Measurements and Application Considerations of Magnetic Materials at High- and Very-High Frequencies

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Presented at:
PSMA Magnetics Workshop
Power Magnetics @ High Frequency – Solving the Black Magic!
March 19, 2016
Converter Examples from ECCE 2015

EPC demonstration – 300 kHz design
Magnetics ~48% of loss, 45% of area

Minjie Chen (MIT) – careful 1 MHz design
Magnetics ~35% of loss, 35% of area
We seek improved design methods, models and materials for power magnetic components at high frequency (High Frequency, HF, 3-30 MHz)

Key questions:

- What is the best way to characterize magnetic materials at high frequencies?
- What capabilities do high-frequency materials really have?
- What are the design considerations for using low-permeability HF materials?
Scaling of Magnetics Size with Frequency

- Increasing $f$ yields smaller $L,C$ for same impedance
  - required energy storage decreases inversely with $f$

- Component size can decrease with frequency, but only over a limited frequency range
  - Limited by core loss
  - Core materials are critical!

Example: Resonant inductor providing $|Z| = 10 \ \Omega$
(1.6 uH at 1 MHz), $Q_{\text{min}} = 100$, $\Delta T < 75 \ ^\circ \text{C}$, $|I_{\text{ac}}| = 0.5 \ \text{A}$

Resonant Cored Inductor Volume vs. Operating Frequency

![Diagram showing volume variation with operating frequency](image)
“Performance Factor” is *approximate* measure of power handling per unit volume of a material

\[ \mathcal{F} \propto \frac{P}{\text{core volume}} \propto \frac{V_{pk} I_{pk}}{A_c l_c} \]

For a given (fixed-size) core, we might imagine that there is a limited \( N \cdot l \) (Ampere-turns) that can be applied, owing to winding area, winding loss, etc. (so treat \( N \cdot l \) as fixed)

Voltage amplitude \(|V|\) is \( N \cdot B \cdot f \cdot A_c \) (\( B \) is core flux density)

(reactive) power handled is proportional to \(|V| \cdot |l|\), so for Fixed \( N \cdot l \), then, is proportional to \( B \cdot f \)

To see how a core material performs across frequency, we adopt a “performance factor” \( B \cdot f \), *where the value of \( B \) at each frequency is selected to provide the same core loss density* (e.g., 500 mW/cm\(^3\))
Calculating Performance Factor

- choose a frequency $f$ and a design core loss density (e.g., 200-500 mW/cm$^3$) and find the allowable flux density $B_{pk}$.

$$F_1 = B_{pk}f$$

1) 500 mW/cm$^3$
2) 16 MHz
3) 5.52 mT
4) $PF = 5.52 \text{ mT} \times 16 \text{ MHz} = 88.31 \text{ mT*MHz}$
The "performance factor" is meant to capture the power handling per unit volume of a magnetic material.

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

Source: Ferroxcube
Core loss data is generally not available at HF (3-30 MHz) on manufacturer datasheets, even for materials designed for HF operation. Why?

- Many HF materials have been developed for applications other than power conversion
- Traditional core loss measurement techniques do not work well at HF owing to phase shift sensitivity
- No commercial equipment works above 10 MHz

Preconditioning and Measuring Apparatus consistent with International Standard IEC 62044-1, 2, 3
Traditional Core Loss Measurement Method

- Conventional methods difficult at HF/VHF
  - Measurements very sensitive to parasitics, phase shift
- Instead, use simple method to directly determine the quality factor $Q_L$ of an RF inductor
  - Extract the core loss from the measurement of $Q_L$
- The new technique (by Han) is tedious but works well

Preconditioning and Measuring Apparatus consistent with International Standard IEC 62044-1, 2, 3

At the resonant frequency \( f_s = \frac{\omega_s}{2\pi} = \frac{1}{2\pi\sqrt{LC}} \) \( \omega_s L = \frac{1}{\omega_s C} \)

\[
\frac{V_{out-pk}}{V_{in-pk}} = \left| \frac{V_{out}(j\omega_s)}{V_{in}(j\omega_s)} \right| = \left| \frac{1}{j\omega_s C} \right| = \frac{\omega_s L}{R_{core} + R_{cu}} = Q_L
\]

The approach of (Han et al.) enables power loss calculation using a ratio of voltage amplitude measurements

Extraction of Core Loss From $Q_L$

Core loss extraction: 

$Q_L = \frac{V_{out-pk}}{V_{in-pk}} = \frac{2\pi f_s L}{R_{core} + R_{cu}}$

$R_{core} = \frac{2\pi f_s L}{Q_L} - R_{cu}$

$P_V = \frac{I_{L-pk}^2 R_{core}}{2V_L}$

Copper loss ($R_{cu}$) estimation: an air-core inductor with the same dimension is fabricated and measured using an impedance analyzer. From Finite Element simulation results, this estimation of $R_{cu}$ has up to 30% error.

