

Magnetics Modeling In Spice Proximity Loss

Dr. Ray Ridley

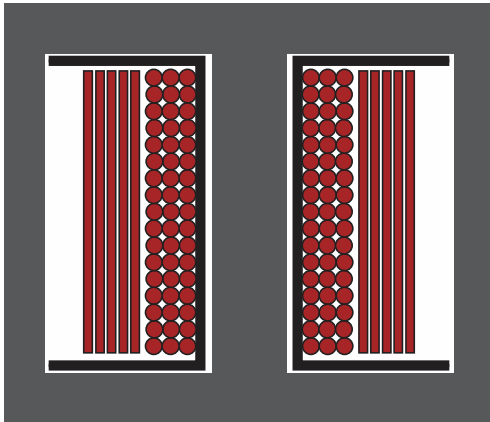
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PSMA Magnetics Session

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:

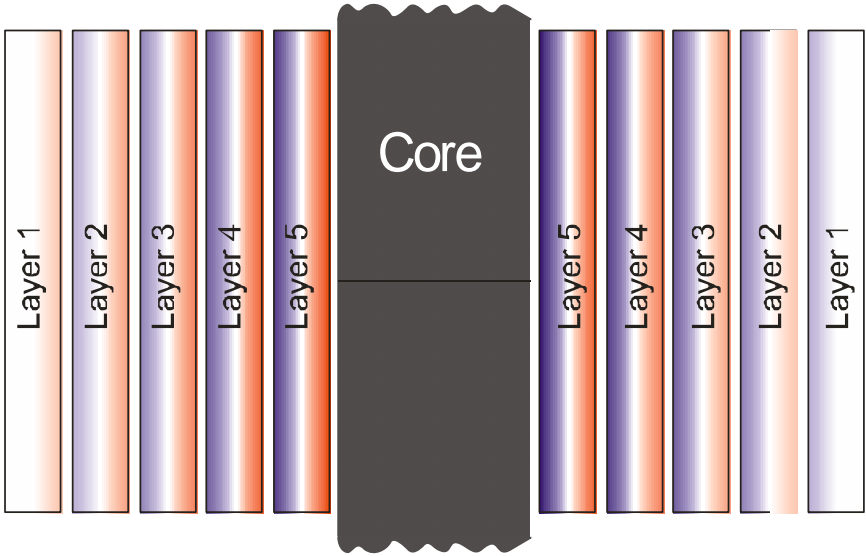
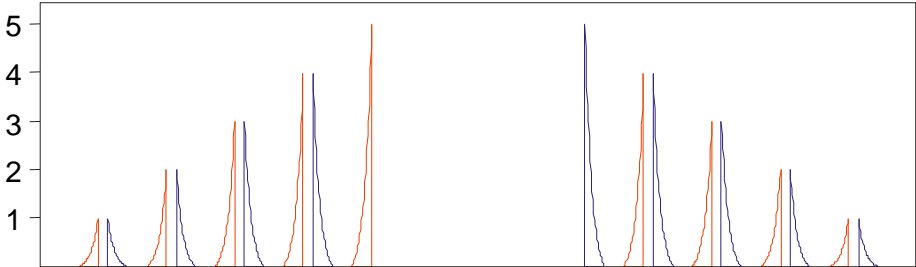
1.04 W

Winding loss with full harmonic analysis

10.77 W

Proximity Effects Current Distribution

Relative Current Density (A)



- Current into page
- Current out of page

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

α_i Ratio of fields on either side of layer

η Porosity of layer (fill factor)

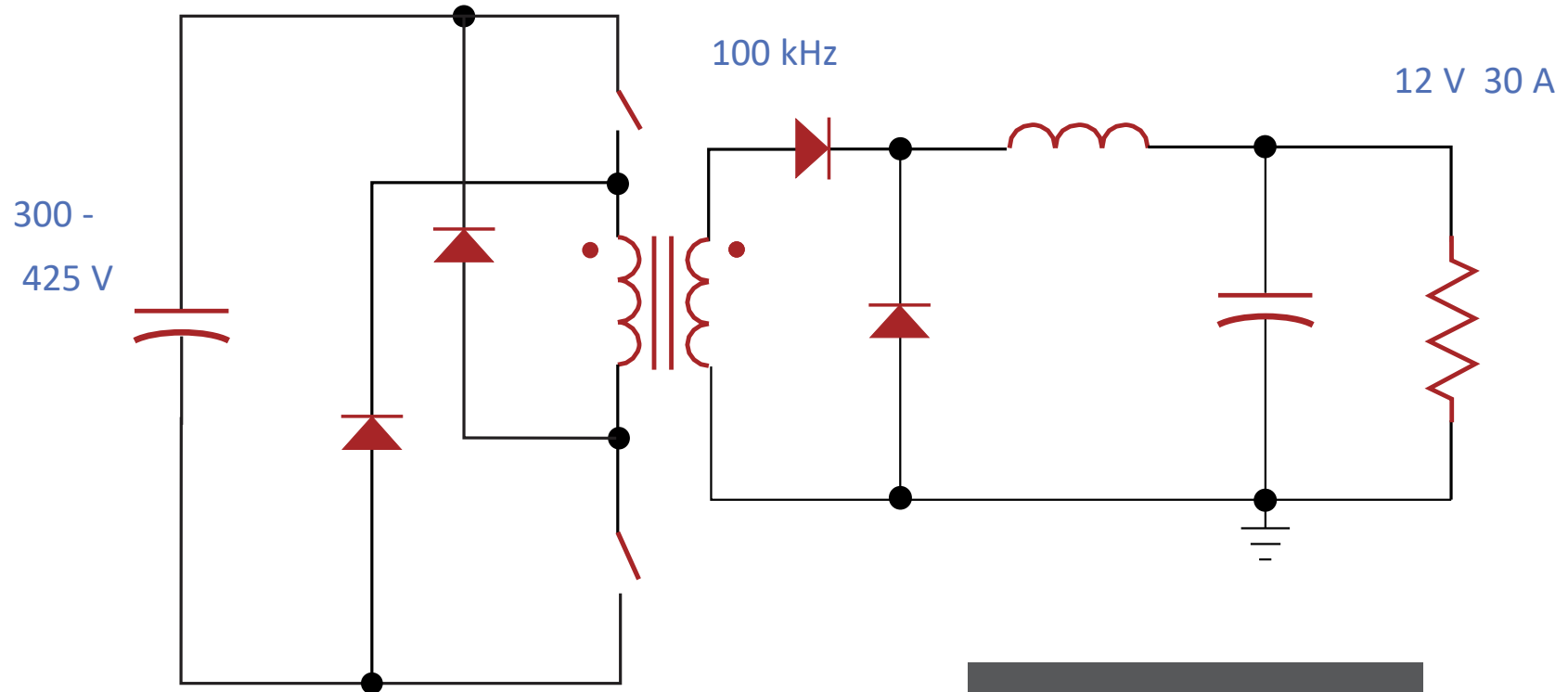
$\delta = \sqrt{\frac{2}{\omega \mu_o \sigma \eta}}$ Skin depth of layer including porosity

