Ira A. Fulton Schools of Engineering
Arizona State University

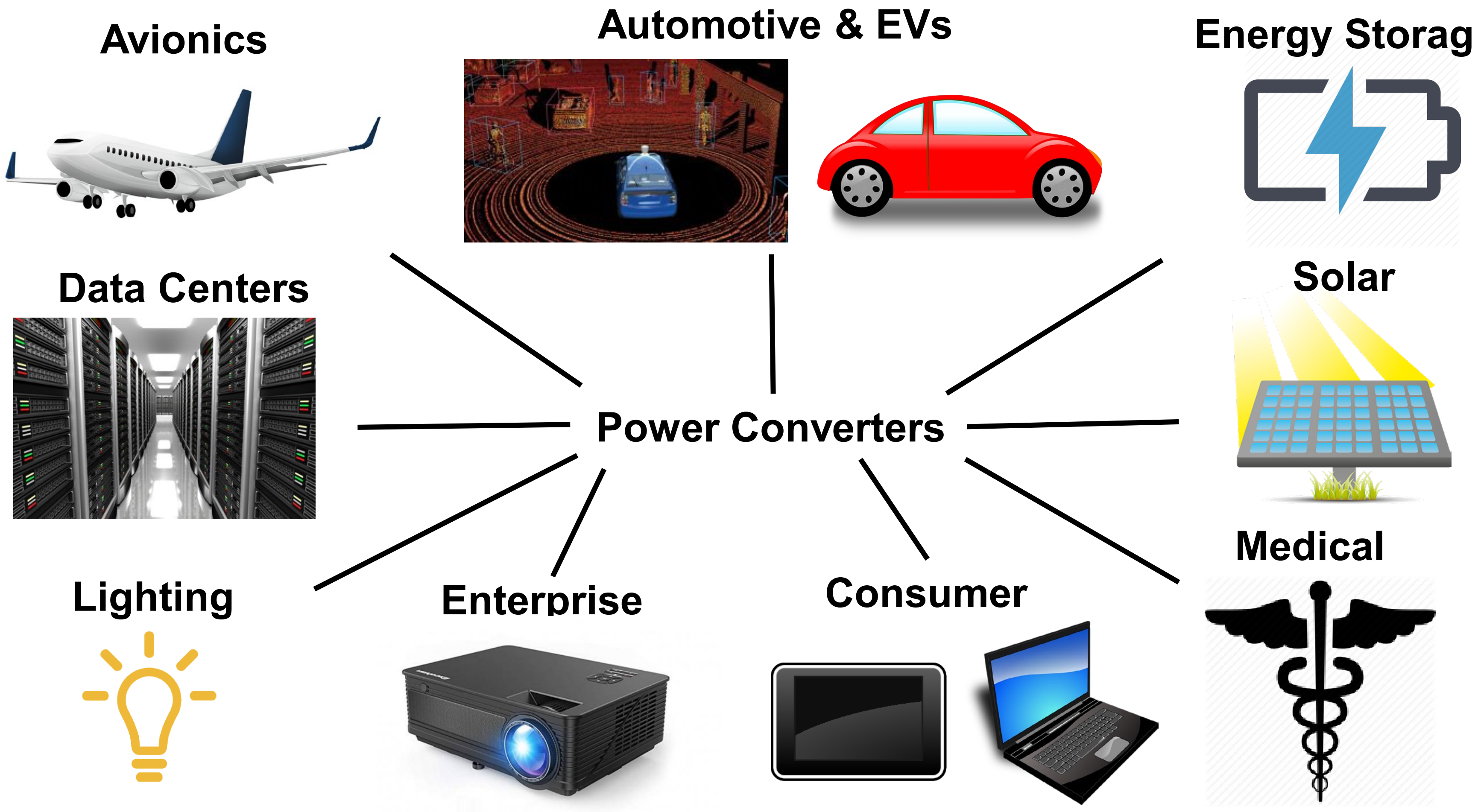
PSERC

# Miniaturizing and Advancing Power Electronics by Targeting Magnetics

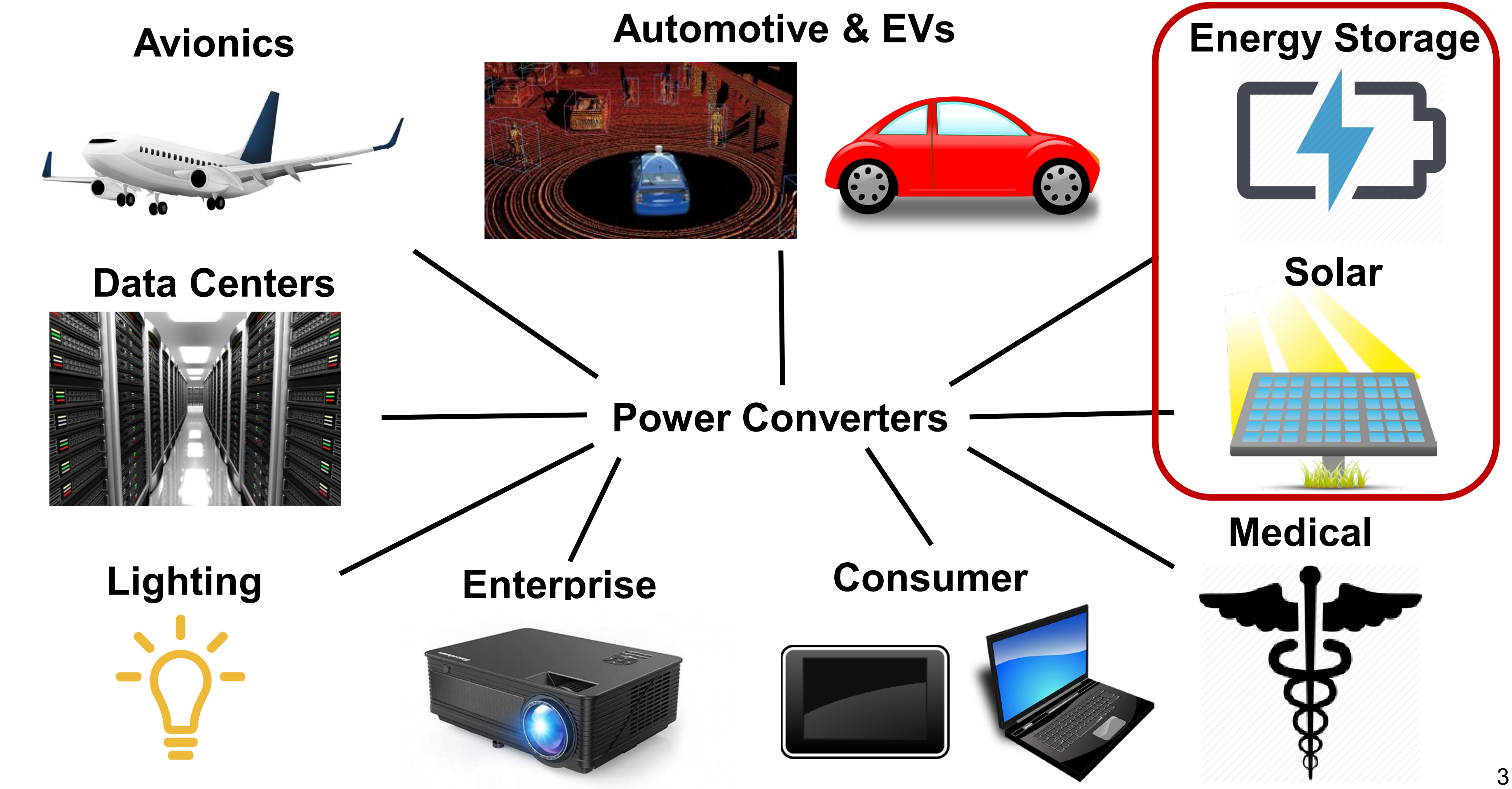
**PSERC Webinar**
**April 19, 2023**

**Mike K. Ranjram** (Mike.Ranjram@asu.edu)

# Why Is It Important To Advance Power Converters?



# Virtually All Our Elec. Systems and Devices Rely on Power Converters



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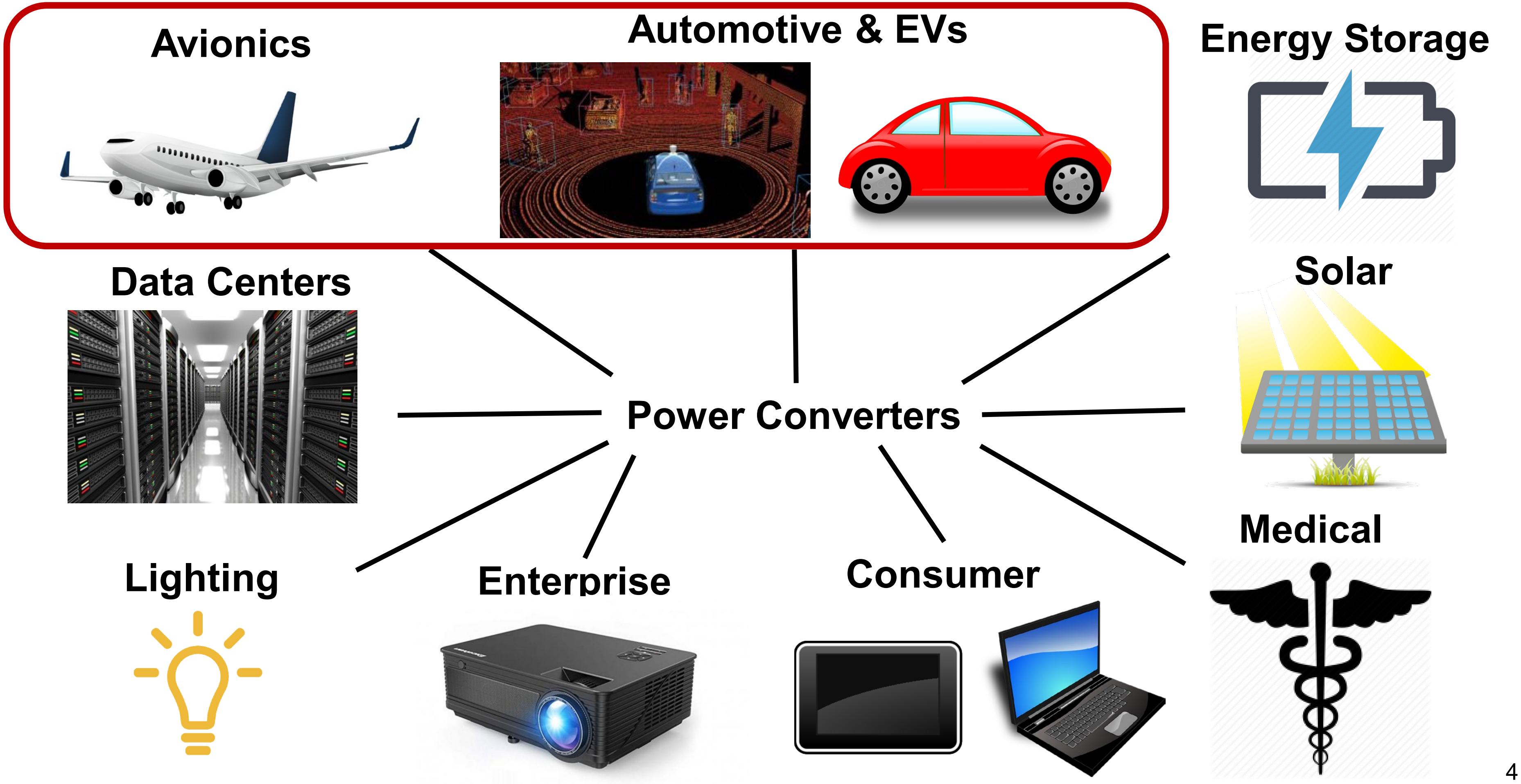

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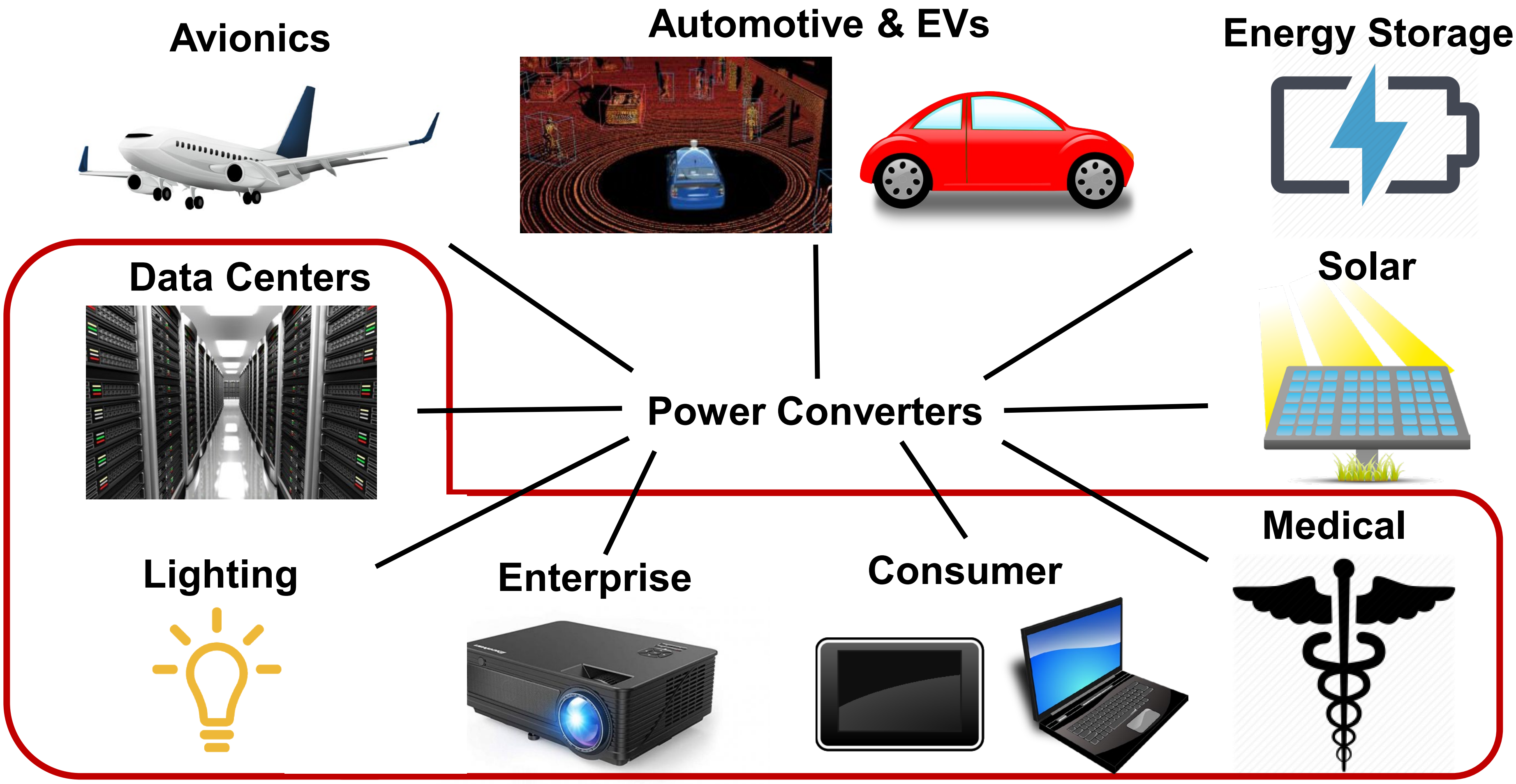
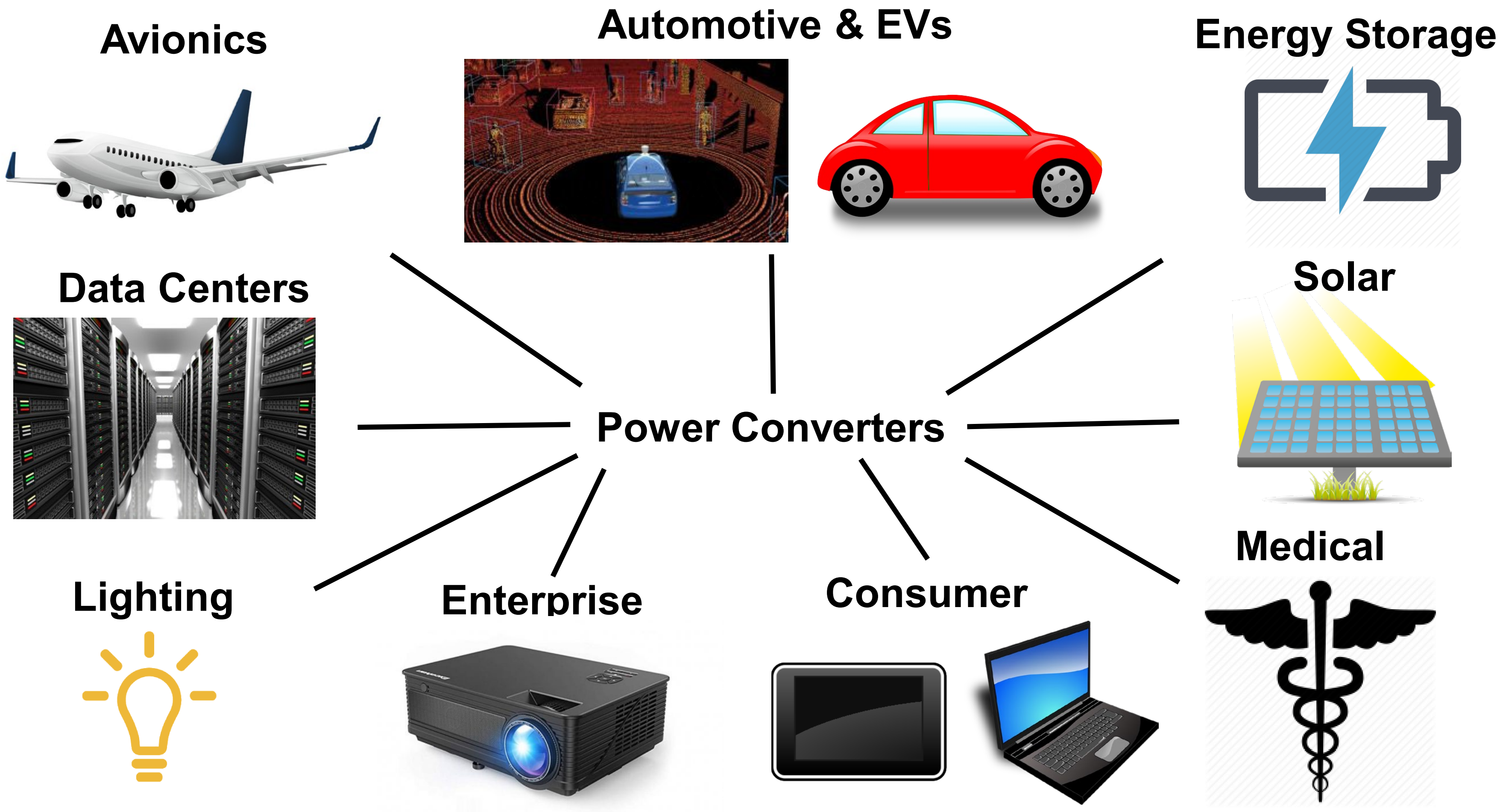
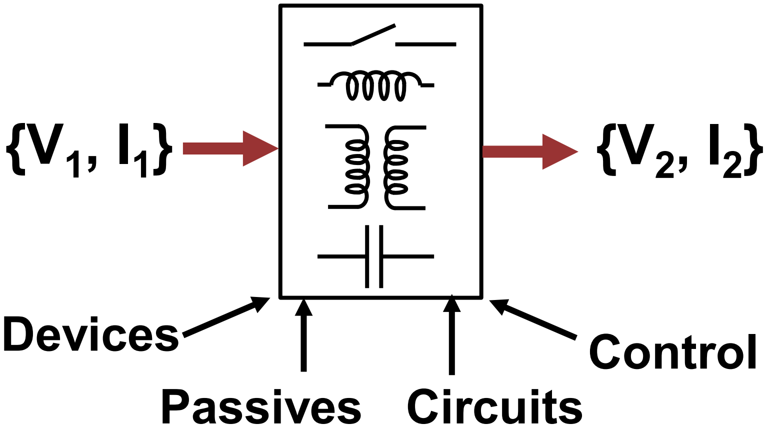


# By Making Power Converters "Better" We Make These Systems Better

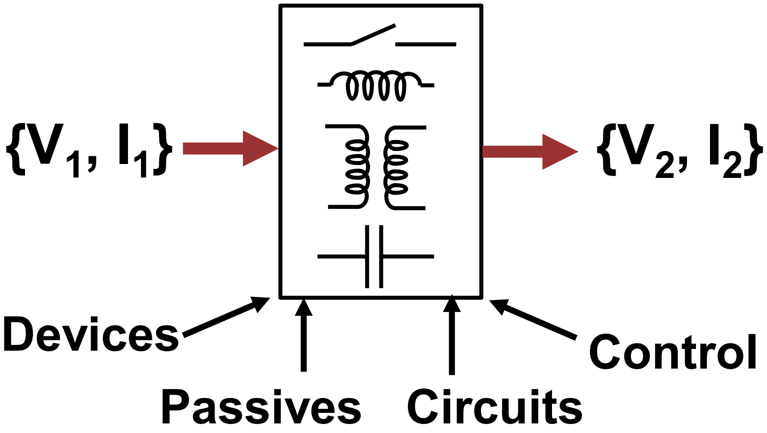


# System Improvements Derived from Advanced Power Converters



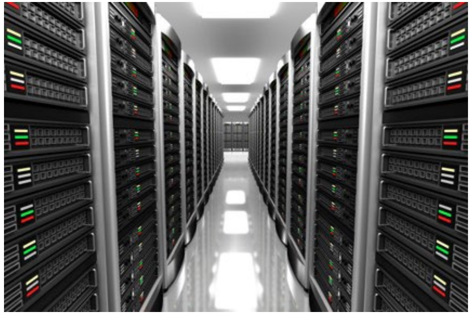

**Increased Efficiency**

# System Improvements Derived from Advanced Power Converters




**Increased Efficiency**

**Increased Capability**



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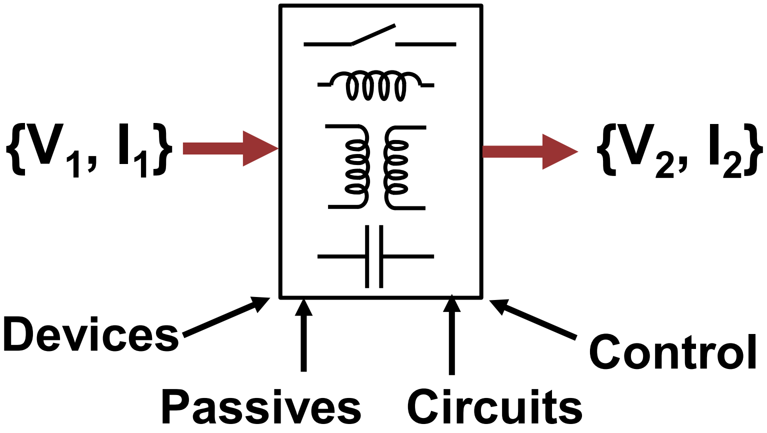
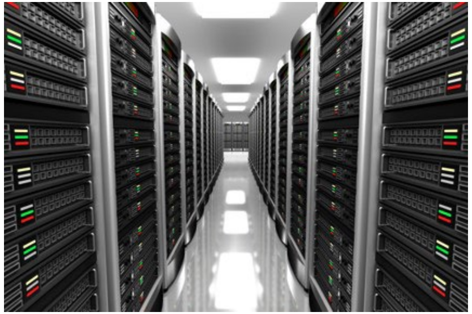
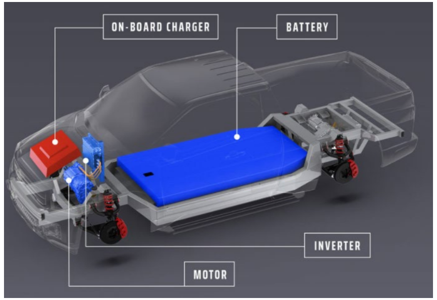



