Core Loss Measurements Across Power Levels, Frequencies and Materials

FRANK OBERLITNER
VICE PRESIDENT OF TECHNOLOGY

MAGNETICS

PRESENTED AT APEC 2023: PSMA INDUSTRY SESSION
MARCH 21, 2023

Core Manufacturer's Perspective

To a core maker, there are two categories of electrical tests:

1) **Production Testing**: for ensuring consistent, in-specification products on a volume scale
2) **Characterization Testing**: for generating useful design materials and guiding product development

Naturally, the scope of production testing is much narrower than the scope of characterization testing.

The obvious reason is cost, but the less obvious reasons are delivery and necessity.

Production Testing

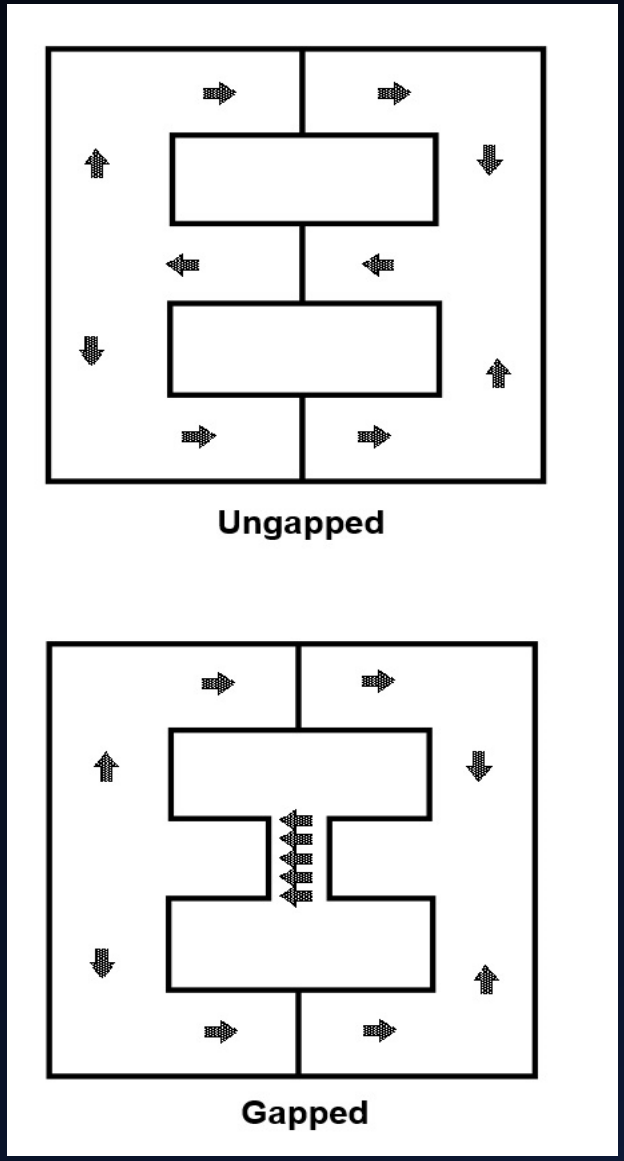
- For primary properties
  - Inductance
  - Core losses
  - Saturation performance
- For process control and feedback
- For QA approval to spec and data certifications
- Must be fast, real-time, and high capacity
- Must run in parallel with other QA testing (dimensions, strength, voltage break down, appearance)

Characterization Testing

- For primary properties
  - Inductance
  - Core losses
  - Saturation performance
- For secondary properties
  - Frequency response
  - Q metrics
  - BH Loop metrics
  - Disaccomodation
  - Audible Noise
- Additional testing:
  - All properties across temperature range
  - All properties across ranges of frequency and flux density
  - All properties across ranges of material grades, core sizes and core shapes
  - Variability of all properties across powder lots, across production batches, and within batches
  - For technology development, roadmap guidance, datasheets, catalogs, design materials and customer inquiries

