# Advanced Magnetics
# Practical Circuit Models

**Webinar May 17, 2023**
**10 am Pacific Coast Time**

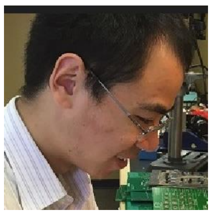
**Dr. Ray Ridley**

**Please click on Handouts to Download Presentation**

# Magnetics Circuit Modeling – Some of the Players

Arthur Nace –aerospace engineer and programmer who automated LTspice models for us and made this work possible. Our longest user of RidleyWorks.

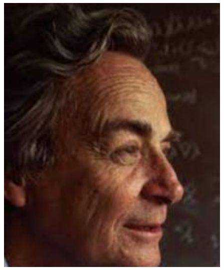
Dr. Vatché Vorpérian – I've had lots of discussions with him on core loss and proximity loss equivalent circuits. (He produced fractal core loss models back in the 1980s.)



Dr. Qichen Yang who solved the math for 5th and 7th-order circuit models for us.

Dr. Shilpa Marti who spent many weeks collecting core loss information (so that you don't have to.)

# Magnetics – Things to Feel Good About



Richard Feynman didn't know how magnets really work either. A great video to watch.

https://www.youtube.com/watch?v=luHDCsYtkTc&ab_channel=AceMon

**Matthew Kallicharran** (Autodidact/Polymath) • 1st 19h •••

Physicist/Engineer - Integrated Magnetics, Embedded Power Converter De...

"We don't actually understand the universe itself. The best we can do is create a model of it and try to understand that..."

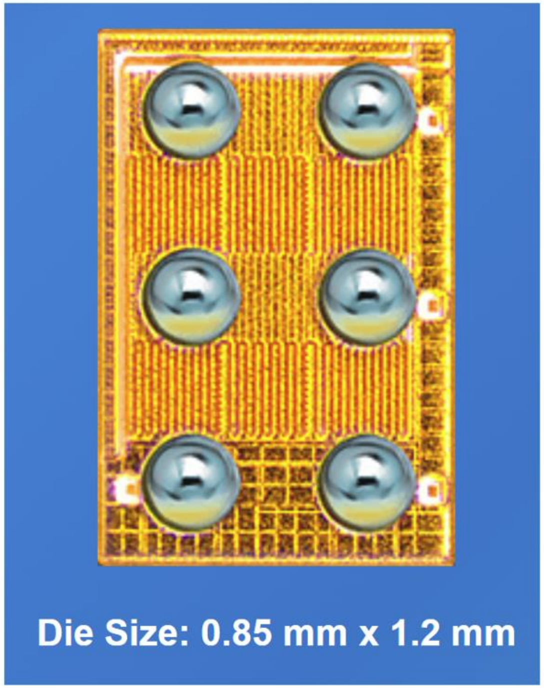
There are ZERO equations in this webinar.

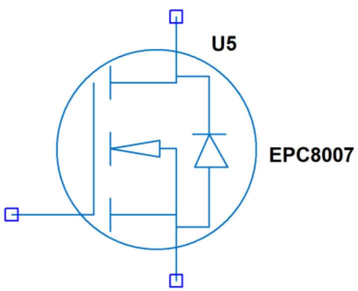
Every equation you might need is in the RidleyWorks software.

At the end of this webinar, we will tell you how to get your **free copy**

 Ridley Engineering

# Semiconductor Models




```
.param scale=40.8/25
.param aWg=scale*25 A1=scale*1.593 k2=2.03 k3=0.177 rpara=0.1412/scale
+     alTc=0.0036 arTc=-0.0036 x0_0=1.02 x0_1=0.1789 x0_1_TC=0.004
+     dgs1=scale*4.3e-7 dgs2=scale*2.6e-13 dgs3=.8 dgs4=.23
+     ags1=(scale*15.6E-12 + 13.1E-12) ags2=scale*8.875E-12 ags3=1.56 ags4=0.26
+     ags5=scale*-2.01E-13 ags6=-7.99 ags7=2.46
+     agd1=scale*0.167E-12 agd2=scale*3.523E-12 agd3=-0.889 agd4=1.044
+     agd5=scale*1.14E-12 agd6=-5.658 agd7=4.445
+     asd1=(scale*2.72E-12 + 1.9E-12) asd2=scale*9.00E-12 asd3=-6.1585 asd4=3.1215
+     asd5=scale*6.37E-12 asd6=-42.978 asd7=28.23


rd drainin drain {(0.75*rpara*(1-arTc*(Temp-25)))}
rs sourcein source {(0.25*rpara*(1-arTc*(Temp-25)))}
rg gatein gate {(.4)}

Rcsdconv drain source {100000Meg/aWg}
Rcgsconv gate source {100000Meg/aWg}
Rcgdconv gate drain {100000Meg/aWg}

bswitch drain source I=if(v(drain,source)>0,
+                    (A1*(1-alTc*(Temp-25))*log(1.0+exp((v(gate,source)-k2)/k3))*
+                    v(drain,source)/(1 + max(x0_0+x0_1*(1-x0_1_TC*(Temp-
25))*v(gate,source),0.2)*v(drain,source)) ),
+                    (-A1*(1-alTc*(Temp-25))*log(1.0+exp((v(gate,drain)-k2)/k3))*
+                    v(source,drain)/(1 + max(x0_0+x0_1*(1-x0_1_TC*(Temp-
25))*v(gate,drain),0.2)*v(source,drain)) ) )

bgsdiode gate source I=if( v(gate,source)>10,
+                    (0.5*aWg/1077*(dgs1*(exp((10.0)/dgs3)-1)+dgs2*(exp((10.0)/dgs4)-1))),
+                    (0.5*aWg/1077*(dgs1*(exp((v(gate,source))/dgs3)-1)+dgs2*(exp((v(gate,source))/dgs4)-1)))
)

bgddiode gate drain I=if( v(gate,drain)>10,
+                    (0.5*aWg/1077*(dgs1*(exp((10.0)/dgs3)-1)+dgs2*(exp((10.0)/dgs4)-1))),
+                    (0.5*aWg/1077*(dgs1*(exp((v(gate,drain))/dgs3)-1)+dgs2*(exp((v(gate,drain))/dgs4)-1))) )


C_GS                 gate source  {ags1}  TC=0,0
C_CGS1               gate source Q=(0.5*ags2*ags4*log(1+exp((v(gate,source)-ags3)/ags4))+
+                    ags5*ags7*log(1+exp((v(source,drain)-ags6)/ags7)) )

C_GD                 gate drain  {agd1}  TC=0,0
C_CGD1               gate drain Q=(0.5*ags2*ags4*log(1+exp((v(gate,drain)-ags3)/ags4))+
+                    agd2*agd4*log(1+exp((v(gate,drain)-agd3)/agd4))+agd5*agd7*log(1+exp((v(gate,drain)-
agd6)/agd7)) )

C_SD                 source drain  {asd1}  TC=0,0
C_CSD1               source drain Q=(asd2*asd4*log(1+exp((v(source,drain)-asd3)/asd4))+
+                    asd5*asd7*log(1+exp((v(source,drain)-asd6)/asd7)) )
```



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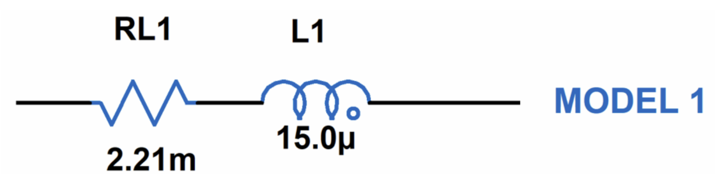
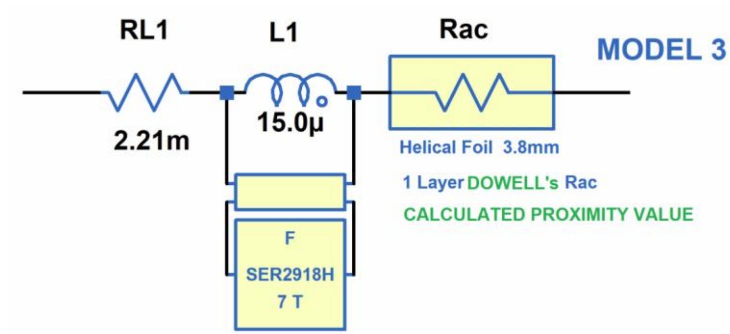
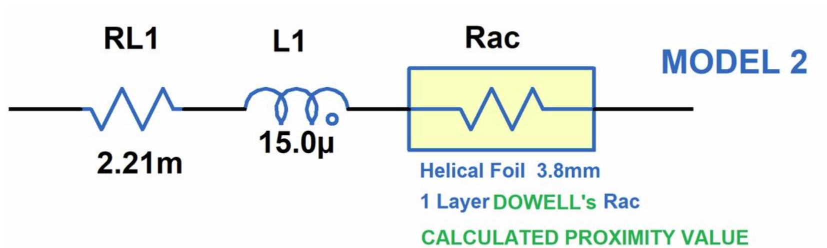
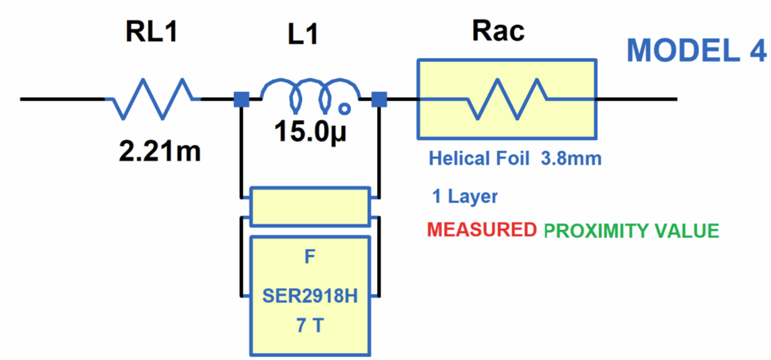
# Magnetics Models

