Magnetics Modeling In Spice
Proximity Loss

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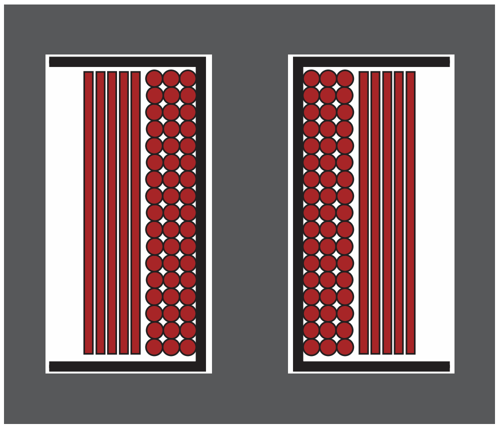
PSMA Magnetics Session

The Biggest Problem with Magnetics Design

The single biggest issue with magnetics design is that 99.9% of engineers don't understand or apply proximity loss properly.

Example: Forward converter transformer



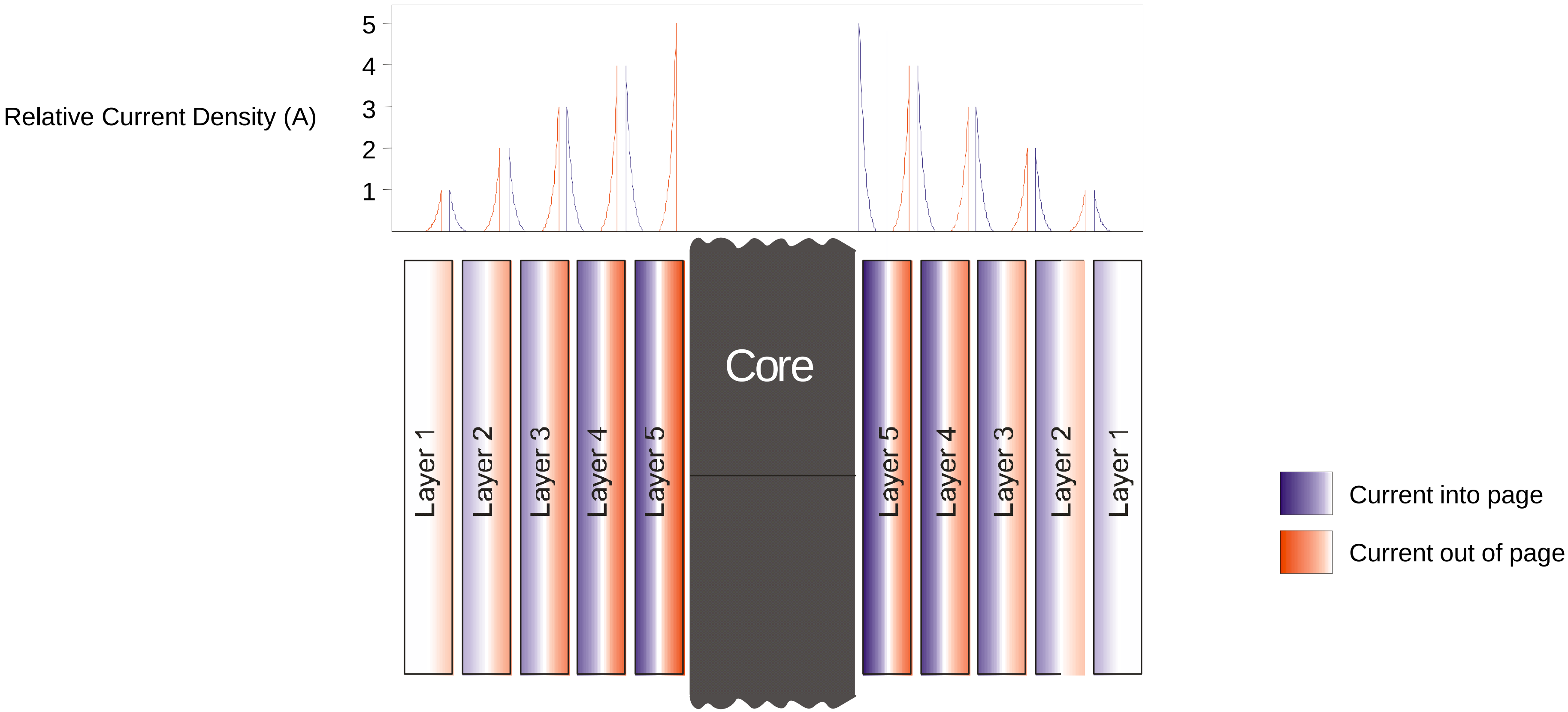
Winding loss if you don't do proximity analysis:

1.04 W

Winding loss with full harmonic analysis

10.77 W

Proximity Effects Current Distribution



1-Dimensional Field Solution from Dowell's Equation

$$P_d = b_w \sum_{i=1}^{n} l_i \frac{1}{h_i \eta_i \sigma} H_i^2 \left[(1+\alpha_i^2) G_1(\Delta_i) - 4\alpha_i G_2(\Delta_i) \right]$$

$$G_1(\Delta_i) = \Delta \frac{\sinh 2\Delta + \sin 2\Delta}{\cosh 2\Delta - \cos 2\Delta}$$

$$G_2(\Delta_i) = \Delta \frac{\sinh \Delta \cos \Delta + \cosh \Delta \sin \Delta}{\cosh 2\Delta - \cos 2\Delta}$$

l_i Mean turn length of layer

η Porosity of layer (fill factor)

