Overview of core loss prediction (and measurement techniques) **for non-sinusoidal waveforms**

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Outline

- Need for loss models for non-sinusoidal waveforms beyond the Steinmetz equation (SE).
- Models: MSE, GSE, NSE, EGSE, iGSE, i^2GSE, WCSE, CWH and FHM (and in the addendum: the DNSE)
- How can they be used?
- Where to go from here?

References are listed on the last slide

Existing models: Physically motivated

- Classical eddy current loss, P_{cl}

  Small part of loss in ferrites.

- Detailed hysteresis models (e.g., Preisach, Jiles-Atherton).
  - Standard methods are only static; do not predict important frequency/rate dependence
    $P = P_h + P_{cl} + P_{exc}$ ("excess loss").
  - Addition of linear dynamics doesn't capture nonlinearity in excess loss.

- Models based on eddy loss induced by domain wall motion:
  - $P_{exc} \propto (Bf)^{\gamma}$; $\gamma = 1.5$ or 2
  - Does not match empirical data ***for ferrites***
    ($\alpha \neq \beta$ in Steinmetz equation).

20^{th} C model for core loss

- Steinmetz equation (SE):

$$P = kf^{\alpha}\hat{B}^{\beta}$$

  - Sinusoidal only (but most power electronics waveforms are not sinusoidal!)
  - Loss is a nonlinear phenomenon: Fourier series does not apply.
  - Other notes:
    - One set of parameters only works for a limited frequency range.
    - Ignores the important effect of dc bias.
- Physically-based models: Not available for ferrites.
  - Possible recent exception: (Van den Bossche, Valchev, and Van de Sype, 2006)

The first SE variation:
Modified Steinmetz Equation (MSE)

(Albach ,Durbau and Brockmeyer, 1996;
Reinert, Brockmeyer, and De Doncker, 1999).

- Modifies Steinmetz equation based on physical motivation that domain wall motion loss depends on *dB/dt.*
- Calculates an equivalent frequency from a weighted average of *dB/dt:*

$$f_{eq} = \frac{2}{\Delta B^2 \pi^2} \int_0^T \left(\frac{dB}{dt}\right)^2 dt$$

- Use equivalent frequency and repetition rate f_r in Steinmetz Equation:

$$P = k f_{eq}^{\alpha-1} \hat{B}^{\beta} f_r$$

- Limitation: arbitrary assumption about type of averaging for equivalent frequency limits accuracy.

Next: Generalized Steinmetz Equation (GSE) (Li, Abdallah, and Sullivan, 2001)

- Failed attempt—useful to see why.
- Hypothesis: p(t) = fcn(B(t), dB/dt) (instantaneous power loss depends only on instantaneous B, dB/dt)
- Combining the instantaneous dissipation hypothesis with the Steinmetz equation yields:

$$P(t) = k_1 \left|\frac{dB}{dt}\right|^a |B(t)|^b$$

- Tests show that it is not accurate—sometimes worse than MSE.

MSE
1996, 1999

GSE
2001

Lesson from GSE failure

- Losses depend on whole cycle, not just B(t), dB/dt.
- Our path forward: Try another hypothesis.
  - GSE was $\overline{P(t)} = \overline{k_i B(t)^x \left|\frac{dB}{dt}\right|^y}$
  - Improved GSE (iGSE) hypothesis:

$$\overline{P(t)} = k_i (\Delta B)^w \overline{\left|\frac{dB}{dt}\right|^z}$$

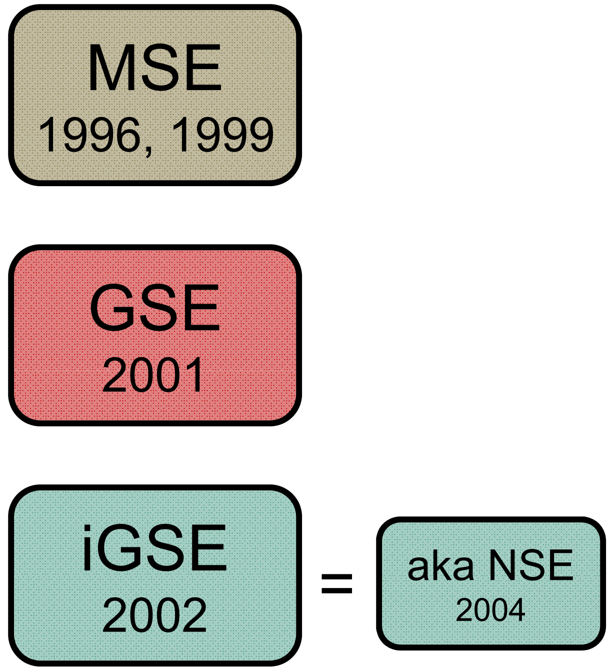
iGSE (improved Generalized SE)

