Variable Inverter/Rectifier Transformers and other Coupled Electronic and Magnetic Systems

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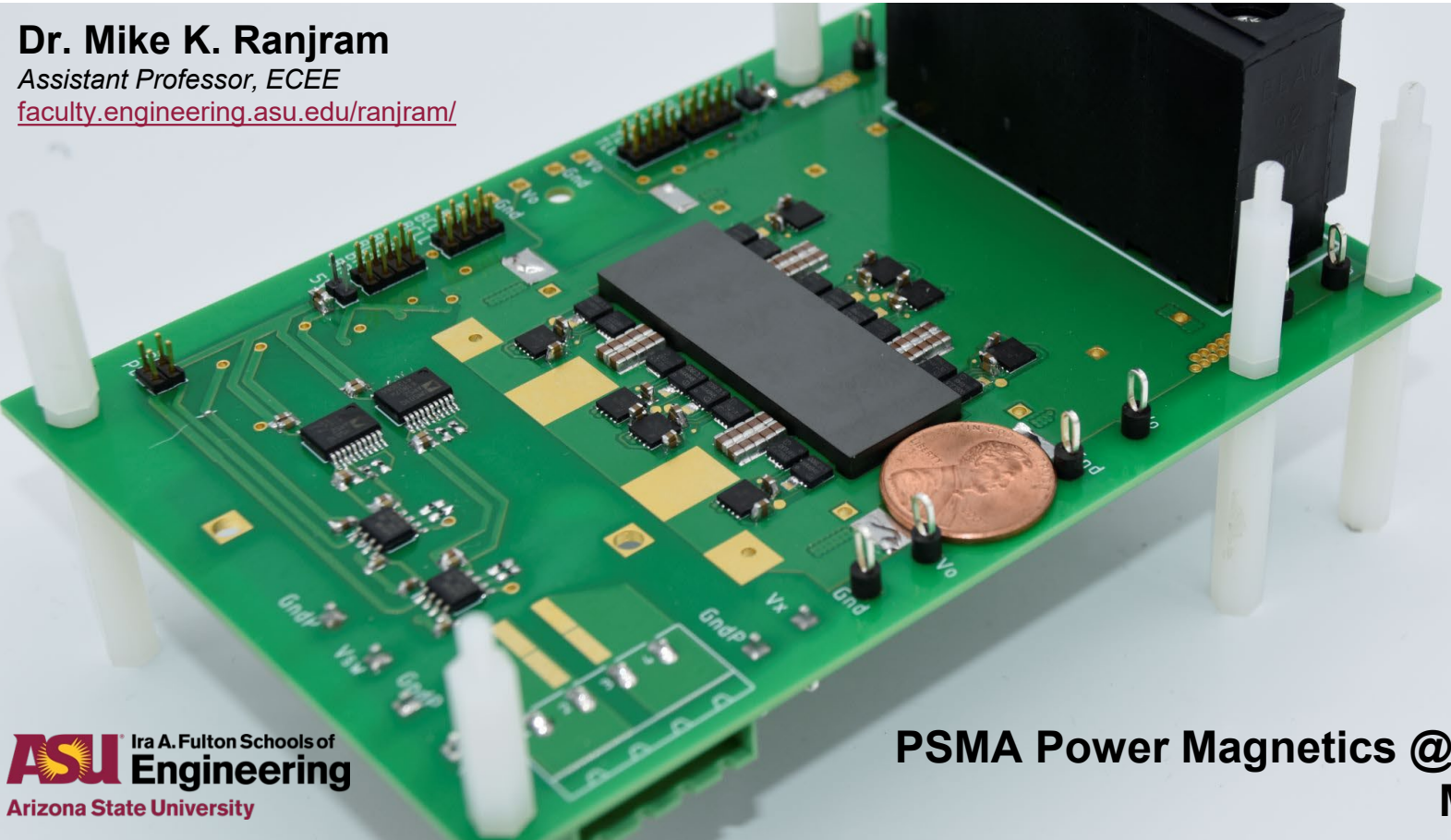
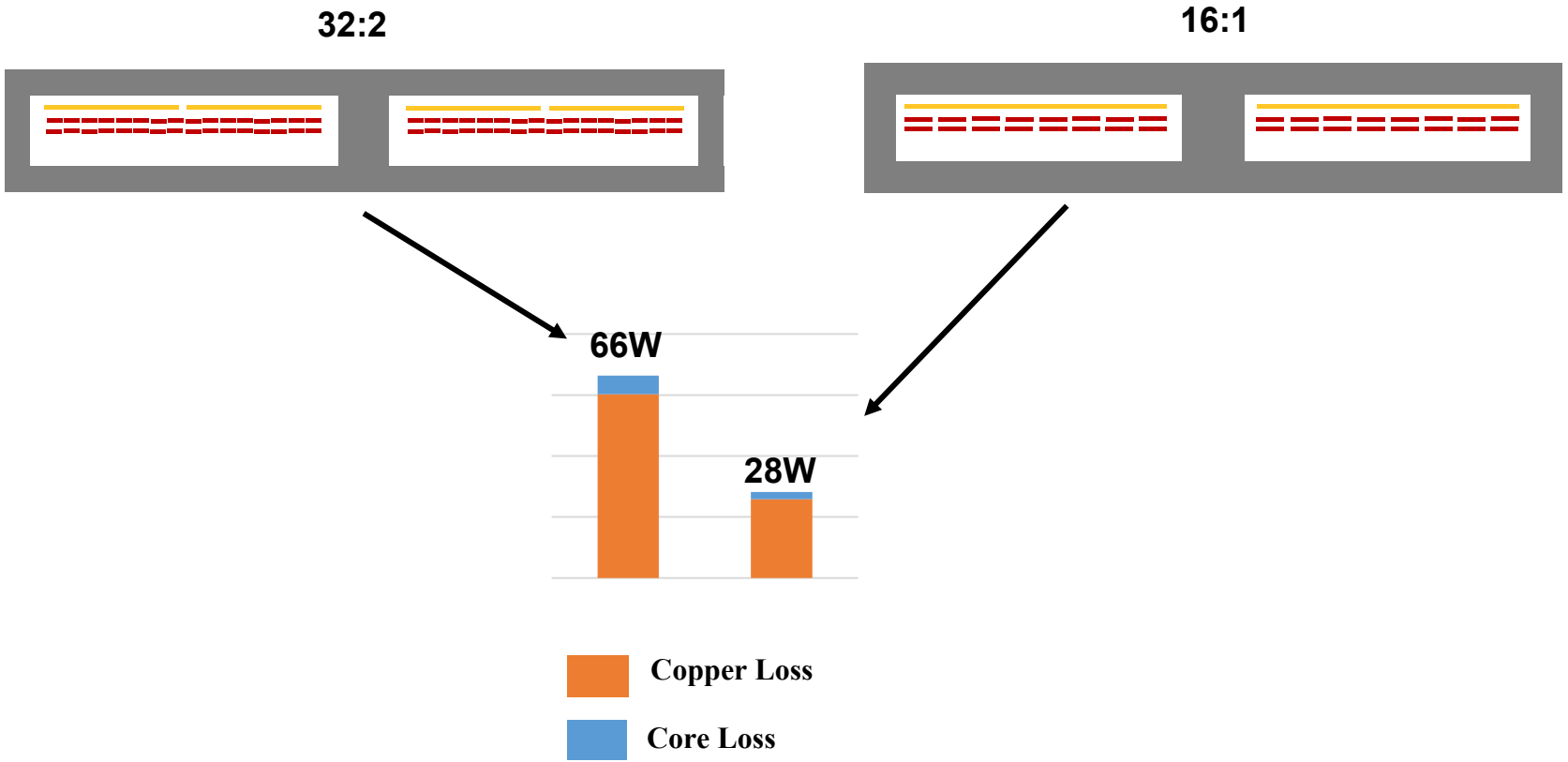