h_i Height of layer

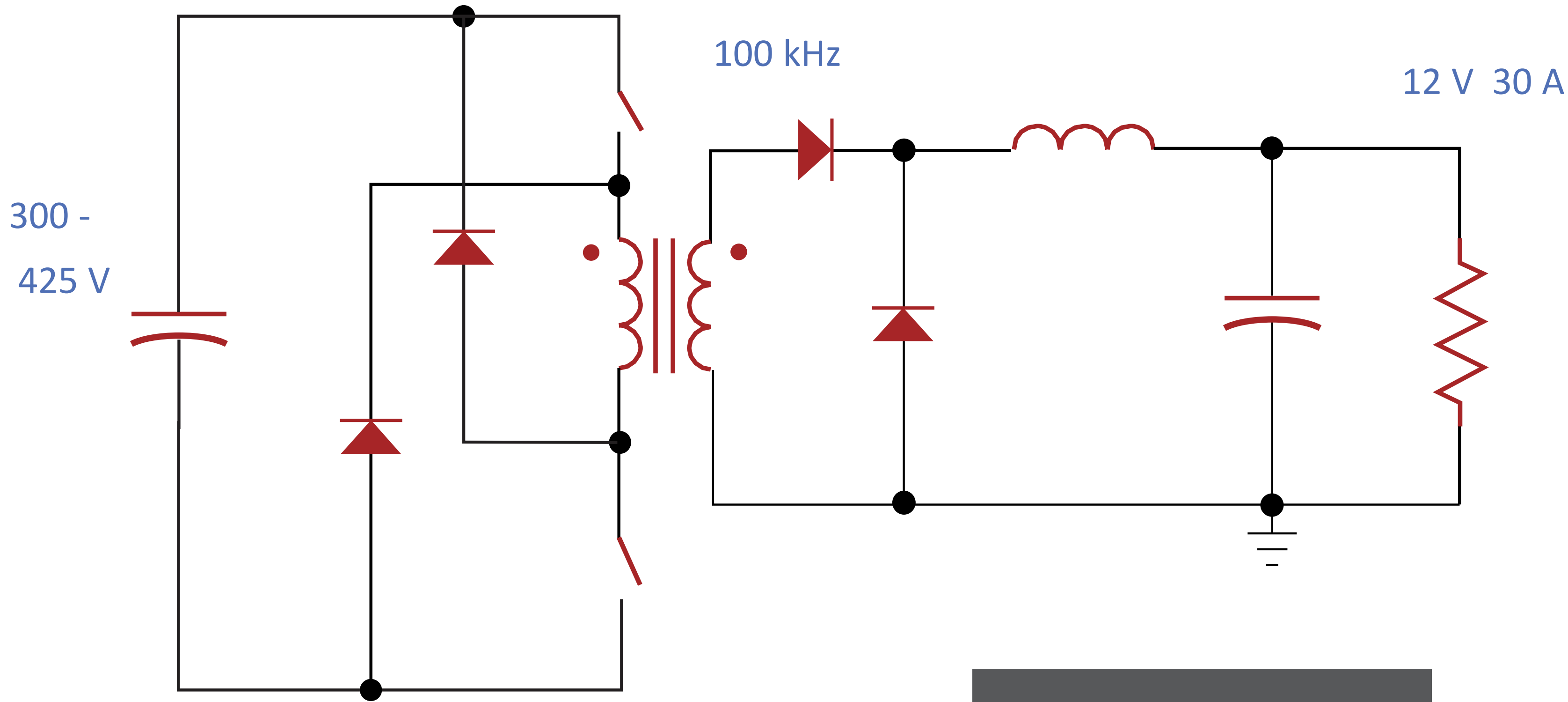
$H_i = \dfrac{n_i I_i}{b_w}$ H field at boundary of layer

α_i Ratio of fields on either side of layer

$\delta = \sqrt{\dfrac{2}{\omega \mu_o \sigma \eta}}$ Skin depth of layer including porosity

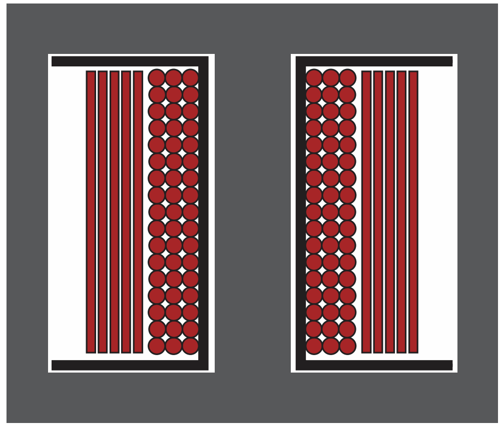
$\Delta_i = \dfrac{h_i}{\delta}$ Normalized height of layer relative to skin depth

Proximity Loss Example



Primary 51 turns 20 awg 3 layers

Secondary 5 turns 10 mil foil



Primary Proximity Loss

$$P_d = b_w \sum_{i=1}^{n} l_i \frac{1}{h_i \eta_i \sigma} H_i^2 \left[\left(1+\alpha_i^2\right) G_{1_i} - 4\alpha_i G_{2_i} \right]$$

The H field is calculated from

$$H_i = \frac{N_i I_i}{b_w} \qquad b_w = \text{winding width}$$

Complex functions are needed to calculate the losses :

$$G_{1_i} = \Delta_i \frac{\sinh 2\Delta_i + \sin 2\Delta_i}{\cosh 2\Delta_i - \cos 2\Delta_i}$$

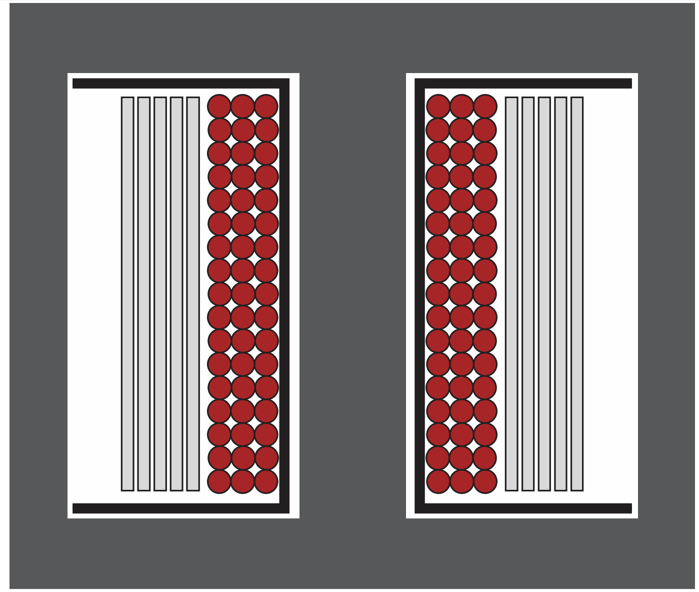
$$G_{2_i} = \Delta_i \frac{\sinh \Delta_i \cos \Delta_i + \cosh \Delta_i \sin \Delta_i}{\cosh 2\Delta_i - \cos 2\Delta_i}$$

The ratio of the winding layer height to skin depth is

$$\Delta_i = \frac{h_{cu_i}}{\delta} \qquad \text{skin depth } \delta = \sqrt{\frac{2}{\omega \mu_o \sigma \eta}}$$

$$\sigma = \text{conductivity} \qquad \mu_o = 4\pi \text{ x} 10^{-7} \qquad \eta = \text{porosity}$$