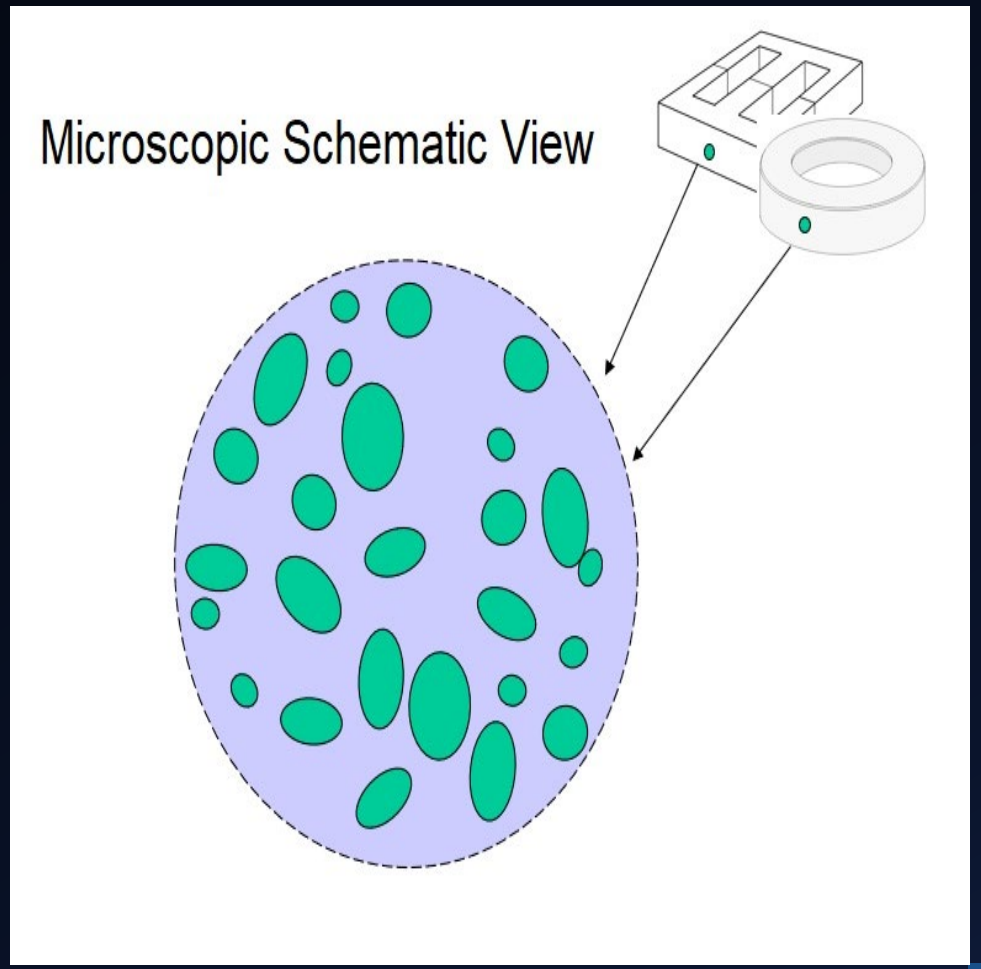
Ungapped core loss testing

- If the DUT presents a high impedance, a repeatable measurement is much easier to capture than if the DUT impedance is low.
- It means ungapped cores are used when possible. For example, even if the component is a gapped ferrite E-core set, the best practice is to measure core loss on sets before gapping.
- Waiting until after the airgap is ground in will result in a less repeatable measurement
- Ungapped cores can include ferrite sets, ferrite toroids, and laminated cores including amorphous and nanocrystalline.



GAPPED CORE LOSS TESTING

- But with any type of powder core, there is a distributed air gap built into the material, so a low DUT impedance is unavoidable, and special care is necessary.
- Powder cores include sendust, MPP, High Flux, silicon-iron powders, and powdered iron.
- Effective permeabilities are most typically 14µ to 125µ.



Loss Definitions

For power inductor cores and transformer cores, we usually assume “loss” means AC core loss.

- There is no DC core loss; only AC flux results in lost energy/heat, not DC.
- Thermal losses in a high frequency material only become meaningful at high drive level, meaning a combination of elevated frequency and elevated AC flux density.
- A ferrite toroid can be measured for loss angle at a low flux density (1 mT, for example). Loss factor is not bulk core loss, but it is relevant to common mode choke impedance performance.
- Any wound device can be measured for loss angle or Q at a low flux density, which can be relevant for passive filter performance.
- Loss angle and Q do not correlate well with AC core loss.

