6.622 Power Electronics *Prof. David Perreault*

Lecture 12 - Magnetics 4

1 Loss mechanisms in magnetics:

We care about loss in magnetics both for converter efficiency and because the loss often sets the required size of a magnetic component.

Generally, we care about two components of loss:

1. Winding loss ("copper" loss)
2. Core loss

2 Winding loss

@ low frequencies (e.g. dc) the loss in the conductor is just due to the dc resistance of the wire

$$R_{wire} = \frac{\rho_{cu} l_{wire}}{A_{wire}}, P_{diss,wire} = i_{RMS}^2 R_{wire} = I_{dc}^2 R_{wire}$$

For DC.

How much current can a wire carry before dissipation is a problem?

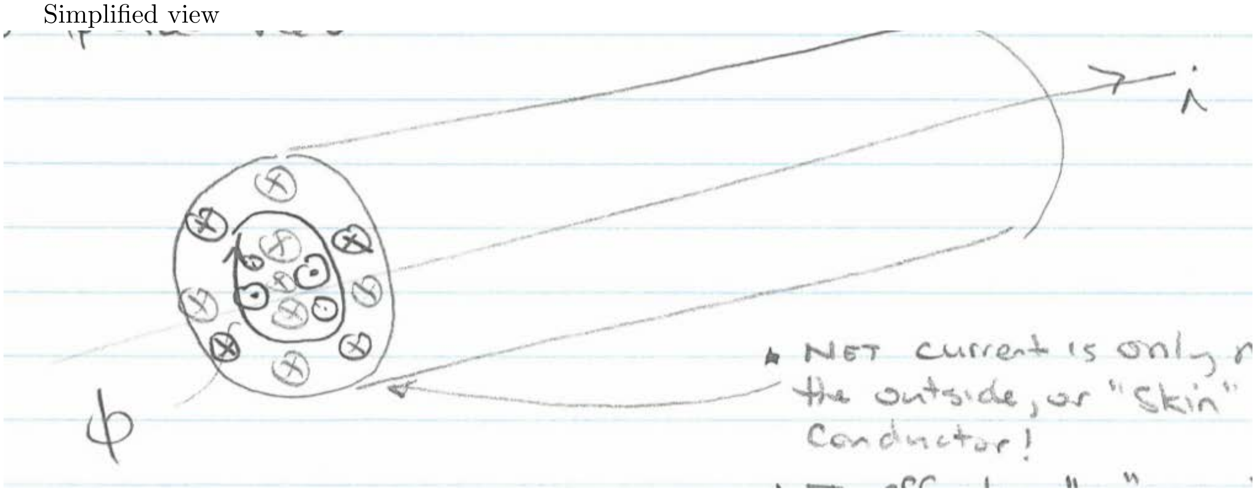
⇒ In general, this depends on heat transfer

∗ ⇒ For many situations (and typical wire sizes) we impose a current density limit in the wire as a rule of thumb to prevent overheating. Typical limit $\sim 500 \frac{A}{cm^2}$

@ higher frequencies, two effects become very important in determining winding resistance and loss: skin effect and proximity effect

Skin effect is the "self shielding" effect of conductors due to the eddy currents driven by the changing magnetic field of an ac current. The total fields and current may not penetrate inside a conductor at high frequency. (Can solve as a "magnetic diffusion" problem.)

Simplified view



- net current is only near the outside, or "skin" of the conductor!
- The effective "ac" resistance is higher than that at dc.

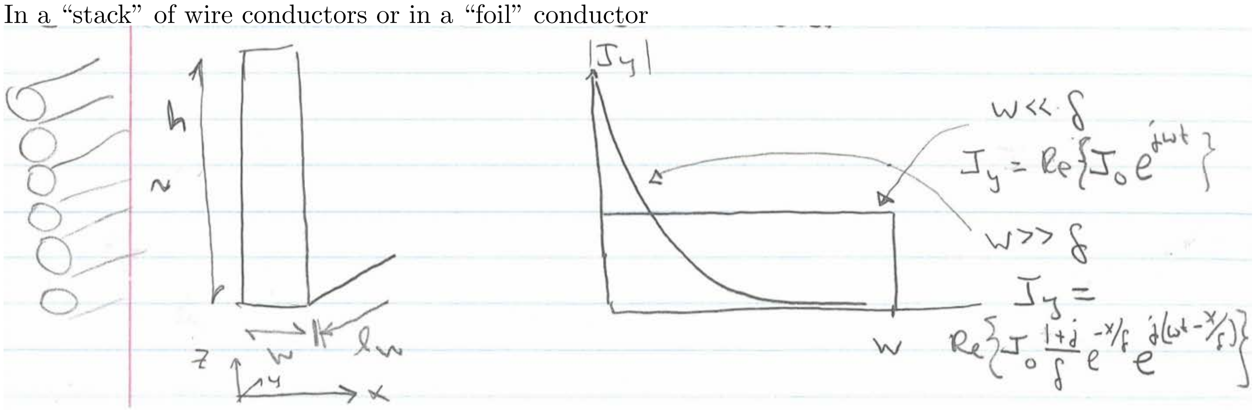
The frequency at which the self shielding becomes important depends on the dimensions of the conductor relative to the "skin depth" (a length constant arising from the solution to the magnetic diffusion problem)

$$\delta \triangleq \sqrt{\frac{\rho_{cu}}{\pi \mu_{cu} f}} = \frac{k}{\sqrt{f}}$$