Each Layer is 3.75223876 Depths



PROXIMITY RESISTANCE MULTIPLIER BY LAYER

1	2	3
3.7575	19.768	51.791

Overall AC/DC Resistance Multiplier 25.1

DC Winding Resistance 0.09657 Ω

AC Winding Resistance 2.4239 Ω

Σ

DC 0.097 Ohm

100 kHz 2.42 Ohm

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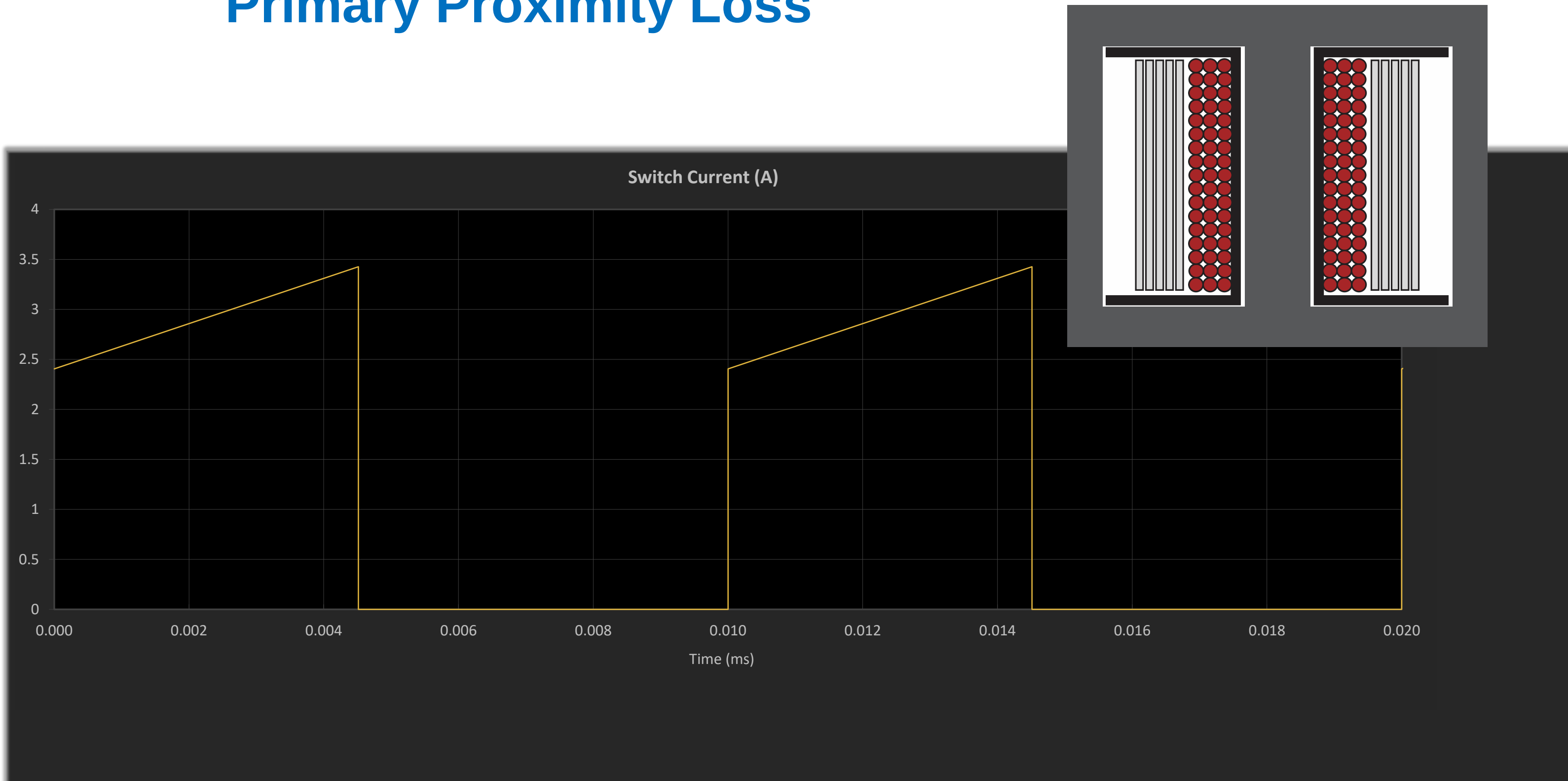
Primary Proximity Loss



WINDING LOSS DETAILS

RMS Current	1.968	A	Winding Loss (Including Proximity)	5.362	W
DC Current	1.315	A	Winding Loss (without Proximity Loss)	0.374	W
AC Current	1.464	A	Winding Surface Area	14.2	sq.cm
DC Resistance	0.09657	Ω			
AC Resistance	2.4239	Ω			

Proximity Loss | Plot AC Resistance | Σ

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Primary Proximity Loss

$$P_d = b_w \sum_{i=1}^{n} l_i \frac{1}{h_i \eta_i \sigma} H_i^2 \left[\left(1+\alpha_i^2\right) G_{1_i} - 4\alpha_i G_{2_i} \right]$$

The H field is calculated from

$$H_i = \frac{N_i I_i}{b_w} \qquad b_w = \text{winding width}$$

Complex functions are needed to calculate the losses:

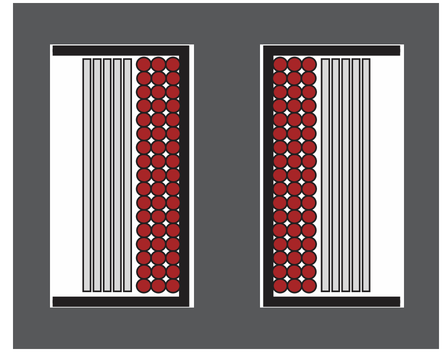
$$G_{1_i} = \Delta_i \frac{\sinh 2\Delta_i + \sin 2\Delta_i}{\cosh 2\Delta_i - \cos 2\Delta_i}$$

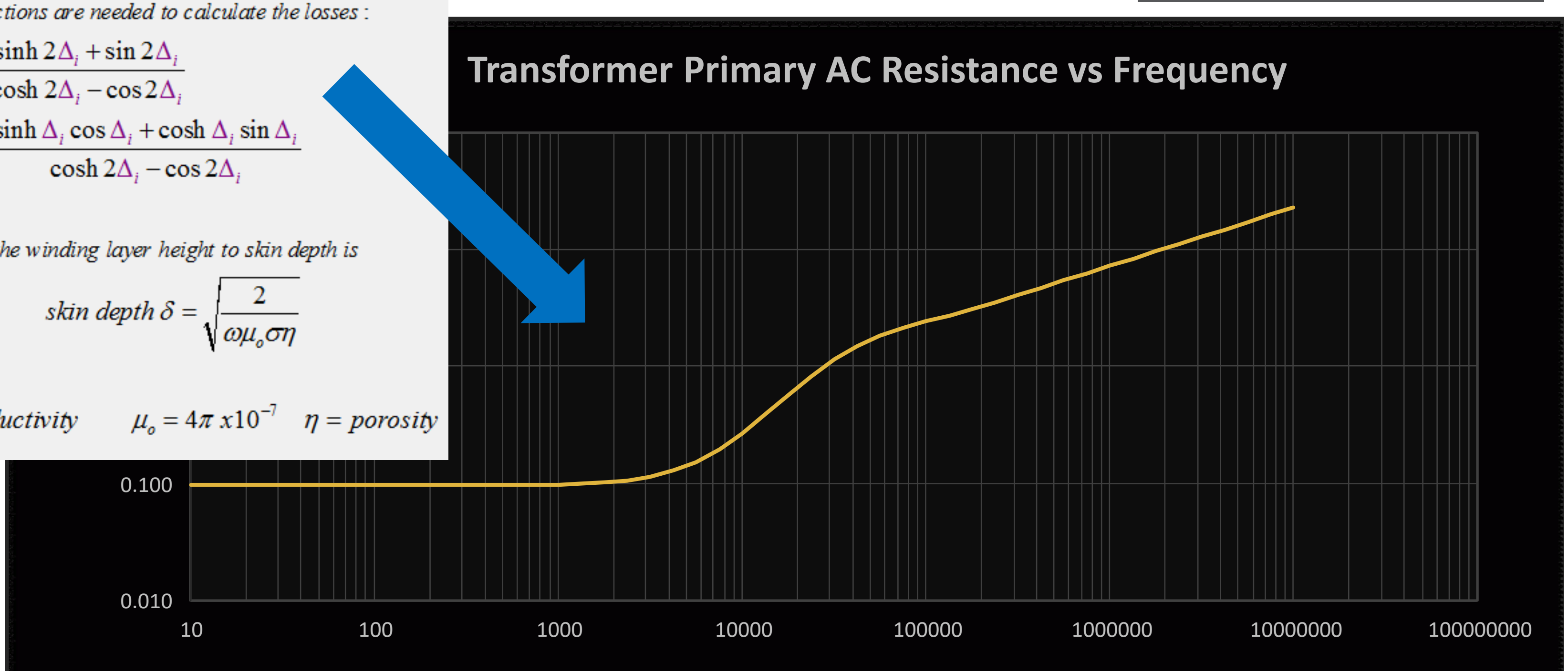
$$G_{2_i} = \Delta_i \frac{\sinh \Delta_i \cos \Delta_i + \cosh \Delta_i \sin \Delta_i}{\cosh 2\Delta_i - \cos 2\Delta_i}$$

