Impact of Fringing Effects on the Design of DC-DC Converters

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2018 APEC PSMA/PELS Magnetics Workshop

Outline

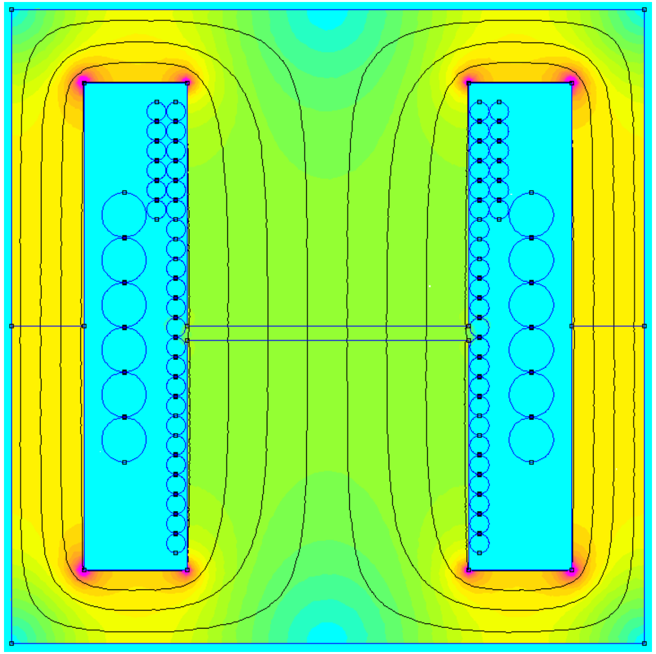
- Fringe-field loss: What does a power supply designer need to know?
- Which magnetic designs and topologies are most affected by fringing effects?
- Fringing effects: Buck and Boost inductors
- Fringing effects: Flyback transformers
- Fringing effects: LLC resonant transformers
- Conclusions and rules of thumb

What is the Fringing Effect?

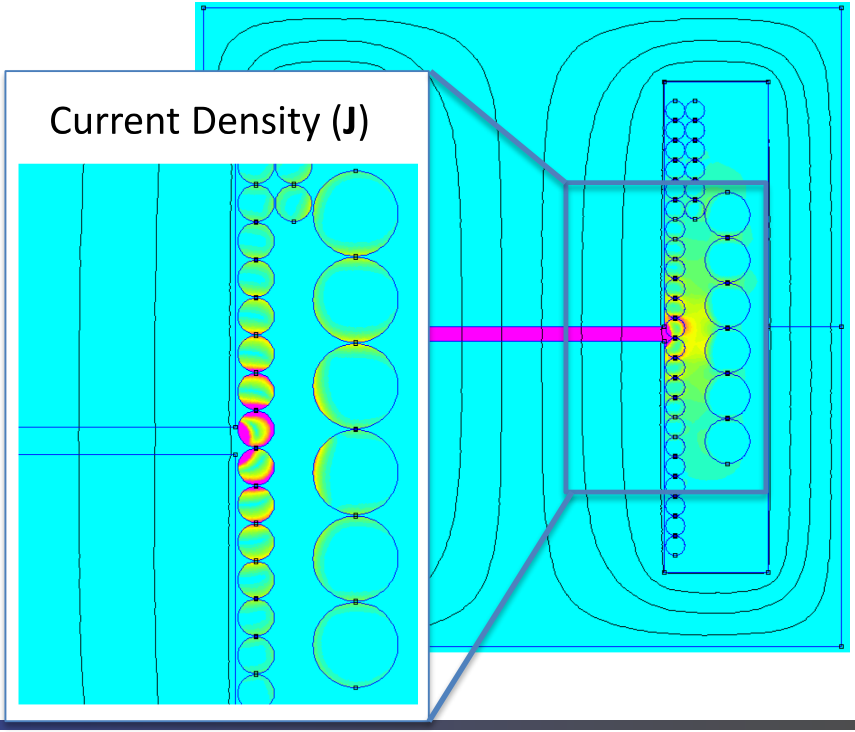
Flux Density (**B**)

$$\boldsymbol{B} = \mu \boldsymbol{H}$$

Field (**H**)



$$E_v =$$

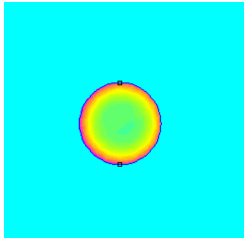


Current Density (**J**)

[1] Finite Element Method Magnetics: http://www.femm.info

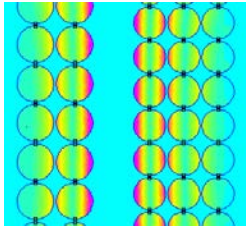
A Unifying Theory of AC Winding Losses

Skin Depth



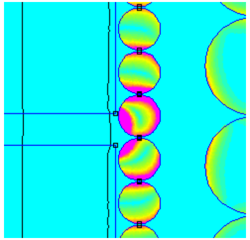
Current in single wire or turn

Proximity



H-field generated by nearby turns and windings

Fringing



Fringing H-field contributed by core gap(s)

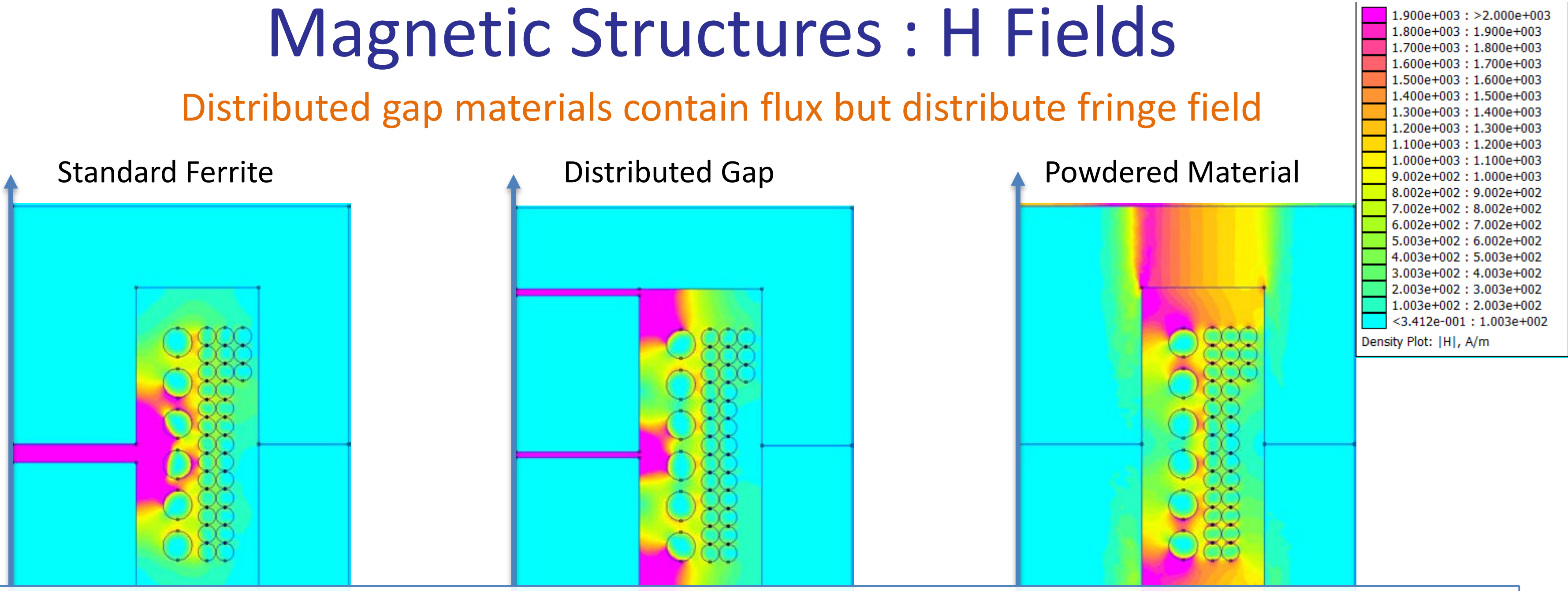
Eddy currents induced to cancel H field

Additional copper losses

[2] Nan, Sullivan, “Simplified High-Accuracy Calculation of Eddy-Current Loss in Round-Wire Windings,” IEEE PESC 2004
[3] Zimmanck, Sullivan, “Efficient Calculation of Winding-Loss Resistance Matrices for Magnetic Components,” IEEE COMPEL 2010