**Increased Efficiency**

**Increased Capability**

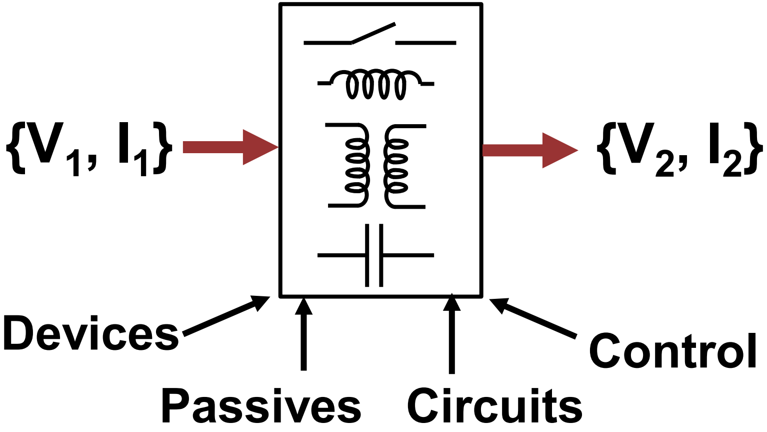


**Miniaturization**



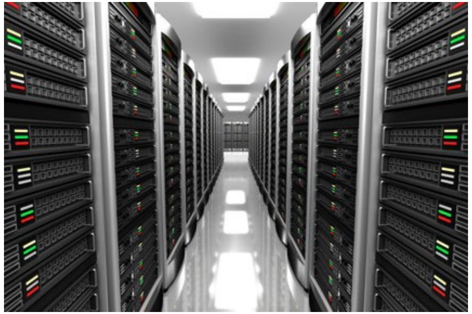

https://www.eleappower.com/products

# Our Goal: Miniaturization

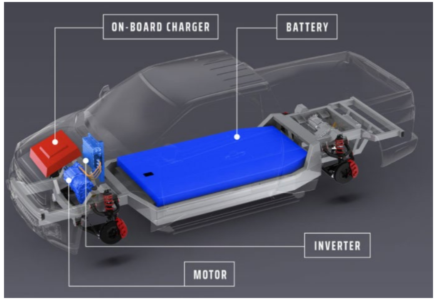



**Increased Efficiency**

**Increased Capability**



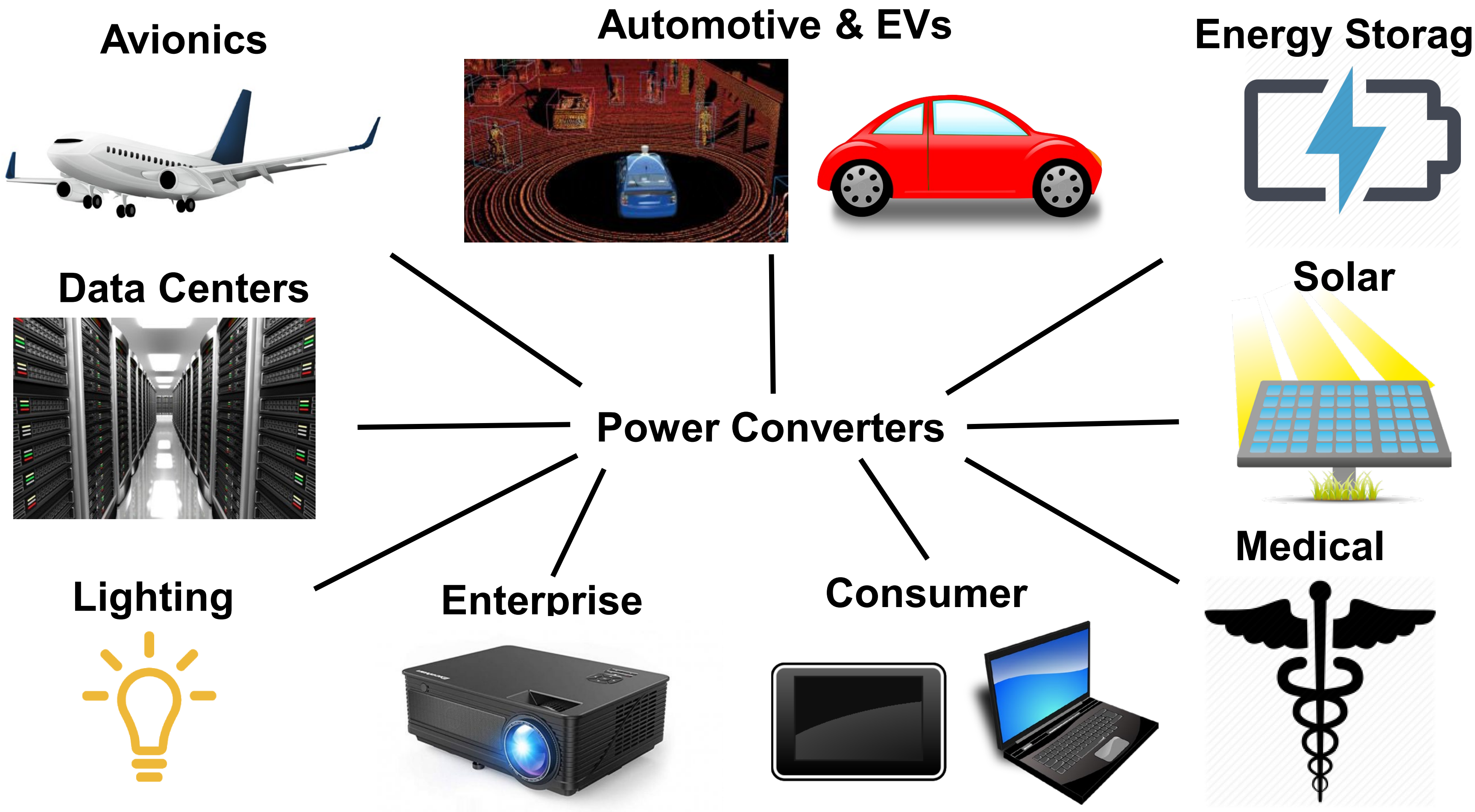
**Miniaturization**




**Make systems smaller,**
**and more efficient,**
**while enabling them to do more**

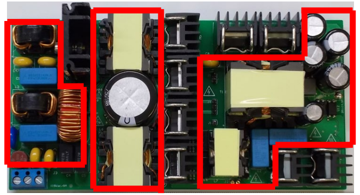
https://www.eleappower.com/products

# What’s Getting in the Way of Miniaturization Today?

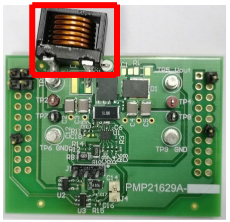


# These and Many Applications are Bottlenecked by Passives

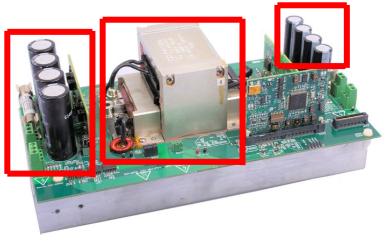
Avionics



Automotive & EVs



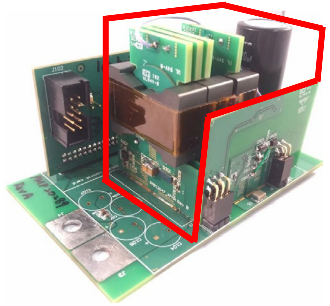




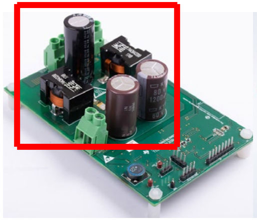
Energy Storage

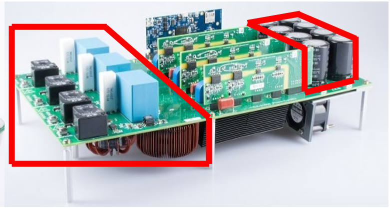


Data Centers



Solar

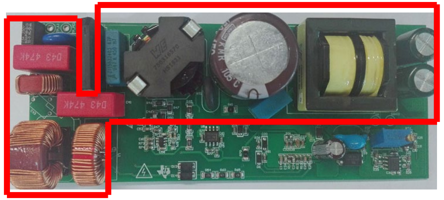




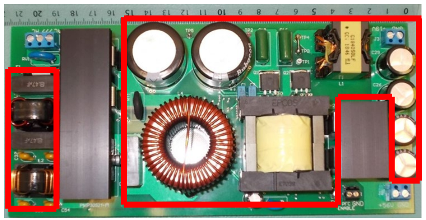
Power Electronics

Reference designs from TI (citations on last slide)

Lighting

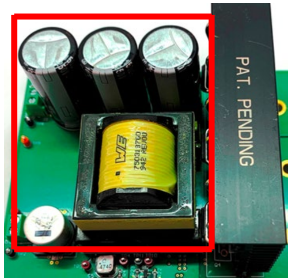


Enterprise



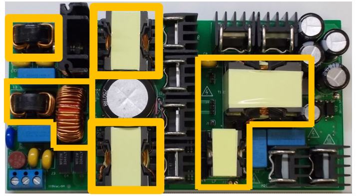
Consumer

Medical

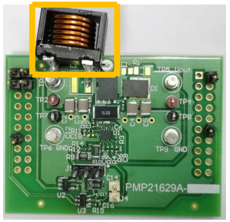


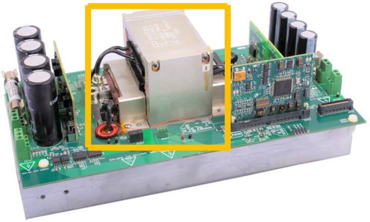
# Our Focus: Magnetics, a Dominant Source of Weight, Loss, and Size

Avionics

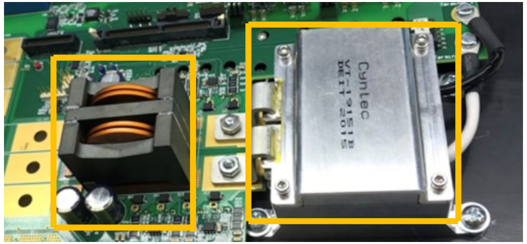


Automotive & EVs

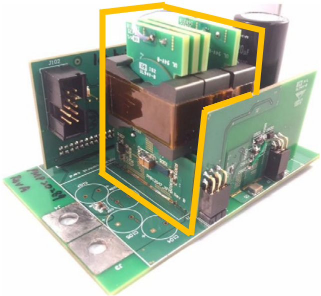




Energy Storage



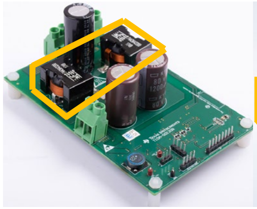
Data Centers

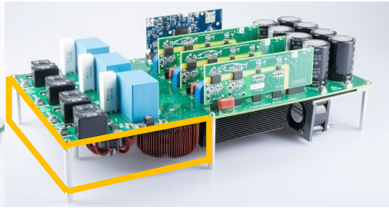


Power Electronics

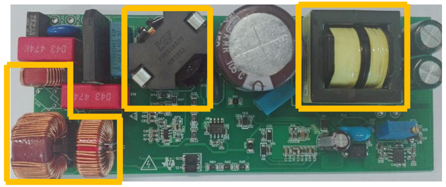
Reference designs from TI (citations on last slide)

Solar

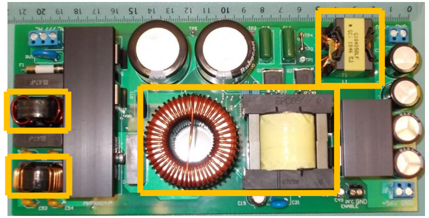




Lighting

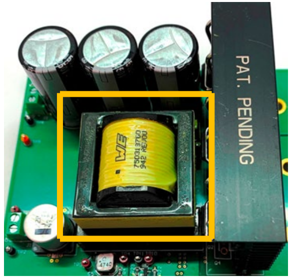


Enterprise



Consumer

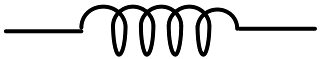
Medical



# Magnetics Perform Many Kinds of Functions

- The magnetics in the previous slide accomplish very different functions!
- Techniques to improve them are highly dependent on how they are used.

**Inductors**



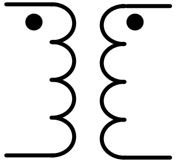
Energy Storage

dc Filtering (harmonic elimination)

ac Filtering (harmonic selection)

Snubbering ($i$ or $\frac{di}{dt}$ limiting)

**Transformers**



Impedance Transformation ("General purpose"

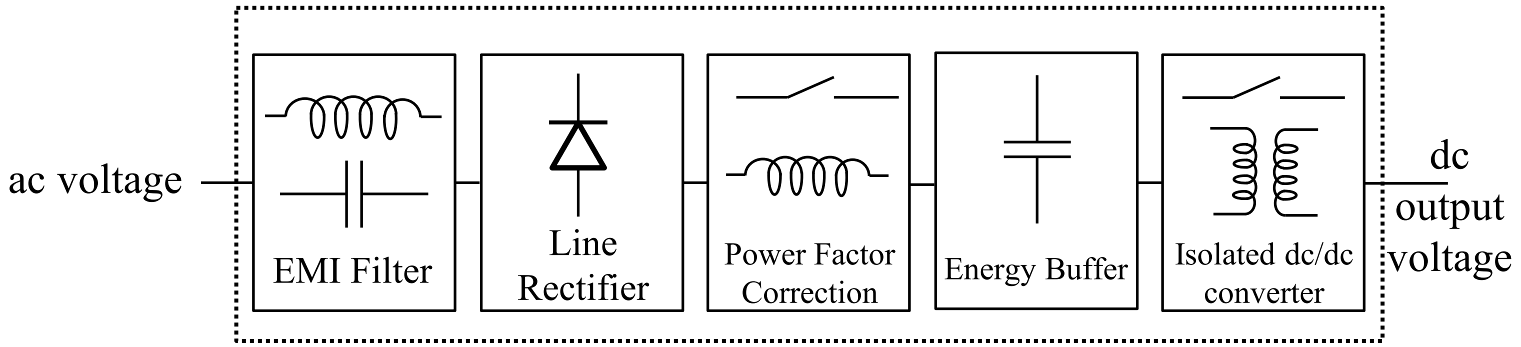
Energy Storage

Sensing

Enforcing multi-winding relationships

*Usually* isolated

# A Classic Architecture: EMI + PFC + Isolated dc/dc



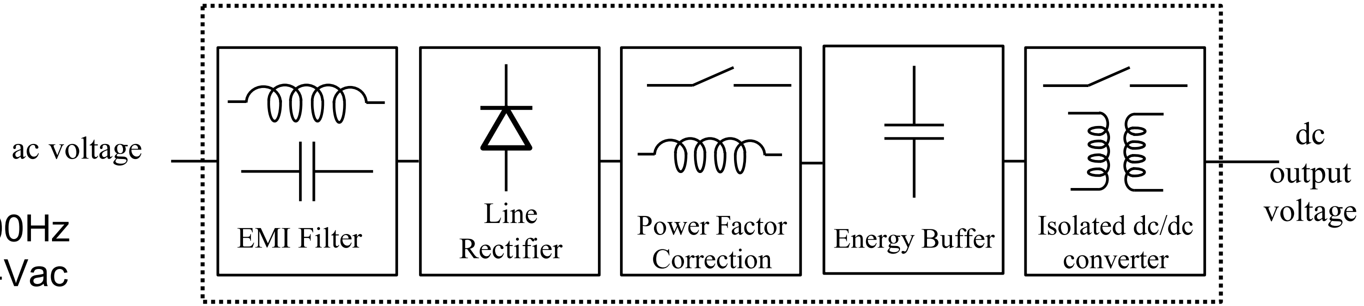

- A “staple” power converter, ac to controlled dc with isolation
- Contains many common magnetic functions - innovation is required “across the board”!

**Inductors**: energy storage, dc filtering, ac filtering

**Transformers**: impedance transformation, energy storage

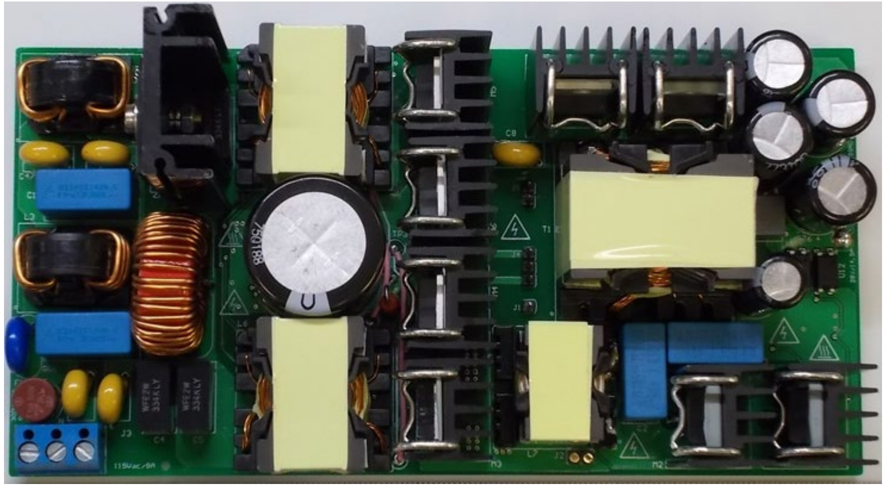
- For example, consider Texas Instruments reference design PMP30763 for avionics

# Consider TI Avionics Converter Reference Design




360-800Hz
96-134Vac

30V, 400W



https://www.ti.com/tool/PMP30763

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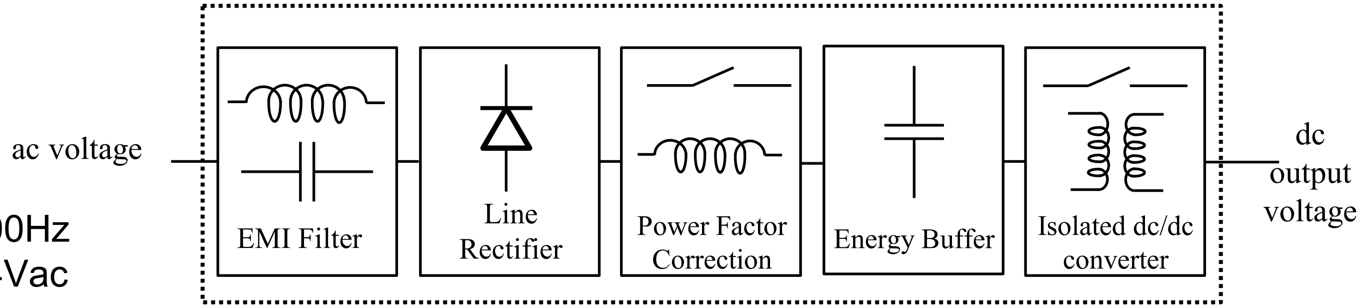
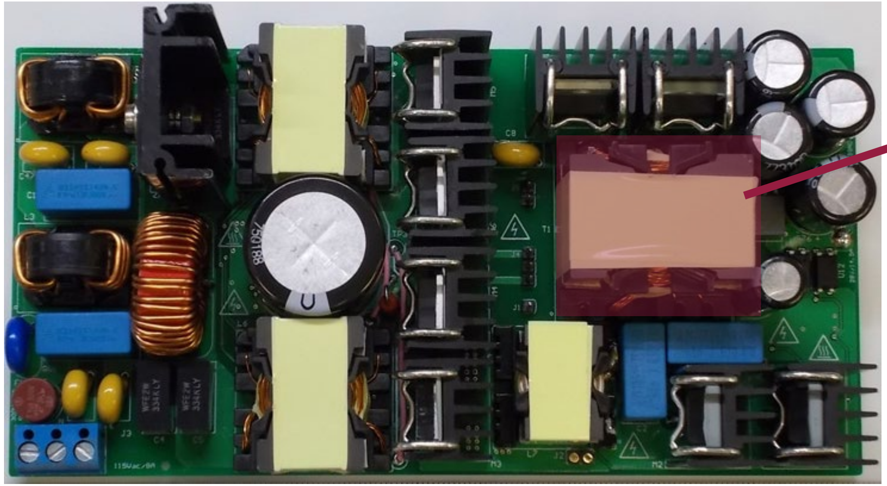



360-800Hz
96-134Vac

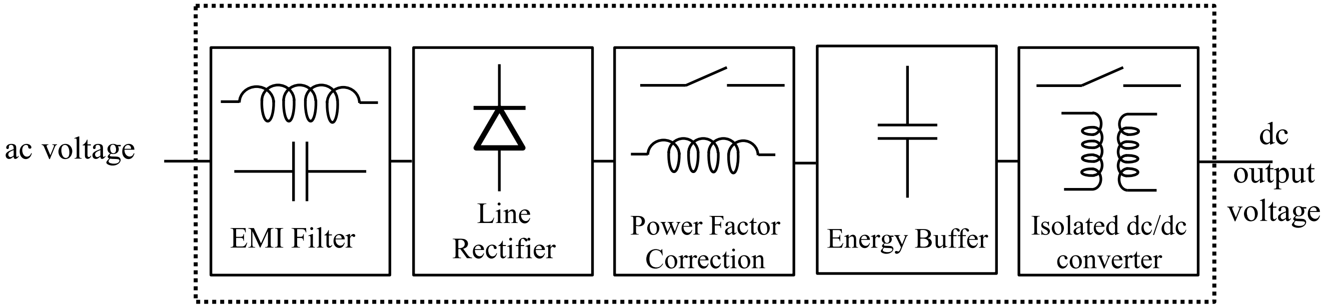
30V, 400W

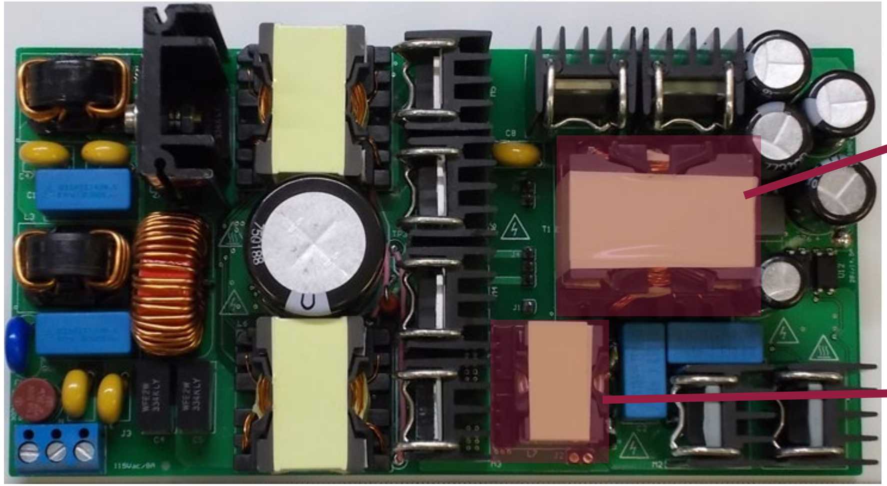


4:1 step-down transformer
1500Vac isolation
(Used in HB LLC)
"Impedance Transformer"
+ "Energy Storage"

https://www.ti.com/tool/PMP30763

# Consider TI Avionics Converter Reference Design



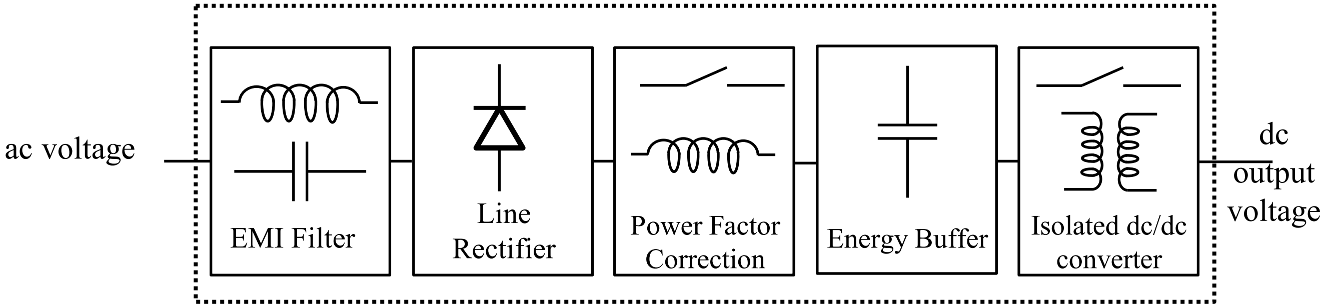



4:1 step-down transformer
1500Vac isolation
(Used in HB LLC)
“Impedance Transformer”
+ “Energy Storage”

