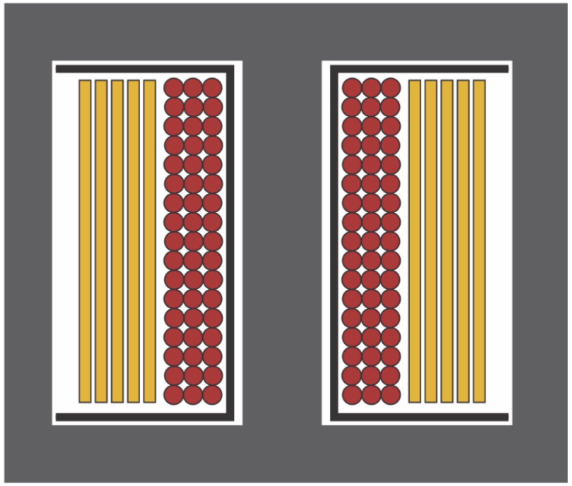
Circuit Modeling of Winding Loss

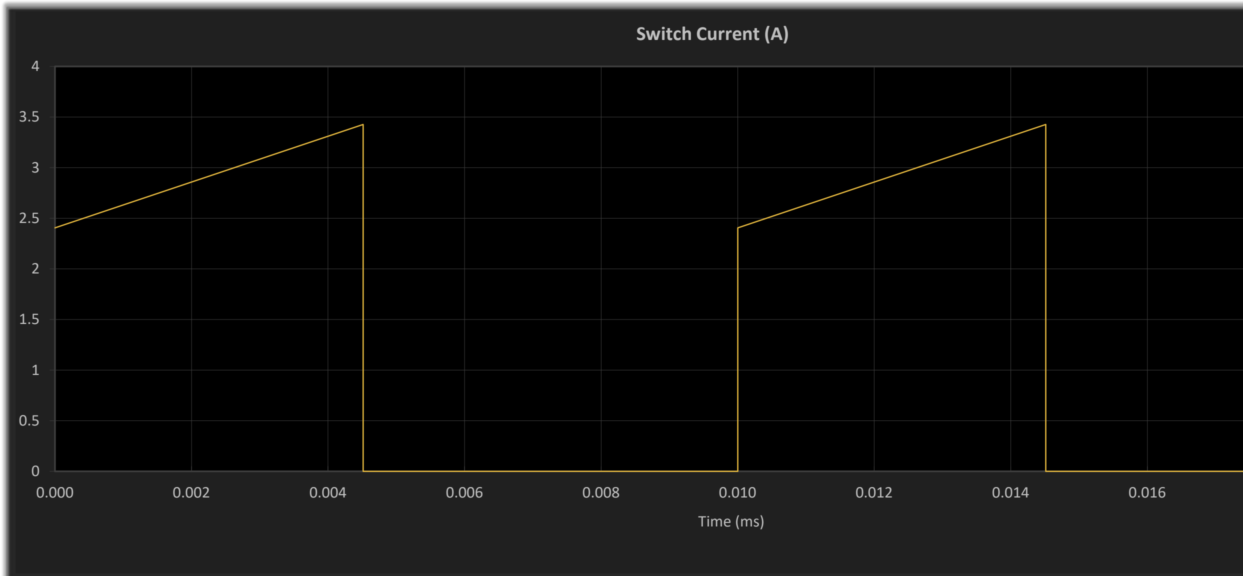
for Inductors and Transformers

Dr. Ray Ridley

ridleyengineering.com

Why do we Need Proximity Loss Analysis?





Primary Winding 0.097 Ohm

51 Turns
3 Layers of 17 Turns 20 awg wire
0.9 mm diameter
Loss = $1.985^2 \times 0.097$ = **0.38 W**

Secondary Winding 1.46 mOhm

5 Turns
5 Layers of 10 mil foil (0.26 mm)
Loss = $21.73^2 \times 0.00146$ = **0.69 W**

Transformer Dissipation		
RMS Calculation	0.38	W
Proximity Fundamental	5.54	W
LTspice Simulation	**8.46**	W
RMS Calculation	0.69	W
Proximity Fundamental	6.02	W
LTspice Simulation	**6.27**	W

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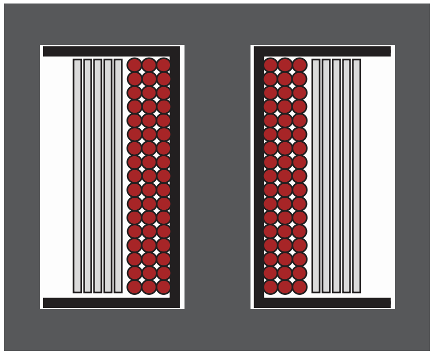
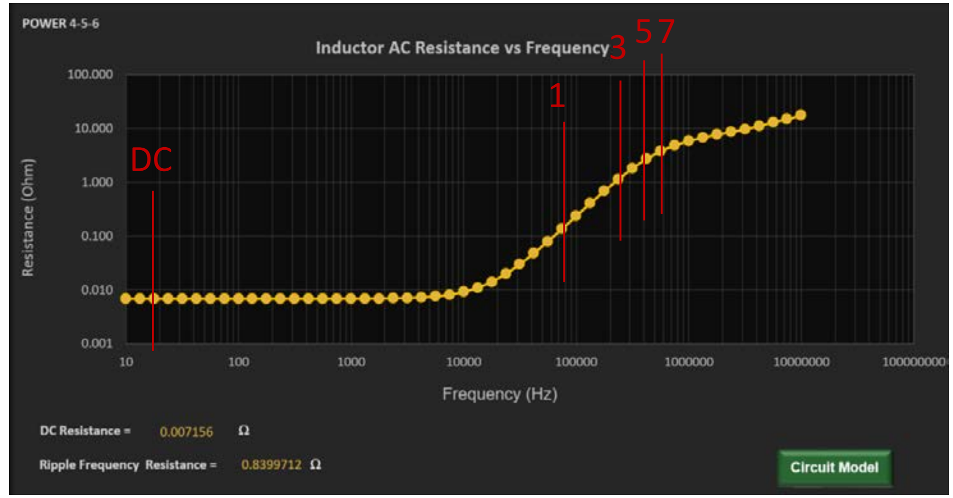
Proximity Loss - the Hard Way

