MAGNETIC CORE DIMENSIONAL EFFECTS – FLUX PROPAGATION IN FERRITES

2018-03-03 - Marcin Kącki, Marek Ryłko, Edward Herbert, John Hayes, Charles Sullivan
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2. Magnetic material comparison and permeability characteristic

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4. Ferrite ring core – flux distribution

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A number of high frequency effects are not considered in a typical EMI choke design.

High power systems exhibit unexpected deterioration of magnetic material performance.

Complex permeability as a function of frequency

This work is to improve EMI choke design approach with high frequency effects.
Magnetic Materials

Magnetic material selection defines choke performance.
Large Cores Permeability Drop in Ferrite Material

Ferroxcube 3E10 material permeability as a function of frequency for various core size.

Magnetic flux undergoes skin effect similar to electric conductors.

- **$f = 10 \text{ kHz}$**
- **$f = 1 \text{ MHz}$**

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**Real permeability $\mu'$**

**Frequency (MHz)**

<table>
<thead>
<tr>
<th>Core Size</th>
<th>TX29</th>
<th>TX50</th>
<th>TX80</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>10.00</td>
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**Imaginary permeability $\mu''$**

**Frequency (MHz)**

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Experimental Investigation

Four main experiments:

1. **Flux distribution in the core**
   Core is divided into 9 sections with wire loops, voltage of each loop is measured.

2. **Flux distribution effect on the impedance**
   Impedance vs. frequency in range between 1 kHz and 30 MHz is recorded.

3. **Isolation of the reluctance effect from the skin effect**
   Frame core is used to provide homogenous flux concentration in the core.

4. **Analysis of various magnetic materials**
   Investigation of the skin effect for various materials:

<table>
<thead>
<tr>
<th>Ring Core</th>
<th>Material</th>
<th>Size</th>
<th>Type</th>
<th>Permeability (manufacturer spec.)</th>
<th>Resistivity (Ωm) (manufacturer spec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferroxcube</td>
<td>3E15</td>
<td>50/30/16.5</td>
<td>MnZn</td>
<td>15 000</td>
<td>0.5</td>
</tr>
<tr>
<td>Ferroxcube</td>
<td>3E10</td>
<td>50/30/16.5</td>
<td>MnZn</td>
<td>10 000</td>
<td>0.5</td>
</tr>
<tr>
<td>Ferroxcube</td>
<td>3E6</td>
<td>50/30/16.5</td>
<td>MnZn</td>
<td>10 000</td>
<td>0.1</td>
</tr>
<tr>
<td>Ferroxcube</td>
<td>4S60</td>
<td>50/30/16.5</td>
<td>NiZn</td>
<td>2000</td>
<td>(10^5)</td>
</tr>
<tr>
<td>FairRite</td>
<td>FR78</td>
<td>105/75/15</td>
<td>MnZn</td>
<td>2300</td>
<td>200</td>
</tr>
<tr>
<td>FairRite</td>
<td>FR61</td>
<td>105/75/15</td>
<td>NiZn</td>
<td>120</td>
<td>(10^9)</td>
</tr>
</tbody>
</table>

<table>
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An experimental investigation uses drilled ferrite cores. Each tested core has two vertical and one horizontal bores. Bore diameter is 0.75 mm. Vertical and horizontal bores allows to characterize 9 regions of the core cross section.

- **Test I - Flux distribution in the core**
  This test determine the voltage of each inner ferrite segment.

- **Test II - Flux distribution effect on the impedance**
  This test determine impedance and phase shift of each inner ferrite segment.
Flux Distribution in the Ring Core – Test I

Test setup:

- Ring core: T50/30/16.5mm MnZn 3E10 ferrite.