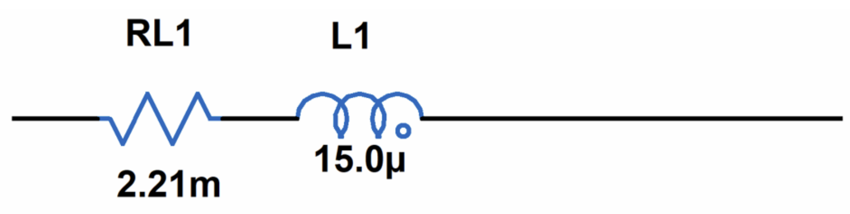



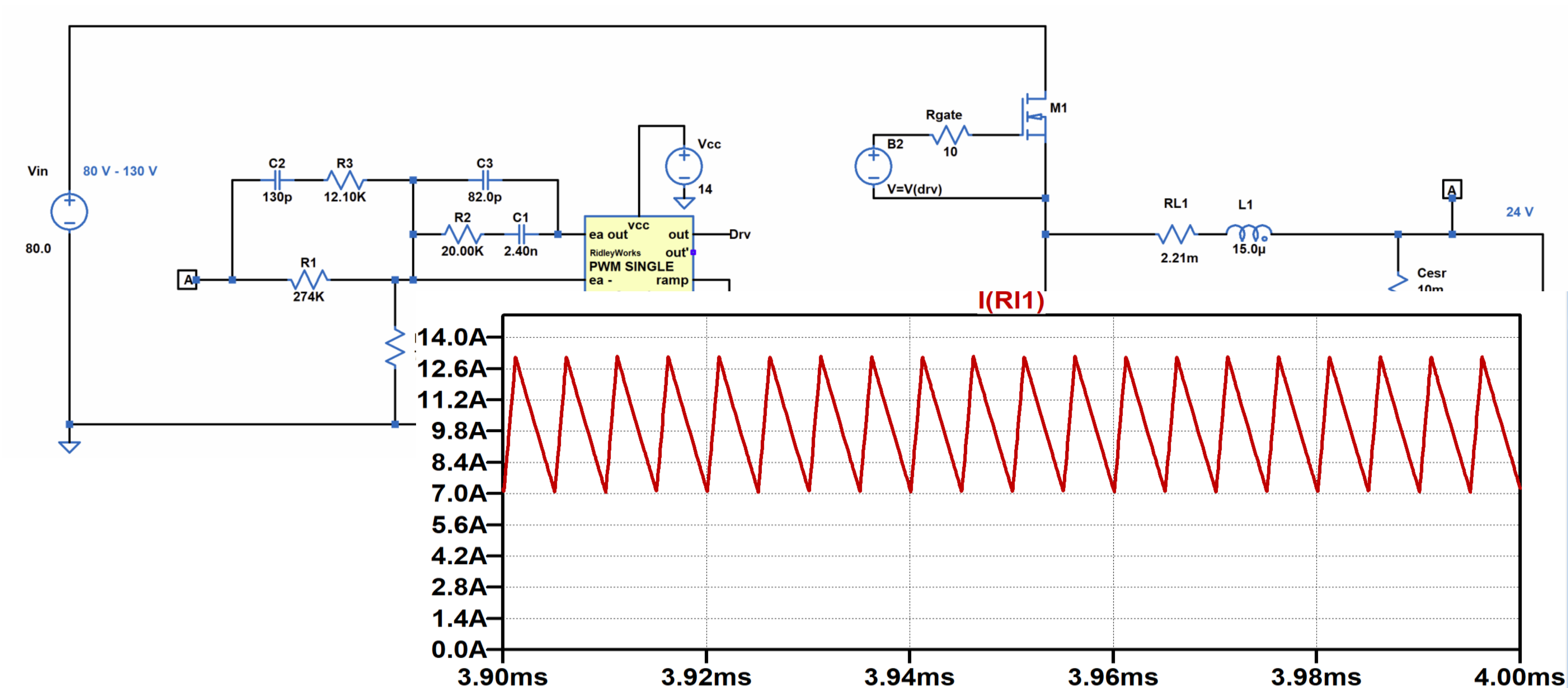



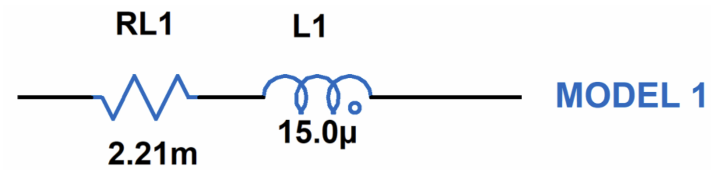
# Magnetics Models

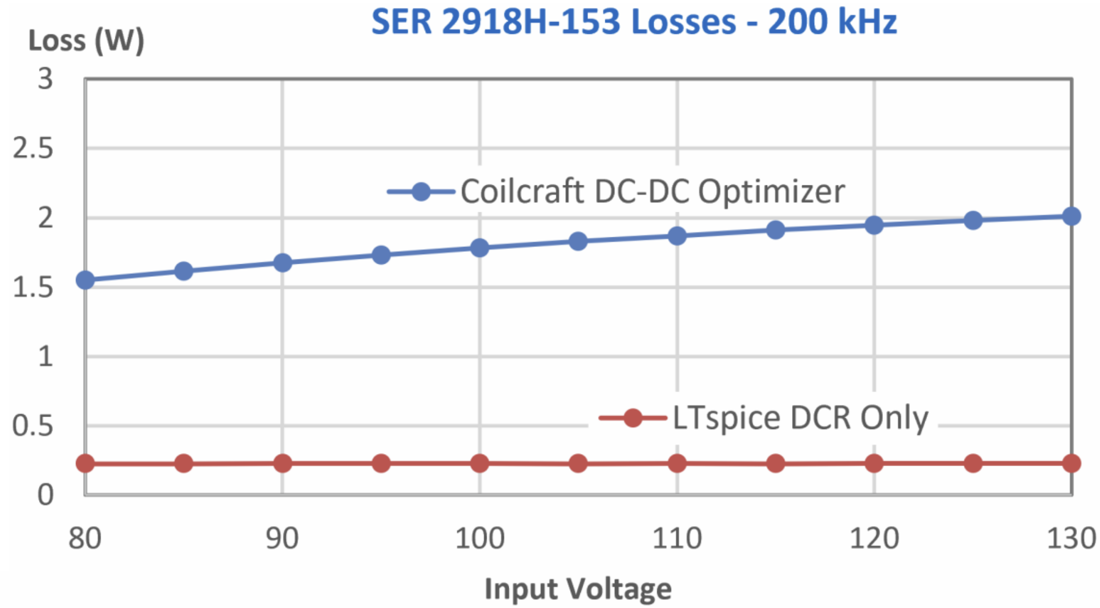


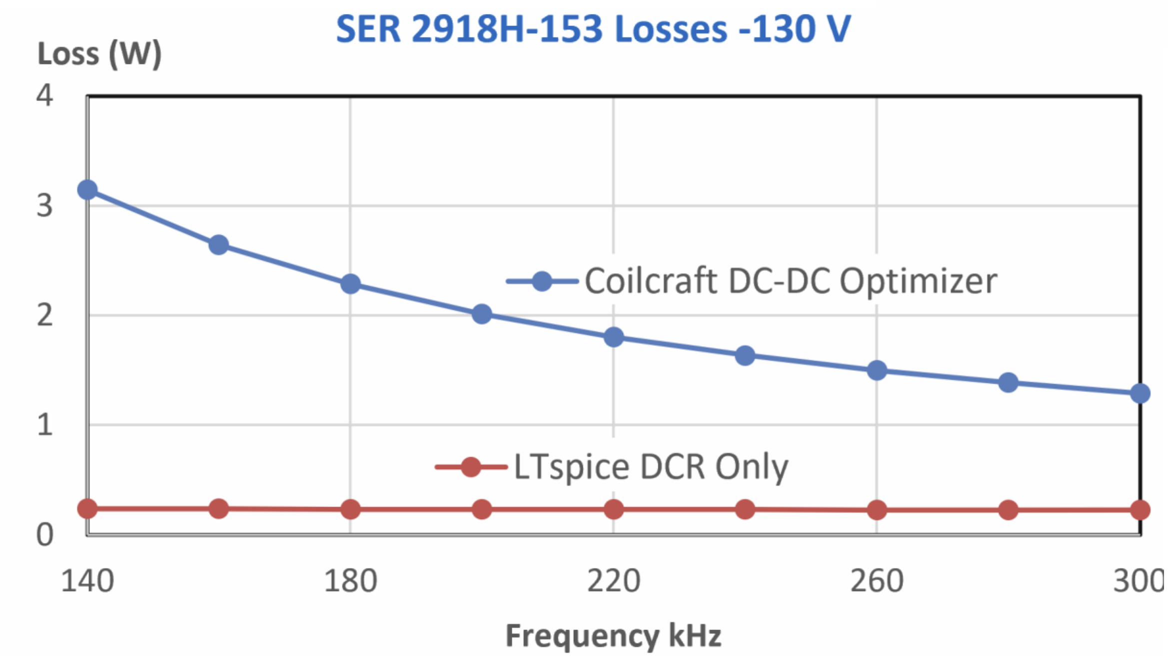

MODEL 1



# Simulation Results Model 1



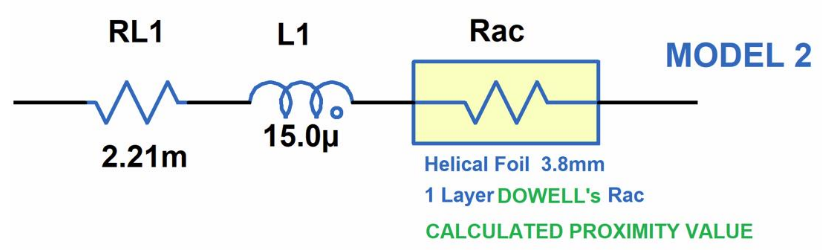