h_i Height of layer

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

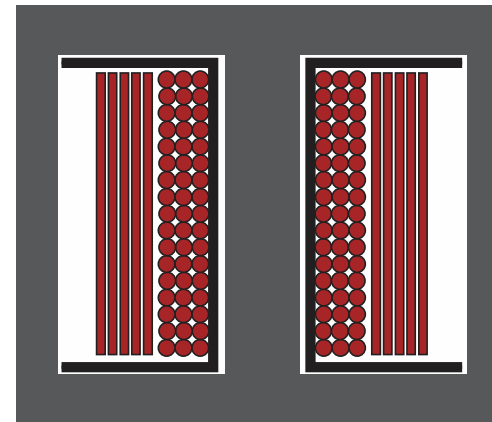
$H_i = \frac{n_i I_i}{b_w}$ H field at boundary of layer

Proximity Loss Example



Primary 51 turns 20 awg 3 layers

Secondary 5 turns 10 mil foil



Primary Proximity Loss

Each Layer is

3.75223876 Depths

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

The H field is calculated from

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

Complex functions are needed to calculate the losses :

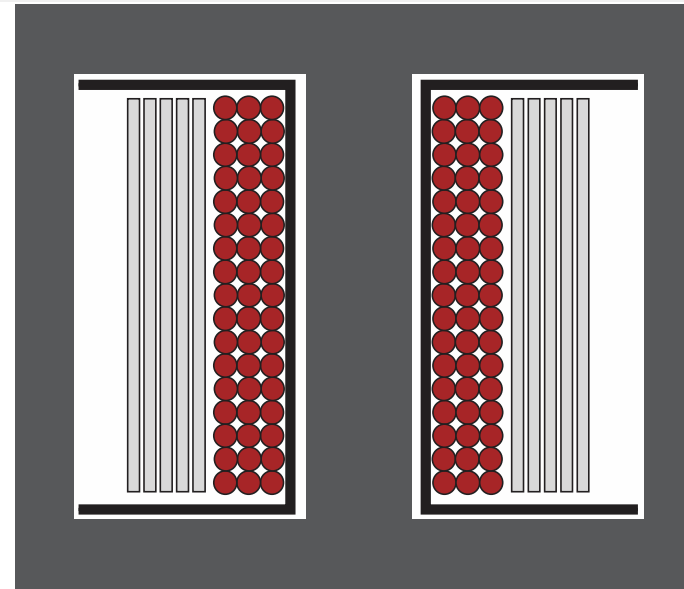
$$G_{1_i} = \Delta_i \frac{\sinh 2\Delta_i + \sin 2\Delta_i}{\cosh 2\Delta_i - \cos 2\Delta_i}$$

