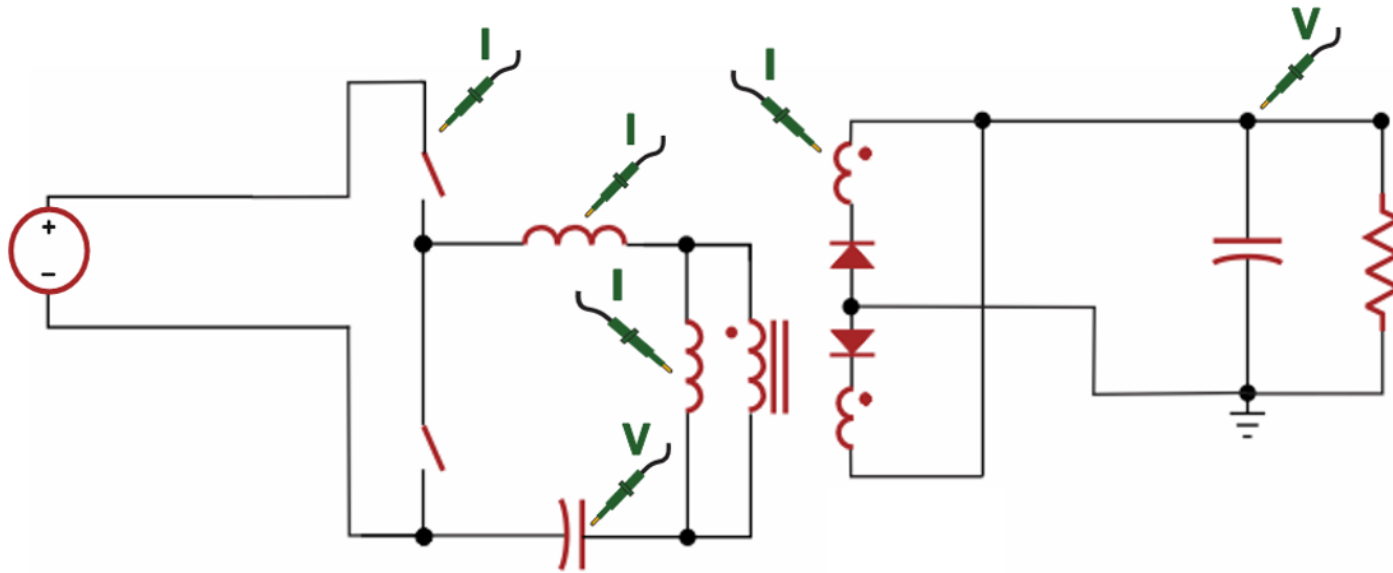


LLC Converter Design Using RidleyWorks



Webinar Thursday, November 17, 2022 10 am PDT

Presented by: **Dr. Ray Ridley**

LLC Converter Design - Acknowledgements

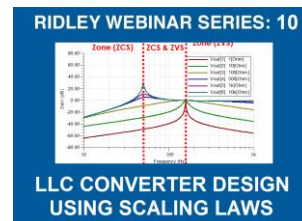


Arthur Nace – retired aerospace engineer and programmer who automated LTspice models for us. Our longest user of RidleyWorks.



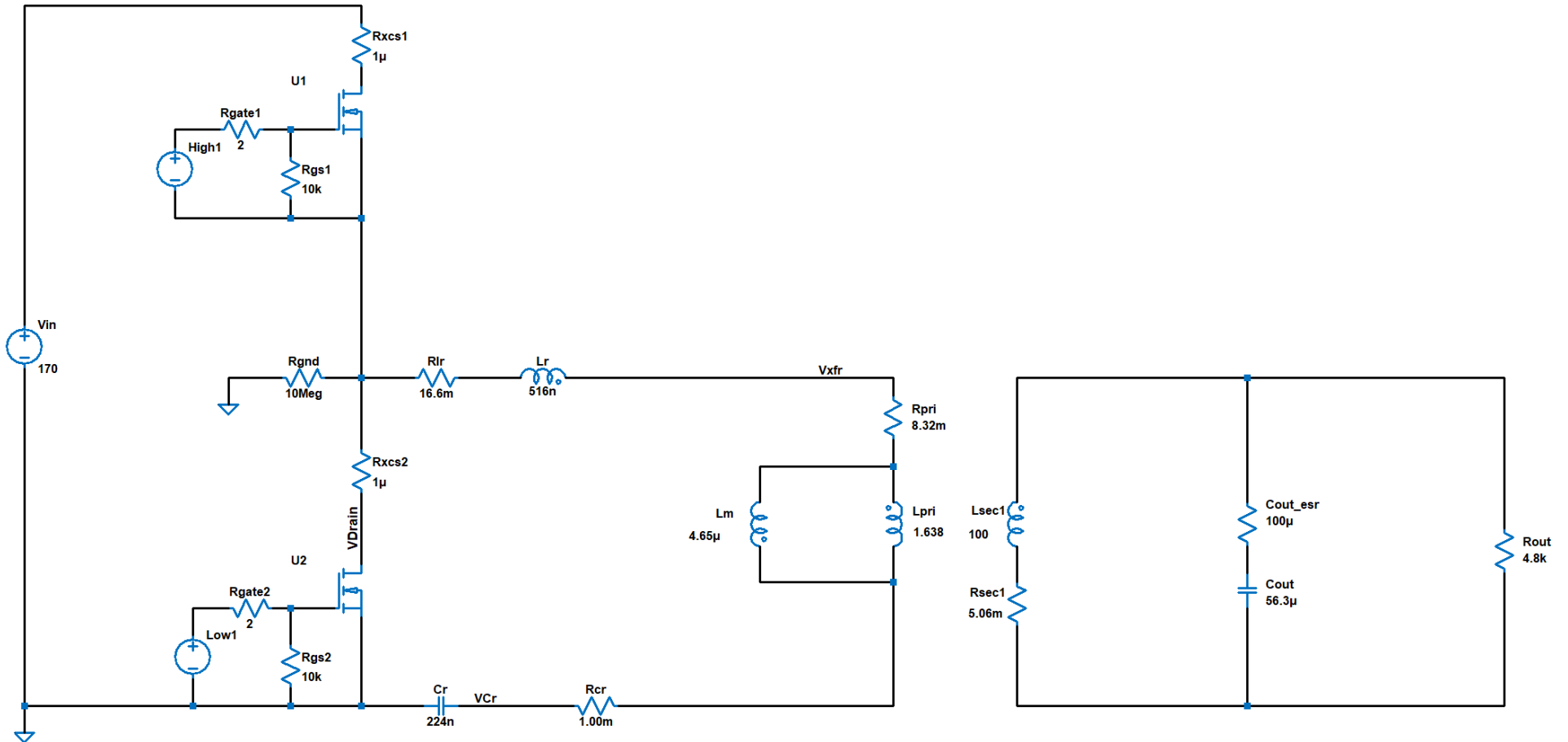
Nicola Rosano – Developed the Rosano impedance curves for designing the LLC the easy way.

No complex math - take one solid design, and scale it for frequency, voltage and power.

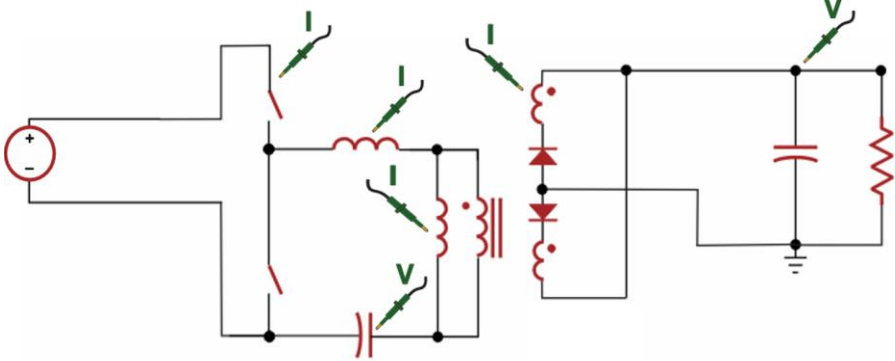


Watch this video for the theory on LLC design with scaling laws

My First LLC (1980)