(Venkatachalam, C. R. Sullivan, T. Abdallah, H. Tacca, 2002)

- Based on $\overline{P(t)} = k_i (\Delta B)^w \overline{\left|\frac{dB}{dt}\right|^z}$, plus compatibility with Steinmetz equation for sine waves.

- Result: $\overline{P(t)} = k_i (\Delta B)^{\beta - \alpha} \overline{\left|\frac{dB}{dt}\right|^\alpha}$

- Two years later, independently discovered and named the Natural Steinmetz Extension (NSE) by Van den Bossche, Valchev and Georgiev, 2004


MSE
1996, 1999
GSE
2001
iGSE
2002
=
aka NSE
2004

iGSE: formulas to use.

(Venkatachalam, C. R. Sullivan, T. Abdallah, H. Tacca, 2002)

- General expression: $\overline{P(t)} = k_i (\Delta B)^{\beta-\alpha} \overline{\left|\frac{dB}{dt}\right|^{\alpha}}$
- Can obtain all parameters from sinusoidal data (i.e., from SE parameters)

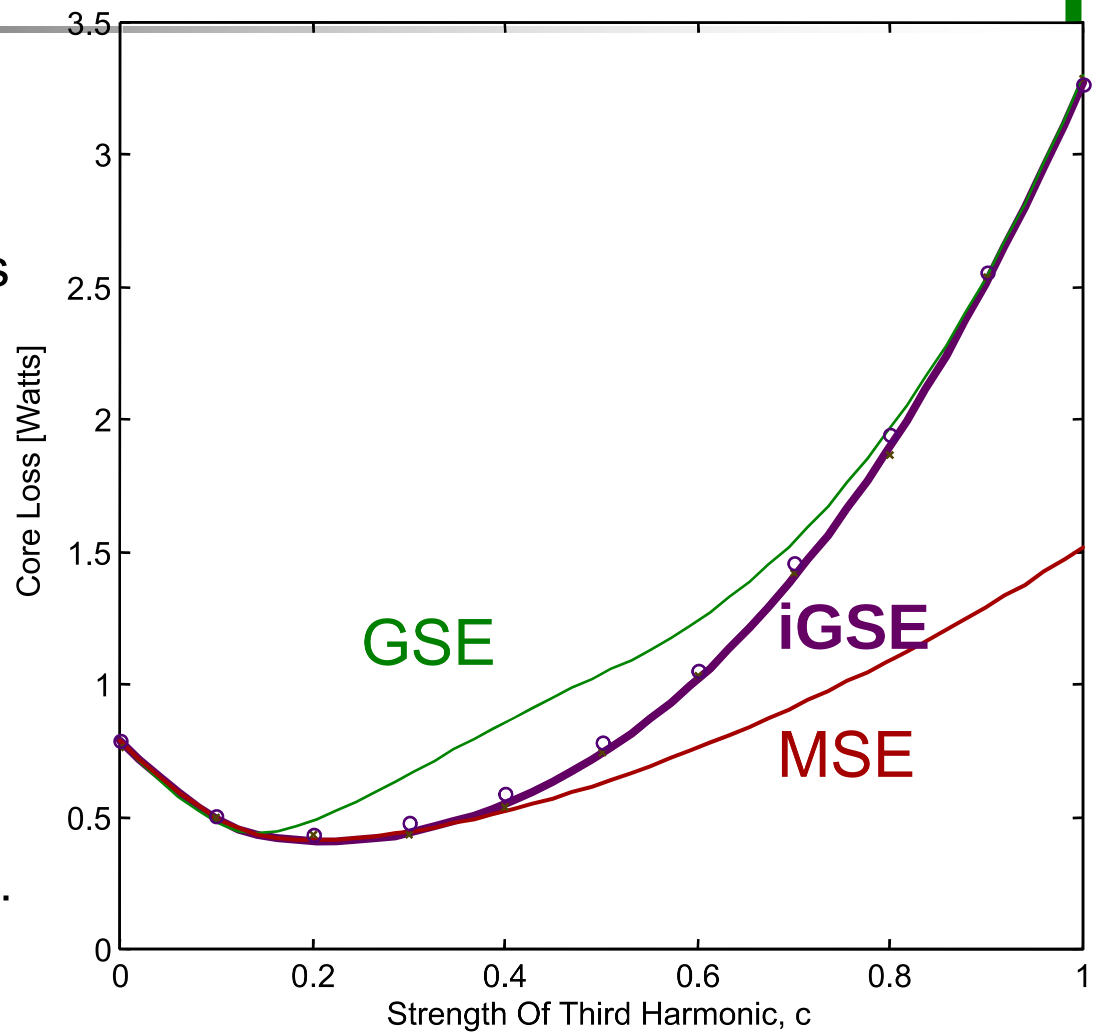
$$k_i = \frac{k f^{\alpha} \left(\frac{1}{2}\right)^{\beta}}{(\Delta B)^{-\alpha} \overline{|\omega \cos(\omega t)|^{\alpha}}} \qquad k_i \cong \frac{k}{2^{\beta+1}\pi^{\alpha-1}\left(0.2761 + \frac{1.7061}{\alpha+1.354}\right)}$$