Magnetic Structures : H Fields

Distributed gap materials contain flux but distribute fringe field


Standard Ferrite

Distributed Gap

Powdered Material

Loss: 337mW

Loss: 188mW

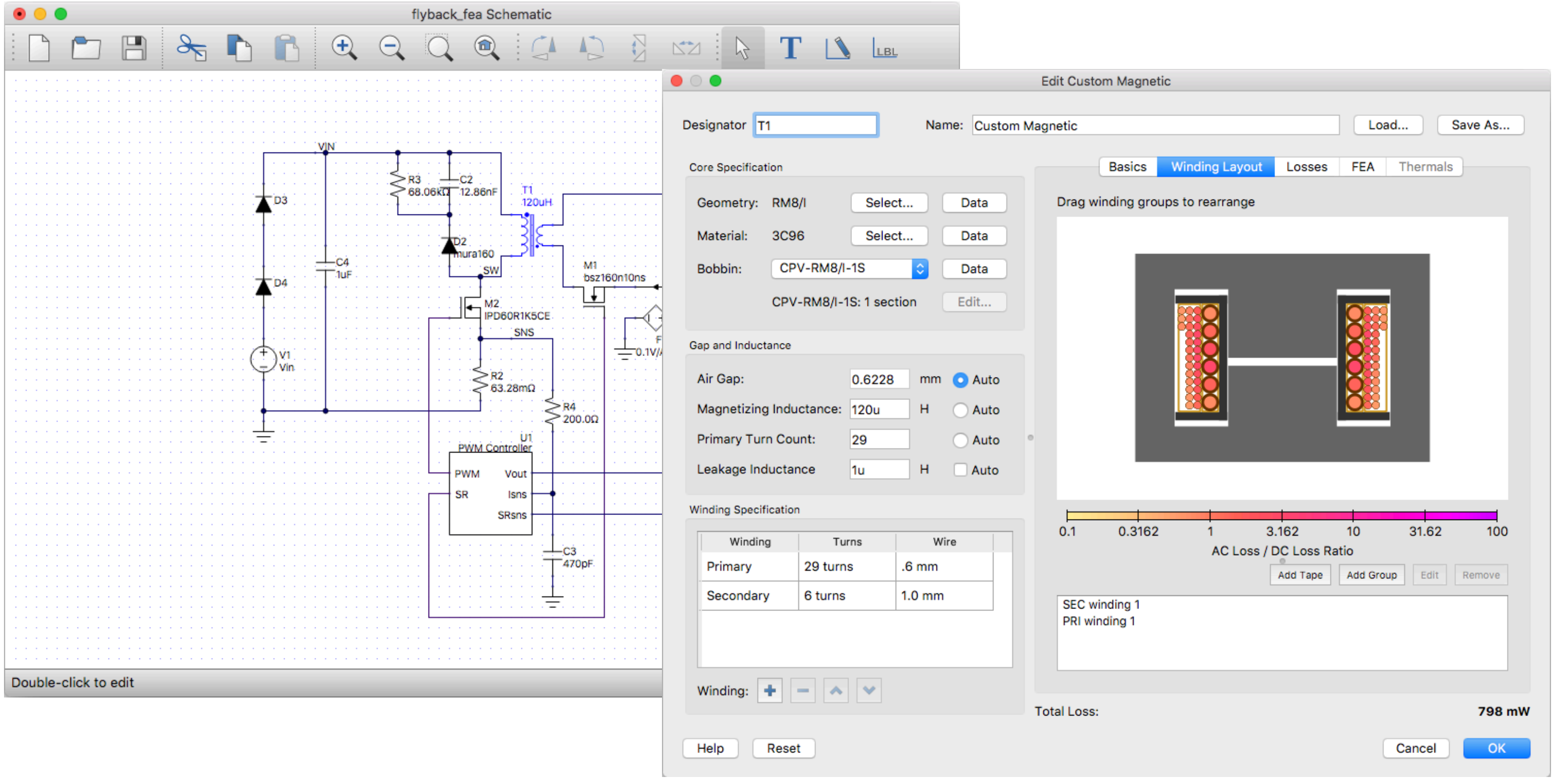
Loss: 360mW

- Single gap can cause large fringing losses in nearby windings
- Distributed gap effective at reducing fringing fields and losses while keeping flux contained in core
- Ungapped material (e.g. powdered iron) not effective in Pot-core shapes in constraining flux.
    - Fringing fields extend into window, not near gap
    - Likely much better in toroid geometries

Example: 120 µH, 45W offline flyback transformer @ 500 kHz, RM8/I core, losses at fundamental current only in FEMM

Eta One Power, Inc

Analyzing Power Magnetics: Software



Edit Custom Magnetic

Designator: T1

Name: Custom Magnetic

Core Specification

Geometry: RM8/I

Material: 3C96

Bobbin: CPV-RM8/I-1S

CPV-RM8/I-1S: 1 section

Gap and Inductance

Air Gap: 0.6228 mm ● Auto

Magnetizing Inductance: 120u H ○ Auto

Primary Turn Count: 29 ○ Auto

Leakage Inductance 1u H ☐ Auto

Winding Specification

Winding	Turns	Wire
Primary	29 turns	.6 mm
Secondary	6 turns	1.0 mm

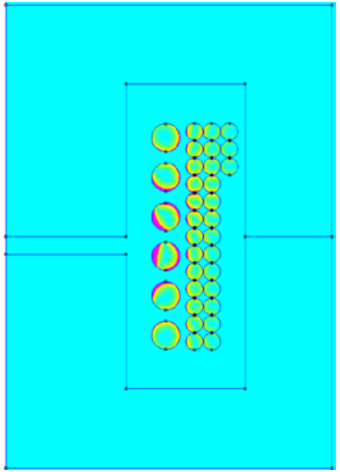
Drag winding groups to rearrange

SEC winding 1
PRI winding 1

Total Loss: 798 mW

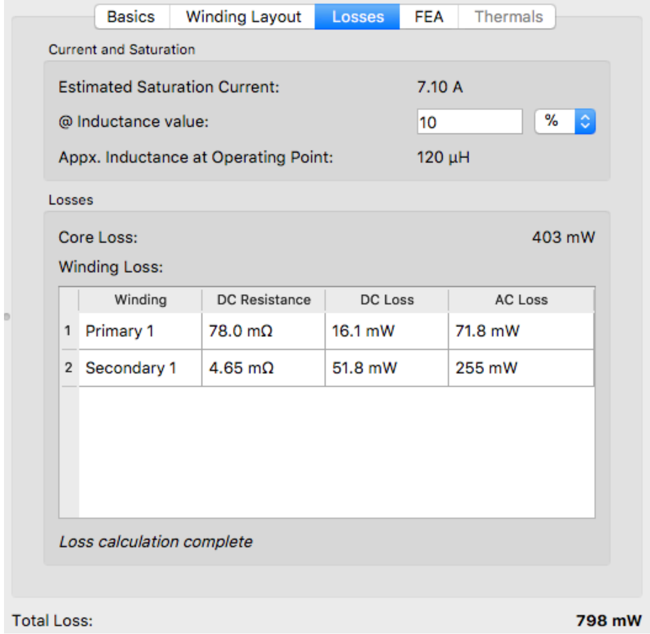
Power Software: Loss Accuracy

FEA / FEMM



Loss: 337mW

EtaDesigner



Current and Saturation

Estimated Saturation Current: 7.10 A

@ Inductance value: 10 %

Appx. Inductance at Operating Point: 120 µH

Losses

Core Loss: 403 mW

Winding Loss:

