Overview of Core Loss Calculation Techniques

ECE 6930

Core Loss in Magnetics

- Two common methods for calculating core loss:
    1. Hysteresis models, often introducing an intermediate step of calculating B-H loop
    2. Empirical equations, often of the form of the Steinmetz equation [1]:

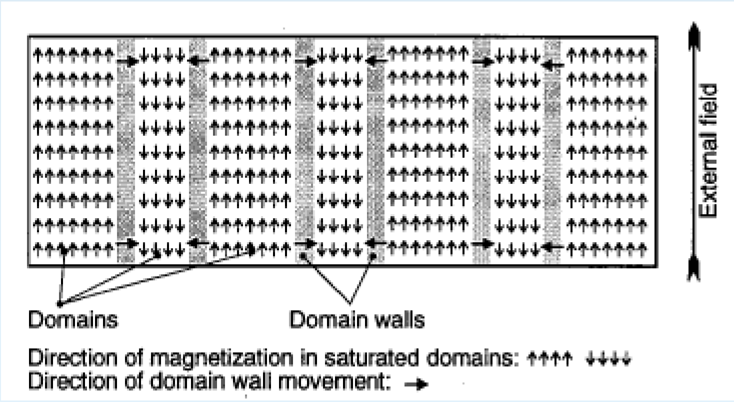
$$P_v = C_m f^{\alpha} B^{\beta}$$

- Steinmetz parameters given in most datasheets for sinusoidal excitation, so we would like to have a Loss calculation methods that takes advantage of this – not requiring additional experimentation so calculations can be iterated over many core materials.

[1] Ch. P. Steinmetz, "On the law of hysteresis", reprint, Proc IEEE, ***72(2), pp. 196-221,2 1984.***

Physical Origin of Core Loss

- Both Hysteresis and Eddy Current losses occur from domain wall shifting, that is, "the damping of domain wall movement by eddy currents and spin-relaxation". [2]



- Therefore, core loss should be directly related to the remagnetization velocity, *dM/dt*, rather than the excitation frequency, *f*.

[2] Reinert, J.; Brockmeyer, A.; De Doncker, R.W.; , "Calculation of losses in ferro- and ferrimagnetic materials based on the modified Steinmetz equation," Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. Conference Record of the 1999 IEEE , vol.3, no., pp.2087-2092 vol.3, 1999

Steinmetz for Non-Sinusoidal Magnetization

- Typically, $1<\alpha<3$ and $2<\beta<3$, indicating the possibility of nonlinearity between losses and flux density, frequency.
  - Therefore, a Taylor series expansion will not provide correct results.
- Rather, we need to find a way of incorporating *dM/dt*, or its proportional equivalent *dB/dt*, into the Steinmetz equation parameters

Modified Steinmetz Equation

- Extends the Steinmetz equation parameters by equating the weighted time derivative of *B* for arbitrary magnetizing currents with those of a sine-wave

$$\left\langle \frac{dB_w}{dt} \right\rangle = \int_0^T \frac{\frac{dB}{dt}^2}{B_{\max} - B_{\min}} dt$$

- Next, a sine-wave of frequency $f_{sin,eq}$ is found such that

$$\left\langle \frac{dB_w}{dt} \right\rangle = \left\langle \frac{dB_{w,\sin}}{dt} \right\rangle$$

- Then, the Steinmetz equation can be used with parameters selected according to $f_{sin,eq}$

[3] Albach, M.; Durbaum, T.; Brockmeyer, A.; , "Calculating core losses in transformers for arbitrary magnetizing currents a comparison of different approaches," Power Electronics Specialists Conference, 1996. PESC '96 Record., 27th Annual IEEE , vol.2, no., pp.1463-1468 vol.2, 23-27 Jun 1996

Modified Steinmetz Equation Results

- Table given for square wave voltage excitation / triangle wave magnetizing current.
- Results show that power loss is slightly less for near 50% triangle wave magnetization than for sine wave magnetization.

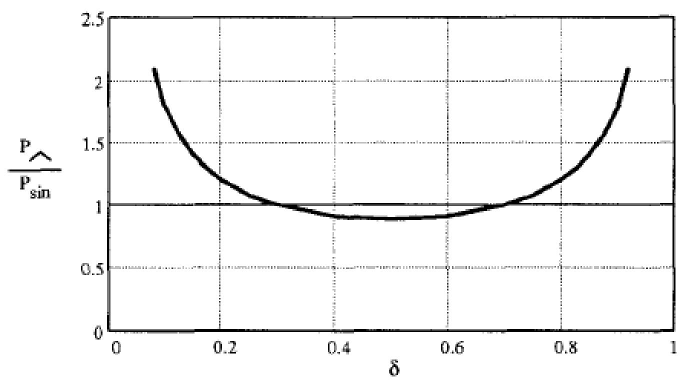


Figure 5: Specific core losses of the current shown in Fig. 4 with a sinewave current as reference

- [3] claims results experimentally confirmed in [4]

[3] Albach, M.; Durbaum, T.; Brockmeyer, A.; , "Calculating core losses in transformers for arbitrary magnetizing currents a comparison of different approaches," Power Electronics Specialists Conference, 1996. PESC '96 Record., 27th Annual IEEE , vol.2, no., pp.1463-1468 vol.2, 23-27 Jun 1996

[4] Chen, D. Y., "Comparison of the High Frequency Magnetic Core Losses under two different Driving Conditions: A Sinusoid Voltage and a Squarewave Voltage", 1978, PESC'78, 237-241

Modified Steinmetz Equation Issues

- Primary issue is the implicit assumption of losses proportional to f^2 while still assuming losses proportional to f^{α}. Thus, losses are only accurate for $\alpha \approx 2$ (Demonstrated in [5])
- Subloops must be extracted and treated individually to maintain validity