- Simple formula for piecewise-linear waveforms:

$$\overline{P_v} = \frac{k_i (\Delta B)^{\beta-\alpha}}{T} \sum_m \left|\frac{B_{m+1}-B_m}{t_{m+1}-t_m}\right|^{\alpha} (t_{m+1}-t_m)$$

Performance of iGSE

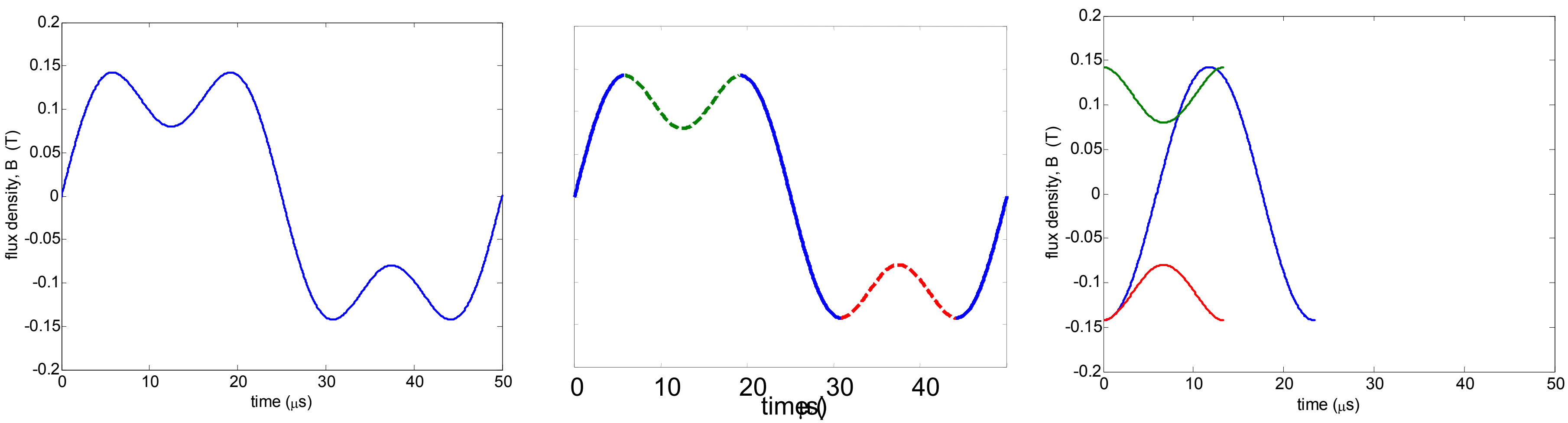
- Matched measurements much better than either previous method.
- Subsequent comparisons have consistently shown that it outperforms alternatives.
- Main limitations:
  - What if fundamental and harmonics are in different frequency ranges where Steinmetz parameters are different?
  - DC bias not accounted for.
  - Relaxation effects
  - For more on these, see (J. Muhlethaler, J. Biela, J.W. Kolar, A. Ecklebe, 2012a, 2012b)