The ratio of the winding layer height to skin depth is

$$\Delta_i = \frac{h_{cu_i}}{\delta} \qquad \text{skin depth } \delta = \sqrt{\frac{2}{\omega \mu_o \sigma \eta}}$$

$$\sigma = \text{conductivity} \qquad \mu_o = 4\pi \times 10^{-7} \qquad \eta = \text{porosity}$$





DC Resistance = 0.09657 Ohm

Ripple Frequency Resistance = 2.4239 Ohm

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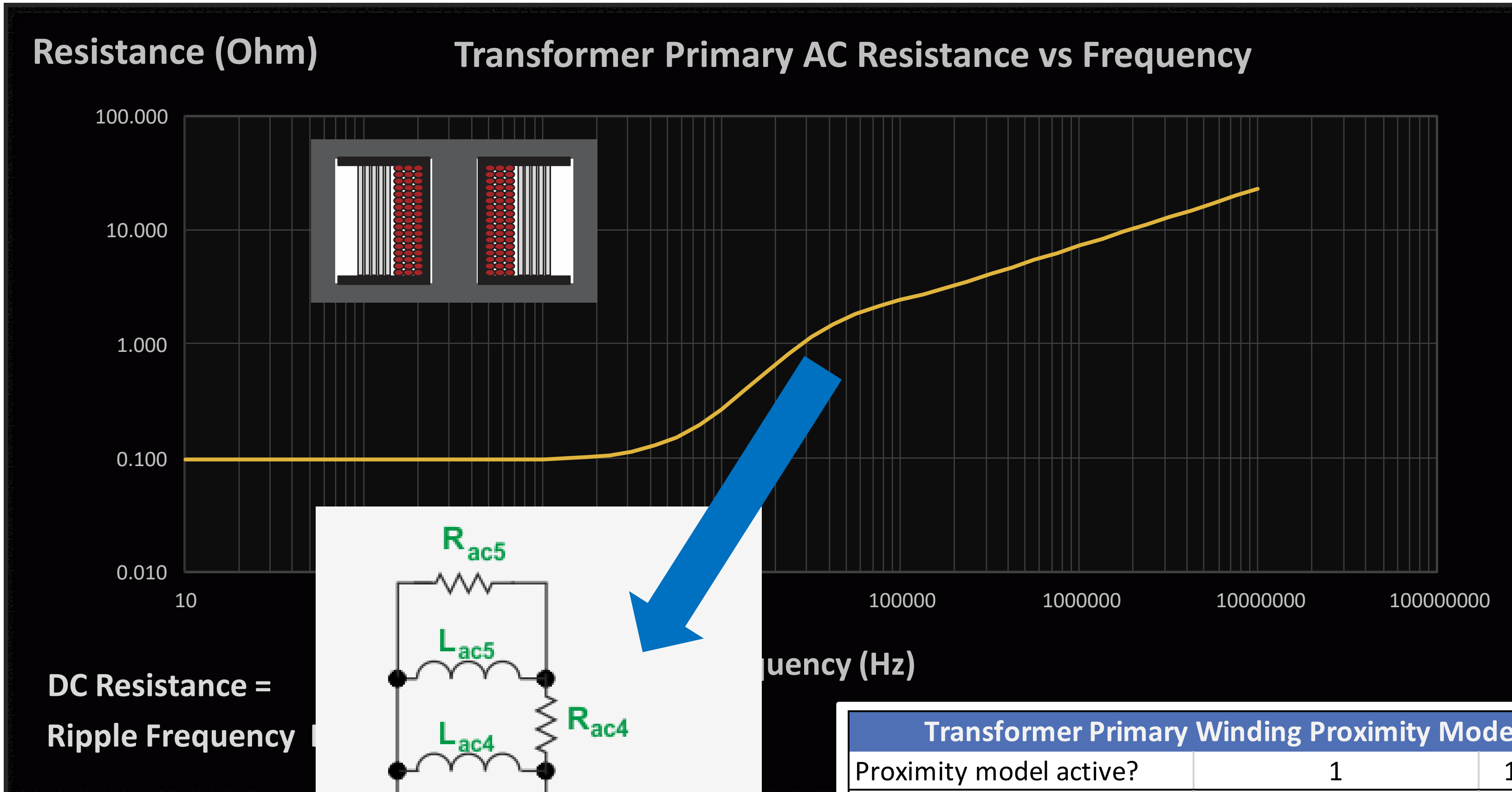
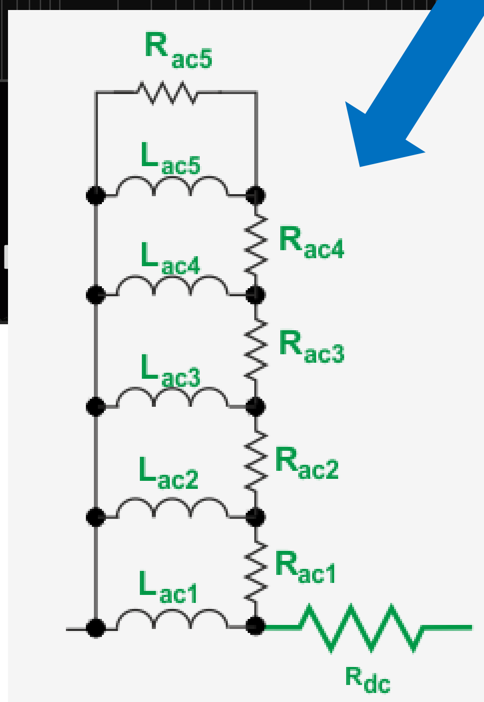
Primary Proximity Loss





Transformer Primary Winding Proximity Model		
Proximity model active?	1	1=yes
Rac1	1.32	mΩ
Rac2	234.43	mΩ
Rac3	2938.35	mΩ
Rac4	6590.55	mΩ
Rac5	21402.18	mΩ
Lac1	41.39685	uH
Lac2	41.0829	uH
Lac3	29.89081	uH
Lac4	8.84732	uH
Lac5	2.55406	uH