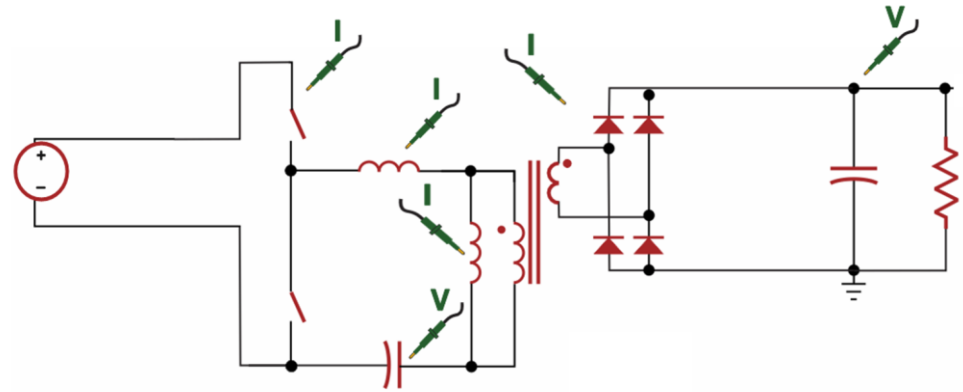


LLC Circuit Variations in RidleyWorks



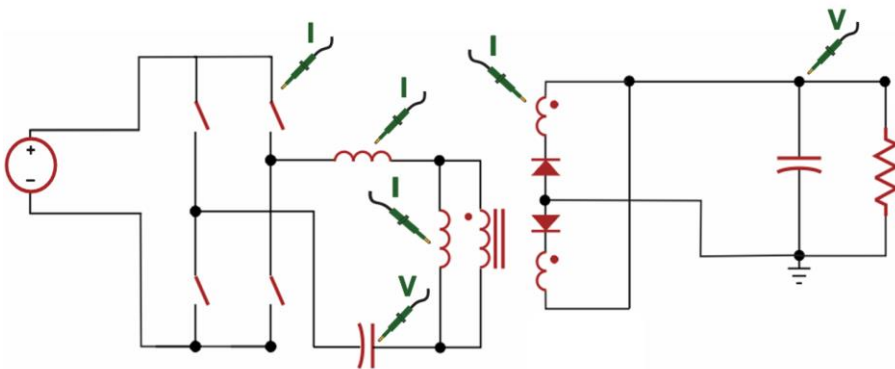
Half-bridge Inverter

Half-wave Rectifier



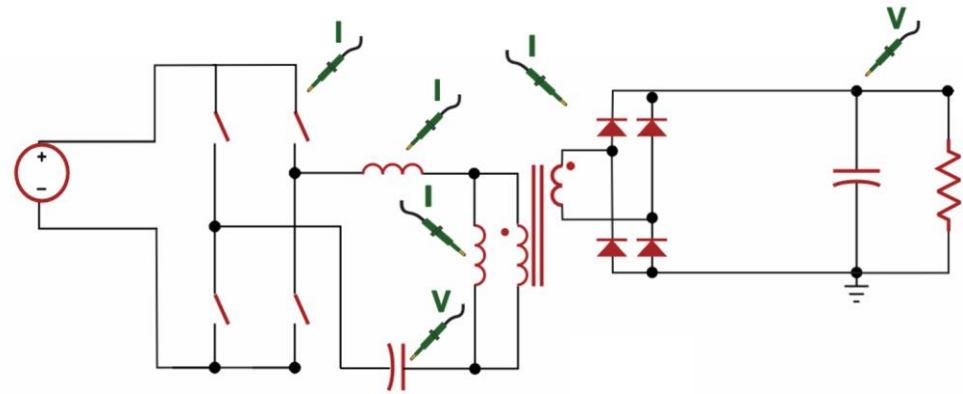
Half-bridge Inverter

Full-wave Rectifier



Full-bridge Inverter

Half-wave Rectifier



Full-bridge Inverter

Full-wave Rectifier

A Few Words About First Harmonic Analysis

Specification Input in RidleyWorks

Input and Output Specifications



LLC Converter Design Webinar

Clear Design

INPUT VOLTAGE RANGE

☐ 120 VAC ☐ 240 VAC ☐ 120-240 VAC ☒ DC Input

Low Line Voltage

Nominal Input Voltage

High Line Voltage

OUTPUT VOLTAGE AND CURRENT

	Main	Aux 1	Aux 2	Aux 3	Aux 4
Output Voltage	<input type="text" value="24"/>	<input type="text" value=""/>	<input type="text" value=""/>	<input type="text" value=""/>	<input type="text" value=""/>
Output Current	<input type="text" value="5"/>	<input type="text" value=""/>	<input type="text" value=""/>	<input type="text" value=""/>	<input type="text" value=""/>

Clear Aux

POWER SUPPLY COOLING

☐ High Airflow ☒ Moderate ☐ Low Airflow ☐ None

FEEDBACK ISOLATION

☒ Non-Isolated ☐ TL431/Opto E/A ☐ TL431/Opto Bias E/A
☐ TL431/Opto I FB ☐ TL431/Opto Bias I FB

Help

OK

POWER SUPPLY OUTPUT

Main Output Voltage V

Main Output Current A

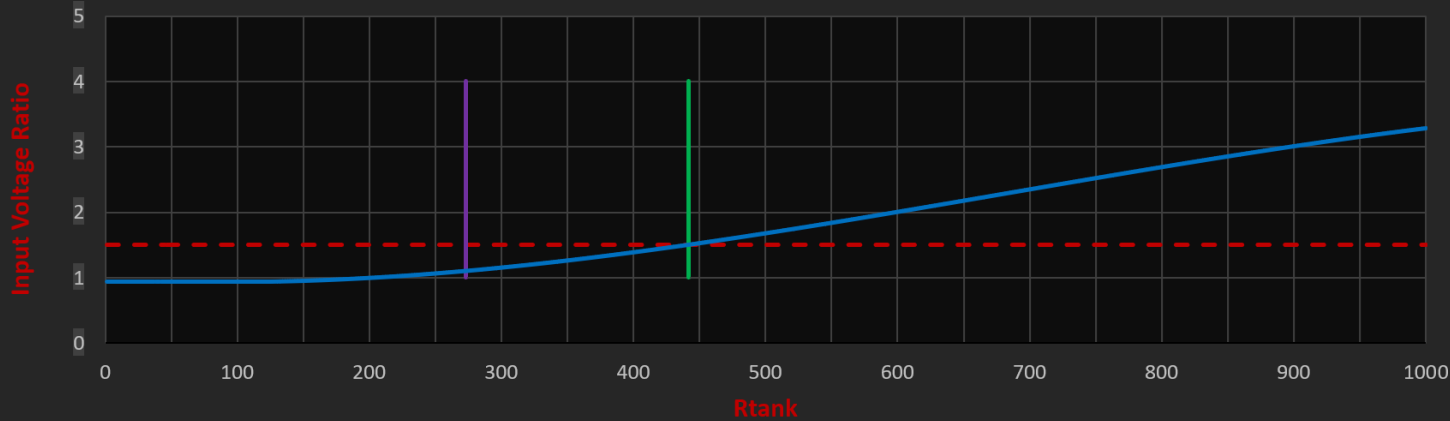
Total Output Power W

SWITCHING FREQUENCY

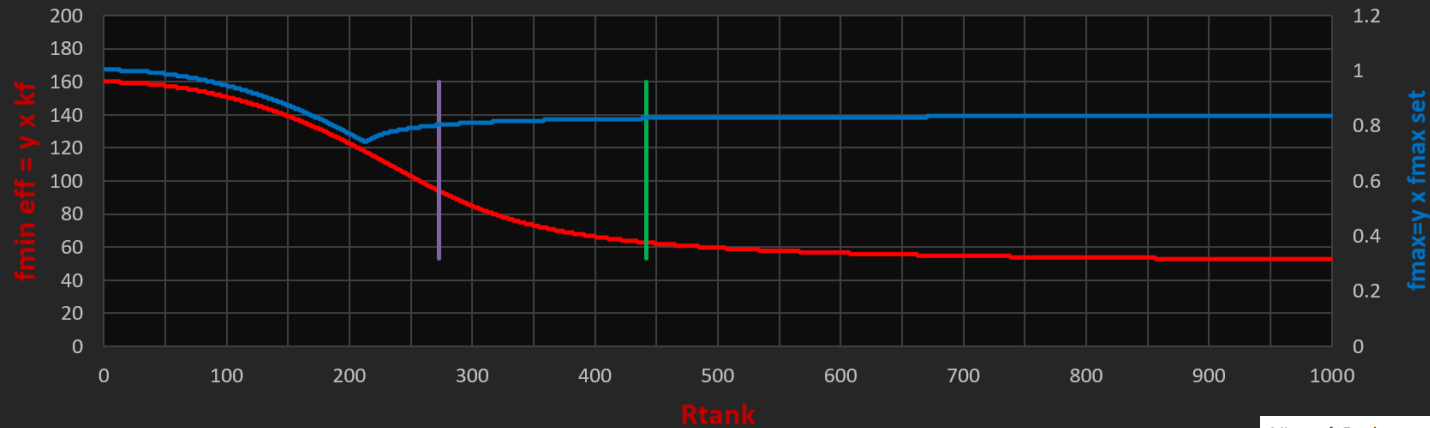
Switching Frequency kHz kHz Default

Designing with Scaling Laws – Rosano Curves

Rosano Curve 1



Rosano Curve 2



LLC Power Stage Designer

INPUT VOLTAGE

Minimum DC Input Voltage	40	V
Nominal DC Input Voltage	48	V
Maximum DC Input Voltage	60	V

OUTPUT POWER

Output Voltage	24	V
Output Current	5	A
Output Power	120	W

MINIMUM FREQUENCY GOAL

Target Frequency	200	kHz
------------------	-----	-----

DESIGN LLC

LLC Design Complete

LLC CONVERTER COMPONENTS

Minimum Working Frequency	200.07	kHz
Maximum Working Frequency	388.15	kHz
Resonant Inductor	0.5156	μH
Magnetizing Inductor	4.6411	μH
Resonant Capacitor	224.26	nF
Transformer Turns Ratio	1.282	