[5] Jieli Li; Abdallah, T.; Sullivan, C.R.; , "Improved calculation of core loss with nonsinusoidal waveforms," Industry Applications Conference, 2001. Thirty-Sixth IAS Annual Meeting. Conference Record of the 2001 IEEE , vol.4, no., pp.2203-2210 vol.4, 30 Sep-4 Oct 2001

Generalized Steinmetz Equation

- Hypothesizes that instantaneous power loss can be given by the "physically plausible" equation:

$$P_v(t) = k_1 \left|\frac{dB}{dt}\right|^{\alpha} \left|B(t)\right|^{\beta-\alpha}$$

- Thus, the per volume power loss can be given by:

$$\left\langle P_v(t) \right\rangle = \frac{1}{T}\int_0^T k_1 \left|\frac{dB}{dt}\right|^{\alpha} \left|B(t)\right|^{\beta-\alpha} dt$$

- Where, by comparison to the result for sine waves,

$$k_1 = \frac{k}{(2\pi)^{\alpha-1}\int_0^{2\pi} \left|\cos\theta\right|^{\alpha} \left|\sin\theta\right|^{\beta-\alpha} d\theta}$$

[5] Jieli Li; Abdallah, T.; Sullivan, C.R.; , "Improved calculation of core loss with nonsinusoidal waveforms," Industry Applications Conference, 2001. Thirty-Sixth IAS Annual Meeting. Conference Record of the 2001 IEEE , vol.4, no., pp.2203-2210 vol.4, 30 Sep-4 Oct 2001

Generalized Steinmetz Equation Issues

- Not, in fact, always a better prediction than MSE.
- Because Steinmetz equation parameters vary with frequency, parameters may need to be selected differently, or results may be inaccurate for waveforms with high harmonic content
- Subloops still need to be treated seperately

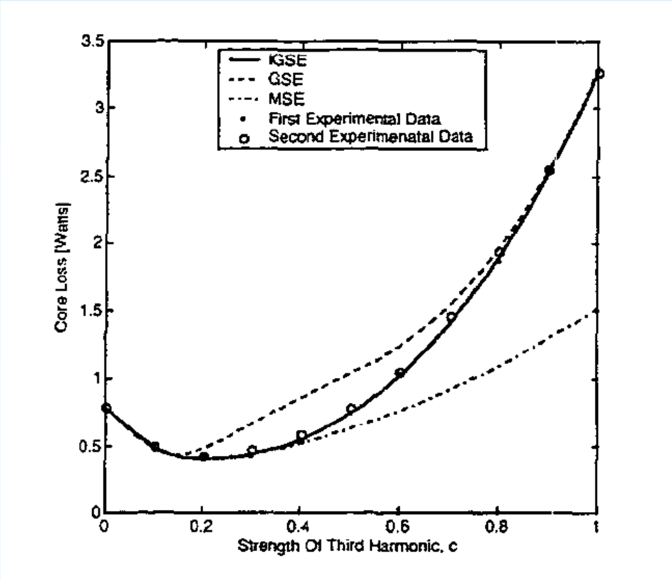
[5] Jieli Li; Abdallah, T.; Sullivan, C.R.; , "Improved calculation of core loss with nonsinusoidal waveforms," Industry Applications Conference, 2001. Thirty-Sixth IAS Annual Meeting. Conference Record of the 2001 IEEE , vol.4, no., pp.2203-2210 vol.4, 30 Sep-4 Oct 2001

Improved General Steinmetz Equation

- States that core loss depends not only on *B* and *dB/dt*, but also on the time-history of the flux waveform
- Incorporates ΔB as in MSE to account for local max and min, as well as take into account local subloops

$$\langle P_v(t) \rangle = \frac{1}{T}\int_0^T k_1 \left|\frac{dB}{dt}\right|^{\alpha} (\Delta B)^{\beta-\alpha} dt$$

- Results show good matching to experimental data, including advantages of both MSE and GSE



[6] Venkatachalam, K.; Sullivan, C.R.; Abdallah, T.; Tacca, H.; , "Accurate prediction of ferrite core loss with nonsinusoidal waveforms using only Steinmetz parameters," Computers in Power Electronics, 2002. Proceedings. 2002 IEEE Workshop on , vol., no., pp. 36-41, 3-4 June 2002

Improved General Steinmetz Equation Issues

- Maintains issues with selection of appropriate parameters for Steinmetz equations; may be inaccurate for waveforms with high harmonic content
- The effects of DC magnetization are not taken into account

[6] Venkatachalam, K.; Sullivan, C.R.; Abdallah, T.; Tacca, H.; , "Accurate prediction of ferrite core loss with nonsinusoidal waveforms using only Steinmetz parameters," Computers in Power Electronics, 2002. Proceedings. 2002 IEEE Workshop on , vol., no., pp. 36-41, 3-4 June 2002

Natural Steinmetz Equation

- Independently developed equation matching exactly iGSE

$$P_{NSE} = \left(\frac{\Delta B}{2} \right)^{\beta - \alpha} \frac{k_N}{T} \int_0^T \left| \frac{dB}{dt} \right|^{\alpha} dt$$

$$k_N = \frac{k}{(2\pi)^{\alpha - 1} \int_0^{2\pi} \left| \cos\theta \right|^{\alpha} d\theta}$$

- Note that, for α=1 or α=2, or D≈.5, the NSE does not differ significantly from the MSE.

[7] Van den Bossche, A.; Valchev, V.C.; Georgiev, G.B.; , "Measurement and loss model of ferrites with non-sinusoidal waveforms," Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual , vol.6, no., pp. 4814- 4818 Vol.6, 20-25 June 2004