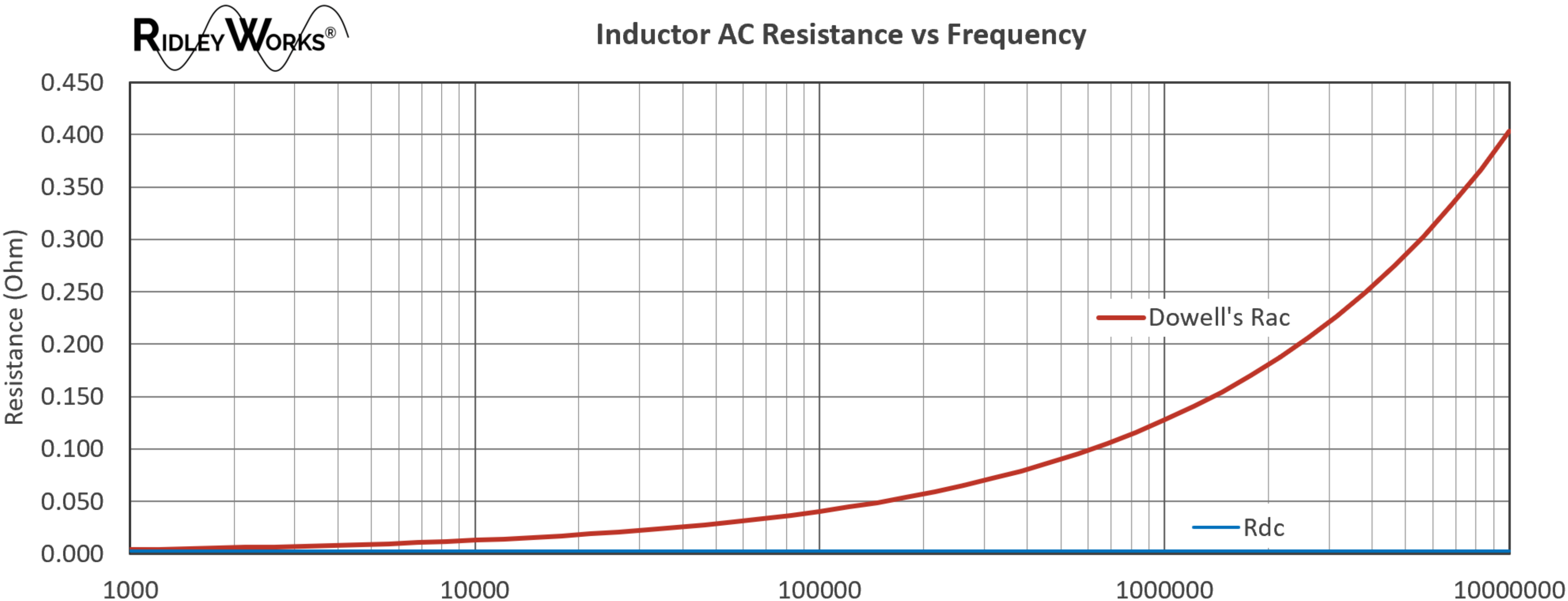

[3] **Coilcraft DC-DC Optimizer**

Nice tool to get the inductor data from.

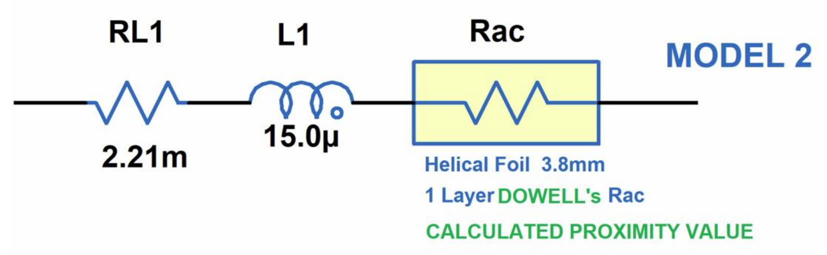
# Adding Dowell's Equation Results [1]



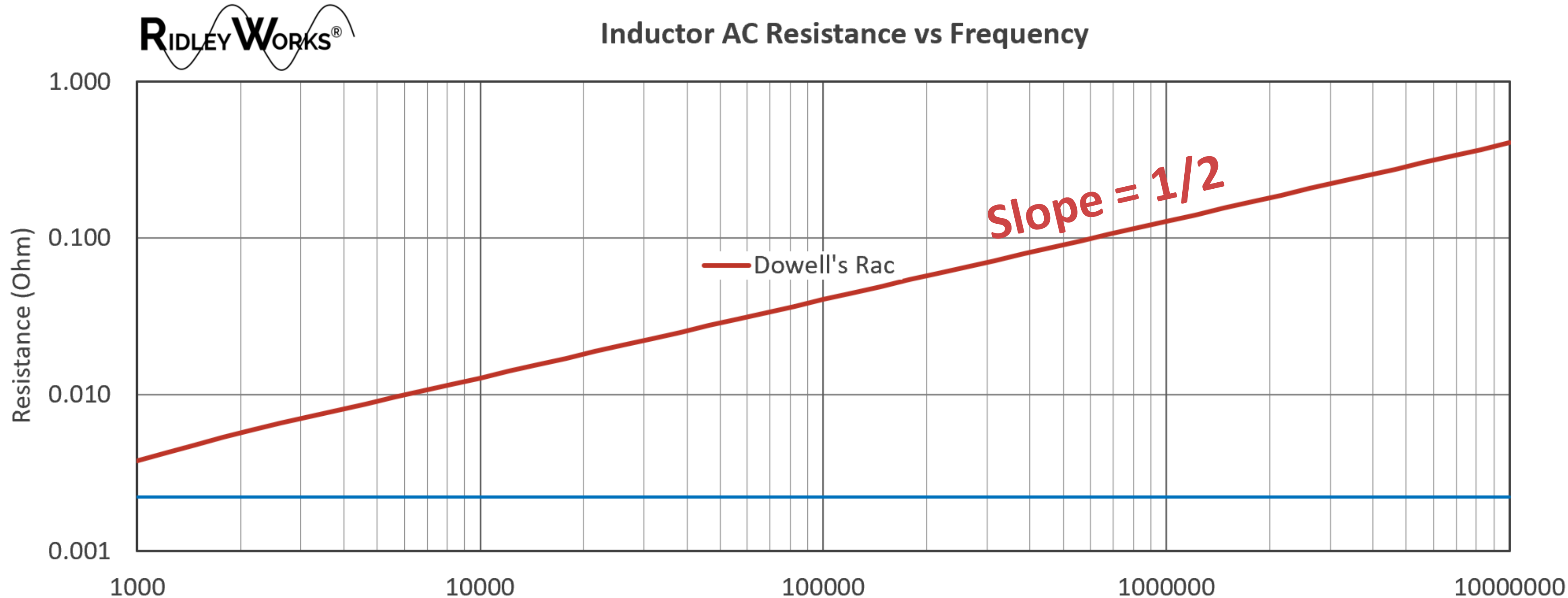

## Linear Plot



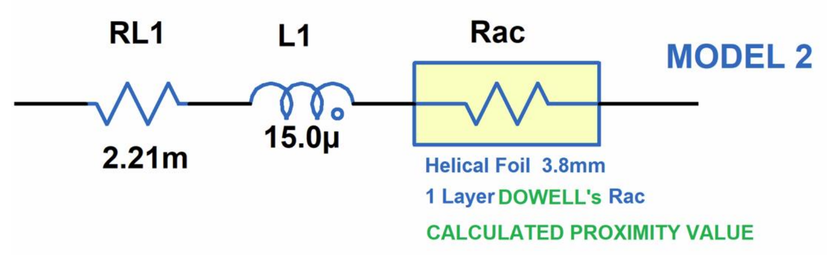
# Adding Dowell's Equation Results [1]