	Winding	DC Resistance	DC Loss	AC Loss
1	Primary 1	78.0 mΩ	16.1 mW	71.8 mW
2	Secondary 1	4.65 mΩ	51.8 mW	255 mW

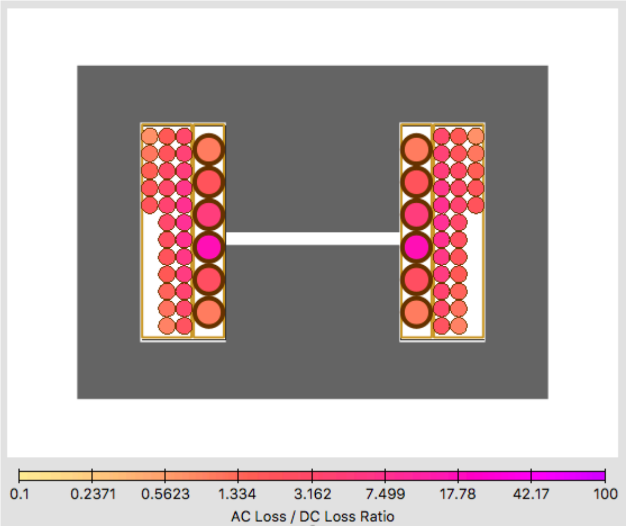
Loss calculation complete

Total Loss: **798 mW**

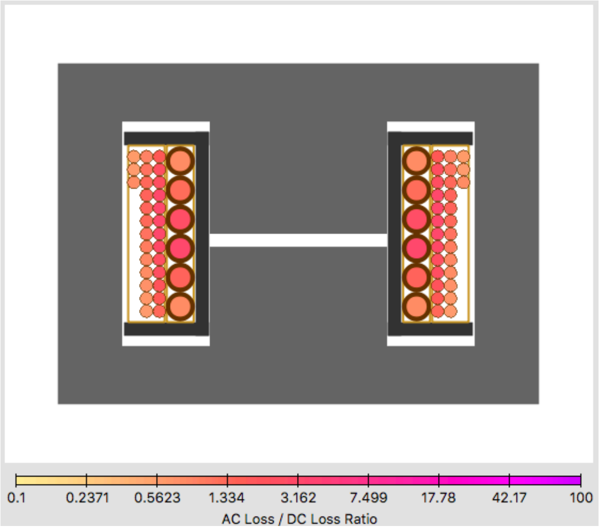
Eta Designer includes core loss and AC/DC winding loss for **actual** waveforms

Examining Winding Location: Eta Designer

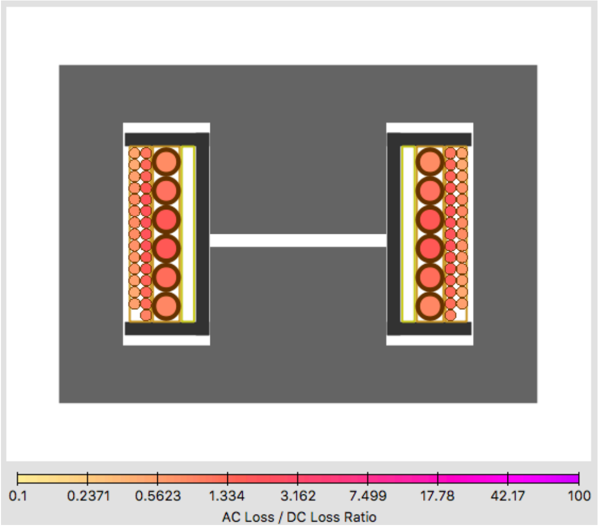
85-265 VAC to 20V/2.25A Flyback @ 500 kHz



Winding Loss: 544 mW



Winding Loss: 382 mW

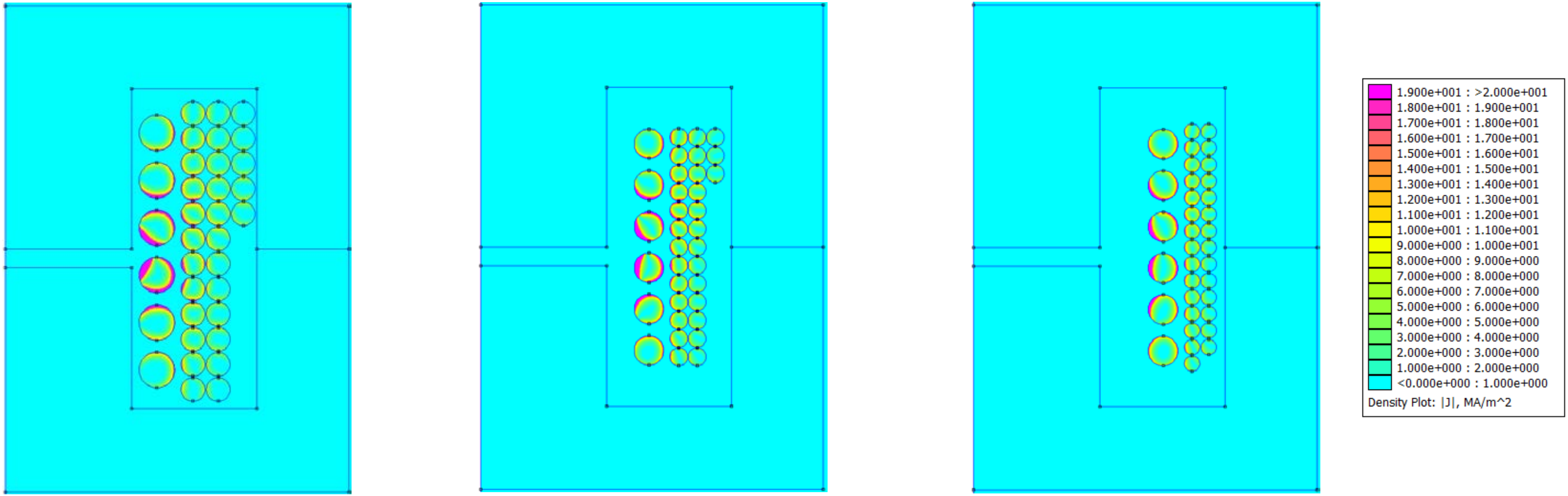


Winding Loss: 308 mW

See [4]: Hu, Sullivan, “Optimization of shapes for round-wire high-frequency gapped-inductor windings,” IEEE Ind. Appl. Soc. Annual Meeting 1998.

Examining Winding Location: FEMM

85-265 VAC to 20V/2.25A Flyback @ 500 kHz



Winding Loss: 560 mW

Winding Loss: 337 mW

Winding Loss: 226 mW

See [4]: Hu, Sullivan, “Optimization of shapes for round-wire high-frequency gapped-inductor windings,” IEEE Ind. Appl. Soc. Annual Meeting 1998.