Step 1
Define the Winding Structure

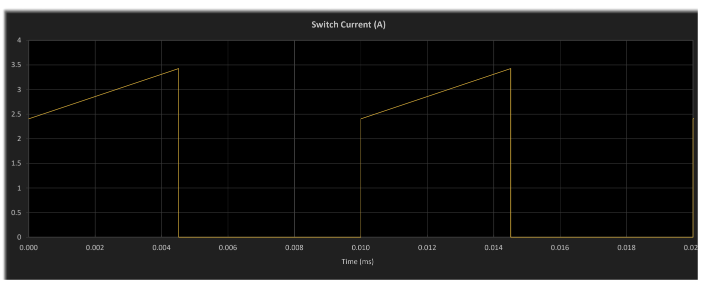


Find n, Rdc and L

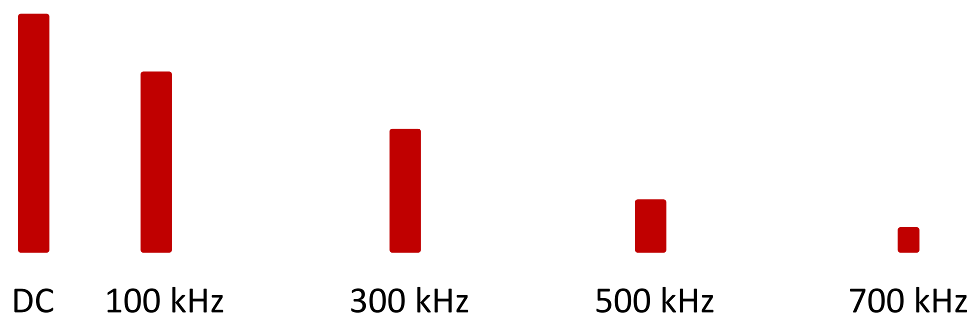
Step 4
Dowell's Eqs for AC Resistance



Step 2
Simulate Waveforms

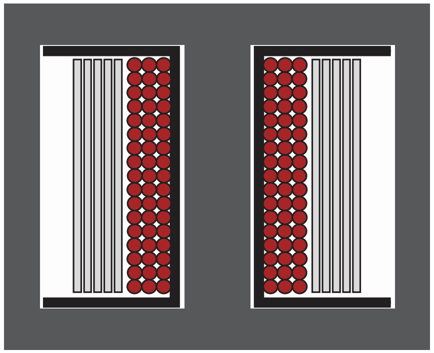


Step 3
Extract Harmonic Content – solve I^2R_{ac} for each



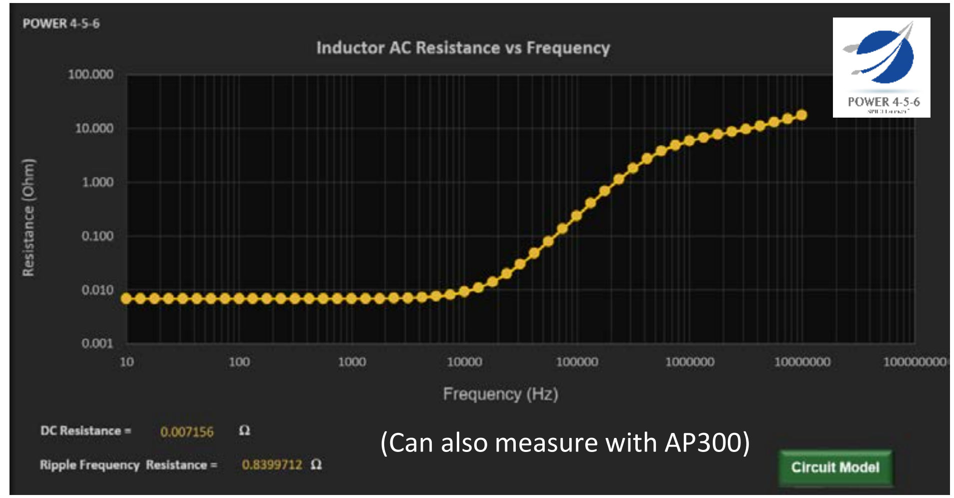
Proximity Loss - the Modern Way

Step 1
Define the Winding Structure

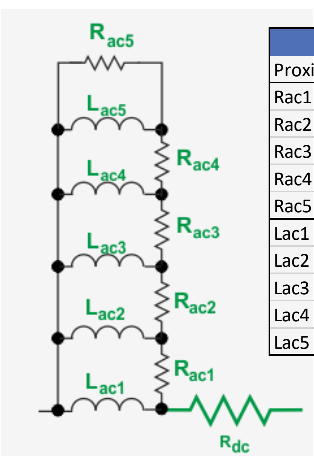