Mathematical equations:

\[ v_1(t) = V_{1M} \sin(\omega t + \phi_1) \]
\[ v_2(t) = V_{2M} \sin(\omega t + \phi_2) \]

Ring core voltage equations:

\[ v_X(t) = V_{XM} \sin(\omega t + \phi_X) \]
\[ v_X(t) = v_1(t) - v_2(t) \]
Flux Distribution in the 3E10 Ring Core – Test 1

![Graph showing magnetic flux distribution](image)

- **Frequency (kHz)**
- **Magnetic Flux ratio**

- $\phi X/\phi_1$
- $\phi X/\phi_2$
- $\phi X/\phi_3$
- $\phi X/\phi_4$
- $\phi X/\phi_5$
Flux Distribution in the 3E10 Ring Core – Test 1

Magnetic Flux ratio

Frequency (kHz)

- FEA Simulation
- Experimental
Core Properties Comparison – 3E10 vs. 3E15 vs. 3E6 – Test I

Ferrite 3E10 vs. Ferrite 3E6 vs. Ferrite 3E15

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<tr>
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<th>Permeability (Manufacturer spec.)</th>
<th>Resistivity (Manufacturer spec.)</th>
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<tbody>
<tr>
<td>Ferrite 3E10</td>
<td>10 000</td>
<td>0.5 Ωm</td>
</tr>
<tr>
<td>Ferrite 3E6</td>
<td>10 000</td>
<td>0.1 Ωm</td>
</tr>
<tr>
<td>Ferrite 3E15</td>
<td>15 000</td>
<td>0.5 Ωm</td>
</tr>
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Flux skin depth depends on material conductivity, permeability and frequency.

Flux skin depth depends on material conductivity, permeability and frequency.
Flux Distribution Effect on the Impedance - Test II

Ring core:
T50/30/16.5mm
MnZn 3E10 ferrite.

Impedance measurement test setup.
Flux Distribution Effect on the 3E10 Ring Core Impedance – Test II

Impedance and phase frequency characteristic.

![Graph showing impedance and phase angle vs. frequency for different sections.](image)
Flux Distribution in the Frame Core – Test I

Frame core is used to mitigate flux concentration effect in order to expose core skin effect.

Frame core dimensions: 106/65/15mm
MnZn ferrite material: FR78
Flux Distribution in the FR78 Frame Core – Test 1
Flux Distribution in the FR78 Ring Core – Test I

Magnetic Flux ratio vs. Frequency (kHz) for different variables:
- \( \phi X/\phi 1 \)
- \( \phi X/\phi 2 \)
- \( \phi X/\phi 3 \)
- \( \phi X/\phi 4 \)
- \( \phi X/\phi 5 \)
Flux Distribution Effect on the Frame Core FR78 Impedance - Test II

Impedance and phase frequency characteristic.
Flux Distribution Effect on the Ring Core FR78 Impedance – Test II

Impedance and phase frequency characteristic.

![Graphs showing impedance and phase angle versus frequency for different sections of the ring core FR78.](image)
Summary

- Magnetic material selection is a key for successful EMI filter design and enables to achieve desired attenuation characteristic
- Core size has strong effect on filter frequency characteristic
- Ferrite material is a subject of core skin effect that results in frequency depended magnetic flux non-uniform distribution
- Core material conductivity and permeability influence the skin depth
- Non-uniform flux distribution has an effect on impedance and phase characteristic of each core segment
- FEA modeling is in line with experimental results
Acknowledgement

> Ferroxcube Polska Eastern Europe
> R&D support and open discussion
> Support with samples for research, short delivery times and involvement

> Fair-Rite Products Corp.
> Machining of the frame core
> Precise drilling
> Samples for research were provided under the sponsorship of PSMA

> PSMA
> Especially Edward Herbert for his enthusiasm and support and valuable discussion on magnetics
> PSMA Comitee for support and financial participation in the research
Future work

- Mathematical model development based on evaluation of various size
  - Ring cores
  - Frame cores
- Simulation model improvement for better accuracy at higher frequency
  - Permittitivity vs. frequency
- Do this research can be applied directly to the design rules? How presented approach contributes to standardized test for magnetic material properties provided by magnetic core manufacturers?

REFERENCES:
Demonstrator

- Results for various materials
- Test system
- Tested samples