A Look at Topologies

Magnetic stores energy

- Buck, Boost, Buck-Boost
- Flyback
- LLC and most resonant topologies

Gapped / low-μ designs

Magnetic does not* store energy

- Forward
- Half-bridge, Full-bridge

Ungapped high-μ designs

But: all have a buck-type inductor at output

All converter types suffer from fringe-field loss in one way or another

Three case studies for scaling: Buck (Boost, Buck-Boost), Flyback, Resonant LLC

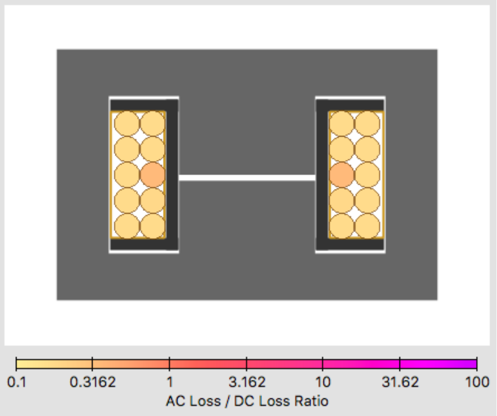
Buck Converter: Two Examples

Both Converters are 48V to 12V, 100W

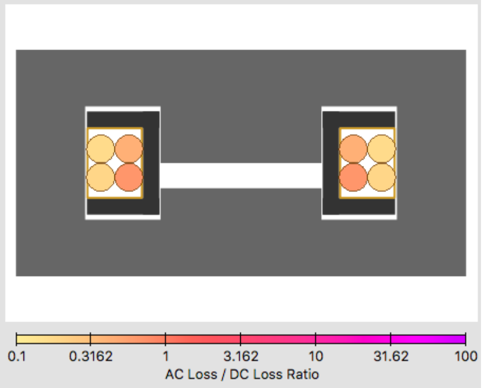
Example 1:
300 kHz, 20% ripple

L = 18 µH (g: 315µm)
10t x AWG 16
RM7/I-3F36

Core Loss: 21 mW
DC Winding: 330 mW
AC Winding: 35 mW
Total: **386 mW** (0.39%)



Example 2:
500 kHz, QSW (200% ripple)



L = 1 µH (g: 1.0 mm)
4t x **360/44 Litz**
RM6S/ILP-3F36

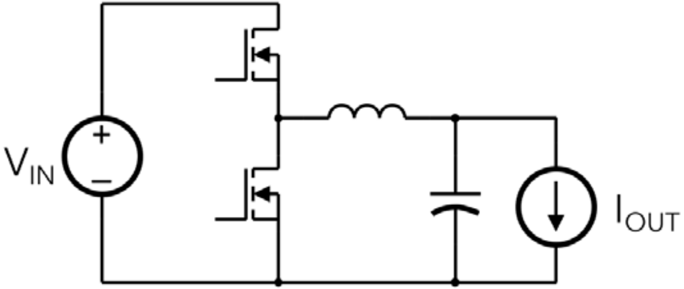
Core Loss: 182 mW
DC Winding: 295 mW
AC Winding: 161 mW
Total: **637 mW** (0.64%)

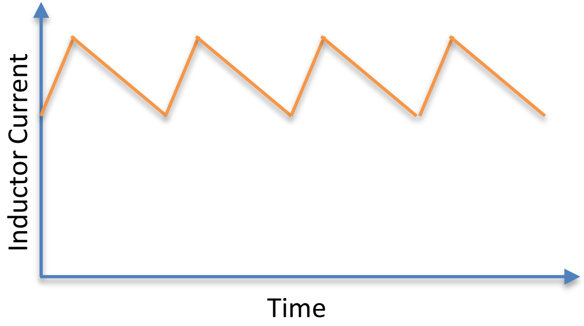
With solid wire, AC loss is 1.0 W!

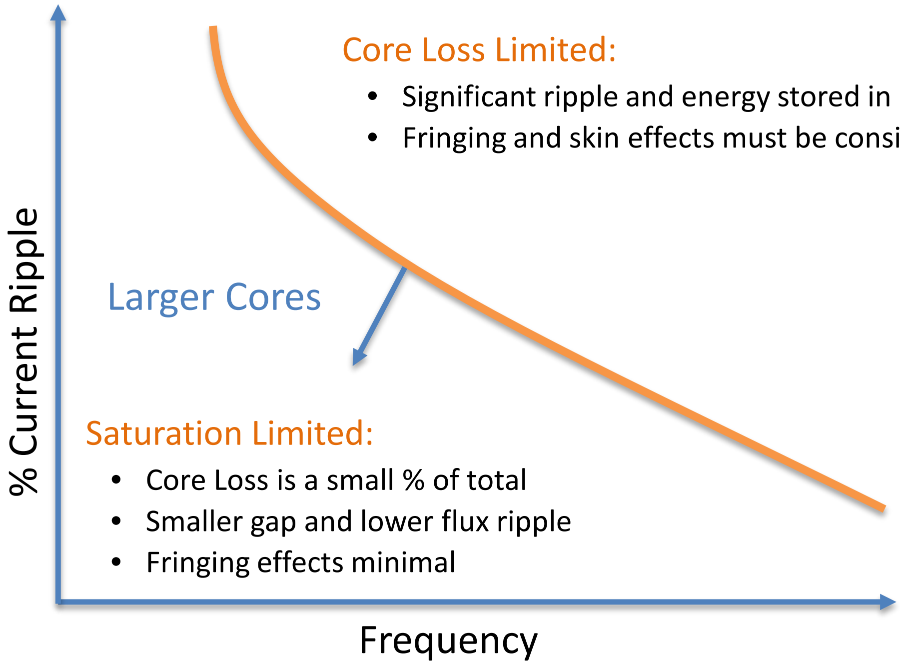
Saturation limited, AC effects negligible

Core loss limited, AC effects dominant

Buck Converter Space







Core Loss Limited:

- Significant ripple and energy stored in core
- Fringing and skin effects must be considered

Saturation Limited:

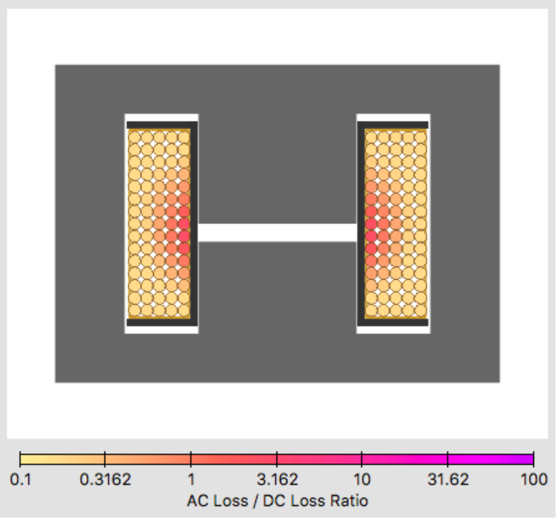
- Core Loss is a small % of total
- Smaller gap and lower flux ripple
- Fringing effects minimal

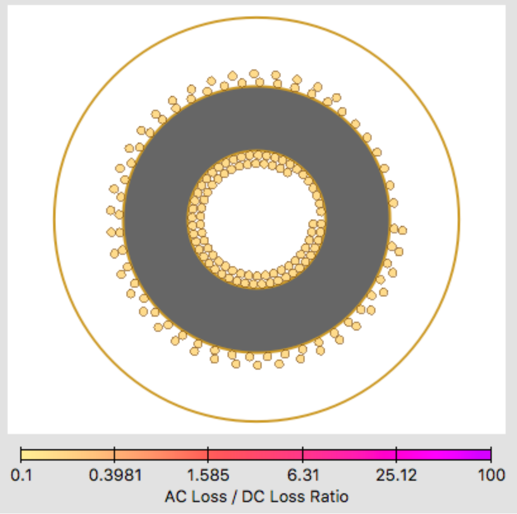
Example 2: PFC Boost

AC input to 400V DC @ 1kW; In this example, Vin = 200 V, fsw = 100 kHz

L = 1 mH (g: 1.7mm)
75t x AWG 17
RM14/I-3C96

Core Loss: 27 mW
DC Winding: 2.26 W
AC Winding: 1.45 W
Total: **3.74 W** (0.37%)