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

The ratio of the winding layer height to skin depth is

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

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



PROXIMITY RESISTANCE MULTIPLIER BY LAYER

1	2	3
3.7575	19.768	51.791

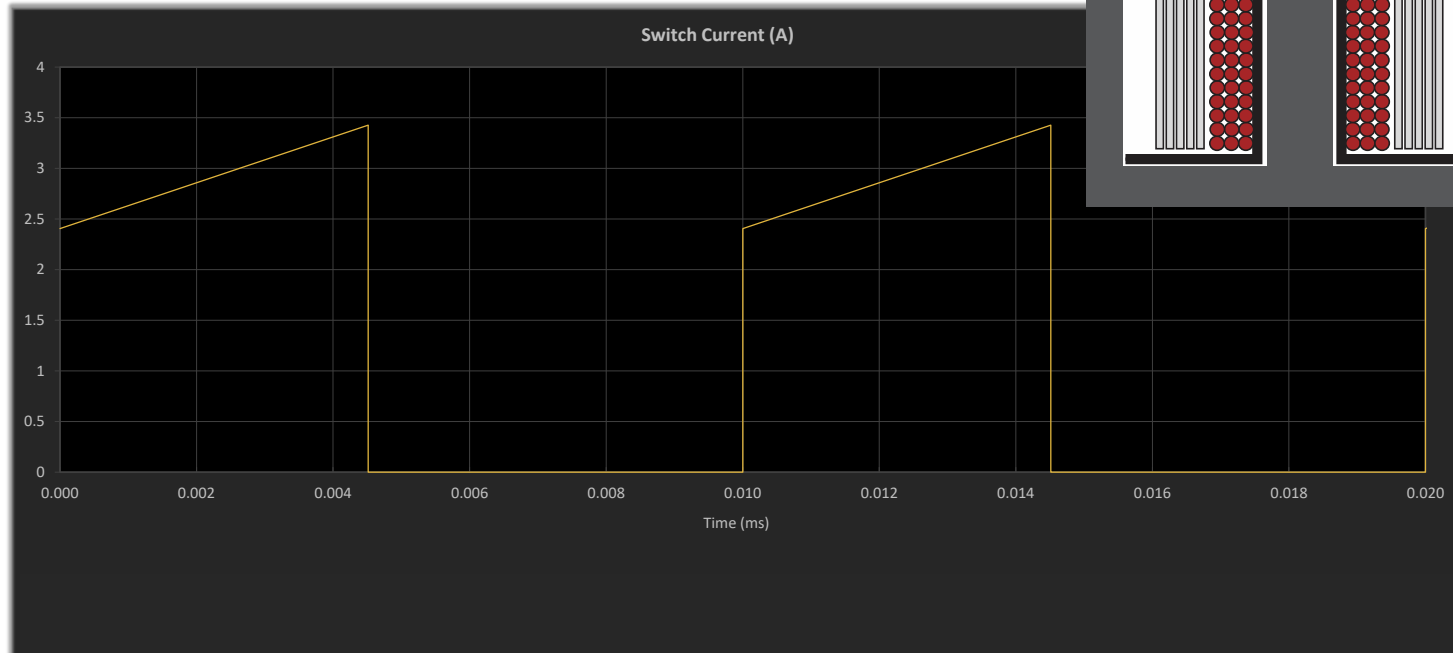
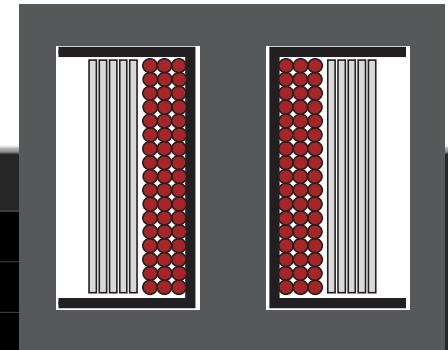
Overall AC/DC Resistance Multiplier 25.1

DC 0.097 Ohm
 100 kHz 2.42 Ohm

DC Winding Resistance	0.09657	Ω
AC Winding Resistance	2.4239	Ω



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

Primary Proximity Loss

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

The H field is calculated from

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

Complex functions are needed to calculate the losses :

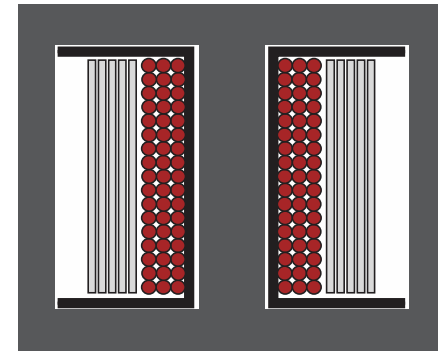
$$G_{1i} = \Delta_i \frac{\sinh 2\Delta_i + \sin 2\Delta_i}{\cosh 2\Delta_i - \cos 2\Delta_i}$$

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

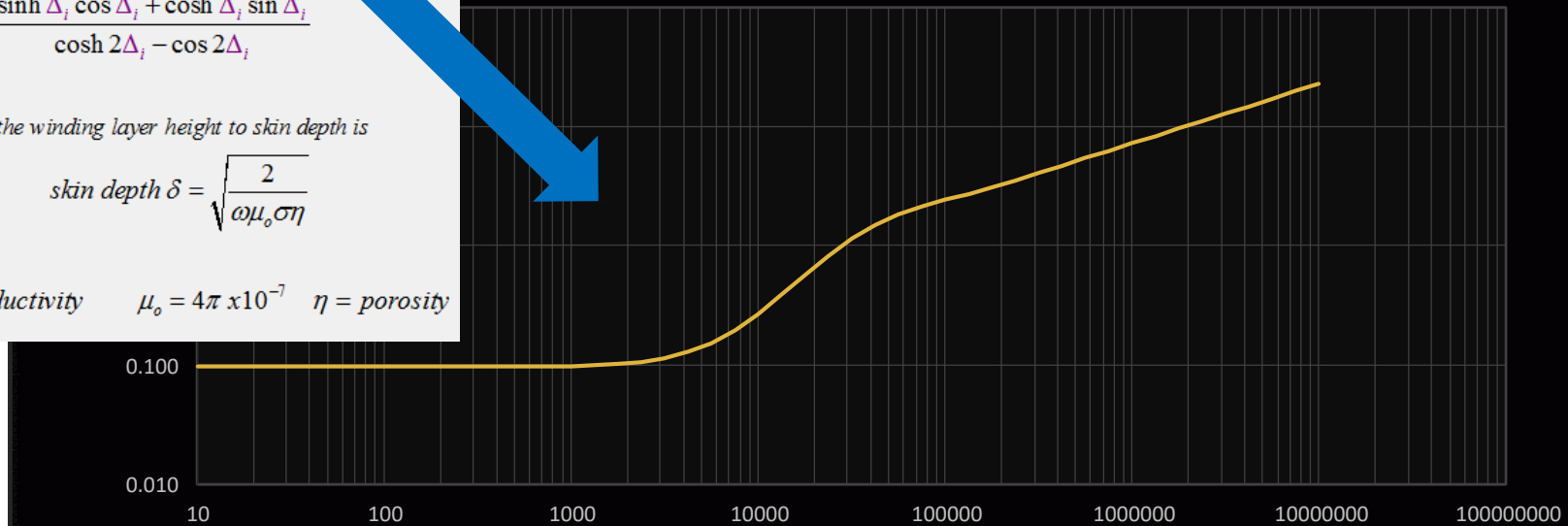
The ratio of the winding layer height to skin depth is