Production loss testing—Drive levels

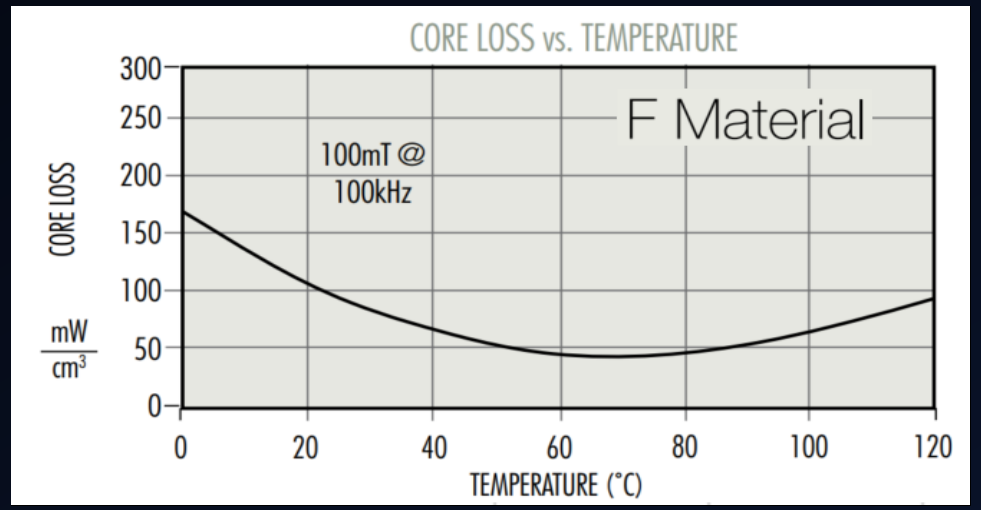
Standard frequency and flux density settings for production testing

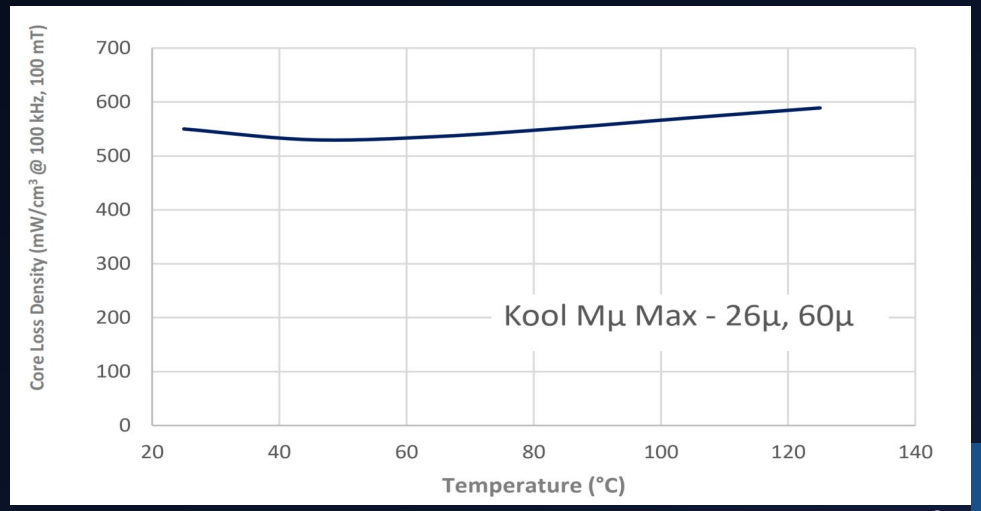
- For many ferrites and powder cores, 100 kHz, 100 mT is selected.
  - 100 kHz/100 mT is a typical, mid-range application drive condition
  - Using the same condition across materials and across time makes for more useful comparisons
  - Using one condition for process control is practical. Two or more is not because they are not independent.
- The standard is adjusted where the typical application is different (e.g. for XFlux SiFe alloy 50 kHz, 100 mT; for Kool Mμ H*f* 2MHz, 10 mT).
- Multiple test conditions can be applied. For example, Kool Mμ H*f* is also specified at 100 kHz, 100 mT and at 500 kHz, 50 mT. Additional standard stops do not add a lot of cost, but the added cost is not zero.
- The production test standard is sine wave drive, because it is the most repeatable and generic.

Production loss testing — Temperature

For power ferrites, loss vs. temperature performance is a fundamental design metric. So, production testing is performed in temperature cabinets.

