POWER ELECTRONICS CONFERENCE 2018

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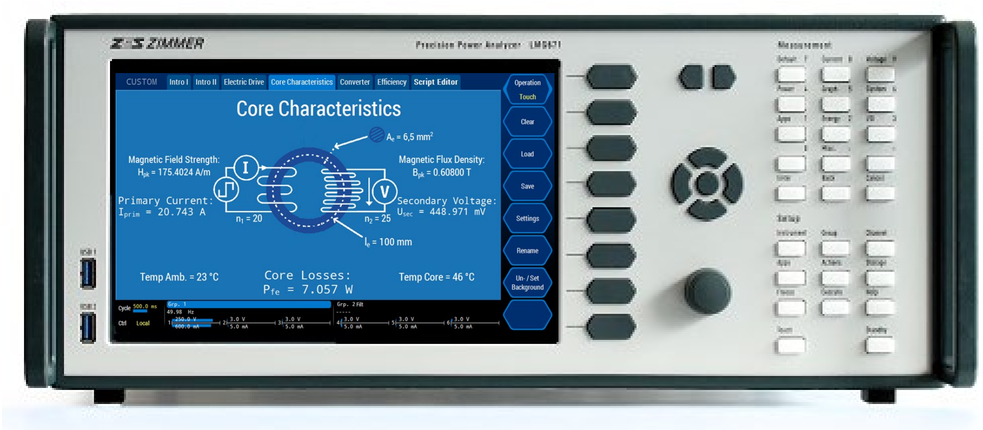
Precision Power Measurement

Precise Core Loss Measurement via Precision Power Analysis

Bernd Neuner
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

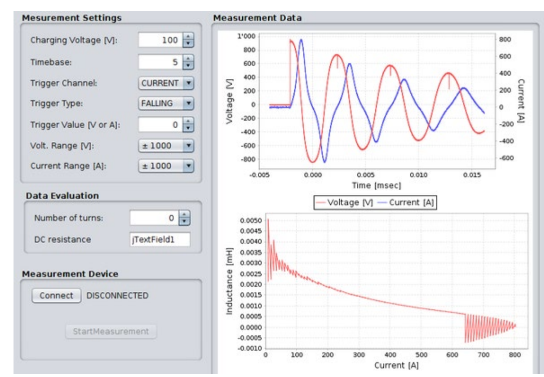
Schematic architecture

Excitation

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

Data Acquisition

Data Processing



https://www.powerlosstester.de/

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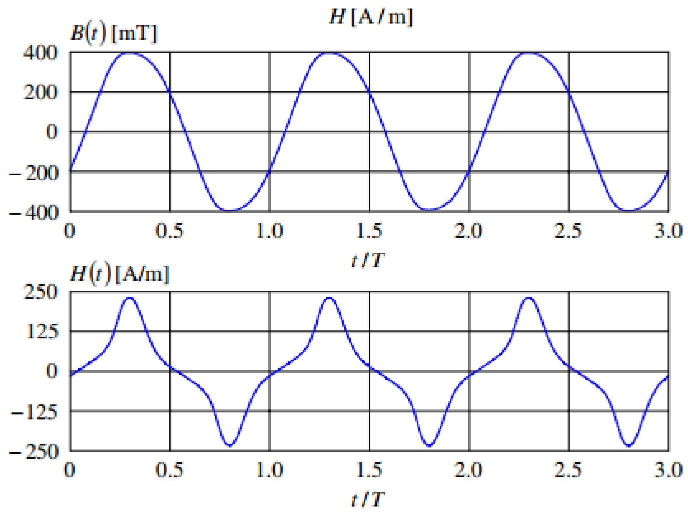
The common way to measure

- 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]