Advanced Settings OK

Microsoft Excel

5 LTspice files are in the folder 'RidleyWorks LTspice' on your desktop

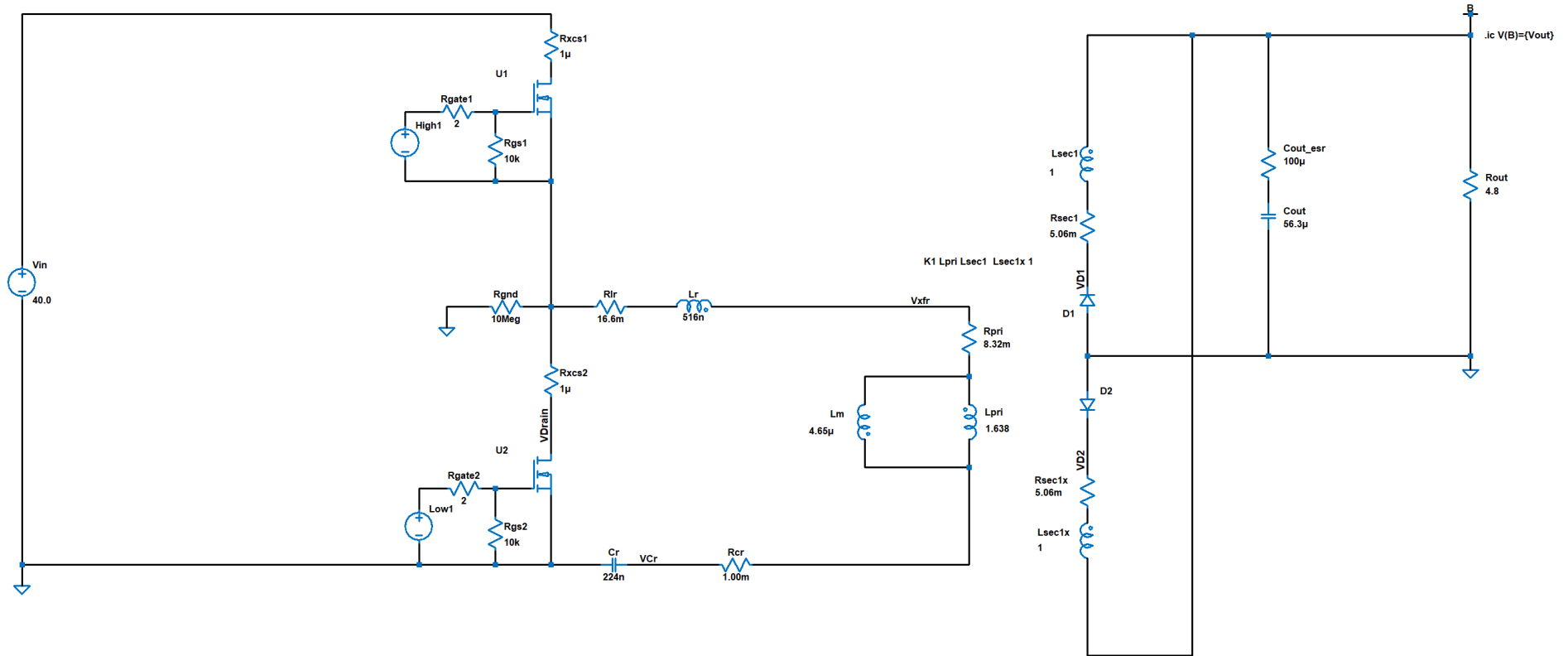
OK

Automatic LTspice Schematic Generation from RidleyWorks

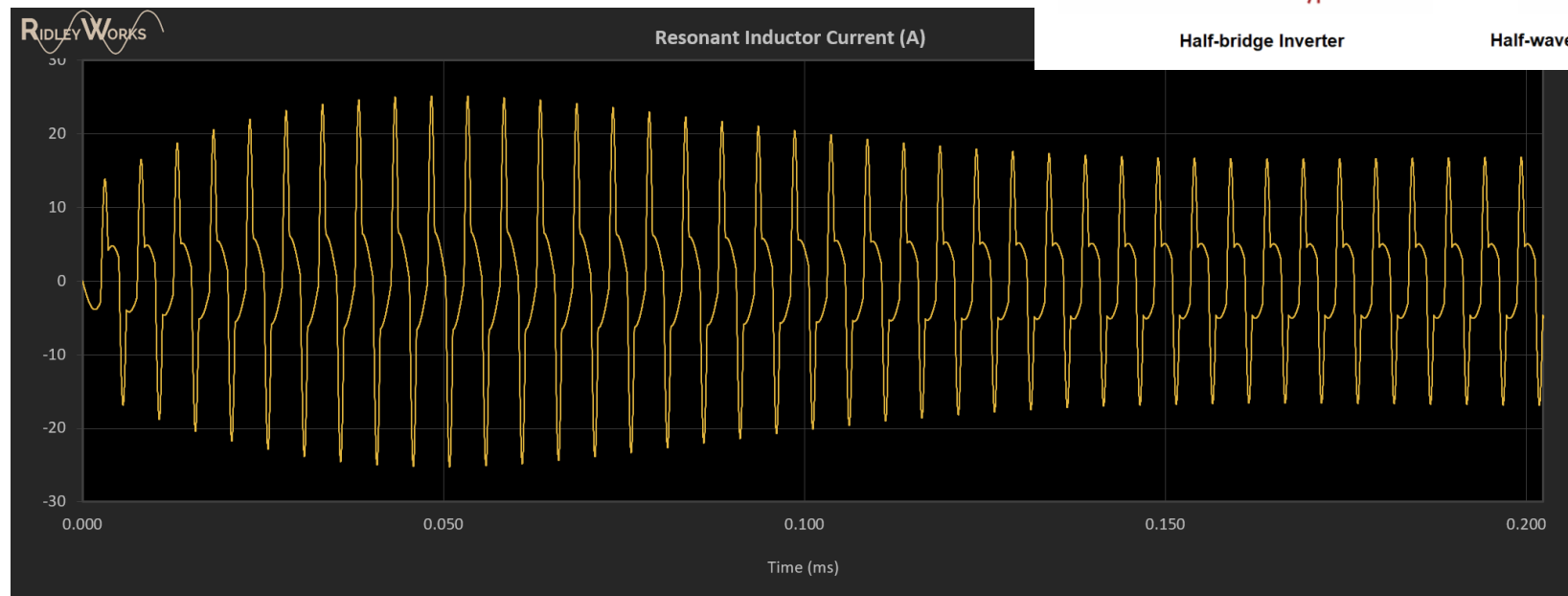
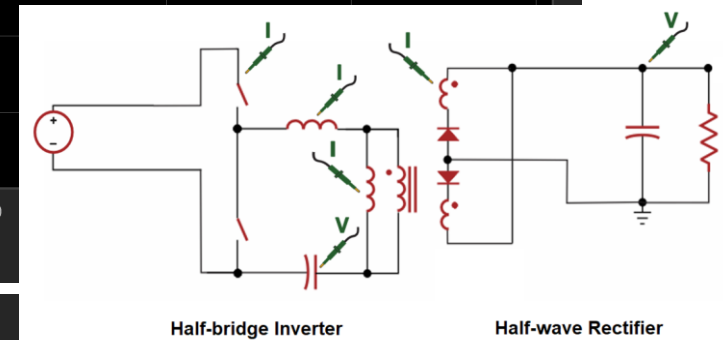
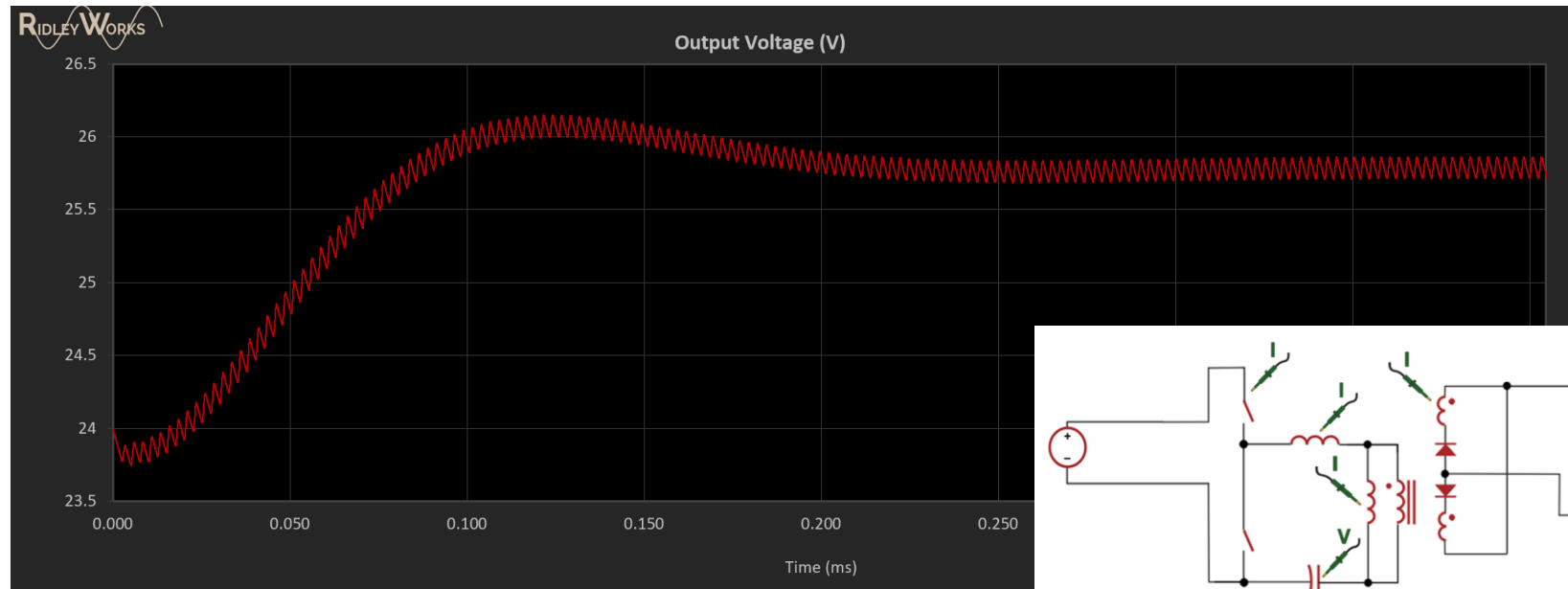
RidleyWorks LTspice Schematic