Find n, Rdc and L

Step 2
Sweep Dowell's Eqs for AC Resistance

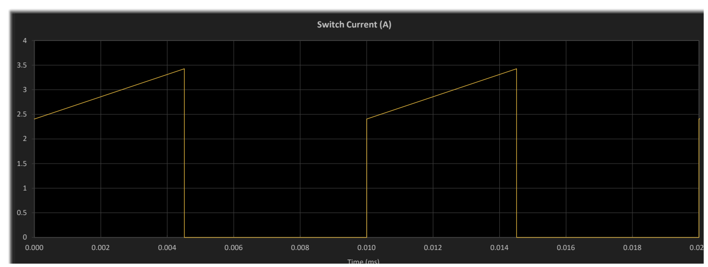


Step 3
Circuit Model to Match Predictions



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

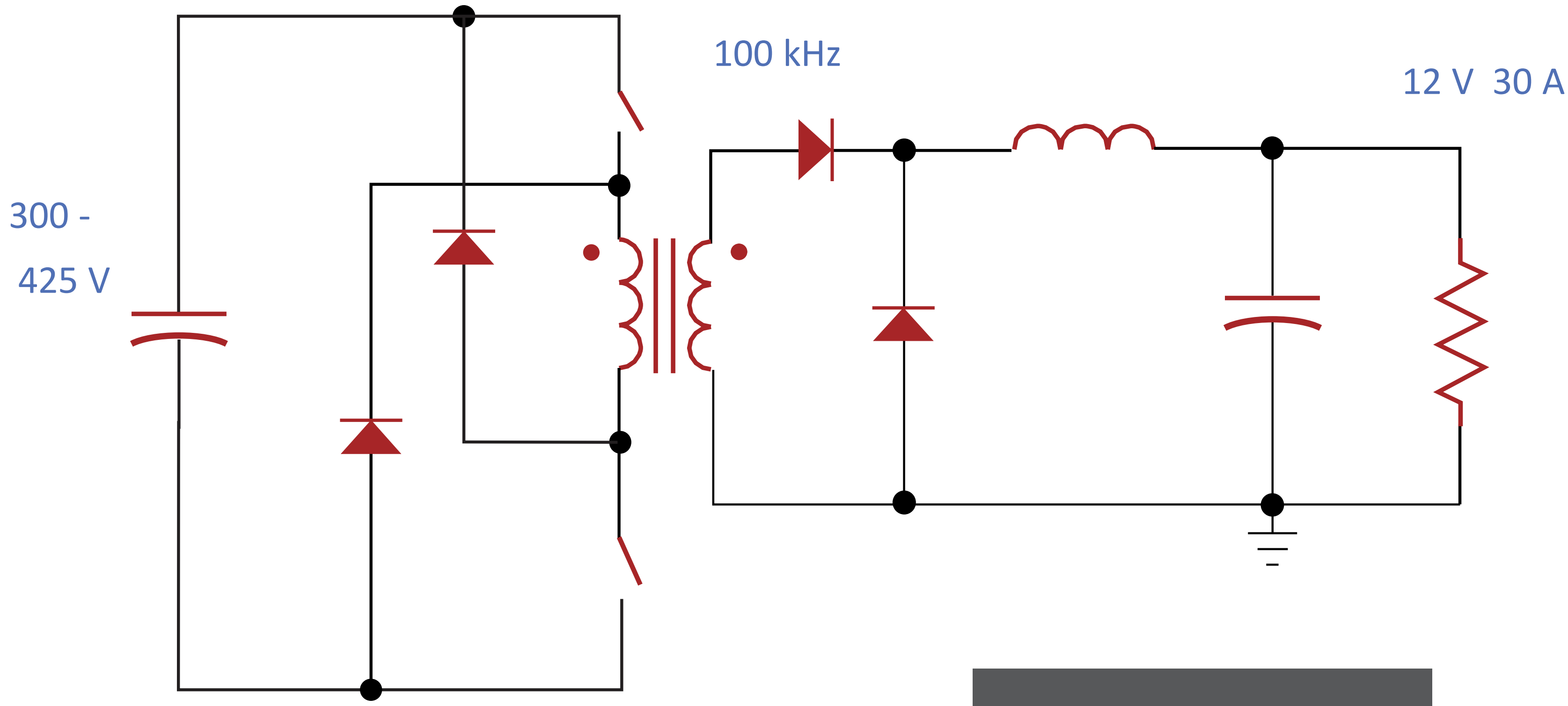
Step 4
Simulate Waveforms - all Proximity Loss is Time Domain



Magnetics Winding Loss

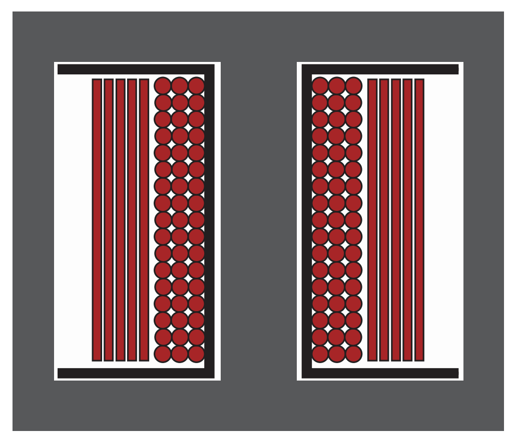
Design Example

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:

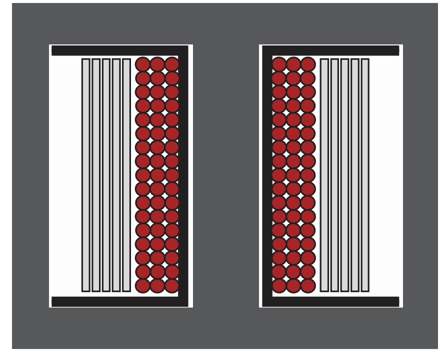
$$G_{1_i} = \Delta_i \frac{\sinh 2\Delta_i + \sin 2\Delta_i}{\cosh 2\Delta_i - \cos 2\Delta_i}$$

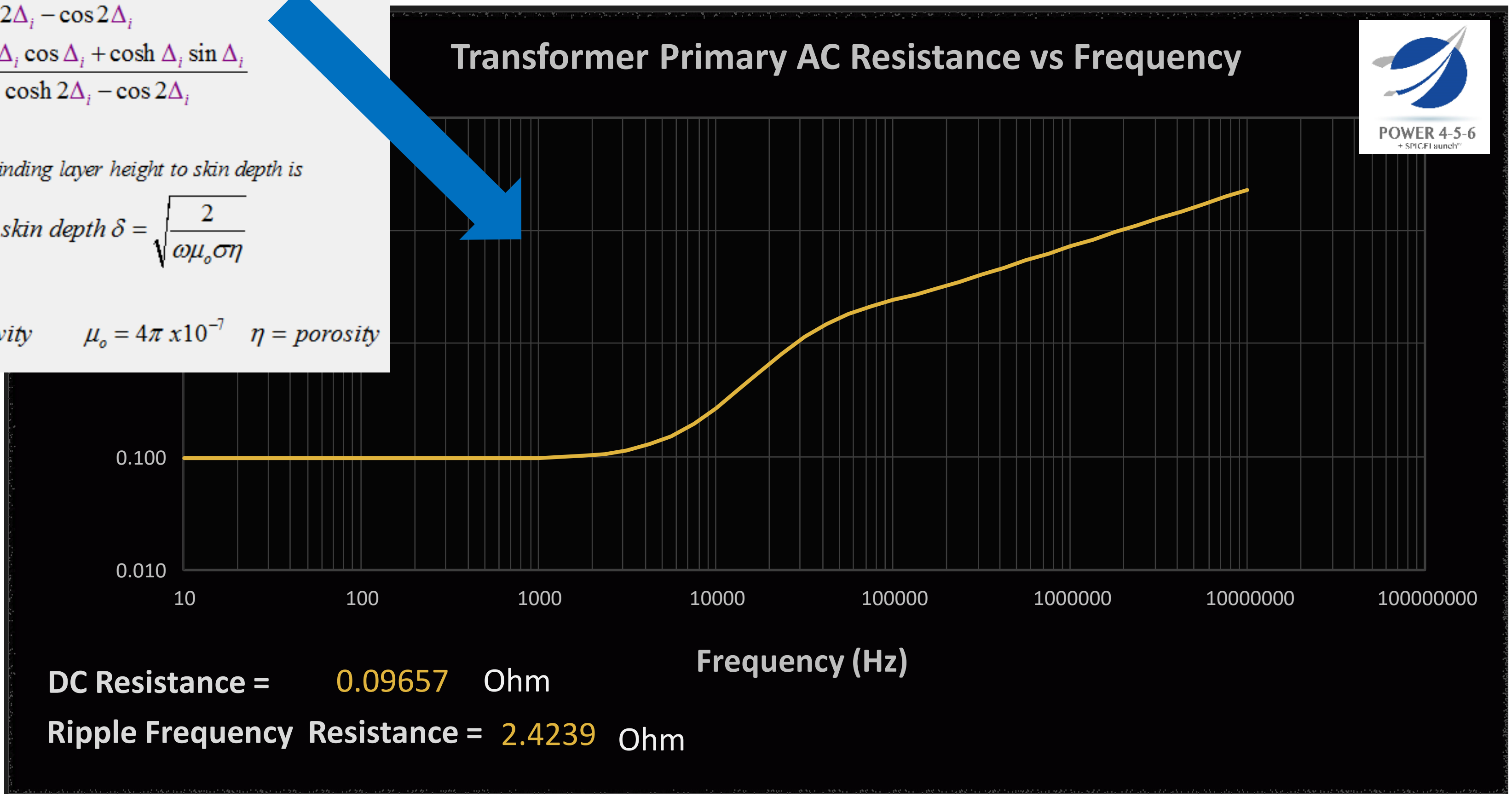
$$G_{2_i} = \Delta_i \frac{\sinh \Delta_i \cos \Delta_i + \cosh \Delta_i \sin \Delta_i}{\cosh 2\Delta_i - \cos 2\Delta_i}$$

