Optimizing Custom Magnetics for High-Performance Power Supplies

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IEEE POWER ELECTRONICS SOCIETY
Powering a Sustainable Future

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Outline

- What is *Power Supply Optimization*?
  - Performance metrics, optimization tools and co-design methodologies
- System requirements placed on magnetic structures
- Inductor and transformer loss mechanisms
  - DC winding loss
  - Core loss
  - AC winding loss: skin depth, proximity effect & fringe-field losses
  - Winding capacitances
- Examining magnetics scaling
- Software tools for whole-converter analysis & optimization
- Case studies
- Conclusions

Power Converter Figures of Merit

Cost, cost, cost

Power Density

Reliability

Time to Market

Supply Chain

Passing EMC, UL…

Efficiency

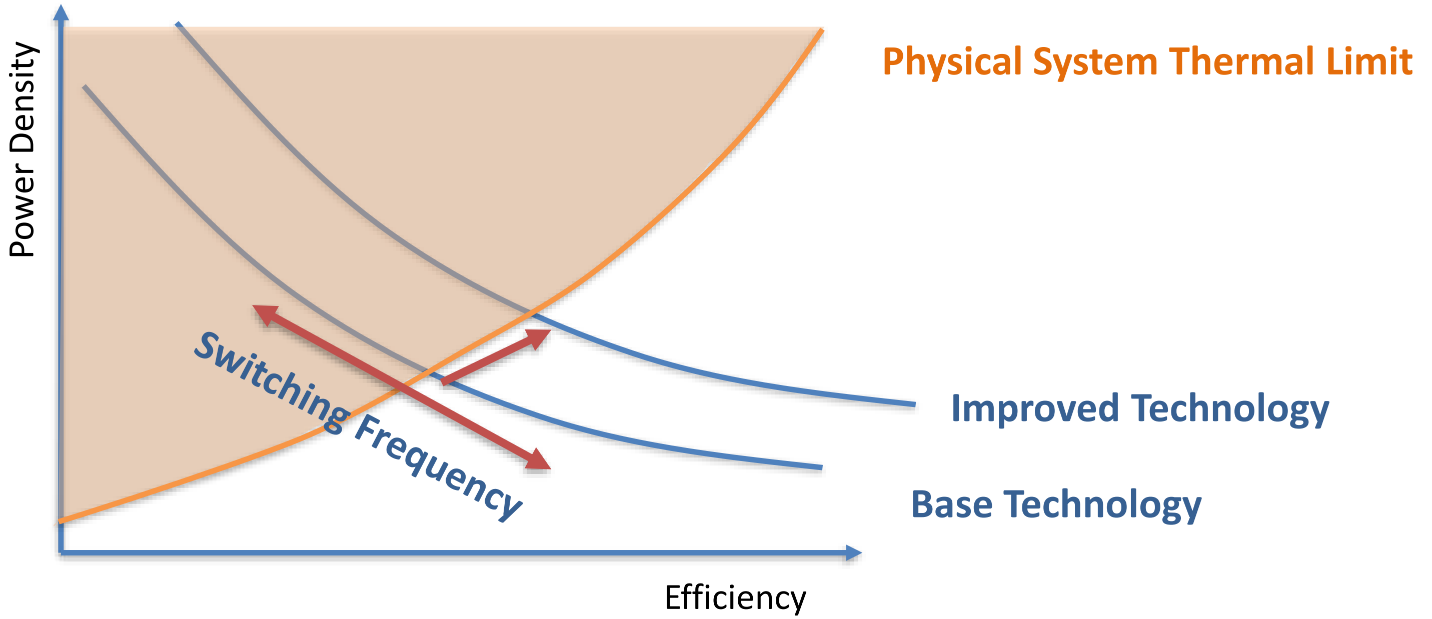
Transient Response

Technology

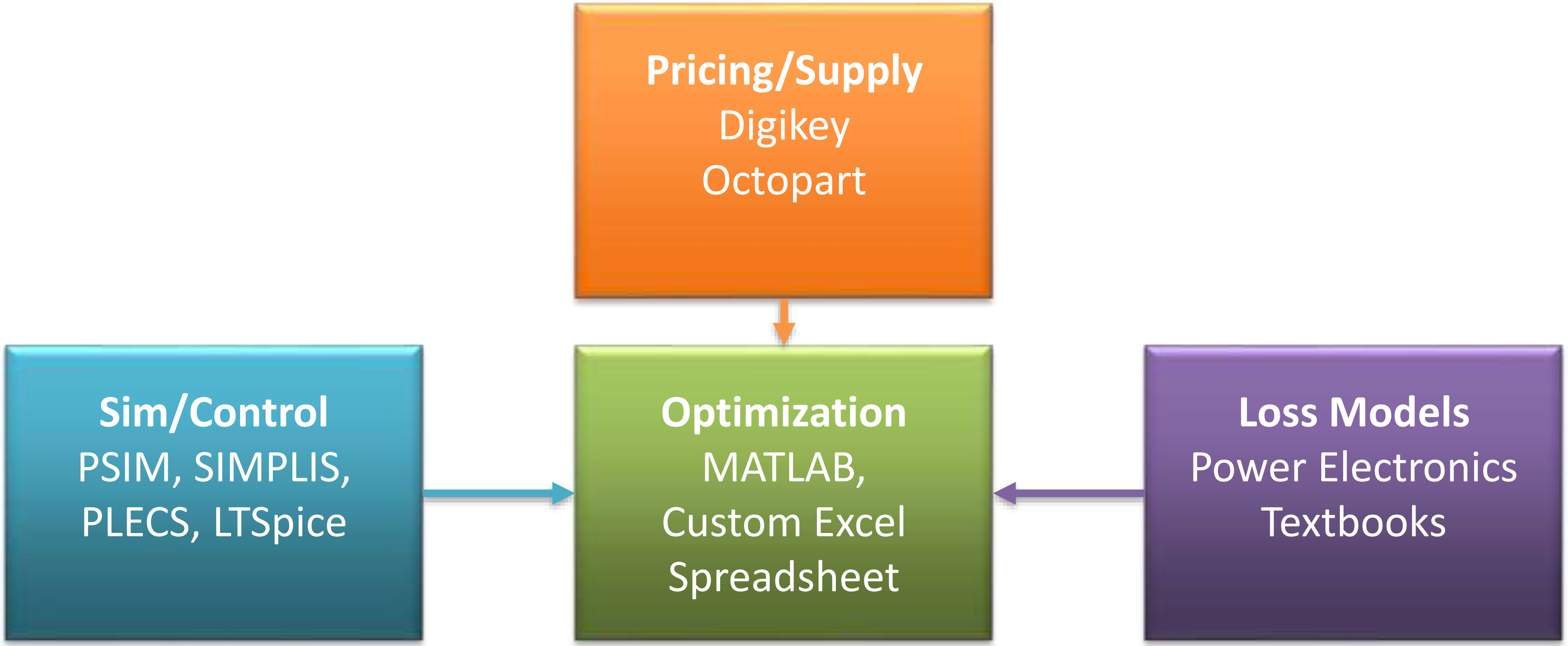
Specifications

Manufacturing

What Matters in Switching Power Converters?



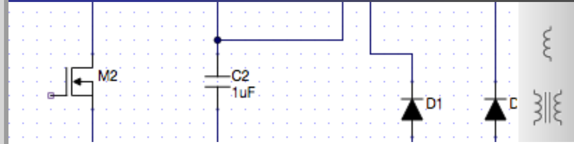
How is Design Optimization Done Today?



The Eta Designer Advantage

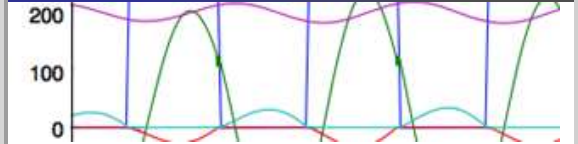
Eta Designer provides instant, simultaneous design and simulation of power systems

Flexible Schematic Editor



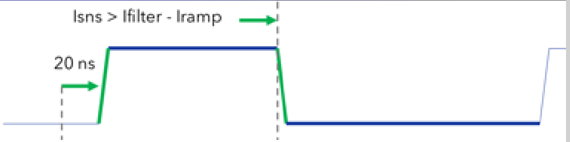
- Create arbitrary topologies
- Parameterize and sweep anything
- Automatically create standard designs

Fast Simulation Engine



- Ultra-fast linear simulation engine
- Instant results – runs in the background
- Control stability and loop response

Powerful Controller Design



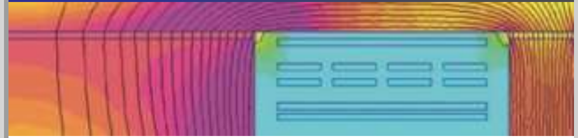
- Flexible, intuitive specification
- PWM and variable-frequency designs
- Arbitrarily control each rising/falling edge

Component Database

Core	Mag Volume	Mag. Area	Mass	Typ. Loss	Max Loss
RM4	230	11	1.5	6.59	9.89
RM4/ILP	251	14.5	1.3	6.31	9.47
RM5/I	574	24.8	3.2	4.17	6.26
RM4/I	322	13.8	1.7	5.57	8.36

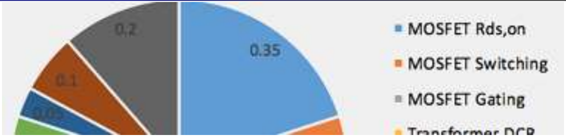
- Vast database of component data
- Chooses top-10 devices, shows power loss for each one

Magnetics Optimization



- Custom designed magnetics integrated with simulation
- Supports Litz & planar designs
- Complex, high-frequency loss analysis

Efficiency Modeling



- Real-time efficiency estimation based on simulated operating conditions
- Modern peer-reviewed loss models
- Free real-time parameter variation

System Requirements of Magnetics

Circuit Requirements

- Winding Config
- Turns Ratio
- Frequency
- Volt-Second Product
- Peak Currents

Transformer Design

- Core Size & Shape
- Core Material
- Turns Count
- Wire size & type
- Winding Procedure
- Isolation Means

Physical Requirements

- Cost
- PCB Area / Height
- Mass
- Safety Isolation
- Ambient Temperature
- Peak Temp. Rise