LLC CONVERTER DESIGN WEBINAR

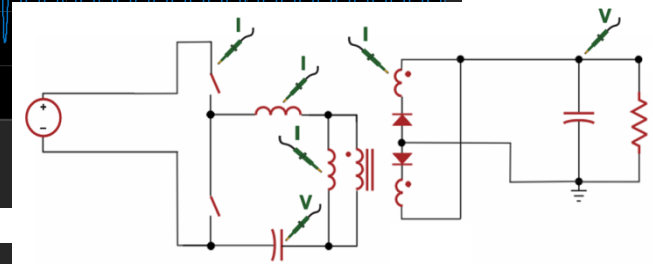
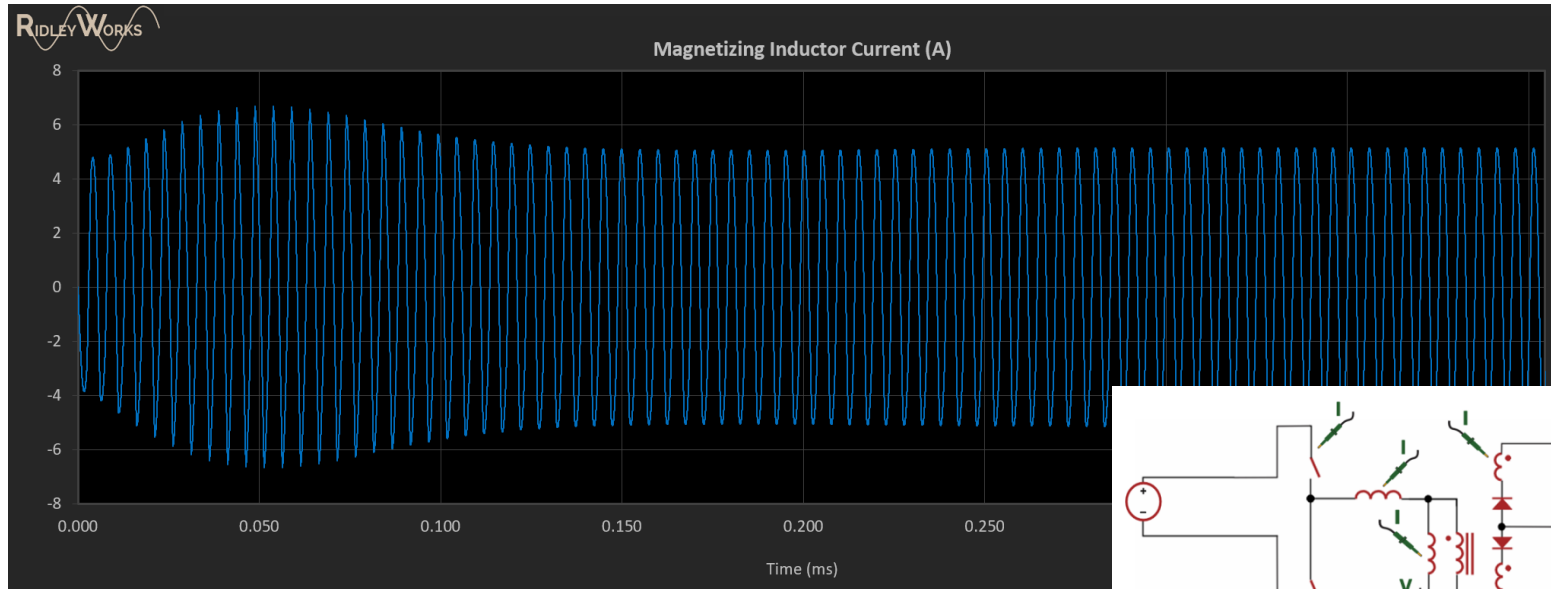
$V_{in} = 40.0$, $V_{out1} = 24.0V$ @ 5A, IIC steady state, voltage-mode