Ira A. Fulton Schools of Engineering
Arizona State University

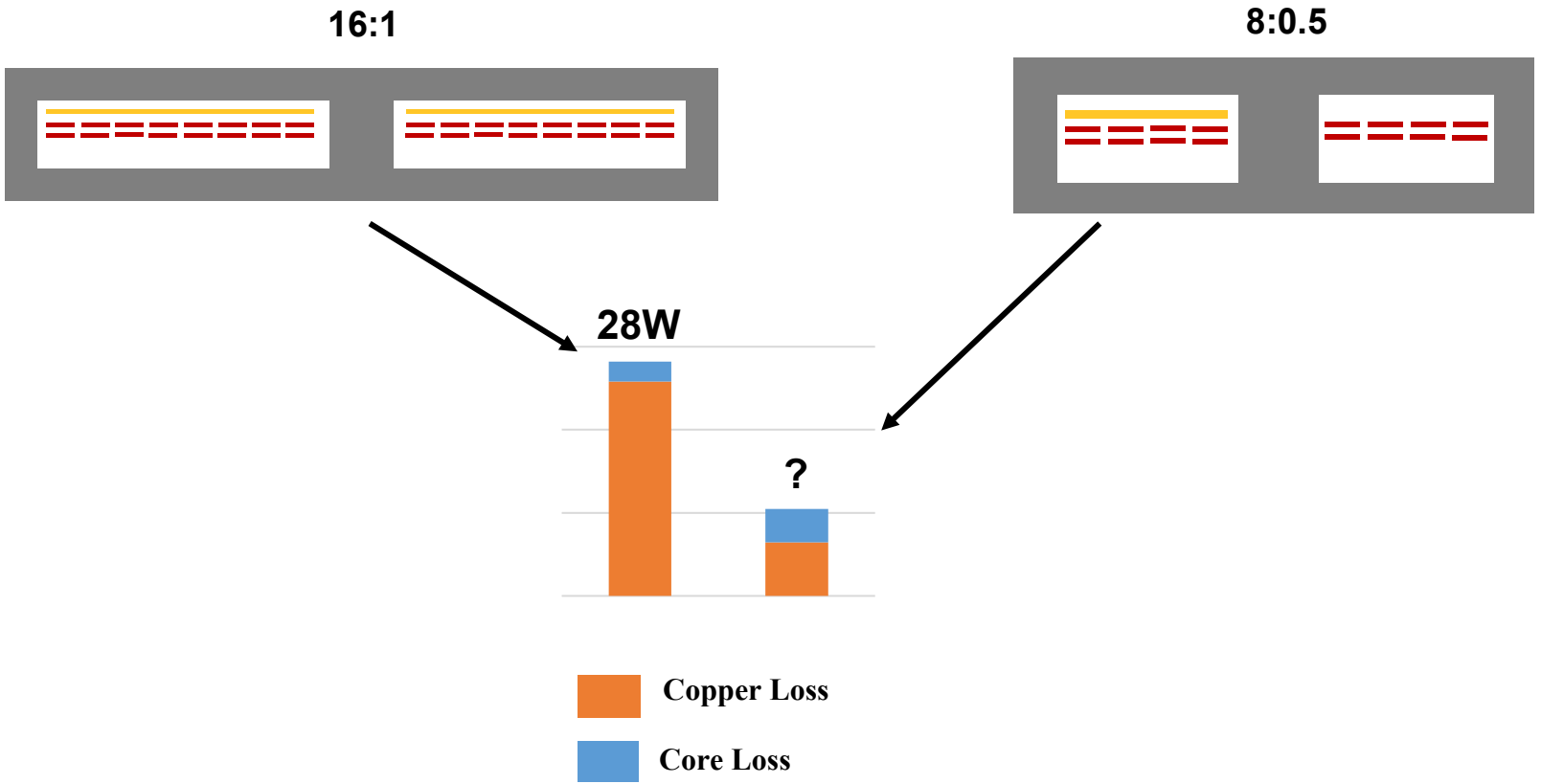
PSMA Power Magnetics @ HF Workshop
March 15, 2025

Minimizing Turns Count Can be Greatly Advantageous

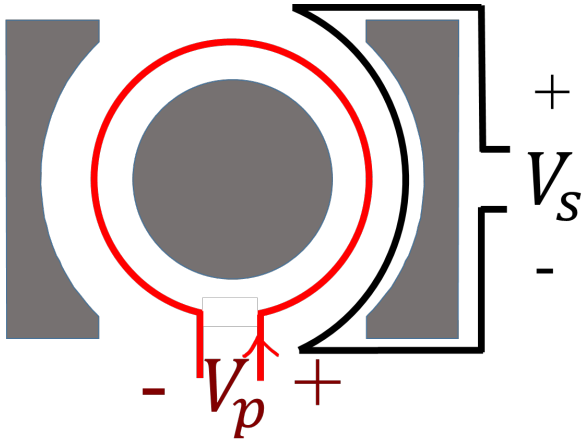
e.g., for high step-down, high output current power conversion with planar PCB magnetics



What About a Fractional Turn?



“Fractional-flux” Concepts (mid-1980s)



Mid 1980s (Perica and Dixon) for multi-channel power supplies

$$\boldsymbol{V_s = xV_p}$$

- $\boldsymbol{x} \in [\mathbf{0}, \mathbf{1}]$ depending on loading of the secondary
- Very high leakage

G. Perica, “Elimination of leakage effects related to the use of windings with fractions of turns,” *IEEE Trans. Power Electron.*, vol. PE-1, no. 1, pp. 39–47, Jan. 1986.
L. H. Dixon, “How to design a transformer with fractional turns,” in *Unitrode/TI Magnetics design Handbook*, no. Topic R6, TI Literature Number: SLUP132, 2000. [Online]. Available: https://www.ti.com/seclit/ml/slup132/slup132.pdf

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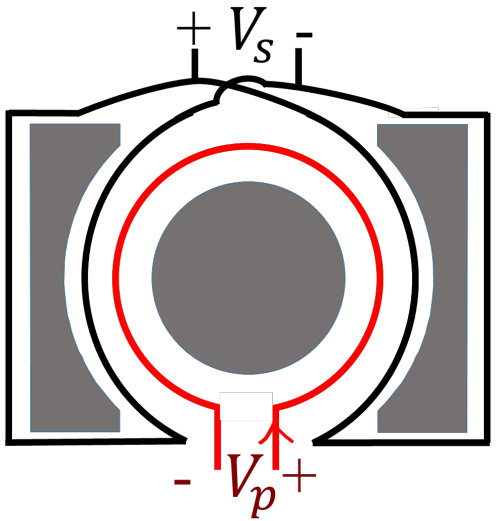


Mid 1980s (Perica and Dixon) for multi-channel power supplies

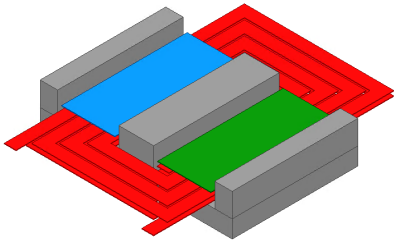
$\boldsymbol{V_s = \frac{V_p}{2}}$ **(N_p:$\frac{1}{2}$ conversion ratio)**

But affects a linear trade-off of copper loss since full loops around outer legs are needed

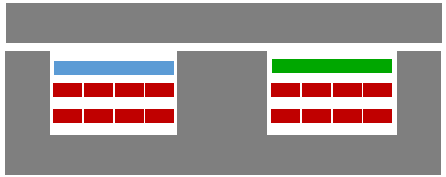
G. Perica, “Elimination of leakage effects related to the use of windings with fractions of turns,” *IEEE Trans. Power Electron.*, vol. PE-1, no. 1, pp. 39–47, Jan. 1986.
L. H. Dixon, “How to design a transformer with fractional turns,” in *Unitrode/TI Magnetics design Handbook*, no. Topic R6, TI Literature Number: SLUP132, 2000. [Online]. Available: https://www.ti.com/seclit/ml/slup132/slup132.pdf