Magnetics Loss Mechanisms

DC Resistance Loss

- Incorporates I^2R copper losses based on RMS currents
- Minimizing DC loss involves choosing a large winding window & short turn length, and maximizing copper fill factor

Core Loss

- Captures core hysteresis and eddy current losses
- Steinmetz equation:

$$P_v = k f^{\alpha} \hat{B}^{\beta}$$

- Non-linear effects with waveform shape, core geometry, and DC bias

AC Winding Losses

- Additional winding loss due to high-frequency skin effect, external H-fields due to other windings (proximity) and core gap (fringing)
- Frequency-dependent; linear with winding currents

Winding Capacitance Losses

- Capacitances between winding turns yields additional switching losses in circuit
- EMC concerns from charge injection from primary to secondary
- Winding construction and shielding layers can mitigate these effects

Magnetics Loss: DC Resistance

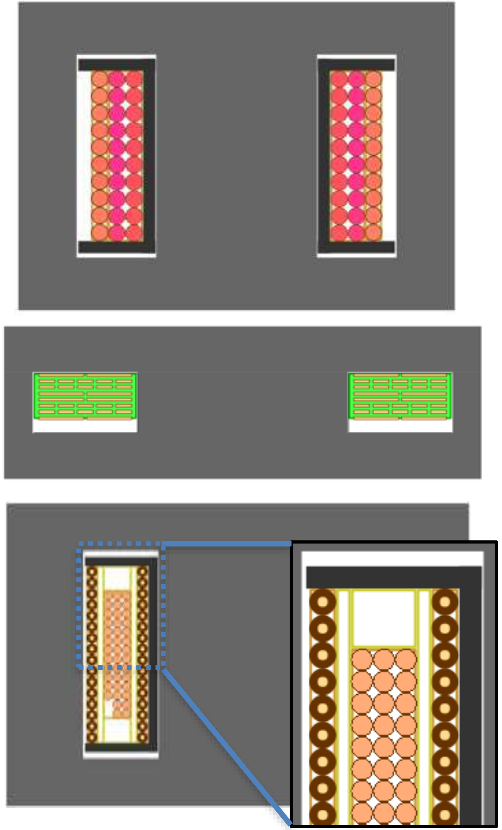
DC Resistance Loss: $P_{DC} = I_{RMS}^2 R_{DC}$

DC Resistance impacted by:

- Average turn length
- Number of turns
- Cross-section area of copper

Things to consider:

- Planar cores have smaller window
- PCB windings have low fill factor
- Isolation requirements may reduce effective fill-factor
    - Margin tape for spacing
    - Thick triple-insulated wire



Magnetics Loss: Core Loss

Core Loss incorporates *hysteretic* and *eddy-current losses* and is a function of Flux Density Amplitude and Frequency

Steinmetz Equation:

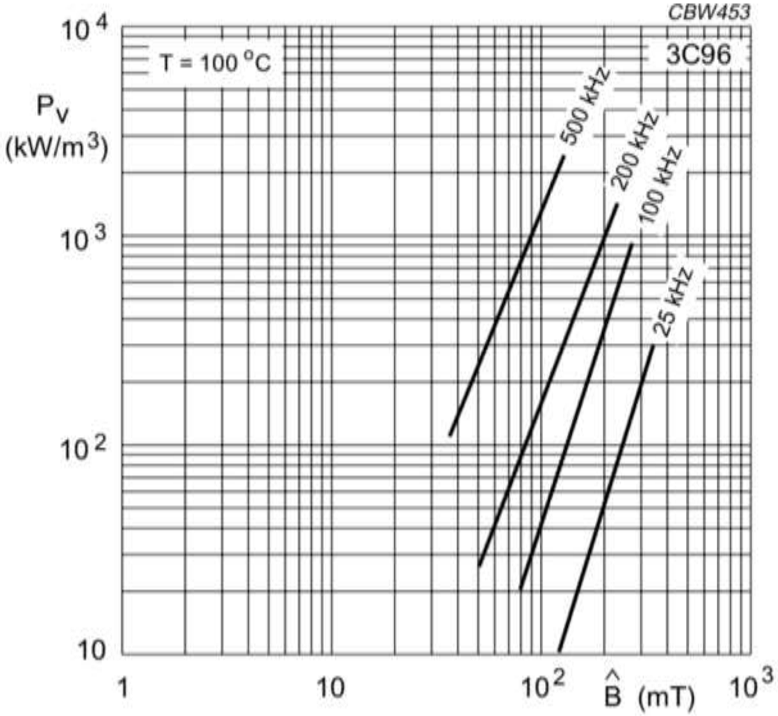
$$P_v = k f^{\alpha} \hat{B}^{\beta} \qquad [\mathrm{kW/m^3}]$$

flux density found using either:

$$\hat{B} = \frac{V\Delta t}{2nA_e}$$ applied volt-seconds

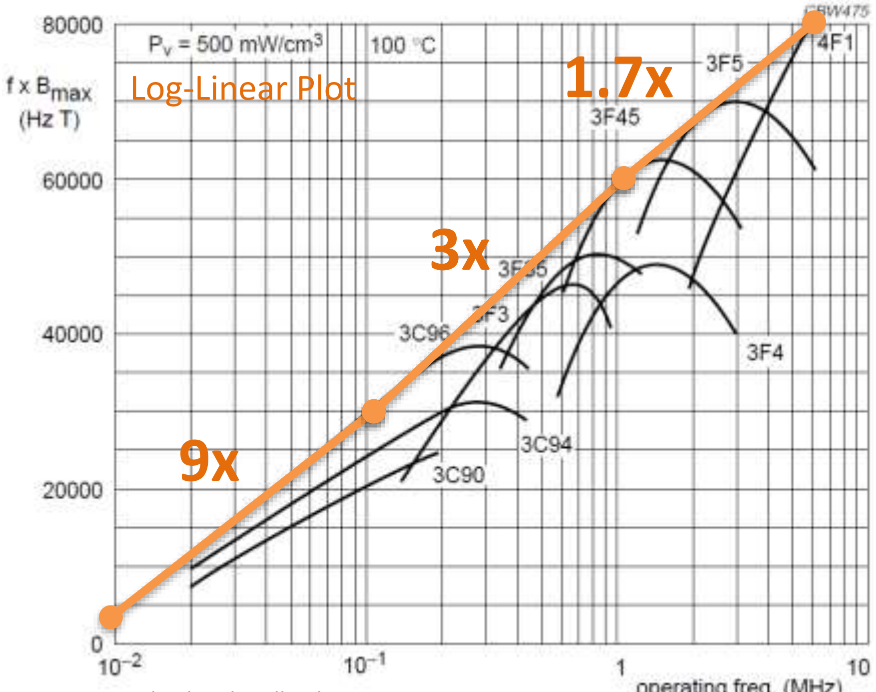
$$\hat{B} = \frac{L\hat{I}}{nA_e}$$ inductance & current ripple

Note: k, α and ß vary with frequency; refer to plots



Ferroxcube Data Handbook

Core Loss vs. Frequency



Ferroxcube data handbook

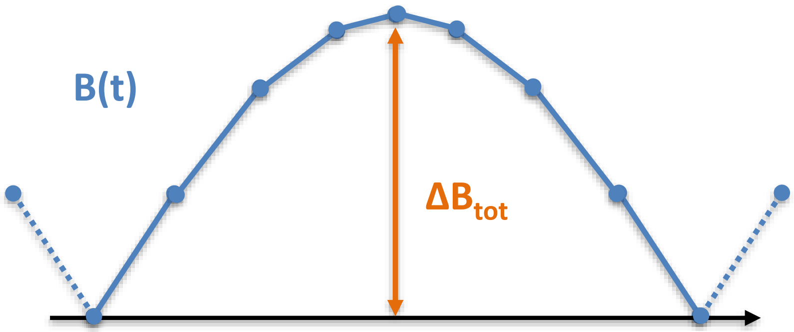
- Core Loss does get better at higher frequency
- Inductors with “small” ripple get better
- “Large” ripple inductors are a mixed bag:
  - Core loss improves
  - Skin & proximity effect is worse
- Transformers are impacted more from skin and proximity loss; gains are modest

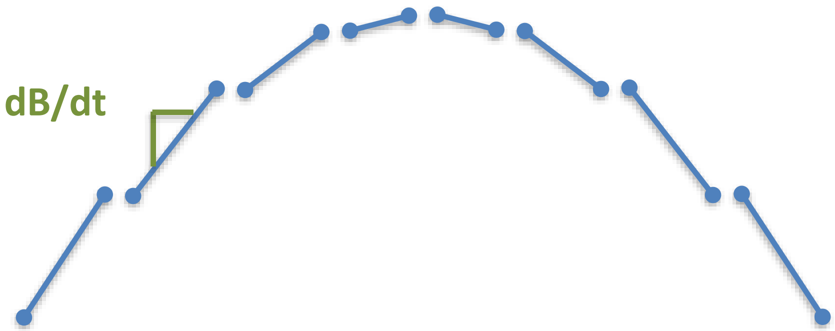
Core Loss: Non-sinusoidal Waveforms

- Most real power converters don't run on sinusoids
- Multiple methods:
    - Harmonic analysis
    - GSE, iGSE, i^2GSE… based on instantaneous methods

iGSE is the easiest-to-use accurate method:

Instantaneous loss depends on overall ΔB and dB/dt: $p(t) = p(\Delta B_{tot}, dB/dt)$

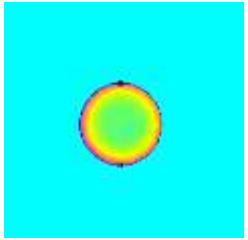




[ref] Venkatachalam, Sullivan, Abdallah and Tacca, "Accurate Prediction of Ferrite Core Loss with Nonsinusoidal Waveforms using only Steinmetz Parameters," IEEE COMPEL 2002.