$$B(t) = A[(1-c)\sin\omega t + c\sin(3\omega t + \phi)]$$

Minor loops

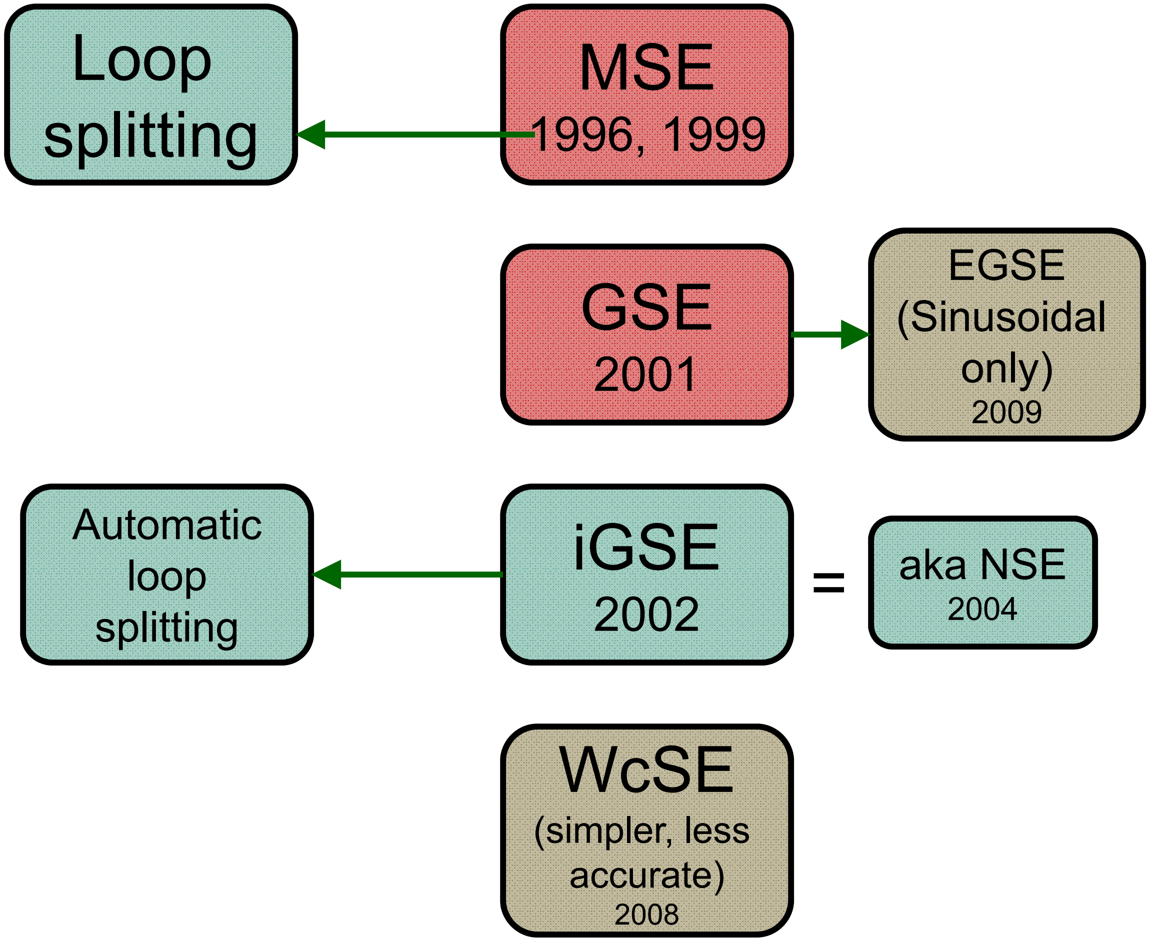
- Not present in simple waveforms.
- Addressed in 1st MSE paper (Albach, Durbau & Brockmeyer, 1996) and in iGSE paper (2002):
  - Algorithm for automatic separation of nested loops in iGSE paper (2002).