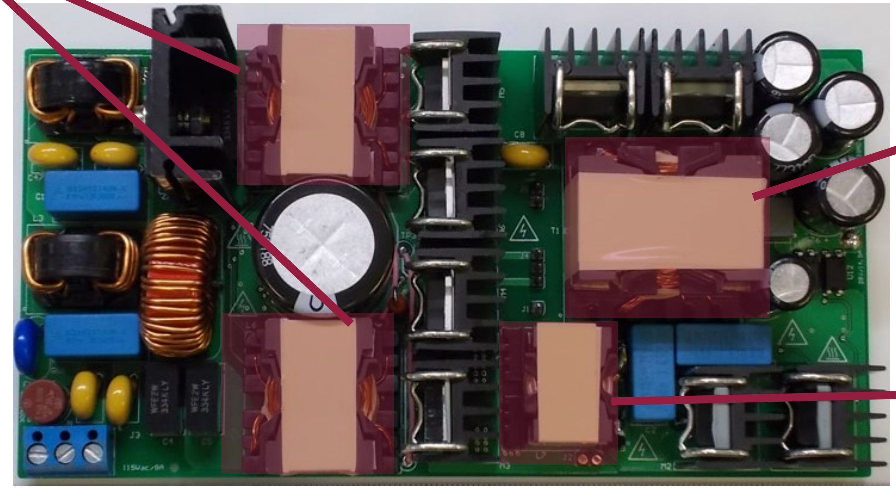
LLC Resonant Inductor
“Harmonic Selection”

https://www.ti.com/tool/PMP30763

# Consider TI Avionics Converter Reference Design




Boost inductors
"Energy Storage"
+ voltage sensing windings
(two-phase construction)

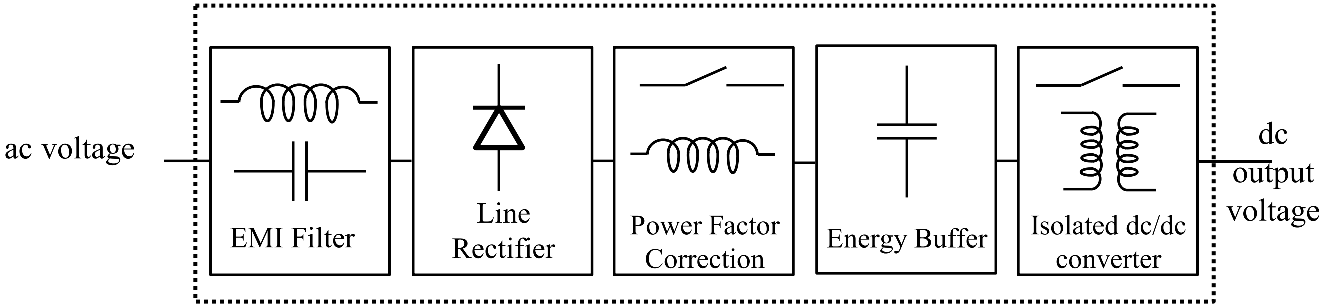


4:1 step-down transformer
1500Vac isolation
(Used in HB LLC)
"Impedance Transformer"
+ "Energy Storage"

LLC Resonant Inductor
"Harmonic Selection"

https://www.ti.com/tool/PMP30763

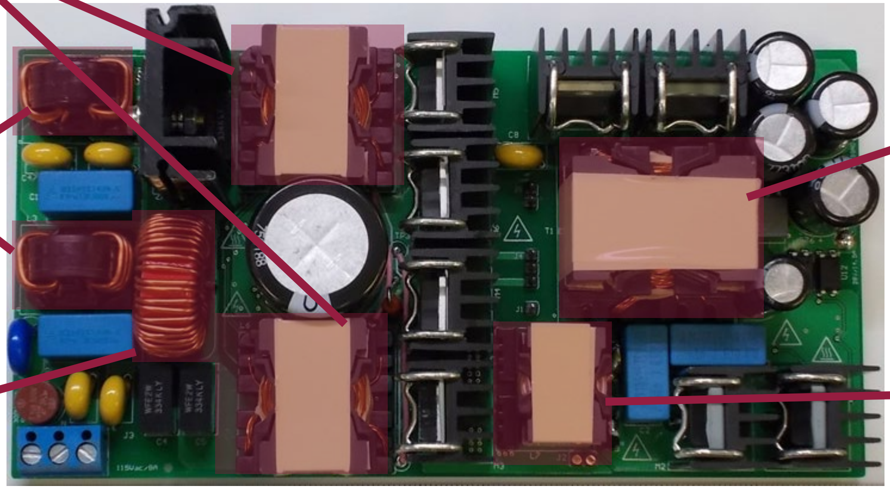
# Consider TI Avionics Converter Reference Design




Boost inductors
"Energy Storage"
+ voltage sensing windings

Common-mode chokes
"dc filtering"

Differential-mode choke
"dc filtering"



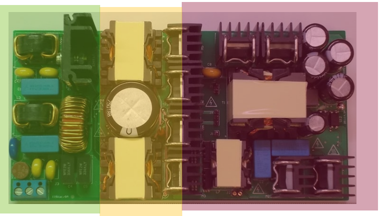
4:1 step-down transformer
1500Vac isolation
(Used in HB LLC)
"Impedance Transformer"
+ "Energy Storage"

LLC Resonant Inductor
"Harmonic Selection"

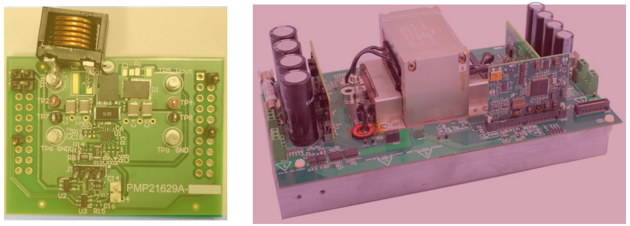
https://www.ti.com/tool/PMP30763

# Our example converters use *many* magnetics

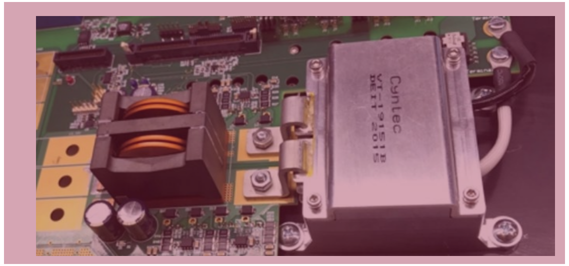
Avionics



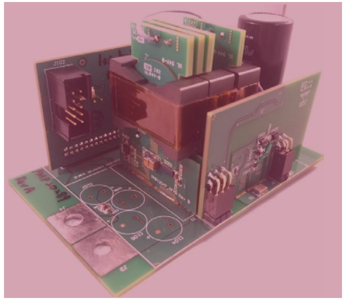
Automotive & EVs




Energy Storage

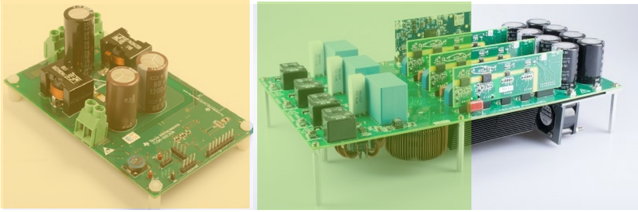


Data Centers

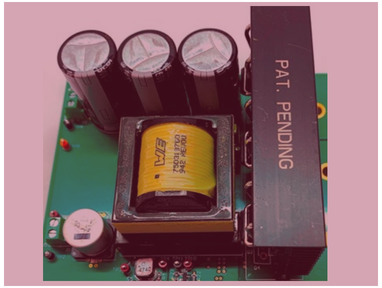


Green = filtering (harmonic elimination)
Yellow = dc/dc conversion (energy storage)
Red = isolated dc/dc conversion (impedance transformation and/or energy storage)

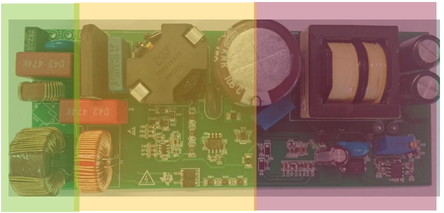
Solar



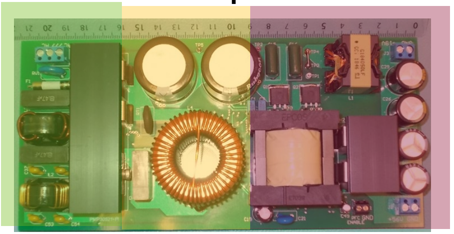
Medical



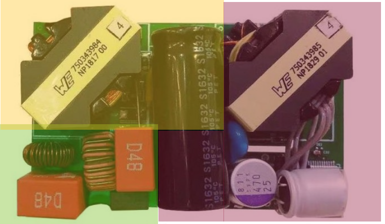

Lighting



Enterprise



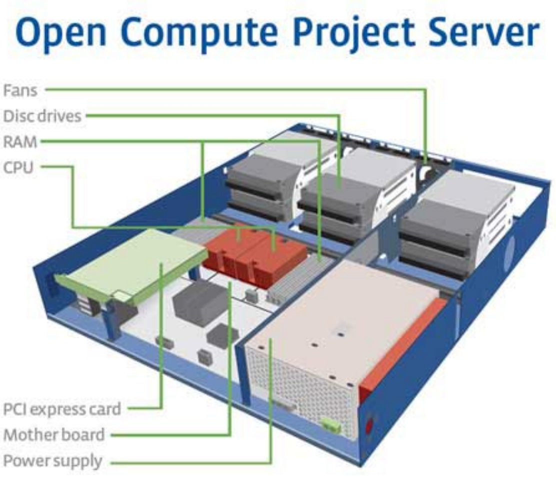
Consumer



# Focus on High Step-Down, High Output Current Conversion

- "Miniaturizing magnetics" is too broad an objective.
- We must target a specific magnetic function under a specific operating regime

**Data Centers**



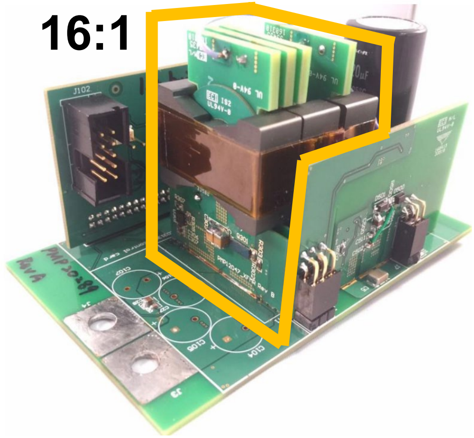

**Consumer**

**Electric Vehicles**

# Bottleneck: High Step-Down Transformer

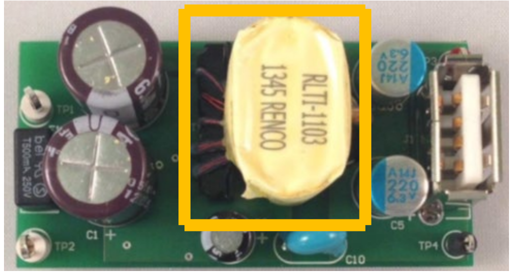
**Data Centers**

16:1



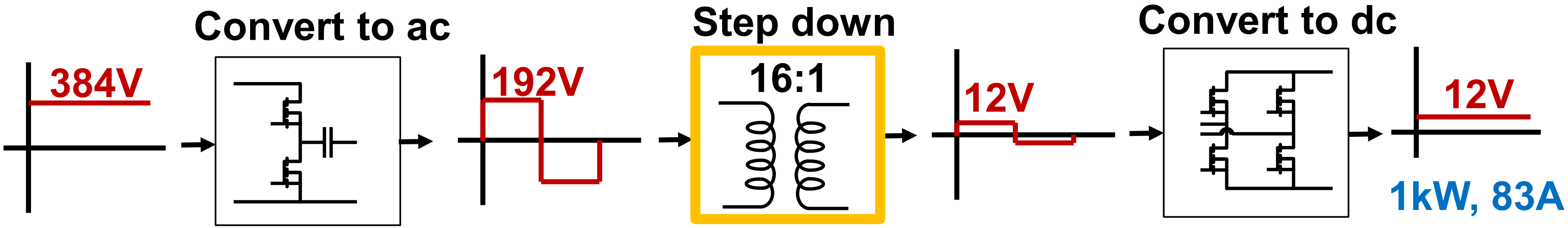
**Consumer**

24:1




**Electric Vehicles**

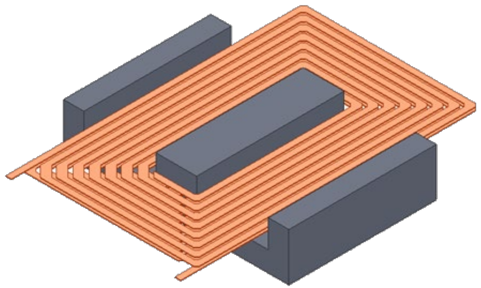
16:1


https://www.ti.com/tool/PMP20289
https://www.ti.com/tool/TIDA-01623
https://www.ti.com/tool/TIDM-02002

# What are Our Approaches to Miniaturize Transformers?

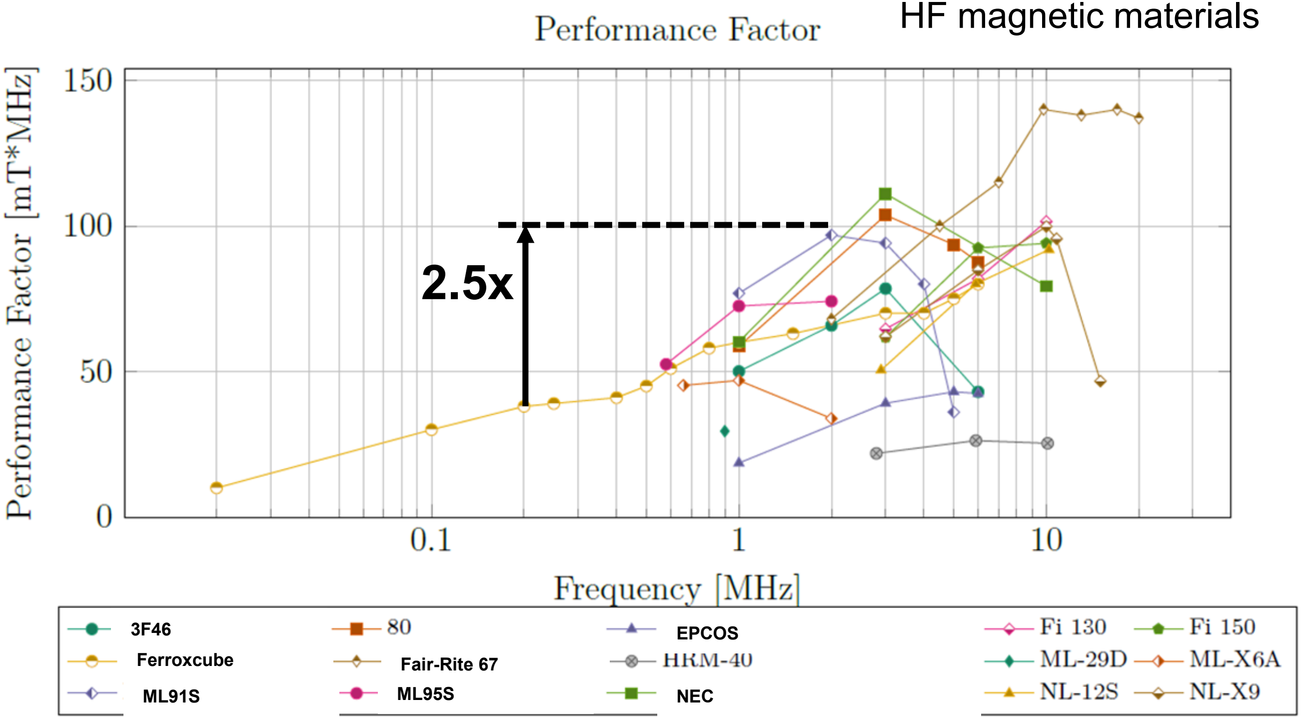
- Today's active areas of research (component-level)
  - High frequency switching (MHz+)
  - High performance magnetic materials at high frequencies
  - Leverage planar magnetics
  - Novel winding techniques



# High Performance Materials at High Frequencies

Low-permeability
HF magnetic materials

Power handling capability per unit volume




R. Bayliss, "Design, Implementation, and Evaluation of High-Efficiency High-Power Radio-Frequency Inductors," Master's Thesis, MIT, 2021

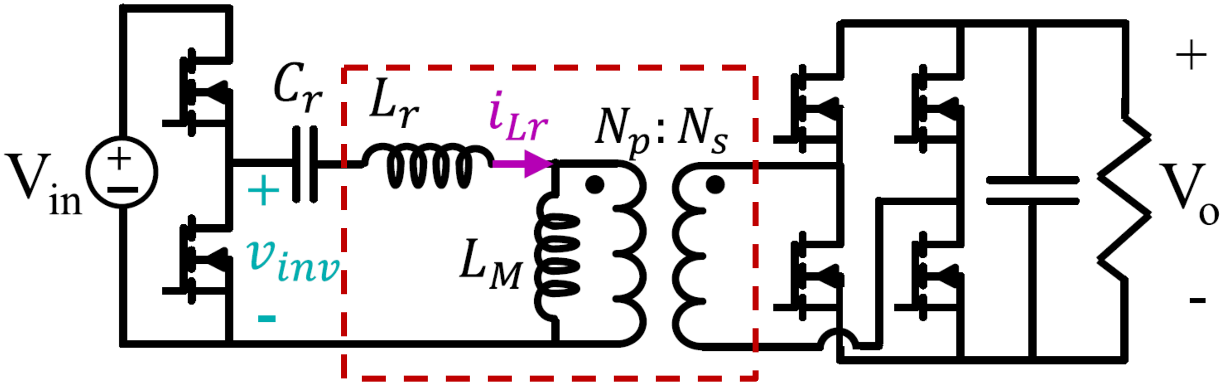
# High Frequency Switching

## Increasing frequency yields smaller L, C for same impedance

$$Z = j\omega L$$

## Transformer benefit: leverage (small) leakage for harmonic selection

HB-LLC converter



# Employing Planar Magnetics

- **Windings of inductors/transformers implemented as copper traces on printed circuit boards (PCBs)**

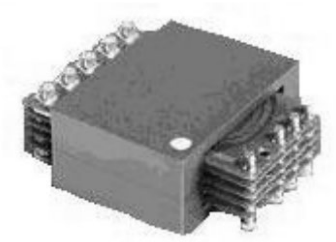
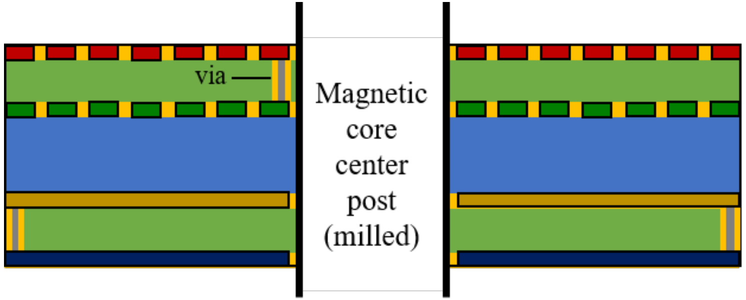
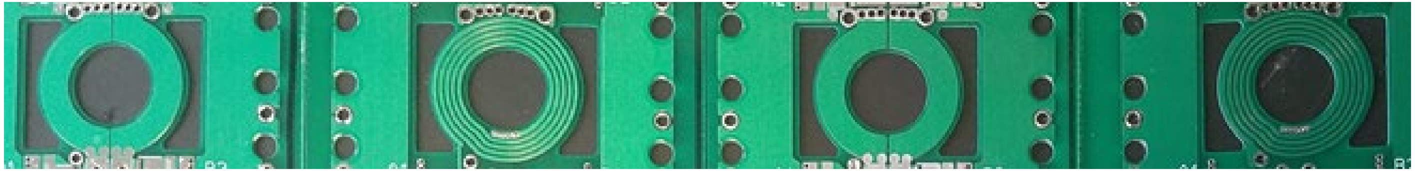


*Fig. 1. Planar transformer.*

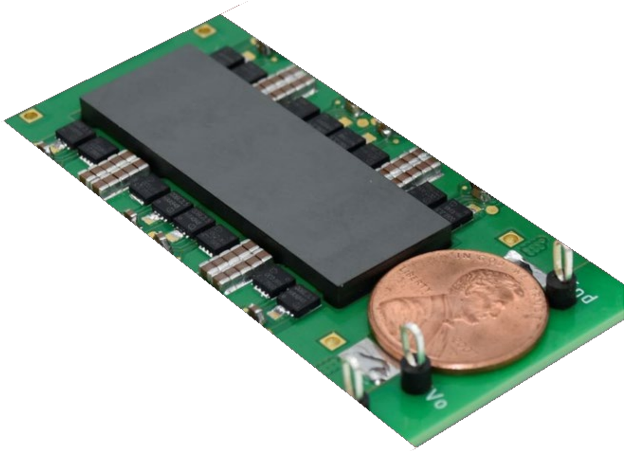


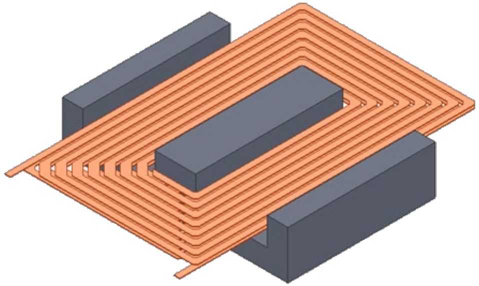



L. H. Dixon, “Designing planar magnetics,” Texas Instruments Application Note. [Online]. Available: http://www.ti.com/download/trng/docs/seminar/Topic4LD.pdf

# Planar Magnetics: Cost-Effective, Easy to Build, with Good Thermals

- Low profile (minimize box volume)
- Good thermal characteristics (high surface area to volume)
- Ease of manufacturability
- Highly repeatable
- Lower cost than wire-wound alternatives



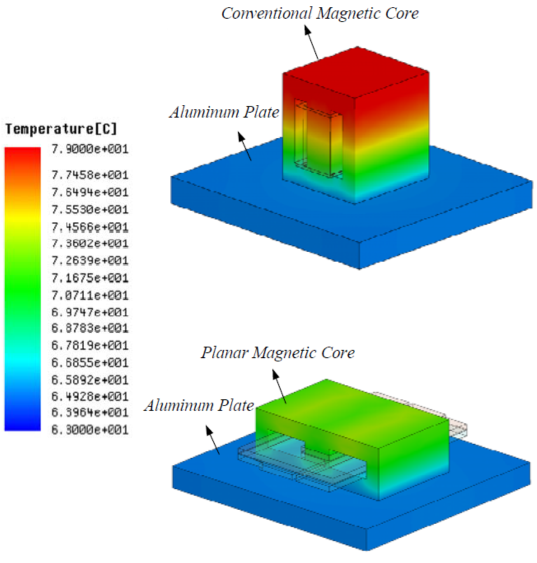
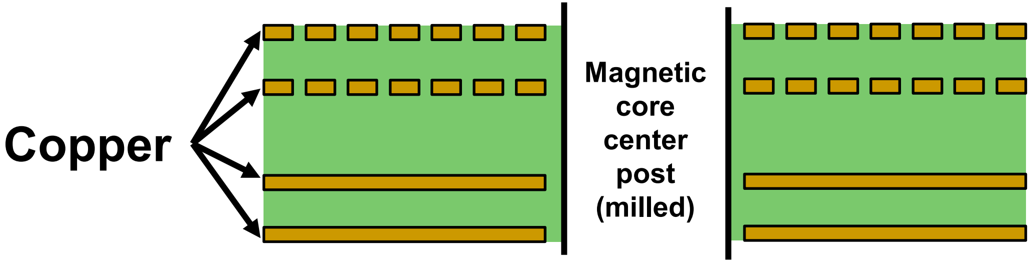


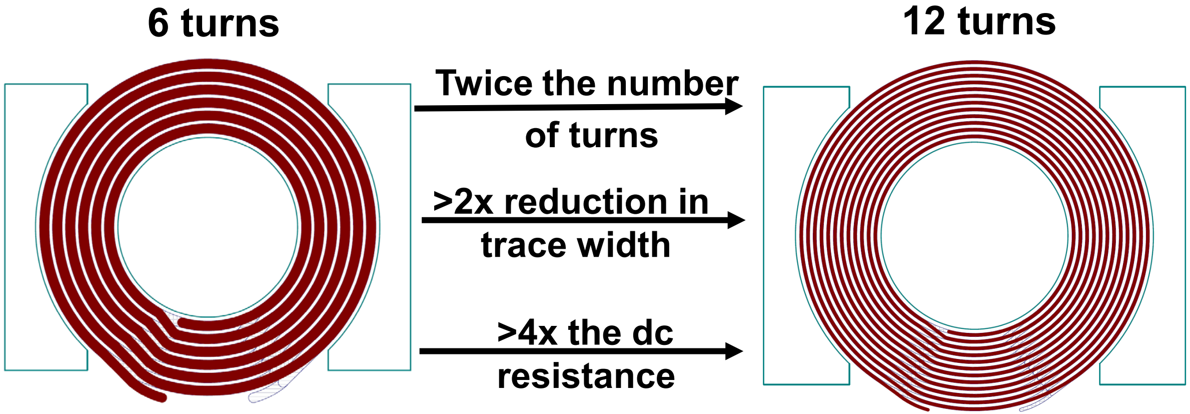

Fig. 1. Comparison of thermal behavior between conventional core and planar core.