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

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



Transformer Primary AC Resistance vs Frequency



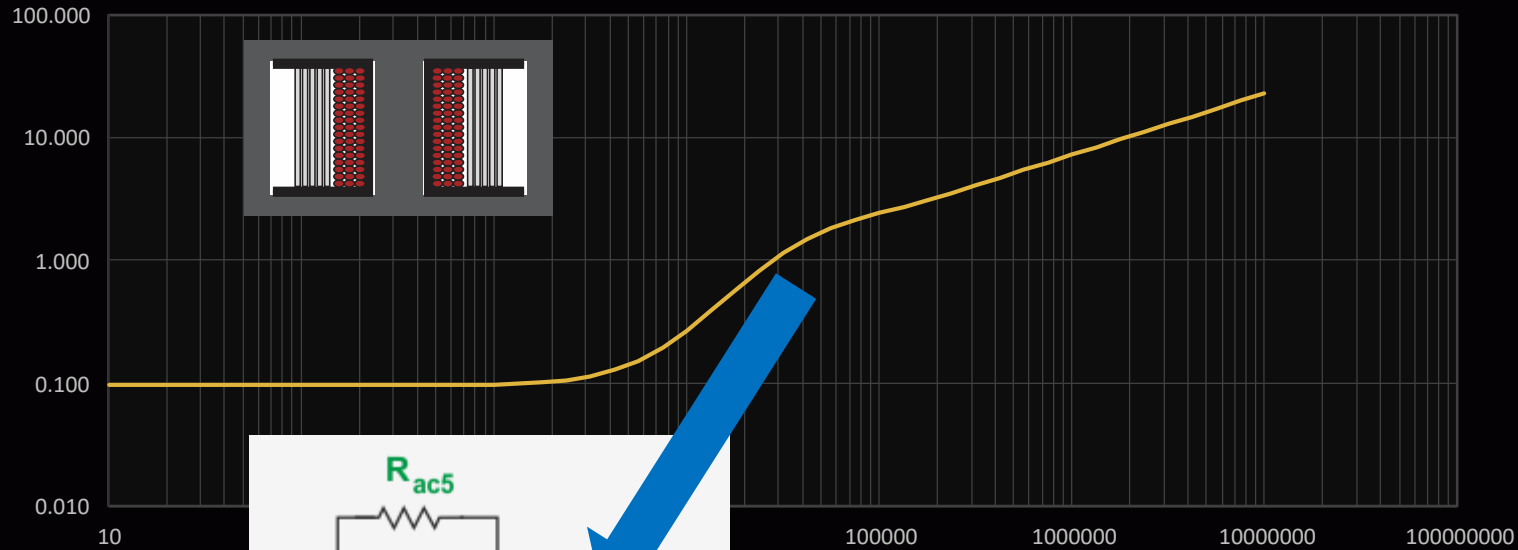
DC Resistance = 0.09657 Ohm

Ripple Frequency Resistance = 2.4239 Ohm

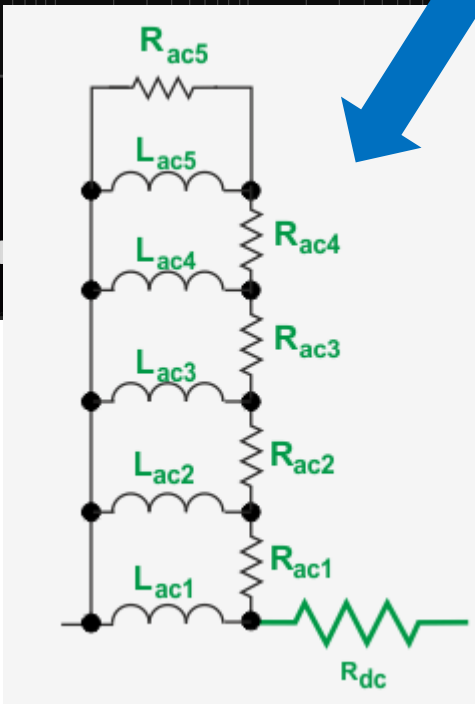
Primary Proximity Loss

Resistance (Ohm)

Transformer Primary AC Resistance vs Frequency



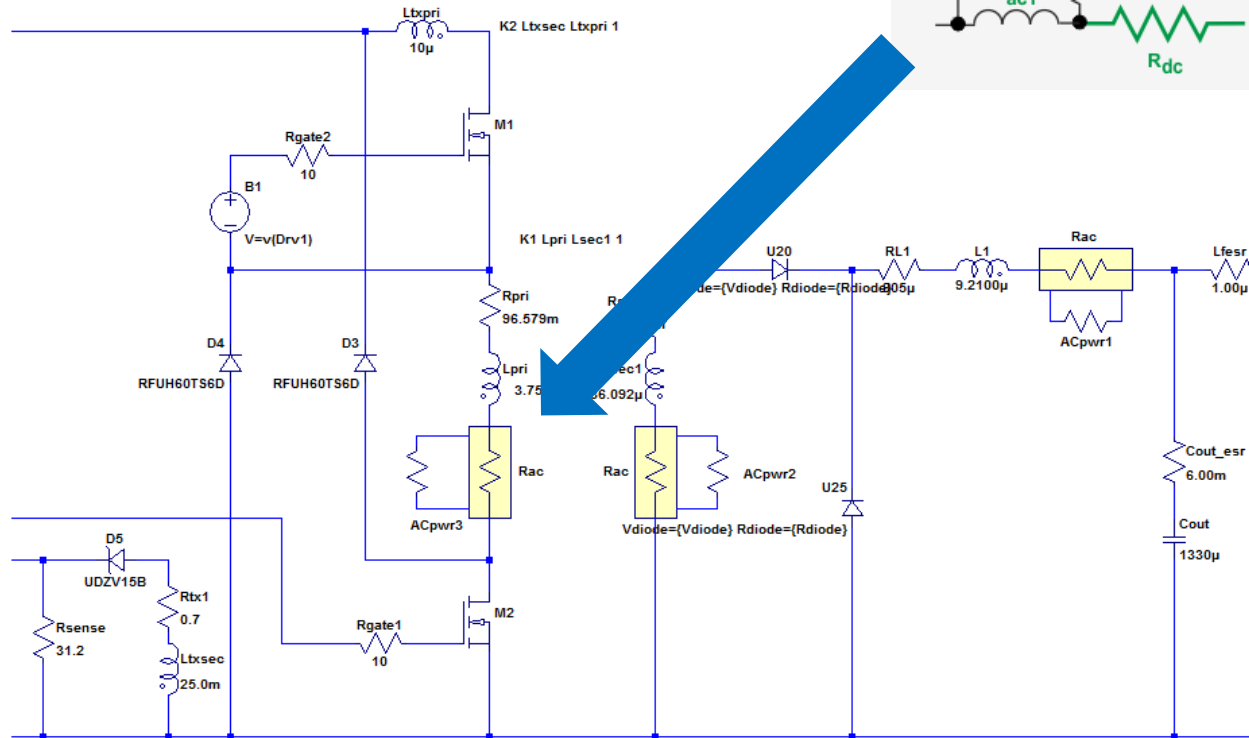
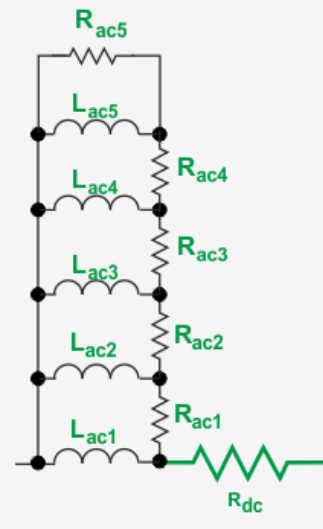
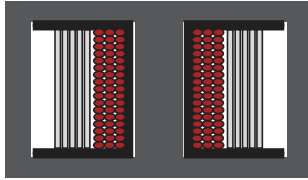
DC Resistance =
Ripple Frequency