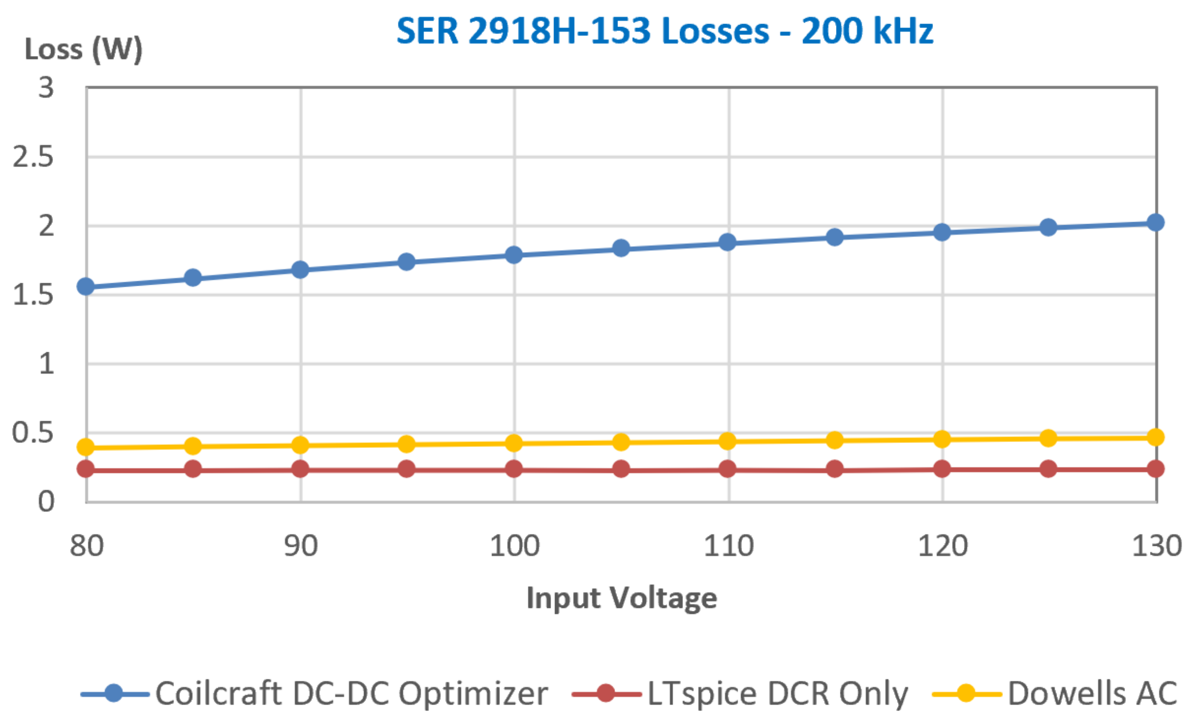



## Logarithmic Plot

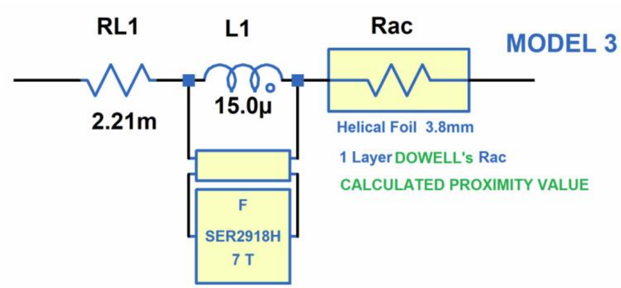


# Simulation Results with Dowell's

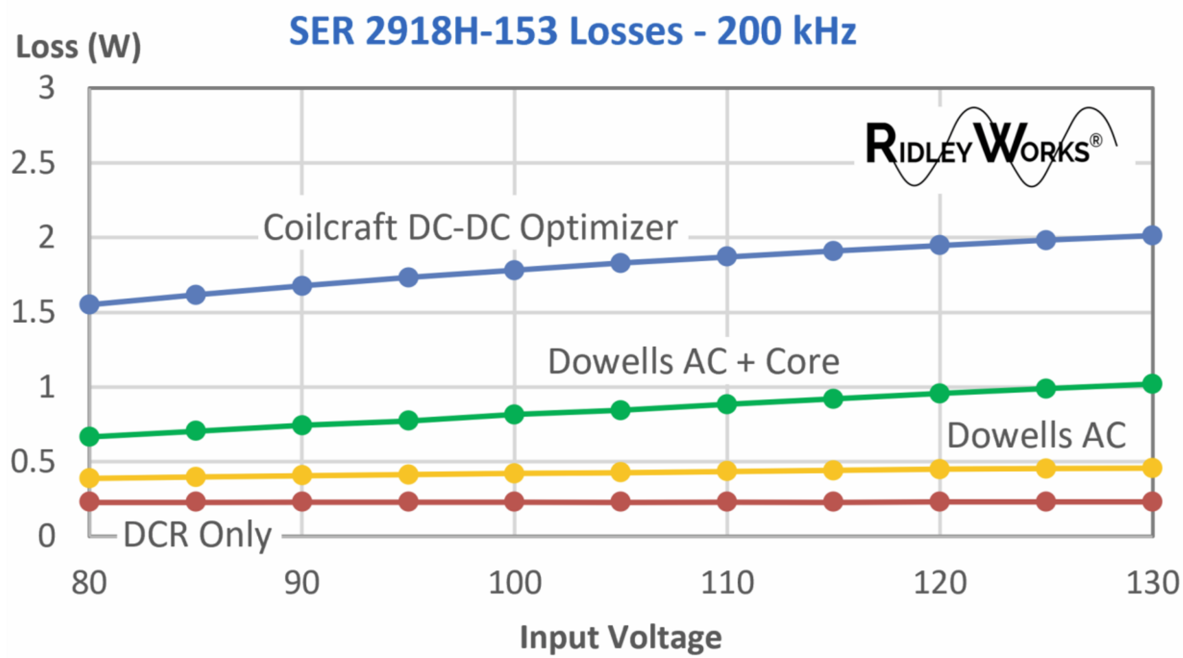


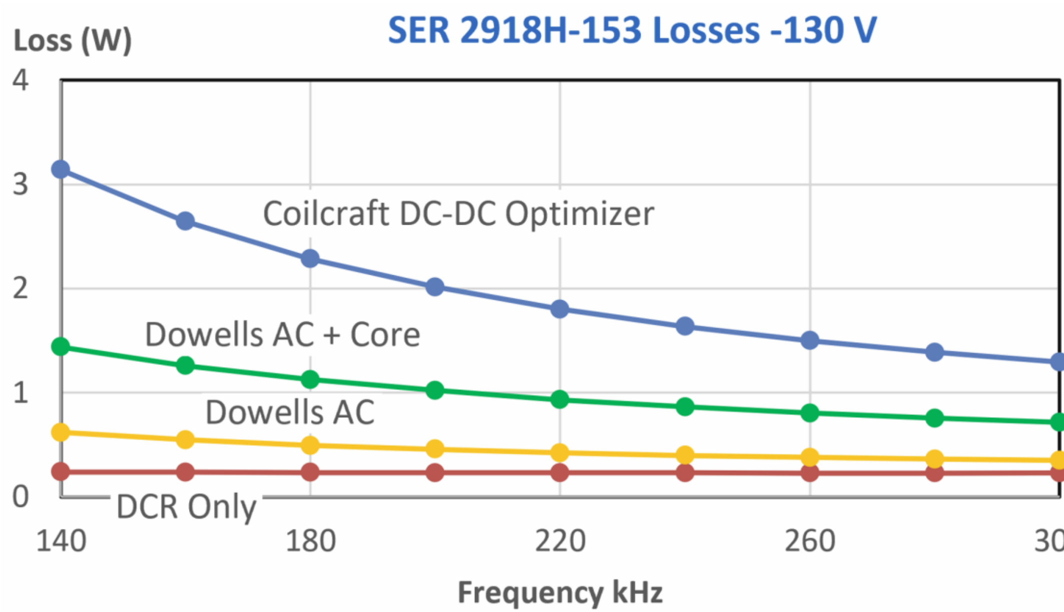



# Adding Core Loss [2]

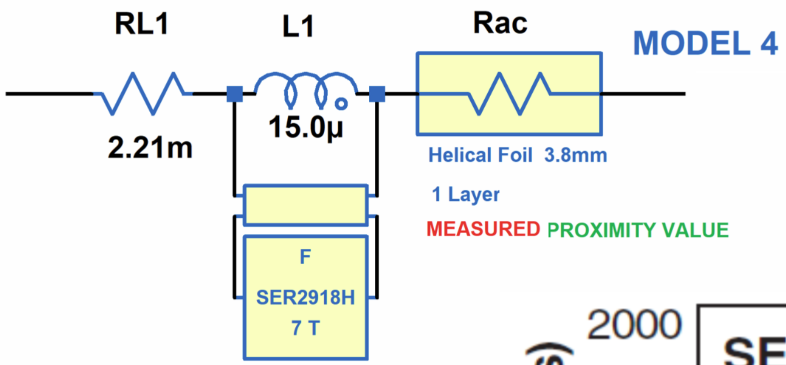


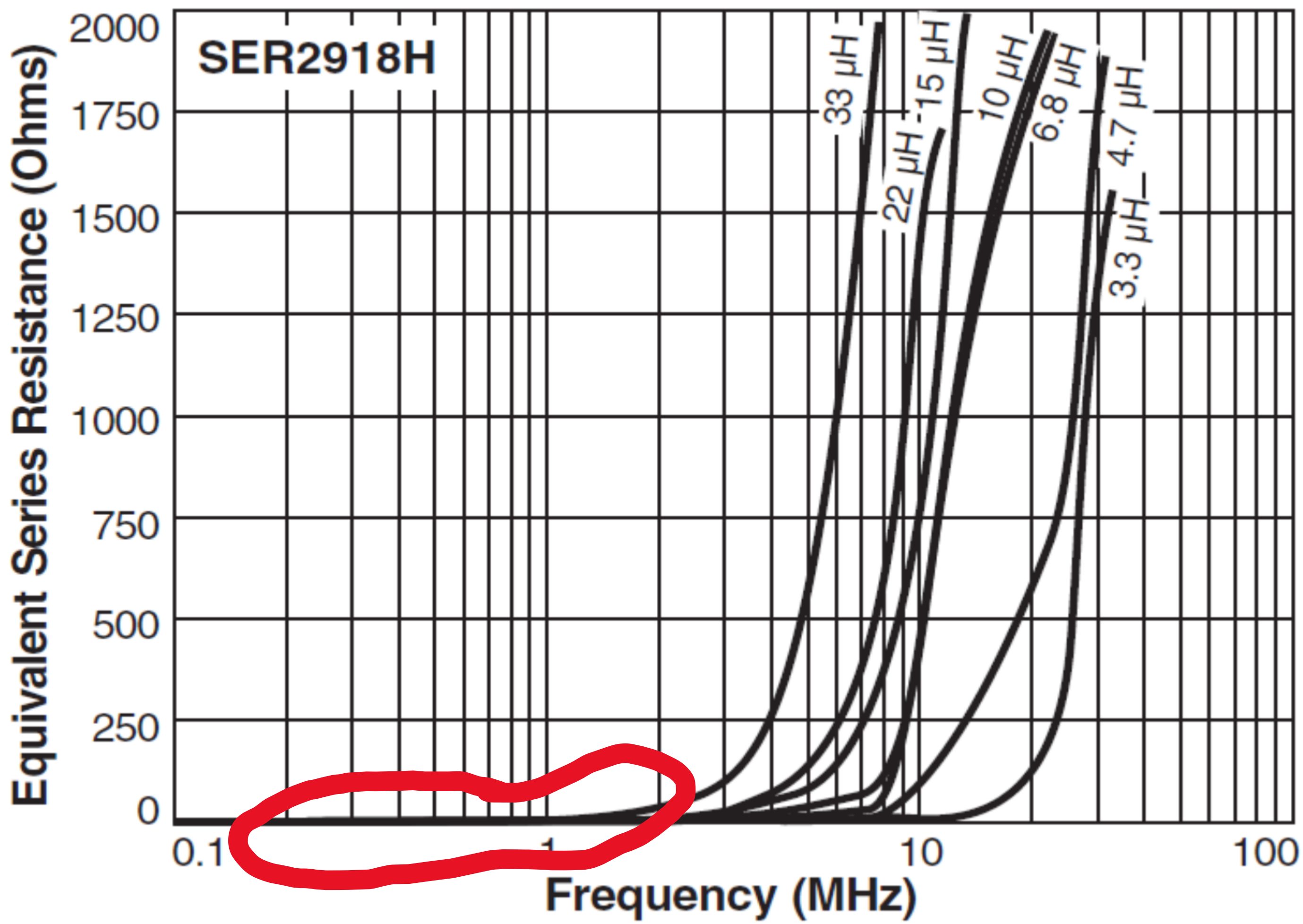

[2] **Magnetics Core Loss Webinar**



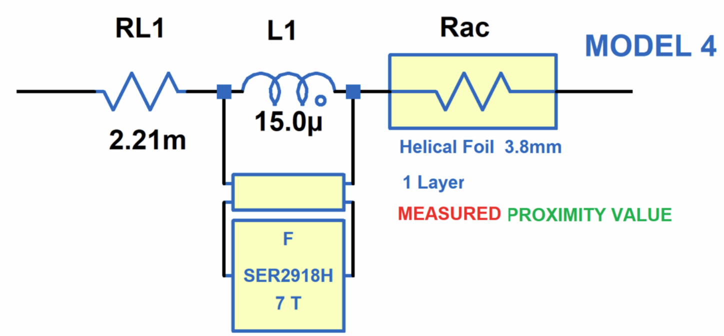