Our Approach to “Fractional Turns” – The “VIRT”

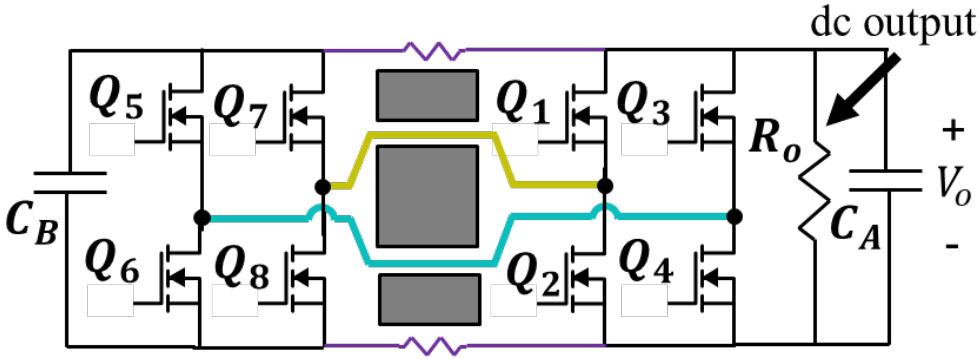
Transformer Orthographic View



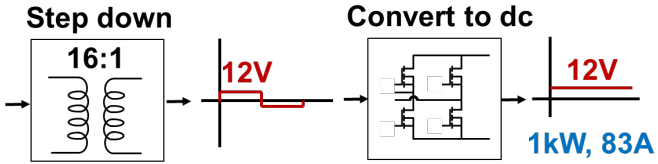
Transformer Side View



Top View – Variable Inverter/Rectifier Transformer



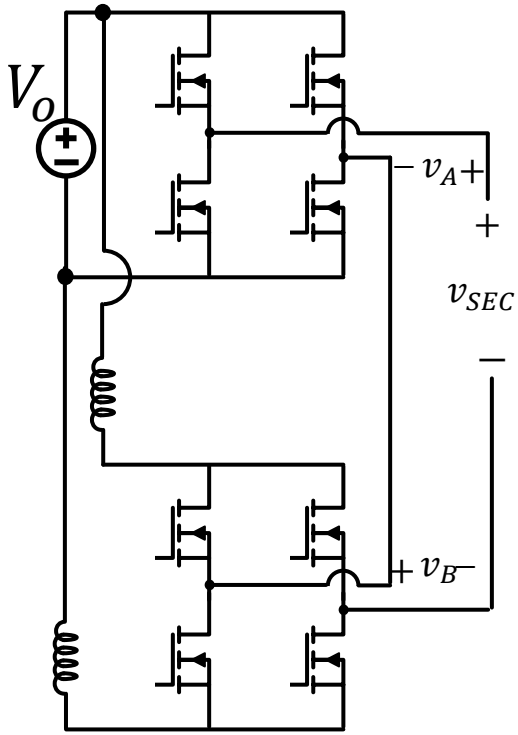
Combines Transformer and Rectifier

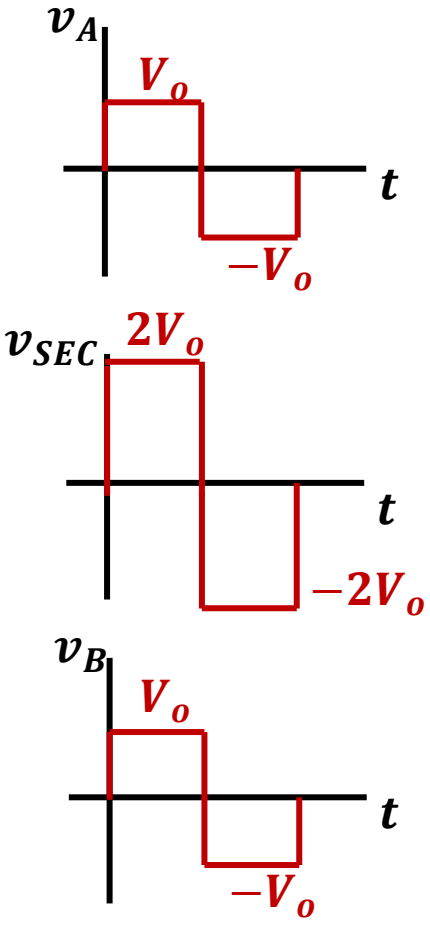


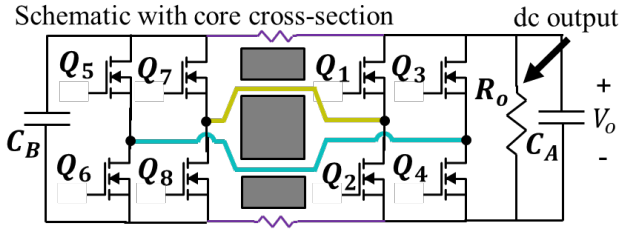
Special placement results in full-bridges being:

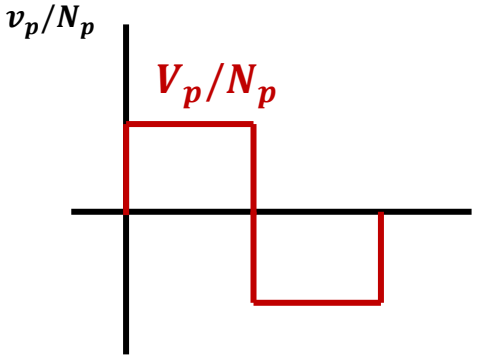
1. dc coupled
2. ac decoupled

Behaves Like a Two-Source Multi-Level Inverter





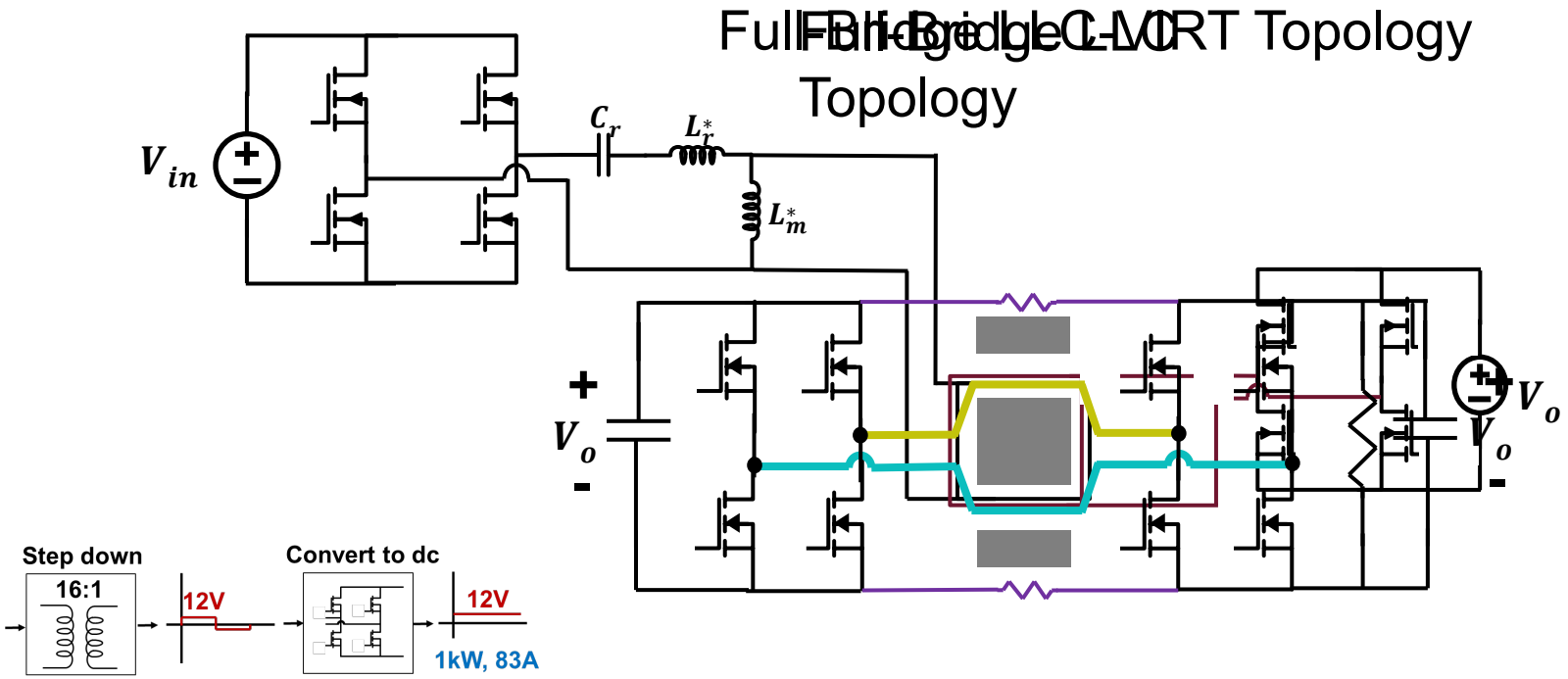




$$2V_o = \frac{V_p}{N_p}$$

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

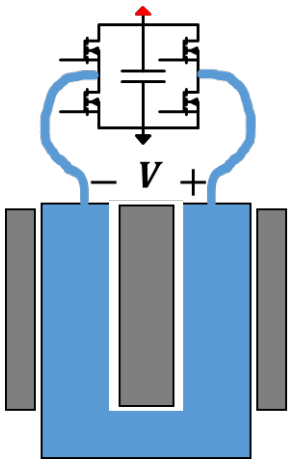
Example Deployment of a VIRT

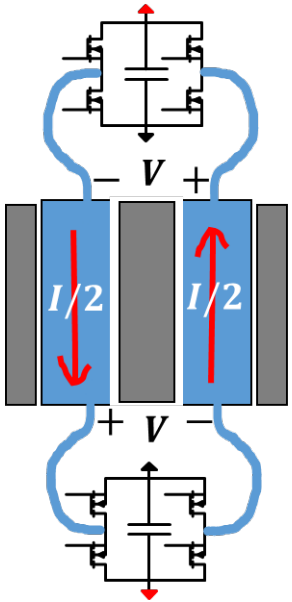


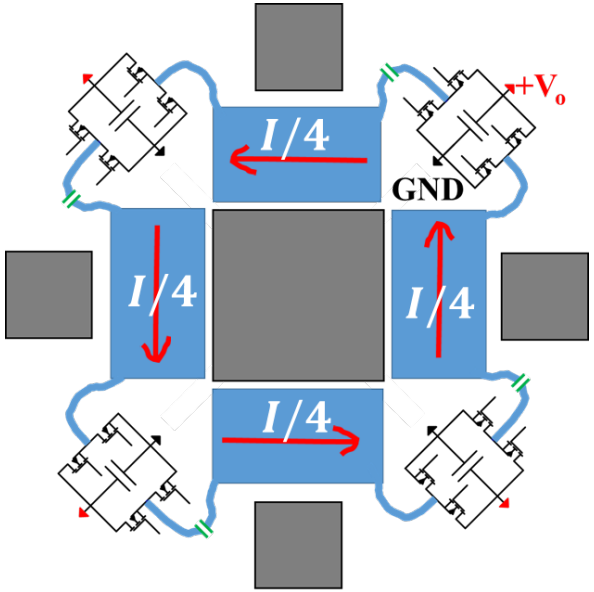
M. K. Ranjram, I. Moon, and D. J. Perreault, "Variable-Inverter-Rectifier-Transformer: A Hybrid Electronic and Magnetic Structure Enabling Adjustable High Step-Down Conversion Ratios," *IEEE Transactions on Power Electronics*, vol. 33, no. 8, pp. 6509–6525, Aug. 2018, doi: 10.1109/TPEL.2018.2795959.

M. K. Ranjram 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.2021.3103432.

Correct Loss Trade-off: Exponential Rebalancing



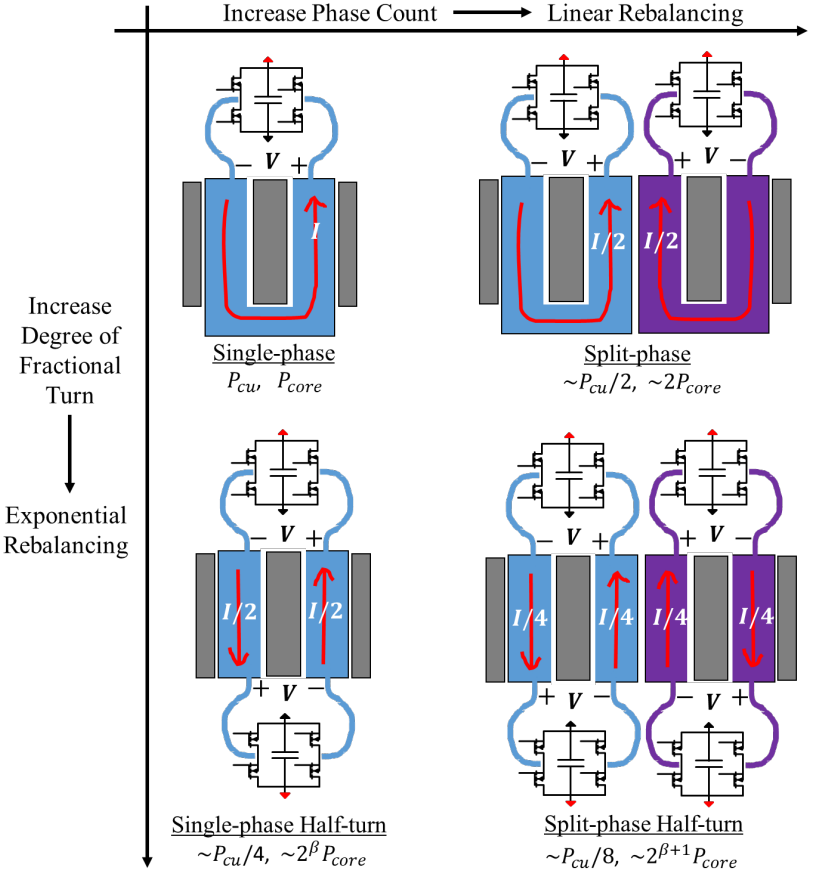




Steinmetz coefficient for core loss ($\beta \approx 2-3$)

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

“Gear Shifting” Transformer Core and Copper Loss



Our View: there is an optimal “magnetic gear” for a given:

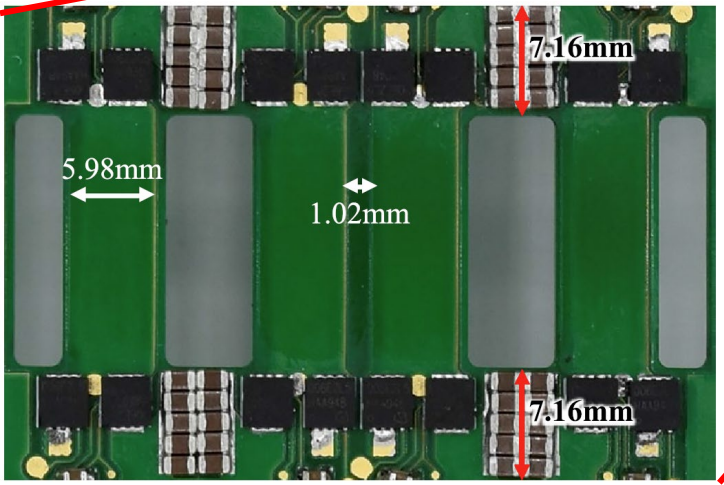
- Conversion specification
- Flux excitation
- Operating frequency
- Magnetic material