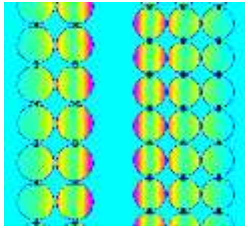
Magnetics Loss: AC Winding Losses

Skin Depth



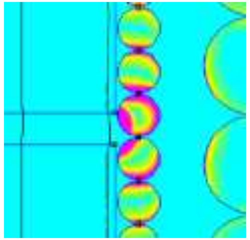
Current in single wire or turn

Proximity



H-field generated by nearby turns and windings

Fringing



Fringing H-field contributed by core gap(s)

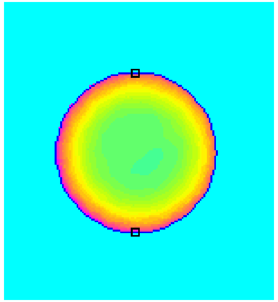
Eddy currents induced to cancel H field

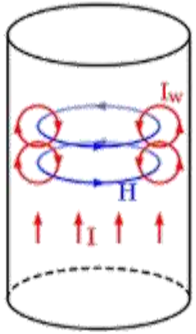
Additional copper losses

AC Winding Losses: Skin Depth

At high frequencies, eddy currents generated by the magnetic field drive the internal current to zero

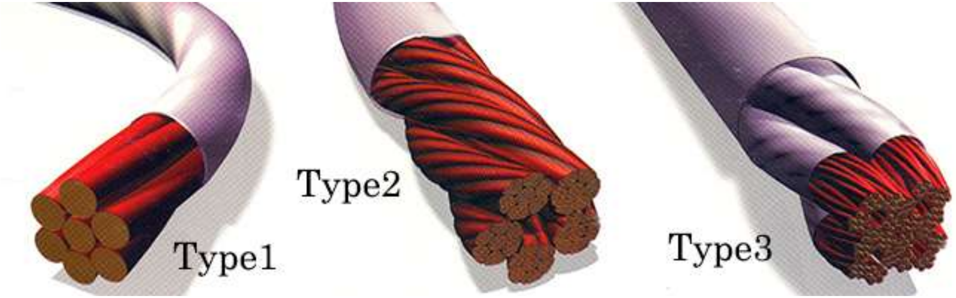
Skin Depth: $$\delta = \frac{1}{\sqrt{\pi \sigma \mu f}}$$

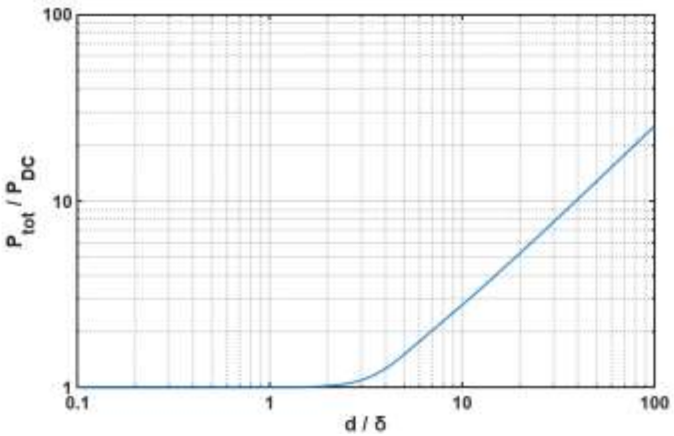




[Wikipedia]

Litz wire or foil can be used to counter skin effect

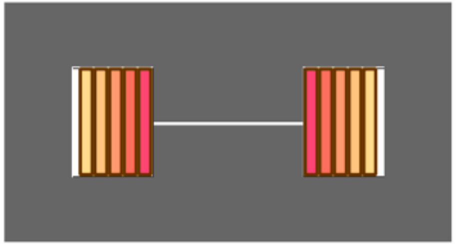




AC Winding Losses: Proximity Effect

Eddy currents in conductors are induced to make
H field approach zero inside conductor (like skin effect)

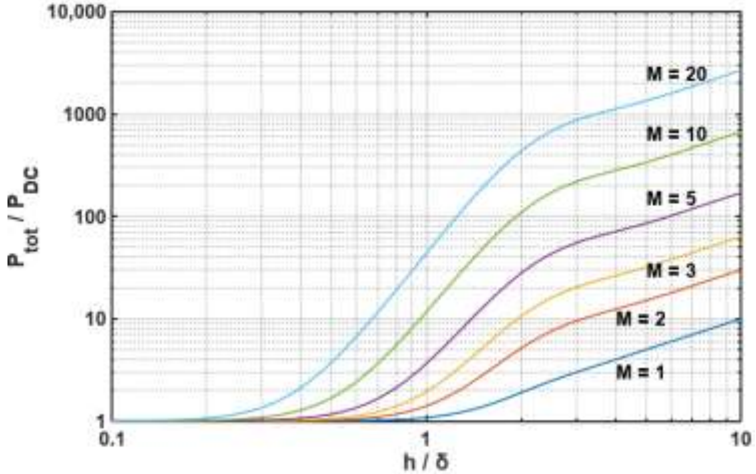
Proximity effect deals with H-field generated
by *other windings*



Often examined in a 1D stacking of foil windings:
easily conceptualized and can be calculated exactly with
Dowell's equation for a single winding with M foil layers:

$$\frac{P_{AC}+P_{DC}}{P_{DC}} = \frac{h}{\delta}\left[G_1\left(\frac{h}{\delta}\right) + \frac{2}{3}(M^2-1)\left(G_1\left(\frac{h}{\delta}\right) - 2G_2\left(\frac{h}{\delta}\right)\right)\right]$$

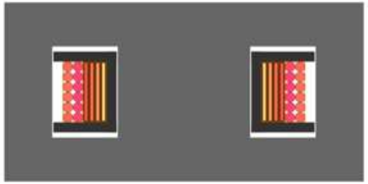
$$G_1(\varphi) = \frac{\sinh(2\varphi)+\sin(2\varphi)}{\cosh(2\varphi)-\cos(2\varphi)} \qquad G_2(\varphi) = \frac{\sinh(2\varphi)\cos(\varphi)+\cosh(\varphi)\sin(\varphi)}{\cosh(2\varphi)-\cos(2\varphi)}$$

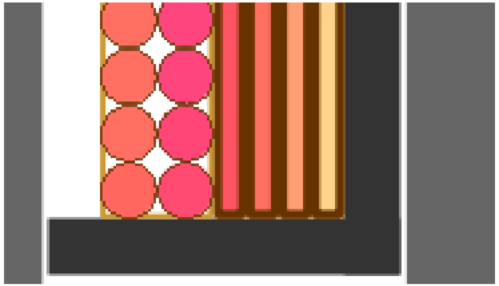


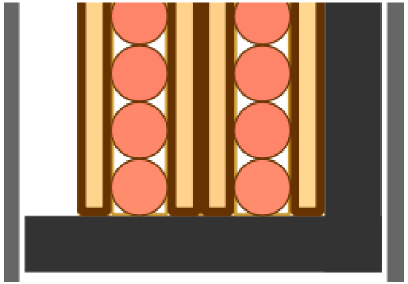
2D and 3D proximity effect losses must use field simulation and
squared-field-derivative method

[1] P. L. Dowell, "Effects of Eddy Currents in Transformer Windings," Proceedings IEE, Aug 1966
[2] L. H. Dixon, "Eddy Current Losses in Transformer Windings and Circuit Wiring," TI/Unitrode Power Supply Design Seminars
[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

Proximity Effect Example



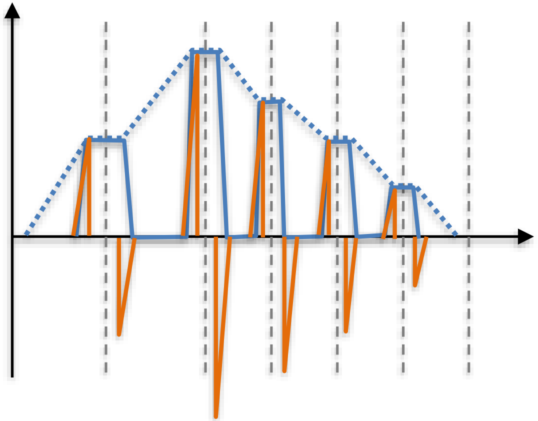




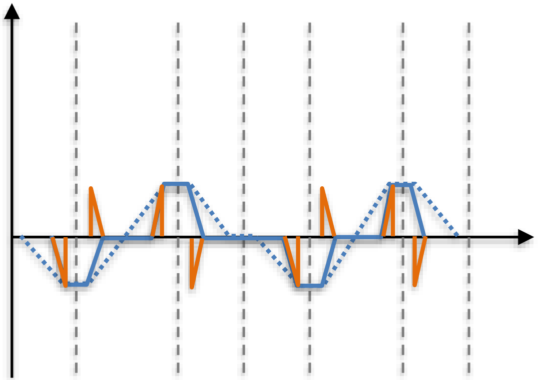
MMF:

$$F = \oint H dl = NI$$

$I(x)$



Rac/Rdc = 4.77



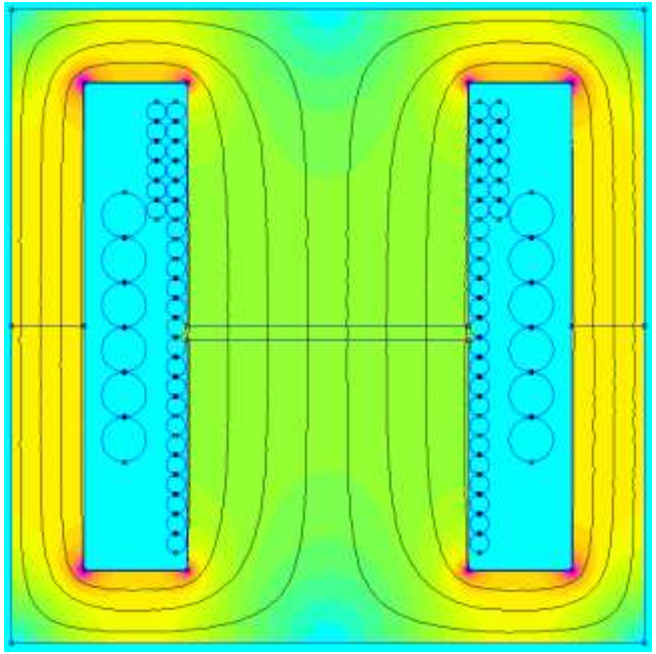
Rac/Rdc = 0.65

AC Winding Losses: Fringe-Field Effect

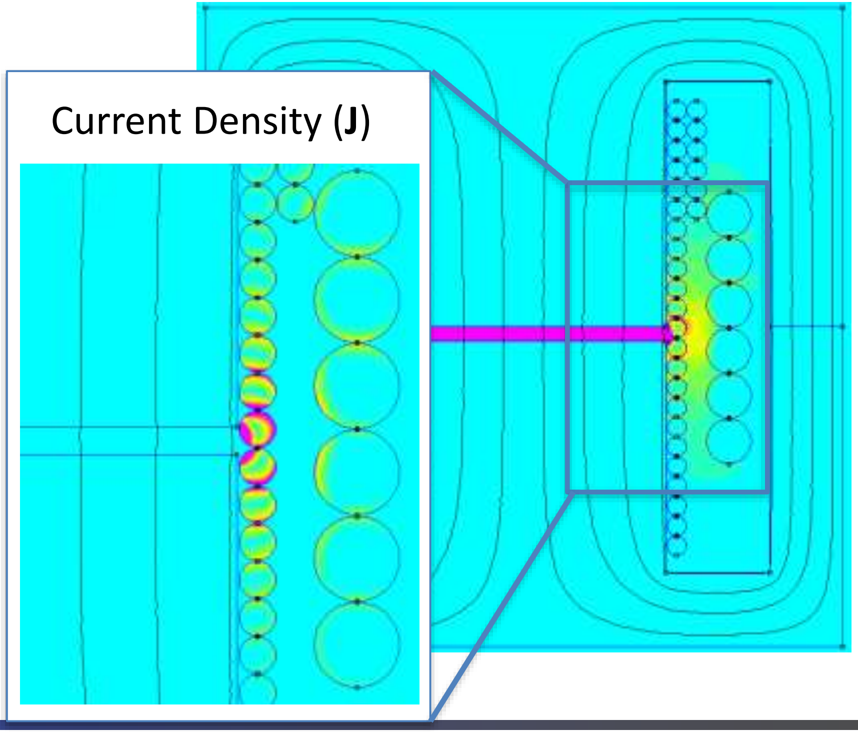
Flux Density (**B**)

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

Field (**H**)



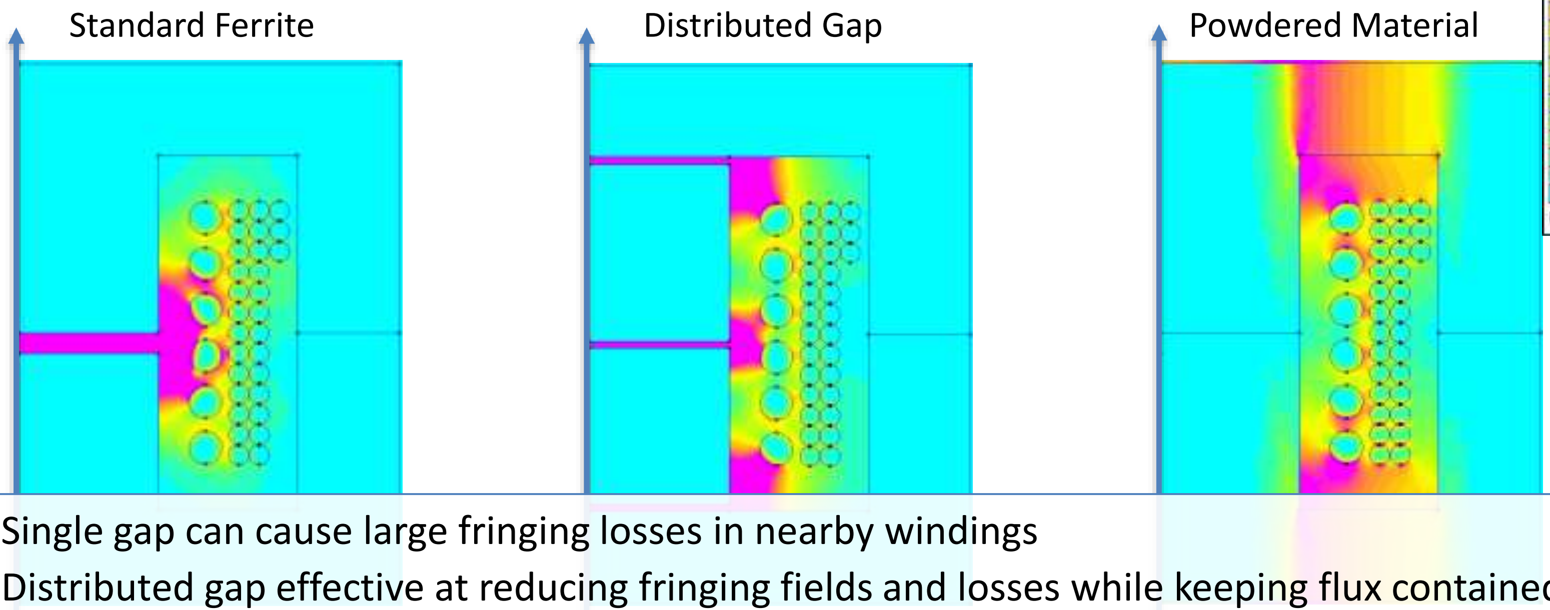
$$E_v =$$

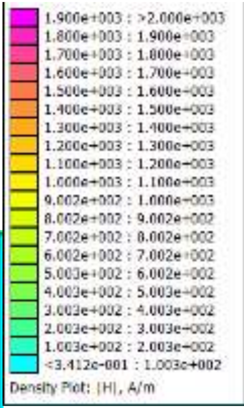


[1] Finite Element Method Magnetics: http://www.femm.info

Magnetic Structures : H Fields

Distributed gap materials contain flux but distribute fringe field



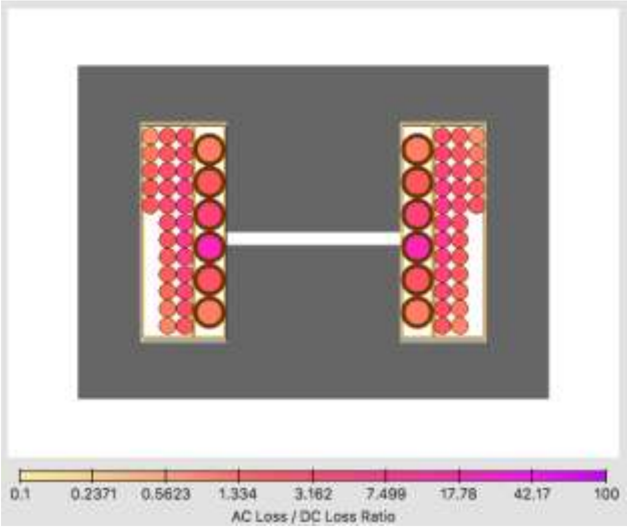


- Single gap can cause large fringing losses in nearby windings
- Distributed gap effective at reducing fringing fields and losses while keeping flux contained in core
- Ungapped material (e.g. powdered iron) not effective in Pot-core shapes in constraining flux.
  - Fringing fields extend into window,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

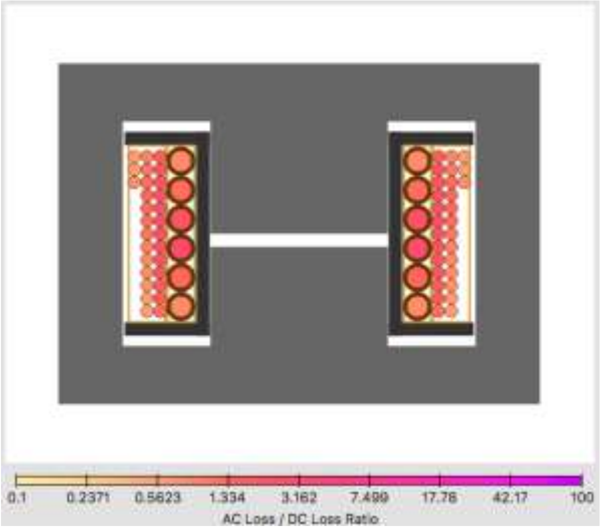
Example: 120 µH, 45W offline flyback transformer @ 500 kHz, RM8/I core, losses at fundamental current only in FEMM

Examining Winding Location: Eta Designer

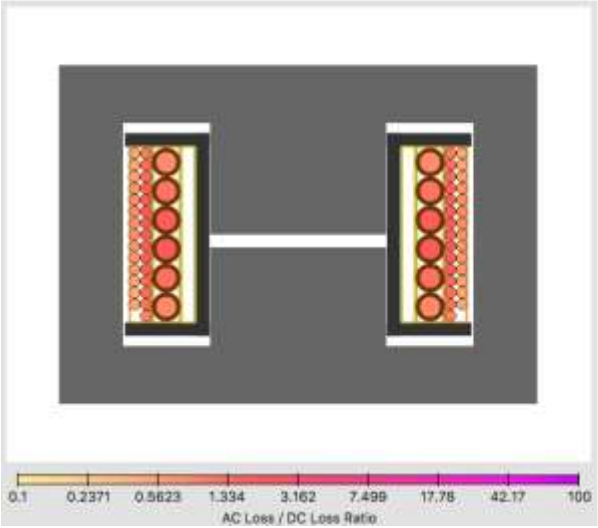
85-265 VAC to 20V/2.25A Flyback @ 500 kHz



Winding Loss: 544 mW



Winding Loss: 382 mW

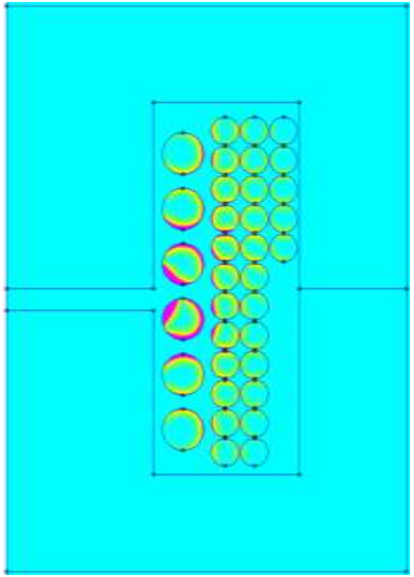


Winding Loss: 308 mW

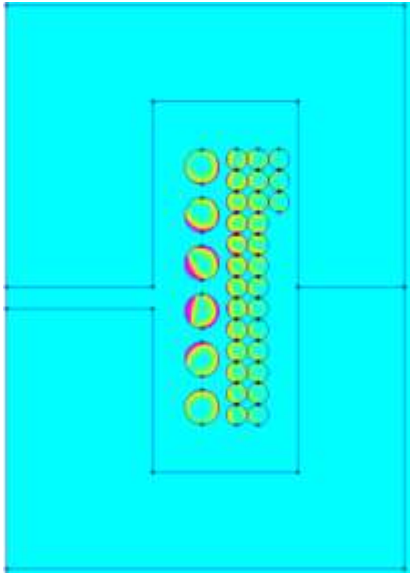
See [2]: Hu, Sullivan, “Optimization of shapes for round-wire high-frequency gapped-inductor windings,” IEEE Ind. Appl. Soc. Annual Meeting 1998.