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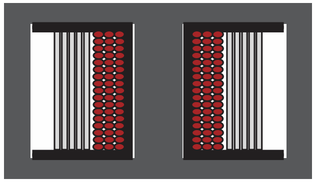
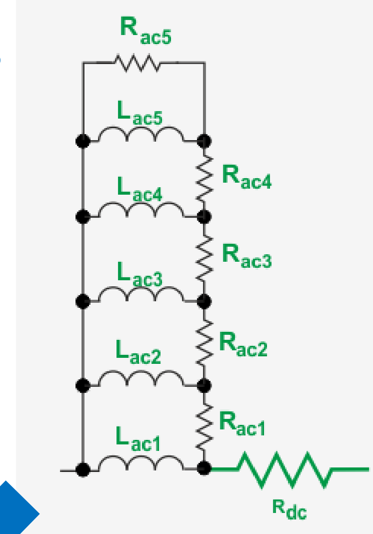
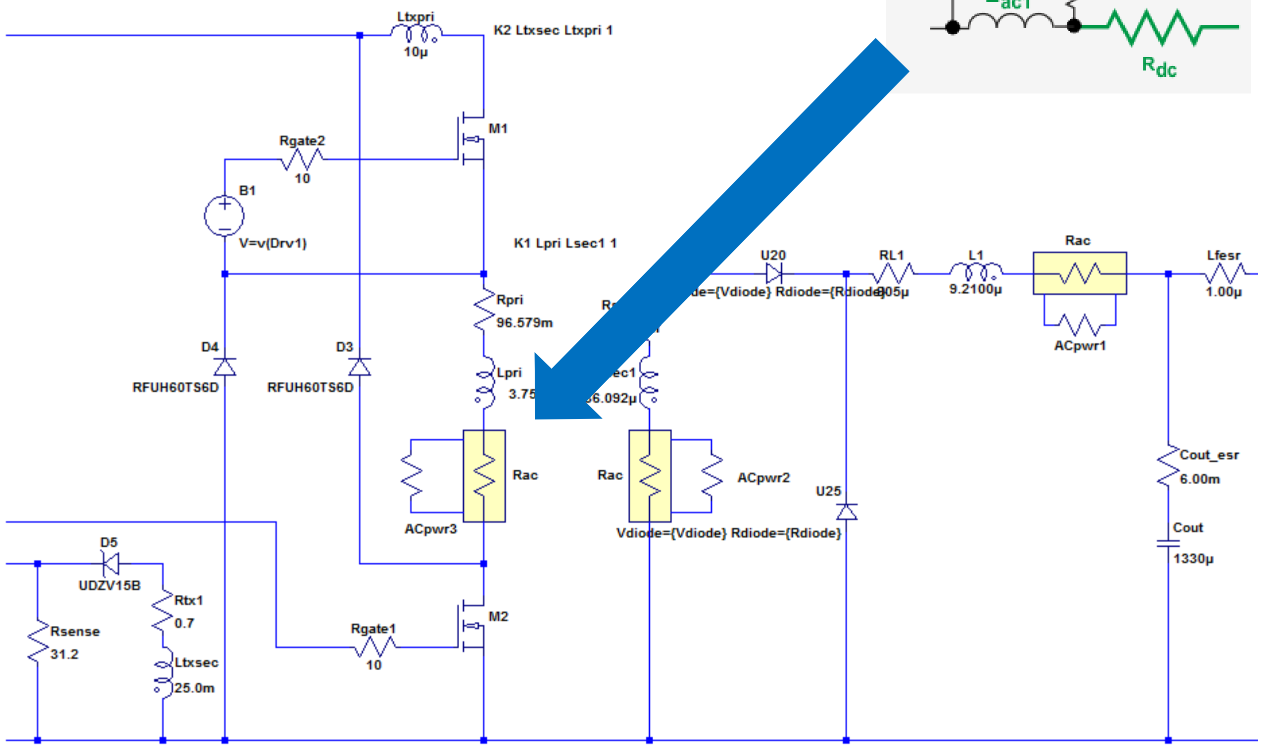
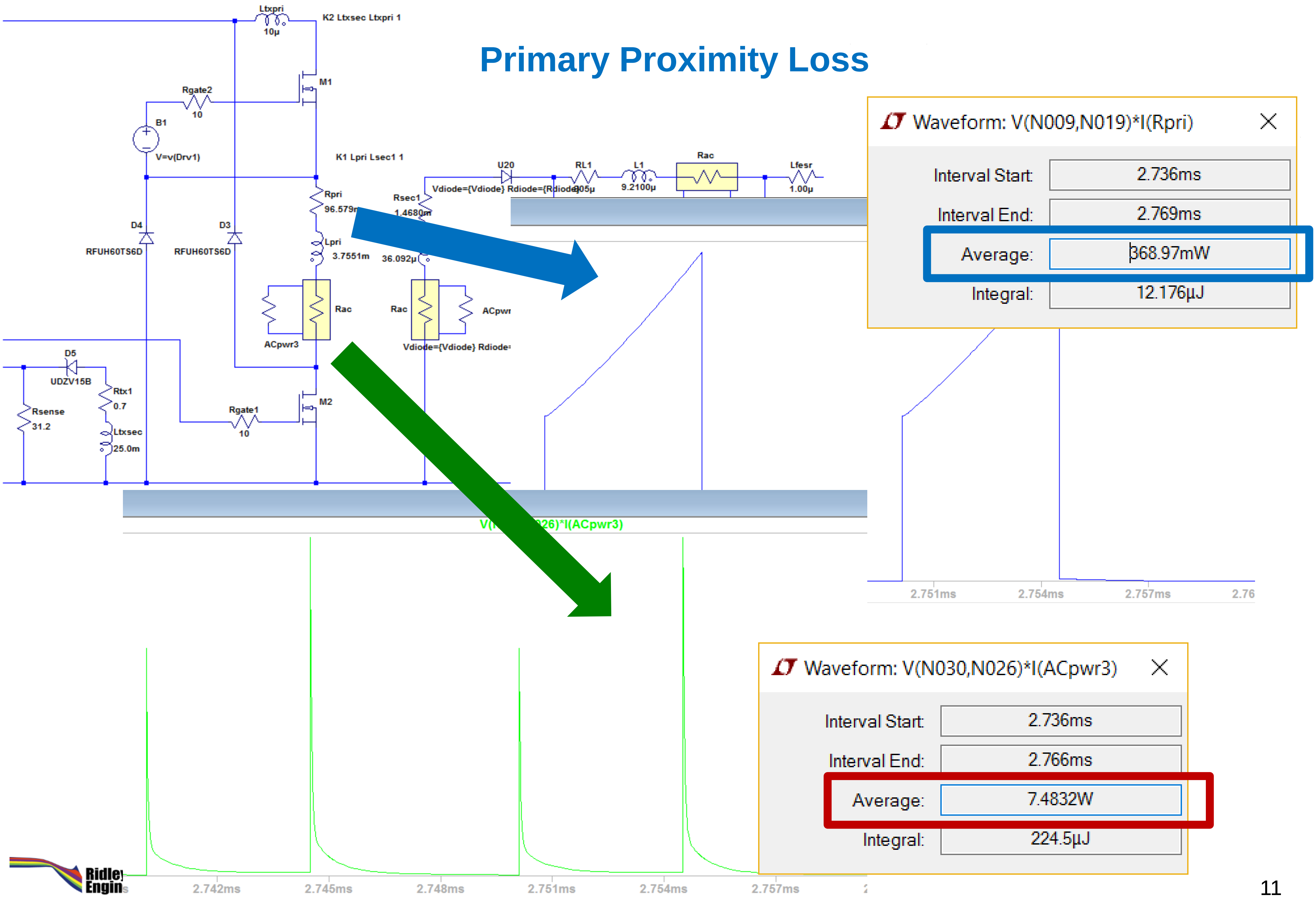
Primary Proximity Loss







Primary Proximity Loss



Secondary Proximity Loss 10 mil Foil

$$P_d = b_w \sum_{i=1}^{n} l_i \frac{1}{h_i \eta_i \sigma} H_i^2 \left[\left(1+\alpha_i^2\right) G_{1_i} - 4\alpha_i G_{2_i} \right]$$