L = 1 mH (g: N/A)
85t x AWG 15
Sendust MS-184-60

Core Loss: 1.38 W
DC Winding: 1.52 W
AC Winding: 26 mW
Total: **2.92 W** (0.29%)

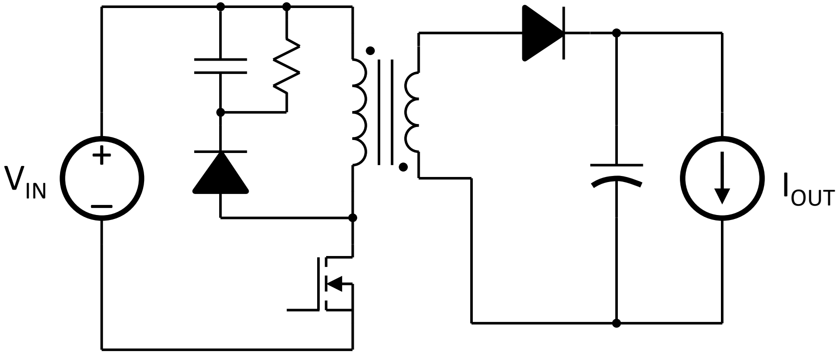
Core loss isn't dominant (saturation limited), but many windings on a highly-gapped core

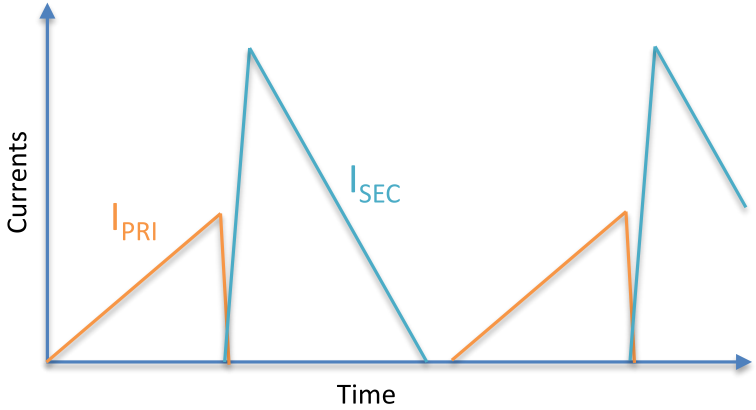
Powdered toroid core will eliminate fringing loss, core and winding loss must be managed

Note: intra-winding capacitance a huge factor in both designs

Fringing Loss in Flyback Converters

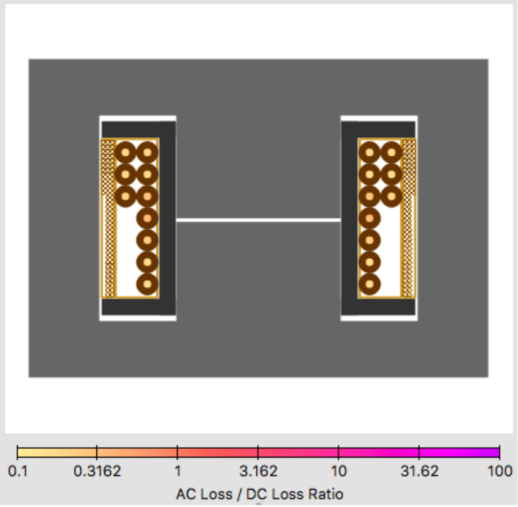
- Simple, low-component count AC-DC/DC-DC converter
- Indirect power conversion means transformer handles all power





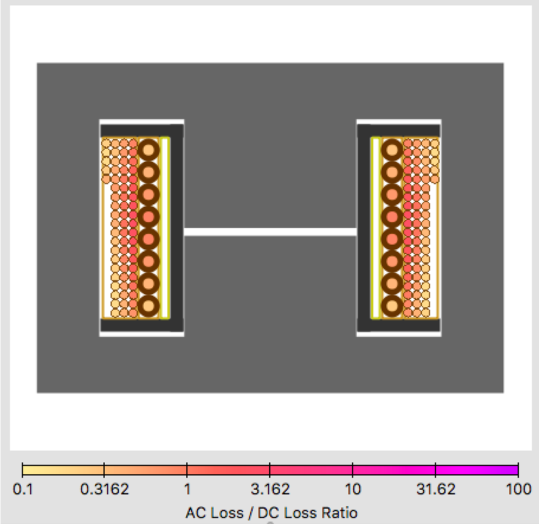
Flyback Converter: Power Scaling

200 Vin, 20 Vout @ **0.5A**
100 kHz, Lm = 2 mH (g: 140µm)
80xAWG35 : 10xAWG28 on RM6S/I-3C96



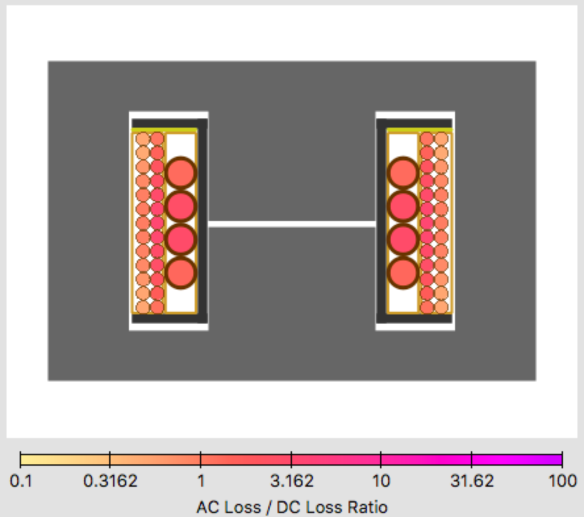
Core Loss: 121 mW
DC Winding: 109 mW
AC Winding: 14 mW
Total: **244 mW** (2.4%)

200 Vin, 20 Vout @ **1.5A**
100 kHz, Lm = 900 µH (g: 387µm)
65xAWG26 : 8xAWG23 on RM8/I-3C96



Core Loss: 128 mW
DC Winding: 205 mW
AC Winding: 267 mW
Total: **600 mW** (2.0%)

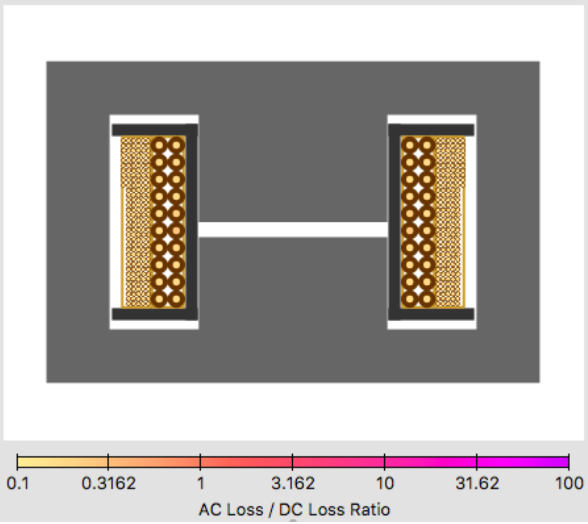
200 Vin, 20 Vout @ **5A**
100 kHz, Lm = 270 µH (g:465µm)
26xAWG18 : 4xAWG12 on RM14/I-3C96



Core Loss: 443 mW
DC Winding: 128 mW
AC Winding: 705 mW
Total: **1.28 W** (1.28%)