@100degC in copper, K $\sim$ 7.5 cm

@60Hz $\delta \sim 0.97cm$

In a "stack" of wire conductors or in a "foil" conductor



Very roughly then we can find the "effective" ac resistance by finding the total loss ($P = I_{rms}^2 R_{eff}$)

Solving this, one gets $R_{cc} \approx R_{oc}\frac{w}{\delta}w >> \delta$

As a crude approximation in a round-wire winding, we can get a detailed solutions (where $\Delta \triangleq \frac{w}{\delta}$)

$$R_{AC} = R_{OC}\Delta[\frac{sinh(2\Delta) + sin(2\Delta)}{cosh(2\Delta) - cos(2\Delta)}]$$

So for large, high-frequency currents, we may want to use Litz wire

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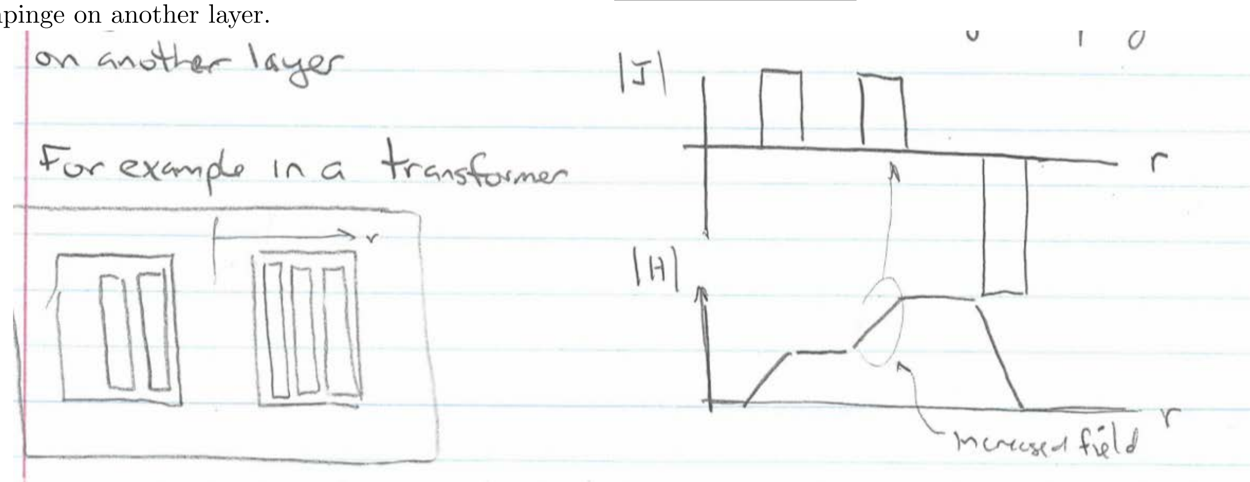
Skin effect is due to the eddy currents generated by a wires own current.

*proximity effect is a loss effect due to eddy currents generated by fields from currents in other nearby conductors.

Proximity effect becomes important when one has "layers" of windings where the fields from one layer impinge on another layer.



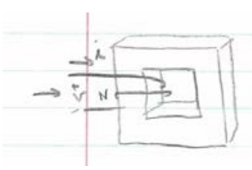
* Because of this loss will be higher, and optimum conductor thickness (2r) will be $\frac{w}{\delta}$ 0.3 − 1 (smaller for more layers)

3 Core Loss

Up to now, we have considered core material to be "ideal". However, there are mechanisms for loss in the core itself, including:

1. Irreversible energy in moving magnetic domain walls
2. Eddy currents within the core itself

Consider the energy into an inductor over a cycle in terms of the fields in the core

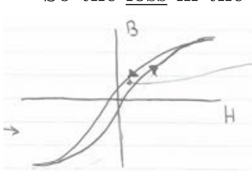


Energy in:

$$
\begin{aligned}
W_{in} &= \int_0^T v(t)i(t)dt \\
&= \int_0^T (NA_c\frac{dB_c}{dt})(\frac{1}{N}H_cl_c)dt \\
&= A_cl_c \oint H_c dB_c
\end{aligned}
$$

Where A_cl_c is the core value

So the loss in the core over a cycle is $\oint H_c dB_c$ (The area inside the B-H curve) per unit volume