Z. Ouyang and M. A. E. Andersen, "Overview of planar magnetic technology - fundamental properties," IEEE Trans. Power Electron., vol. 29, no. 9, pp. 4888-4900, Sep. 2014

# Planar Magnetics Difficult w/ High Step-Down, High Current

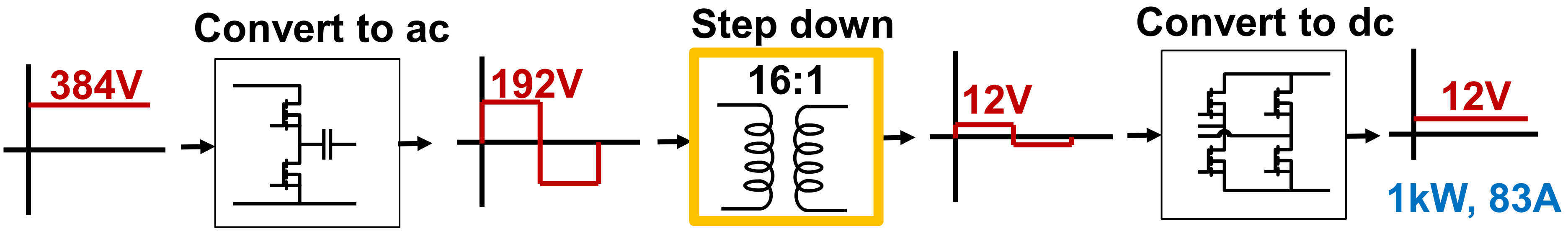



- Poor "fill factor"
- Little area for copper




- Large penalty for many turns on a layer

# Develop 1MHz Planar Transformer at 16:1 Turns Ratio



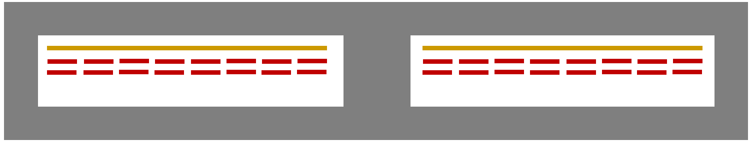

- Let's miniaturize this 16:1 transformer using these approaches:
  - Switch at 1MHz – target high performance ML91S material
  - Use planar magnetics

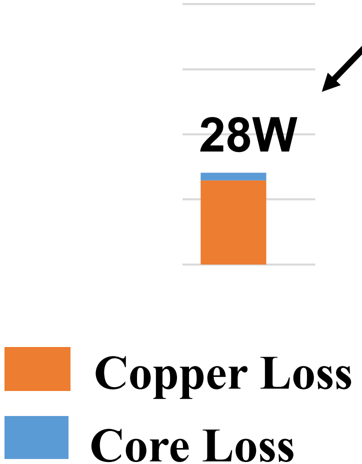
# Develop 1MHz Planar Transformer at 16:1 Turns Ratio

- Create the lowest loss design in a 10cc volume

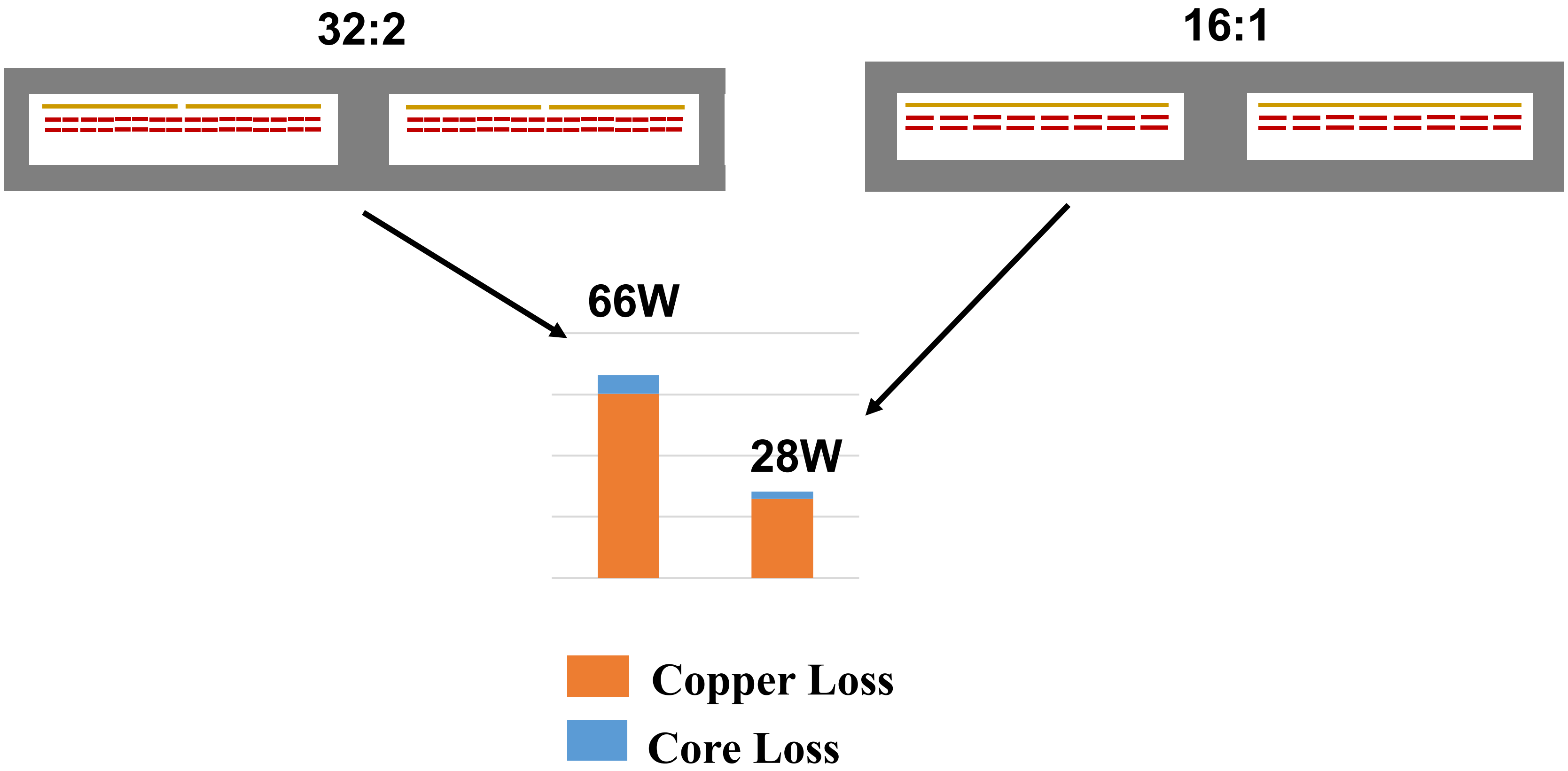
- Can we do better? Play with turns implementation?

16:1

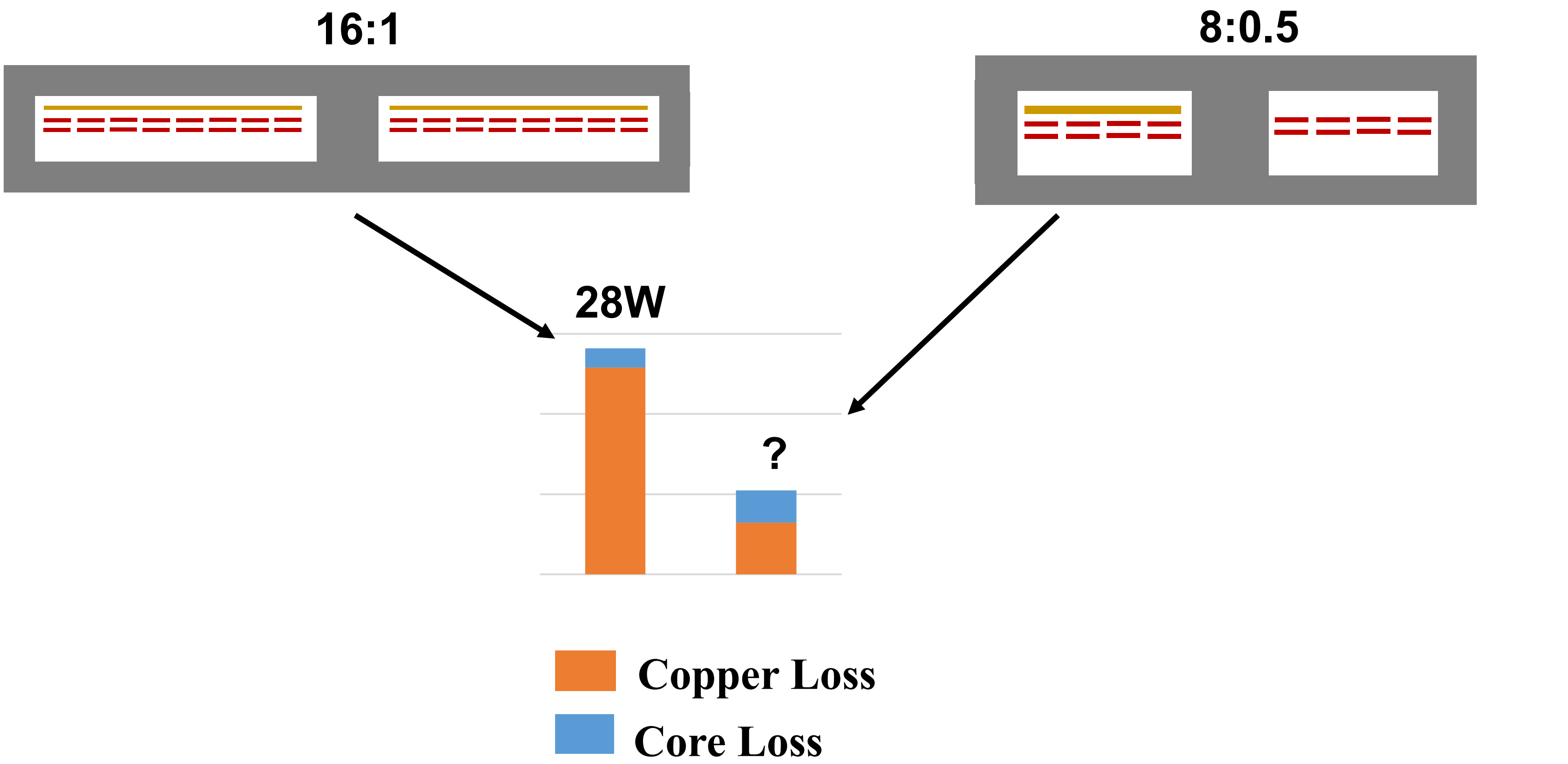




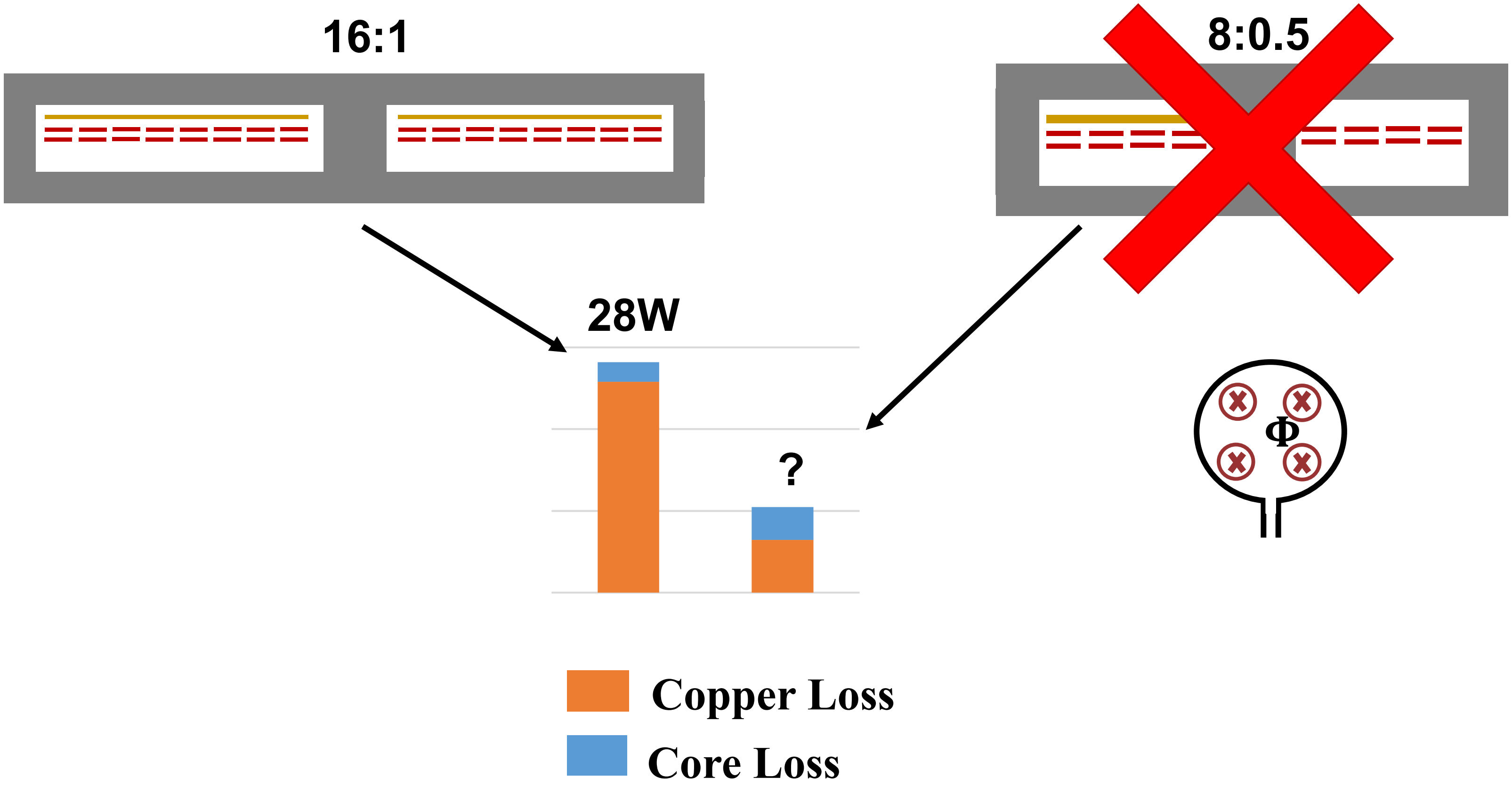
# Minimizing Turns Count is Greatly Advantageous



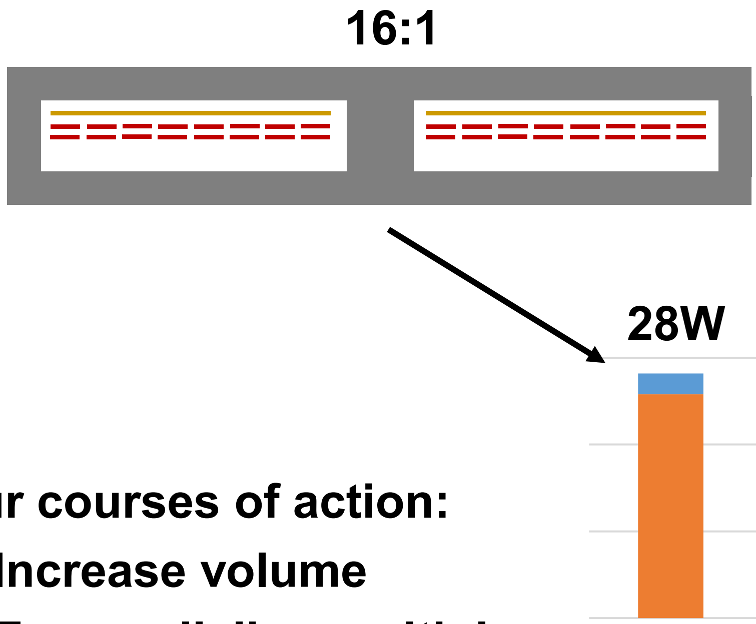
# A Fractional Turn Would Help...

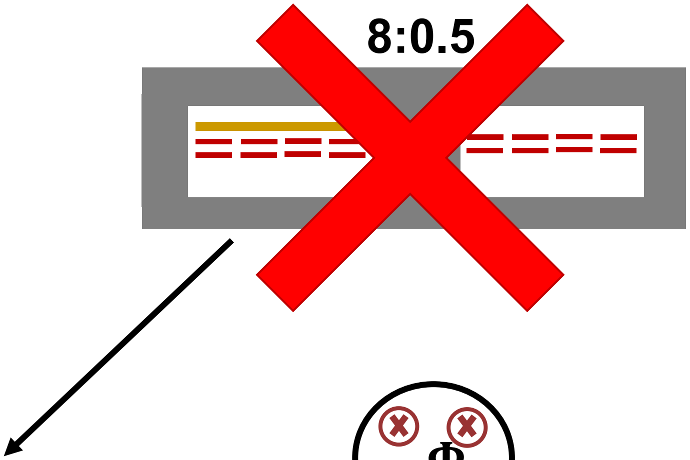


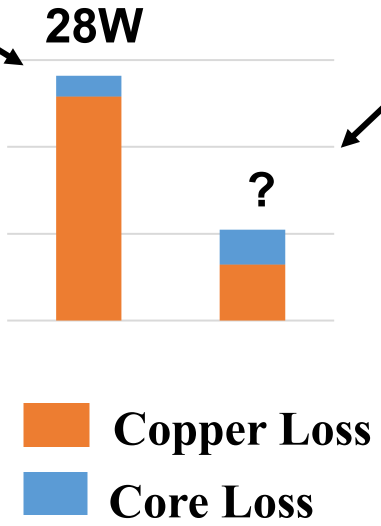
# A Fractional Turn as Defined this Way Is Not Practical

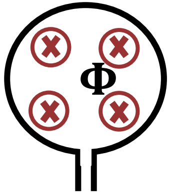


# A Fractional Turn as Defined this Way Is Not Practical



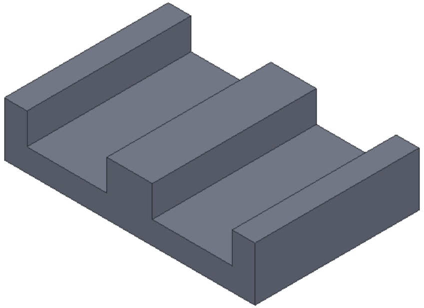



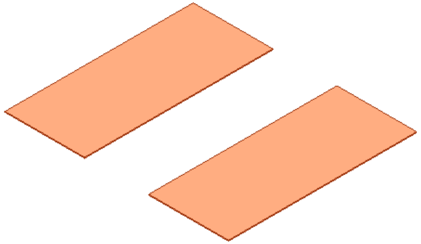

**Our courses of action:**

- Increase volume
- Try paralleling multiple converters or multiple transformers (matrix transformer)

# Taking a Step Back



Magnetic materials

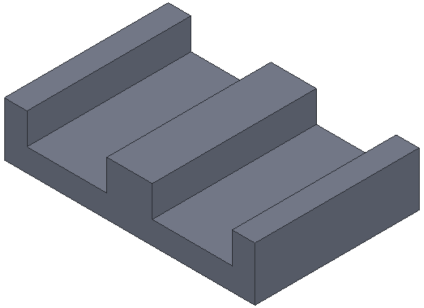


Conductors

Electronics

**We can reduce this design into these three key elements**

# Creating Magnetic Components



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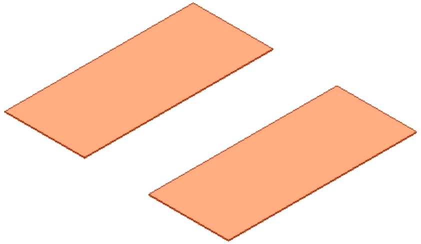
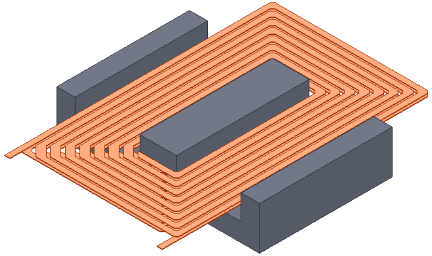


Magnetic materials

Conductors

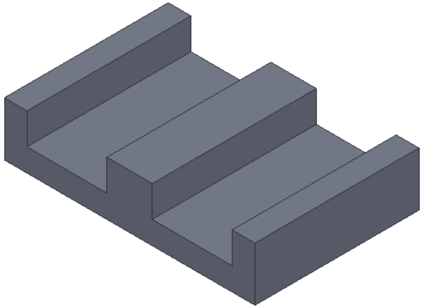
Electronics

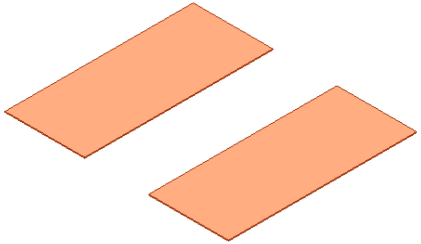


Inductors and transformers

- Today's active areas of research
  - High frequency switching (MHz+)
  - New magnetic materials
  - New winding techniques
  - Planar magnetics
- "Physical domain"