# Try Using Measured Rac?



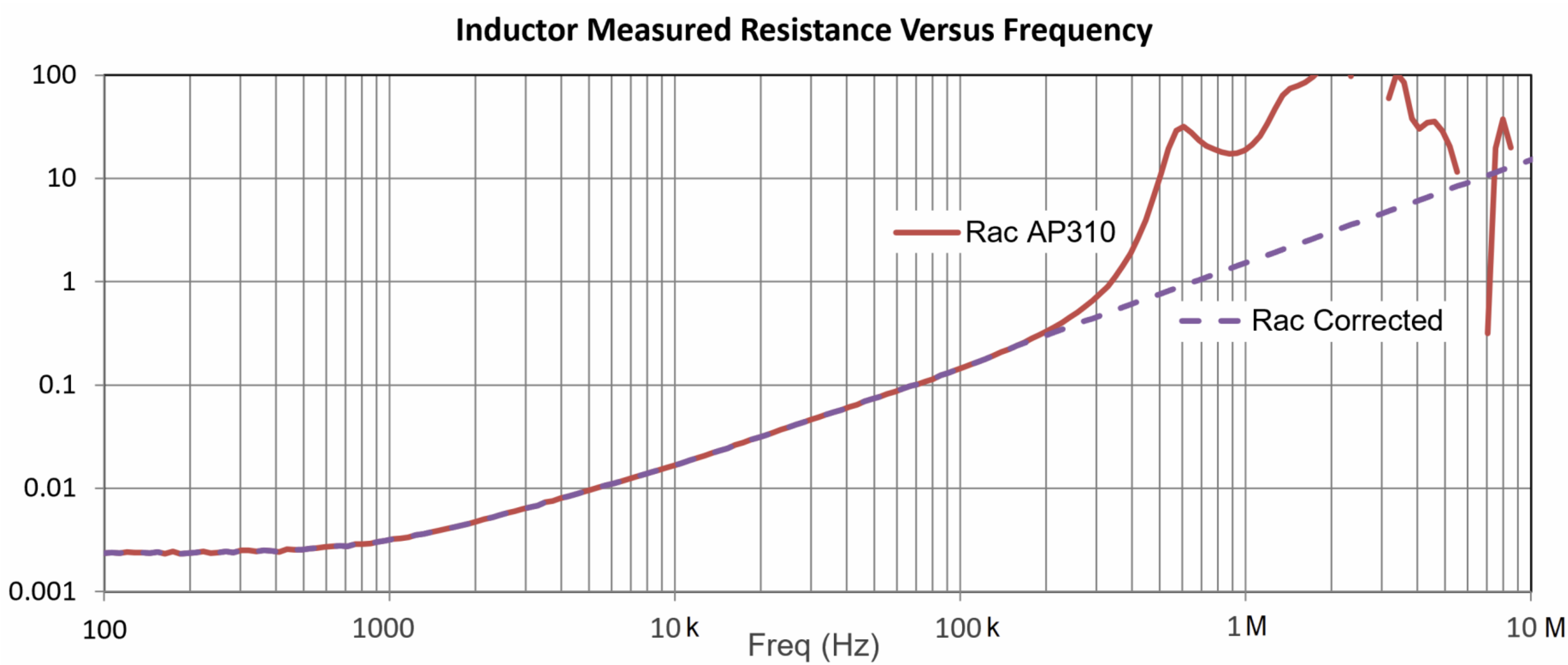
# Measuring Rac with the AP310 Analyzer





Thevenin connection for low impedances below 1 mOhm

# “Correcting” Measured Rac





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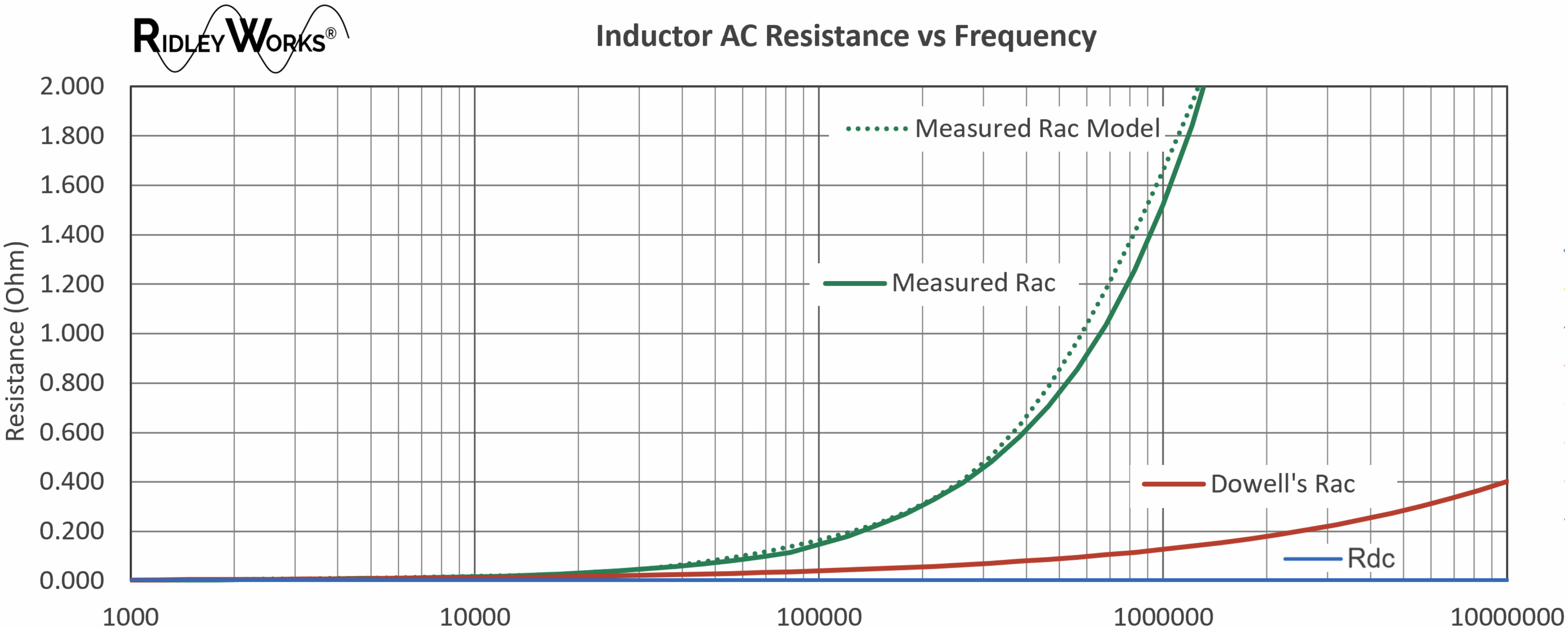
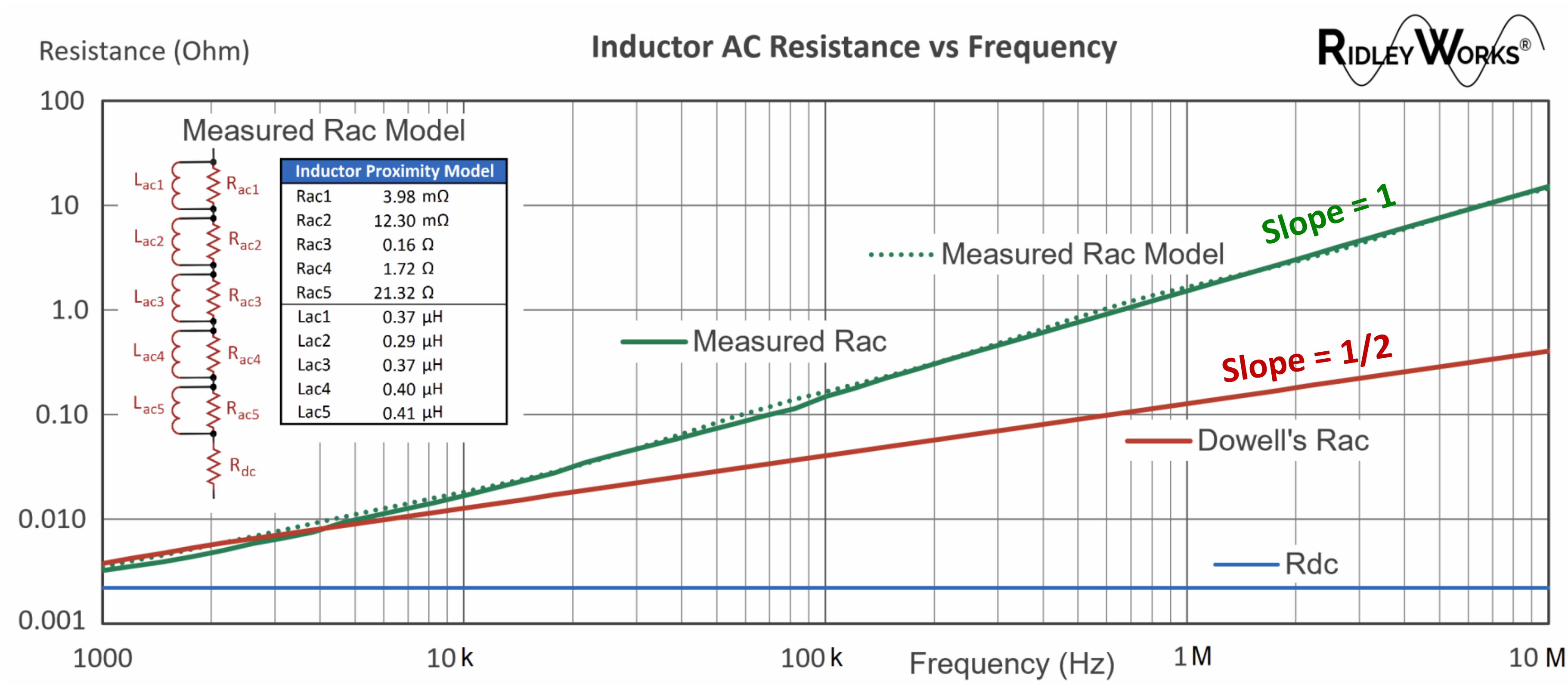
# Comparison of Different Winding Resistances (Linear Scale)