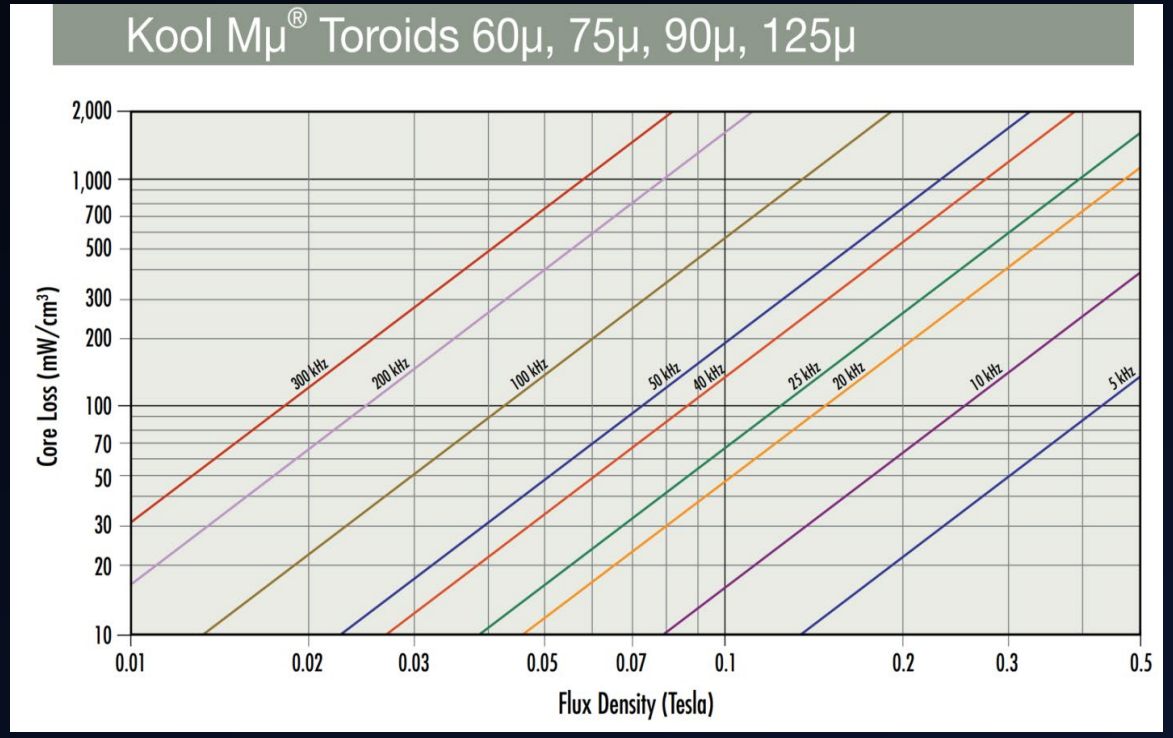
Powder cores are inherently much more stable across temperature and production testing at elevated temp is not necessary as a standard.





CHARACTERIZATION LOSS TESTING—DRIVE LEVELS

- 100 kHz, 100 mT sine wave is a standard production point because it lies in a typical application range.
- Of course, very few applications happen to be exactly 100 kHz, 100 mT sine wave.
- Material curves are built with large numbers of measurements spread within the design space to find the typical values across different batches and different cores.