The ratio of the winding layer height to skin depth is

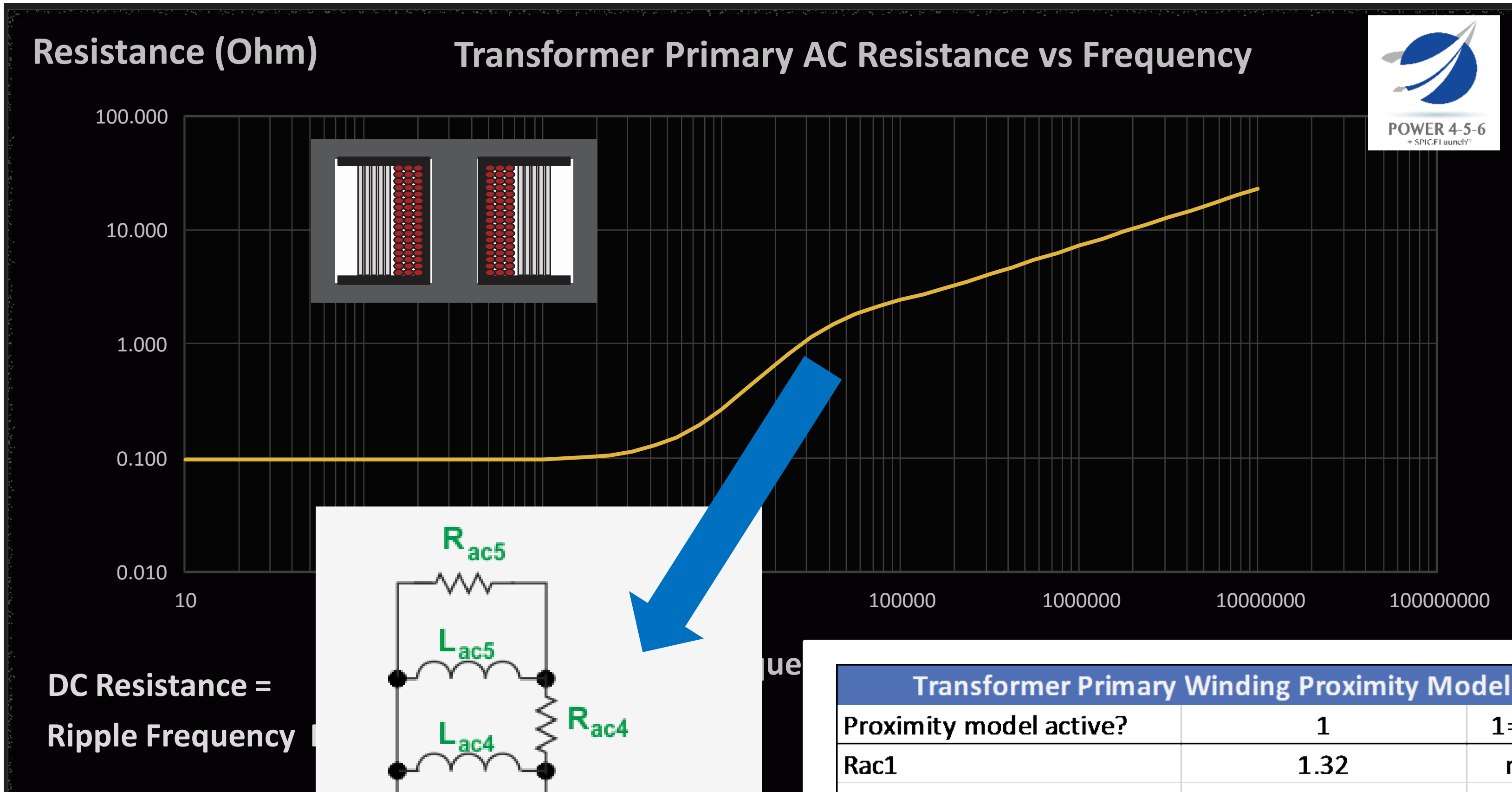
$$\Delta_i = \frac{h_{cu_i}}{\delta} \qquad \text{skin depth } \delta = \sqrt{\frac{2}{\omega \mu_o \sigma \eta}}$$

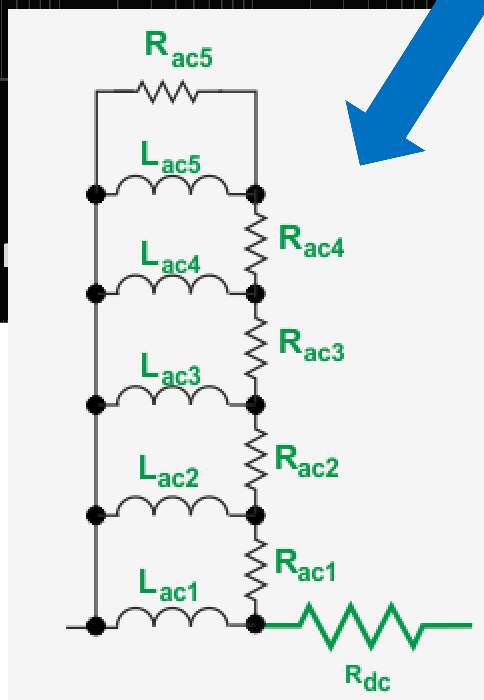
$$\sigma = \text{conductivity} \qquad \mu_o = 4\pi \, x10^{-7} \qquad \eta = \text{porosity}$$





