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.

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, $f$. 
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

$$\left\langle \frac{dB_w}{dt} \right\rangle = \frac{1}{T} \int_{0}^{T} \frac{dB^2}{dt} \frac{dB}{B_{\text{max}} - B_{\text{min}}} dt$$

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

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

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

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.


Modified Steinmetz Equation Issues

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

Generalized Steinmetz Equation

• Hypothesizes that instantaneous power loss can be given by the “physically plausible” equation:

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

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

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

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

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

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 separately

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 $\Delta B$ 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

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

Natural Steinmetz Equation

- Independently developed equation matching exactly iGSE

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

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

- Note that, for \(\alpha = 1\) or \(\alpha = 2\), or \(D \approx 0.5\), the NSE does not differ significantly from the MSE.