# Comparison of Different Winding Resistances (Logarithmic Scale)



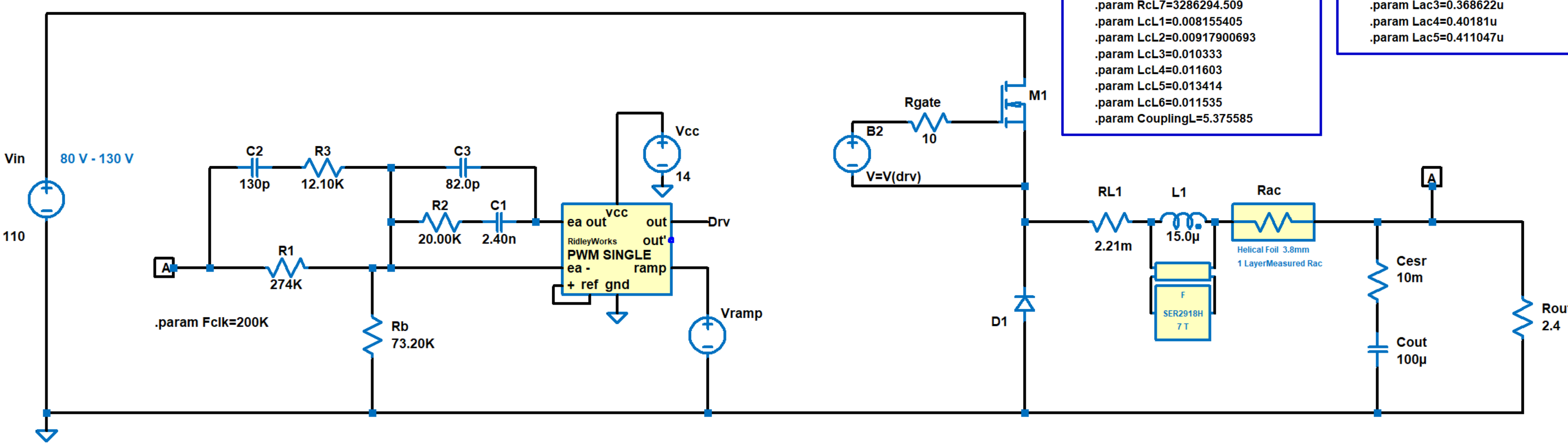

Interesting +1 slope. Where does this come from?

Let's see if it works first….

# Final Circuit for Simulation

**Inductor Core Loss Model**
.param CLexpL=2.22
.param RcL1=29.607
.param RcL2=199.943
.param RcL3=1350.531
.param RcL4=9099.202
.param RcL5=63117.514
.param RcL6=325651.919
.param RcL7=3286294.509
.param LcL1=0.008155405
.param LcL2=0.00917900693
.param LcL3=0.010333
.param LcL4=0.011603
.param LcL5=0.013414
.param LcL6=0.011535
.param CouplingL=5.375585

**Inductor Proximity Loss Model**
.param Rac1=3.983709m
.param Rac2=12.298663m
.param Rac3=157.795046m
.param Rac4=1720.022612m
.param Rac5=21317.604652m
.param Lac1=0.367871u
.param Lac2=0.287344u
.param Lac3=0.368622u
.param Lac4=0.40181u
.param Lac5=0.411047u




## DCR Loss

Waveform: V(N008,N010)*I(RL1)

Interval Start: 1.36ms
Interval End: 1.84ms
Average: 231.36mW
Integral: 111.05µJ

## Core Loss

Waveform: V(N015)*Ix(U4:P1)+V(...

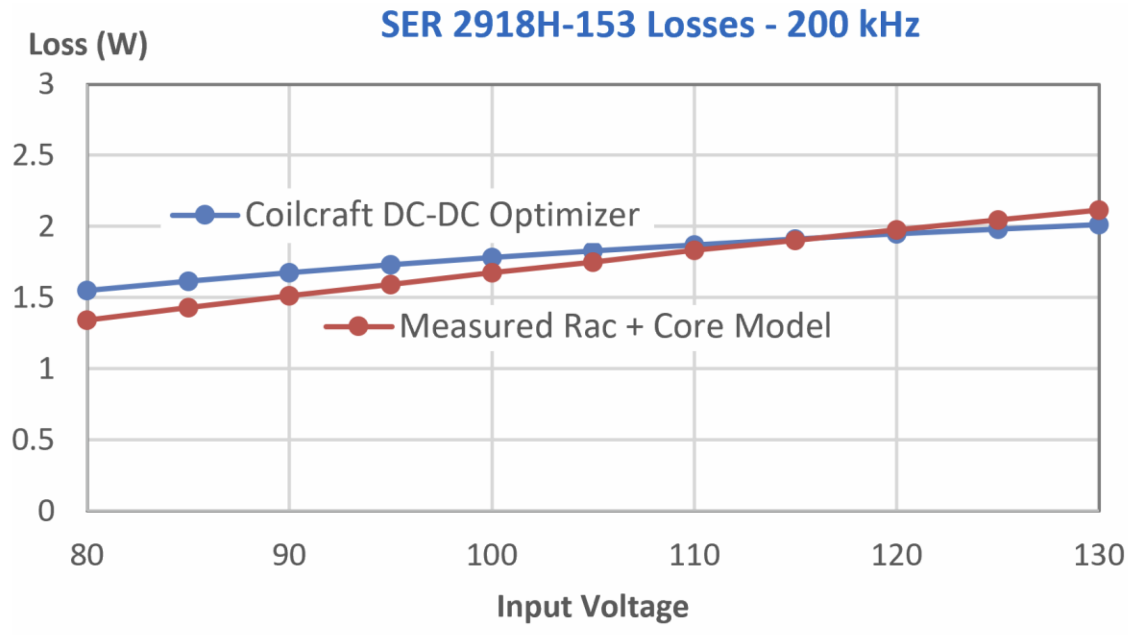
Interval Start: 1.36ms
Interval End: 1.84ms
Average: 437.46mW
Integral: 209.98µJ

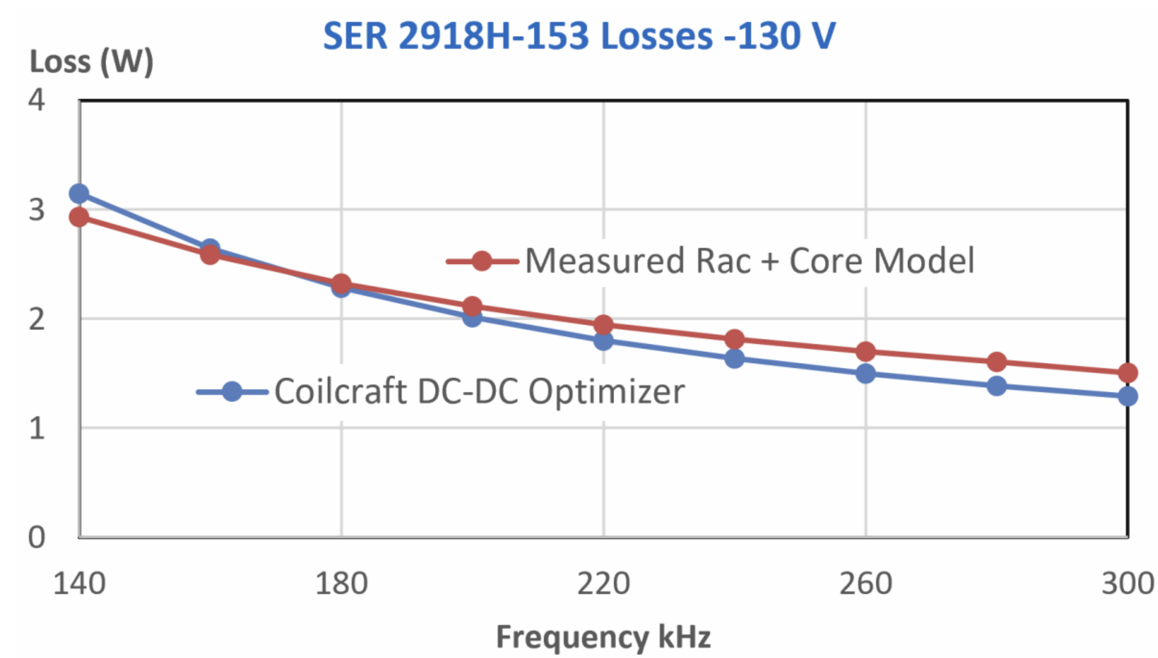
## ACR Loss

Waveform: V(N011)*Ix(Rac_Ind:in)...

Interval Start: 1.36ms
Interval End: 1.84ms
Average: 1.1507W
Integral: 552.34µJ

## Final Simulation Results




I'm happy!