Primary Proximity Loss





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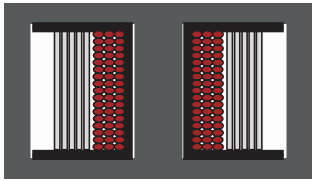
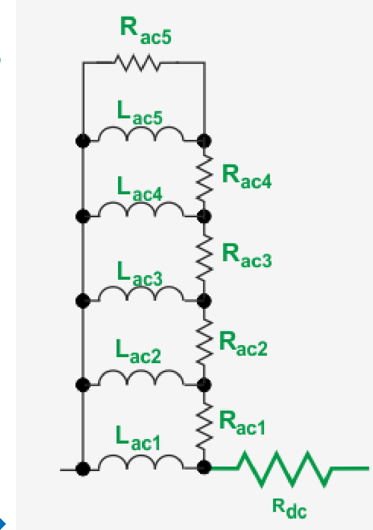
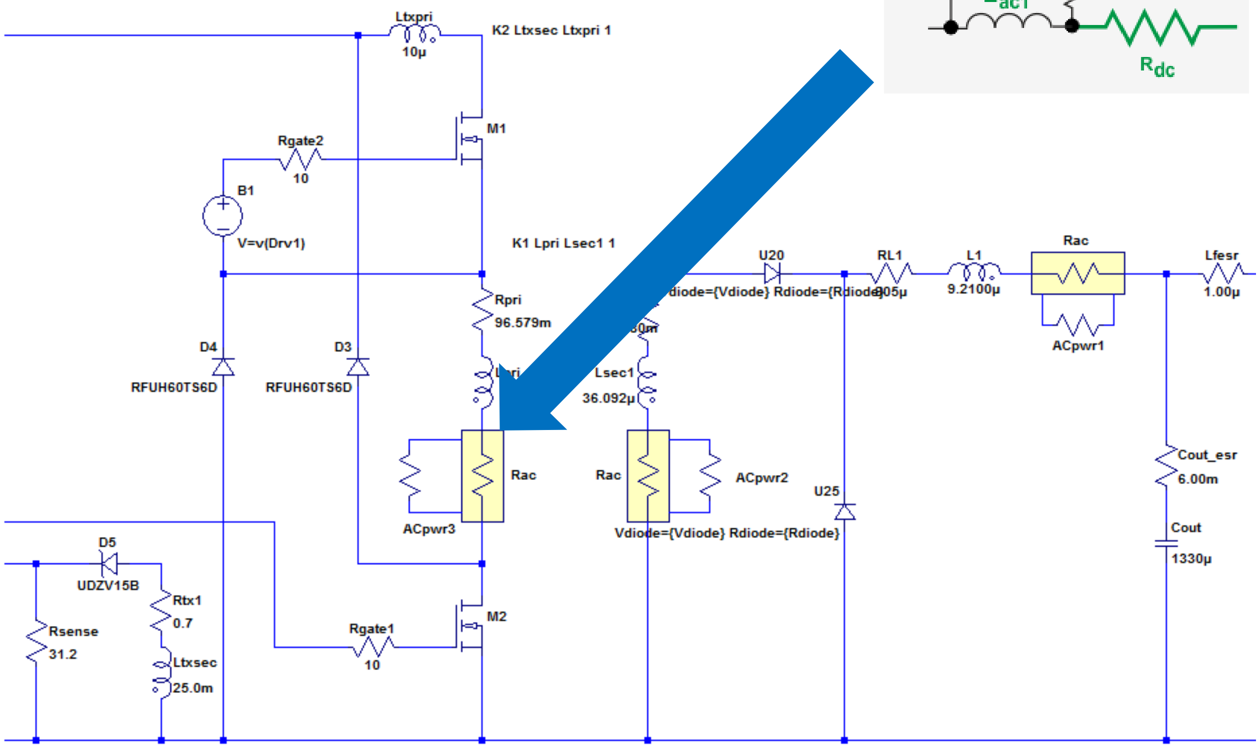
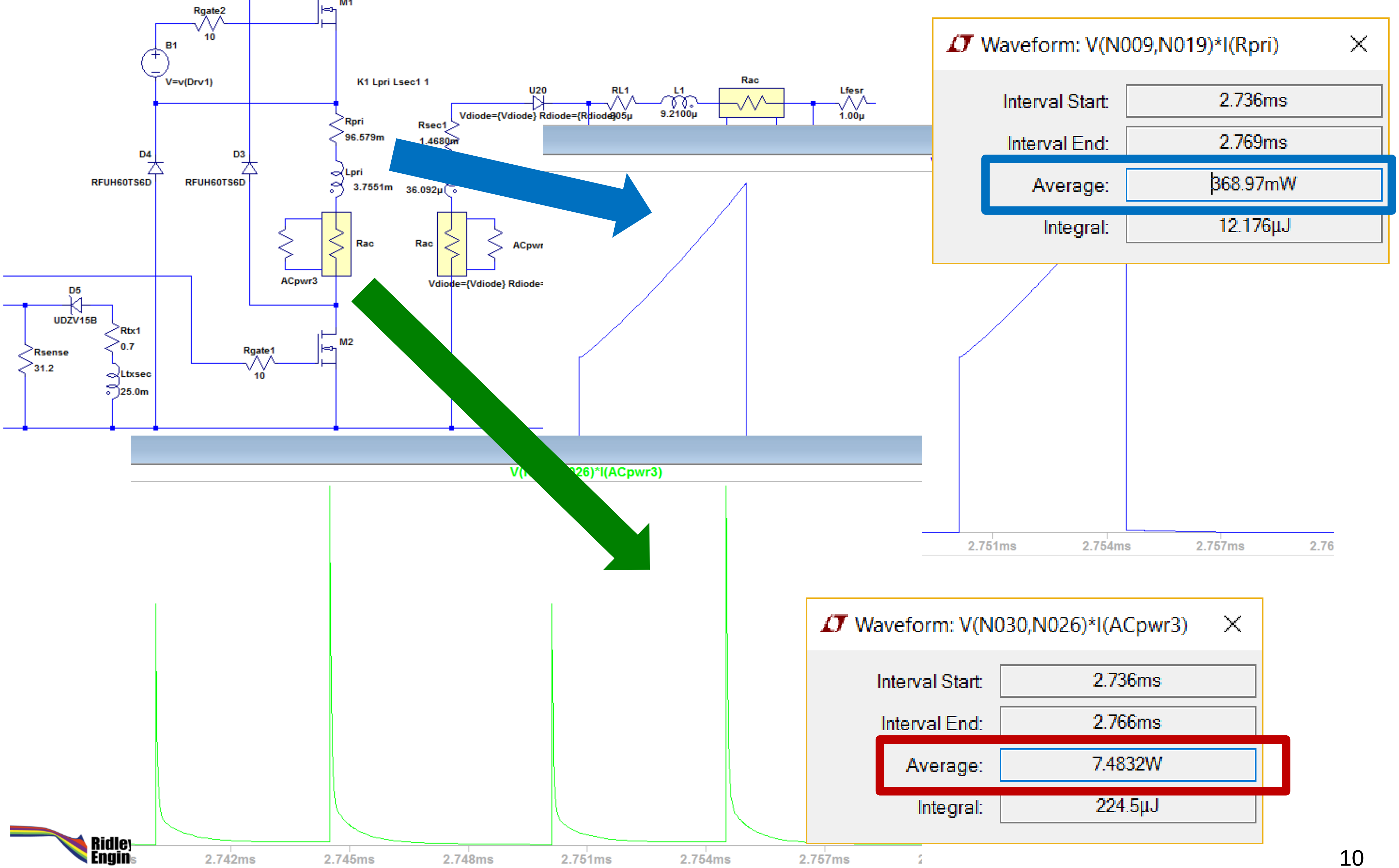