LLC Waveforms in RidleyWorks

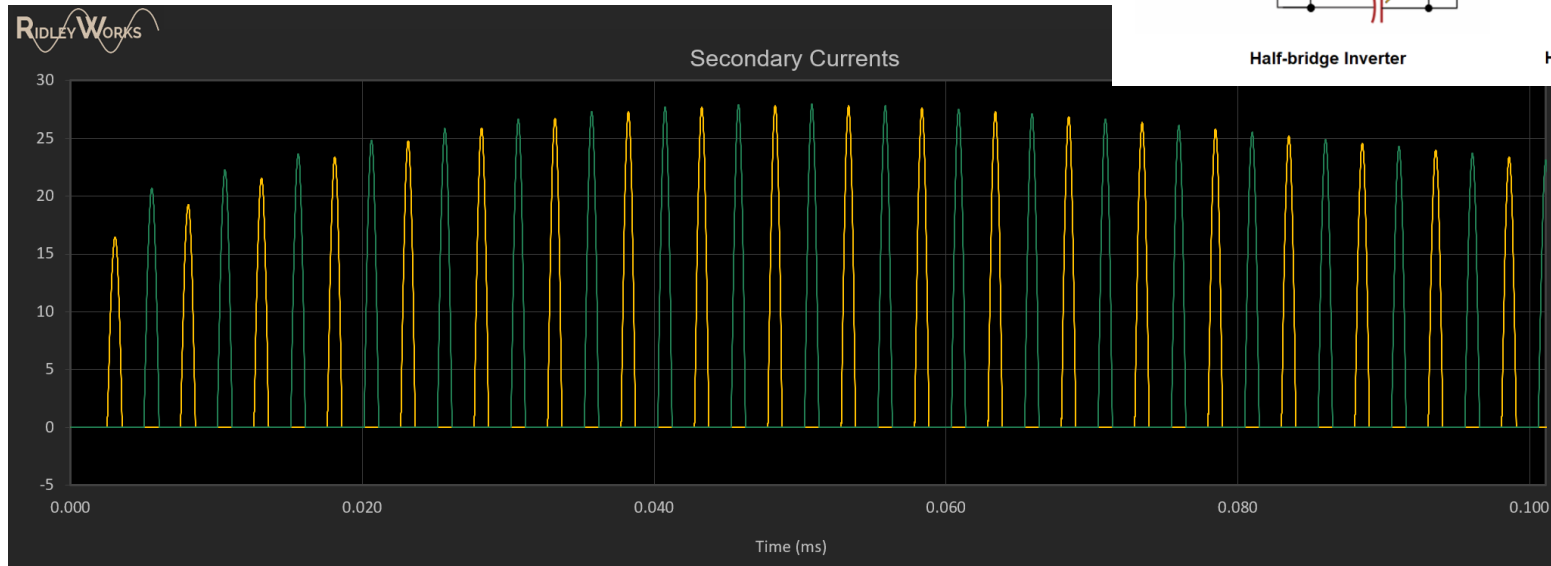


LLC Waveforms in RidleyWorks

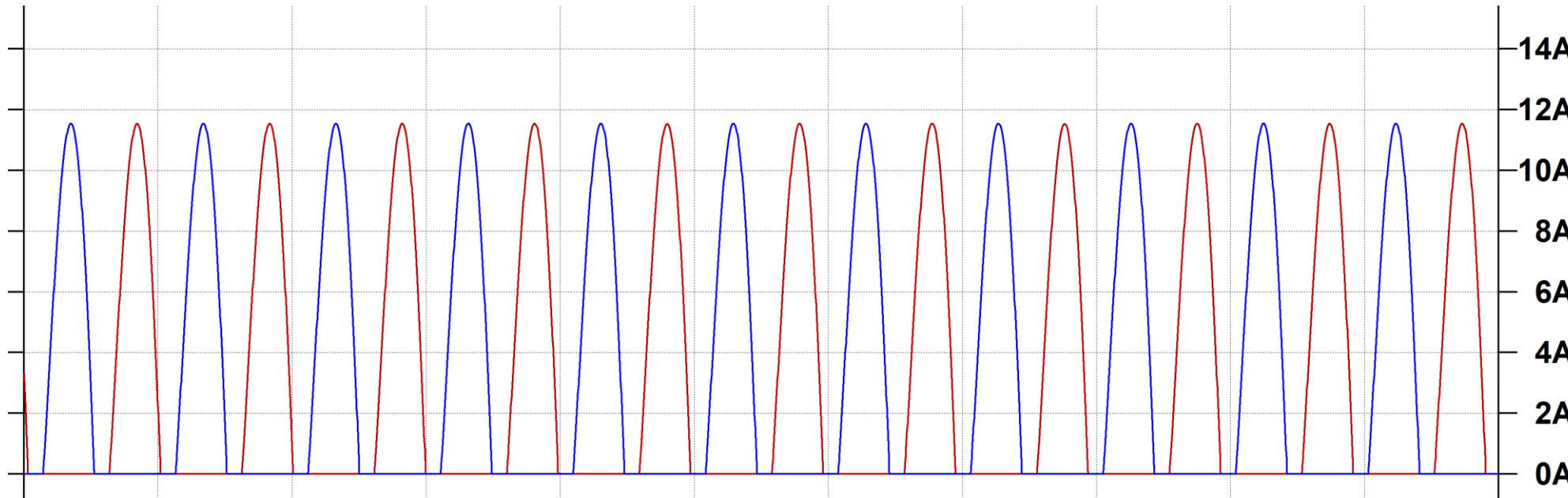


Half-bridge Inverter

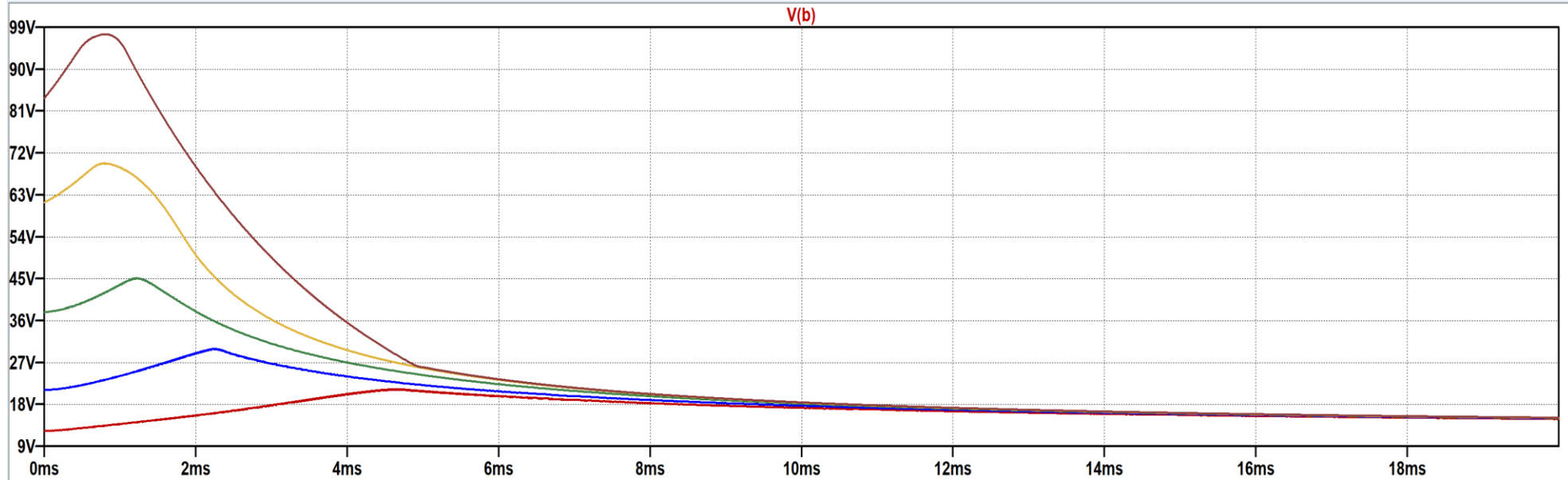
Half-wave Rectifier



High-Line Secondary LLC Waveforms



LLC Gain Curves



Load from $RL/2$ (overload) to $8RL$

Sweep from F_{min} to F_{max}

2 LLC CURVE TRACER.asc

Transformer Core Design in RidleyWorks

LLC TRANSFORMER CORE SELECTION

Approximate Core Area **0.203** sq. cm

☐ Generic Core

☒ Use Selected Core

CORE TYPE AND AREA

Core Type Primary Inductance **4.6497** μH

Minimum Area sq. cm Peak Current **6.6896** A

MAXIMUM FLUX LEVEL SETTING

0.3 T

This value impacts the number of turns needed
 0.3 T rugged commercial supply with ferrite
 0.25 T aerospace supply with ferrite

FLYBACK TRANSFORMER TURNS

Primary Turns

Secondary Turns
 Maximum Flux Density **0.258** T

$B_s n A_e > L I_p$

CORE PHYSICAL DETAILS

Core Volume cu. cm

Window Width cm

Window Build cm

Inner Turn Length cm

Outer Turn cm

CORE GAPPING

0.19 mm **7.6** mils

Note that gap length is a rough guide only. Manufacturing design is specified by AI, and the core is gapped to achieve the correct value

AI value **129.15** nH/n2

Once you select OK, values appearing on this form will be used in the converter simulation.

Transformer Core Material Choices

OPERATING CONDITIONS

Operating Delta B	0.198 T	Core Area	0.2004 cm2
Core Excitation Frequency	200 kHz	Peak Flux at Max Duty	0.258 T
Duty Cycle D1 (Flux Rise)	0.5	Number of Turns	6
Duty Cycle D2 (Flux Fall)	0.5	Core Volume	1.04 cm3
Temperature	25 deg C		

TRANSFORMER CORE MATERIAL SELECTION

Ferroxcube	TDK	Magnetics	All Vendors
<input type="radio"/> 3C90	<input type="radio"/> PC40	<input type="radio"/> P	<input type="radio"/> MPP 200u
<input type="radio"/> 3F3	<input type="radio"/> PC90	<input type="radio"/> F	<input type="radio"/> Hi-Flux 60μ
<input type="radio"/> 3C96	<input type="radio"/> PC44	<input type="radio"/> R	<input type="radio"/> New
	<input checked="" type="radio"/> PC95	<input type="radio"/> New	<input type="radio"/> New
		<input type="radio"/> New	<input type="radio"/> New
		<input type="radio"/> New	<input type="radio"/> New
		<input type="radio"/> New	<input type="radio"/> New

CHARACTERISTICS FOR SELECTED MATERIAL

Permeability **3300**
 Magnetizing Inductance **0.0348** mH
 Core Loss **0.927** W

PSIM/LTSPICE CORE LOSS MODEL

Inductors

LC1	1.561 mH	LC4	0.791 mH
LC2	1.245 mH	LC5	0.651 mH
LC3	0.994 mH	LC6	0.37 mH

Voltage Exponent **1.1715**

Resistors

RC1	6.87 Ω	RC5	3.71543 k Ω
RC2	32.9 Ω	RC6	12.68668 k Ω
RC3	157.55 Ω	RC7	121.18486 k Ω
RC4	752.51 Ω		

PSIM/LTspice Core Models

☐ Enable
☒ Disable

Core loss is high – add more turns, but check Winding loss first.

Transformer Primary Winding Design in RidleyWorks

Transformer Primary Winding Design

PRIMARY WINDING ALLOCATION

Window Allocation: 0.5
Number of Turns: 6

AVAILABLE WINDOW

Margin Required: 0 mm each end 1.2 cm Available Window
Insulation Required: 0 mm total 0.1175 cm

WINDING STRUCTURE

☐ Magnet Wire ☐ Triple Insulated Wire ☒ Foil

Number of Layers: 6 Number of Parallel Wires: 1

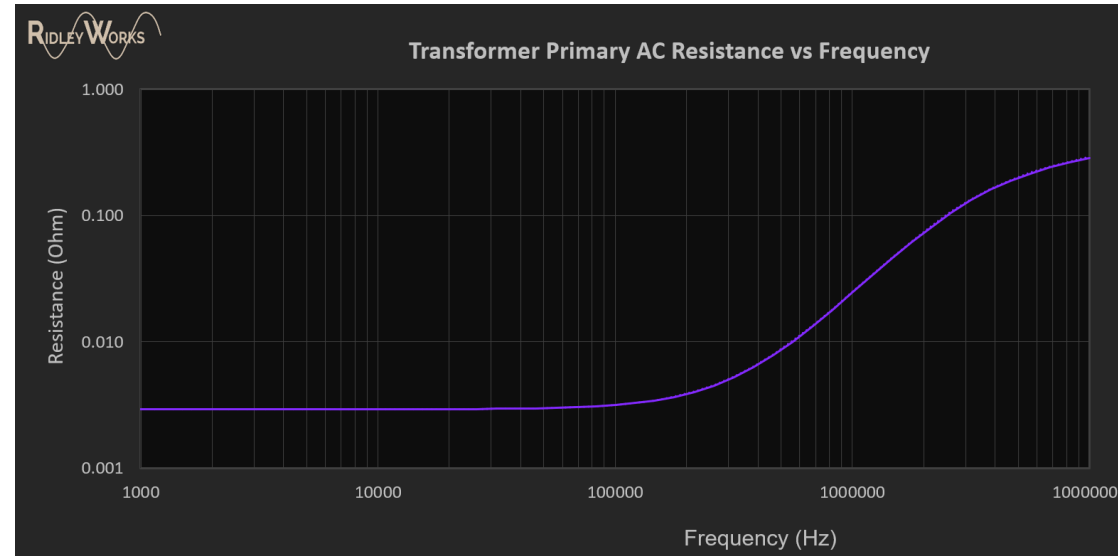
Maximum Conductor Size That Will Fit Exactly is: 0.185 mm = 7.28 mills
Your Choice of Conductor Size: 0.1111 mm = 4.37 mills

☐ Split Primary Winding Leakage Inductance: 0.091 μ H

WINDING LOSS DETAILS

RMS Current	9.484	A	Winding Loss (Including Proximity)	0.346	W
DC Current	0	A	Winding Loss (without Proximity Loss)	0.263	W
AC Current	9.484	A	Winding Surface Area	5.4	sq.cm
DC Resistance	0.00293	Ω			
AC Resistance	0.003857	Ω			

Buttons: Proximity Loss, Sweep AC Resistance, Σ



Note – thin value of foil gives best results.

Transformer Secondary Winding Design in RidleyWorks

Transformer Secondary Winding Design

AVAILABLE WINDOW

Margin Required: 0 mm each end 1.2 cm Available Window: 0.168 cm

Insulation Required: 0 mm total

MAIN SECONDARY OUTPUT

Output Voltage: 24 V Output Power: 120 W

Number of Turns: 5

WINDING STRUCTURE

☐ Magnet Wire ☐ Triple Insulated Wire ☒ Foil

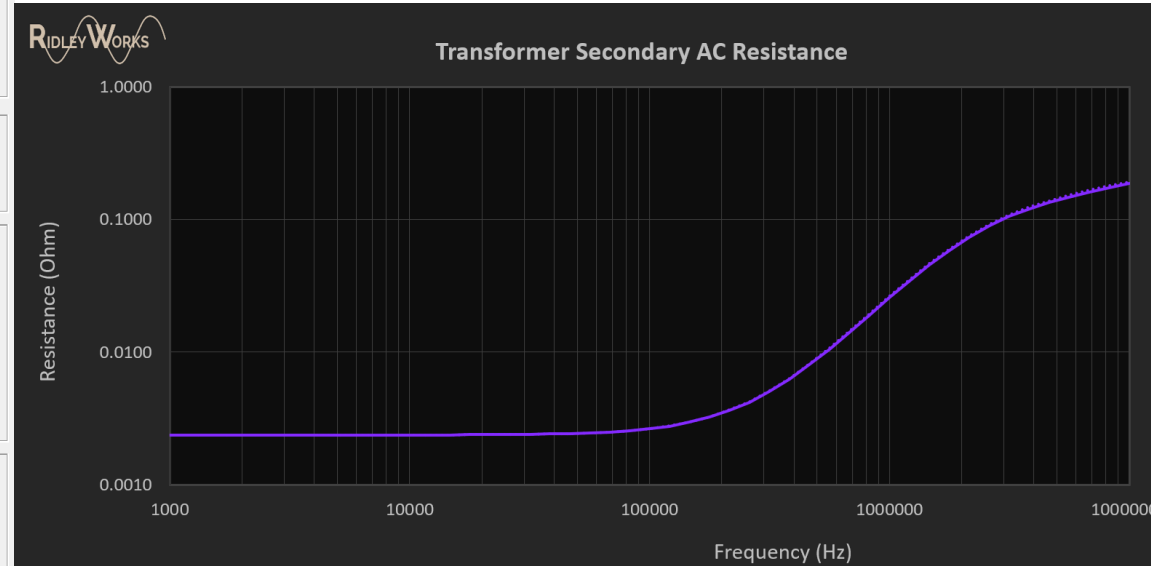
Number of Layers: 5 Number of Parallel Wires: 1

Maximum Conductor Size That Will Fit Exactly is: 0.323 mm = 12.73 mills

Your Choice of Conductor Size: 0.1333 mm = 5.24 mills

WINDING LOSS DETAILS

RMS Current	7.033 A	Winding Loss (Including Proximity)	0.304 W
DC Current	2.827 A	Winding Loss (without Proximity Loss)	0.234 W
AC Current	6.439 A	Winding Surface Area	5 sq.cm
DC Resistance	0.0023726 Ω		
AC Resistance	0.003447 Ω		



Note – thin value of foil gives best results.