Alternative approach: dumb signal, smart measurement

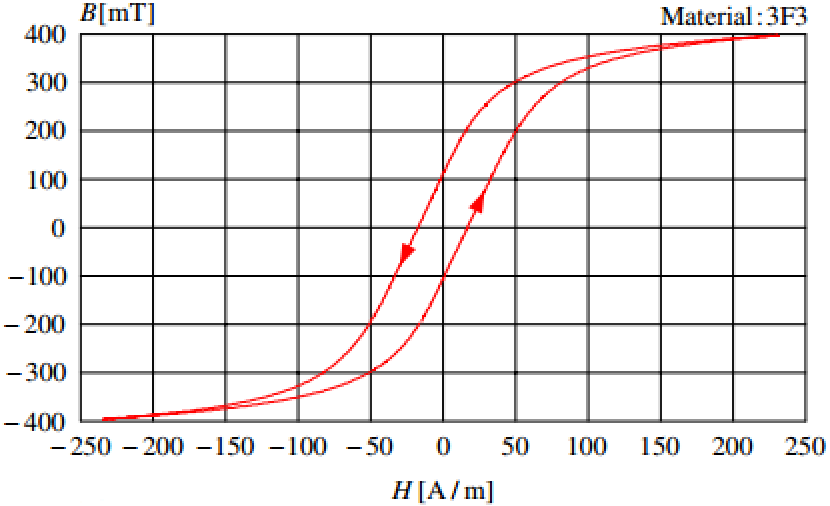
- Intelligent measurement apparatus allows arbitrary voltage and current waveforms
- Even mains voltage with harmonic content becomes useable
- Procedure based on measuring primary current and secondary voltage on magnetic cores – details to follow.

Core loss basics: components

$$P_{loss} = P_{hysteresis} + P_{eddy\_currents} + P_{winding} + P_{rest}$$

Core losses basics: hysteresis loop

dissipative core losses ~ area enclosed by hysteresis loop



B-H characteristics, material 3F3, [1]

$$\int H \cdot dB \sim A_H$$

$$P_H = f \cdot V_{Fe} \cdot A_H$$

H: magnetic field strength

A_H: area enclosed by B-H loop

V_{Fe}: core volume

Influences on core losses:

- frequency
- temperature
- material
- geometry
- flux density

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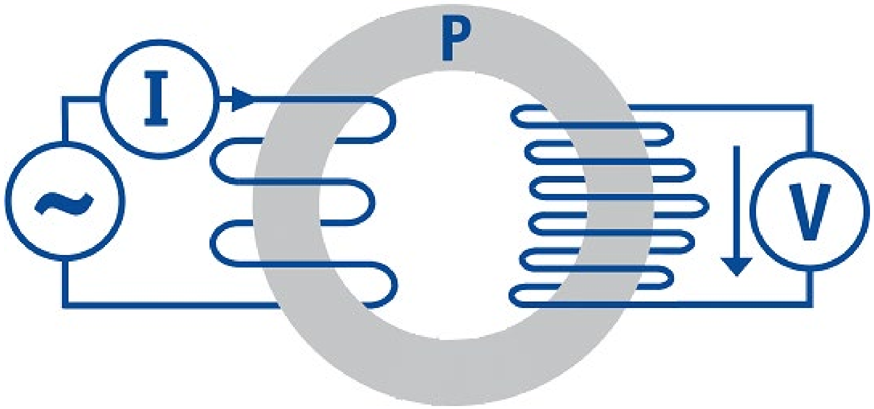
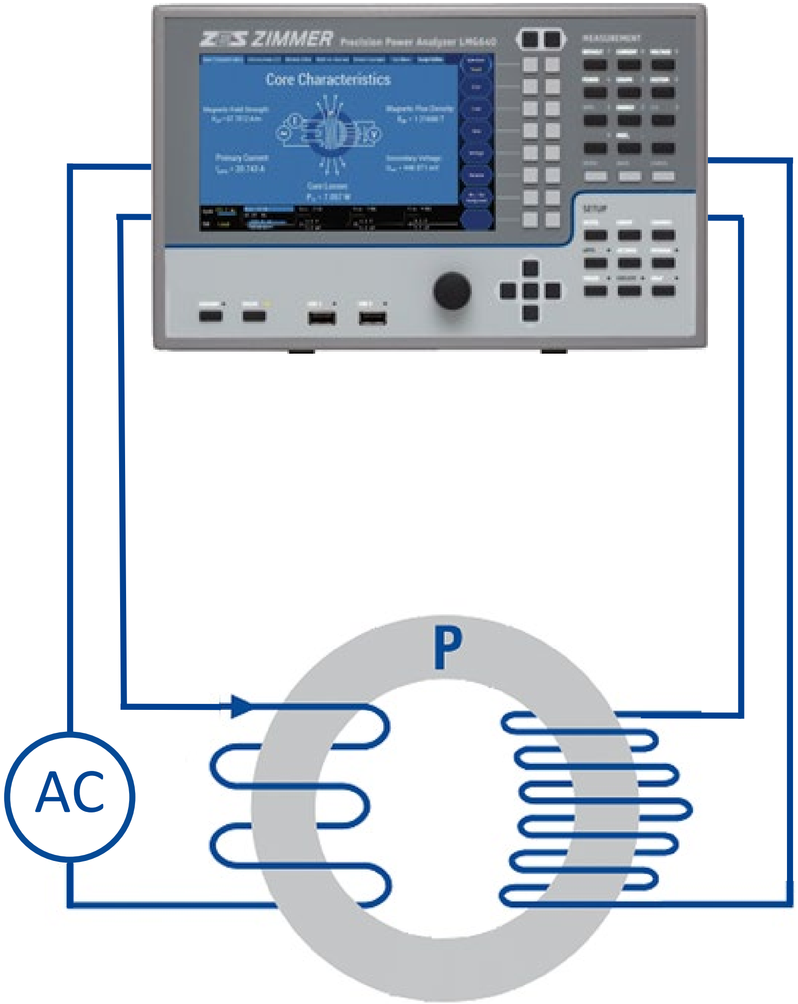
Measuring core losses: smart measurement