Primary Proximity Loss



Secondary Proximity Loss
(5 mil Foil)

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

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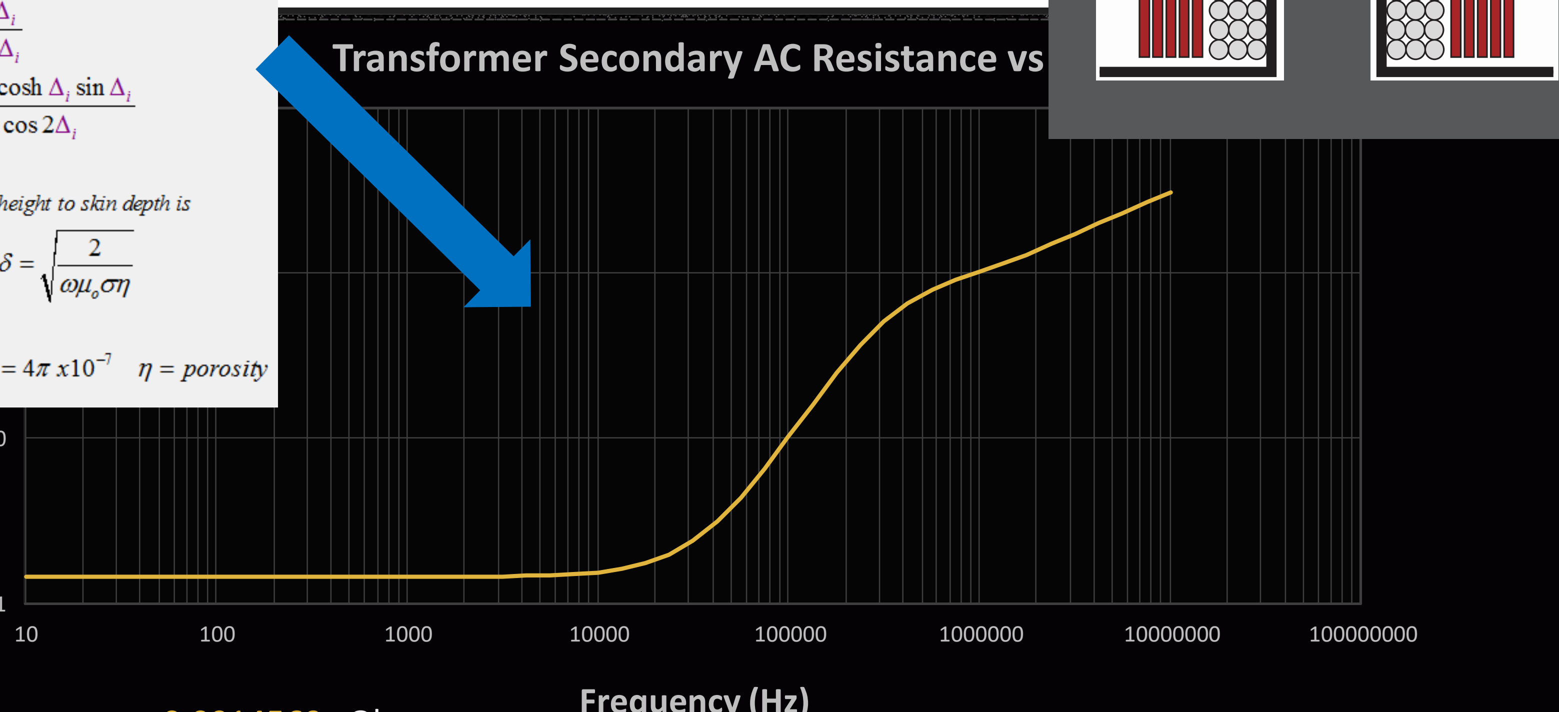