Other SE methods

- WcSE: Waveform coefficient SE
  (Shen, Wang, Boroyevich, Tipton, 2008)
  - Multiply SE result by a factor: $$\frac{\int_0^{T/2} |B(t)|\,dt}{\int_0^{T/2} \hat{B}\sin(\omega t)\,dt}$$
  - Intended to be easier than iGSE; authors' results show similar accuracy to iGSE.
  - Others' results show it's significantly less accurate for some situations (Villar, Viscarret, Etxeberria-Otadui and Rufer, 2009)
- EGSE: Expanded GSE (Chen, 2009)
  - For LF sine waves in steel; captures frequency dependence better.

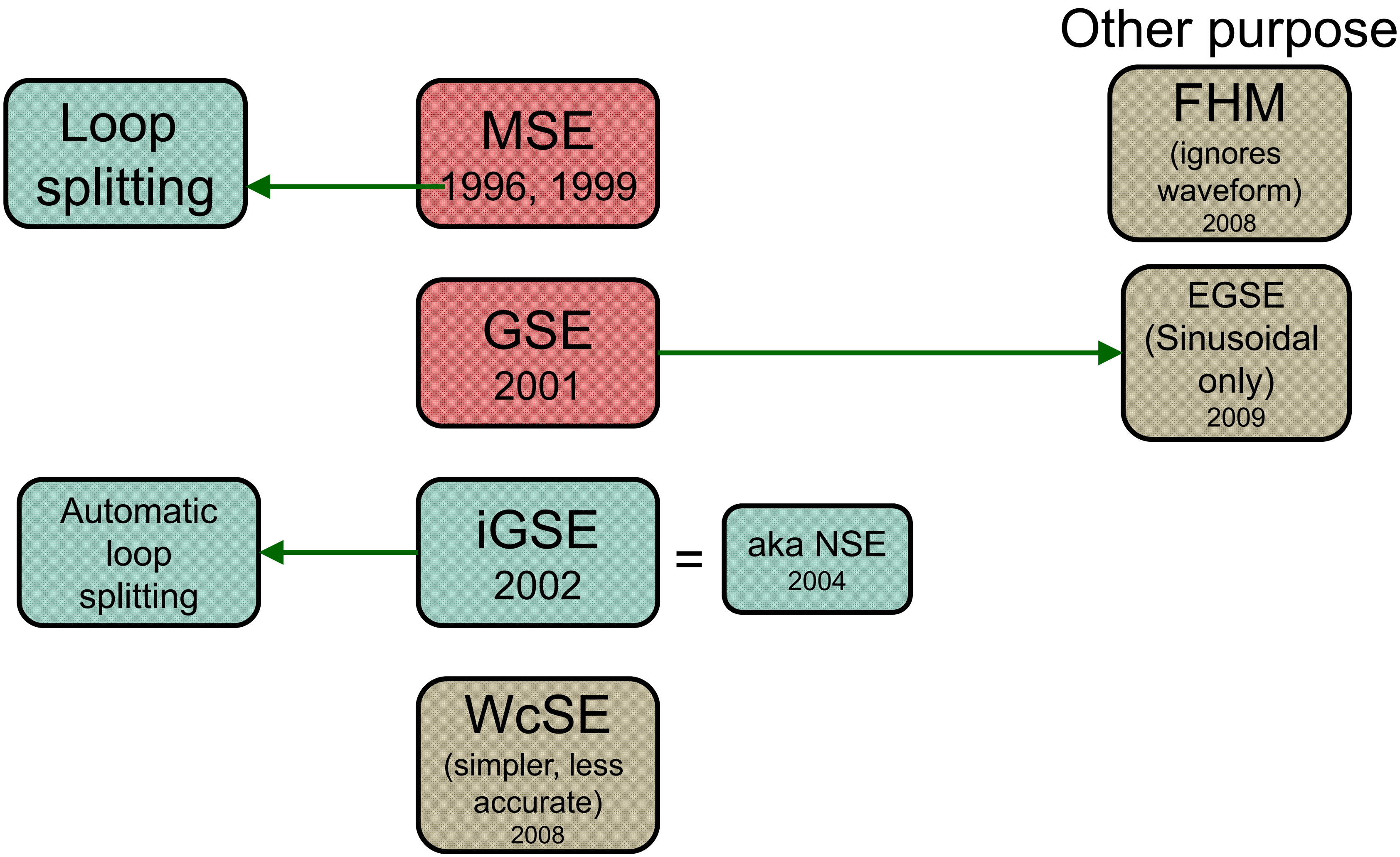
$$P(t) = k_2 \left|\frac{dB}{dt}\right|^{m \left|\frac{dB}{dt}\right|^{e}} |B(t)|^{n}$$