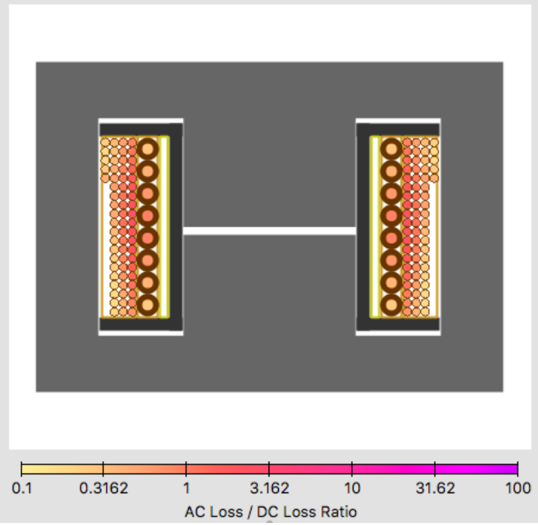
Flyback Converter: Frequency Scaling

200 Vin, 20 Vout @ 1.5A
20 kHz, Lm = 5.2 mH (g: 870µm)
180xAWG30 : 20xAWG25 on RM10/I-3C96



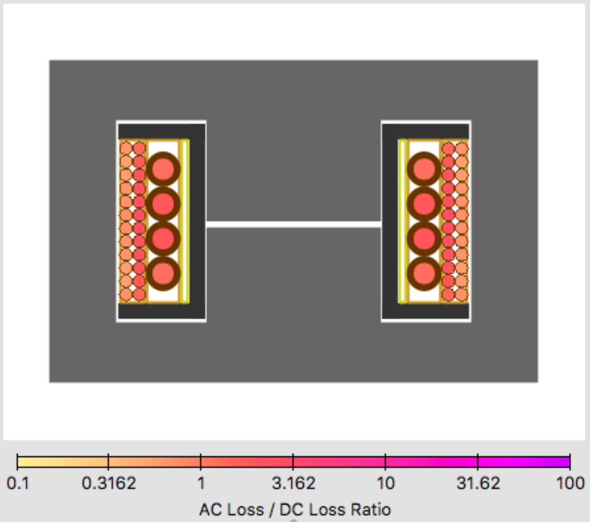
Core Loss: 41.1 mW
DC Winding: 1043 mW
AC Winding: 77 mW
Total: **1.16 W** (3.86%)

200 Vin, 20 Vout @ 1.5A
100 kHz, Lm = 900 µH (g: 387µm)
65xAWG26 : 8xAWG23 on RM8/I-3C96



Core Loss: 128 mW
DC Winding: 205 mW
AC Winding: 267 mW
Total: **600 mW** (2.0%)

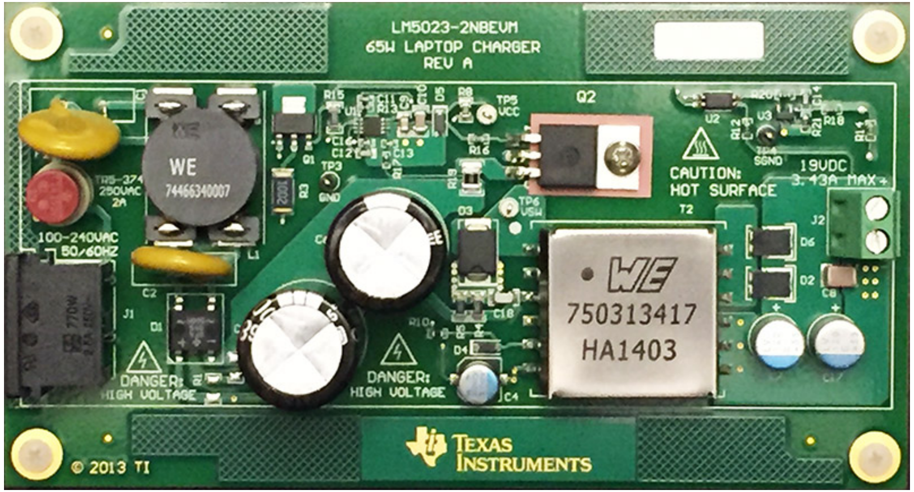
200 Vin, 20 Vout @ 1.5A
500 kHz, Lm = 125 µH (g: 253µm)
24xAWG24 : 4xAWG20 on RM7/I-3F36



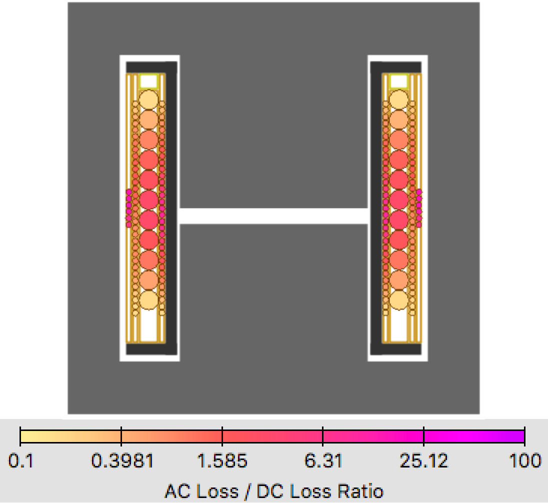
Core Loss: 273 mW
DC Winding: 55 mW
AC Winding: 188 mW
Total: **516 mW** (1.7%)

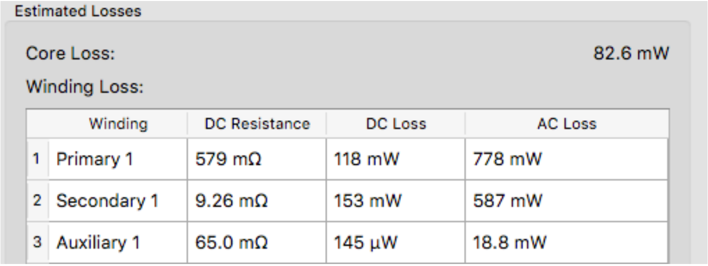
Flyback: Simulation vs. Bench

65W Universal AC to 19V Flyback Converter
LM5023 Valley-mode flyback controller EVM



In Eta Designer:





Estimated Losses

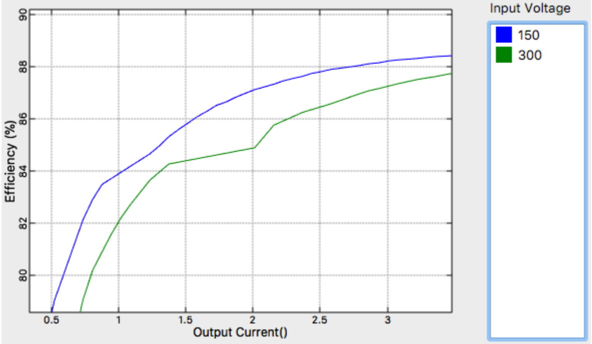
Core Loss: 82.6 mW

Winding Loss:

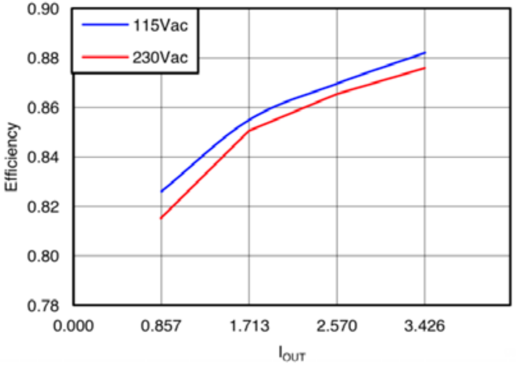
	Winding	DC Resistance	DC Loss	AC Loss
1	Primary 1	579 mΩ	118 mW	778 mW
2	Secondary 1	9.26 mΩ	153 mW	587 mW
3	Auxiliary 1	65.0 mΩ	145 µW	18.8 mW