The H field is calculated from

$$H_i = \frac{N_i I_i}{b_w} \qquad b_w = winding\ width$$

Complex functions are needed to calculate the losses :

$$G_{1_i} = \Delta_i \frac{\sinh 2\Delta_i + \sin 2\Delta_i}{\cosh 2\Delta_i - \cos 2\Delta_i}$$

$$G_{2_i} = \Delta_i \frac{\sinh \Delta_i \cos \Delta_i + \cosh \Delta_i \sin \Delta_i}{\cosh 2\Delta_i - \cos 2\Delta_i}$$

The ratio of the winding layer height to skin depth is

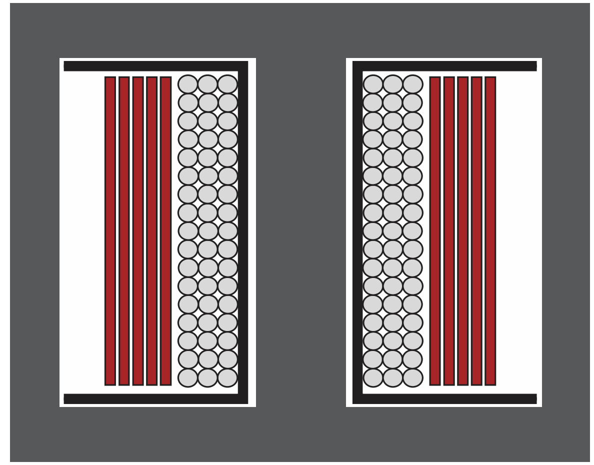
$$\Delta_i = \frac{h_{cu_i}}{\delta} \qquad skin\ depth\ \delta = \sqrt{\frac{2}{\omega \mu_o \sigma \eta}}$$

$$\sigma = conductivity \qquad \mu_o = 4\pi\ x 10^{-7} \qquad \eta = porosity$$

DC 0.00145 Ohm

100 kHz 0.0102 Ohm

Each Layer is 1.24413415 Depths



PROXIMITY RESISTANCE MULTIPLIER BY LAYER

1	2	3	4	5
1.1952	2.6515	5.5639	9.9327	15.757

Overall AC/DC Resistance Multiplier 7.020231

DC Winding Resistance 0.0014569 Ω

AC Winding Resistance 0.010227 Ω

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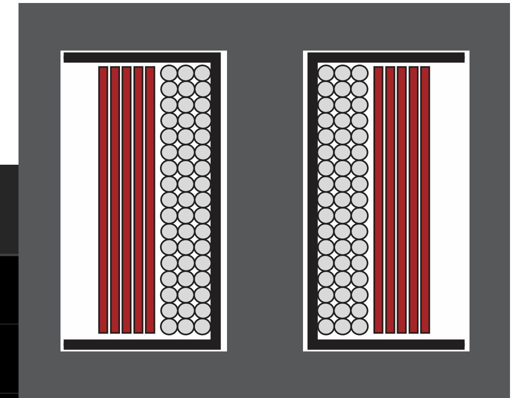
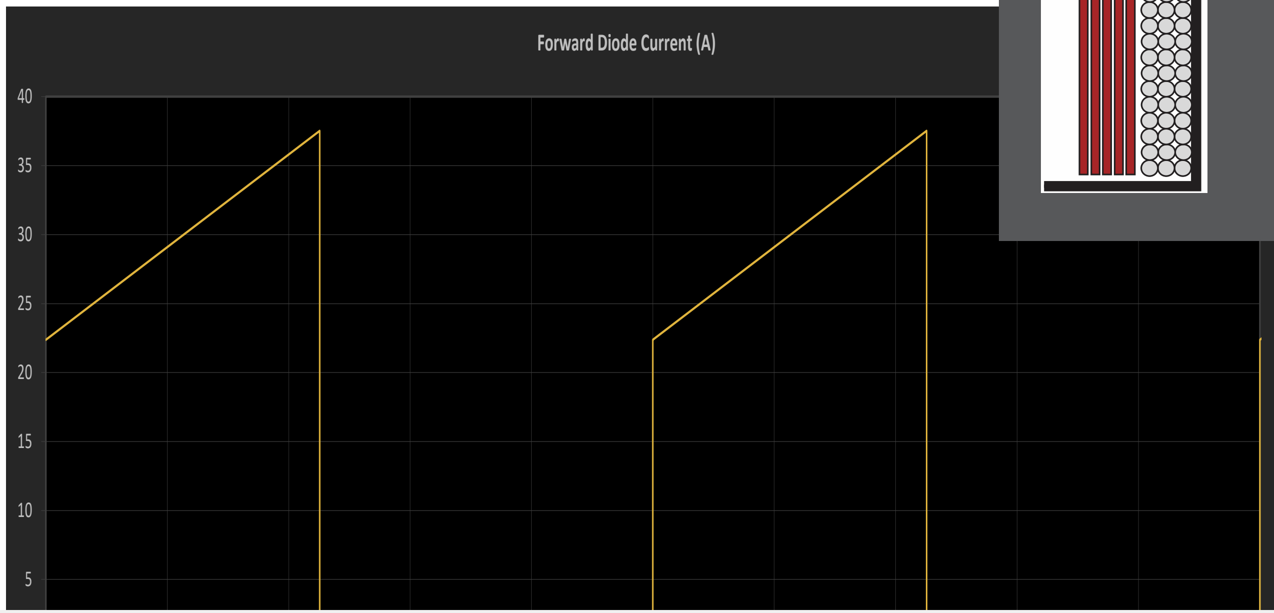
Secondary Waveforms and Proximity Loss





WINDING LOSS DETAILS

RMS Current	21.549	A	Winding Loss (Including Proximity)	2.93	W
DC Current	14.398	A	Winding Loss (without Proximity Loss)	0.676	W
AC Current	16.032	A	Winding Surface Area	14.2	sq.cm
DC Resistance	0.0014569	Ω			
AC Resistance	0.010227	Ω			

Proximity Loss   Plot AC Resistance   Σ

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Secondary Proximity Loss

$$P_d = b_w \sum_{i=1}^{n} l_i \frac{1}{h_i \eta_i \sigma} H_i^2 \left[\left(1+\alpha_i^2\right) G_{1_i} - 4\alpha_i G_{2_i} \right]$$

The H field is calculated from

$$H_i = \frac{N_i I_i}{b_w} \qquad b_w = \text{winding width}$$

Complex functions are needed to calculate the losses :

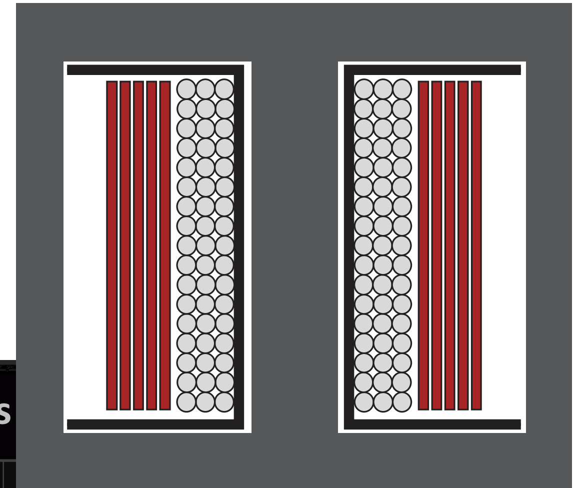
$$G_{1_i} = \Delta_i \frac{\sinh 2\Delta_i + \sin 2\Delta_i}{\cosh 2\Delta_i - \cos 2\Delta_i}$$