# Leveraging Magnetic Components

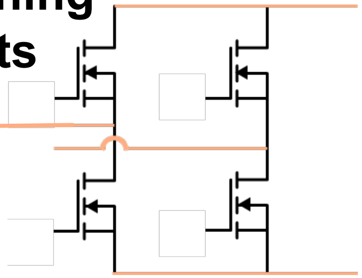


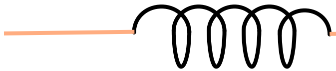


+

**Magnetic materials** | **Conductors** | **Electronics**

**Switching circuits**

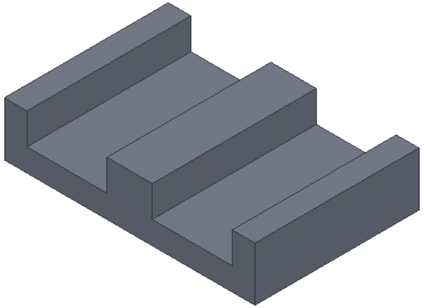




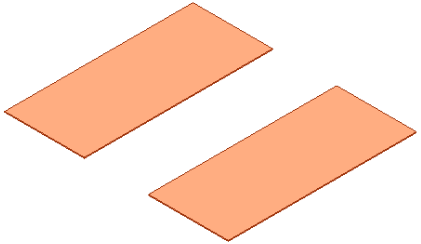
**Inductors and transformers**

- **System/Topology selection**
- **“Electrical domain”**

# Can We Explore Something More Fundamental?



Magnetic materials



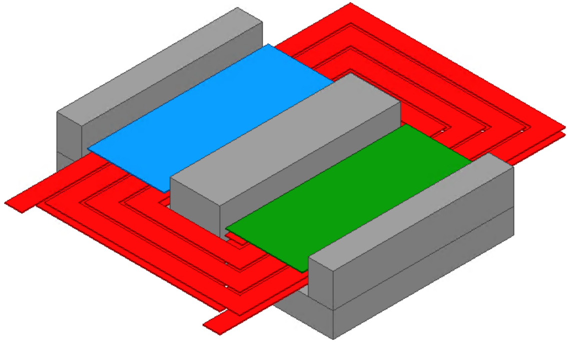
Conductors

Electronics

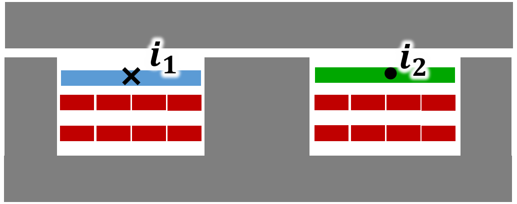
**Can we create something different by treating these elements more fundamentally?**

# A Fractional-Turn Transformer Using a New Kind of Structure

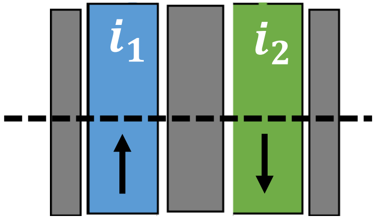
**Orthographic View**



**Side View**



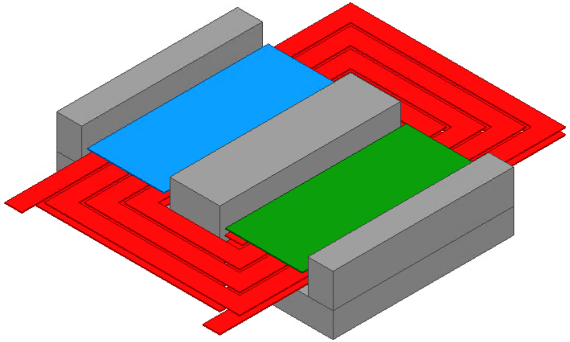

**Top View**



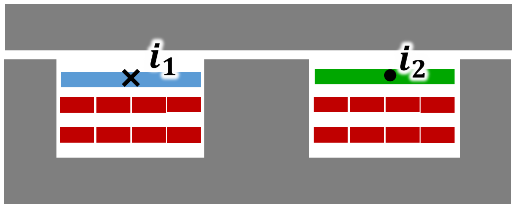
# Assume Physical Symmetry About Center of the Core

**Assume symmetry**

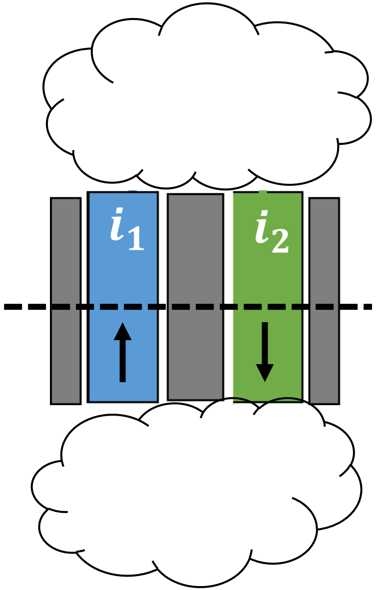
## Orthographic View



## Side View



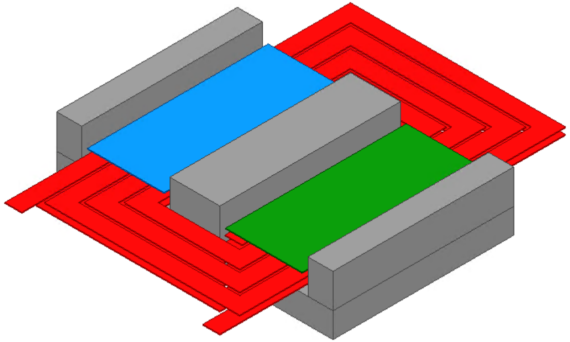

## Top View



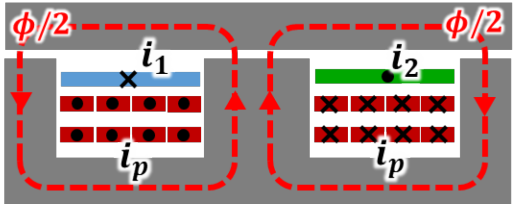
# Excite the Primary Winding, Flux Flows Symmetrically

**Assume symmetry**

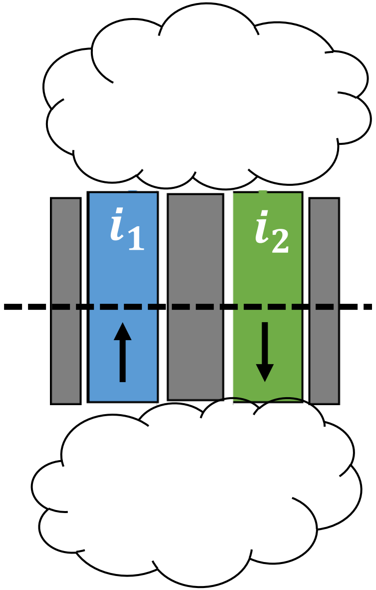
**Orthographic View**



**Side View**



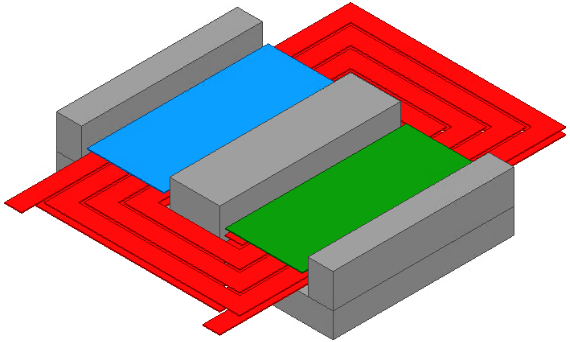

**Top View**



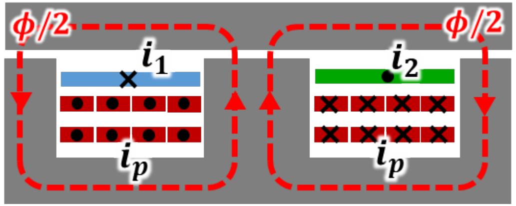
# Symmetry and Magnetic Core Enforce Equal Currents

**Assume symmetry**

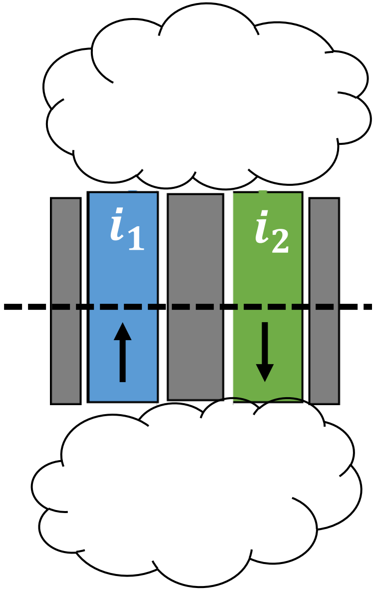
**Orthographic View**



**Side View**



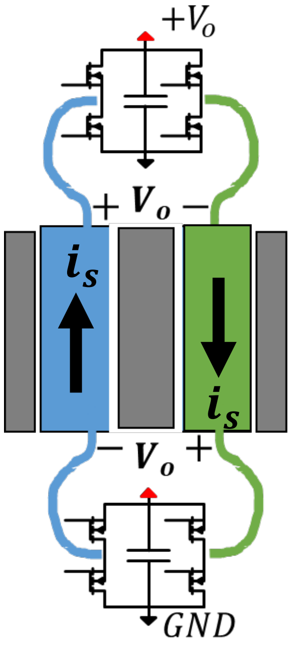

**Top View**

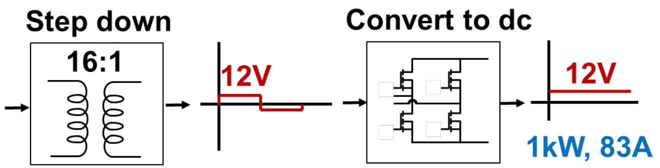



$$\oint H.dl = 8i_p - i_1 = 8i_p - i_2 \quad \Rightarrow \quad i_1 = i_2 \text{ by symmetry}$$

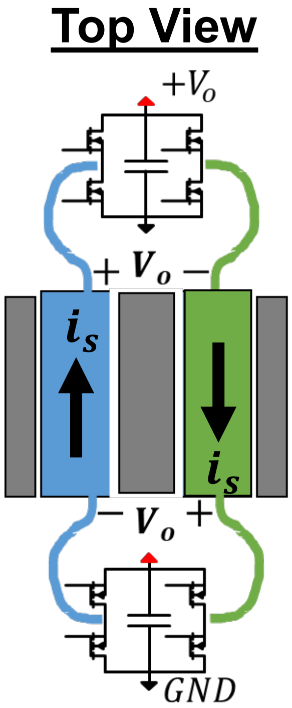
# Symmetrically Distribute Two Full Bridge Rectifiers Around the Core

**Top View**



# The Structure Behaves Like a Fractional Turn Transformer

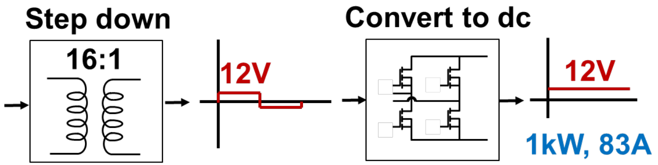



- Free to treat conductors as independent elements
- Connections yield:

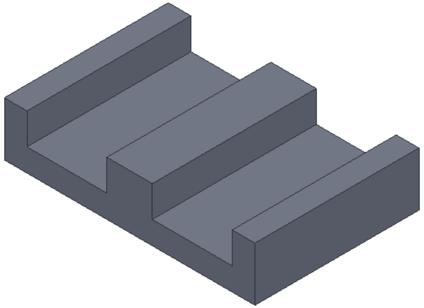
$$2V_o = \frac{V_p}{N_p}$$

$$\frac{V_o}{V_p} = \frac{1/2}{N_p}$$

A fractional turn transformer



## The CEMS Concept: A tighter integration of these elements



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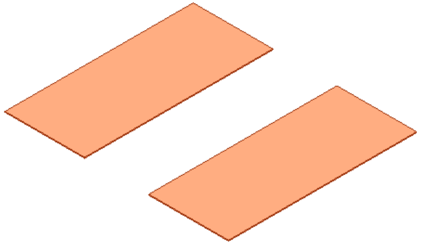


+

**Magnetic materials** **Conductors** **Electronics**

**Physical domain** **+** **Electrical domain**

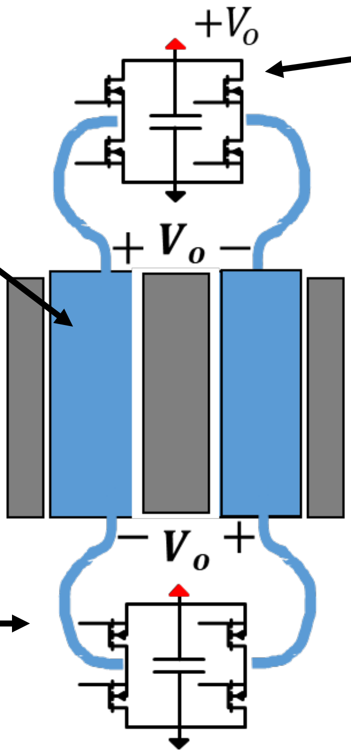
**View and design these as one coupled system**

**We call this a “Coupled Electronic and Magnetic System” (CEMS)**

# VIRT: An Example of a Coupled Electronic and Magnetic System

**Equivalence of induced currents is ensured by symmetry**

**Connecting electronics are physically distributed around the core**




**Electronics can be controlled to modify magnetic properties**

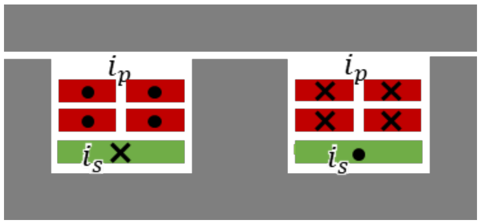
| | |
|---|---|
| **FB/FB:** | $N_p : \frac{1}{2}$ |
| **FB/HB:** | $N_p : \frac{2}{3}$ |
| **HB/HB:** | $N_p : 1$ |
| **HB/0:** | $N_p : 2$ |

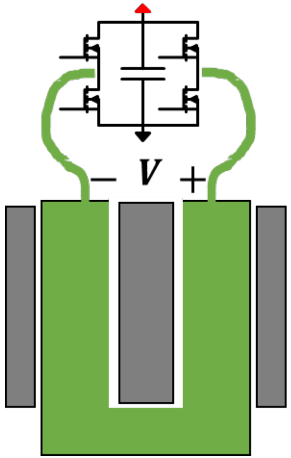
**Requires a different modeling framework**

M. K. Ranjram, I. Moon and D. J. Perreault, "Variable-Inverter-Rectifier-Transformer: A Hybrid Electronic and Magnetic Structure Enabling Adjustable High Step-Down Conversion Ratios," in *IEEE Transactions on Power Electronics*, vol. 33, no. 8, pp. 6509-6525, Aug. 2018, doi: 10.1109/TPEL.2018.2795959.

# How Turns Implementation Affects Losses

- **Copper loss** $\propto i^2 R \longrightarrow \propto N^2$
- **Core loss** $\propto \left(\frac{V}{N}\right)^{\beta} \longrightarrow \propto \left(\frac{1}{N}\right)^{3}$

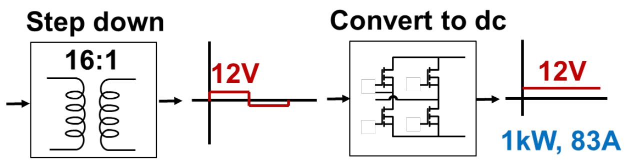


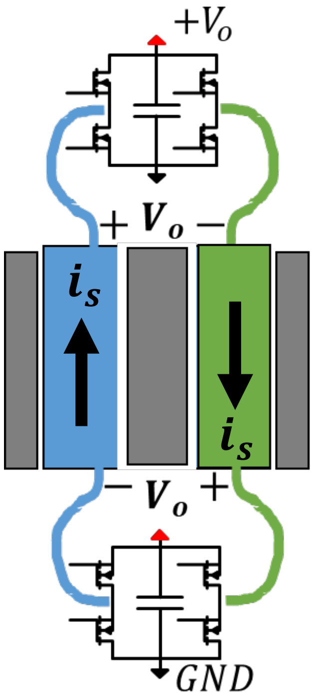

| Turns Implementation | Relative Cu loss | Relative Core Loss |
|---|---|---|
| 32:2 | 4 | 1/8 |
| 16:1 | 1 | 1 |

# How Turns Implementation Affects Losses

- **Copper loss** $\propto i^2 R \longrightarrow \propto N^2$
- **Core loss** $\propto \left(\frac{V}{N}\right)^{\beta} \longrightarrow \propto \left(\frac{1}{N}\right)^{3}$

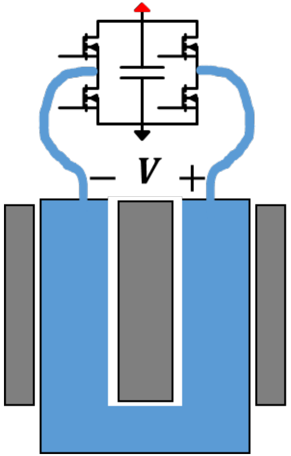


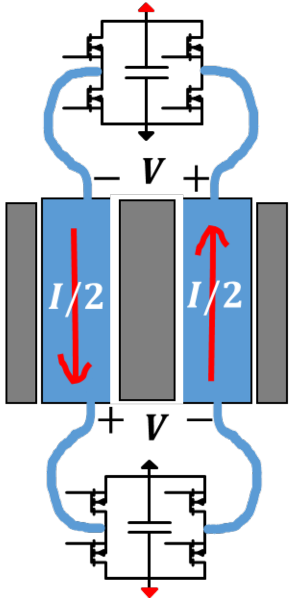

| Turns Implementation | Relative Cu loss | Relative Core Loss |
|---|---|---|
| 32:2 | 4 | 1/8 |
| 16:1 | 1 | 1 |
| 8:0.5 | ¼ | 8 |

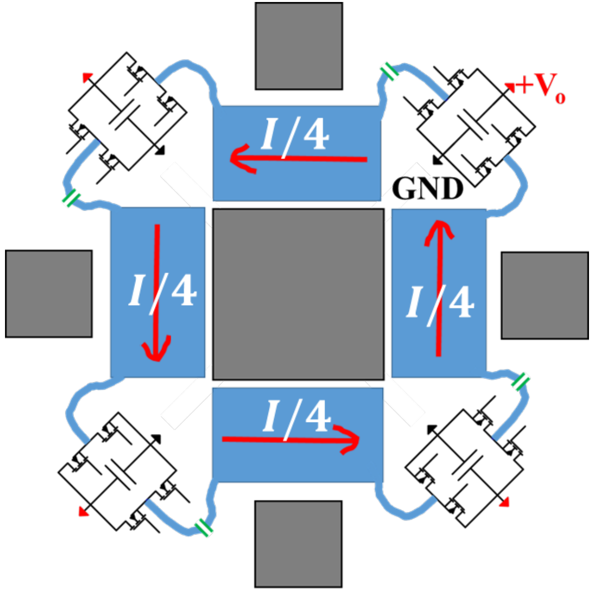



- **Follows the right trend**

# Correct Trade-off: Exponential Rebalancing



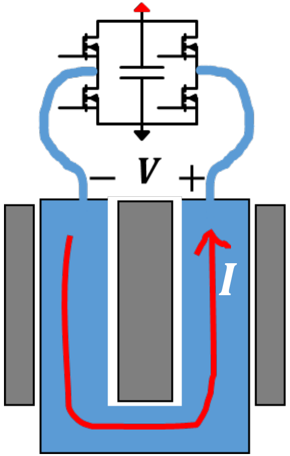



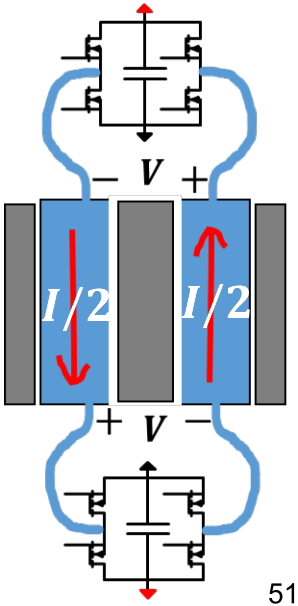

| | $2N_p:2$ | $N_p:1$ | Half-turn VIRT $N_p:0.5$ | Quarter-turn VIRT $N_p:0.25$ |
|---|---|---|---|---|
| $P_{cu}$ | 4 | 1 | ~1/4 | ~1/16 |
| $P_{core}$ | $2^{-\beta}$ | 1 | $\sim 2^{\beta}$ | $\sim 2^{2\beta}$ |

# What about the Transistors?

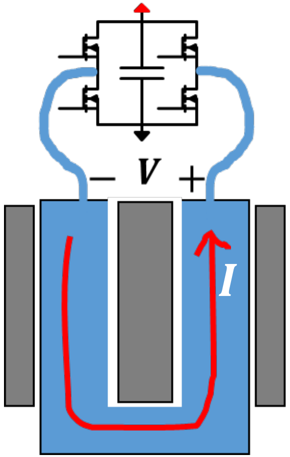
- Twice as many switches, but each carries half the current for the same output power and voltage
- For same transistor area, identical transistor loss
- An advantage at high output currents, easier terminations without direct parallelization.



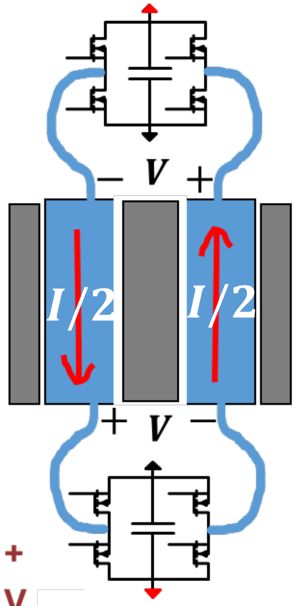

| Mode | NON-VIRT | VIRT |
|---|---|---|
| FB-FB | $P_{cond} = 2\frac{R_{on}}{2} I_o^2 = R_{on}I_o^2$ | $P_{cond} = 4R_{on}\left(\frac{I_o}{2}\right)^2 = R_{on}I_o^2$ |
| HB-HB | $P_{cond} = 2\frac{R_{on}}{2} I_o^2 = R_{on}I_o^2$ | $P_{cond} = 4R_{on}\left(\frac{I_o}{2}\right)^2 = R_{on}I_o^2$ |

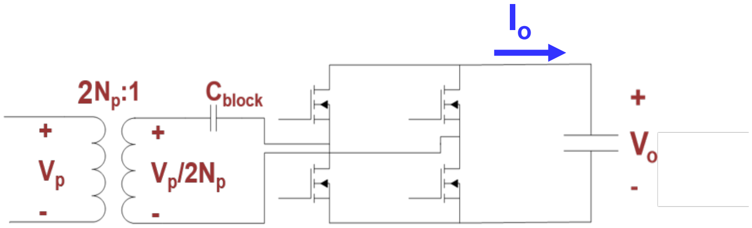


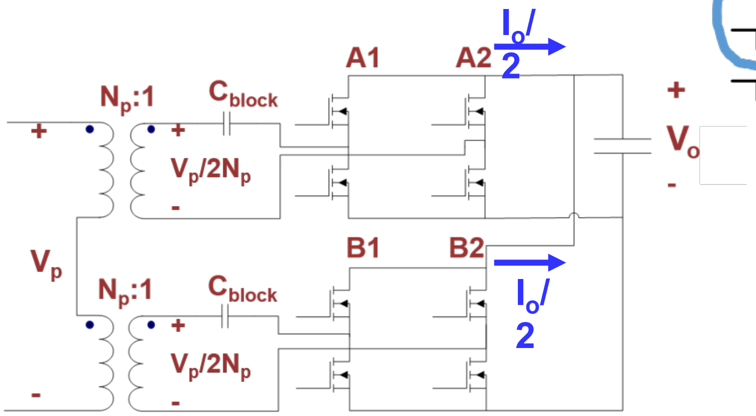
# What about the Transistors?