In our experiments, the core loss is controlled to be at least 5 times larger than the copper loss to reduce the error caused by $R_{cu}$.
Estimation of Errors

- Error caused by the capacitor ESR
- Error caused by circuit parasitics
- Error caused by copper loss
- Error caused by the measurement frequency
- Error caused by uneven flux density:

The total error: less than 20%

Details shown in the Han paper:

Example inductor fabricated from copper foil and a commercial magnetic core M3-998.

The $Q_L$ of inductor fabricated with an M3 toroidal core (OD= 12.7 mm, ID= 7.82 mm, Ht= 6.35 mm) having $N = 5$ turns, and $L = 190 \text{ nH}$

- $Q_L$ measurement only depends on the ratio of voltage amplitudes
- Eliminates the influence of parasitics & phase shifts
- Yields an accurate means to find loss density of a core material as a function of flux density at VHF
Each curve can be described by Steinmetz parameters $k, \beta$

$$P_V = k B_{pk}^\beta$$
## 20 Materials Tested

All measured data was fit to the Steinmetz equation: \( P_V = k B_{pk}^\beta \)

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<th>( \beta )</th>
<th>k</th>
<th>( \beta )</th>
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Performance Factor at HF

Traditional Performance Factor $F_1 = B_{pkf}$ assumes a fixed $(N \cdot l)$ as a function of frequency (winding loss is independent of frequency).

As frequency increases, high frequency winding effects become significant, making the current handling of the windings frequency dependent.

For example, skin effect makes the effective resistance $R \propto \sqrt{f}$. To maintain constant $I^2R$ winding loss across frequency, current handling must drop as $f^{-1/4}$, changing the performance factor to:

$$F_3 = \left(B_{pkf}\right) \cdot \left(f^{-\frac{1}{4}}\right) = B_{pkf}^{\frac{3}{4}}$$

(Voltage) (Current)

For other assumptions, it can be shown that $F_w = B_{pkf}^w \left(\frac{1}{2} < w < 1\right)$ is appropriate. This modified performance factor, especially $F_3^{\frac{3}{4}}$, is valuable for HF material evaluation.
Modified Performance Factor at HF

\[ f_{3/4} = \tilde{B} f_4^3 \text{ (mT, MHz}^3\text{)} \]

Frequency (MHz)
Modified Performance Factor at HF

\[ \frac{\gamma_{3/4}}{\gamma_f} = B_f^3 \text{ (mT, MHz}^3) \]

\[ \approx 1.45x \text{ may be more realistic, but still substantial} \]
Implications for Power Density

There is great opportunity for power conversion at HF!

- Main power stage (loss-limited) magnetics density: 1.45x – 2x improvement
- Other components (EMI filters, etc.) scale freely with frequency for substantial improvement.

Inductors
EMI Filter

5-10 MHz Off-Line LED Driver
(Seungbum Lim, MIT)
What about Permeability?

- Many low-frequency materials have $\mu_r > 500$, but most HF/VHF materials have $\mu_r$ in the range of 4 - 425

\[ F = Bf \text{ (mT.MHz)} \]

\[ \mu_r \]

- $\mu_r$ 20-40
- $\mu_r$ 80-125
- $\mu_r$ 175-425
- $\mu_r$ 4-16

Frequency (MHz)
For an ungapped inductor:

\[ L_{\text{ungapped}} = \frac{N^2}{R_c} = \frac{\mu_0 \mu_r N^2 A_c}{l_c} \]

- Couldn’t we use high \( \mu_r \) to reduce the number of turns and decrease total losses?
Power inductors are almost always *gapped* to balance core/copper loss and reduce overall loss.