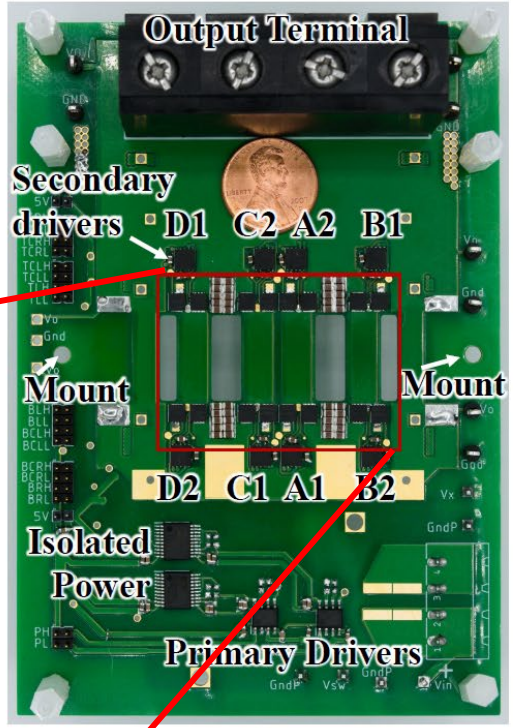
M. K. Ranjram and D. J. Perreault, "Leveraging Multi-Phase and Fractional-Turn Integrated Planar Transformers for Miniaturization in Data Center Applications," *2020 IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL)*, Aalborg, Denmark, 2020, pp. 1-8, doi: 10.1109/COMPEL49091.2020.9265752.

1kW, 380-12V SPHTV Prototype

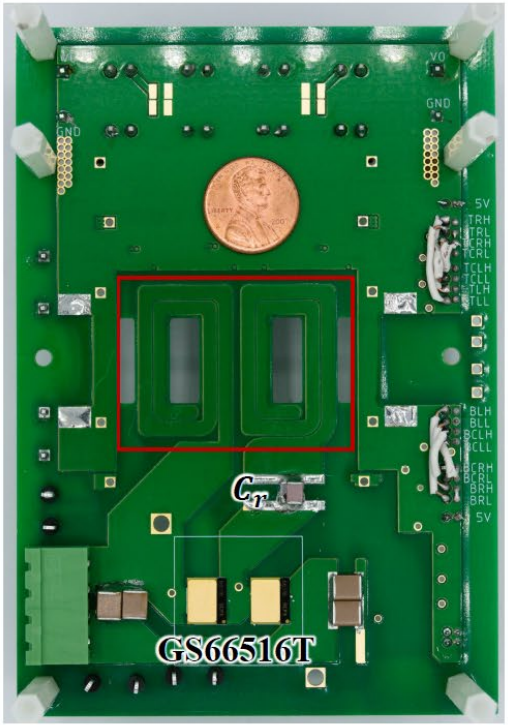
Custom core from Proterial (ML91S)

(a)





(c)



(d)

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

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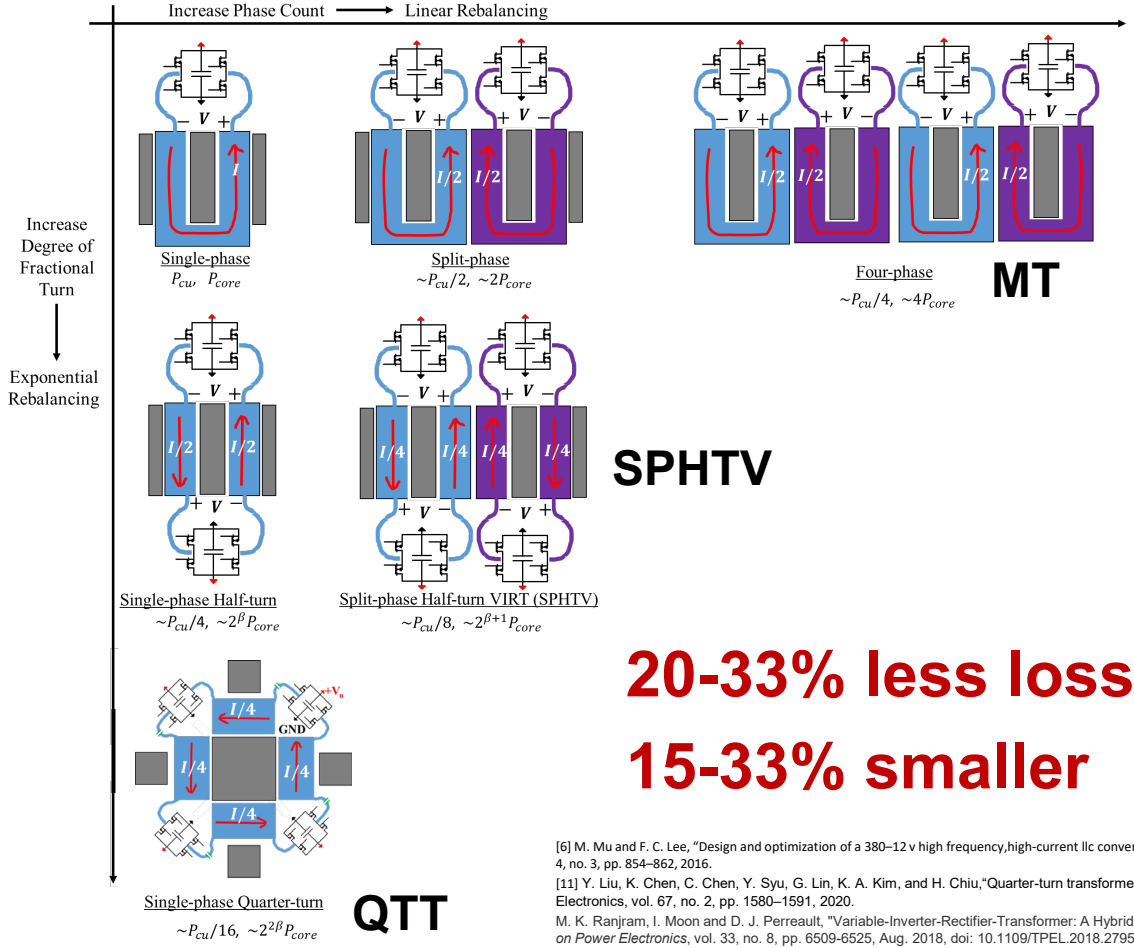
SPHTV: Well-suited for 380-12V, 1kW Step-Down



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

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

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.