Alternate Secondary Winding Design in RidleyWorks

Transformer Secondary Winding Design

AVAILABLE WINDOW

Margin Required: 0 mm each end, 1.2 cm Available Window

Insulation Required: 0 mm total, 0.168 cm

MAIN SECONDARY OUTPUT

Output Voltage: 24 V Output Power: 120 W

Number of Turns: 5

WINDING STRUCTURE

☒ Litz Wire ☐ Magnet Wire ☐ Triple Insulated Wire ☐ Foil

Number of Layers: 1 **Minimize Loss** Number of Parallel Wires: 2

Maximum Conductor Size That Will Fit Exactly is: 20 awg

Your Choice of Conductor Size: 20 awg

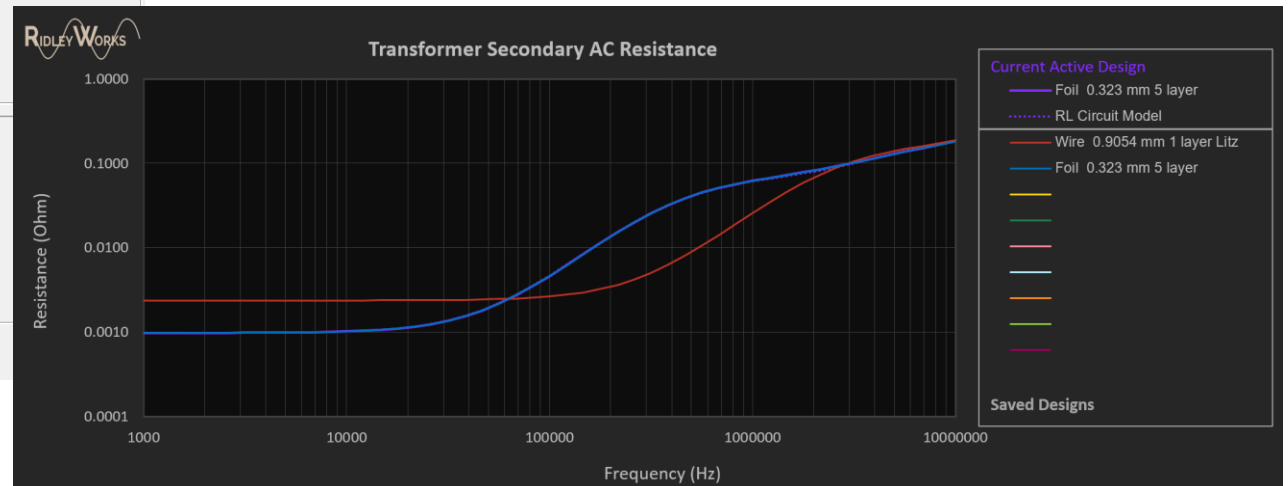
Update

WINDING LOSS DETAILS

RMS Current	7.033 A	Winding Loss (Including Proximity)	0.377
DC Current	2.827 A	Winding Loss (without Proximity Loss)	0.346
AC Current	6.439 A	Winding Surface Area	5.2
DC Resistance	0.0035138 Ω		
AC Resistance	0.004213 Ω		

Proximity Loss **Sweep AC Resistance**

Help Once you select OK, values appearing on this form will be used in the converter simulation.



Note – there are lots of choices for winding design

Resonant Inductor Core Design in RidleyWorks

LLC RESONANT INDUCTOR CORE SELECTION

Approximate Core Area 0.08 sq. cm

☐ Generic Core

☒ Use Selected Core

CORE TYPE AND AREA

Core Type RM4 Inductance 0.4167 μH

Minimum Area 0.14 sq cm Peak Current 30.2809 A

MAXIMUM FLUX LEVEL SETTING

0.3 T

This value will determine the number of turns needed

INDUCTOR TURNS REQUIRED

Turns 4

Maximum Flux Density at Peak Current Limit: 0.2253 T

CORE PHYSICAL DETAILS

Core Volume 0.31 cu. cm

Window Width 0.58 cm

Window Build 0.13 cm

Inner Turn Length 1.55 cm

Outer Turn Length 2.41 cm

CORE GAPPING

0.67 mm 26.8 mills

Note that gap length is a rough guide only. Manufacturing design is specified by Al, and the core is gapped to achieve the correct value

Al value 26.04 nH/n2

LLC RESONANT INDUCTOR CORE MATERIAL

OPERATING CONDITIONS

Operating Delta B	0.187 T	Core Area	0.14 cm2
Core Excitation Frequency	200 kHz	Peak Flux at Current Limit	0.2253 T
Duty Cycle D1 (Flux Rise)	0.5	Number of Turns	4
Duty Cycle D2 (Flux Fall)	0.509	Core Volume	0.31 cm3
Temperature	25 deg C		

LLC RESONANT INDUCTOR CORE MATERIAL

Ferroxcube	TDK	Magnetics	Any		
<input type="radio"/> 3C90	<input type="radio"/> PC40	<input type="radio"/> P	<input type="radio"/> MPP 200u	<input type="radio"/> New	<input type="radio"/> New
<input type="radio"/> 3F3	<input type="radio"/> PC90	<input type="radio"/> F	<input type="radio"/> Hi-Flux 60 μ	<input type="radio"/> New	<input type="radio"/> New
<input type="radio"/> 3C96	<input type="radio"/> PC44	<input type="radio"/> R	<input type="radio"/> New	<input type="radio"/> New	<input type="radio"/> New
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<input type="radio"/> 3C94	<input type="radio"/> N95	<input type="radio"/> New	<input type="radio"/> New	<input type="radio"/> New	<input type="radio"/> New
<input type="radio"/> 3C95	<input checked="" type="radio"/> PC95	<input type="radio"/> New	<input type="radio"/> New	<input type="radio"/> New	<input type="radio"/> New

CHARACTERISTICS FOR SELECTED MATERIAL

Permeability	3300	Core Loss	0.241 W
--------------	-------------------	-----------	----------------------

LTSPICE CORE LOSS MODEL

Inductors		Resistors	
LC1	0.874176 mH	RC1	3.848 Ω
LC2	0.697502918 mH	RC2	18.423 Ω
LC3	0.556 mH	RC3	88.218 Ω
		RC4	421.343 Ω
		RC5	2.080322 k Ω
		RC6	7.103454 k Ω
		RC7	67.853121 k Ω

Voltage Exponent 1.1715

PSIM/LTspice Core Models

☐ Enable
☒ Disable

Resonant Inductor Winding Design in RidleyWorks

INDUCTOR DESIGN

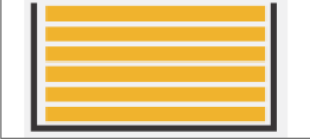
Inductor Value **0.4167** uH Number of Turns **4**