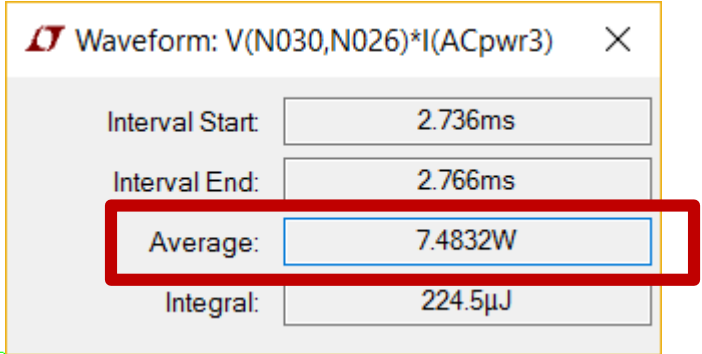
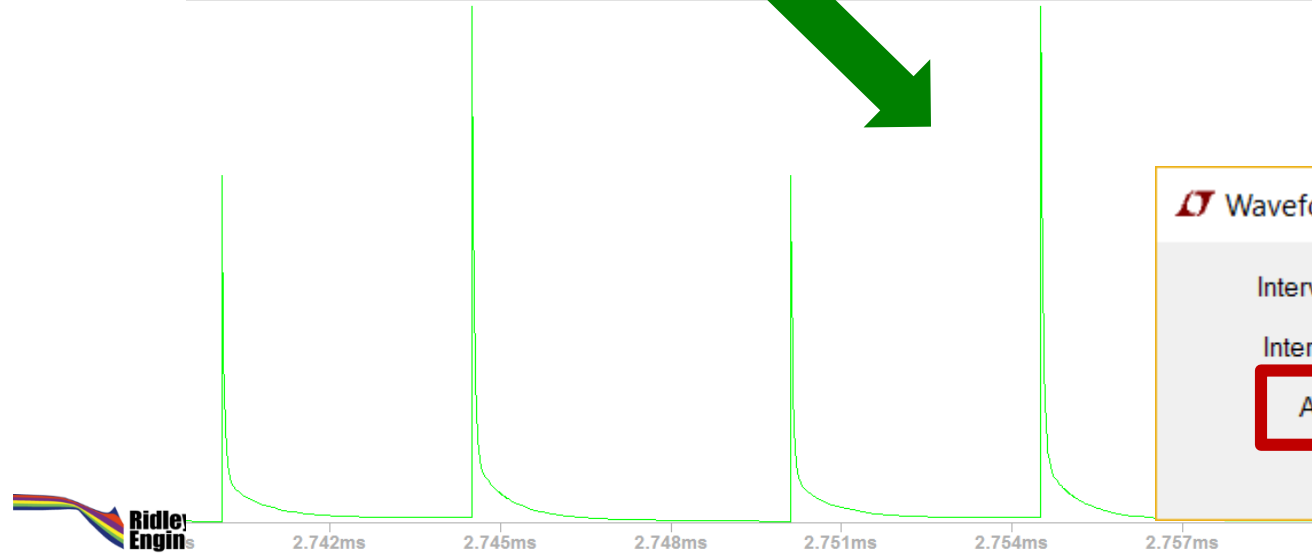
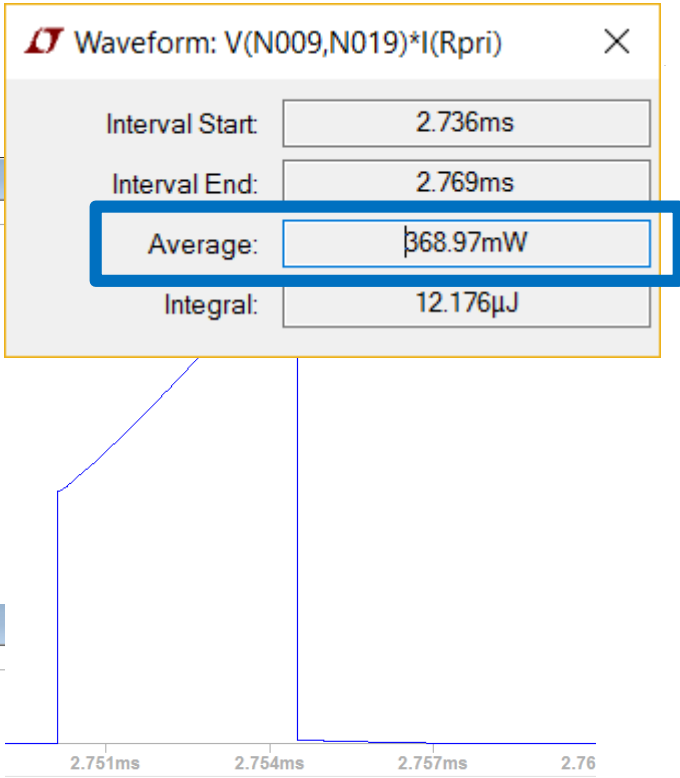
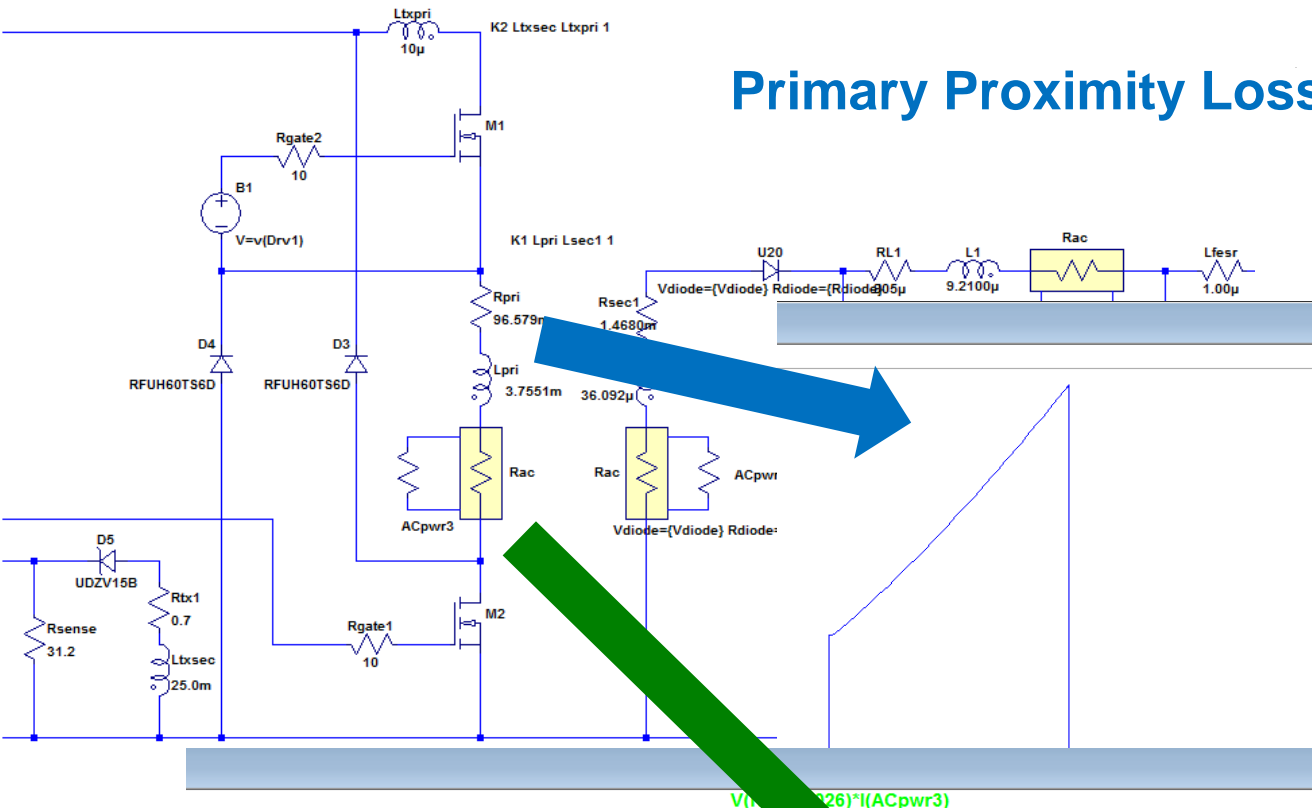
Frequency (Hz)