[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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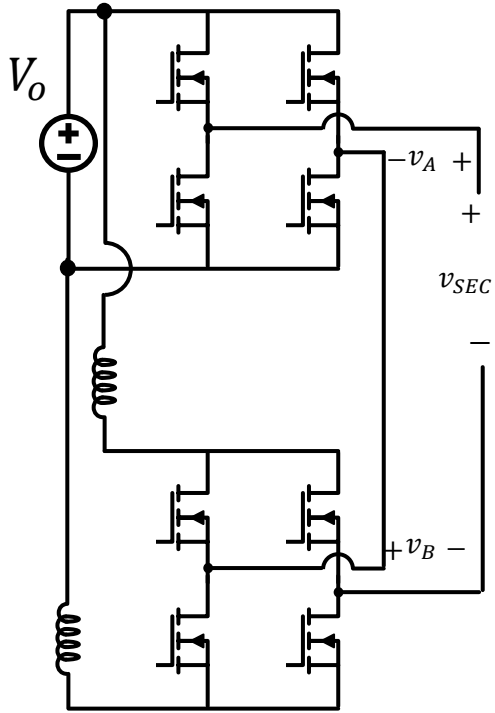
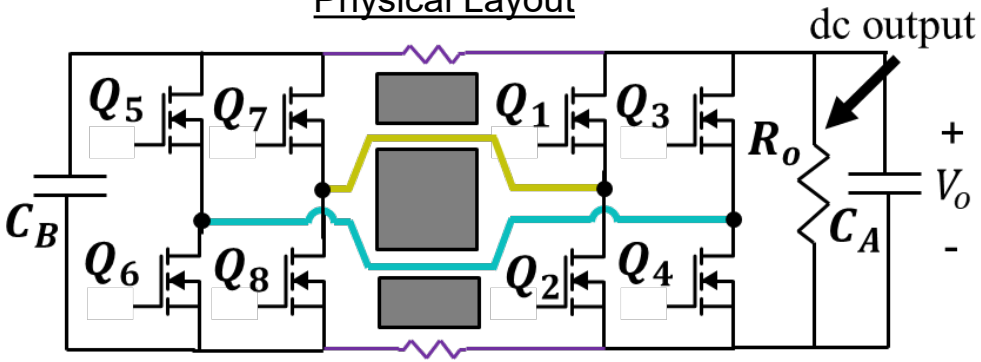
ac-decoupling of Co-Location is Important

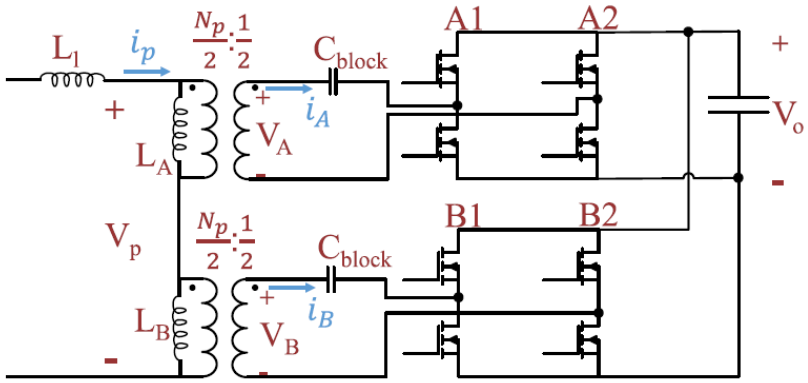
Mental Model



Physical Layout

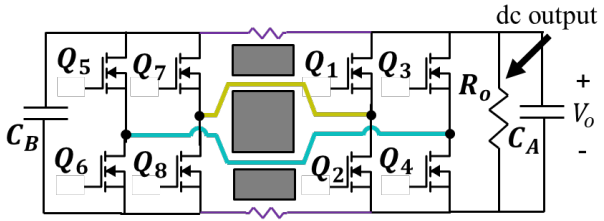


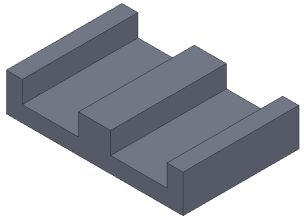
Original (Simplified) Electrical Model



Coupled Electronic and Magnetic Systems

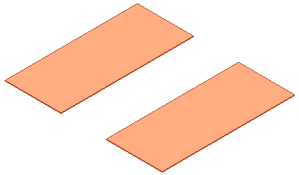
- Our name for the general class of components where electronics interrupt conductive loops around the magnetic core.





Magnetic materials

\+



Conductors

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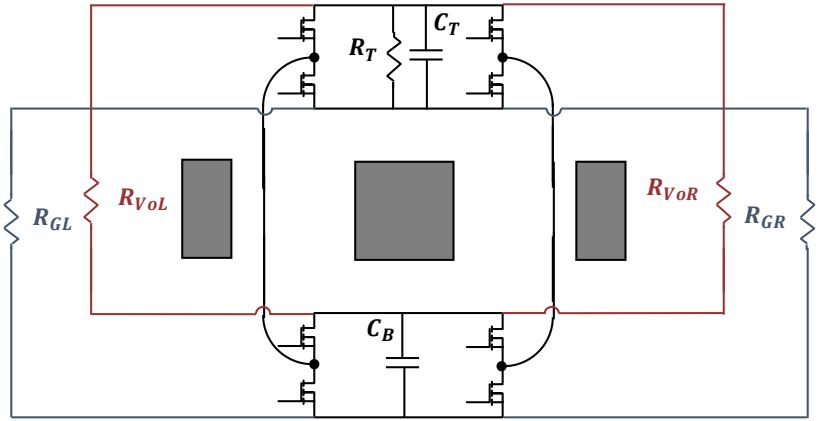
Electronics

Physical domain + Electrical domain

- View and design these elements as one coupled system
- We may be interested in general variations in any of these elements

M. K. Ranjram and D. J. Perreault, "A Modeling Approach for the VIRT and Other Coupled Electronic and Magnetic Systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, pp. 1–1, 2021, doi: 10.1109/JESTPE.2021.3120434.

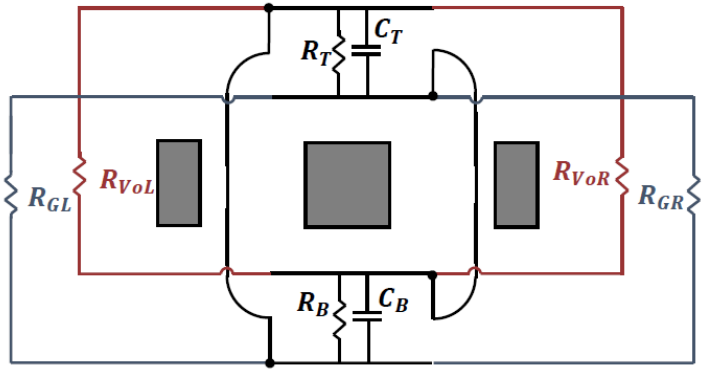
General Modeling Procedure



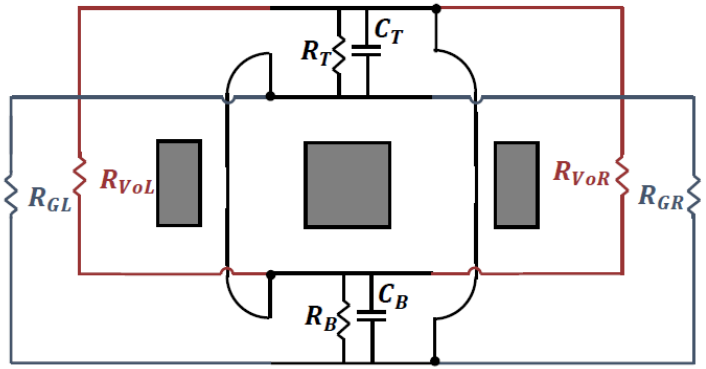
Electrical (Circuit) Domain	Magnetic (Physical) Domain
1. Enforce switch states	
2. Count circuit nodes (n) and branches (b)	
	3. Count the single-node loops encircling core sections (p)
4. Identify b-n+p+1 KVL loops	
	5. Use the loop currents to create a magnetic circuit model
6. Transform the magnetic circuit model of Step 5 into an electric circuit model	
7. Replace loop current sources in the model of Step 6 with the circuit components comprising each loop	