AVAILABLE WINDOW

Margin Required mm each end

Insulation Required mm total

0.58 cm winding length



0.13 cm build

WINDING STRUCTURE

☐ Use Magnet Wire ☒ Use Foil ☐ Helical Foil

Number of Layers

Number of Parallel Wires

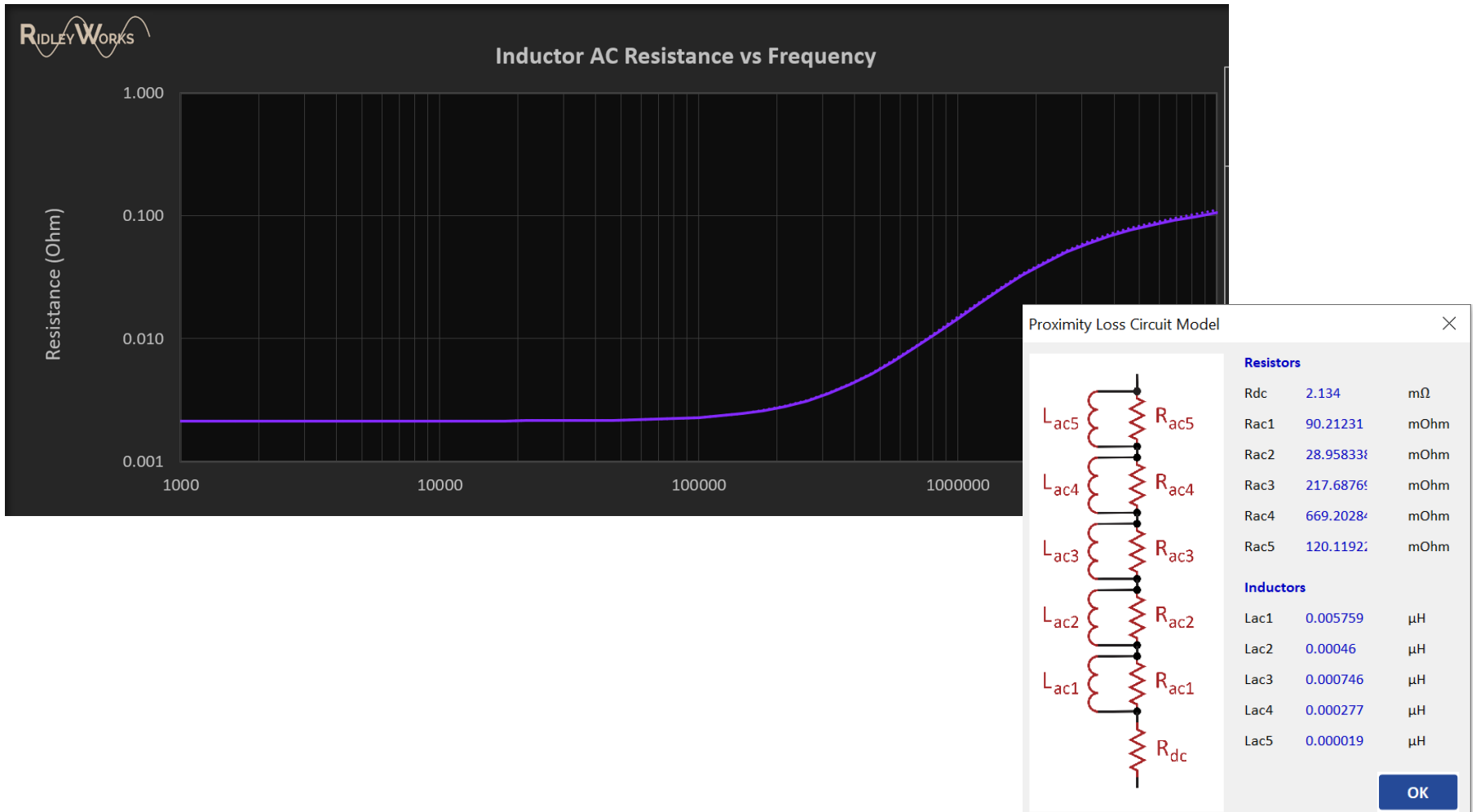
Maximum Conductor Size That Will Fit Exactly is **0.31** mm = **12.2** mills

Your Choice of Conductor Size mm = **3.64** mills

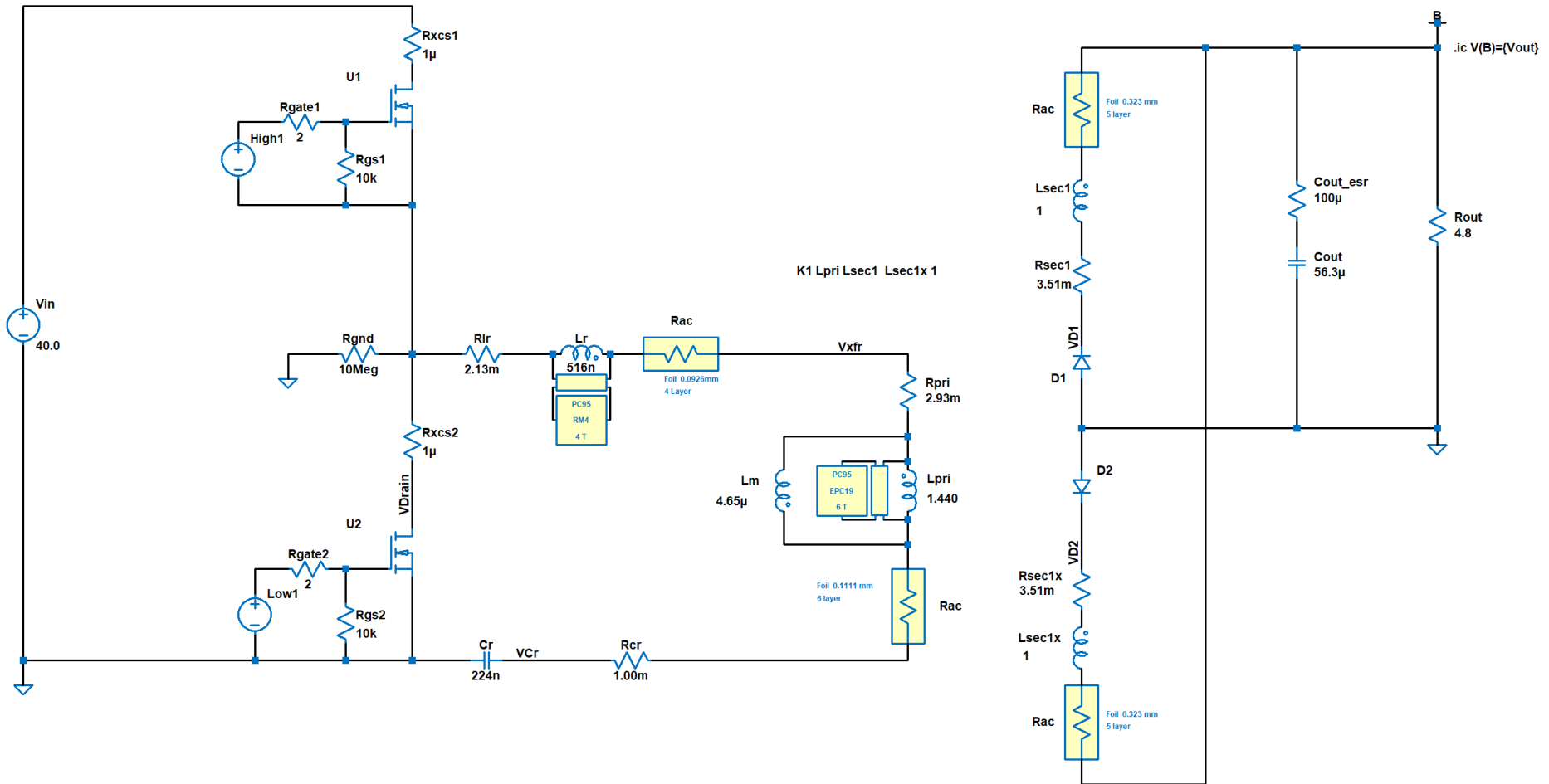
WINDING LOSS DETAILS

RMS Current	9.484050	A	Winding Loss (Including Proximity)	0.243	W
DC Current	0	A	Winding Loss (without Proximity Loss)	0.1919	W
AC Current	25.172693	A	Winding Surface Area	1.04	sq.cm
DC Resistance	2.13E-03	Ω			
AC Resistance	2.71E-03	Ω			

Resonant Inductor AC Resistance from RidleyWorks

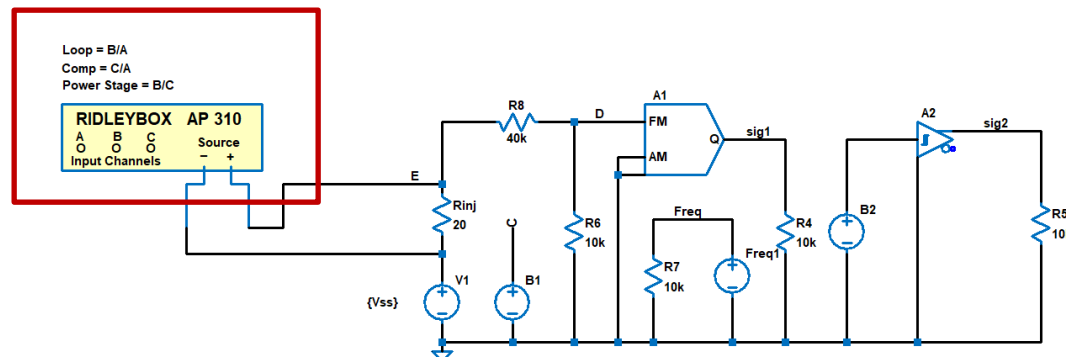
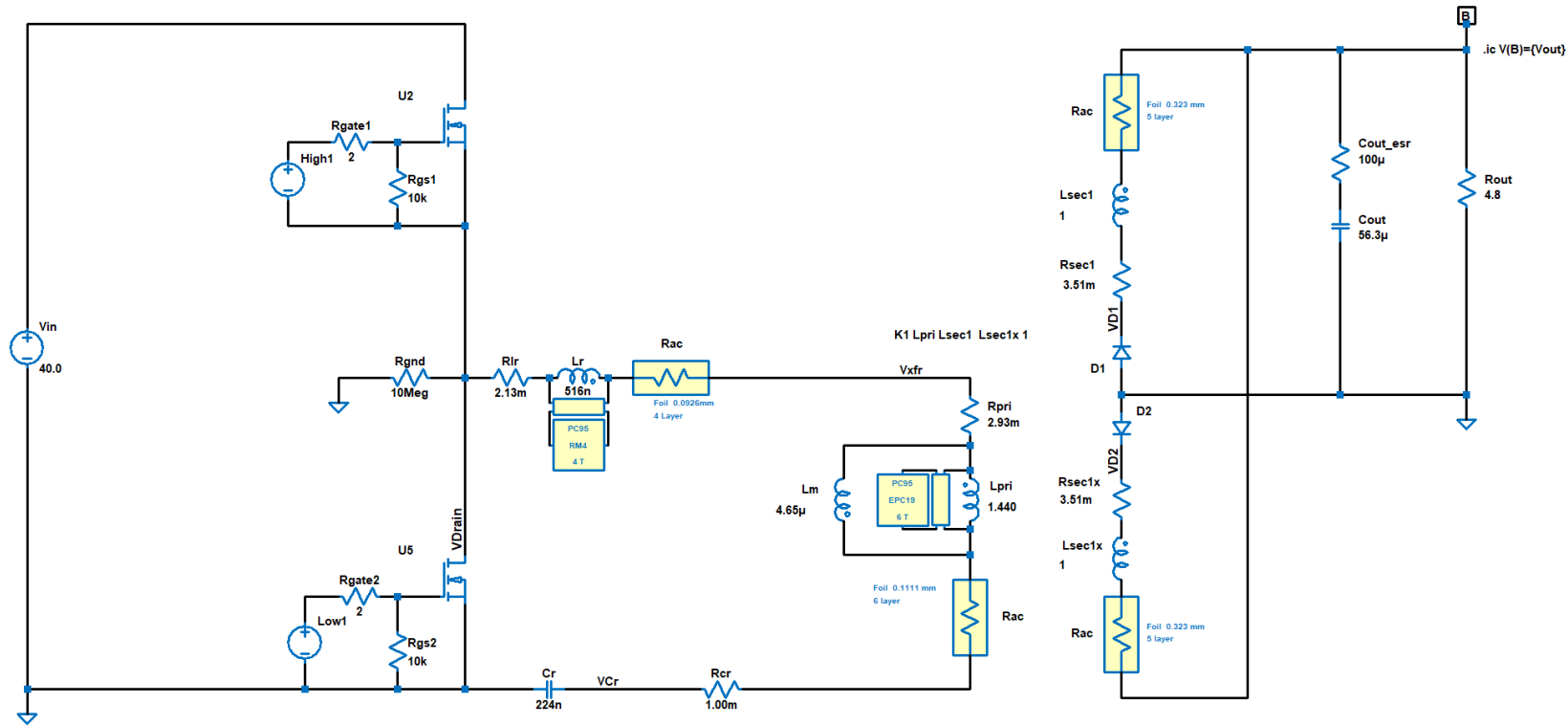


