

## Announcements

- SAIS open now

Friday, November 20, 2015 12-2:30pm Min Kao Room 121

### CURRENT Open House

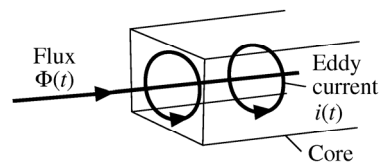
<p><b>Learn About</b></p> <p>Research Opportunities Graduate School Funding Benefits of CURENT</p>	<p><b>Come Visit Our Labs</b></p> <p>Visualization Room Power Electronics Lab High Power Electronics Lab Hardware Testbed FNET</p>	<p><b>Refreshments</b></p> <p>Pizza and Drinks Provided Starting at Noon</p>
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Discover the Exciting Applications of Power and Power Electronics  
in Grid, IT, EV, Renewables, and more!

RSVP to Help Us Order Pizza!

## 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.

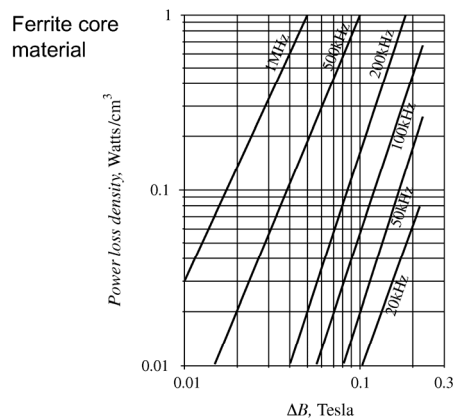


Eddy current  
loss  $i^2(t)R$

## 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  $i^2(t)R$  then varies with square of excitation frequency  $f$ .
- Ferrite core material impedance is capacitive. This causes eddy current power loss to increase as  $f^4$ .

## The Steinmetz Equation



Empirical equation, at a fixed frequency:

$$P_{fe} = K_{fe} (\Delta B)^\beta A_c \ell_m$$

Alternately:

$$P_v = K_m f^\alpha (\Delta B)^\beta$$

## 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<sup>2</sup>GSE



## Some Example Core Materials

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



## DC Copper Loss

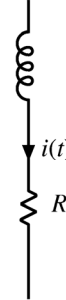
DC resistance of wire

$$R = \rho \frac{\ell_b}{A_w}$$

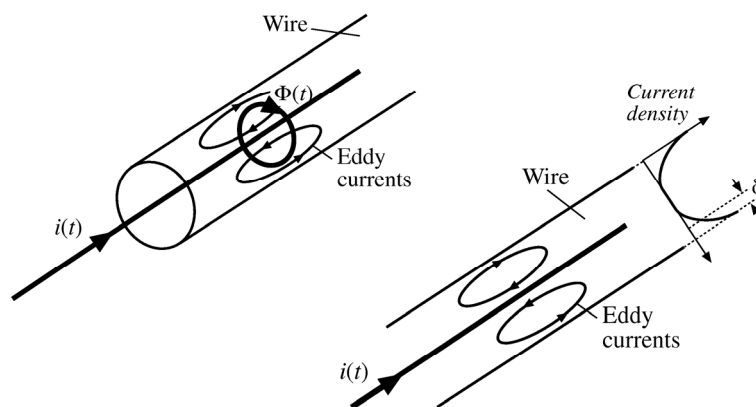
where  $A_w$  is the wire bare cross-sectional area, and  $\ell_b$  is the length of the wire. The resistivity  $\rho$  is equal to  $1.724 \cdot 10^{-6} \Omega \text{ cm}$  for soft-annealed copper at room temperature. This resistivity increases to  $2.3 \cdot 10^{-6} \Omega \text{ cm}$  at  $100^\circ\text{C}$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