Examining Winding Location: FEMM

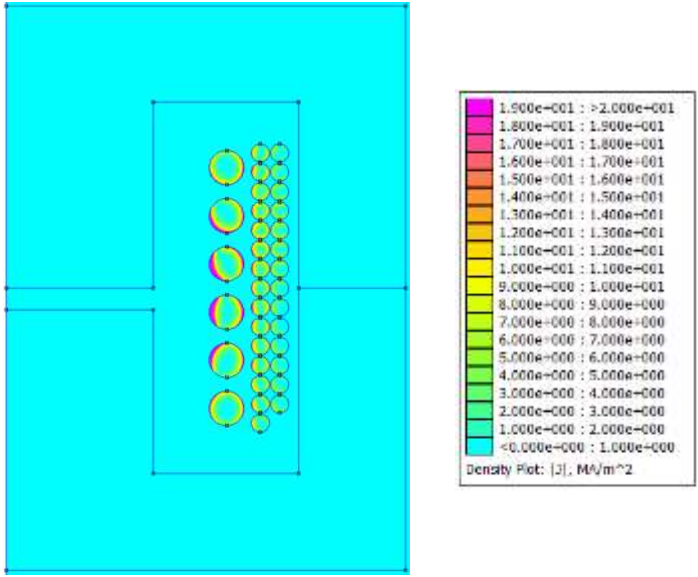
85-265 VAC to 20V/2.25A Flyback @ 500 kHz



Winding Loss: 560 mW



Winding Loss: 337 mW



Winding Loss: 226 mW

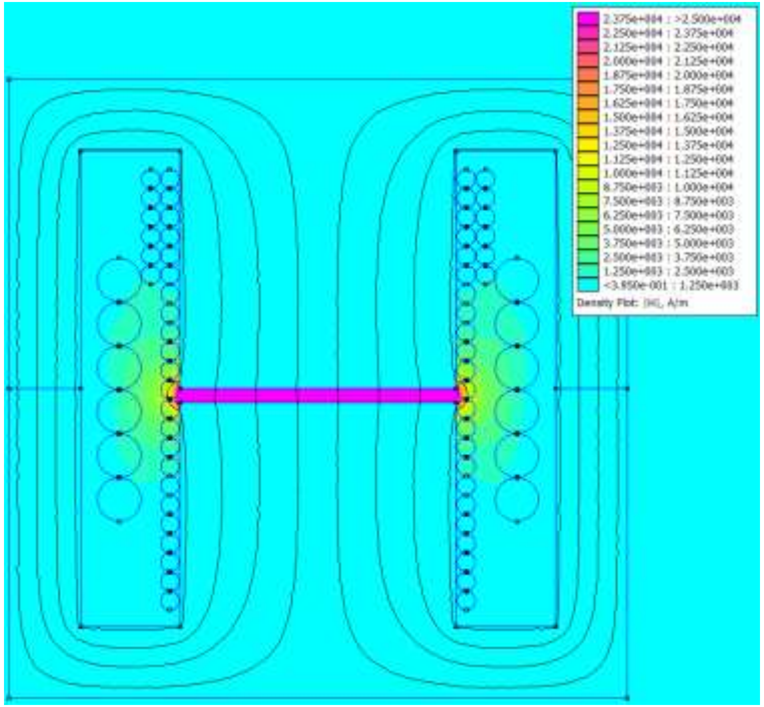
See [2]: Hu, Sullivan, “Optimization of shapes for round-wire high-frequency gapped-inductor windings,” IEEE Ind. Appl. Soc. Annual Meeting 1998.

Approach to Simulating Fringe-Field (& Proximity) Losses

1) Determine H field at wire / winding turn locations
2) Compute AC loss for specific wire given H field [3-5]

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

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

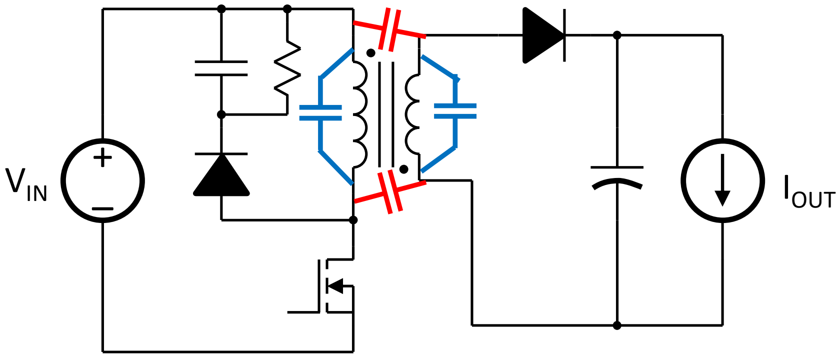
Winding Capacitances

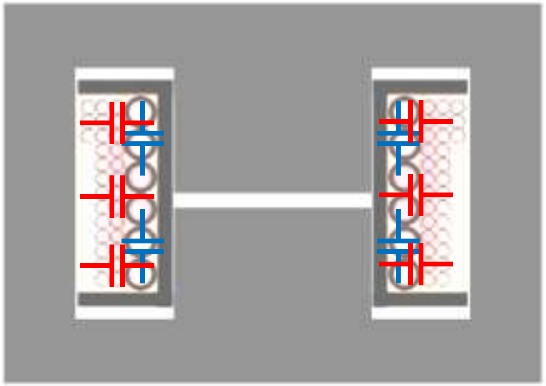
Intrawinding capacitance:

- Distributed capacitance between turns of same winding
- "Lumped" capacitance falls across switching node, adds to switching loss
- Leads to ringing in circuit and other resonant modes

Interwinding capacitance:

- Distributed capacitance between different windings
- Capacitive charge injection across barrier
- Leads to common-mode noise injected into output, trouble at the EMC lab

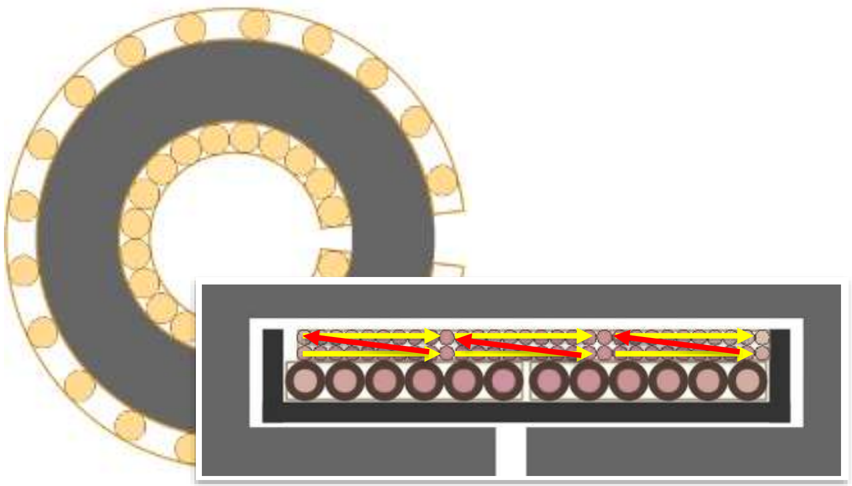




Reducing Winding Capacitance

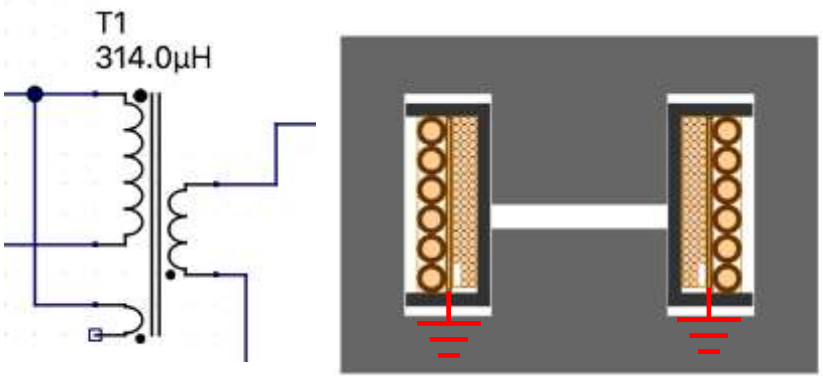
Reducing intrawinding capacitance:

- Reduce ΔV between adjacent turns
- Single-layer windings
- Wind two-layer windings in same direction
- Stagger-wind to avoid large overlap ΔV

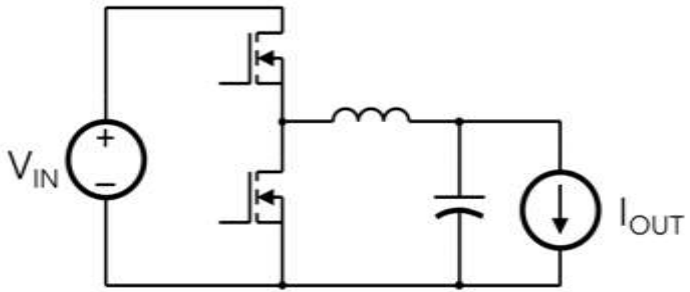


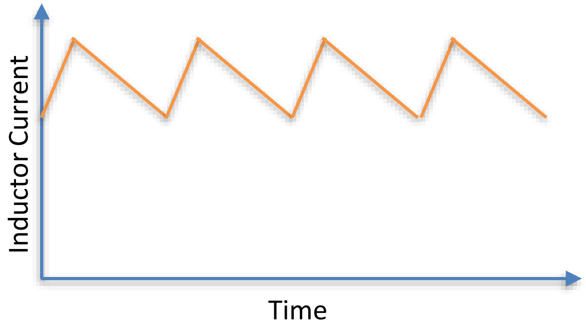
Reducing interwinding capacitance:

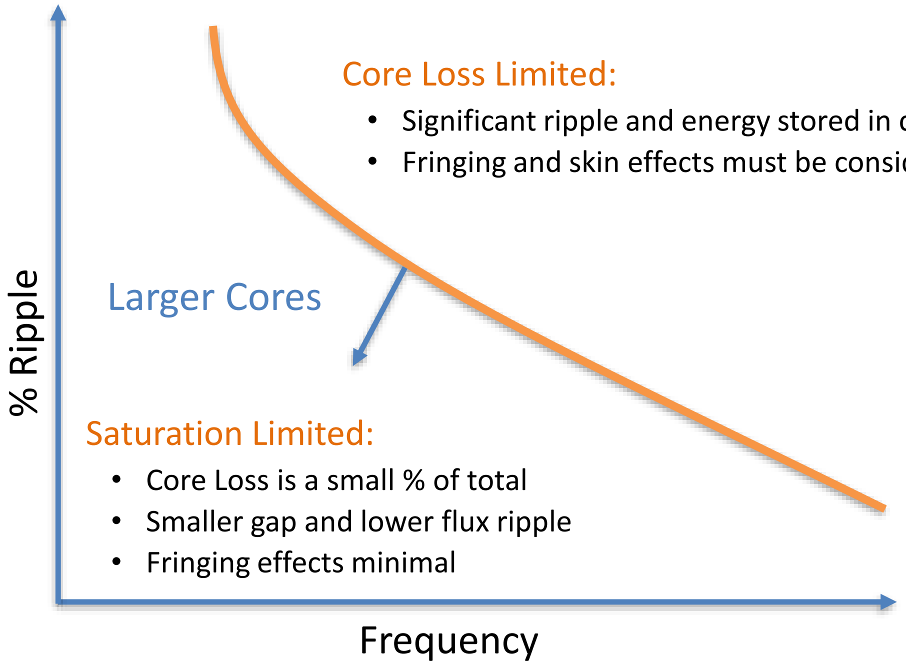
- Minimize interleaving between windings
  - Counter to minimizing proximity loss
- Space windings apart with tape / insulation
- Add shielding layer



Buck Converter: Inductor Scaling







Magnetics scaling: Generalization

Goal: Create a representation of power capability (via V-A product) for a general magnetic

$$VA = V \cdot I = (NfB_0A_c)\left(\frac{J_0A_w}{N}\right) = f(B_0J_0)(A_cA_w)$$

Max current density in winding window

Max flux in core

Power handling capability

Applied voltage & winding current

For low frequency operation, saturation limited and for a linear dimension α:

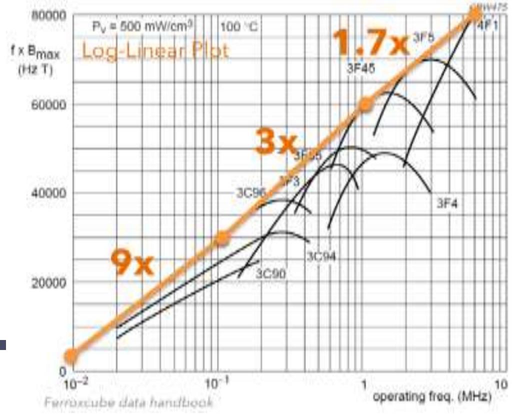
- Power is proportional to α^4 – power density improves with magnetic size
- Power is proportional to frequency f ($B_0 = B_{sat}$)

ref: Sullivan, et. al. "On Size and Magnetics: Why Small Efficient Power Inductors are Rare," IEEE 3D-PEIM 2016

Magnetics Scaling: Frequency

Operating Condition	Power Density by Size	Power Density by Frequency
Low freq, saturation limited, fixed temp rise	α^1	f^1
Low freq, core loss limited, fixed temp rise	α^0 to $\alpha^{0.2}$ *	$f\ B_0(f)$
High freq, core loss limited, fixed temp rise	$\alpha^{-0.5}$ to $\alpha^{-0.3}$ *	$\sim f^{0.5}\ B_0(f)$

Material performance factor

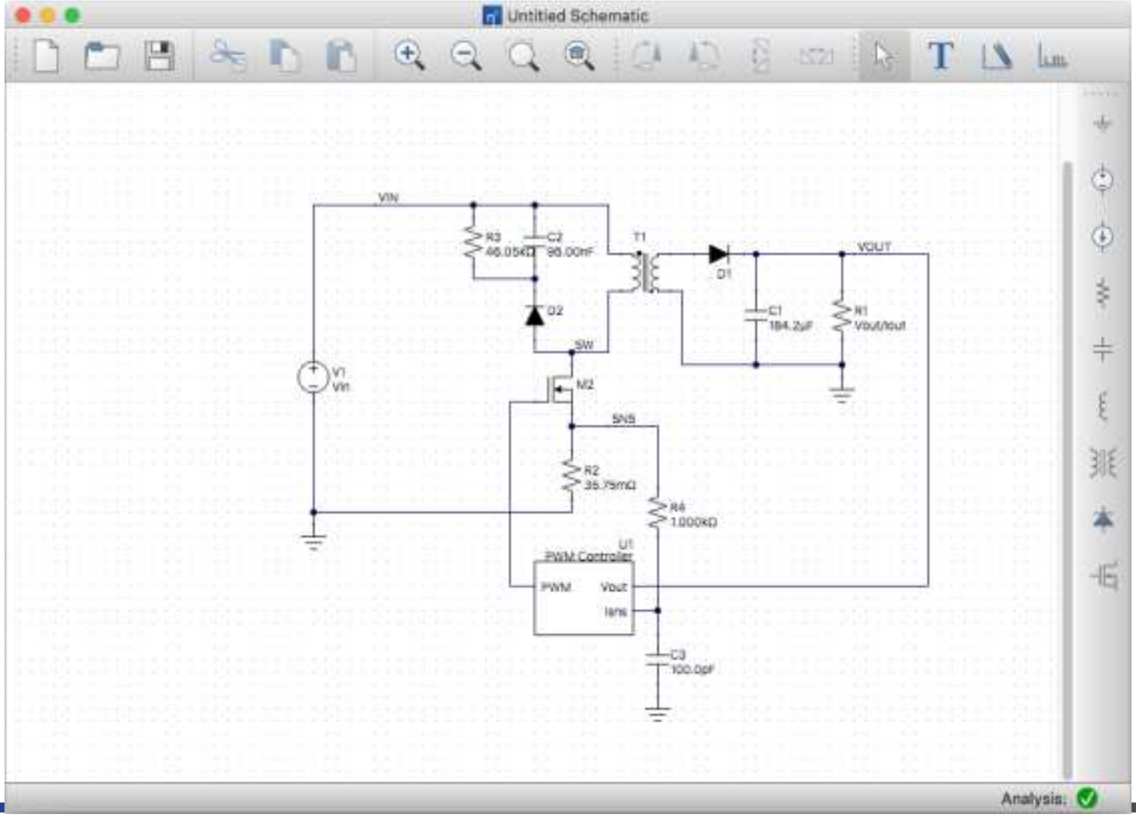


* based on Steinmetz β for core material @ frequency (β = 2 to 3)

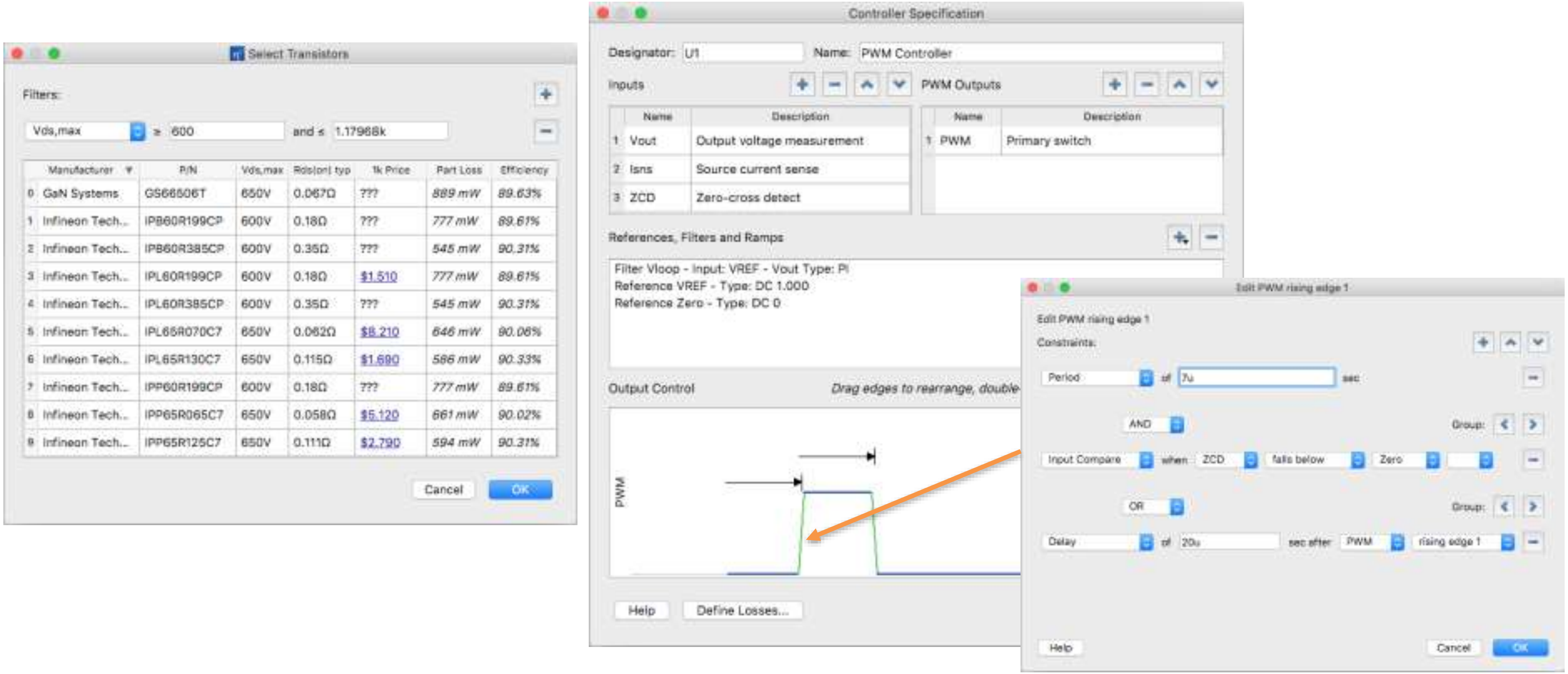
ref: Sullivan, et. al. "On Size and Magnetics: Why Small Efficient Power Inductors are Rare," IEEE 3D-PEIM 2016