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

Primary Proximity Loss

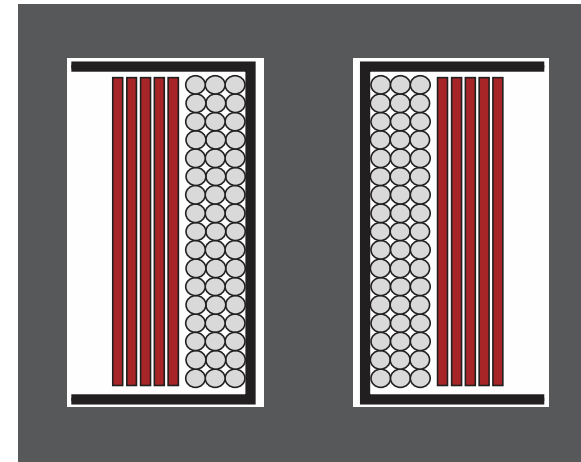


Primary Proximity Loss



Secondary Proximity Loss 10 mil Foil

Each Layer is 1.24413415 Depths



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

The H field is calculated from

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

Complex functions are needed to calculate the losses :

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

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

The ratio of the winding layer height to skin depth is

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

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

PROXIMITY RESISTANCE MULTIPLIER BY LAYER

1	2	3	4	5
1.1952	2.6515	5.5639	9.9327	15.757

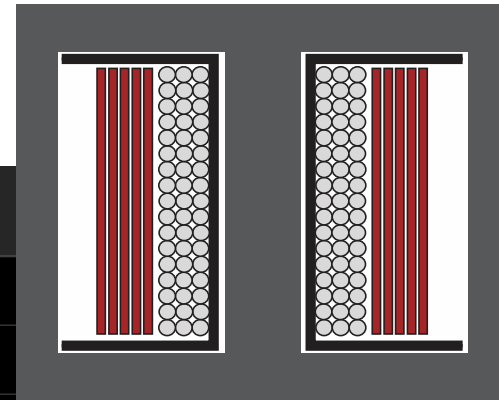
Overall AC/DC Resistance Multiplier 7.020231