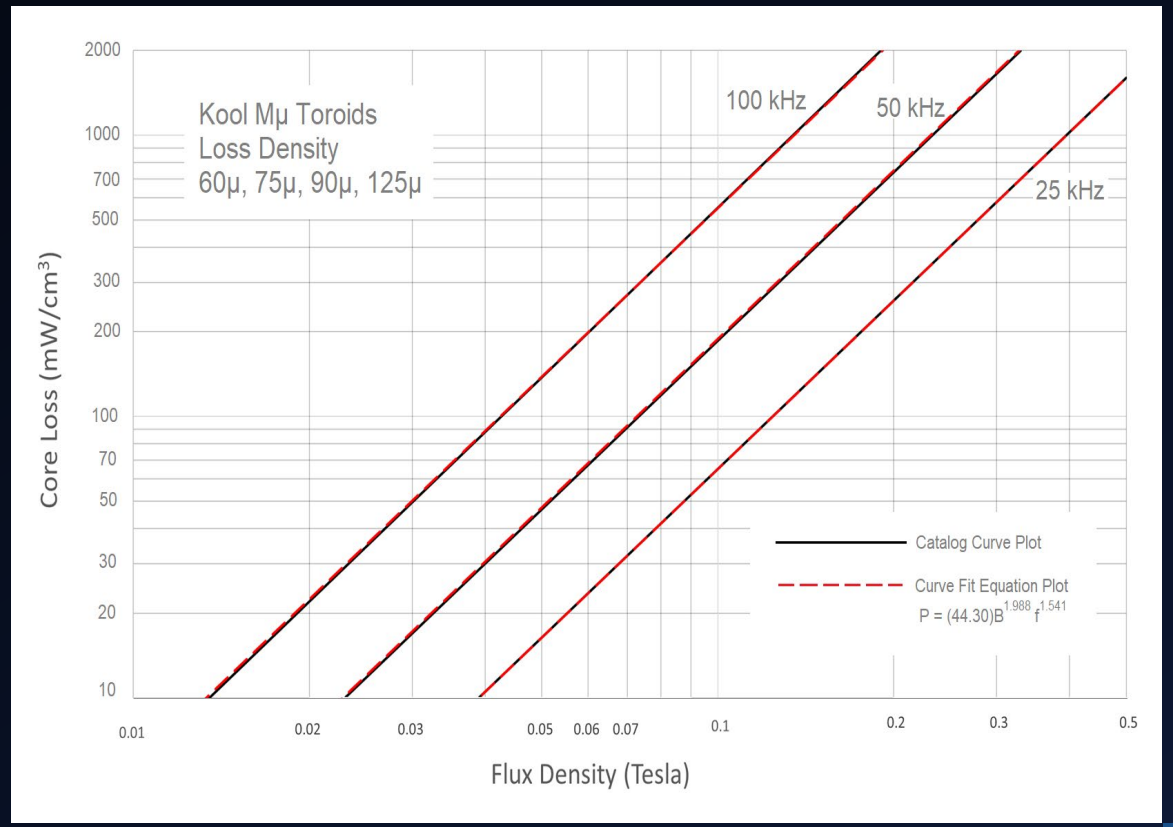


Curve Fit vs. Modeling

Manufacturers' curves are necessarily empirical.

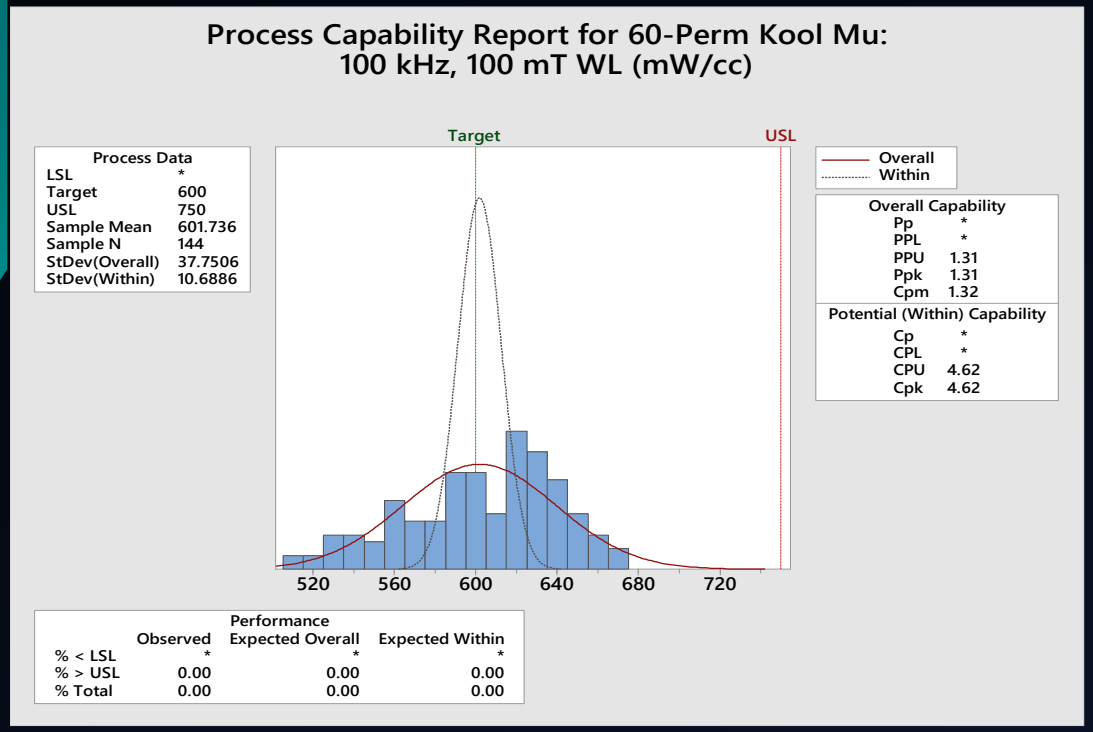
- Curve fit equations arise from the observed data, not from theory.