- 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



$$P_{\text{loss}} = U_{\text{trms}} \cdot I_{\text{trms}} \cdot \cos\varphi \cdot \frac{n_1}{n_2}^{*}$$

- 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

$$\frac{\Delta P_{\mathrm{loss}}}{P_{\mathrm{loss}}} = \frac{\Delta U_{\mathrm{trms}}}{U_{\mathrm{trms}}} + \frac{\Delta I_{\mathrm{trms}}}{I_{\mathrm{trms}}} + \frac{\Delta \cos\varphi}{\cos\varphi}$$

amplitude error voltage

amplitude error current

phase error

Error influences – example: phase error

Taking a closer look at:

$$\frac{\cos(\varphi + \Delta\varphi)}{\cos\varphi} \sim \frac{\Delta P_{loss}}{P_{loss}}$$

Assumptions:

primary current sinusoidal
f = 50kHz
PF = cosφ = 0.06
⇨ $\varphi = \cos^{-1}(0.06) = 86.56°$

Exemplary additional skew:

$\tau = 3.8ns$

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

$$\frac{\cos(\varphi+\Delta\varphi)}{\cos\varphi} = 0.98 \cong 2\%$$

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Evaluation (with data-log file)

	Batch Nr :							
	Date & Time :	02-01-01, 00:13						
Piece Nr	Code Nr	Temp(℃)	Freq(kHz)	Vpp_Sp(V)	Vpp_Mv	Vrms_Mv	V_CF	V_DC
1	0000 000 00001	25	25	11,517	11,511	4,004	1,438	-0,584
1	0000 000 00001	25	25	23,034	23,414	8,076	1,450	-0,509
1	0000 000 00001	25	25	34,551	34,992	12,007	1,457	-0,360
1	0000 000 00001	25	25	46,068	46,922	15,859	1,479	-0,315
1	0000 000 00001	25	25	57,585	58,176	19,380	1,501	-0,281
1	0000 000 00001	25	25	69,102	70,065	22,433	1,562	-0,156

Ipp_Mv(A)	Irms_Mv	I_CF	I_DC
0,212	0,073	1,451	-0,001
0,385	0,133	1,450	0,001
0,537	0,184	1,460	0,002
0,722	0,240	1,501	0,004
0,979	0,313	1,570	-0,019
1,380	0,421	1,645	-0,013

PhaseShift	Phi_Cal	Phi_Corrected	CosQ
1,457	76,503	75,062	0,258
1,457	74,435	72,978	0,293
1,457	72,654	71,196	0,322
1,457	71,622	70,177	0,339
1,457	71,965	70,558	0,333
1,457	73,774	72,456	0,301

Pv_Cal(mW)	Pv_Corrected	Pv_Final	Pv_FinalOffset
68,357	75,501	79,910	78,504
287,997	314,175	318,410	316,329
658,207	711,587	734,394	729,695
1201,240	1292,009	1366,165	1358,309
1879,682	2020,949	2263,251	2243,208
2636,412	2844,095	3488,736	3465,131