DC 0.00145 Ohm
100 kHz 0.0102 Ohm

DC Winding Resistance	0.0014569	Ω
AC Winding Resistance	0.010227	Ω



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	<div style="display: flex; justify-content: space-around; align-items: center;"> <div style="border: 1px solid black; padding: 5px; background-color: #0056b3; color: white; border-radius: 5px;">Proximity Loss</div> <div style="border: 1px solid black; padding: 5px; background-color: #0056b3; color: white; border-radius: 5px;">Plot AC Resistance</div> <div style="border: 1px solid black; padding: 5px; background-color: #ffc107; color: black; border-radius: 5px; width: 30px; height: 30px; display: flex; align-items: center; justify-content: center; font-size: 20px;">Σ</div> </div>		
AC Resistance	0.010227	Ω			

Secondary Proximity Loss

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

The H field is calculated from

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

Complex functions are needed to calculate the losses :

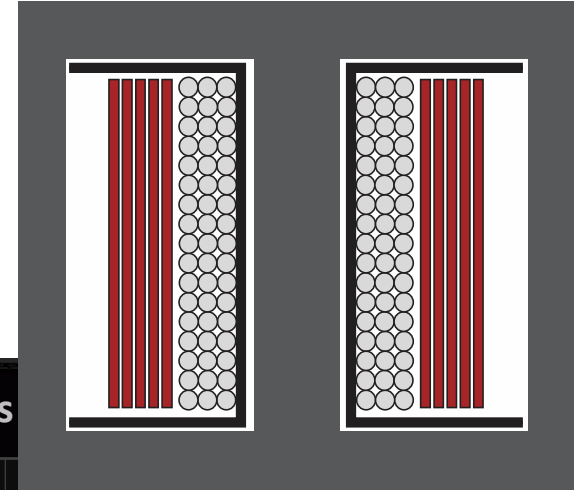
$$G_1 = \Delta_i \frac{\sinh 2\Delta_i + \sin 2\Delta_i}{\cosh 2\Delta_i - \cos 2\Delta_i}$$

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

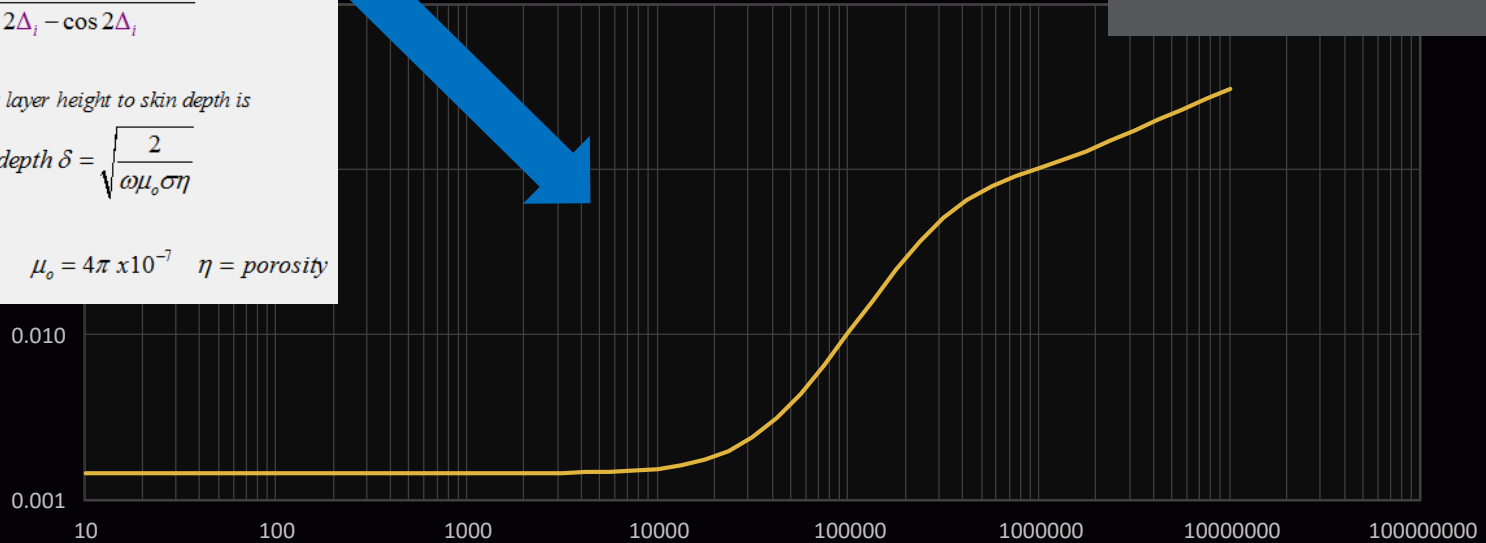
The ratio of the winding layer height to skin depth is