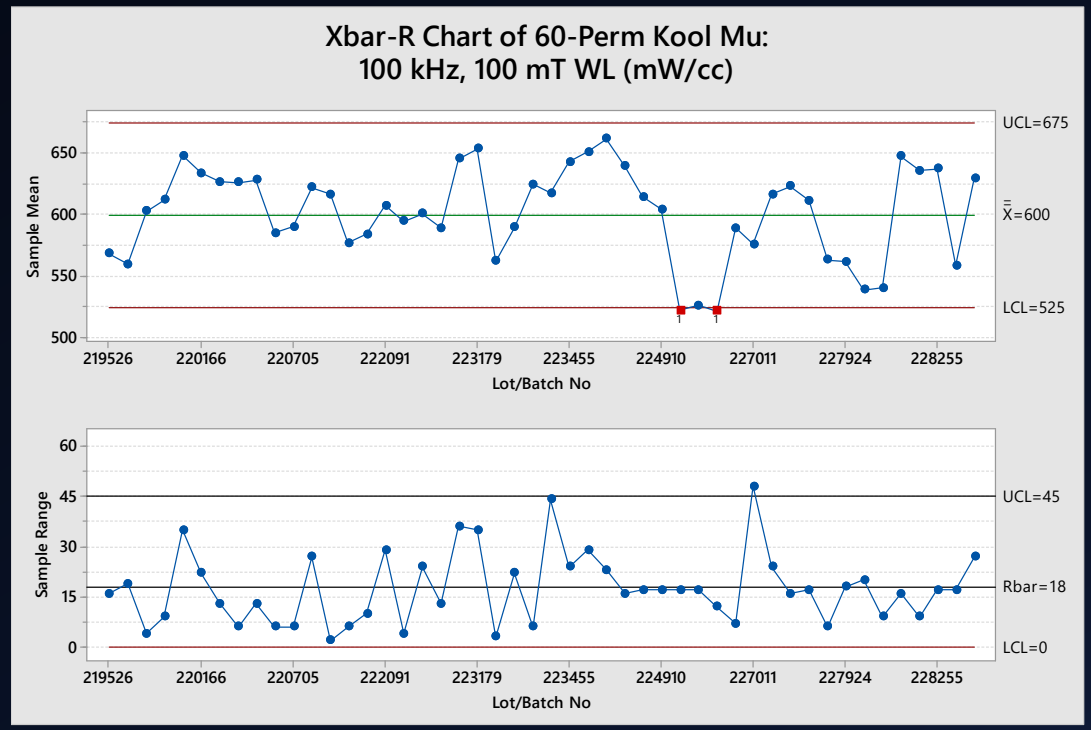
- Steinmetz Equation format is convenient and widely used.
- But a misconception can result when catalog Steinmetz coefficients are misunderstood as theoretical models.
- In reality, catalog Steinmetz coefficients are curve fit values valid within the range observed, for the estimated typical losses.



Loss performance variation

- It would be convenient if every core were exactly typical; that is not the reality.
- Designs need to account for both typical and limit.
- Ferrites, powder cores, and laminated alloys all exhibit similar variability from core to core and batch to batch.





FAQ #1

Q: What causes the variation, not only in core loss, but in inductance and saturation? Why can't these parameters be tightened?

A: They **have** been tightened.

- Exceedingly subtle variations in many factors result in measurable shifts in magnetic properties.
- Factors include:
  - Atmosphere
  - Temperature
  - Heat Flow
  - Particle Size
  - Particle Shape
  - Grain Insulation
  - Compaction Pressure
  - Ejection Forces
  - Minor Elements
  - Oxidation State
  - Secondary Treatments

Magnetic Variation drivers

- Powder core effective material permeability can generally be controlled to ±8%, whereas ferrites need ±20% or ±30%.
- On the other hand, powder core saturation is characterized by a DC bias curve that varies, whereas ferrite saturation is pretty well locked into the chemistry and does not vary significantly (and hence is not generally a production measurement.)
- Core losses vary on the order of ±30% or ±40%. The driver for ferrite tends to be sintering conditions of atmosphere and temperature. The drivers for powder cores tend to be powder morphology, insulation variation, and processing conditions.

Core loss measurement technique

As the other presentations make clear, there are multiple options.

From a manufacturer's point of view, for production testing, three requirements:

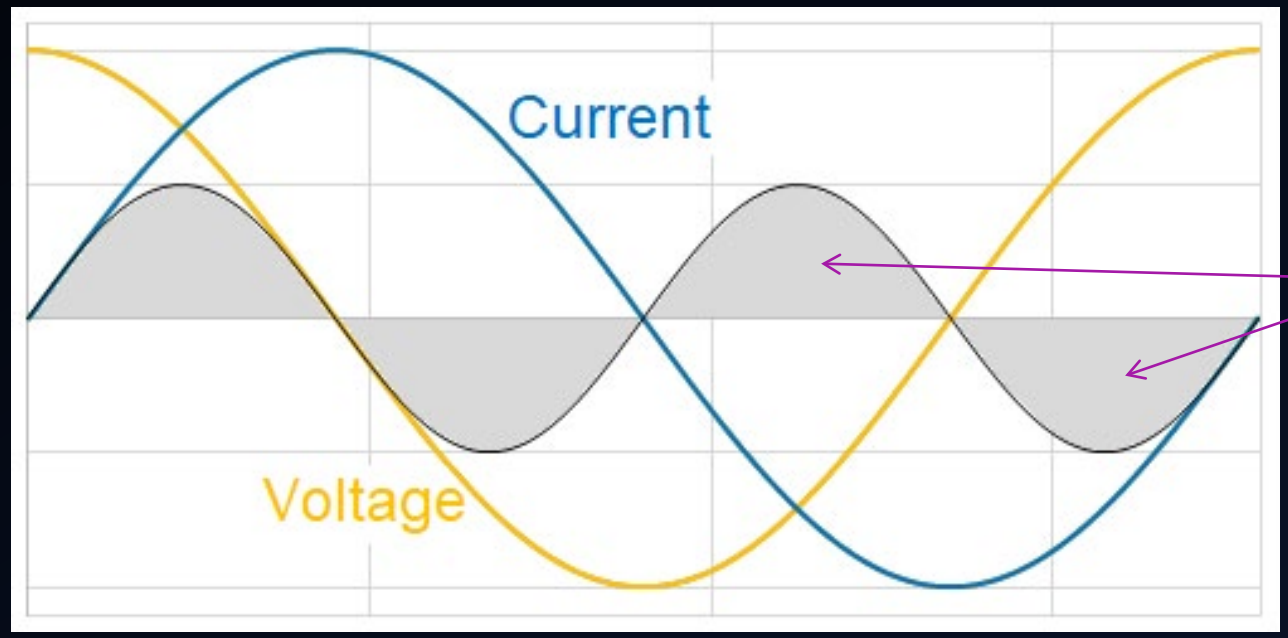
1. Above all, repeatability. Because the best we can do for core users is the most consistent product possible.
2. Also required, precision. Because there can be no doubt about whether parts meet spec or do not meet spec.
3. Also required, economy. Because prices will not support unnecessary testing cost.