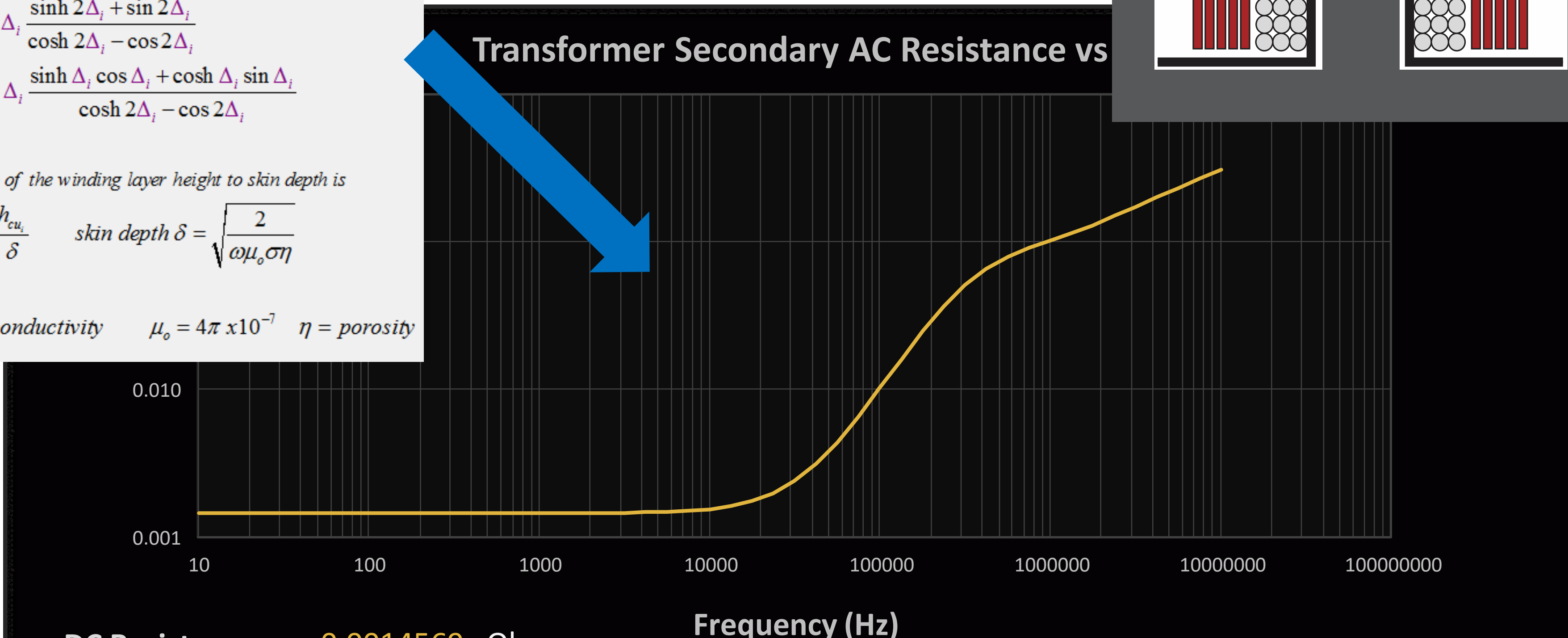
$$G_{2_i} = \Delta_i \frac{\sinh \Delta_i \cos \Delta_i + \cosh \Delta_i \sin \Delta_i}{\cosh 2\Delta_i - \cos 2\Delta_i}$$

The ratio of the winding layer height to skin depth is

$$\Delta_i = \frac{h_{cu_i}}{\delta} \qquad \text{skin depth } \delta = \sqrt{\frac{2}{\omega \mu_o \sigma \eta}}$$

σ = conductivity $\quad \mu_o = 4\pi \, x10^{-7} \quad \eta$ = porosity

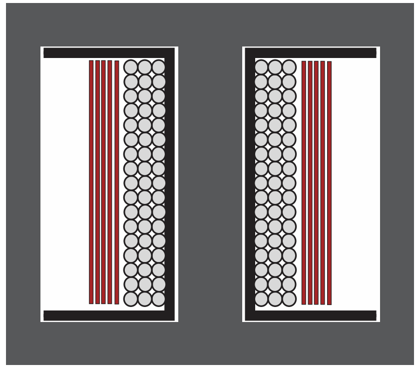




DC Resistance = 0.0014569 Ohm

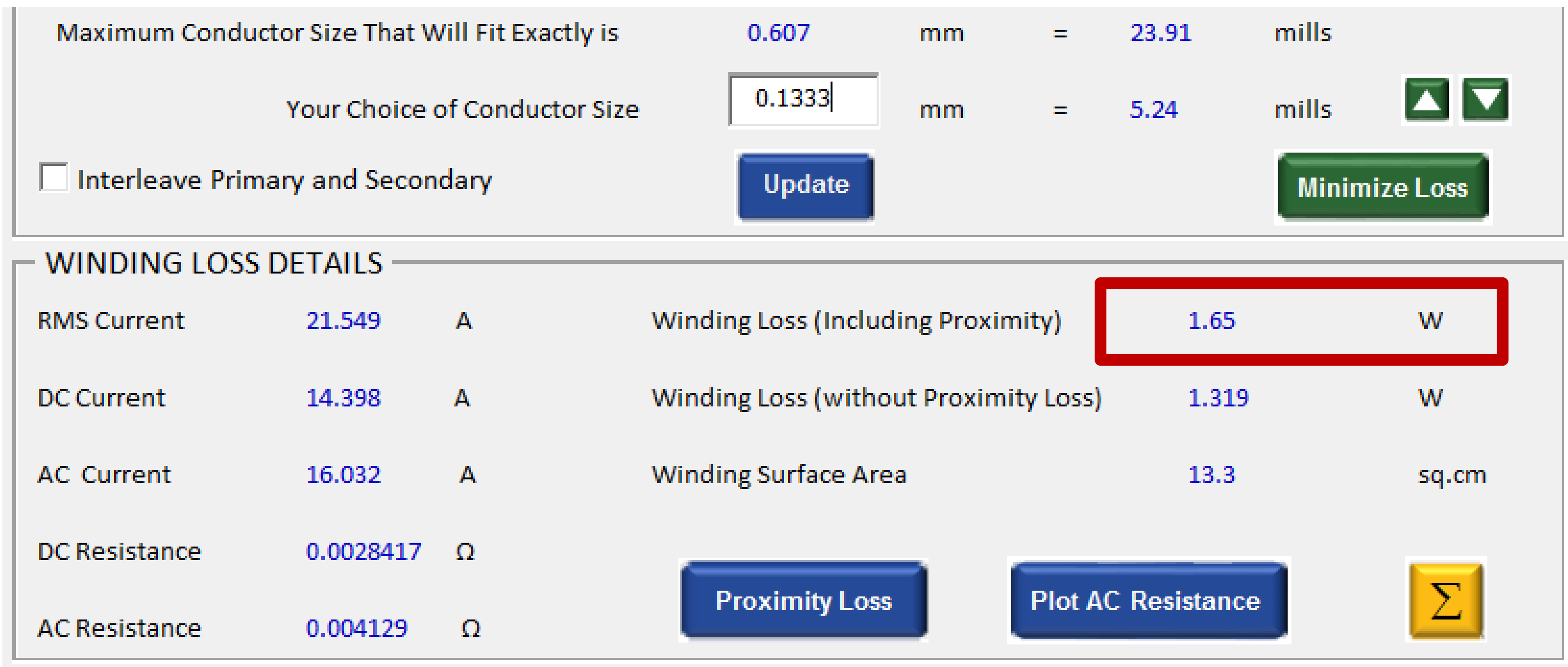
Ripple Frequency Resistance = 0.0102 Ohm