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

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

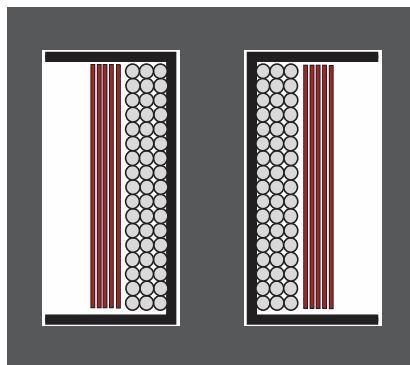


Transformer Secondary AC Resistance vs



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

Maximum Conductor Size That Will Fit Exactly is **0.607** mm = **23.91** mills

Your Choice of Conductor Size mm = **5.24** mills ▲ ▼

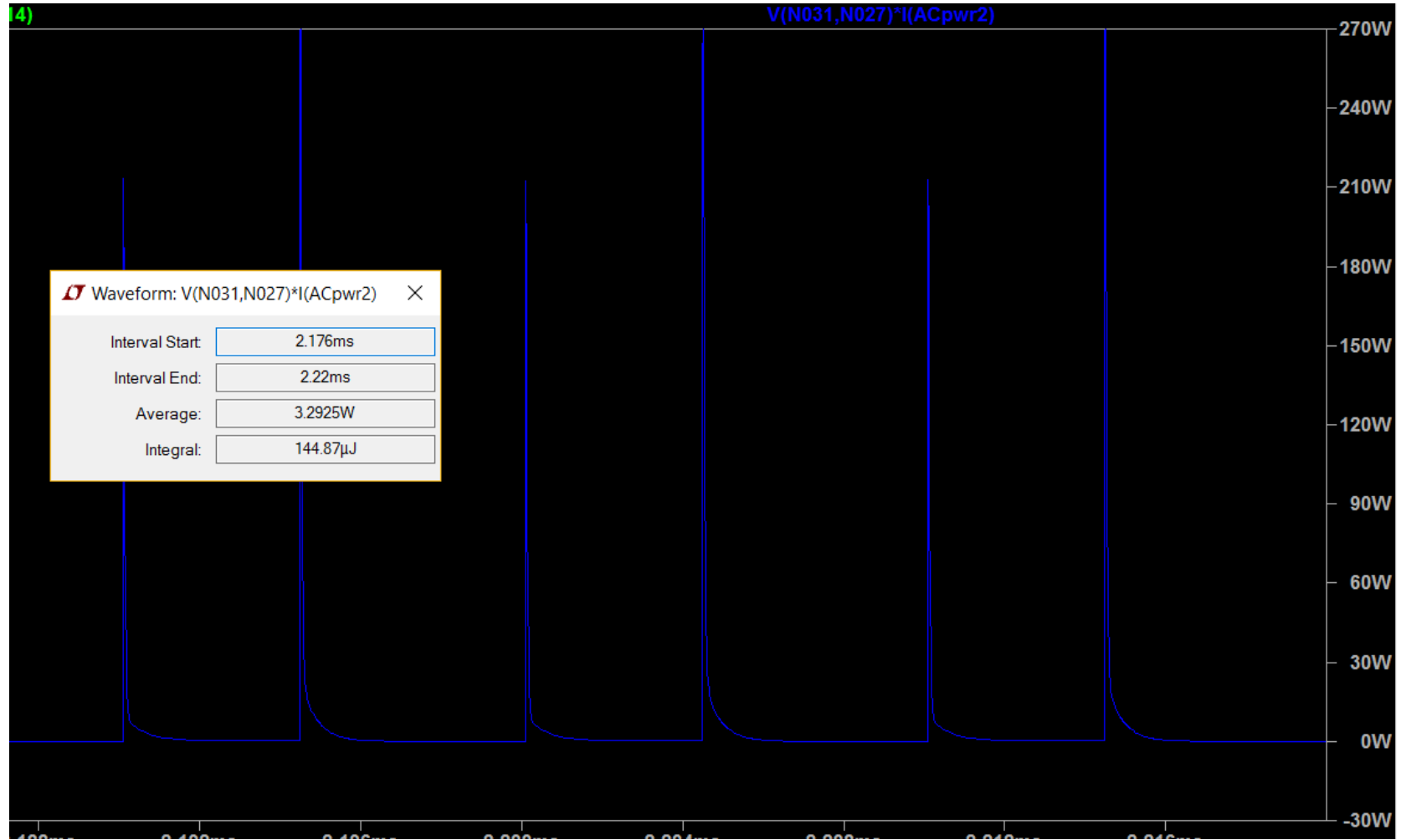
Interleave Primary and Secondary Update Minimize Loss

WINDING LOSS DETAILS

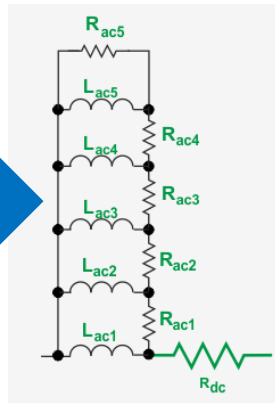
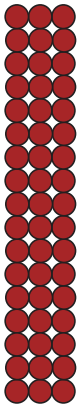
RMS Current	21.549	A	Winding Loss (Including Proximity)	1.65	W
DC Current	14.398	A	Winding Loss (without Proximity Loss)	1.319	W
AC Current	16.032	A	Winding Surface Area	13.3	sq.cm
DC Resistance	0.0028417	Ω			
AC Resistance	0.004129	Ω			

Proximity Loss Plot AC Resistance Σ

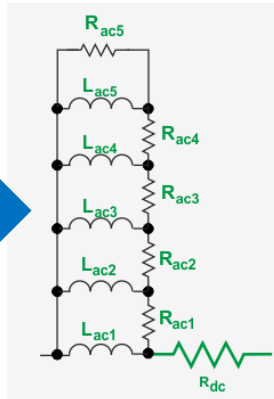
Secondary Proximity Loss Simulation



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
Lac3	29.89081	uH
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

Proximity Loss Circuit Model ✕

This LINEAR circuit can be used in Spice to generate accurate ac losses without more Dowell's equations.

Inductors		Resistors	
Lac1	9.414 μH	Rdc	17.777 mOhm
Lac2	5.546 μH	Rac1	8.1 mOhm
Lac3	1.681 μH	Rac2	80.95 mOhm
Lac4	0.496 μH	Rac3	248.416 mOhm
Lac5	0.124 μH	Rac4	780.391 mOhm
		Rac5	2629.17 mOhm

OK