CASE STUDY:
FLYBACK CONVERTER

Modeling a Flyback Converter in Eta Designer

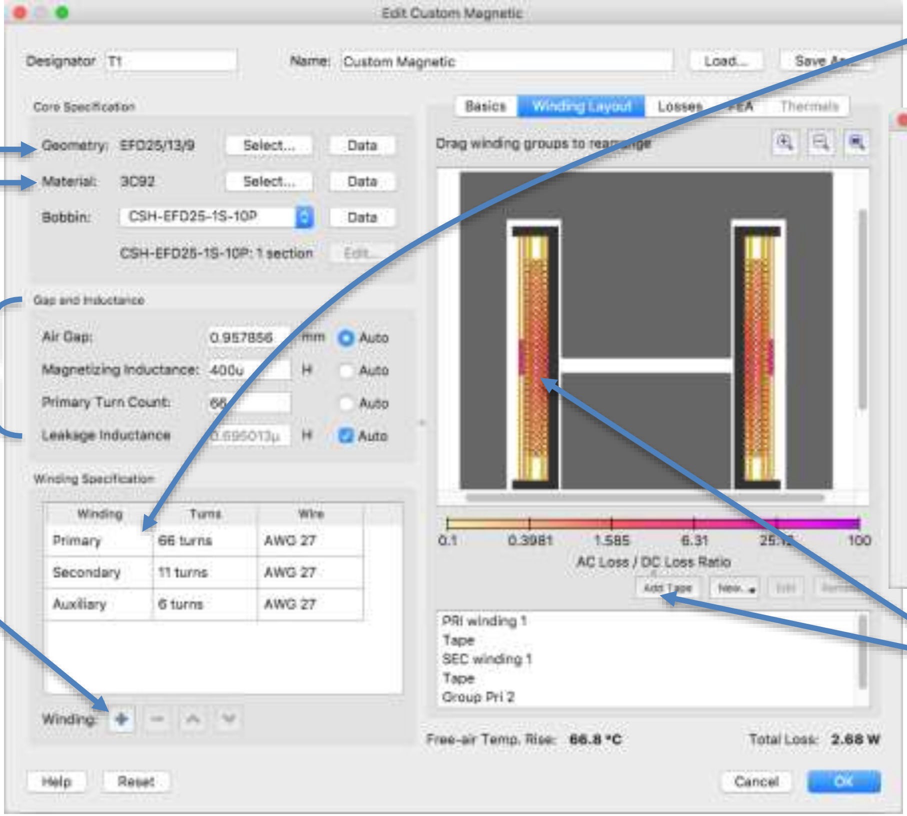


Modeling a Flyback Converter in Eta Designer (2)



Designing Flyback Magnetics

1. Choose core geometry and material
2. Choose gap size, mag. inductance and/or turn count
3. Add an auxiliary winding



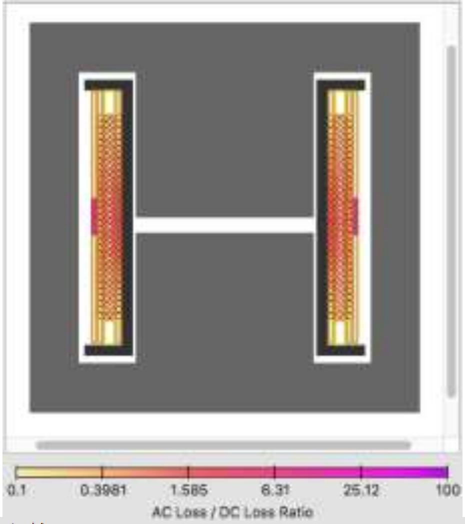
4. Edit windings as needed

5. Drag windings and add tape to arrange as desired

Flyback: Simulation vs. Bench

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

In Eta Designer:



Estimated Losses

Core Loss: 138 mW

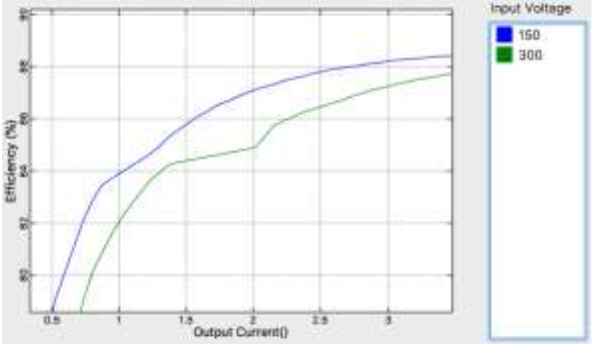
Winding Loss:

	Winding	DC Resistance	DC Loss	AC Loss
1	Primary 1	555 mΩ	348 mW	844 mW
2	Secondary 1	15.4 mΩ	395 mW	929 mW
3	Auxiliary 1	60.6 mΩ	69.5 µW	24.3 mW

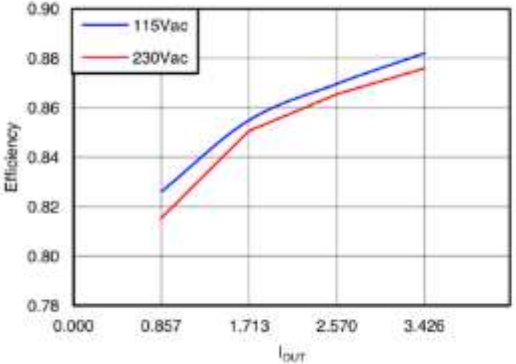
Total Loss: 2.68 W @ 3 A

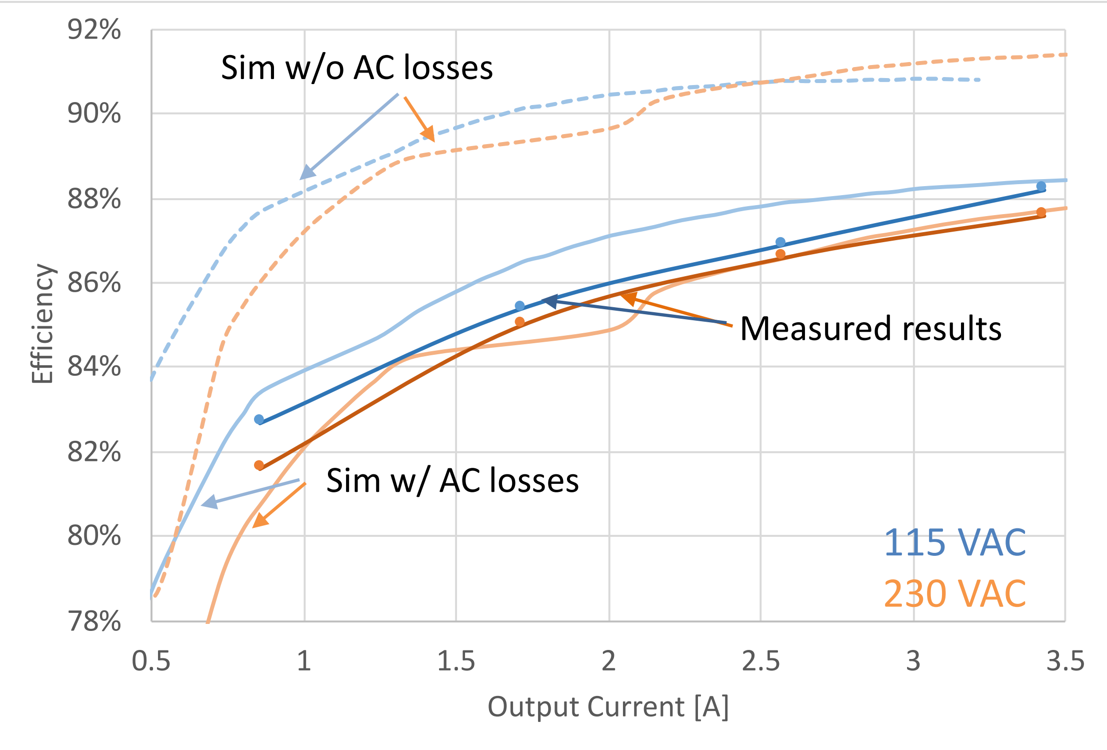
Flyback: Simulation vs. Bench (2)