A straight ahead (V)x(I) approach meets these requirements best.

At Magnetics, for powder cores, we selected MCLT.

Magnetics core loss tester (MCLT)

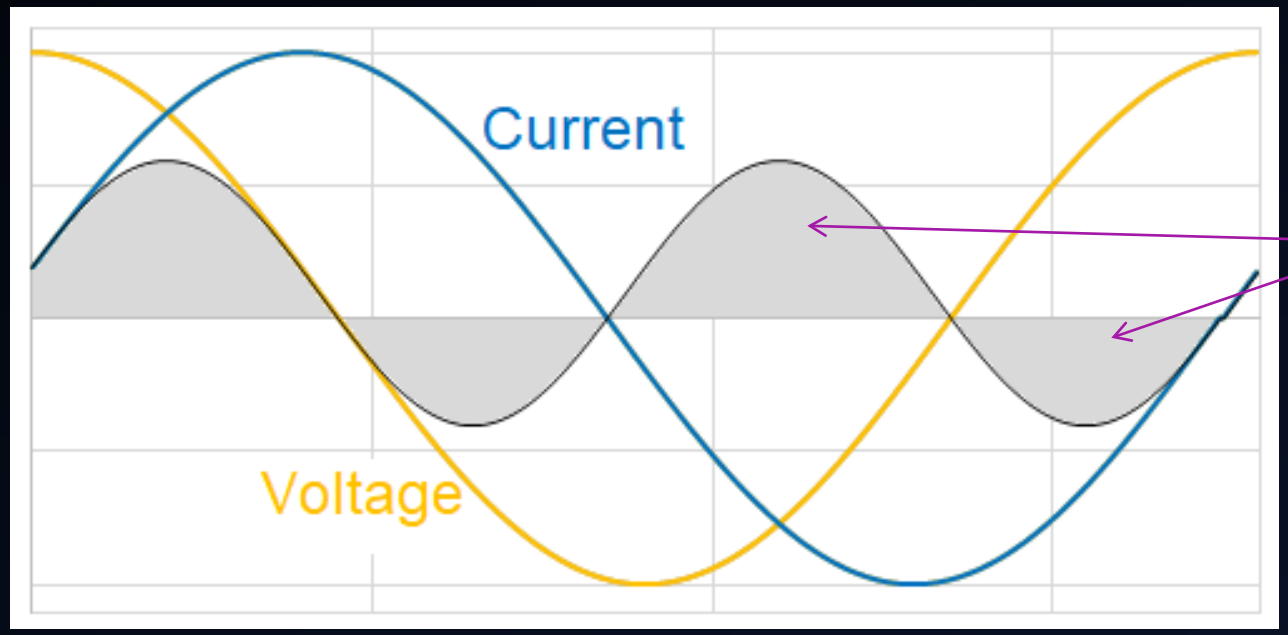
- In an ideal test of an ideal (zero loss) core, V and I are 90° out of phase. The vector product (V) x (I) is zero.



Average power is zero.

Magnetics core loss tester (MCLT)

- In an ideal test of a real core, the phase angle is not quite 90°, and (V) x (I) is a value of power which is the core loss.



Average power is not zero.