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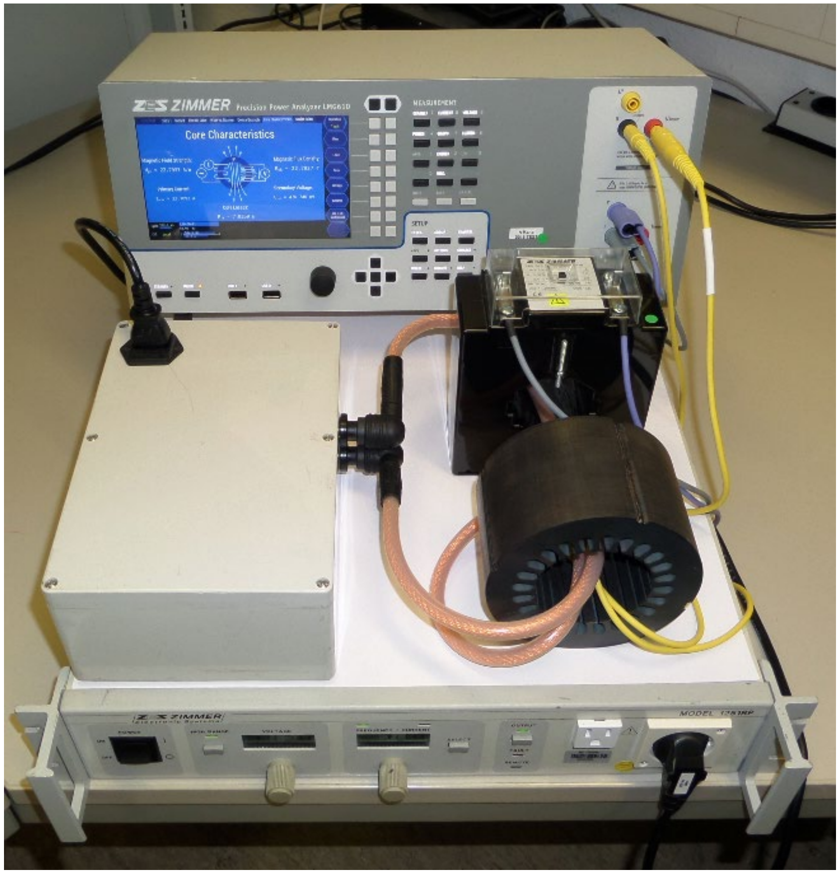
Example setup: laminated core / electric motor

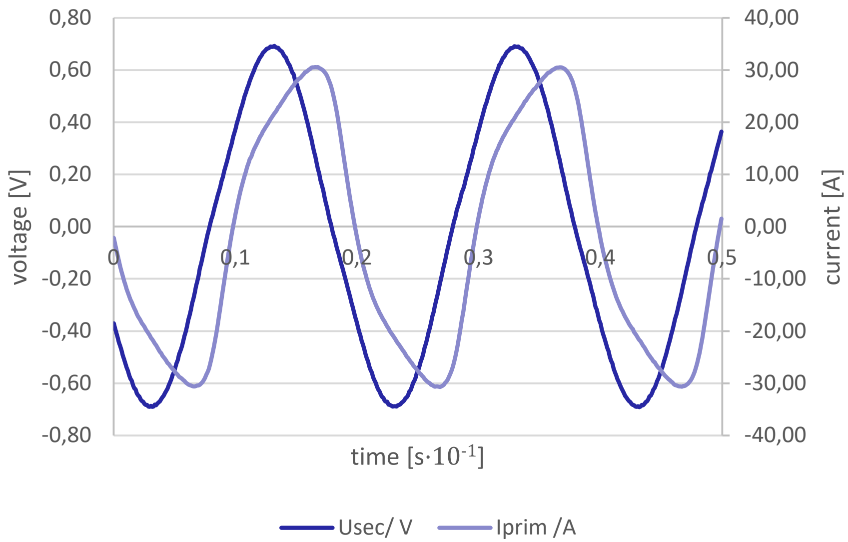


ZES ZIMMER LMG610

AC source: 115V

frequency: 50Hz

$$\frac{n_1}{n_2} = \frac{2}{2} = 1$$



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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

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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 :

$$\frac{1}{dA}\oint \vec{E}\, d\vec{s} = -\frac{d\vec{B}}{dt}$$

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

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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:

$$-\frac{1}{n_2 \cdot A} \cdot \int_{t0}^{t1} u(t)\, dt = B_{pp}$$

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:

$$\int_{t0}^{t1} u(t)\,dt = -\int_{t1}^{T} u(t)\,dt = \frac{1}{2}\int_{t0}^{T} |u(t)|\,dt$$