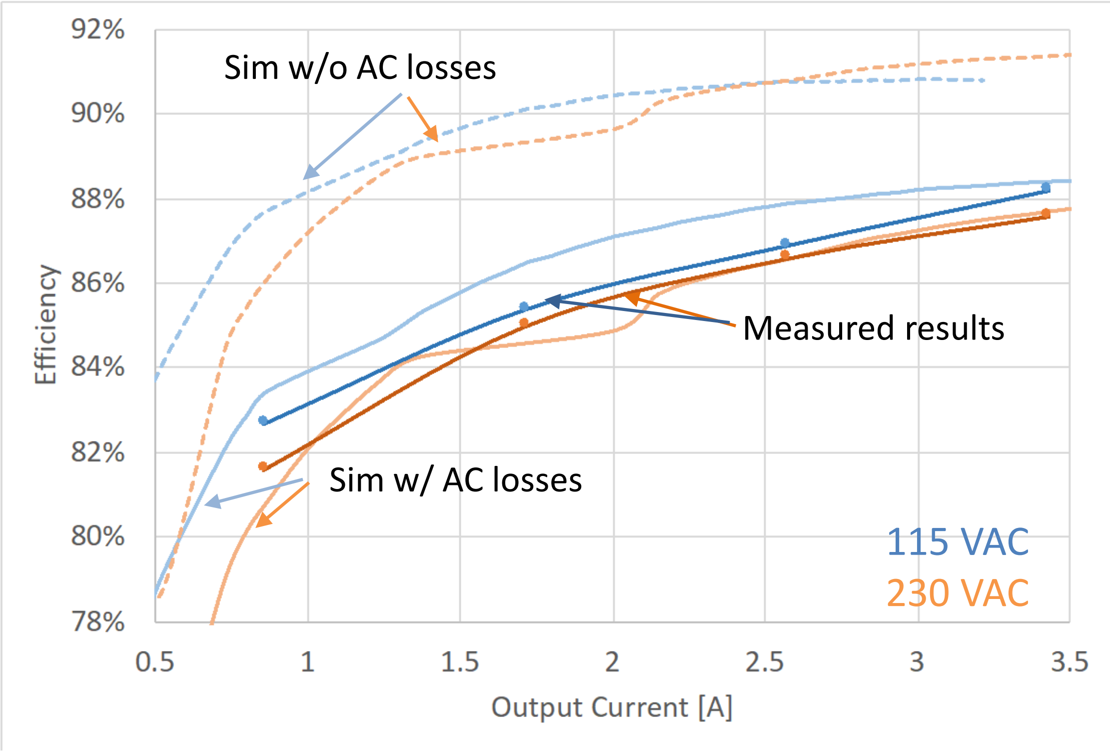
Flyback: Simulation vs. Bench (2)

Simulated: From Eta Designer

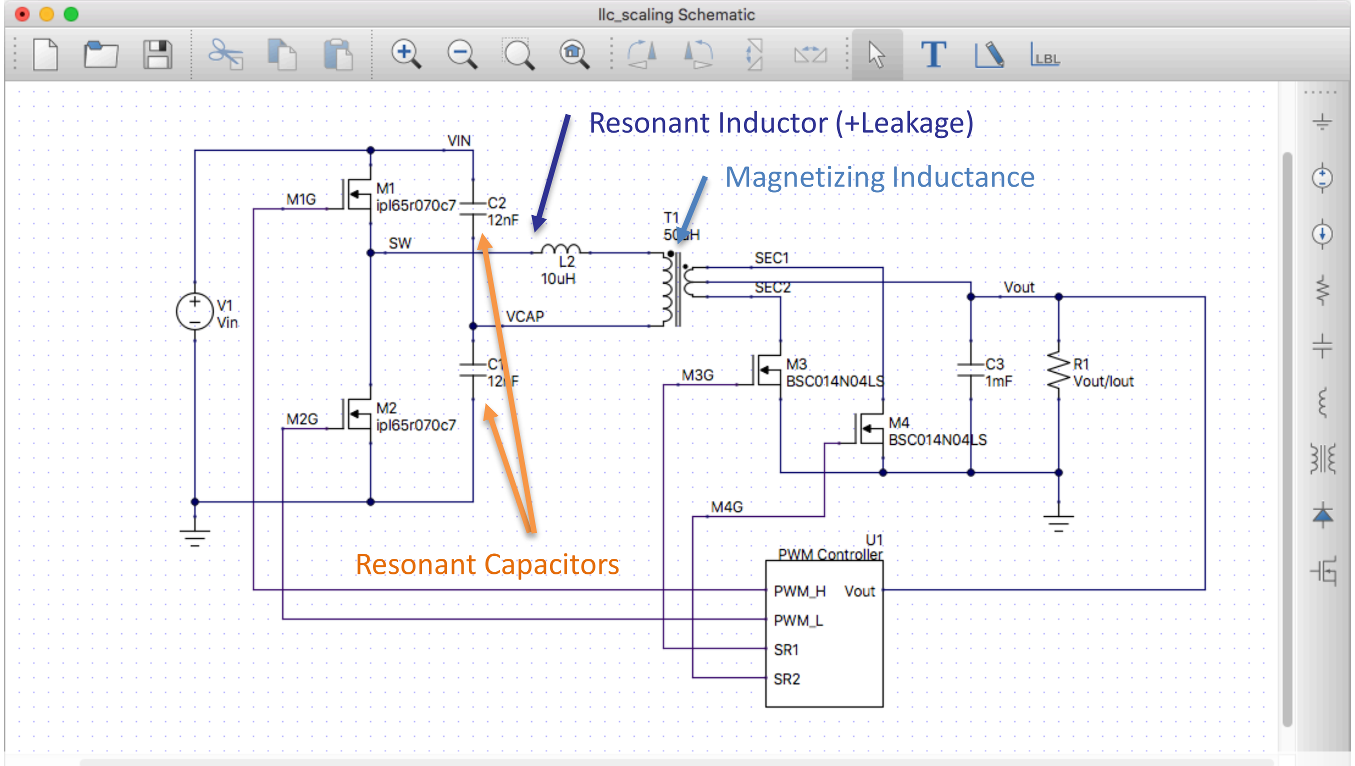


Measured: From EVM Datasheet





Fringing Loss in LLC/Resonant Converters



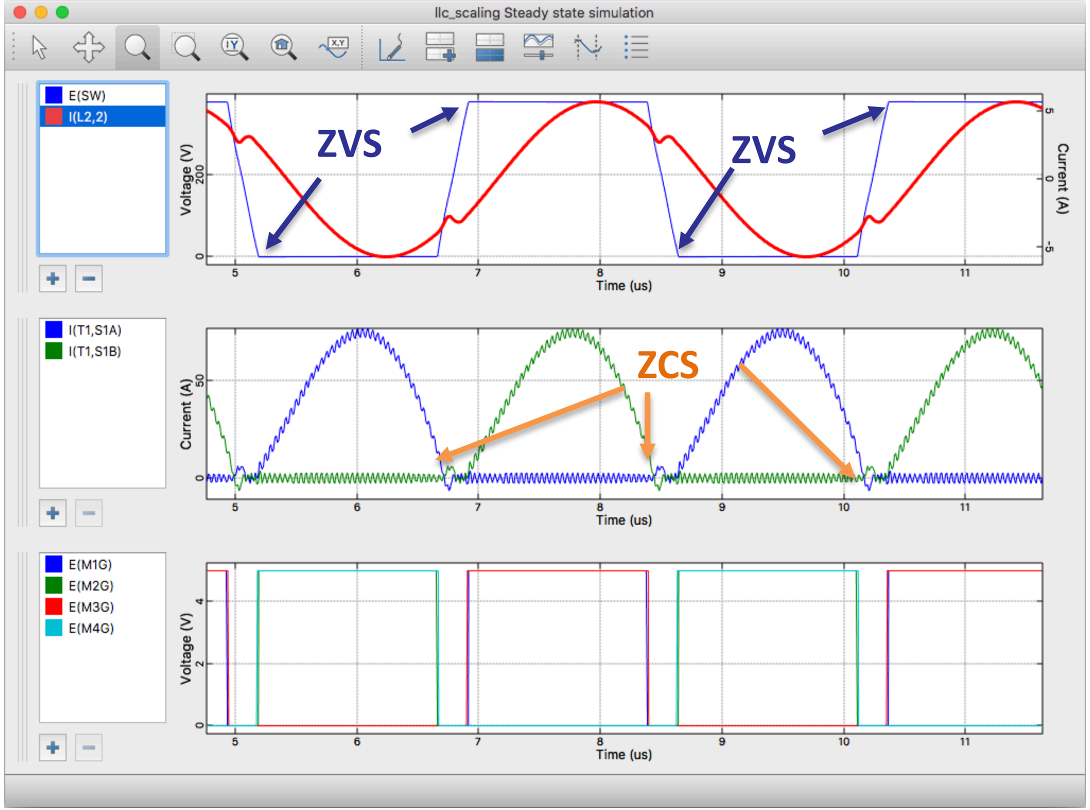
Resonant Inductor (+Leakage)