Secondary Proximity Loss Reduced Foil Thickness
10 mil Reduced to 5 mil Foil

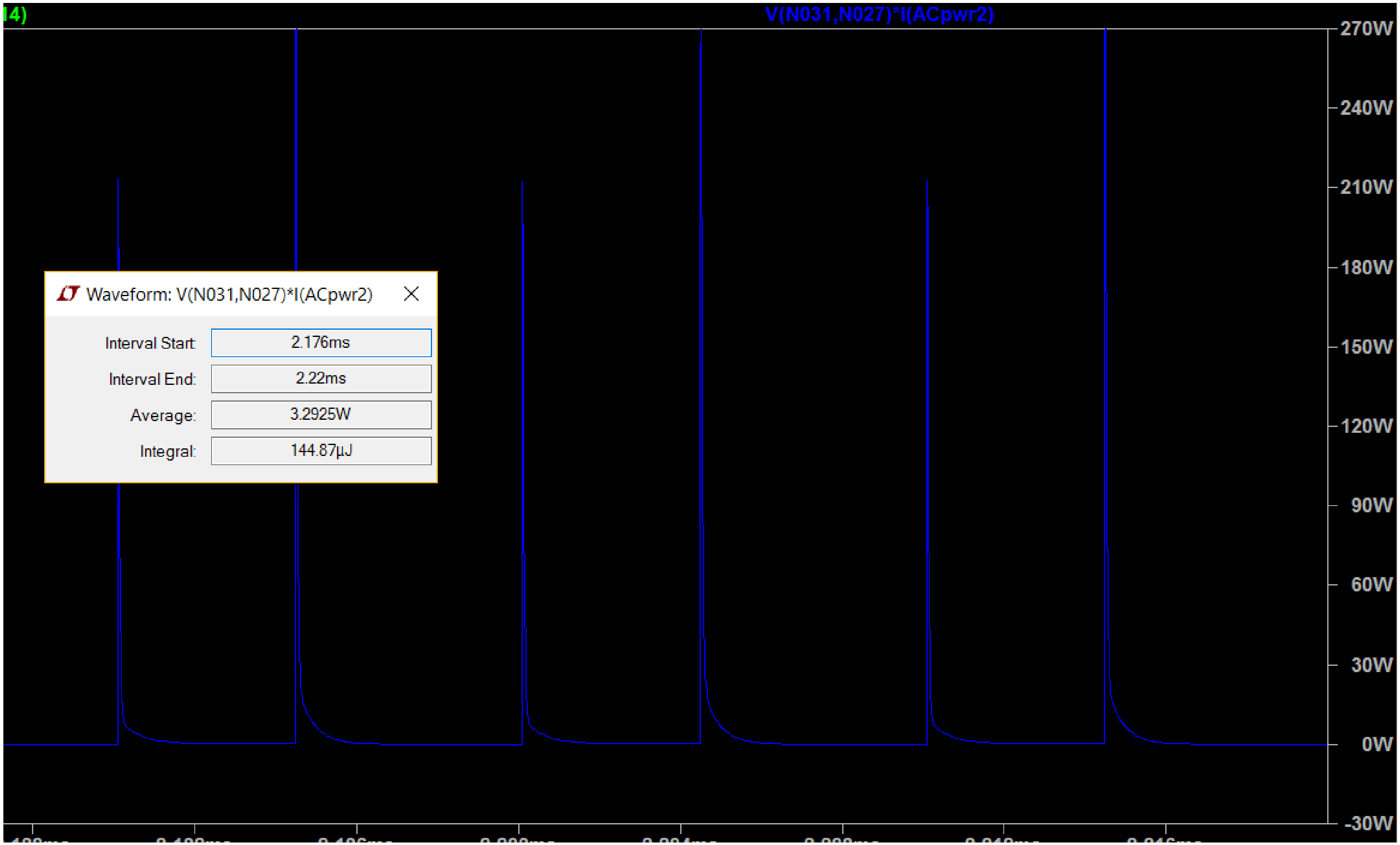


10 mil Foil

2.93 W



Secondary Proximity Loss Simulation



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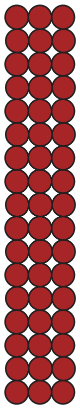
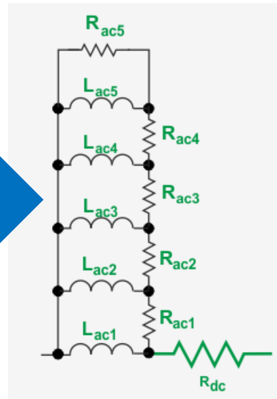
Winding Structure to Spice Model in 1 Step





Transformer Primary Winding Proximity Model		
Proximity model active?	1	1=yes
Rac1	1.32	mΩ
Rac2	234.43	mΩ
Rac3	2938.35	mΩ
Rac4	6590.55	mΩ
Rac5	21402.18	mΩ
Lac1	41.39685	uH
Lac2	41.0829	uH
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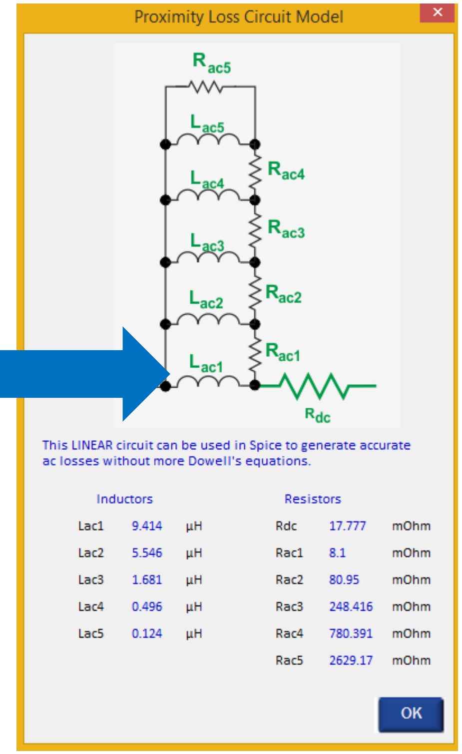
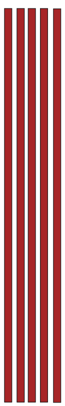
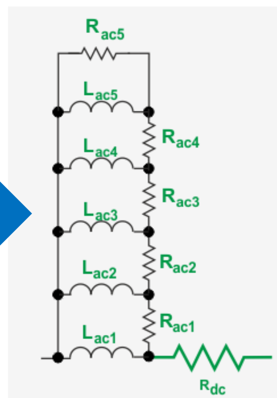
Lac4	8.84732	uH
Lac5	2.55406	uH







Transformer Secondary Winding Proximity Model		
Proximity model active?	1	1=yes
Rac1	0.00	mΩ
Rac2	0.02	mΩ
Rac3	1.80	mΩ
Rac4	108.50	mΩ
Rac5	319.92	mΩ
Lac1	0.15451	uH
Lac2	0.15451	uH
Lac3	0.15451	uH
Lac4	0.14178	uH
Lac5	0.03818	uH