The wire resistance leads to a power loss of

$$P_{cu} = I_{rms}^2 R$$

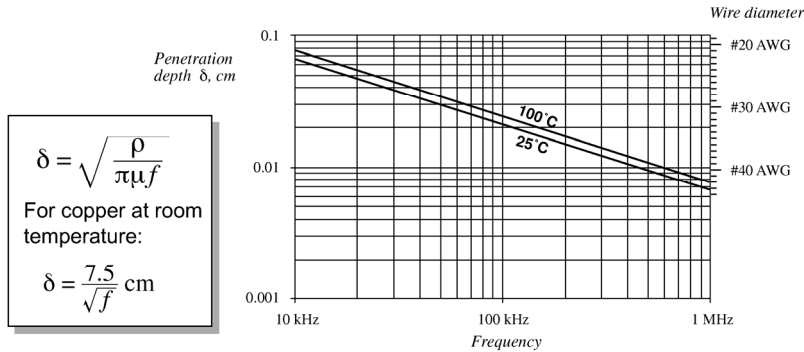


## Skin Effect



## Skin Depth

For sinusoidal currents: current density is an exponentially decaying function of distance into the conductor, with characteristic length  $\delta$  known as the *penetration depth* or *skin depth*.



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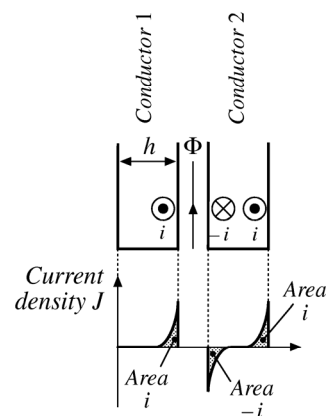
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## Proximity Effect

Ac current in a conductor induces eddy currents in adjacent conductors by a process called the *proximity effect*. This causes significant power loss in the windings of high-frequency transformers and ac inductors.

A multi-layer foil winding, with  $h \gg \delta$ . Each layer carries net current  $i(t)$ .



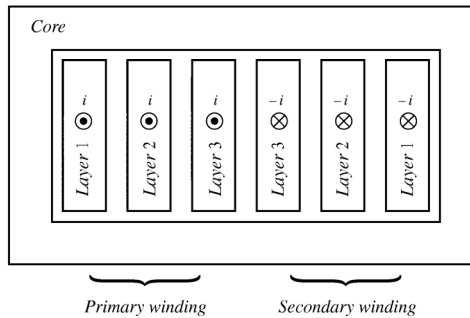
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## Two-Winding Transformer Example

Cross-sectional view of two-winding transformer example. Primary turns are wound in three layers. For this example, let's assume that each layer is one turn of a flat foil conductor. The secondary is a similar three-layer winding. Each layer carries net current  $i(t)$ . Portions of the windings that lie outside of the core window are not illustrated. Each layer has thickness  $h \gg \delta$ .



## Current Distribution

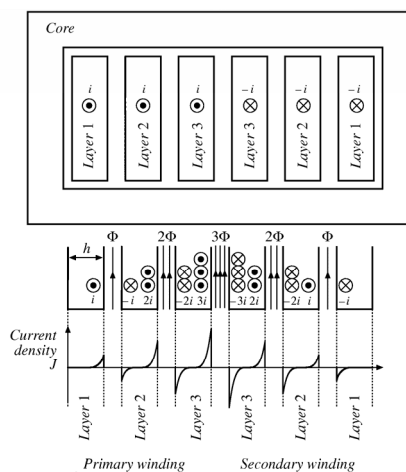
Skin effect causes currents to concentrate on surfaces of conductors

Surface current induces equal and opposite current on adjacent conductor

This induced current returns on opposite side of conductor

Net conductor current is equal to  $i(t)$  for each layer, since layers are connected in series

Circulating currents within layers increase with the numbers of layers



## High Frequency Estimation

The current  $i(t)$  having rms value  $I$  is confined to thickness  $d$  on the surface of layer 1. Hence the effective "ac" resistance of layer 1 is:

$$R_{ac} = \frac{h}{\delta} R_{dc}$$

This induces copper loss  $P_1$  in layer 1:

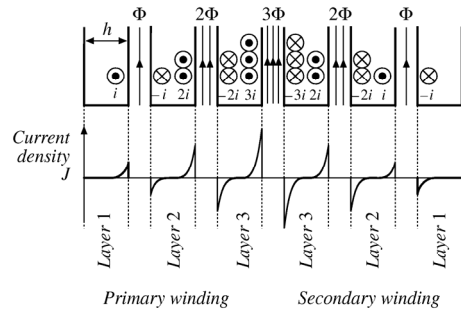
$$P_1 = I^2 R_{ac}$$

Power loss  $P_2$  in layer 2 is:

$$P_2 = P_1 + 4P_1 = 5P_1$$

Power loss  $P_3$  in layer 3 is:

$$P_3 = (2^2 + 3^2)P_1 = 13P_1$$



Power loss  $P_m$  in layer  $m$  is:

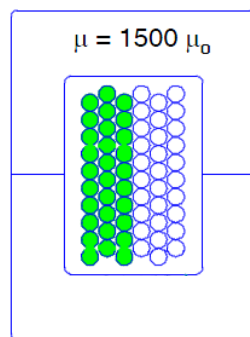
$$P_m = I^2 \left[ (m-1)^2 + m^2 \right] \left( \frac{h}{\delta} R_{dc} \right)$$

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## Simulation Example

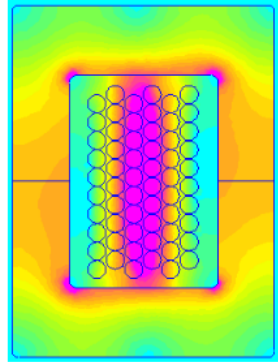


- AWG#30 copper wire
  - Diameter  $d = 0.294$  mm
  - $d = \delta$  at around 50 kHz
- 1:1 transformer
  - Primary and secondary are the same, 30 turns in 3 layers
- Sinusoidal currents,
 
$$I_{1rms} = I_{2rms} = 1 \text{ A}$$

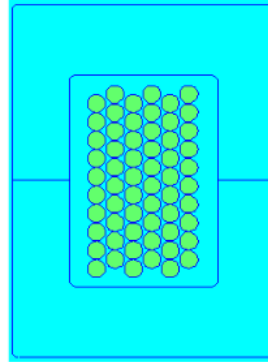
Numerical field and current density solutions using FEMM (Finite Element Method Magnetics), a free 2D solver, <http://www.femm.info/wiki/HomePage>

## Frequency: 1 kHz

Flux density



Current Density

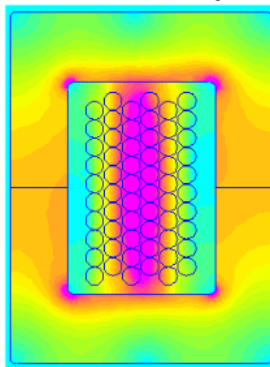


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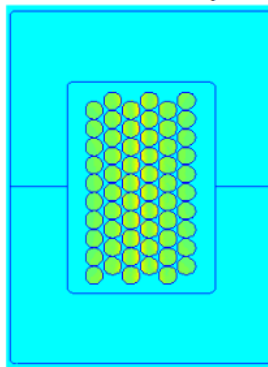


## Frequency: 100 kHz

Flux density



Current Density



Total copper losses 1.8 larger than at 1 kHz

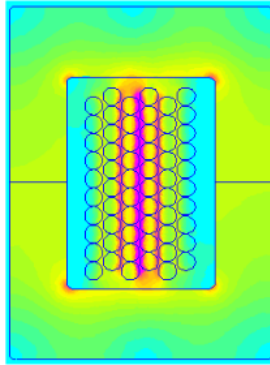
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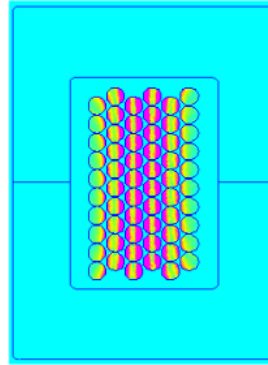


## Frequency: 1 MHz

Flux density



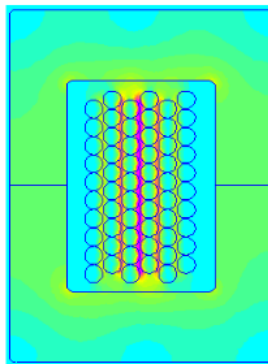
Current Density



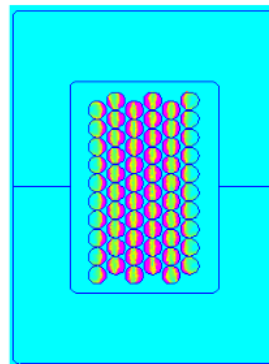
Total copper losses 20 times larger than at 1 kHz

## Frequency: 10 MHz

Flux density



Current Density



Very significant proximity effect  
Total copper losses = 65 times larger than at 1 KHz