Loop splitting
MSE
1996, 1999
GSE
2001
EGSE (Sinusoidal only)
2009
Automatic loop splitting
iGSE
2002
=
aka NSE
2004
WcSE
(simpler, less accurate)
2008

FHM (Field-extrema Hysteresis Model)

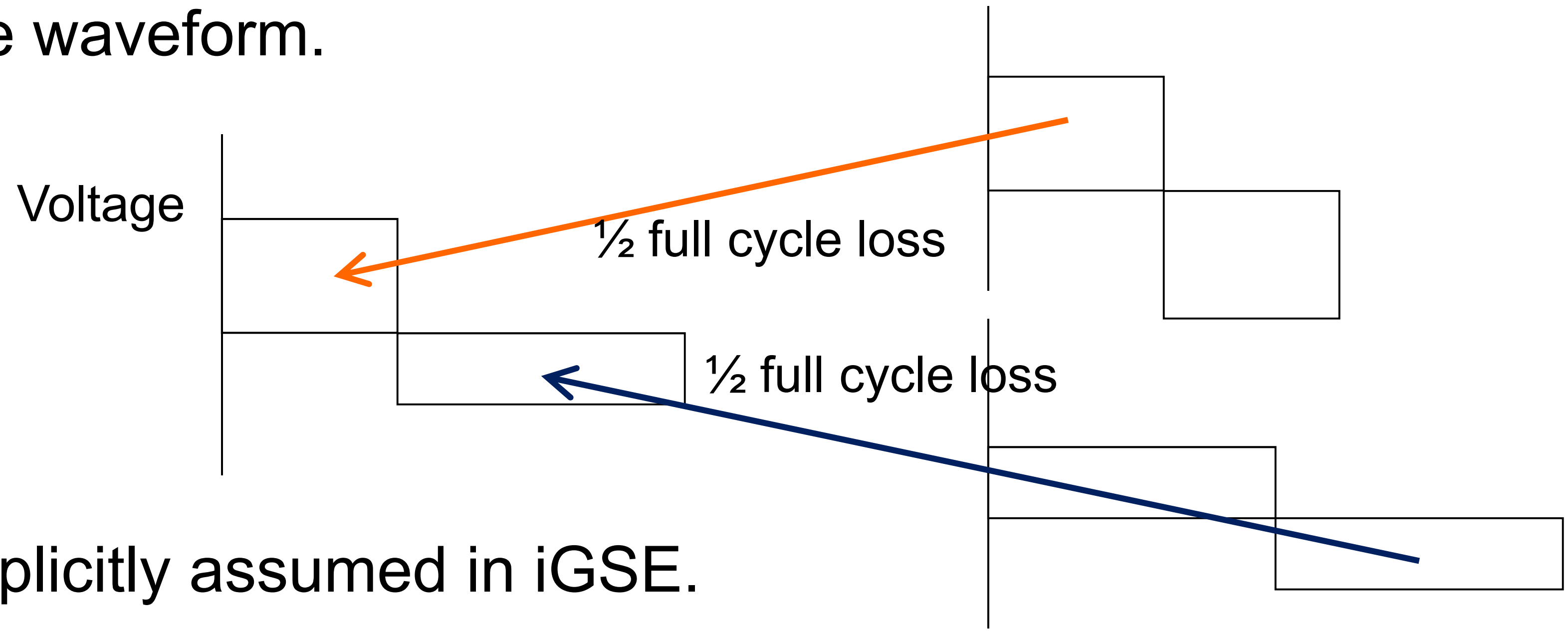
(Cale, Sudhoff, and Chan, 2008)

- By definition, this assumes that the shape of the waveform doesn’t matter and only looks at peaks.
  - Does not capture effect of waveform.
- Starts by assuming that a frequency-dependent Jiles-Atherton model is correct—aims to duplicate its behavior.
  - Does capture DC bias effect as in JA model.