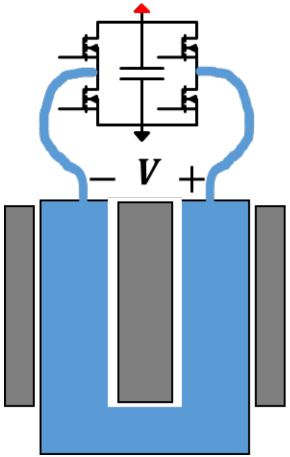

| Mode | NON-VIRT | VIRT |
|---|---|---|
| FB-FB | $P_{cond} = 2\frac{R_{on}}{2} I_o^2 = R_{on} I_o^2$ | $P_{cond} = 4R_{on}\left(\frac{I_o}{2}\right)^2 = R_{on} I_o^2$ |
| HB-HB | $P_{cond} = 2\frac{R_{on}}{2} I_o^2 = R_{on} I_o^2$ | $P_{cond} = 4R_{on}\left(\frac{I_o}{2}\right)^2 = R_{on} I_o^2$ |



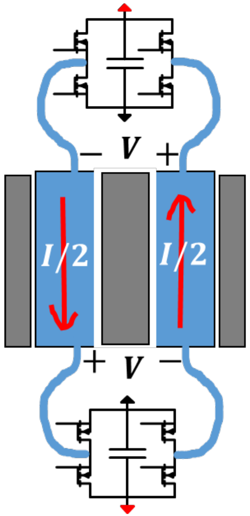
# Variability Comparison




FB: $N_p : 1$

HB: $N_p : 2$

## Half-turn VIRT



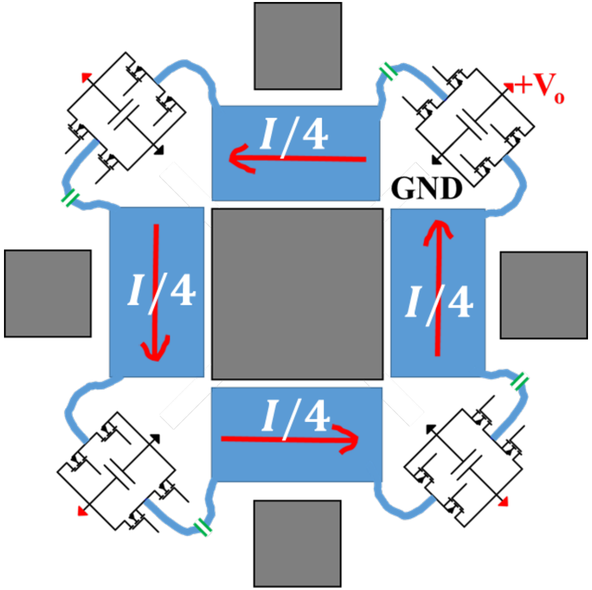

FB/FB: $N_p : \frac{1}{2}$

FB/HB: $N_p : \frac{2}{3}$

HB/HB: $N_p : 1$

HB/0: $N_p : 2$

## Quarter-turn VIRT




**8 possibilities,**

$N_p : \frac{1}{4}, \frac{2}{7}, \frac{1}{3}, \frac{2}{5}, \frac{1}{2}, \frac{2}{3}, 1, 2$

# Two Key VIRT Features

## Variable Inverter/Rectifier Transformer

- Variability for:
  - Accommodating wide voltage variations

# Two Key VIRT Features

## Variable Inverter/Rectifier Transformer

- **Variability for:**
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- **Fractional turns for:**
  - **High current carrying capability**
  - **Reducing the number of primary turns in high step-down transformers (adv. for planar magnetics)**

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  - Reducing the number of primary turns in high step-down transformers (adv. for planar magnetics)

**We used these properties for high efficiency wide voltage range chargers**

M. K. Ranjram, I. Moon, and D. J. Perreault, "Variable-Inverter-Rectifier-Transformer: A Hybrid Electronic and Magnetic Structure Enabling Adjustable High Step-Down Conversion Ratios," *IEEE Transactions on Power Electronics*, vol. 33, no. 8, pp. 6509–6525, Aug. 2018, doi: 10.1109/TPEL.2018.2795959.

M. K. Ranjram, C. Zhang, and D. J. Perreault, "A Two-Stage Universal Input Charger With Wide Output Voltage Range," *IEEE Open Journal of Power Electronics*, vol. 1, pp. 88–102, 2020, doi: 10.1109/OJPEL.2020.2983382.

# Two Key VIRT Features

## Variable Inverter/Rectifier Transformer

- Variability for:
  - Accommodating wide voltage variations
- Fractional turns for:
  - High current carrying capability
  - Reducing the number of primary turns in high step-down transformers (adv. for planar magnetics)

**This feature is more widely applicable, and is what we'll focus on**

# What About Winding Techniques?

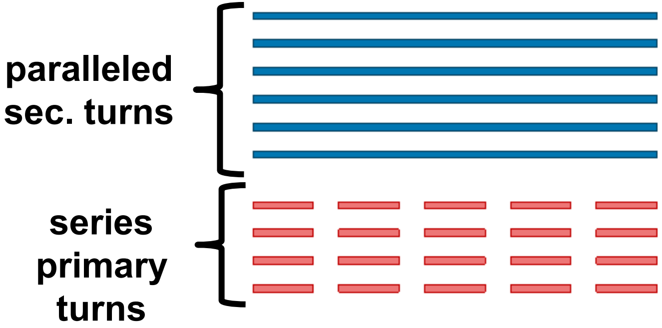
- Today’s active areas of research
  - High frequency switching (MHz+)
  - New magnetic materials
  - Planar magnetics
  - Novel winding techniques

- The magnetic component’s ability to carry current is strongly dependent on how it’s wound, especially at high frequencies.

# Copper Loss Reduction by Paralleled Windings

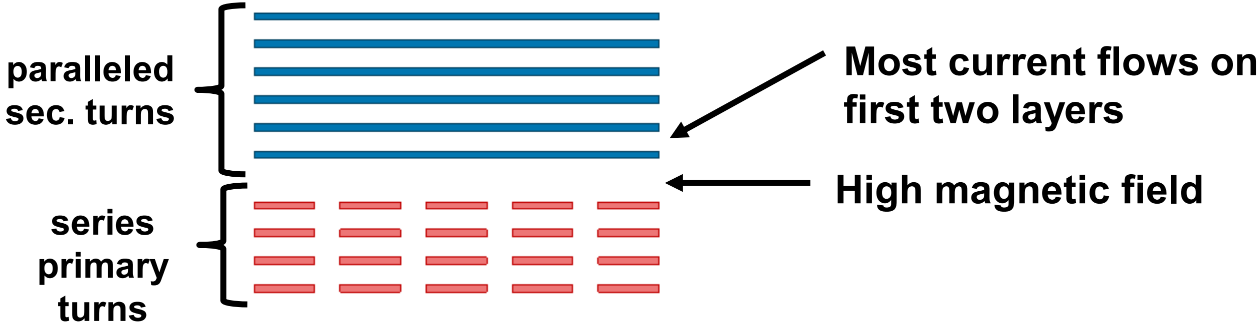
- A common method for improving current-handling is to employ parallelization

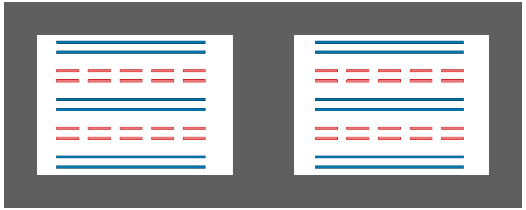
- Planar magnetics make it simple to control winding stack-up



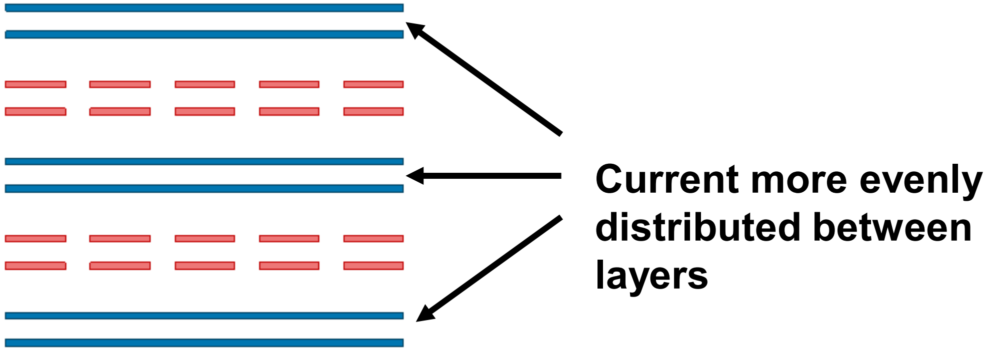
# Copper Loss Reduction by Parallelizing Windings With Interleaving

## Non-interleaved

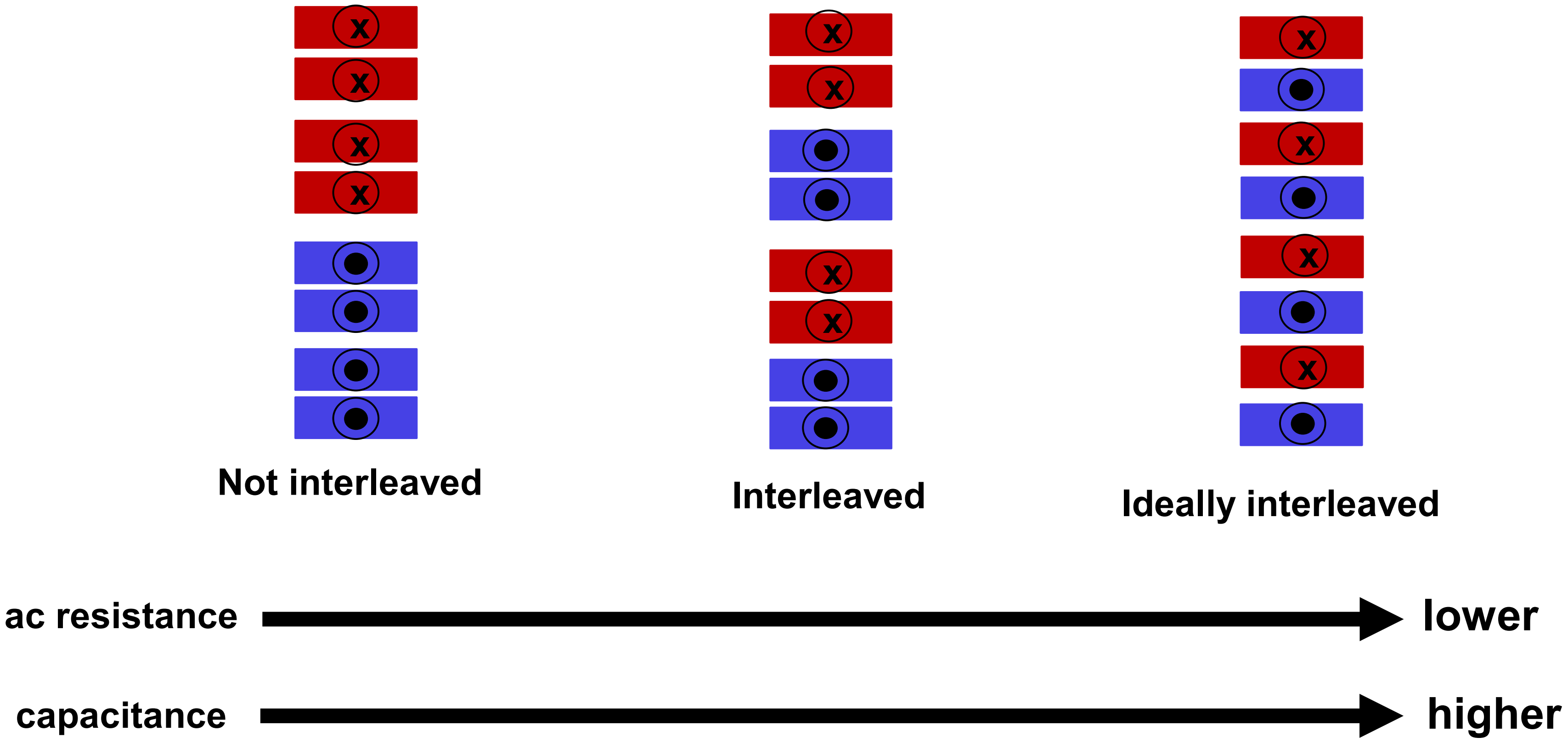


## Interleaved



# Resistance vs. Capacitance Trade-off of Interleaving



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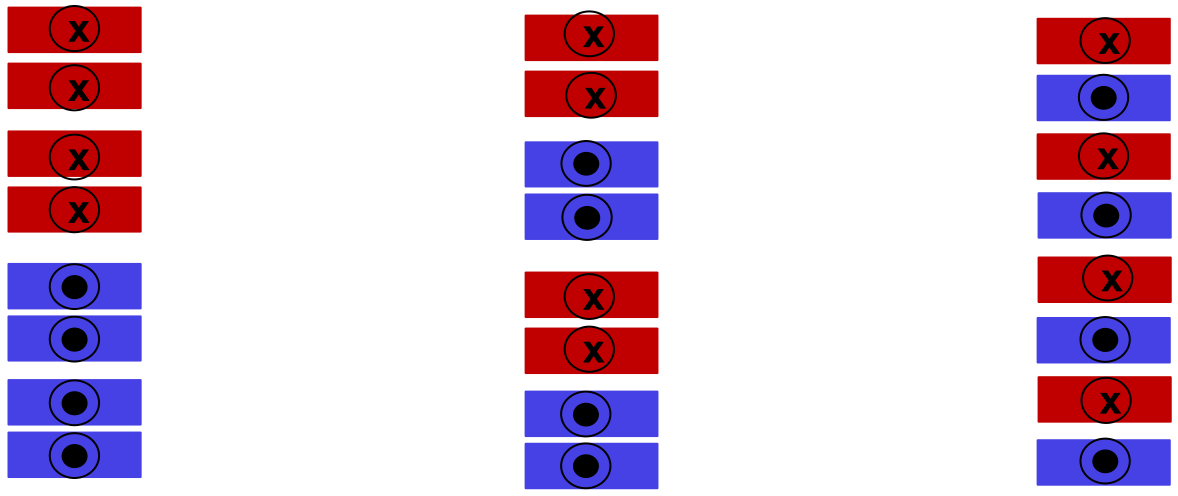


Not interleaved | Interleaved | Ideally interleaved

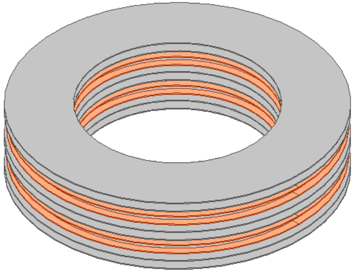
ac resistance $\longrightarrow$ lower

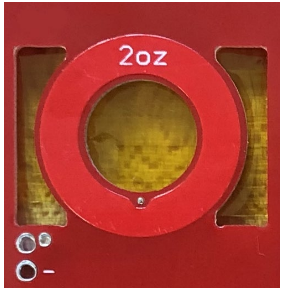
capacitance $\longrightarrow$ higher

termination loss $\longrightarrow$ Much higher

# With Realistic Terminations, Loss is 2.5x Higher Than Expected

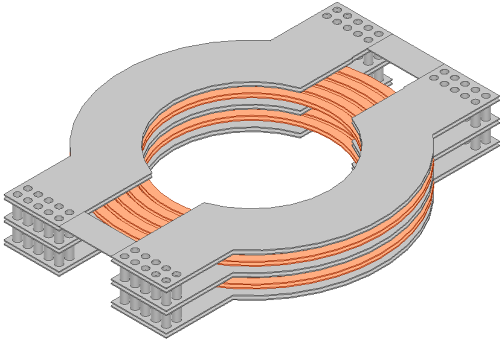
**Ideal, perfectly terminated**

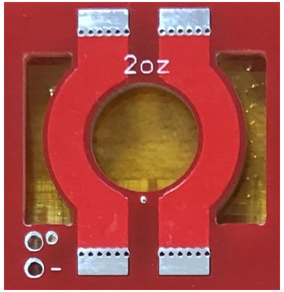





**0.29Ω**

**Practically terminated**






**0.73Ω**

M. K. Ranjram, P. Acosta, and D. J. Perreault, "Design Considerations for Planar Magnetic Terminations," in *2019 20th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Jun. 2019, pp. 1–8. doi: 10.1109/COMPEL.2019.8769642.

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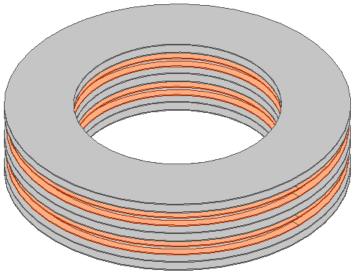

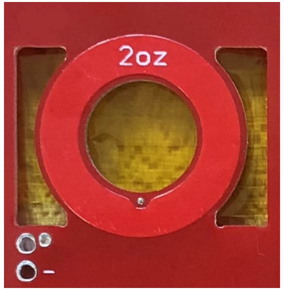


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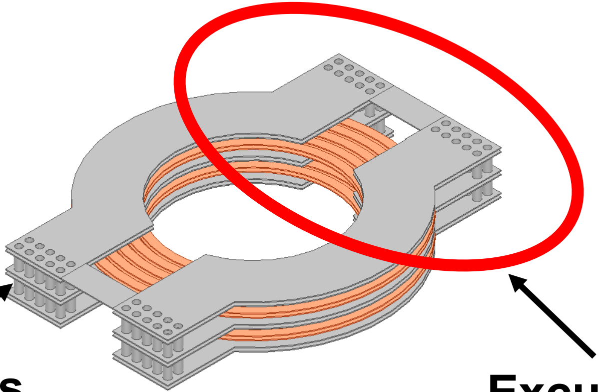
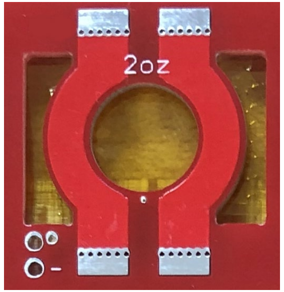


**Via losses**

**Excursion penalties**



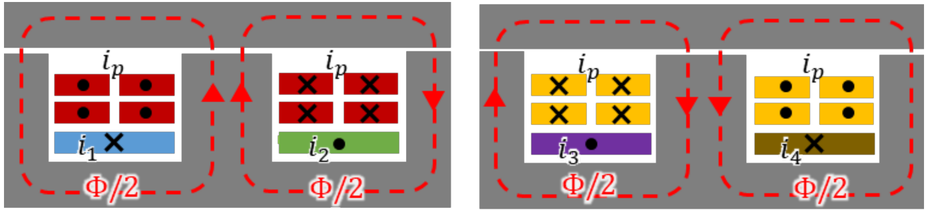

**0.73Ω**

# High Current Planar Magnetics

- **If we want to carry high current in a planar magnetic, complex vertical stack-ups are problematic**

# High Current Planar Magnetics

- If we want to carry high current in a planar magnetic, complex vertical stack-ups are problematic
- A better choice: transformer parallelization



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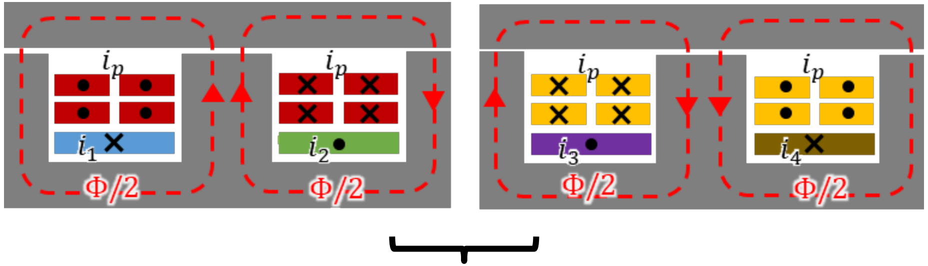
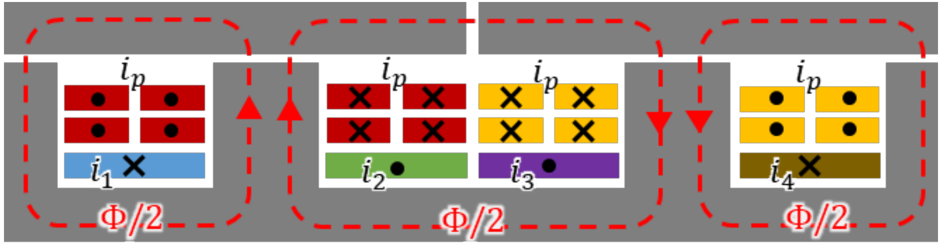



Wound such that equal and opposite flux flows on outer legs

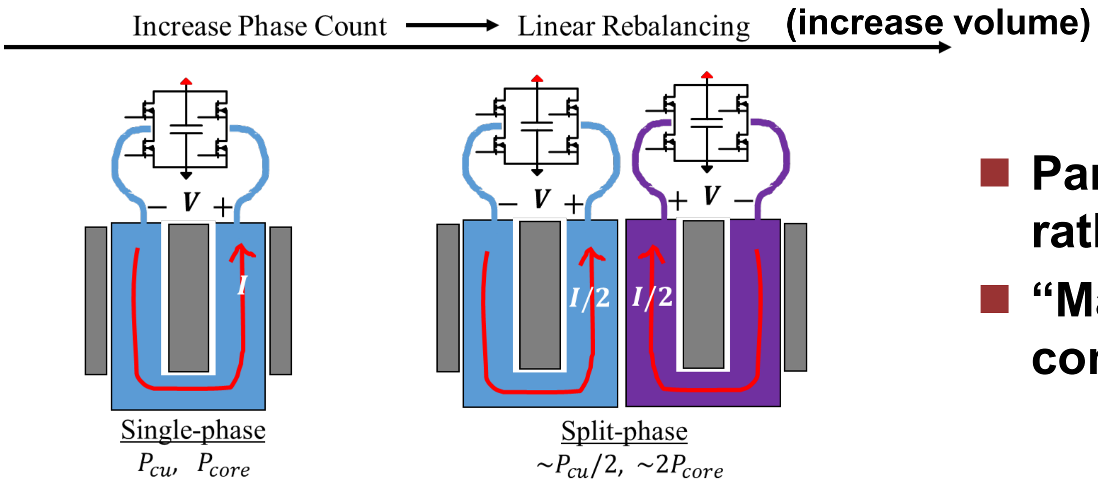
Combine



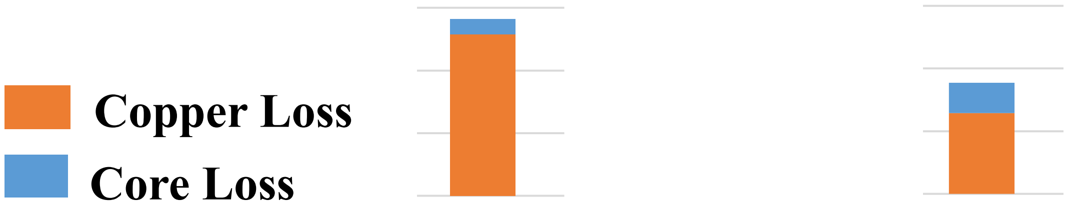

Combine cores for volume reduction

# High Current Planar Magnetics

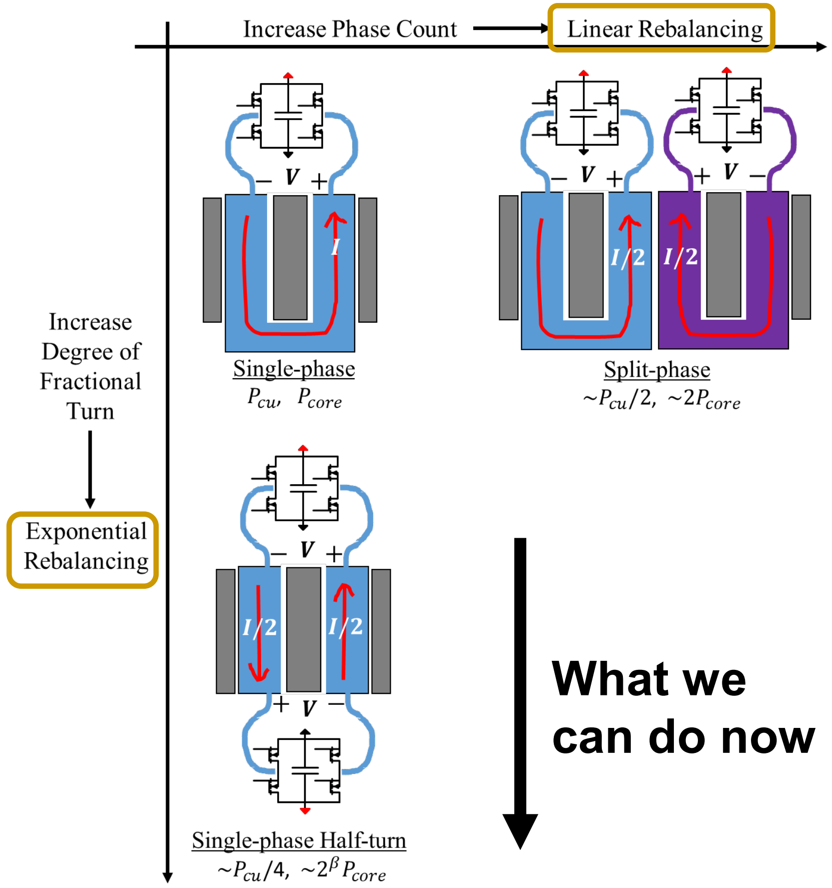
- If we want to carry high current in a planar magnetic, complex vertical stack-ups are problematic
- A better choice:




- Parallel "horizontally" rather than "vertically"
- "Matrix transformer" concept applies here



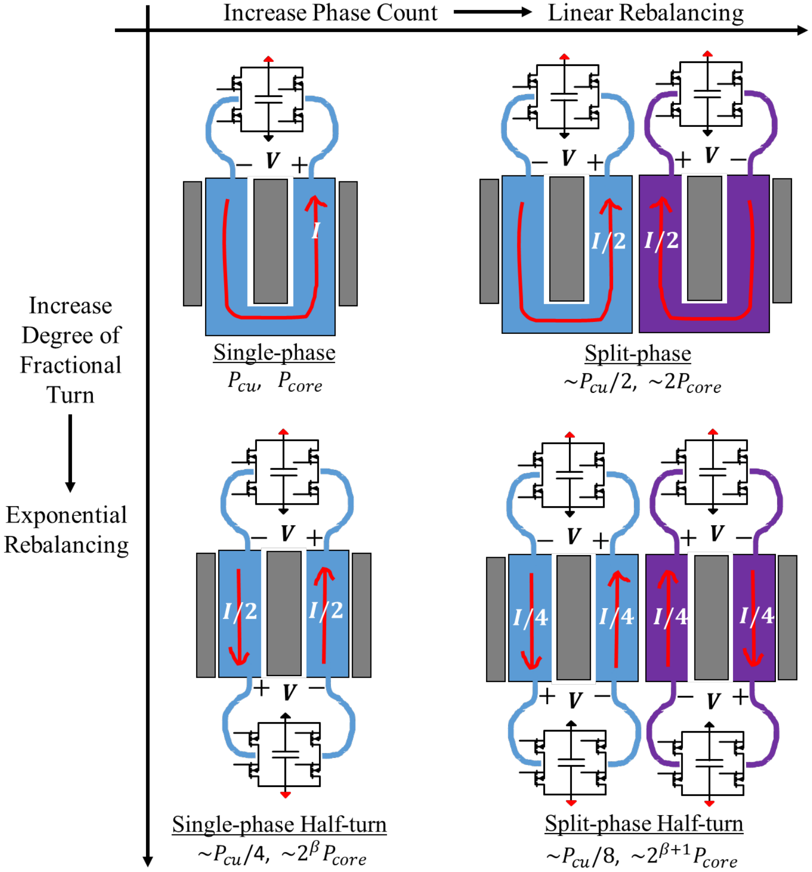
# These Techniques Offer Distinct Loss Trade-offs




**What we've been doing**

**What we can do now**

# “Gear Shifting” Transformer Core and Copper Loss





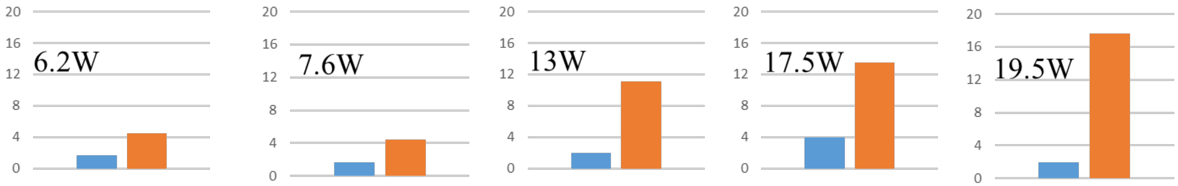
**SPHTV**

M. K. Ranjram and D. J. Perreault, "Leveraging Multi-Phase and Fractional-Turn Integrated Planar Transformers for Miniaturization in Data Center Applications," *2020 IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL)*, Aalborg, Denmark, 2020, pp. 1-8, doi: 10.1109/COMPEL49091.2020.9265752.

# Transformer loss "Gear Shifting" Is Beneficial

Split-VIRT | Single-VIRT | Split | Three | Single

12V/1kW




***Estimated Losses**

**Using iGSE and Dowell's equation**

**Core loss**

**Copper loss**


K. Venkatachalam, C. R. Sullivan, T. Abdallah, and H. Tacca, "Accurate prediction of ferrite core loss with nonsinusoidal waveforms using only Steinmetz parameters," in *Proc. IEEE Workshop Comput. Power Electron,*2002, pp. 36–41

P. L. Dowell, "Effects of eddy currents in transformer windings," in *Proc. Inst. Elect. Engineers*, vol. 113, no. 8, pp. 1387–1394, 1966

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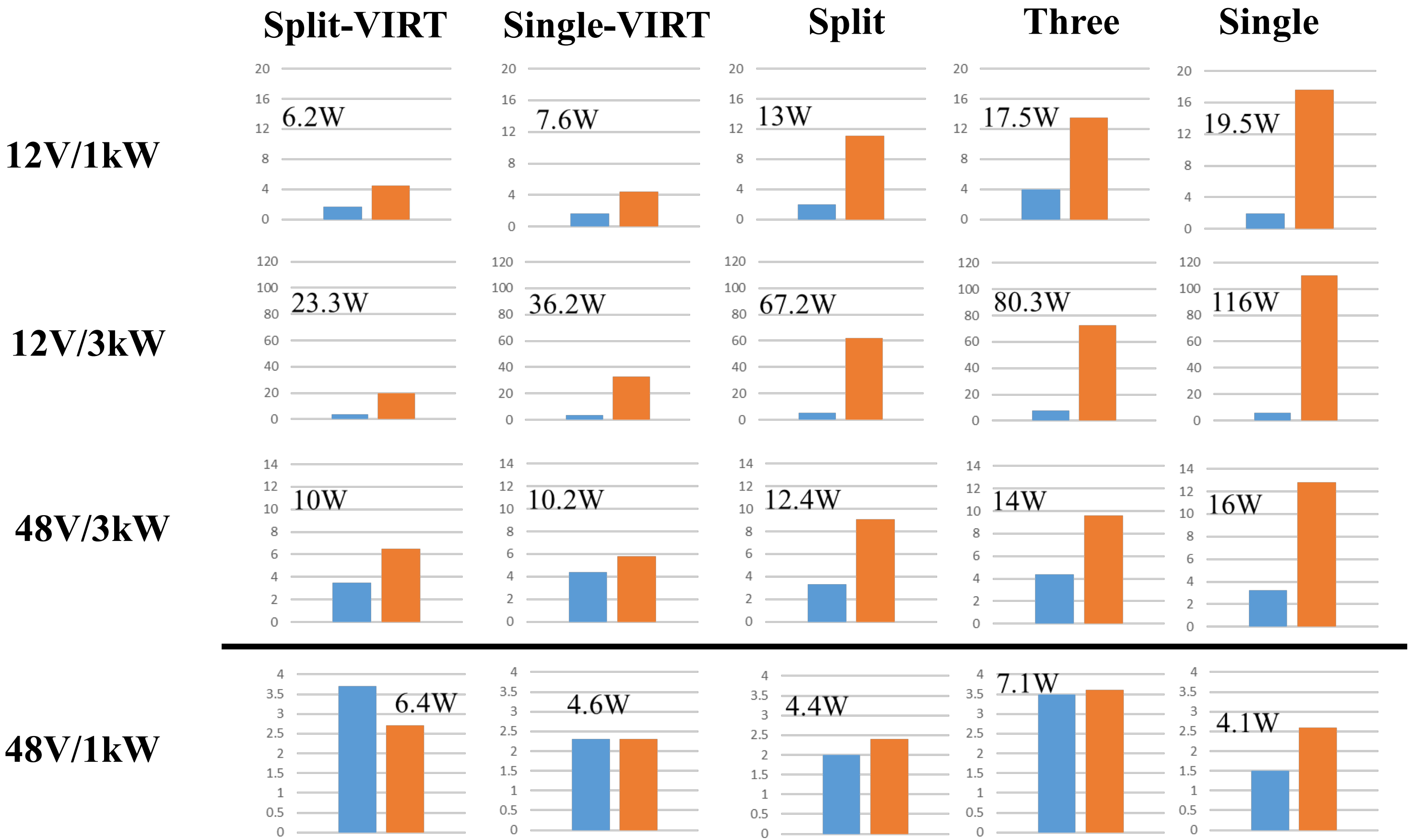


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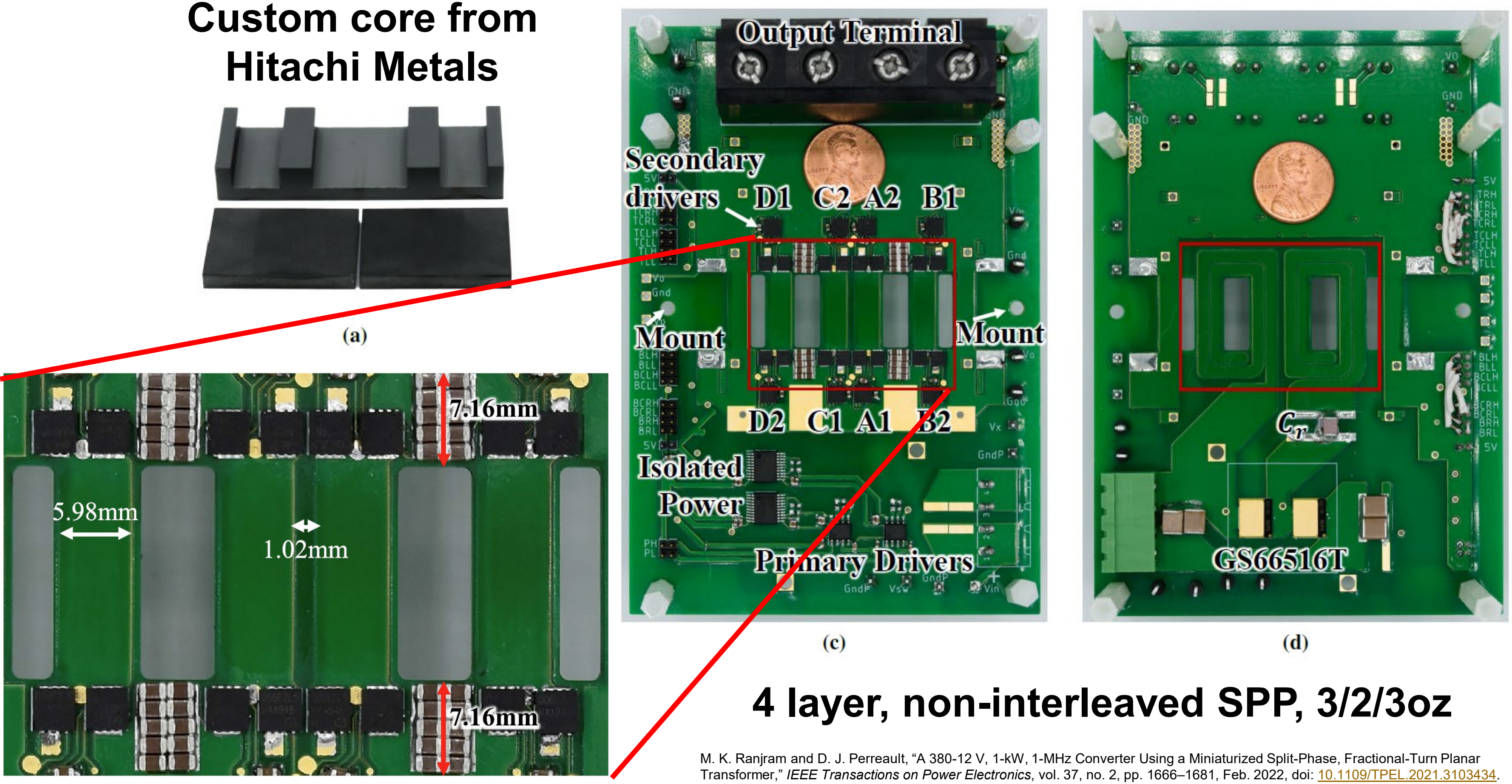
# SPHTV Prototype

## Custom core from Hitachi Metals




## 4 layer, non-interleaved SPP, 3/2/3oz


M. K. Ranjram and D. J. Perreault, "A 380-12 V, 1-kW, 1-MHz Converter Using a Miniaturized Split-Phase, Fractional-Turn Planar Transformer," *IEEE Transactions on Power Electronics*, vol. 37, no. 2, pp. 1666–1681, Feb. 2022, doi: 10.1109/TPEL.2021.3103434.

# Losses and Thermal Performance Well Predicted

## Losses fit expectation

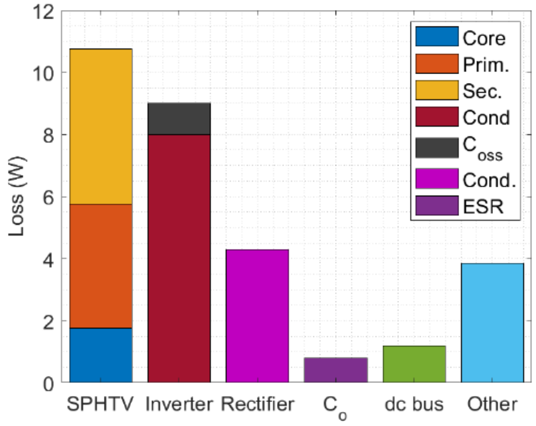



**Fig. 12:** Estimated loss breakdown at full load, not including hotel power (2.7W) and fan power (1.44W).

## Thermal performance

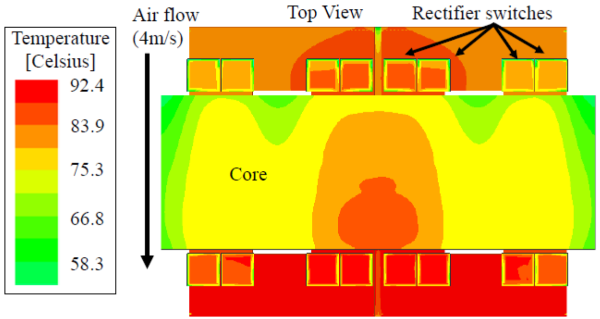



**Fig. 7:** ANSYS Icepak thermal simulation of the transformer.

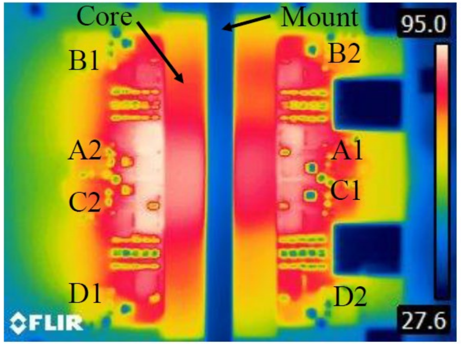
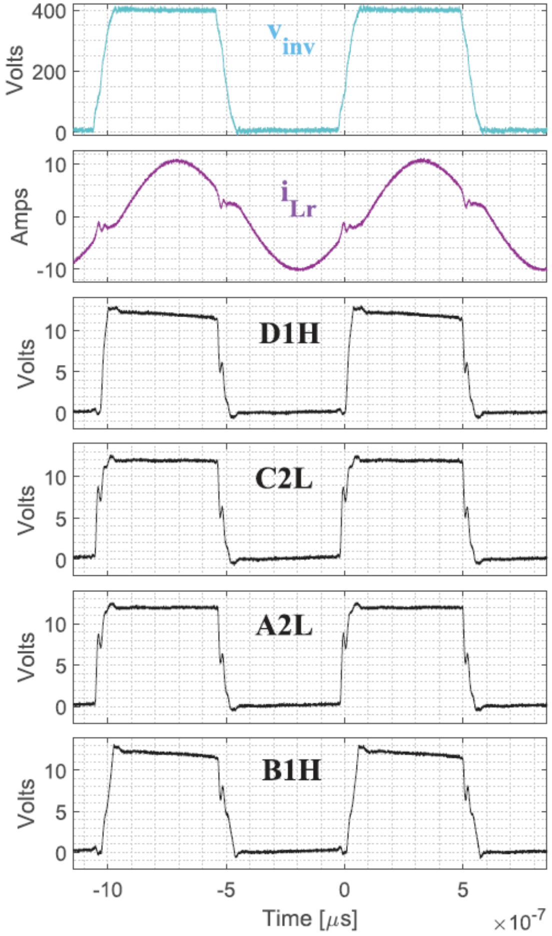



**Fig. 11:** Thermal image of secondary-side under full-load (obtained after 15 minutes of continuous operation, 22°C room temperature). The fan is located to the right of the PCB.

# Example Operating Waveforms



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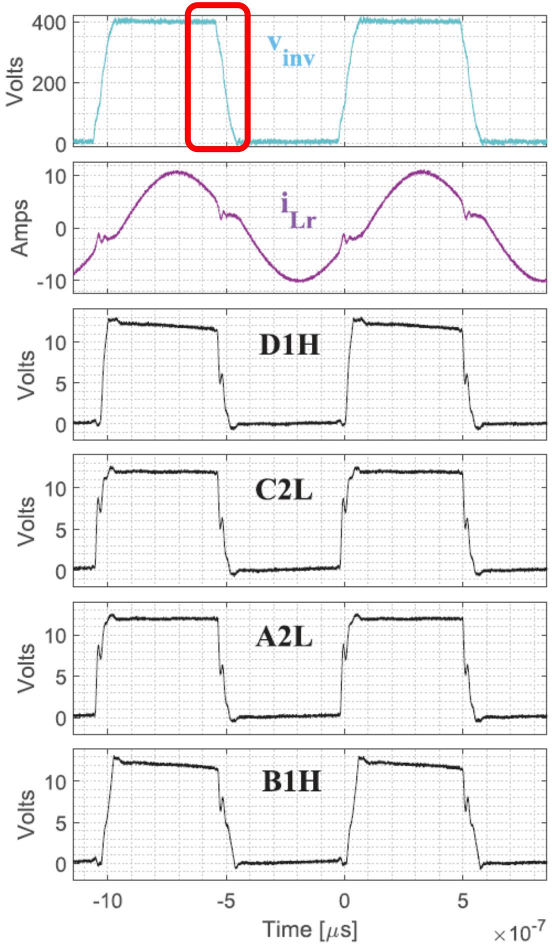
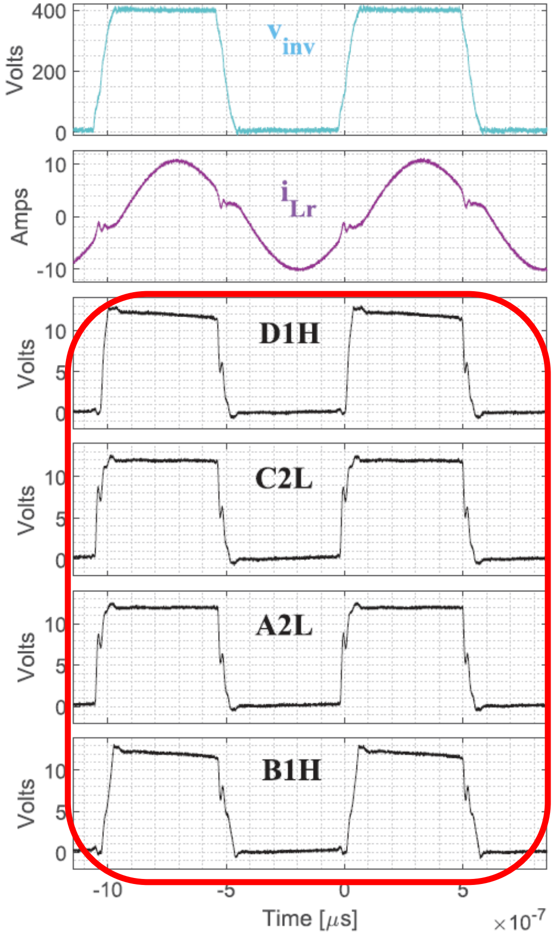


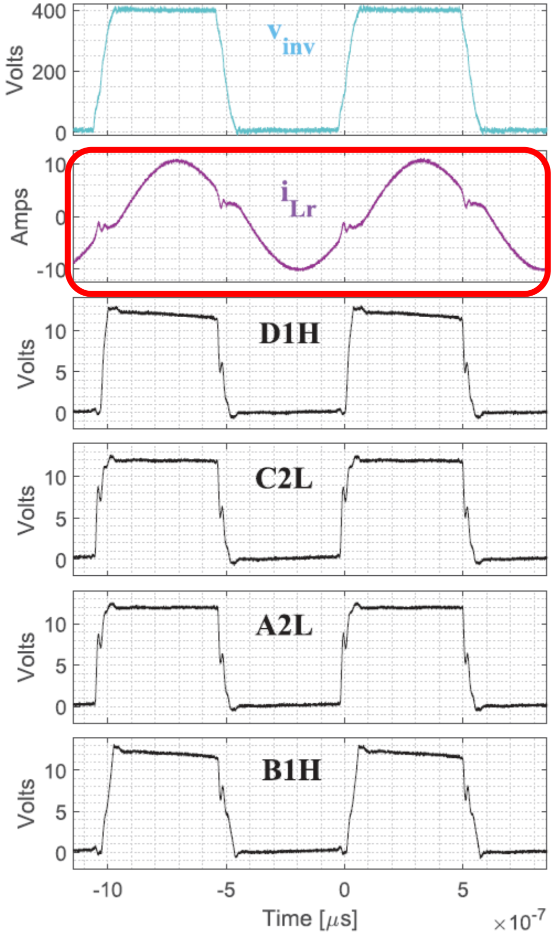

- Inverter ZVS achieved

# Example Operating Waveforms



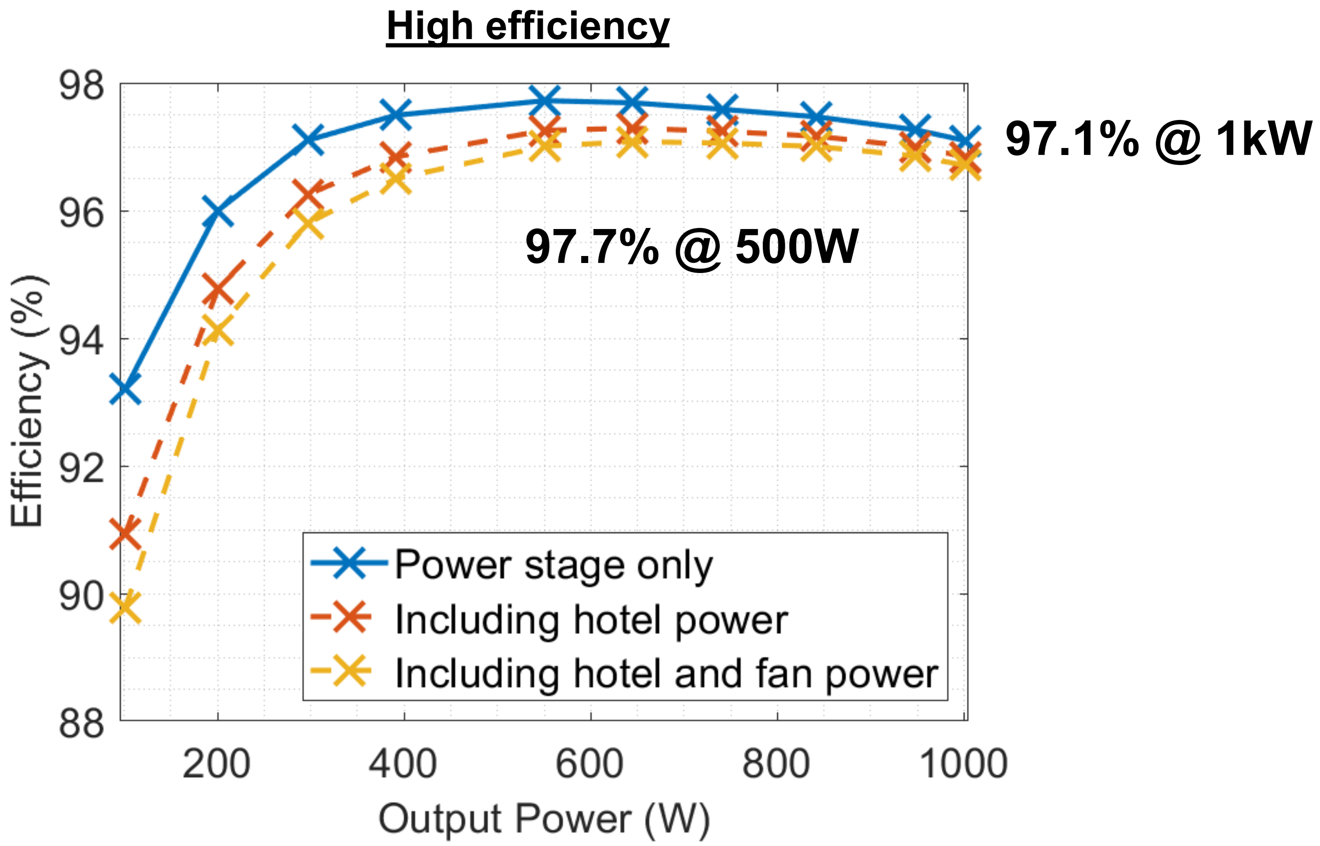

- Inverter ZVS achieved
- All half-bridges are operated identically, experience slightly different deadtime transitions owing to local decoupling loops