Magnetics core loss tester (MCLT)

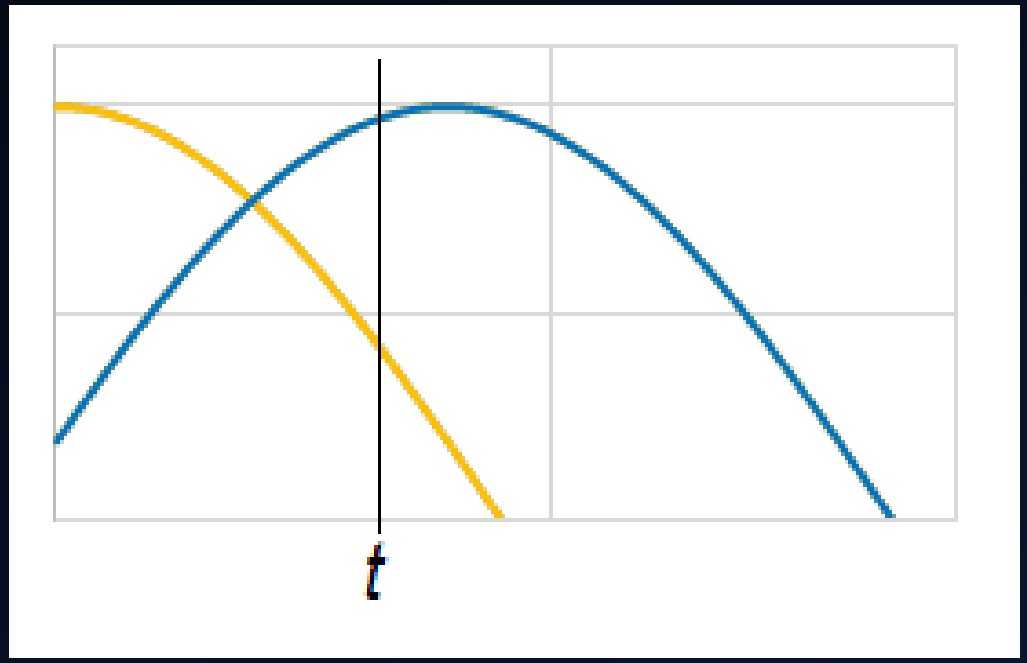
- Custom built system to find core loss from phase angle.
- MCLT takes advantage of the fact that there are only so many different cores a manufacturer will need to test.
- We can set up the conditions for each different core very precisely (namely turns, wire gauge and jig layout.) Then just repeat the same set up from then on.
- To approach ideal test conditions the set up corrects for winding resistance and propagation delays.

Magnetics core loss tester (MCLT)

- Custom-built system.
- The measurement relies on a good impedance match, using a capacitive tuning bank.
- Cores vary in inductance, so each core is automatically tuned.
- Sample set wound and tested for each production batch.

Phase accuracy means timing accuracy

- Accurate power factor measurement in such a system ultimately comes down to accurate timing of signals. MCLT is designed for minimized variability due to timing offsets.
- Due to high phase angles with powder cores, satisfactory repeatability is in the range of 5-15%.
- MCLT achieves excellent repeatability – 5%.
- 1 nanosecond shift can be the difference between in-spec and out-of-spec.
- Changing leads could easily change timing by 10s of nanoseconds.



FAQ #2

Q: Why only sine wave, why not square or triangle?

A: Repeatability is paramount. Sine is most straightforward to implement and easiest to notice if it is wrong.

Also, core loss is not like copper loss. Sine drive is the worst case, not the best case. And the differences are not on the scale of watt loss variability generally.

Also, sine has continuity with our own process control history. It is the best way to be apples-to-apples with competitor or customer comparisons.

FAQ #3

Q: What if I need to know core loss with my particular wave form and duty cycle?

A: That is knowable information. MCLT, like most other systems, can apply an arbitrary wave form. Not unusual to do in characterization testing.

But in production testing, it is a question of cost and benefit. Much more expensive to do a non-standard test in the factory. In reality, the products will be the same whether controlled by a custom test or a by a standard test that has been correlated to the custom test.

FAQ #4

Q: Where is the resistivity information?

A: We have tried to measure it, and the conclusion is that in powder cores it varies A LOT. We certainly do not control resistivity. Nor is resistivity directly controlled in ferrites or laminated alloys.

FAQ #5

Q: How can we demonstrate accuracy?

A: What is the ultimate referee? There really is not one because repeatability is so tough. Industry round robin testing over the years suggests 10-20% correlation from one lab to the next is about the best that can be expected.

That is for ferrites. Powder cores are tougher still.

From a core manufacturer's perspective, maximizing repeatability is the priority.

Thank you for your interest

BY: FRANK OBERLITNER, VP OF TECHNOLOGY, MAGNETICS
EMAIL: FOBERLITNER@SPANG.COM
PHONE: 412-963-5517
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