Other purpose
Loop splitting
MSE 1996, 1999
FHM (ignores waveform) 2008
GSE 2001
EGSE (Sinusoidal only) 2009
Automatic loop splitting
iGSE 2002
=
aka NSE 2004
WcSE (simpler, less accurate) 2008

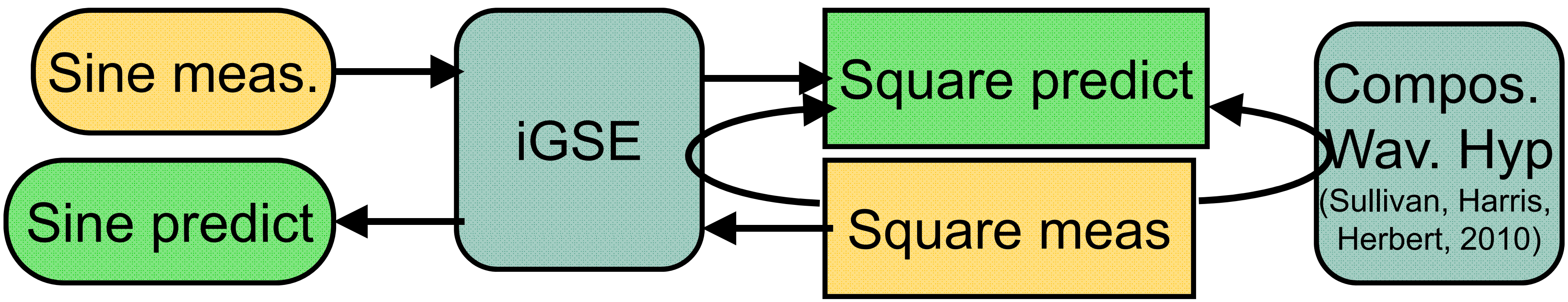
Composite Waveform Hypothesis

- Idea that total energy lost in a cycle can be calculated by summing the loss that occurs during each segment of the waveform.



