Airgap

Toroid

- The highest $Ae/le$ ratio
- Highest impedance, AL value vs volume
- Not suitable for winding large conductors

Oval

- Higher leakage inductance compared to toroid
- More space for windings
- Lower impedance, AL vs volume compared to toroid

Frame

With Airgap

EE Planar

- Facility to assembly
- Good saturation properties
- 40%-50% reduction of impedance, AL value
- Worse mechanical stability

C core

U core
Magnetic Material Impact

Assumptions:

- Core shape - toroidal
- Type of magnetic material – nanocrystalline and ferrite MnZn
- Dimension of ferrite core and nanocrystalline core are the same
- Different permeability
- The same number of turns
- To illustrate impact of the choke on the performance of the EMI filter, demo filter with 7 version of choke was tested
- Only difference was current-compensated choke
## Magnetic Material Impact

<table>
<thead>
<tr>
<th>Material</th>
<th>Ferrite</th>
<th>Nanocrystalline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>no.1</td>
<td>no.2</td>
</tr>
<tr>
<td>Permeability</td>
<td>15 000</td>
<td>10 000</td>
</tr>
<tr>
<td>Max. Flux Density [T]</td>
<td>0.40/0.17</td>
<td>0.41/0.21</td>
</tr>
<tr>
<td>Curie Temperature</td>
<td>110°C</td>
<td>130°C</td>
</tr>
<tr>
<td>Operation Temperature</td>
<td>100°C</td>
<td>120°C</td>
</tr>
<tr>
<td>Dimension [mm]</td>
<td>63x38x28</td>
<td>65x40x28</td>
</tr>
<tr>
<td>Turns</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>L@10kHz [mH]</td>
<td>15.2</td>
<td>10.4</td>
</tr>
<tr>
<td>L@100kHz [mH]</td>
<td>5.0</td>
<td>5.4</td>
</tr>
<tr>
<td>L@150kHz [mH]</td>
<td>3.5</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Core of choke no.1, no.2, no.3 come from supplier A, no.4 supplier B, no.5, no.6, no.7 from supplier C
Magnetic Material Impact: Different Permeability

Choke no.5 $\mu$100 000
Highest impedance @10kHz
The lowest impedance @ 150kHz

Choke no.3 & no.4 $\mu$ 5000
The same impedance up to 100kHz
Differences above 300kHz

IL [dB]

Ferrite MnZn

Core 65mmx38mmx28mm, N=23

Nanocrystalline

Core 65mmx40mmx28mm, N=23

(no.5) $\mu$ 100 000
(no.6) $\mu$ 70 000
(no.7) $\mu$ 50 000

(no.1) $\mu$ 15 000
(no.2) $\mu$ 10 000
(no.3) $\mu$ 5 000
(no.4) $\mu$ 5 000

Higher impedance @10kHz
The lowest impedance @ 150kHz
The same impedance up to 100kHz
Differences above 300kHz
Magnetic Material Impact (Nanocrystalline): Different Permeability

The level of EMI noise is the highest for high permeability material (μ100 000).

The EMI noise level of choke no.7 μ50 000 is similar than no.5 μ100 000

No impact on EMI noise level

Nanocrystalline

(no.5) μ 100 000
(no.6) μ 70 000
(no.7) μ 50 000
Magnetic Material Impact (Ferrite MnZn): Different Permeability

EMI noise is the lowest with low permeability material

No EMI noise differences for choke with permeability $\mu_{15\,000}$ and $\mu_{10\,000}$

No impact on EMI noise level
Magnetic Material Impact: Comparison Nanocrystalline vs. Ferrite

**Very high impedance of choke made out of nanocrystalline material**

Impedance of choke no.4 (ferrite) is higher than no.5 (nanocrystalline) between 250 kHz and 500 kHz.

- **Ferrite**: 63x38x28mm, N=23
- **Nanocrystalline**: 65x40x28mm, N=23

The impedance is similar in MHz range.

- (no.3) MnZn $\mu$ 5000
- (no.4) MnZn $\mu$ 5000
- (no.5) Nano $\mu$ 100 000
- (no.6) Nano $\mu$ 70 000
Magnetic Material Impact: Comparison Nanocrystalline vs. Ferrite

Ferrite 63x38x28mm  
N=23

Nanocrystalline 65x40x28mm  
N=23

No impact on EMI noise level

No differences between 200-300 kHz

Maximum noise reduction between 750 kHz-1 MHz

(No.5) Nano \(\mu\) 100 000
(No.4) MnZn \(\mu\) 5000

(No.6) Nano \(\mu\) 70000
(No.4) MnZn \(\mu\) 5000

EMI Noise dBuV

Frequency Hz

10k 100k 1M 10M 30M

IL [dB]

Frequency Hz

10 10k 100k 1M 10M 30M

32dB

15dB

61dBuV

56dBuV

30dBuV

39dBuV

750kHz

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Saturation due to common mode current:

**Ferrite MnZn** $\mu_{5000}$  **Nanocrystalline** $\mu_{50\ 000}$

\[
I_{s1} = \frac{B_{s1} l_{e1}}{\mu_e \mu_1 N_1} \\
I_{s2} = \frac{B_{s2} l_{e2}}{\mu_e \mu_2 N_2}
\]

\[
l_{e1} \approx l_{e2}
\]

\[
N_1 = N_2
\]

\[
\frac{I_{s1}}{I_{s2}} = \frac{B_{s1} \mu_2}{B_{s2} \mu_1}
\]

The saturation current of nanocrystalline core will be higher only if permeability of cores will be equal.