1. Enforce Switch States

Stage 1



Stage 2



Electrical (Circuit) Domain	Magnetic (Physical) Domain
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	5. Use the loop currents to create a magnetic circuit model
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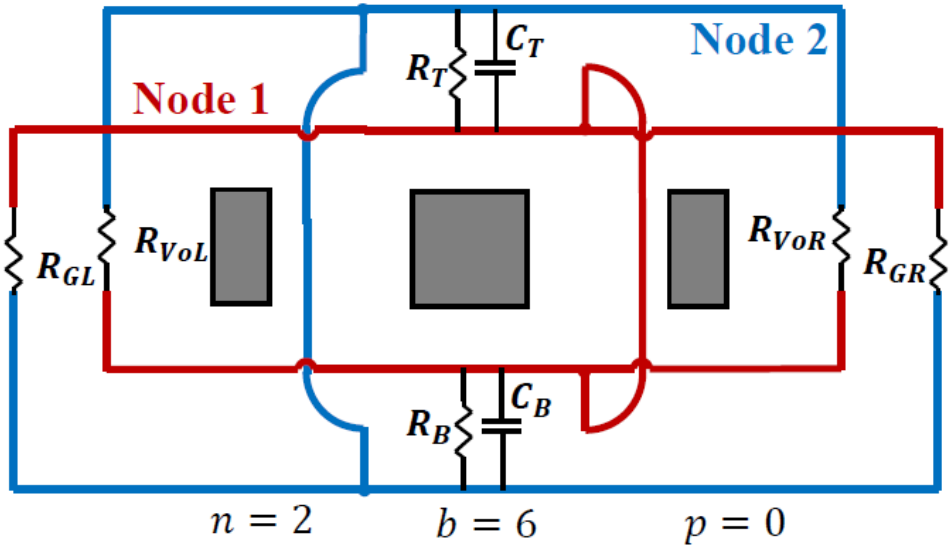
7. Replace loop current sources in the model of Step 6 with the circuit components comprising each loop	

2 and 3. Count Circuit Nodes (n), Branches (b), and single-node loops that encircle core sections (p)



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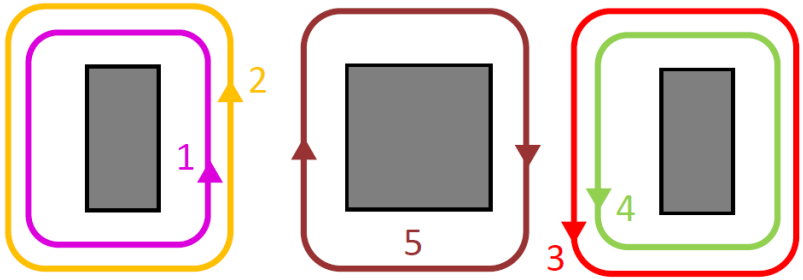
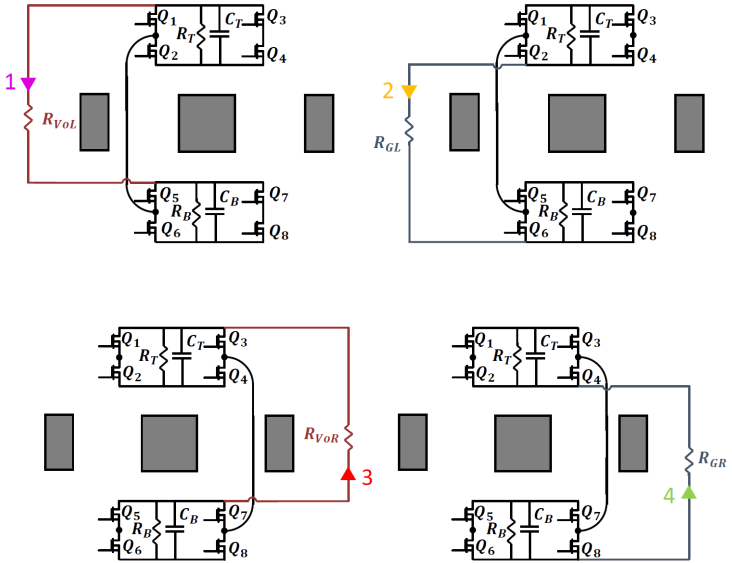
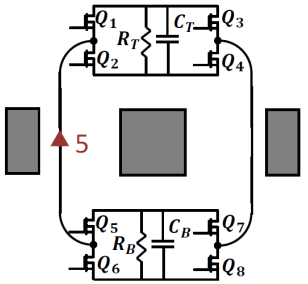
4. Define *b-n+p+1* Independent KVL Loops

$n = 2, b = 6, p = 0 \Rightarrow 5$ loops

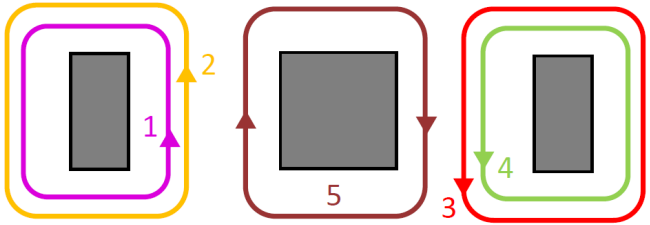


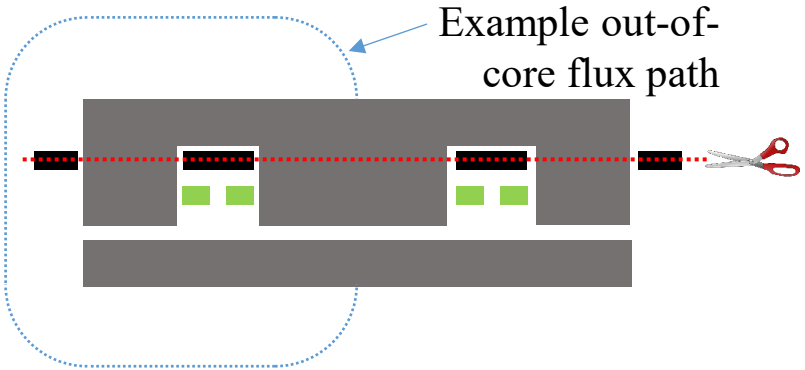


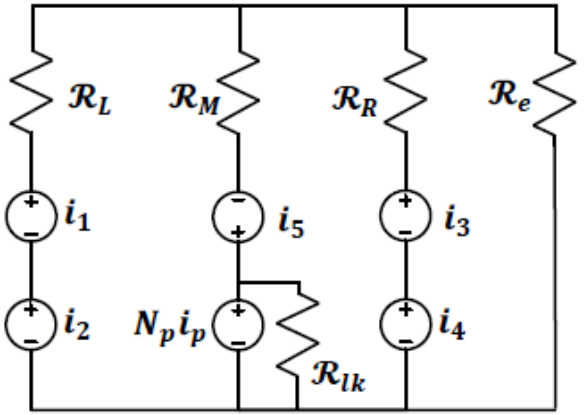


Electrical (Circuit) Domain	Magnetic (Physical) Domain
1. Enforce switch states	
2. Count circuit nodes (*n*) and branches (*b*)	
	3. Count the single-node loops encircling core sections (*p*)
4. Identify *b-n+p+1* KVL loops	
	5. Use the loop currents to create a magnetic circuit model
6. Transform the magnetic circuit model of Step 5 into an electric circuit model	
7. Replace loop current sources in the model of Step 6 with the circuit components comprising each loop	