Are you?



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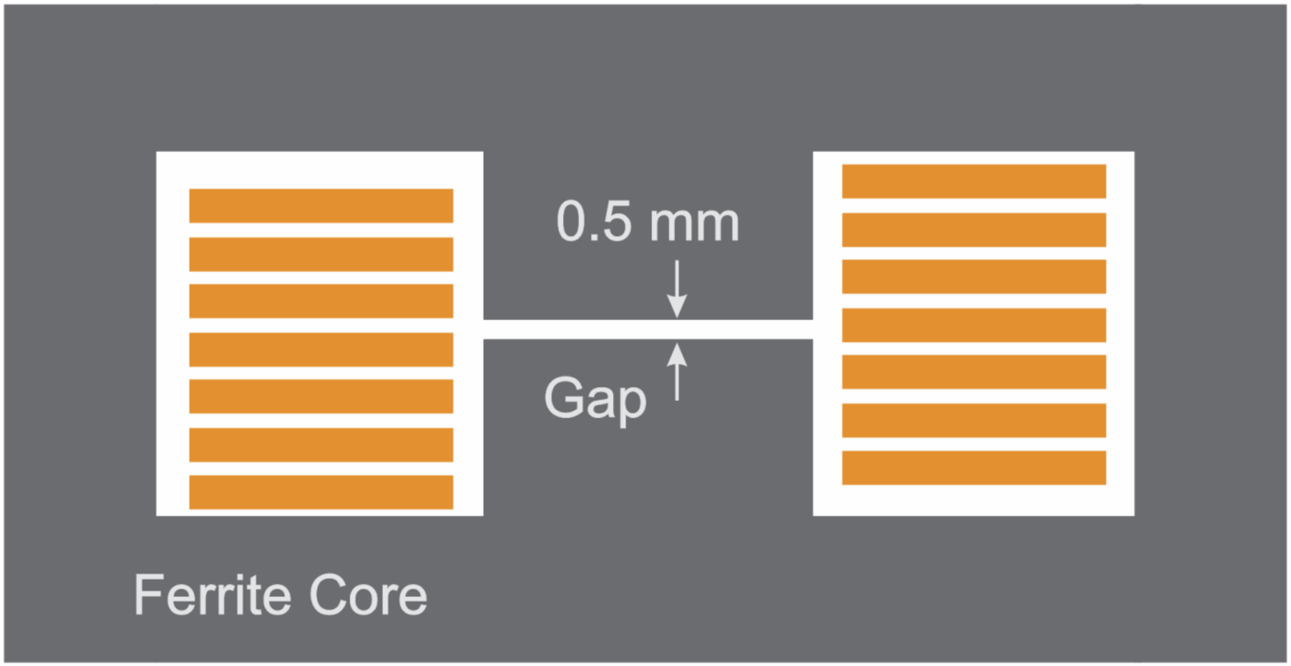
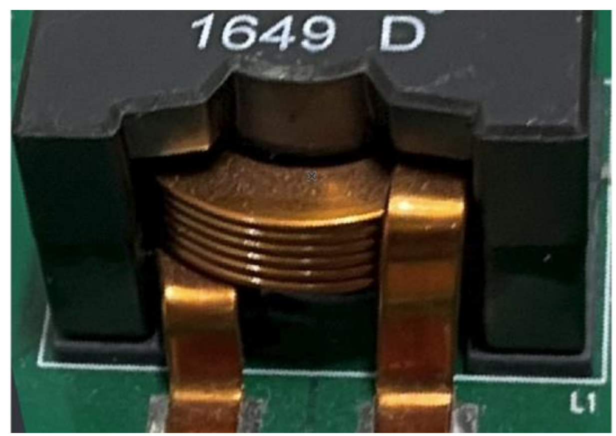
# Extra Rac is Due to the Gap



# Additional Learning Material

[1] **Magnetics Winding Loss**
Learn how the winding loss circuit used in today's presentation are generated automatically by RidleyWorks from Dowell's equation solutions.

[2] **Magnetics Core Loss**
Learn how the core loss circuit used in today's presentation are generated automatically by RidleyWorks

[3] **Coilcraft DC-DC Optimizer**
Nice tool to get the inductor data from. Maybe they'll have some LTspice models soon.

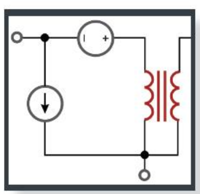
[4] Francisco de Leon, Adam Semlyen, "TIME DOMAIN MODELING OF EDDY CURRENT EFFECTS FOR TRANSFORMER TRANSIENTS" IEEE Transactions on Power Delivery, Vol. 8, No. 1, January 1993.

Thanks to **Jimmy Daniel** for verifying some of the simulation results for us

# Ridley Engineering Products and Events

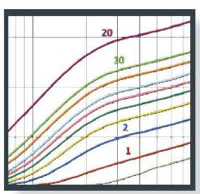

### Control & Small Signal

Gain a unique insight into power circuit analysis, from historical applications to modern techniques. Learn how to apply new models to any system from the expert in the industry.



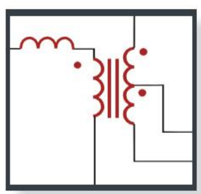
### Magnetics Design

Take full control of every magnetics design by learning how to remove the mystery. Understand practical design techniques, proximity loss, core loss, fringing loss and more.



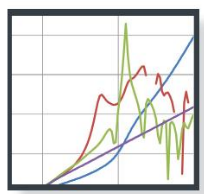
### Modern Topologies

Learn how advanced modern topologies use the same techniques to achieve high performance. Understand which topologies are important and how to use them.



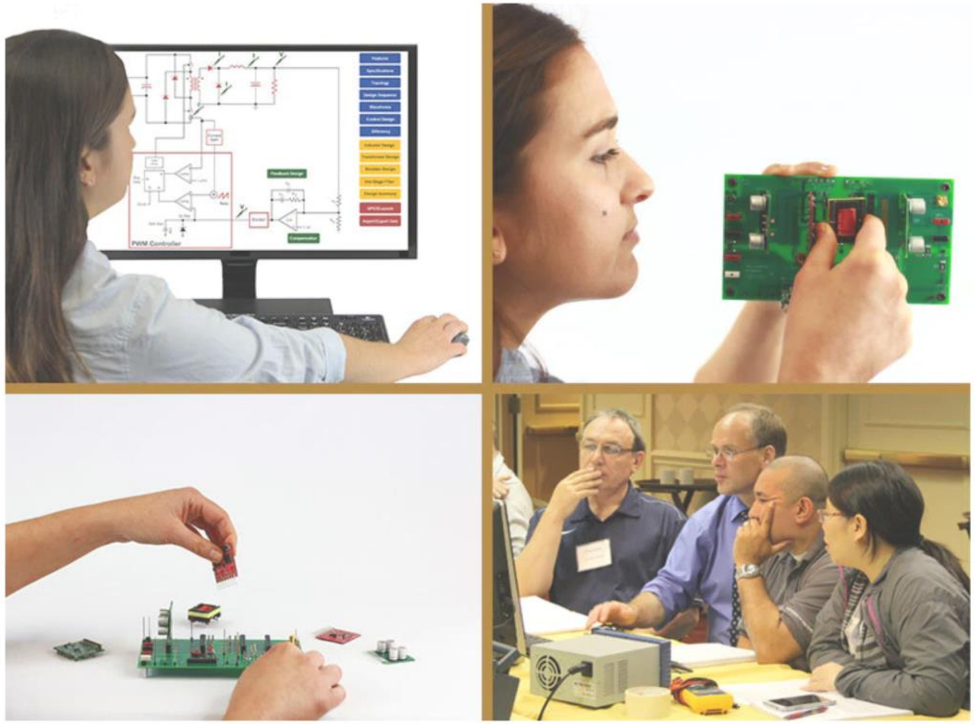
### Measurement Techniques

Component and circuit measurement is an essential step of product development. Learn from our 40+ years experience in measuring magnetics, loop gains, impedances and more.



**Registration is $500**. Limited spaces available.
In-person and remote attendance options.
Get RidleyWorks® software free after registration.
**https://shop.ridleyengineering.com/collections/education**

## Hands-On Training Workshops

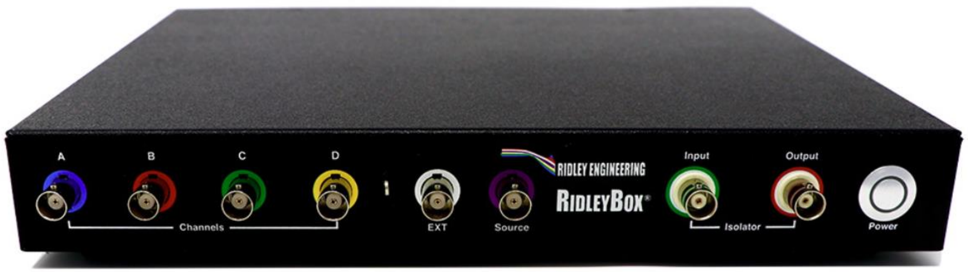


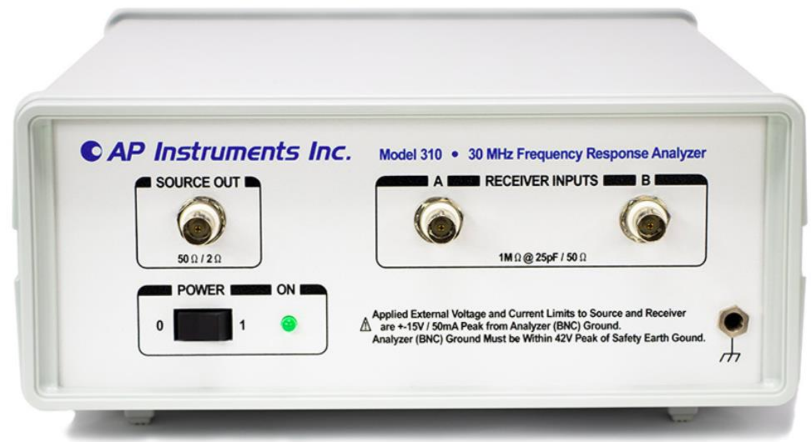
5-Day Workshop: SEP 18-22, 2023 in Camarillo, CA