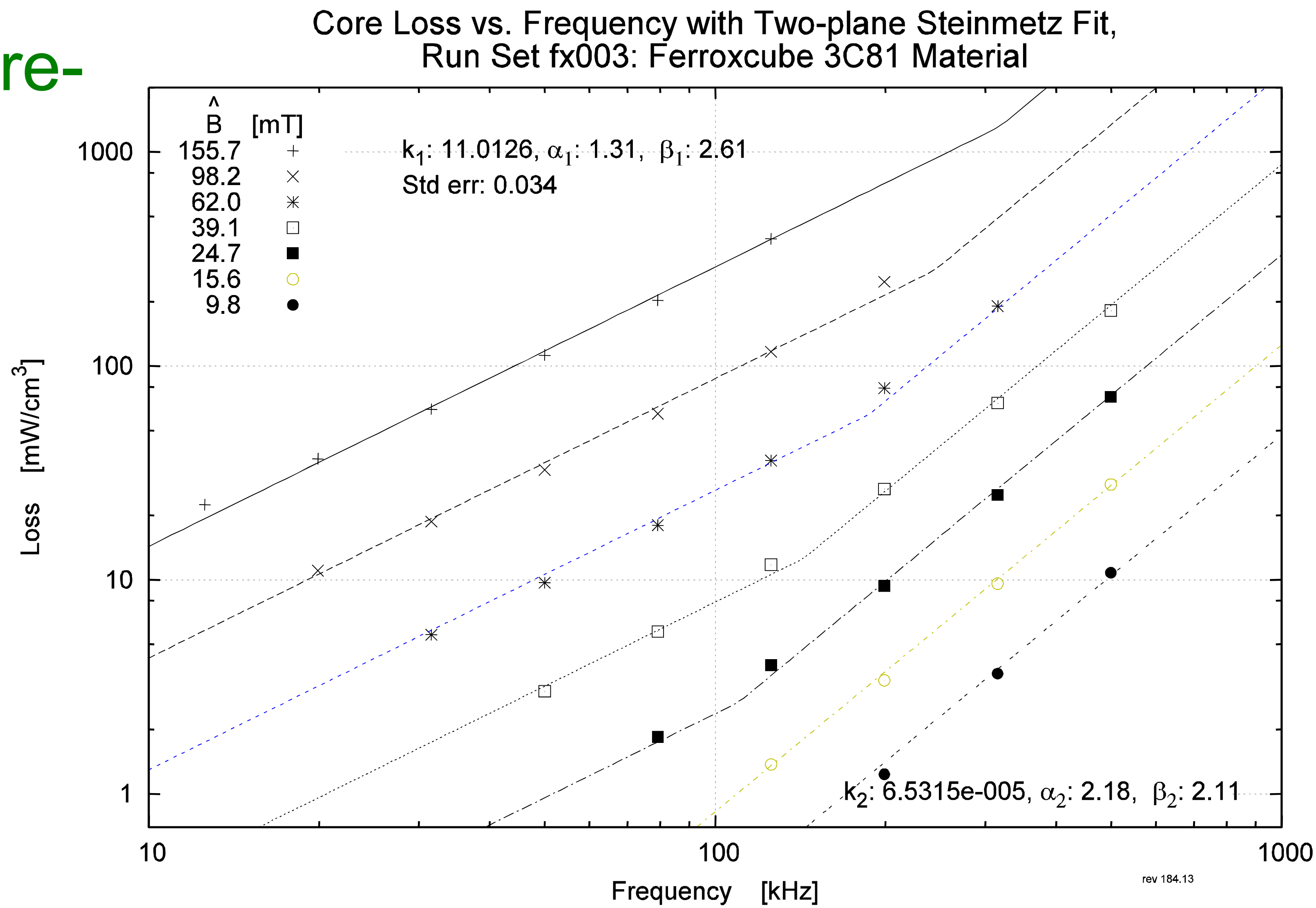
- Implicitly assumed in iGSE.
- Explicitly stated and tested in (Sullivan, Harris and Herbert, 2010)
  - Results mixed—see next talk.

Measuring with sine waves vs. measuring square-wave voltage?



- Predicting square with square data: Comp. Wav. Hyp. and iGSE give exactly the same results.
- Making predictions with the same class of waveforms is more accurate. Because:
  - Steinmetz parameters are different for different frequencies.
  - Square wave includes harmonics—can span two ranges.

Square-wave data



- Can fit with “two-plane Steinmetz” equation (Sullivan & Harris, 2011)

$$P_v = \max\left(K_1 f^{\alpha_1} \hat{B}^{\beta_1}, K_2 f^{\alpha_2} \hat{B}^{\beta_2}\right)$$

Conclusions

- iGSE:
  - Works surprisingly well; better than most alternatives.
  - Allows the use of square or sine data for square or sign predictions.
  - Is equivalent to the composite waveform hypothesis for square predictions with square waveforms.
  - Is simple to use for PWL waveforms without minor loops, and minor loop separation can be used for waveforms with minor loops.

  But

  - Does not account for dc bias effect or "relaxation effects."
- Square-wave data is a better basis for predicting loss with square voltage applications.
  - Can fit with two-plane Steinmetz equation.

Moving forward

- Square-wave data from manufacturers.
  - Including dc and temperature effects
    - Automated data collection!
    - Standardized database format.
- Research topics:
  - Reduce data collection needed for dc, temperature, and relaxation effects based on underlying mechanisms.
  - Nonlinear dynamic model that matches behavior and captures loss accurately.
    - Constrain model development to match known loss behavior, as in development of iGSE.

Addendum

- One more method omitted from the original presentation: the DNSE. (A.P. Van den Bossche, D.M. Van de Sype, V.C. Valchev, 2005)
- Uses iGSE (aka NSE) with the sum of two Steinmetz equations, one for pure hysteresis and one for anomalous losses.
- This is one solution to the problem of needing different frequency ranges in a Steinmetz fit.

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