Magnetizing Inductance

Resonant Capacitors

Examine transformer design in 500W, 380V to 12V LLC running at 300 kHz

LLC Waveforms (at resonance)



Primary switch-node voltage

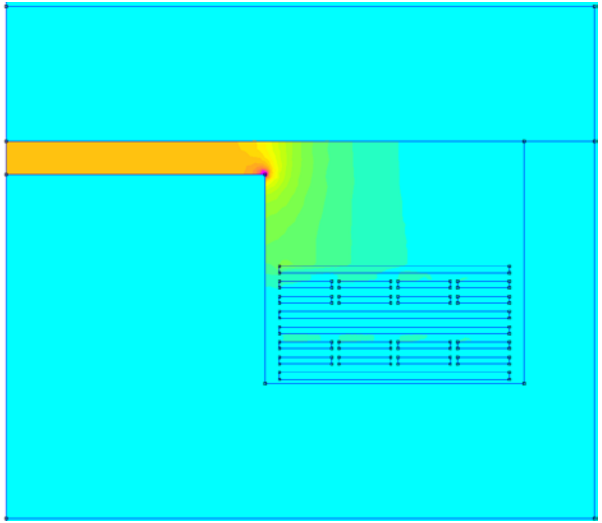
Primary resonant current

Secondary-side currents

Gating Waveforms

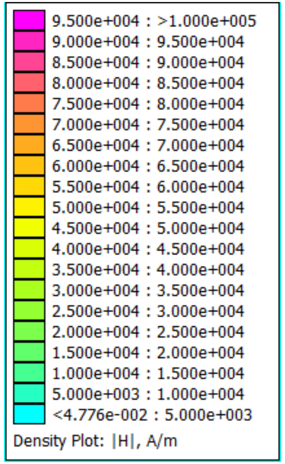
LLC Silicon vs. GaN: Magnetic Effects

Silicon Version:
70 mΩ 650V Superjunction
Cr: 24nF, Lr: 10µH, **Lm: 50µH**

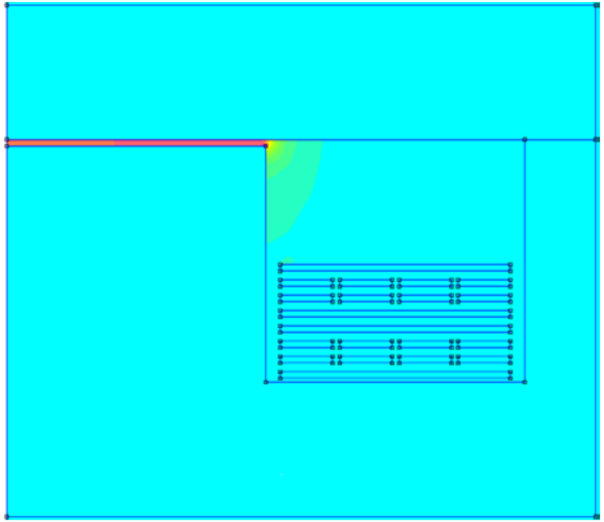


16:1CT on 8L x 140 um PCB in EQ25+PLT-3F36

Total Winding Loss: 5.43 W



GaN Version:
67 mΩ 650V e-mode GaN
Cr: 24nF, Lr: 10µH, **Lm: 200µH**



16:1CT on 8L x 140 um PCB in EQ25+PLT-3F36

Total Winding Loss: 2.991 W

Conclusions

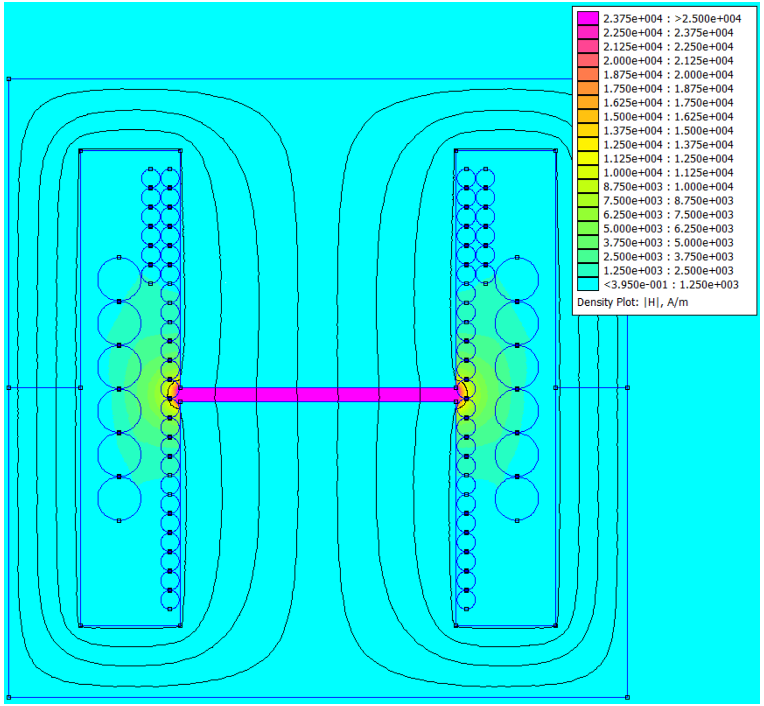
- Fringing effects can dramatically increase losses for gapped magnetics designs
- Fringing fields should be examined in gapped designs when flux ripple is big (core loss > 10% of total) and/or when Litz wire would be considered
- Spacing winding structures to separate copper and gap help – even at the expense of DC resistance
- Circuit choices can be made to reduce AC magnetics loss including fringe field losses
- Simulation tools exist to help designers understand and mitigate fringe-field losses in magnetics in the context of power converters

Appendix 1: Approach to Fringe-Field (& Proximity) Losses

1) Determine H field at wire / winding turn locations
2) Compute AC loss for specific wire given H field [2-4]

$$P_{ext} = \frac{\hat{G}(geometry)}{\sigma}\hat{H}^2$$

3) Add in skin depth loss, DC Loss, core loss
4) Evaluate and optimize magnetic structure…



DC FEM Simulation determines external H

[3] Sullivan, "Computationally Efficient Winding Loss Calculation with Multiple Windings, Arbitrary Waveforms, and Two-Dimensional or Three-Dimensional Field Geometry," IEEE Trans. Power. Elec. Jan 2001

[4] Nan, Sullivan, "Simplified High-Accuracy Calculation of Eddy-Current Loss in Round-Wire Windings," IEEE PESC 2004

[5] Zimmanck, Sullivan, "Efficient Calculation of Winding-Loss Resistance Matrices for Magnetic Components," IEEE COMPEL 2010