5-Day Workshop: DEC 4-8, 2023 in Camarillo, CA

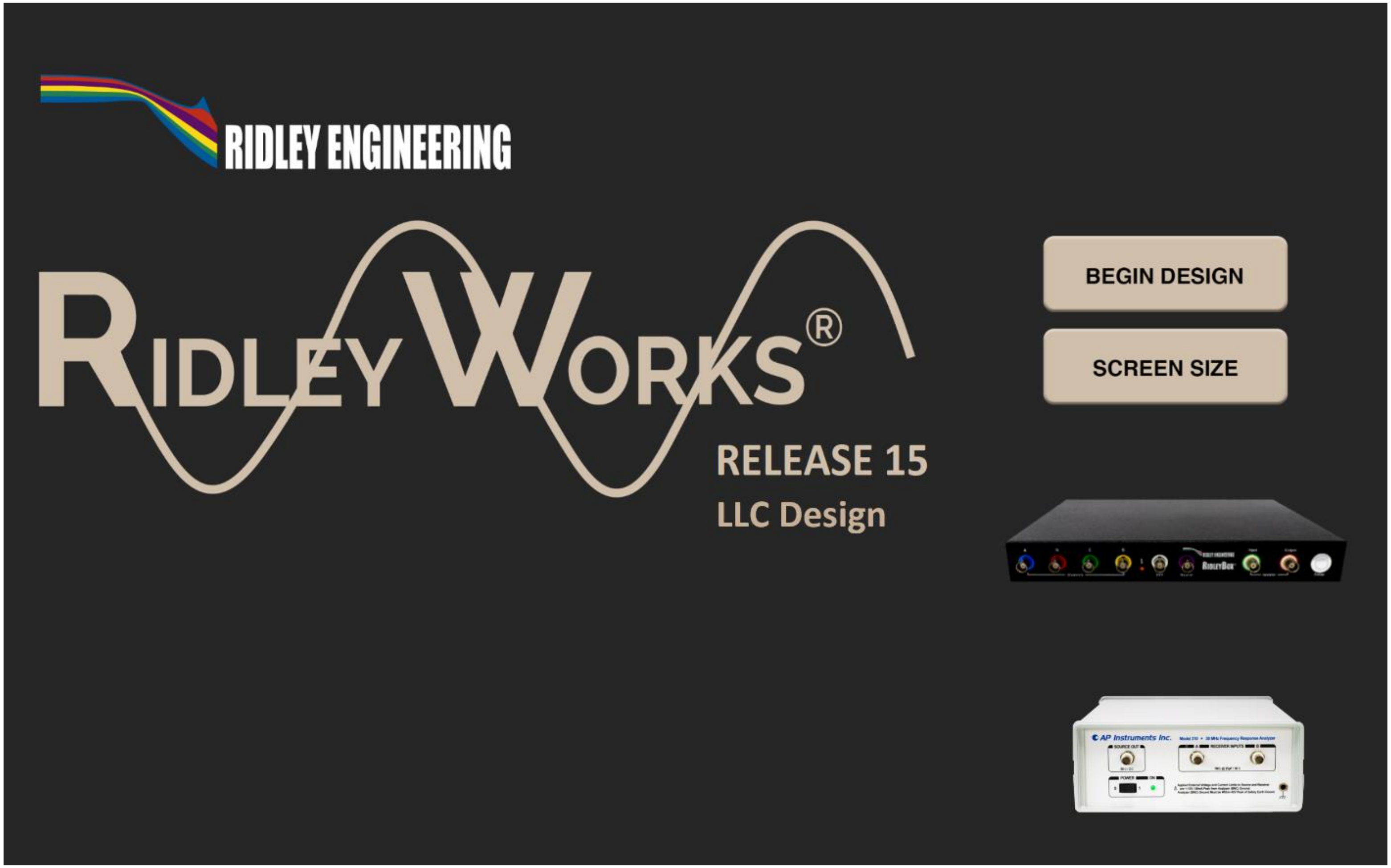
*** 8 spaces left for September**

# The Industry's Best Frequency Response Analyzers



# The Industry's Best Power Supply Design Software

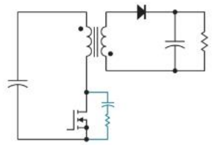


# Learn From Our Power Supply Design Center

## Articles and Webinar Series

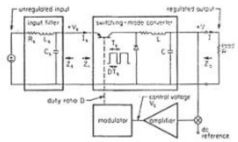
[A24] FLYBACK CONVERTER SNUBBER DESIGN

*In this article, we will talk about practical design techniques for the most commonly used snubber and clamp circuits for the flyback converter.*



MIDDLEBROOK1976

*Middlebrook's original 1976 paper on input filter interactions. Make sure you design your filter properly to avoid interactions with your switching power supply.*




S.S. KELKAR DISSERTATION

*S.S. Kelkar's original 1982 dissertation on feedforward control. This is the first known attempt at controlling the input filter with the converter cell.*


INPUT FILTER COMPENSATION FOR SWITCHING REGULATORS

by

Shriram S Kelkar

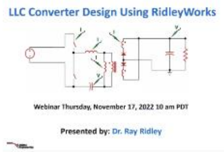
Dissertation submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Electrical Engineering

RIDLEYBOX PERFORMANCE MEASUREMENTS

*Compare the RidleyBox Performance for frequency response measurements*

LLC CONVERTER DESIGN USING RIDLEYWORKS

The design of the LLC converter is simple and straightforward when using RidleyWorks. No equations are needed, and the design process becomes a pleasure for the engineer rather than a chore.




DUAL ACTIVE BRIDGE DESIGN USING SCALING LAWS

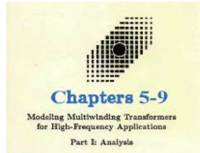
This unique presentation is by our guest speaker Nicola Rosano. The complex process of dual active bridge converter design is greatly simplified with the application of standardized curves combined with power and frequency scaling concepts.


MAGNETICS AND DOWELL'S EQUATIONS CHAPTERS 1-4

*This early report shows impressively detailed and complex application of Dowell's equations. Chapters 1-4 of the work.*

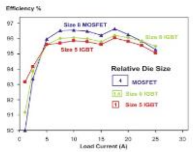

MAGNETICS AND DOWELL'S EQUATIONS CHAPTERS 5-9

*Only 1% of engineers will ever attempt to use this work - will you be one of them? For the other 99%, RidleyWorks does all the hard work for you.*



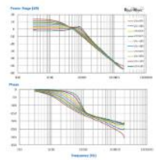

[A07] IGBTS CHALLENGE MOSFETS

*Small die size makes IGBTs competitive in high frequency conversion.*



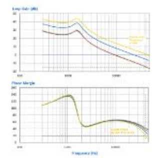

[115] SWEPT TRANSIENT FREQUENCY RESPONSE FOR THE LLC CONVERTER

*Part III: Swept loops in LTspice® can be used for the LLC converter where no small-signal model exists.*



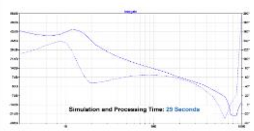
[114] TRANSIENT LOOP SWEEPS OUTPERFORM SMALL-SIGNAL MODELS

*Part II: Swept loops in LTspice® provide more accurate and useful results than small-signal models.*



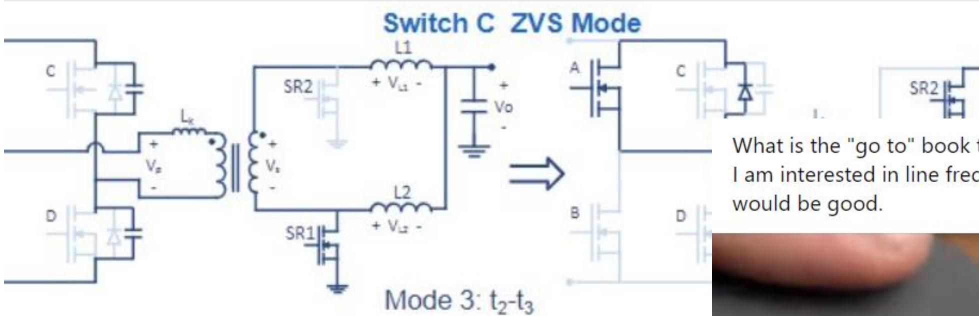
[113] HIGH-PERFORMANCE LOOP SWEEPS IN LTSPICE

*Part I: Learn how to emulate the RidleyBox and AP310 Analyzers in LTspice®.*



# Power Supply Design Center Group on Facebook
# 6300 Members

I was going thru a design app note from Infineon for a PSFB converter. I was confused by the turn-off loss calculation.
At beginning of mode 3, switch D was conducting. Then it is turned off and the inductor current will discharge Switch C cap and charge Switch D cap. I thought that if Switch D is turned off fast, the charging capacitive current will not dissipate any heat loss on Switch D. It will just be part of the total system lossed.... **See more**




Since it's a ZVS converter, turn-on loss and output capacitance Cos

Turn-off time and loss are:

$$t_{off} = Q_{gd} \cdot \frac{R_g}{V_{pl}} + Q_{gs} \cdot \frac{V_{pl} - V_{th}}{V_{pl}} \cdot \frac{2 \cdot R_g}{V_{pl} + V_{th}}$$

$$= 22 \cdot 10^{-9} \cdot \frac{3}{6.4} + 7 \cdot 10^{-9} \cdot \frac{6.4 - 4}{6.4} \cdot \frac{2 \cdot 3}{6.4 + 4} = 11.83 \cdot 1$$

$$P_{S,off} = 0.5 \cdot I_{L,pk} \cdot \frac{N_s}{\;} \cdot V_{in} \cdot t_{off} \cdot f$$

What is the "go to" book that everyone has (and recommends) for transformer winding & design? I am interested in line frequency transformers but if the book also covers SMPS (kHz) types that would be good.