Transformer Example
B-H Curve: Filter Inductor

B-H Curve: Transformer
13.3 Magnetics Losses

- **Copper Loss**
  - DC Copper Loss
  - AC Copper Loss
- **Core Loss**
  - Eddy Current
  - Residual
- **Residual**
  - Hysteresis
- **Skin Effect**
  - Proximity Effect
  - Fringing Flux
- **High Frequency Losses**
- **Magnetic Device Losses**

**Core Loss**

- Physical origin due to magnetic domains
- Modeling Approaches
  - Empirical (curve fit) models of materials
  - Direct measurement-based models
  - Physics-based models
Hysteresis Loss

Eddy Currents in Magnetic Materials

Magnetic core materials are reasonably good conductors of electric current. Hence, according to Lenz’s law, magnetic fields within the core induce currents (“eddy currents”) to flow within the core. The eddy currents flow such that they tend to generate a flux which opposes changes in the core flux $\Phi(t)$. The eddy currents tend to prevent flux from penetrating the core.

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Eddy Current Losses

- Ac flux $\Phi(t)$ induces voltage $v(t)$ in core, according to Faraday’s law. Induced voltage is proportional to derivative of $\Phi(t)$. In consequence, magnitude of induced voltage is directly proportional to excitation frequency $f$.

- If core material impedance $Z$ is purely resistive and independent of frequency, $Z = R$, then eddy current magnitude is proportional to voltage: $i(t) = v(t)/R$. Hence magnitude of $i(t)$ is directly proportional to excitation frequency $f$.

- Eddy current power loss $P(t)R$ then varies with square of excitation frequency $f$.

- Ferrite core material impedance is capacitive. This causes eddy current power loss to increase as $f^2$.

The Steinmetz Equation

Empirical equation, at a fixed frequency:

$$P_w = K_R (\Delta B)^{\alpha} A_m f_m$$

Alternatively:

$$P_w = K_m f^{\alpha} (\Delta B)^{\beta}$$
Steinmetz Equation: Notes

- Purely empirical; not physics-based
- Parameters $\alpha$, $\beta$, $K$ vary with frequency
- Correct only for sinusoidal excitation
  - Nonlinear; Fourier expansion of waveforms cannot be used
- Modified empirical equations perform better with nonsinusoidal waveforms
  - MSE
  - GSE
  - $iGSE$
  - $i^2GSE$

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Some Example Core Materials

<table>
<thead>
<tr>
<th>Core type</th>
<th>$B_{sat}$</th>
<th>Relative core loss</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminations iron, silicon steel</td>
<td>1.5 - 2.0 T</td>
<td>high</td>
<td>50-60 Hz transformers, inductors</td>
</tr>
<tr>
<td>Powdered cores, powdered iron, molybdenum</td>
<td>0.6 - 0.8 T</td>
<td>medium</td>
<td>1 kHz transformers, 100 kHz filter inductors</td>
</tr>
<tr>
<td>Ferrite Manganese-zinc, Nickel-zinc</td>
<td>0.25 - 0.5 T</td>
<td>low</td>
<td>20 kHz - 1 MHz transformers, ac inductors</td>
</tr>
</tbody>
</table>

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DC Copper Loss

DC resistance of wire

\[ R = \rho \frac{L_w}{A_w} \]

where \( A_w \) is the wire bare cross-sectional area, and \( L_w \) is the length of the wire. The resistivity \( \rho \) is equal to \( 1.724 \times 10^{-6} \, \Omega \text{ cm} \) for soft-annealed copper at room temperature. This resistivity increases to \( 2.3 \times 10^{-6} \, \Omega \text{ cm} \) at 100°C.

The wire resistance leads to a power loss of

\[ P_{\text{loss}} = I_{\text{rms}}^2 R \]