Saturation current is higher for ferrite
Magnetic Material Impact: Saturation Properties

Saturation due to volt-time product:

\[ \int V_1 \, dt = N_1 B_{S1} A_{e1} \quad \int V_2 \, dt = N_2 B_{S2} A_{e2} \]

\[ N_1 = N_2 \]

\[ A_{e1} \approx A_{e2} \]

\[ \frac{\int V_1 \, dt}{\int V_2 \, dt} = \frac{B_{S1}}{B_{S2}} \]

Ferrite MnZn \( \mu \) 5 000

Nanocrystalline \( \mu \) 50 000

The nanocrystalline is more immune to saturation than ferrite.
Assumptions:
- Core shape - toroidal
- Material - ferrite 15,000
- Core dimension 63x38x28 mm
- The number of turns is 23
- Three methods of winding are compared, single layer, double layer, "bifilar"
- The "bifilar" winding is made with cable with silicon isolation to achieve required isolation
- To illustrate impact of the choke on the performance of the EMI filter, demo filter with 3 version of choke was tested
- Only difference was current compensated choke
Impact of Winding Method on Current – Compensated Choke Properties

**Single layer**
- ✓ Good attenuation at high frequency
- × Require more space for windings

**Double layer**
- ✓ Require less space for windings
- × Less attenuation at high frequency

**Bifilar**
- ✓ Good attenuation at high frequency
- × Require more space for windings
- × Low attenuation at low frequency
- × Require cable with thicker isolation
Impact of Winding Method on Current – Compensated Choke Properties

Single layer

- Low value of parasitic capacitance

Double layer

- High value of parasitic capacitance
- High value of leakage inductance

Core

Cu Cu

Ctt

Ctt

Ctc

Ctc

Impact of Winding Method on Current – Compensated Choke Properties

- Double Layer Winding
- Single Layer Winding
- "Bifilar" Winding

Low value of leakage inductance
Impact of Winding Method on Current – Compensated Choke Properties

No impact on EMI level up to 150kHz

Impact of low leakage inductance

Double Layer Winding
Single Layer Winding

Bifilar Winding

Double Layer Winding
Single Layer Winding

Bifilar Winding

Impact of Winding Method on Current – Compensated Choke Properties
Impact of Winding Method on Current – Compensated Choke Properties

- **Double Layer Winding**
- **Single Layer Winding**

**Impact of parasitic capacitance**

**Impact of low leakage inductance**

- "Bifilar" Winding
- Single Layer Winding
Conclusion

<table>
<thead>
<tr>
<th>Core shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroid cores have highest CM impedance, AL vs. volume, low leakage inductance but difficult to wind big wires</td>
</tr>
<tr>
<td>Rectangular cores have higher leakage inductance and more space for winding but lower impedance, AL</td>
</tr>
<tr>
<td>Cores with air gap have reduction by 50% of CM insertion loss</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Core material</th>
</tr>
</thead>
<tbody>
<tr>
<td>A high permeability material does not guarantee high EMI noise reduction at all frequencies</td>
</tr>
<tr>
<td>Lower permeability material more often gives better EMI noise reduction above 150kHz</td>
</tr>
<tr>
<td>Chokes with nanocrystalline material have higher CM insertion loss below 150 kHz compared to ferrite. However nanocrystalline are no better than ferrite when DM noise dominates</td>
</tr>
<tr>
<td>Nanocrystalline cores are ca 5 times expensive than ferrite</td>
</tr>
</tbody>
</table>
Conclusion

Saturation properties

Saturation current is proportional to the ratio $B_s/\mu$ when $I_e$ and $N$ are not changed.

Maximum flux density $B_s$ for nanocrystalline is always higher than that for ferrite (ca 3 times), but if $\mu$ for nanocrystalline is much higher than that for ferrite then saturation current for the ferrite will be the higher.

Then nanocrystalline is more immune to saturation than ferrite if saturation is due to volt-time product. However if $N$ and $A_e$ are significantly reduced the advantage of nanocrystalline can be negated.
Method of Winding

- Single layer winding has the highest EMI noise reduction at high frequencies due to the lowest value of parasitic capacitance.

- Double layer winding has less EMI noise reduction at high frequencies due to higher parasitic capacitance. Therefore EMI noise is higher at high frequency range.

- Bifilar winding has less parasitic capacitance but needs more space due to thicker insulation.

- Bifilar has low leakage inductance so DM noise is higher especially at low frequencies (up to 300kHz).
Thank you for your attention