Precise Core Loss Measurement via Precision Power Analysis

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December 4, Hilton at Munich Airport
Situation today

• Power losses in magnetic components limiting factor for development of power electronics, especially core losses of different materials
• Problem gets exacerbated by new generation of wideband-gap semiconductors like SiC/GaN
• Qualification of components and materials more of an art than a science
Core losses – measure or simulate?

Challenges for simulation:
- Behavior of core materials strongly non-linear
- No generalization between soft and hard magnetic materials
- Approximative formulas resting on measured values

Advantages of measurements:
- Direct quantification of losses
- Magnetic characteristics as by-products
- Verification of theoretical models
- Basis for development of new core materials
Schematic architecture

Excitation

Data Acquisition

Data Processing

http://www.mspm-power.de/

https://www.powerlosstester.de/
The common way to measure

- Standard procedures: sinusoidal field strength or flux density required
- Consequence:
  - sophisticated, expensive signal sources
  - complex measurement apparatus
- Practical relevance limited:
  - suitable signal sources allow to generate approximately sinusoidal flux density
  - field strength remains non-sinusoidal

Characteristics of field strength and flux density, [1]
Intelligent measurement apparatus allows arbitrary voltage and current waveforms

Even mains voltage with harmonic content becomes useable

Procedure based on measuring primary current and secondary voltage on magnetic cores – details to follow.
Core loss basics: components

\[ P_{\text{loss}} = P_{\text{hysteresis}} + P_{\text{eddy\_currents}} + P_{\text{winding}} + P_{\text{rest}} \]
Core losses basics: hysteresis loop

dissipative core losses $\sim$ area enclosed by hysteresis loop

\[ \int H \cdot dB \sim A_H \]

\[ P_H = f \cdot V_{Fe} \cdot A_H \]

Influences on core losses:
- frequency
- temperature
- material
- geometry
- flux density

$H$: magnetic field strength
$A_H$: area enclosed by B-H loop
$V_{Fe}$: core volume
Measuring core losses: smart measurement

- ANY signal on primary side
- open circuit voltage measurement on secondary side
- $I_{pk,primary} \sim H_{pk}$
- $U_{rect,secondary} \sim B$

($P_{winding}$ to be excluded.)
Measuring core losses: smart measurement

\[ P_{\text{loss}} = U_{\text{trms}} \cdot I_{\text{trms}} \cdot \cos \phi \cdot \frac{n_1}{n_2} * \]

- voltage drop on primary excluded
- no current flow on secondary

Preconditions

- optimal voltage accuracy
- optimal current accuracy
- minimal phase error

* for sinusoidal signals
Error analysis

\[
\Delta P_{\text{loss}} = \frac{\Delta U_{\text{trms}}}{U_{\text{trms}}} + \frac{\Delta I_{\text{trms}}}{I_{\text{trms}}} + \frac{\Delta \cos \phi}{\cos \phi}
\]

- Amplitude error voltage
- Amplitude error current
- Phase error
Error influences – example: phase error

Taking a closer look at:

primary current sinusoidal
f = 50kHz
PF = \cos \phi = 0.06
\Rightarrow \phi = \cos^{-1}(0.06) = 86.56°

Assumptions:

\Delta \phi = 2\pi \cdot f \cdot \tau =
= 360° \cdot 50kHz \cdot 3.8ns =
= 0.0684°

Exemplary additional skew:

\tau = 3.8ns

\cos(\phi + \Delta \phi) \approx \Delta P_{\text{loss}}
\cos \phi

\sim \frac{\Delta P_{\text{loss}}}{P_{\text{loss}}}

\cos(\phi + \Delta \phi) = 0.98 \approx 2\%
### Evaluation (with data-log file)

<table>
<thead>
<tr>
<th>Batch Nr</th>
<th>Piece Nr</th>
<th>Code Nr</th>
<th>Temp(°C)</th>
<th>Freq(kHz)</th>
<th>Vpp_Sp(V)</th>
<th>Vpp_Mv</th>
<th>Vrms_Mv</th>
<th>V_CF</th>
<th>V_DC</th>
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</table>

<table>
<thead>
<tr>
<th>Ipp_Mv(A)</th>
<th>Irms_Mv</th>
<th>I_CF</th>
<th>I_DC</th>
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<tbody>
<tr>
<td>0,212</td>
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<td>0,385</td>
<td>0,133</td>
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<td>0,001</td>
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<td>0,537</td>
<td>0,184</td>
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<td>0,002</td>
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<td>0,722</td>
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<tr>
<td>0,979</td>
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<tr>
<td>1,380</td>
<td>0,421</td>
<td>1,645</td>
<td>-0,013</td>
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</table>

<table>
<thead>
<tr>
<th>PhaseShift</th>
<th>Phi_Cal</th>
<th>Phi_Corrected</th>
<th>CosQ</th>
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<tbody>
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<tr>
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<td>0,301</td>
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</table>