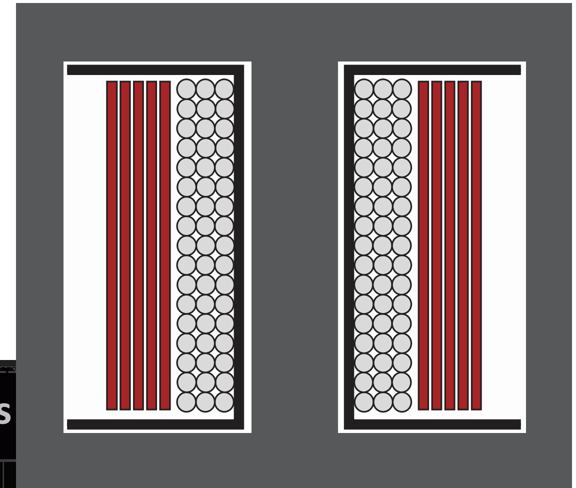
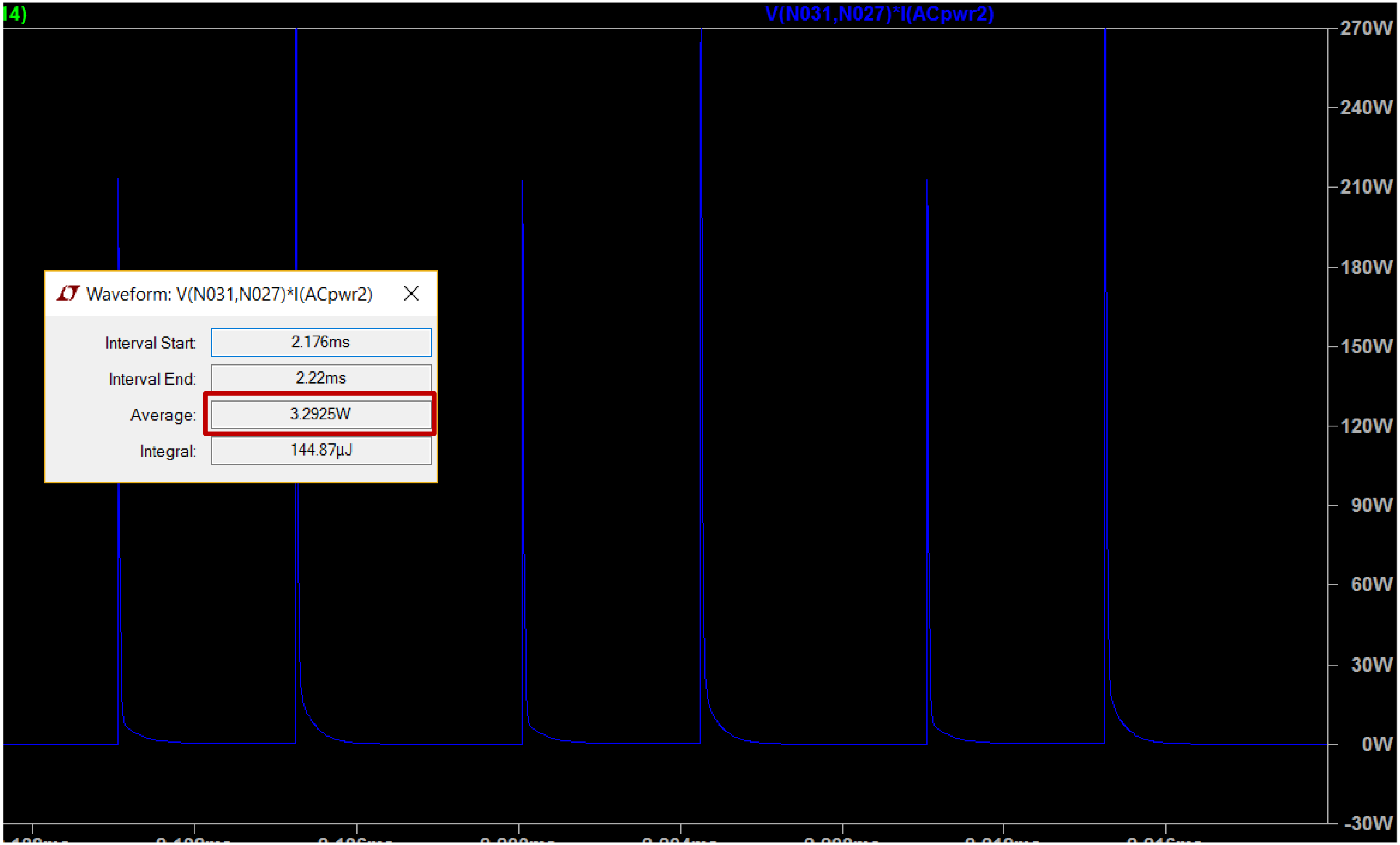


DC Resistance = 0.0014569 Ohm

Ripple Frequency Resistance = 0.0102 Ohm



Secondary Proximity Loss Simulation



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