LTspice Simulation with Full Inductor and Transformer Proximity and Core Loss Models

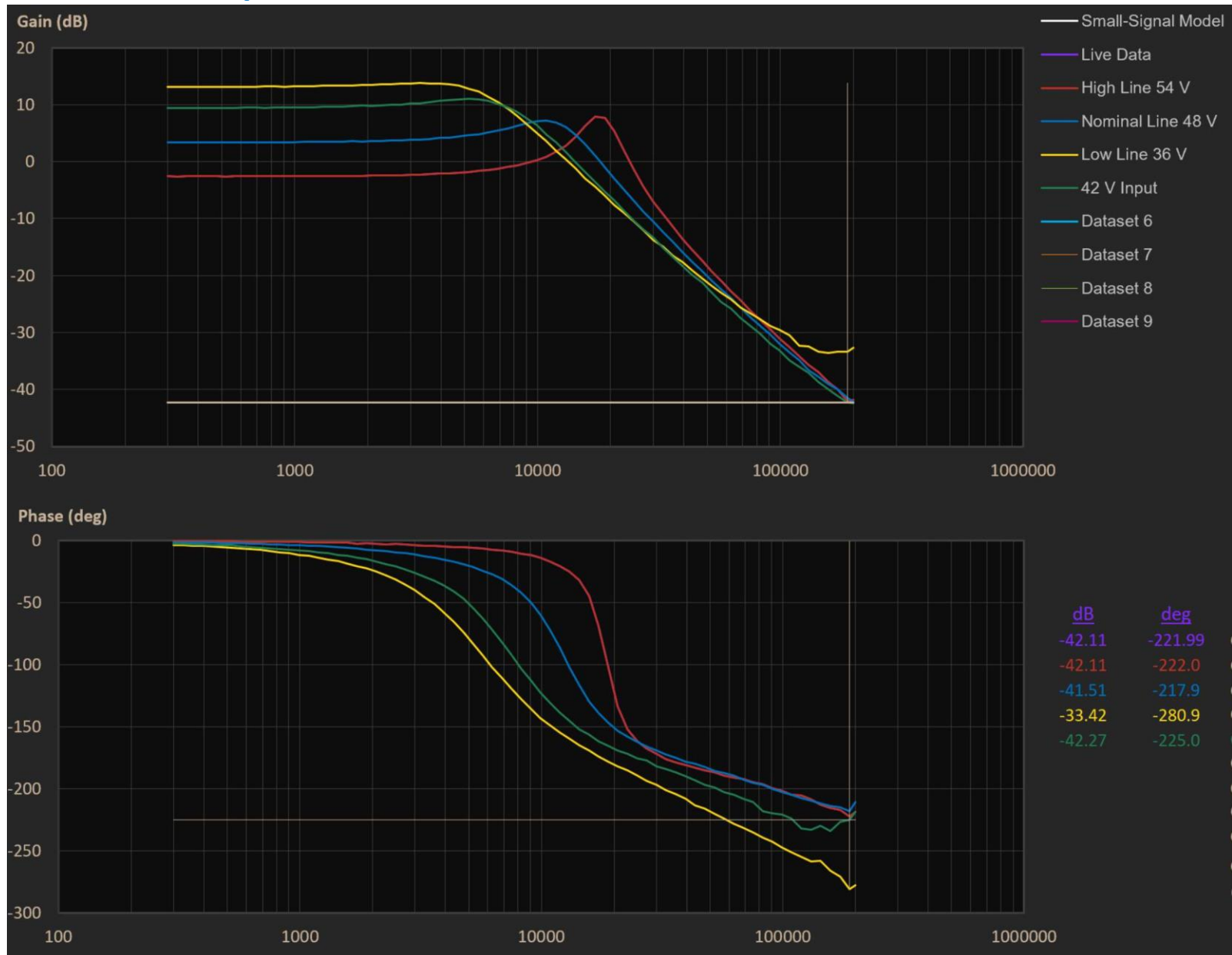


Note – 34 extra inductors in simulation circuit.
LTspice doesn't have any problem with this

LTspice Simulation of Control Transfer Function



LTspice Simulation of Control Transfer Function



Next Webinar Topic?

Magnetics?

Control?

Modeling?

Measurement?

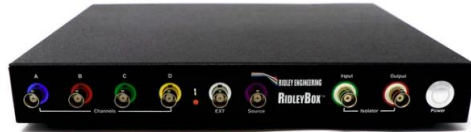
Topologies?

Simulation?

Other?

Ridley Engineering Products

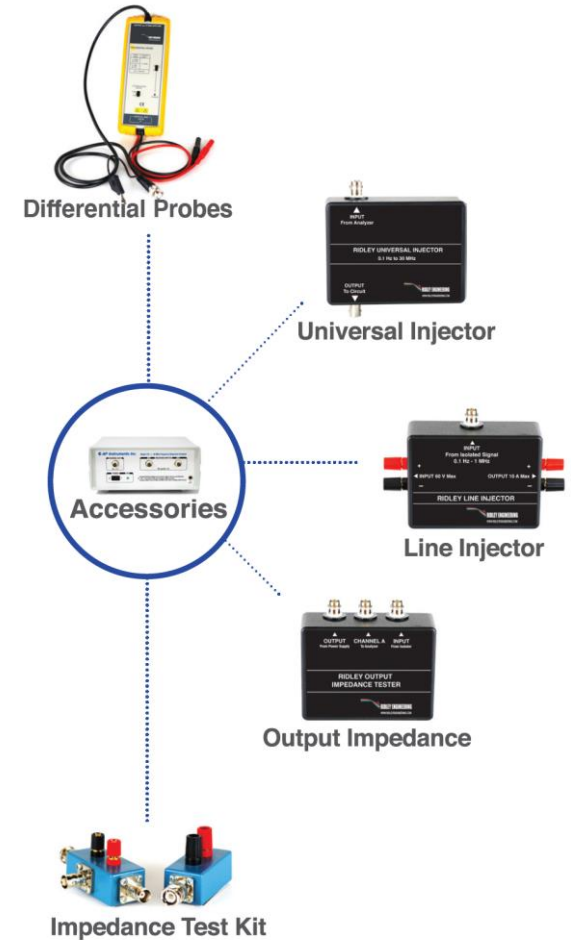
Frequency Response Analysis Tools



RidleyBox



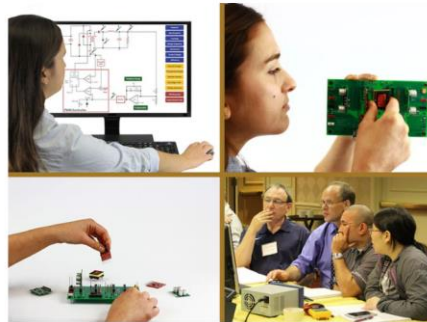
AP Model 310



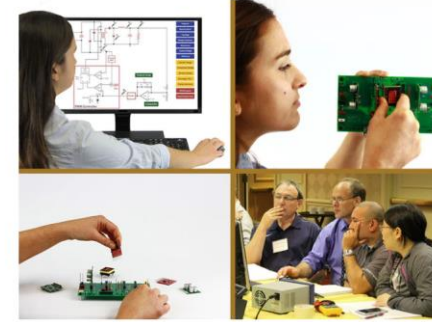
Hands-On Design Workshops



**5-Day Workshop: DEC 5-9, 2022 in
Camarillo, CA**
Sold out



**5-Day Workshop: MAR 6-10, 2023 in
Camarillo, CA**
\$3,500.00

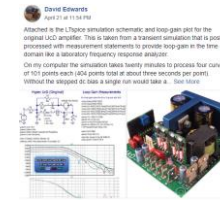


**5-Day Workshop: JUN 12-16, 2023 in
Camarillo, CA**
\$3,500.00



Email info@ridleyengineering.com
For full demo

Power Supply Design Center Facebook Group



A New Small-Signal Model for Current-Mode Control

Raymond B. Ridley

Free
Book

Power Supply Design Center Articles