Simulated: From Eta Designer



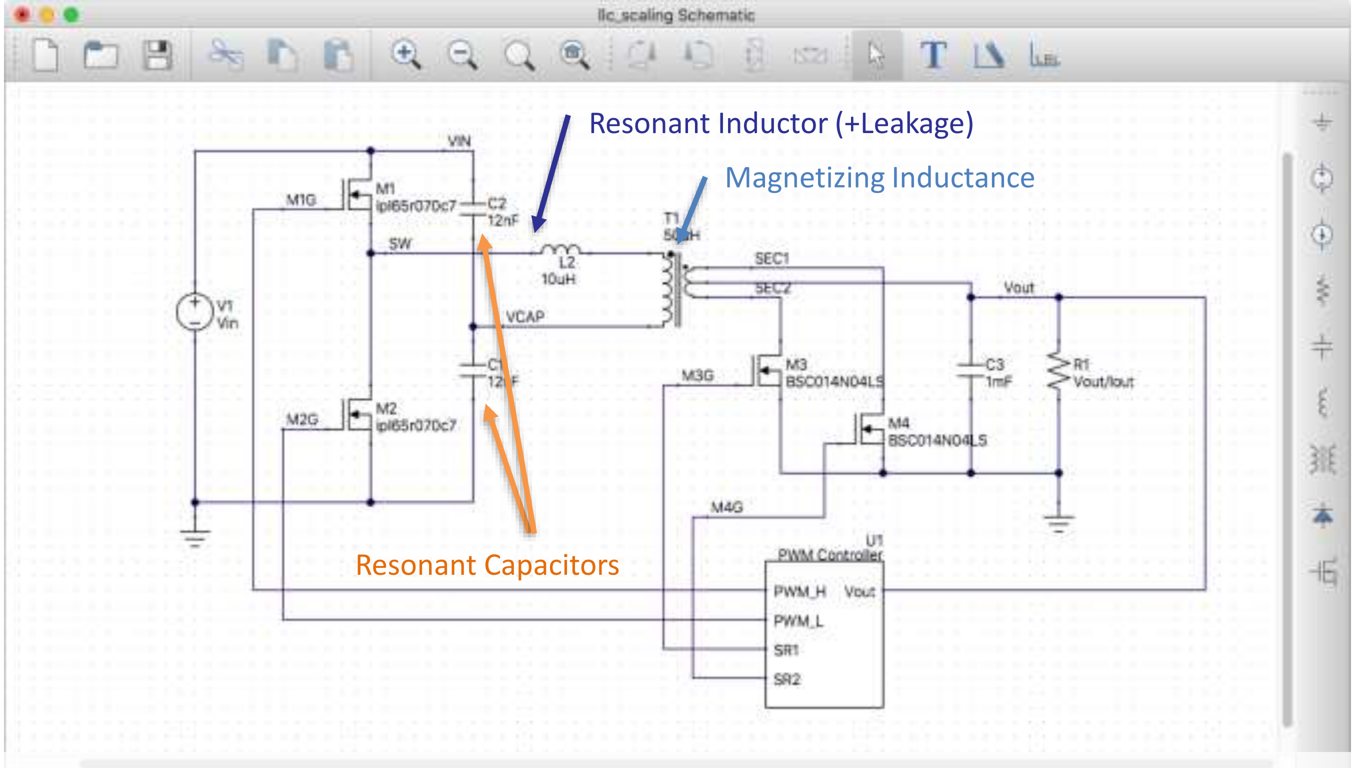
Measured: From EVM Datasheet





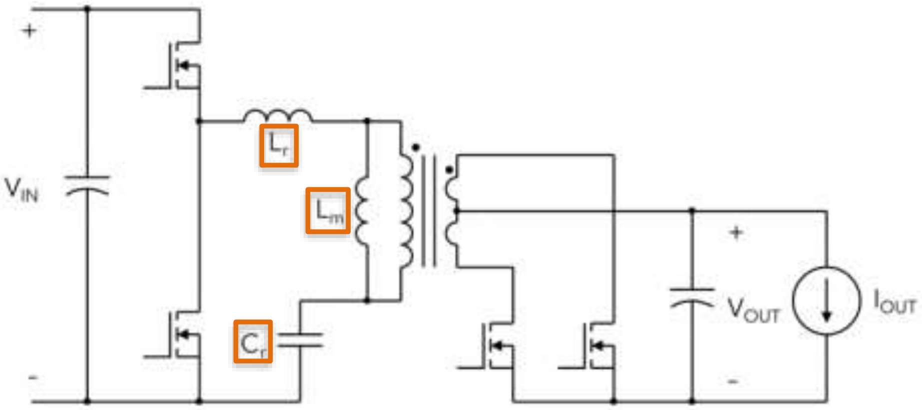
CASE STUDY: LLC CONVERTER

Fringing Loss in LLC/Resonant Converters



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

LLC: Initial Design Decisions



Magnetizing Current:

$$I_{m,pk} = \frac{V_{IN}}{8L_m f_{sw}}$$

- Determines dead-time and ZVS
- Adds additional circulating current

Resonant Frequency:

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}}$$

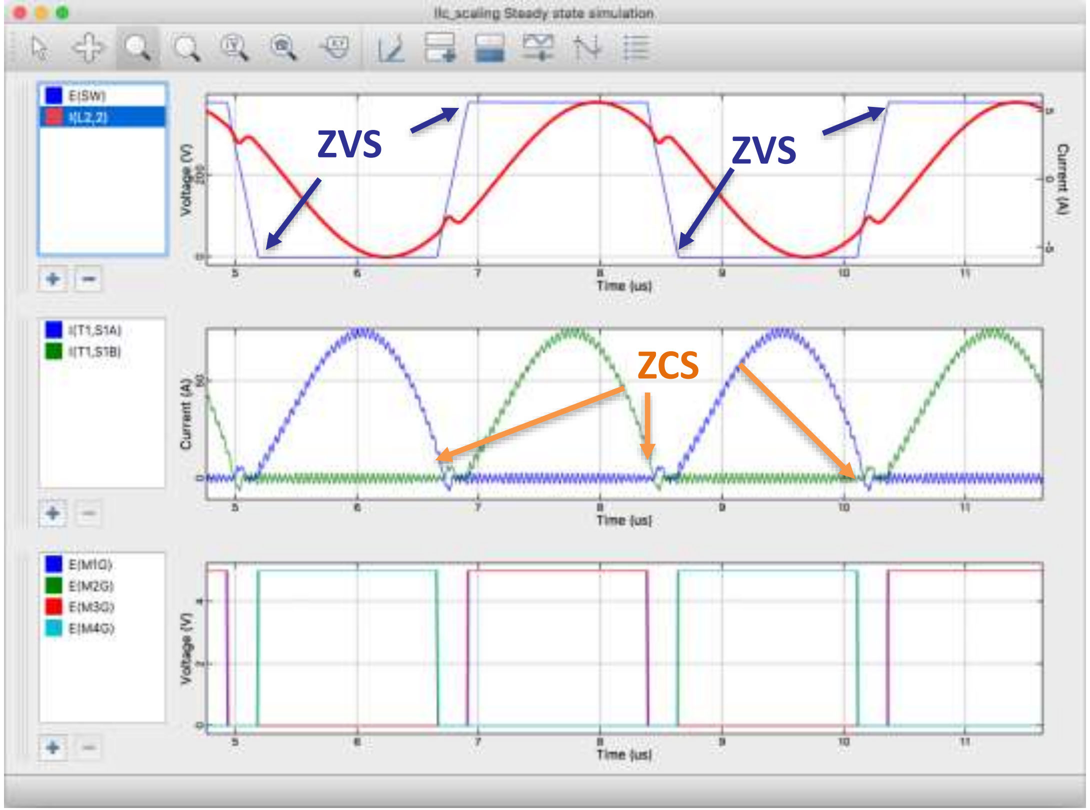
- Sets typical operating frequency
- Sets approximate component size

Q:

$$Q = \frac{\sqrt{L_r/C_r}}{n^2\, V_{OUT}/I_{OUT}}$$

- Sets regulation capability
- Determines necessary resonant components

LLC Waveforms (at resonance)



Primary switch-node voltage

Primary resonant current

Secondary-side currents

Gating Waveforms

LLC Silicon vs. GaN: Magnetic Effects

Silicon Version:

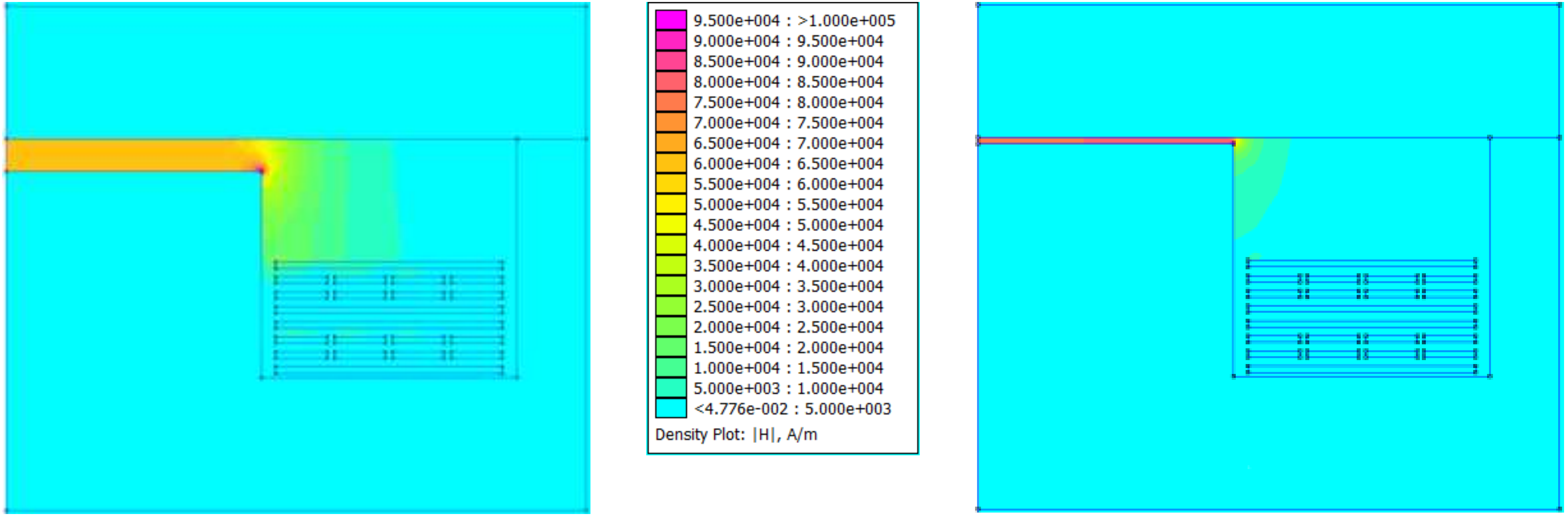
70 mΩ 650V Superjunction

Cr: 24nF, Lr: 10µH, **Lm: 50µH**

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: 5.43 W

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

Total Winding Loss: 2.991 W

Conclusions

- Magnetics design is complex with many tradeoffs
  - Custom designs are needed for almost every power supply
- Magnetic design comes down to understanding losses and their tradeoff in the context of the specific power converter
  - Easy: DC winding loss
  - Medium: Core loss (but non-sinusoidal waveforms are hard)
  - Hard: Skin-depth, proximity and fringe-field losses
- Understanding the trends in magnetics design can help drive converter design decisions
- Software like Eta Designer helps designers understand the tradeoffs easily to quickly develop an optimized solution.