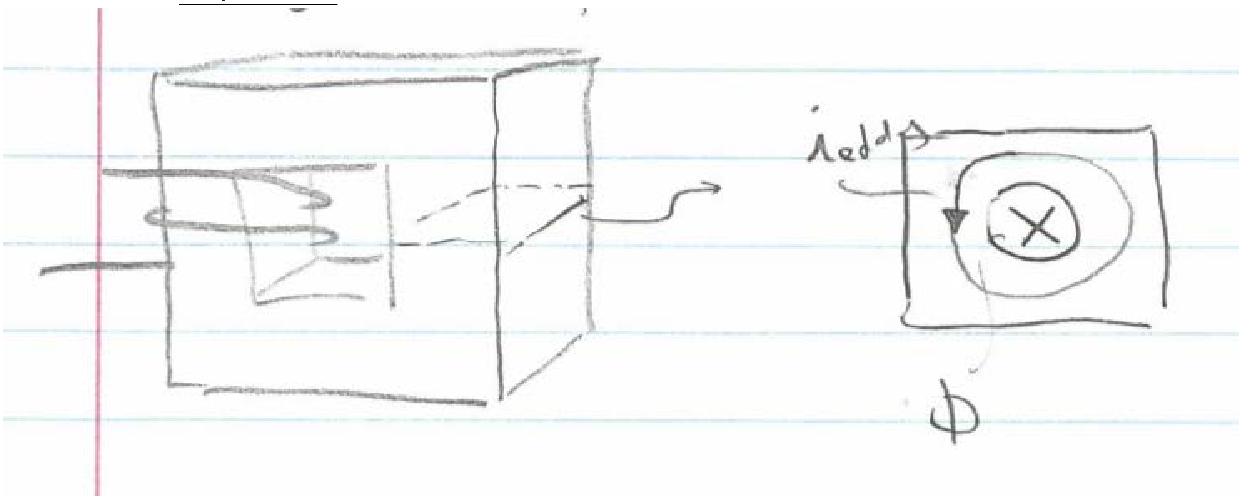


Show demo! Ideally, it would be a straight line.

The area within the hystersis loop is the loss within a cycle.
*suggests that a per unit volume calculation is good

If the shape of the loop were constant with frequency (in general it is not), then we'd find a loss $\propto$ frequency! (This is sometimes called "classic hysteresis loss", and is sometimes approximately true @ low f.)

In some materials (especially with high resistivity) characterizing the hysteresis loop (e.g. at a given frequency over the desired range of flux densities) is a good way to get loss per unit volume. However, we also have to worry about additional geometry considerations in core materials that are significantly conductive due to eddy currents:



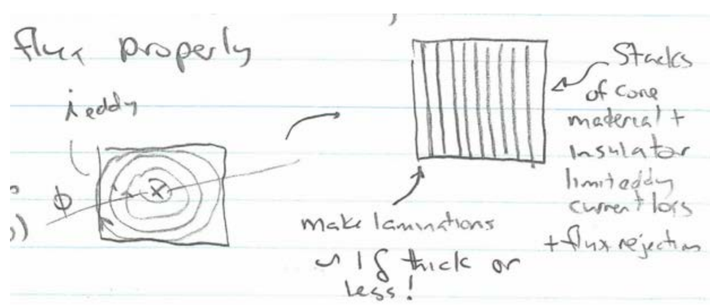
$\frac{dB}{dt}$ in core drives eddy currents around core. These eddy currents oppose changing core flux.

This generates two effects

1. Loss $i_{eddy} \propto \frac{dB}{dt} \propto f$ so we get losses that scales (ideally, w/ constant conductivity) as B_{pkj}^2, f^2 reality conductivity is a function of frequency, flux density, so losses are even worse.) Also, eddy current loss (per volume) increase with cross-sectional area (proportionally, in the simplest case) ⇒ So our loss per volume gets worse in bigger cores if core eddy currents are important.

2. Flux guiding: once the core dimension is on the order of a skin depth (of the core material), flux will start to be rejected from the center of the core, and the core will not guide flux properly.

* Both of these problms can be fixed with lamination or insulation (distributed gap) to limit eddy currents!



To model loss per unit volume in a core, we often use the empirical steinmets model (named for Charles Proteus Steinmetz)

Loss per unit volume (of core)

$$P_v \approx C_\mu f^\alpha \hat{B_{AC}}^\beta$$

Where C_μ, α, β are determined from manufacturers data or core B-H measurements.

e.g. for 3F3 ferrite

- C_μ $9.6 \times 10^{-13} \frac{W}{cm^3}$
- α 1.231 (f in Hz)
- $\beta = 2.793$ (B in Gauss)

These parameters are only calculated for sinusoidal flux drive. The shape of the BH loop area also depends on drive waveform, dc flux, etc., so this is only crudely useful under non sinusoidal drive conditions.

(However, it is also the only loss information one has available!)