For a gapped inductor, **permeability trades with gap length**:

\[
L_{\text{gapped}} = \frac{N^2}{R_{\text{tot}}} = \frac{\mu_0 N^2 A_C}{l_g + \frac{l_c}{\mu_r}} \approx \frac{\mu_0 N^2 A_C}{l_g}
\]
As long as permeability is high enough that a gap is required, additional permeability does not affect loss.

\[ \mu_{r,\text{threshold}} = \frac{L^2 l_C}{\mu_0 N_{opt}^2 A_C} \]

→ Permeability above \( \mu_{r,\text{threshold}} \) is much less useful.
Conclusion

- We have investigated the loss characteristics of many commercial rf magnetic materials for power conversion applications at HF/VHF (> 3 MHz)
- A experimental method to directly measure inductor quality factor has been described
  - Estimate core loss characteristics based on quality factor measurements
- Measurements of many HF materials have been made
- Material “Performance Factor” continues to increase up to at least the high HF range (3-30 MHz)
- Modified performance factor (accounting for ac winding loss effects) also improves to 10+ MHz
- Reduced permeability of HF materials is ok
- Power conversion at HF poses major opportunities!
Contributors:
- Alex Hanson
- Julia Belk
- Prof. Charles Sullivan (Dartmouth)
- Dr. Yehui Han

Sponsorship:
- Lockheed Martin
- National Science Foundation
- MIT CICS

Publications:
- (Also to appear, IEEE Transactions on Power Electronics)
Permeability Needs for Transformers

- Reduced permeability increases the magnetizing current one must drive to magnetize the core
  - e.g., in a transformer
  - Causes added conduction loss (but current orthogonal to load)

- Define acceptable loss levels at: $B = \hat{B}$
  $$NI = K = \hat{K}l_C$$
Permeability Extension

\[ P_{DEL} = V_{in}I_{eff} = \frac{1}{2} 2\pi f \cdot NA_c \hat{B} \cdot \sqrt{\left(\frac{\hat{K}l_c}{N}\right)^2 - \left(\frac{l_c}{N^2 \mu_c A_c \cdot 2\pi f}\right)^2} \]

\[ = \pi A_c l_c \cdot \hat{B} f \cdot \sqrt{\hat{K}^2 - \left(\frac{\hat{B}}{\mu_c}\right)^2} \]

\[ = (\pi \hat{K}) \cdot (A_c l_c) \cdot (\hat{B} f) \sqrt{1 - \left(\frac{\hat{B}}{\hat{K} \mu_c}\right)^2} \]

\[ = (\text{scale}) \cdot (\text{volume}) \cdot (F_1) \cdot (\mu \text{ factor}) \]
Permeability Extension

- Modified performance factor can be thought of as an adjustment to $\hat{K}$

- Once permeability is above a certain level (relative to $\hat{B}$, $\hat{K}$), then added permeability DOES NOT reduce loss owing to magnetizing current
  - There is an upper bound to the amount of permeability that one needs, and this permeability reduces with $\hat{B}$
  - One *needs* less permeability at HF, VHF

$$P_{DEL} = (\pi \hat{K}) \cdot (A_c l_c) \cdot (\hat{B} f) \sqrt{1 - \left(\frac{\hat{B}}{\hat{K} \mu_c}\right)^2}$$
Earlier work by Han, et. al., characterized some materials in the (30+ MHz) VHF range, but left out materials suitable for the HF (3-30 MHz) range.

- We aim to fill this void

Example inductor fabricated from copper foil and a commercial magnetic core M3-998.

The $Q_L$ of inductor fabricated with an M3 toroidal core (OD= 12.7 mm, ID= 7.82 mm, Ht= 6.35 mm) having $N = 5$ turns, and $L = 190$ nH

- $Q_L$ measurement only depends on the ratio of voltage amplitudes
- Eliminates the influence of parasitics & phase shifts
- Yields an accurate means to find loss density of a core material as a function of flux density at VHF
Find the Measurement Frequency

- **Challenge:** the precise resonant frequency $f_s$ is unknown because of the parasitics and components’ errors.

- **To address this issue,** we pre-calculate the capacitor value to achieve the approximate resonant frequency, then adjust the frequency around the calculated resonant frequency to find the frequency point $f'_s$ where $\frac{V_{out} - pk}{V_{in} - pk}$ has the maximum value.

- $f'_s = f_s \sqrt{1 - \frac{1}{2Q_L^2}}$  
  As $Q_L \gg 1$ for all cases of interest, $f'_s$ is approximately equal to $f_s$. 
Achievable Power Density (crude example)

- Ungapped cores with identical $Z$, $Q$, and current $I$ (not optimal; for illustration only)

**Fair-Rite 67**

$\mu_r = 40$

$I_{pk} = 1.6 \text{ A}$

(Can be made in planar shapes!)