# Example Operating Waveforms

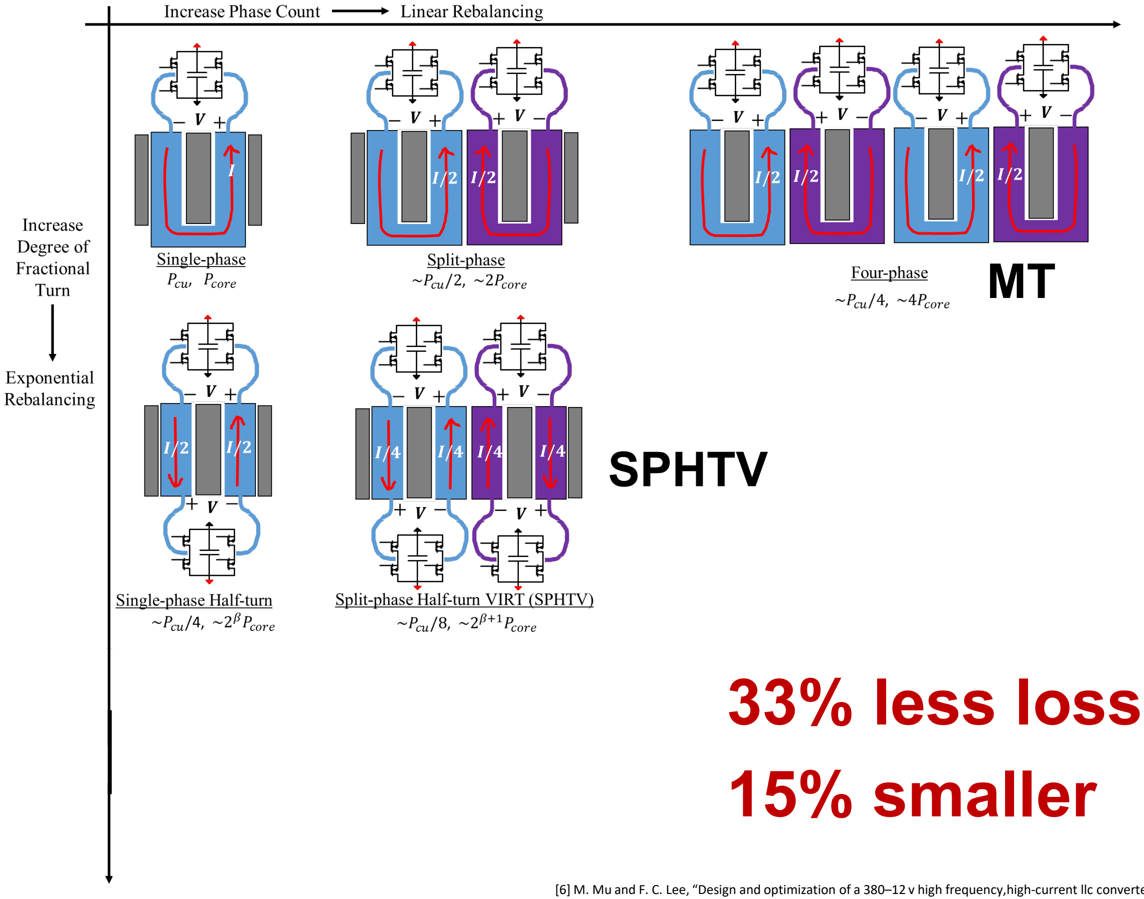



- Inverter ZVS achieved
- All half-bridges are operated identically, experience slightly different deadtime transitions owing to local decoupling loops
- Near-resonant current in primary tank

# Prototype is Extremely Efficient



# SPHTV: Much Lower Loss and Much Smaller than Best Alternatives




## 380-12V, 1kW

| | This work | MT [6] |
|---|---|---|
| Stack-up | S/_/P/P | S/P/P/S |
| Peak power stage efficiency | 97.7% | - |
| Peak efficiency including hotel power | 97.3% | 97.1% |
| Full load loss (power stage only) [W] | 29.9 | 34.4 |
| Transformer loss at full load [W] | 10.8 | 16.3 |
| Transformer footprint [$mm^2$] | 1536 | 2200 |
| Height [mm] | 9.23 | 7.3 |
| Transformer box volume [$cm^3$] | 14.2 | 16.1 |

[a] 'G' is a secondary layer tied directly to secondary ground

## 33% less loss

## 15% smaller


[6] M. Mu and F. C. Lee, "Design and optimization of a 380–12 v high frequency,high-current llc converter with gan devices and planar matrix transformers," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 3, pp. 854–862, 2016.

[11] Y. Liu, K. Chen, C. Chen, Y. Syu, G. Lin, K. A. Kim, and H. Chiu,"Quarter-turn transformer design and optimization for high power density 1-mhz llc resonant converter," IEEE Transactions on Industrial Electronics, vol. 67, no. 2, pp. 1580–1591, 2020.

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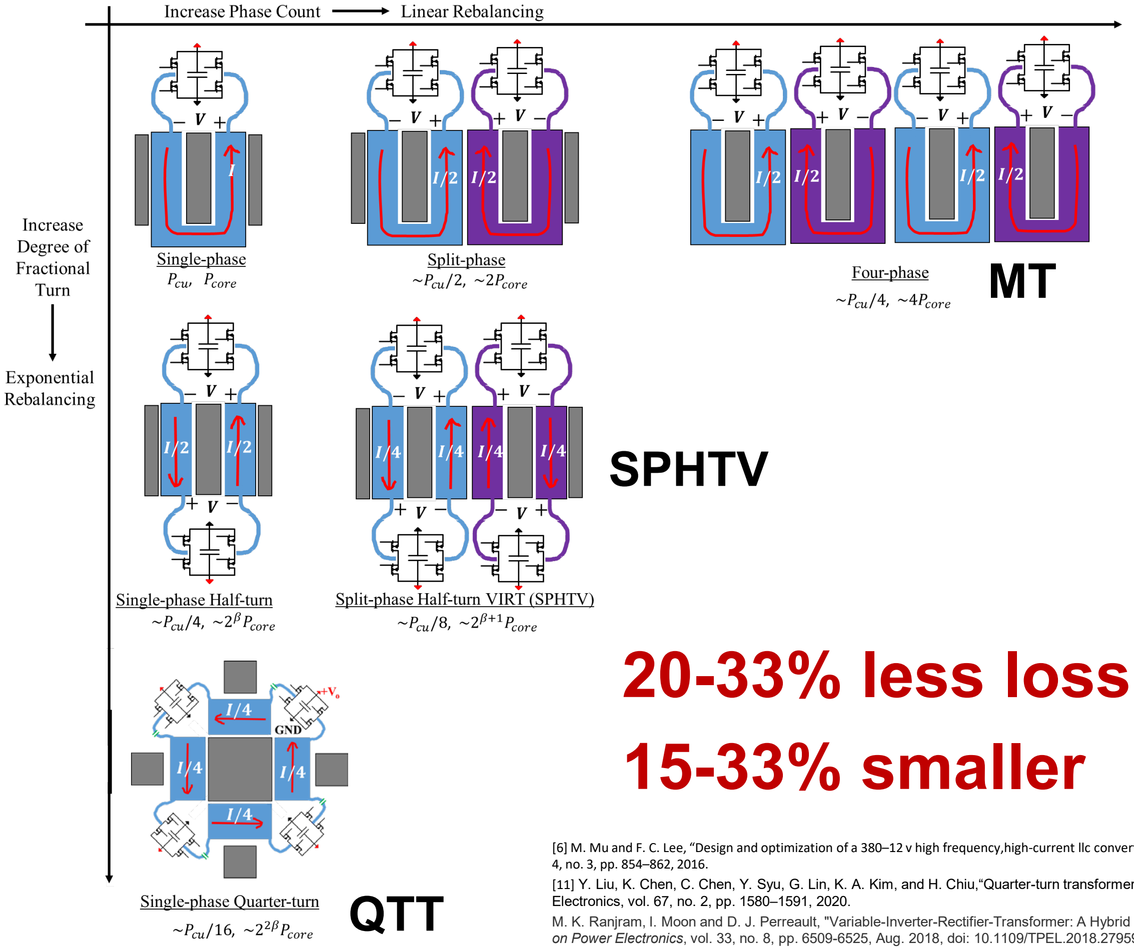


## 380-12V, 1kW

| | This work | MT [6] | QTT [11] |
|---|---|---|---|
| **Stack-up** | S/_/P/P | S/P/P/S | S/G/P/P/G/S[a] |
| **Peak power stage efficiency** | 97.7% | - | 97.0% |
| **Peak efficiency including hotel power** | 97.3% | 97.1% | - |
| **Full load loss (power stage only) [W]** | 29.9 | 34.4 | 41 |
| **Transformer loss at full load [W]** | 10.8 | 16.3 | 13.2 |
| **Transformer footprint [mm$^2$]** | 1536 | 2200 | 2500 |
| **Height [mm]** | 9.23 | 7.3 | 8.9 |
| **Transformer box volume [cm$^3$]** | 14.2 | 16.1 | 22.3 |

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## 20-33% less loss

## 15-33% smaller


[6] M. Mu and F. C. Lee, "Design and optimization of a 380–12 v high frequency,high-current llc converter with gan devices and planar matrix transformers," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 3, pp. 854–862, 2016.

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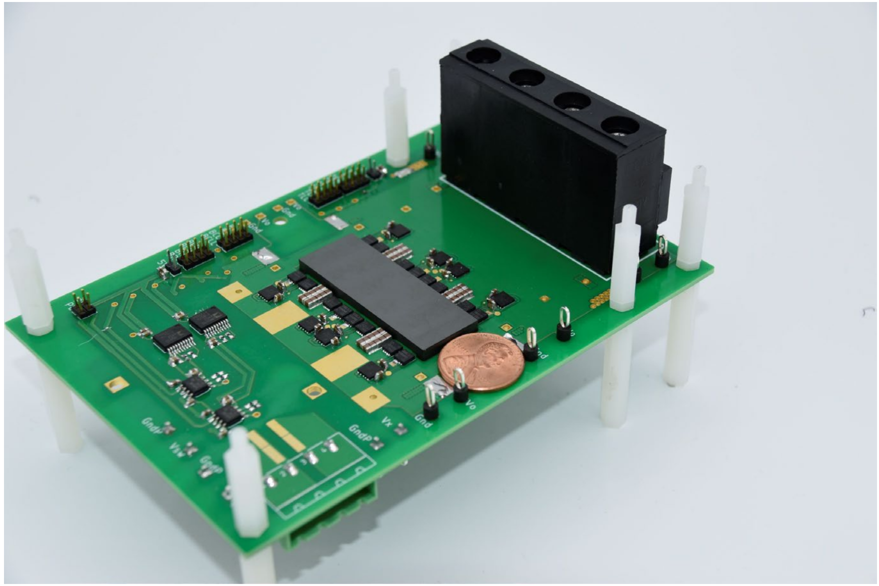
# Summary of the Half-Turn VIRT

- Coupled Electronic and Magnetic System (CEMS) paradigm enables the VIRT concept
- Fractional and variable turns ratios unachievable in conventional design
- Used to build much smaller and much more efficient datacenter supply



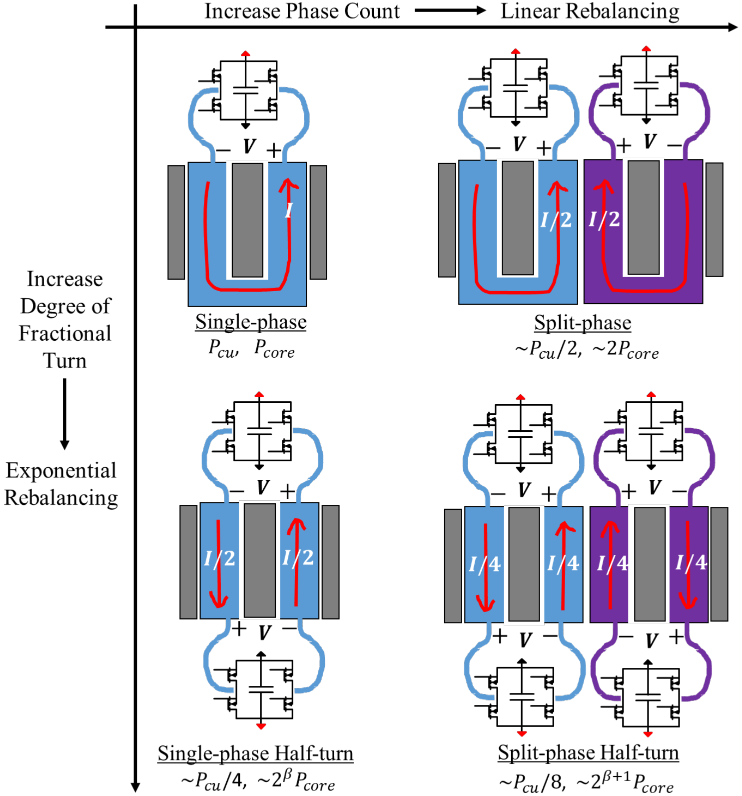
# The Roadmap for CEMS

Coupled Electronic and Magnetic Systems Paradigm

Variable and Fractional Turn Transformers

New CEMS to Eliminate Passive Bottleneck

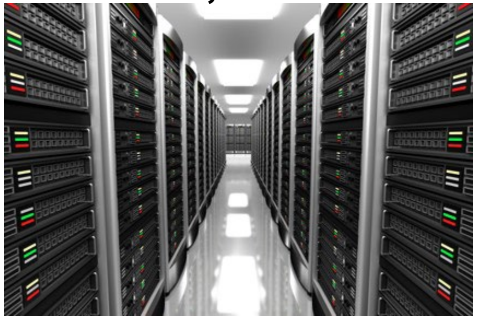
# Future Applications for Variable + Fractional Turn Transformers




200-500V to 10-15V

1-5kW

48V, 3kW+

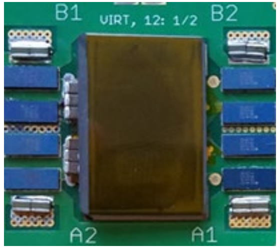


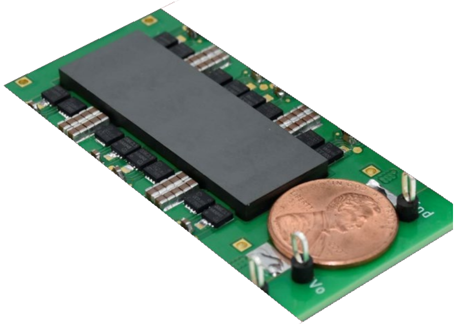
48V to 1V, 0.5-1kW

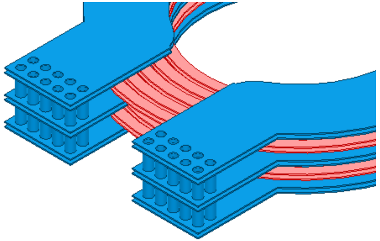
# Miniaturized and Advanced Power Electronics Laboratory

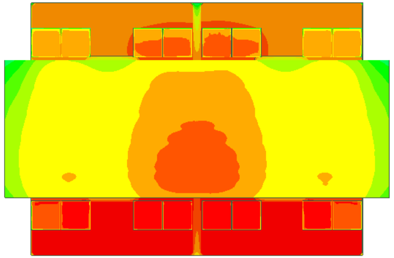
Advance the size, efficiency, and capability of power electronics

| Coupled Electronic and Magnetic Systems Paradigm | | Designing at the Limits of Miniaturization | | Leverage cutting-edge materials and devices | |
|---|---|---|---|---|---|
| Variable and Fractional Turn Transformers | New CEMS to Eliminate Passive Bottleneck | Address bottleneck of parasitic connections | Optimal loss distributions | Push to higher switching frequencies | Develop architectures to maximize their benefits |



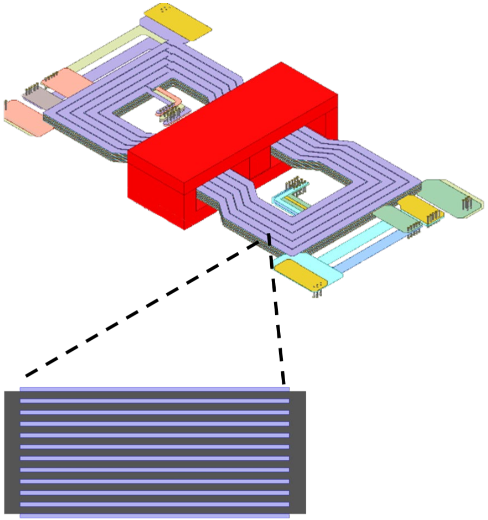



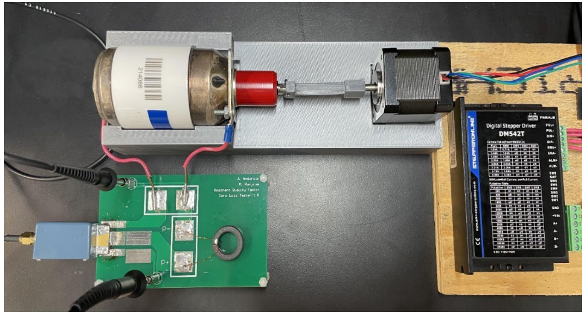


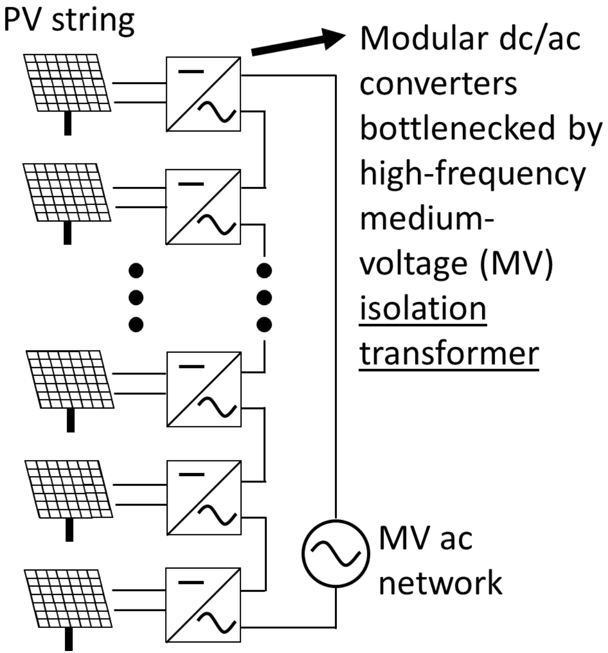


# Planar Magnetics for Renewable Energy Systems

- Improved cost modeling
- Study insulation properties
- Designing to minimize detriment of poor fill factor
- Better assessments of magnetic core loss










S. Mukherjee *et al.*, “A High-Frequency Planar Transformer with Medium-Voltage Isolation,” in *2021 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Phoenix, AZ, USA, Jun. 2021, pp. 2065–2070. doi: 10.1109/APEC42165.2021.9487061

# Leveraging Saturation w/ Modern Materials

Leveraging **low permeability, high frequency** materials as "magnetic amplifiers" to create a dummy load system for plasmas.

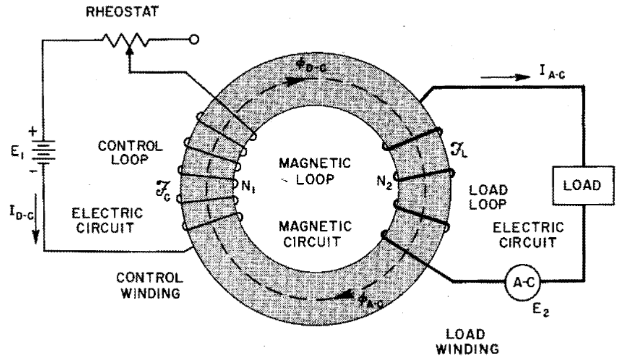
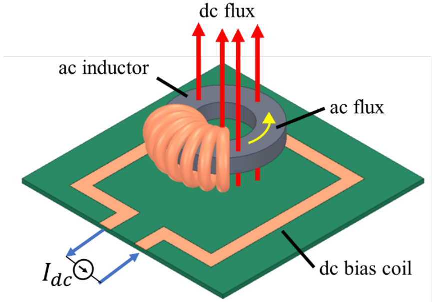
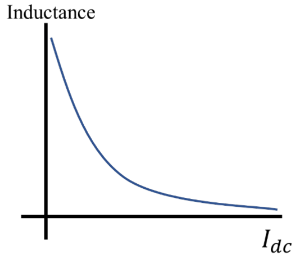



Fig. 30. Simple saturable reactor.



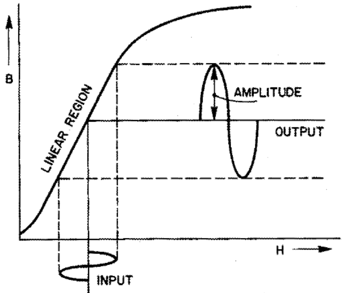




Fig. 35. Amplification in a simple saturable reactor.

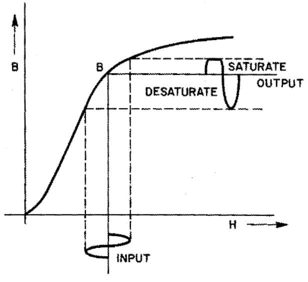


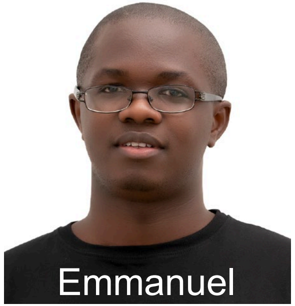

Fig. 33. Distorted output waveform.

Paul Mali, "Magnetic Amplifiers: Principles and Applications", John F. Rider Publisher, Inc., New York, 1960

# Miniaturized and Advanced Power Electronics Laboratory

- Magnetics bottleneck the efficiency, size, and weight of many power electronic converters
- Our group (MAPEL@ASU) works to miniaturize power converters by:
  - Novel circuit architectures centered on the magnetics
  - High-frequency operation of power converters
  - Maximizing the capability of planar magnetic constructions
  - Improving core loss measurement techniques


Sakib
Ahmed


Emmanuel
Havugimana


Darshan
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Anderson