From the definition of the rectified value we know:

$$U_{rect} = \frac{1}{T}\int_{0}^{T} |u(t)|\,dt$$

Calculating peak value of magnetic flux density

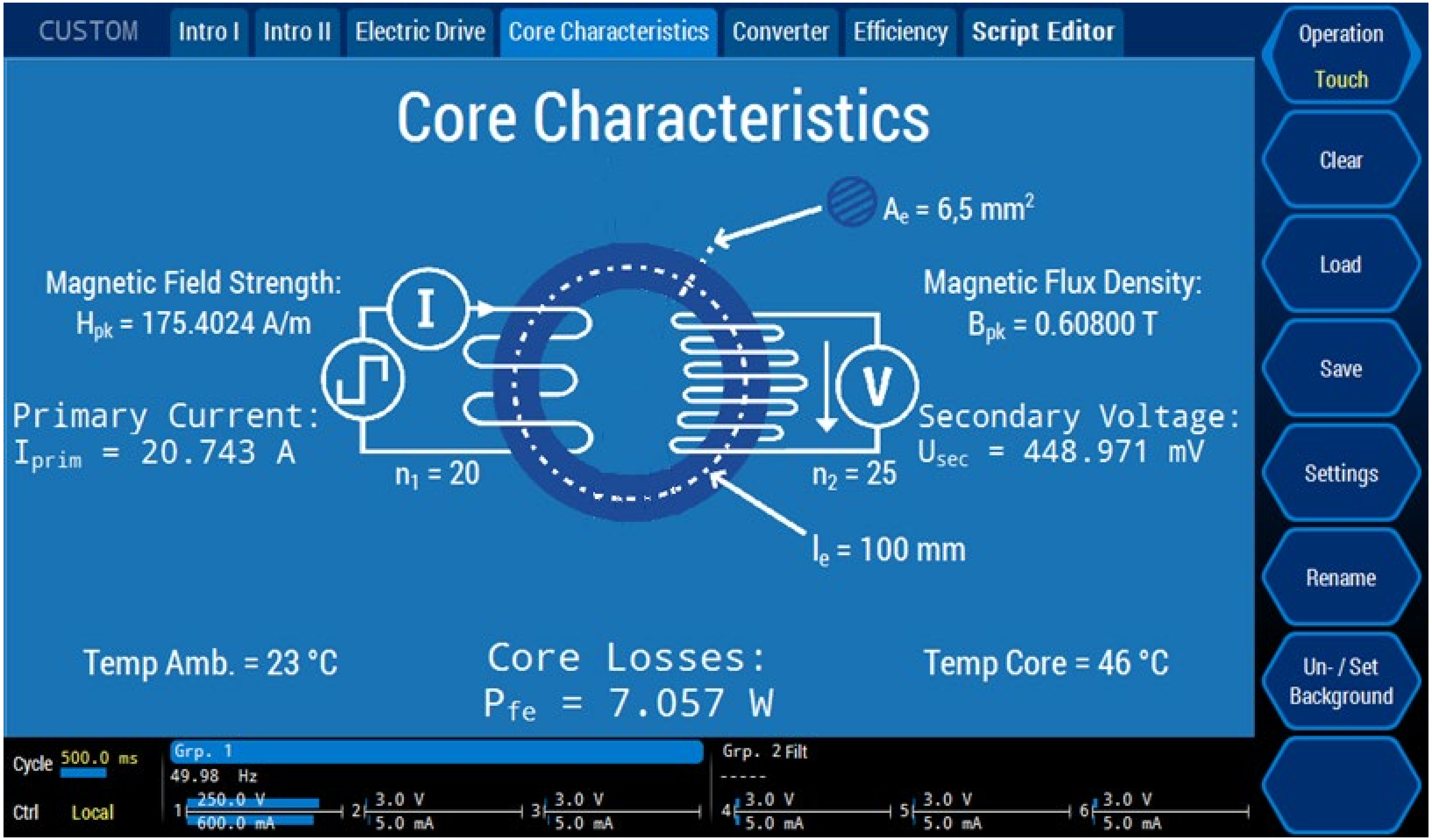
Thus, the peak value of flux density can be expressed as:

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

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



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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:

energy	E	$\int_{t0}^{t1} (u \cdot i)dt$
charge	Q	$\int_{t0}^{t1} (i)dt$
magnetic flux	Φ	$\int_{t0}^{t1} (u)dt$
Joule heating integral	I^2t	$\int_{t0}^{t1} (i^2)dt$

Take-home messages

- 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.

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Questions?

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Thank you very much for your attention!

Dipl.-Inf. Bernd Neuner
ZES ZIMMER Electronic Systems GmbH
Director of Sales, Applications & Support
bneuner@zes.com
+49 (0) 6171 88832-93
www.zes.com