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Many high permeability and low frequency (<10 MHz) magnetic materials:

- Exhibit unacceptable high losses at frequencies above a few megahertz (e.g., 3F4 from Ferroxcube shown in Fig. 1)

Fig. 1. 3F4 (NiZn, $\mu_r=900$) Complex permeability as a function of frequency (Adapted from Ferroxcube 3F4 Material Specification Data Sheet).

$$Q_{L_{\text{max}}} = \frac{\mu_s'}{\mu_s}$$  (Core loss only)
Some low permeability and high frequency (>3 MHz) magnetic materials are available:

- Low loss characteristics under large AC flux swings make these materials potentially suitable for HF/VHF applications (e.g. M3 from National Magnetics Group, Inc. shown in Fig. 2)

- ONLY characterized for small-signal drive condition, and NOT under the high flux-density conditions desired for VHF power conversion

Fig. 2. M3 (NiZn, $\mu_r=20$) Complex permeability as a function of frequency (Adapted from National Magnetics Group M3 Material Specification Data Sheet).
What about Permeability?

Many low-frequency materials have $\mu_r > 500$, but the HF/VHF materials have $\mu_r$ in the range of 4 - 425.

Some of the best materials have $\mu_r = 40$.

$\mu_r$ 4-40

$\mu_r$ 80-125

$\mu_r$ 250-425
Consideration of Permeability

- Reduced permeability increases the magnetizing current one must drive to magnetize the core
  - e.g., in a transformer
  - Causes added conduction loss (but current orthogonal to load)

- Define acceptable loss levels at: \( B = \hat{B} \)
  \[
  NI = K = \hat{K}l_c
  \]
Permeability Extension

\[ P_{DEL} = V_{in} I_{eff} = \frac{1}{2} 2\pi f \cdot NA_c \hat{B} \cdot \sqrt{\left(\frac{kl_c}{N}\right)^2 - \left(\frac{l_c}{N^2 \mu_c A_c \times 2\pi f}\right)^2} \]

\[ = \pi A_c l_c \cdot \hat{B} f \cdot \sqrt{\hat{K}^2 - \left(\frac{\hat{B}}{\mu_c}\right)^2} \]

\[ = (\pi \hat{K}) \cdot (A_c l_c) \cdot (\hat{B} f) \sqrt{1 - \left(\frac{\hat{B}}{\hat{K} \mu_c}\right)^2} \]

\[ = (\text{scale}) \cdot (\text{volume}) \cdot (F_1) \cdot (\mu \text{ factor}) \]
Modified performance factor can be thought of as an adjustment to $\hat{K}$.

Once permeability is above a certain level (relative to $\hat{B}$, $\hat{K}$), then added permeability DOES NOT reduce loss owing to magnetizing current.

- There is an upper bound to the amount of permeability that one needs, and this permeability reduces with $\hat{B}$.
- One needs less permeability at HF, VHF.

\[
P_{DEL} = (\pi \hat{K}) \cdot (A_c l_c) \cdot (\hat{B} f) \sqrt{1 - \left(\frac{\hat{B}}{\hat{K} \mu_c}\right)^2}
\]
When magnetic field isn’t AC

- Many popular DC/DC converters have a DC component to inductor current (and hence to magnetic field)
  - Buck, Boost, Buck-Boost, Ćuk
  - Forward
  - Flyback
  - Etc.

- Most textbooks (including Kassakian\textsuperscript{26} and Erikson\textsuperscript{27}) ignore the DC component and take the AC component only

- While the effects of AC harmonics have been extensively studied\textsuperscript{21-24}, the fact that the loss curves change with bias has not as much

Ref 28

Ref 29
Longitudinal Bias: Experimental Setup
Longitudinal Bias: Effect on Loss

- Bpk = 6.5 mT
- Frequency = 10 MHz
- Loss: 241 → 746 mW/cm^3
- 3x increase
- Zero bias loss level increases

![Graph showing power loss vs. B_dc (mT)]
- Bpk = 2.8 mT
- Resonant frequency varies from 9 to 12 MHz
Transverse Bias

- Material: Fair-Rite 67 ($\mu_r = 40$)
- Nominal $B_{\text{trans}} = 80$ mT
- $B_{\text{pk}} = 5.6$ mT
- 4.5x loss increase

<table>
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<tr>
<th># Plates</th>
<th>$P_v$ (mW/cm^3)</th>
<th>$\mu_r$</th>
<th>$f_r$ (MHz)</th>
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</tbody>
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Experimental Setup (1 plate)