<table>
<thead>
<tr>
<th>Pv_Cal(mW)</th>
<th>Pv_Corrected</th>
<th>Pv_Final</th>
<th>Pv_FinalOffset</th>
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<tbody>
<tr>
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<td>75,501</td>
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<td>287,997</td>
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<td>658,207</td>
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<td>729,695</td>
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<tr>
<td>1201,240</td>
<td>1292,009</td>
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<td>1358,309</td>
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<td>1879,682</td>
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<td>2636,412</td>
<td>2844,095</td>
<td>3488,736</td>
<td>3465,131</td>
</tr>
</tbody>
</table>
Example setup: laminated core / electric motor

AC source: 115V
frequency: 50Hz

\[
\frac{n_1}{n_2} = \frac{2}{2} = 1
\]
Calculating peak value of magnetic field strength

According to the Maxwell–Ampère equation:

$$\oint \vec{H} \, d\vec{s} = \int_A \vec{j} \, d\vec{A} + \frac{d}{dt} \int_A \vec{D} \, d\vec{A}$$

Assuming quasi-stationary fields: $\omega \varepsilon \ll 1$

$$H_{pk} = \frac{I_{pk} \cdot n_1}{l_{magn}}$$

$H_{pk}$: peak value of magnetic field strength

$I_{pk}$: peak value of primary current

$n_1$: no. of primary windings

$l_{magn}$: magnetic path length
Calculating peak value of magnetic field strength

Signal shape of primary current irrelevant, as long as symmetrical:

\[ I_{pk} = \frac{I_{pp}}{2} \]

Resulting formula for \( H_{pk} \):

\[ H_{pk} = \frac{I_{pp}}{2} \cdot \frac{n_1}{l_{magn}} \]

- \( H_{pk} \): peak value of magnetic field strength
- \( I_{pp} \): peak-to-peak value of primary current
- \( n_1 \): no. of primary windings
- \( l_{magn} \): magnetic path length
Calculating peak value of magnetic flux density

From the Maxwell–Faraday equation:

$$\frac{1}{dA} \int \vec{E} \, d\vec{s} = -\frac{dB}{dt}$$

Assuming quasi-stationary fields: $\omega \varepsilon \ll 1$

$$- \frac{1}{n_2 \cdot A} \cdot u(t) = \frac{dB(t)}{dt}$$

- $B(t)$: magnetic flux density
- $u(t)$: induced secondary voltage
- $n_2$: no. of secondary windings
- $A$: core cross section
Calculating peak value of magnetic flux density

Integrating the induced voltage between two zero crossings allows us to calculate the peak value of magnetic flux density:

\[- \frac{1}{n_2 \cdot A} \cdot \int_{t_0}^{t_1} u(t) \, dt = B_{pp}\]

- $B_{pp}$: peak-to-peak value of magnetic flux density
- $u(t)$: induced secondary voltage
- $n_2$: no. of secondary windings
- $A$: core cross section
Calculating peak value of magnetic flux density

Since the induced voltage has no DC content:

\[
\int_{t_0}^{t_1} u(t) \, dt = - \int_{t_1}^{T} u(t) \, dt = \frac{1}{2} \int_{t_0}^{T} |u(t)| \, dt
\]

From the definition of the rectified value we know:

\[
U_{\text{rect}} = \frac{1}{T} \int_{0}^{T} |u(t)| \, dt
\]
Calculating peak value of magnetic flux density

Thus, the peak value of flux density can be expressed as:

\[ B_{pk} = \frac{U_{rect}}{4 \cdot f \cdot n_2 \cdot A} \]

The calculation is independent of signal shape. Taking into account the windings ratio, core losses can be established as:

\[ P_{loss} = P \cdot \frac{n_1}{n_2} \]
Comprehensive results

Magnetic Field Strength:
\[ H_{pk} = 175.4024 \text{ A/m} \]

Primary Current:
\[ I_{prim} = 20.743 \text{ A} \]

Secondary Voltage:
\[ U_{sec} = 448.971 \text{ mV} \]

Core Losses:
\[ P_{fe} = 7.057 \text{ W} \]

Temperature:
\[ \text{Temp Amb.} = 23 ^\circ C \]
\[ \text{Temp Core} = 46 ^\circ C \]
## Outlook: further possibilities

In analogy to:

\[- \frac{1}{n_2 \cdot A} \cdot \int_{t_0}^{t_1} u(t) dt = B_{pp}\]

the following parameters can also be derived:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td>$E = \int_{t_0}^{t_1} (u \cdot i) dt$</td>
</tr>
<tr>
<td>charge</td>
<td>$Q = \int_{t_0}^{t_1} (i) dt$</td>
</tr>
<tr>
<td>magnetic flux</td>
<td>$\Phi = \int_{t_0}^{t_1} (u) dt$</td>
</tr>
<tr>
<td>Joule heating integral</td>
<td>$I^2t = \int_{t_0}^{t_1} (i^2) dt$</td>
</tr>
</tbody>
</table>
By directly measuring frequency, the peak value of primary current and the rectified value of secondary voltage, core losses can be calculated with high accuracy.

The basis of precise core loss measurement is the precise measurement of voltage, current and power.

Depending on the frequency range used, both ample analog bandwidth and minimal phase error, also at high frequencies, are mandatory.

Every detail of the measurement setup matters when it comes to minimizing overall error.

For a known core geometry, the peak value of magnetic field strength and flux density as well as relative permeability can be derived in the same measurement without additional effort.
Thank you very much for your attention!

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