5. Use the Loop Currents to Create a Magnetic Circuit Model







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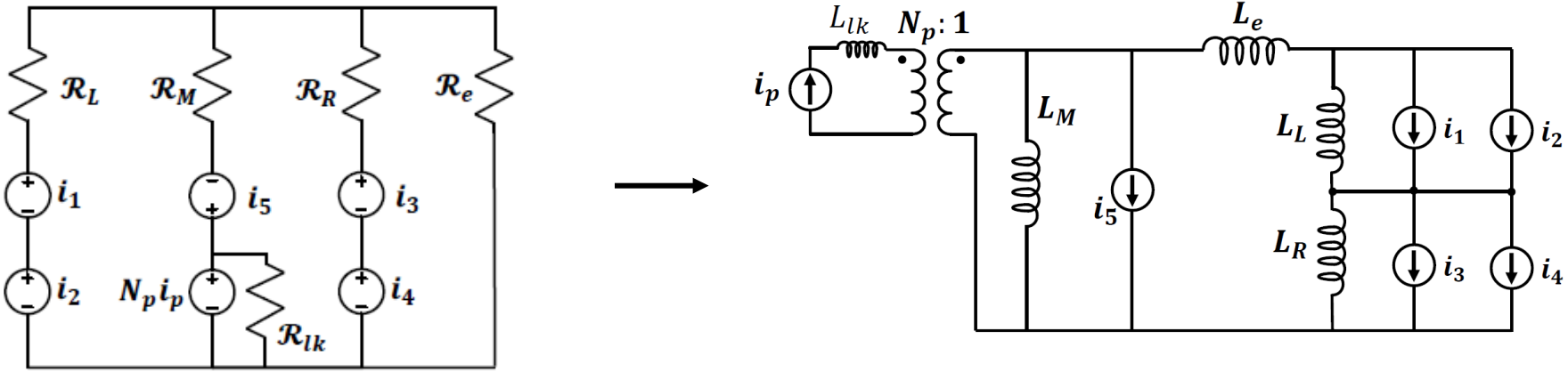
	5. Use the loop currents to create a magnetic circuit model
6. Transform the magnetic circuit model of Step 5 into an electric circuit model	
7. Replace loop current sources in the model of Step 6 with the circuit components comprising each loop	

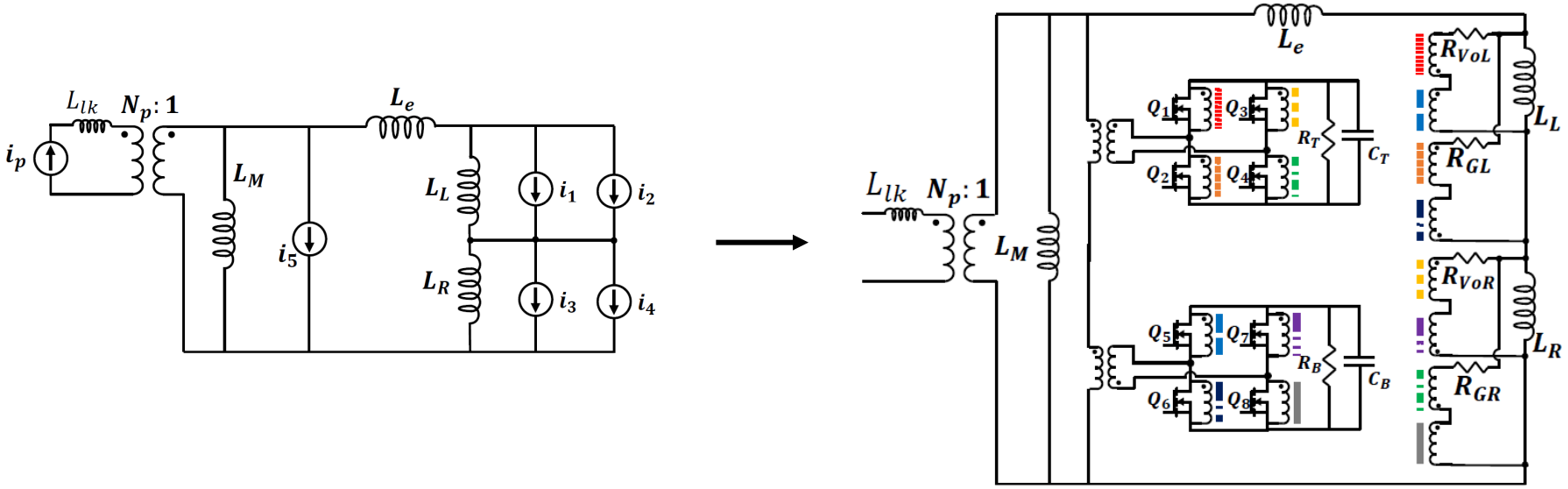
6. Transform Into an Electric Circuit Model



Electrical (Circuit) Domain	Magnetic (Physical) Domain
1. Enforce switch states	
2. Count circuit nodes (n) and branches (b)	
	3. Count the single-node loops encircling core sections (p)
4. Identify b-n+p+1 KVL loops	
	5. Use the loop currents to create a magnetic circuit model
6. Transform the magnetic circuit model of Step 5 into an electric circuit model	
7. Replace loop current sources in the model of Step 6 with the circuit components comprising each loop	

A. J. Hanson and D. J. Perreault, "Modeling the magnetic behavior of n-winding components: Approaches for unshackling switching superheroes," IEEE Power Electronics Magazine, vol. 7, no. 1, pp. 35–45, 2020.
J. Kassakian, D. J. Perreault, M. F. Schlecht, and G. C. Verghese, "Magnetic component modeling," in Principles of Power Electronics. Cambridge University Press, 2022.

7. Replace loop current sources with circuit components comprising each loop



Electrical (Circuit) Domain	Magnetic (Physical) Domain
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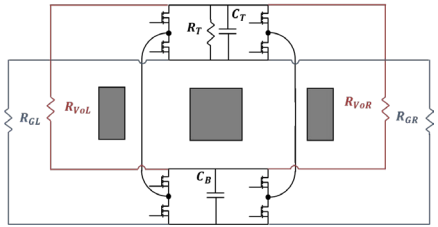
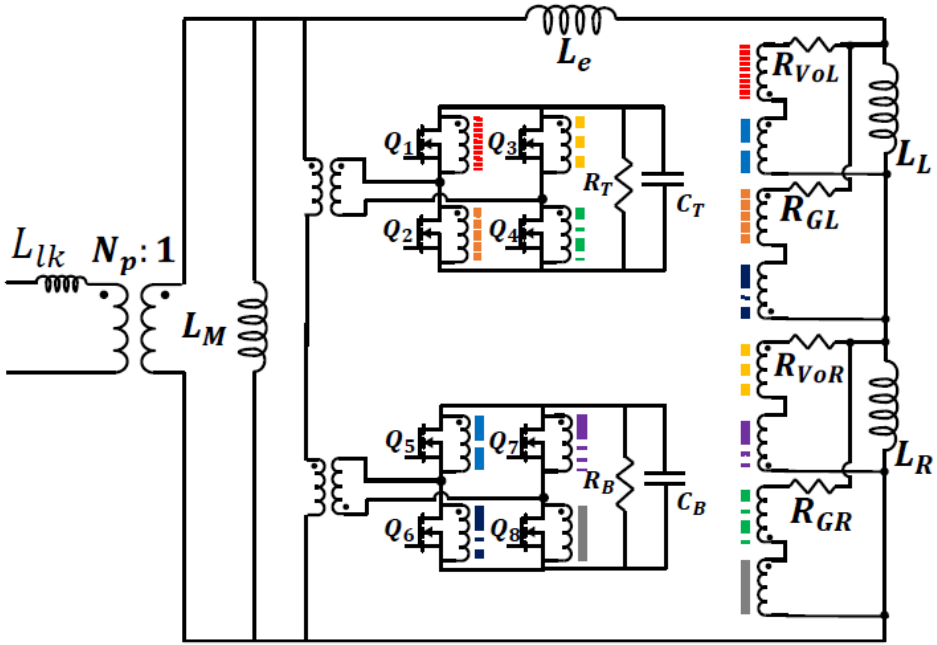


A General (but Complex) Model

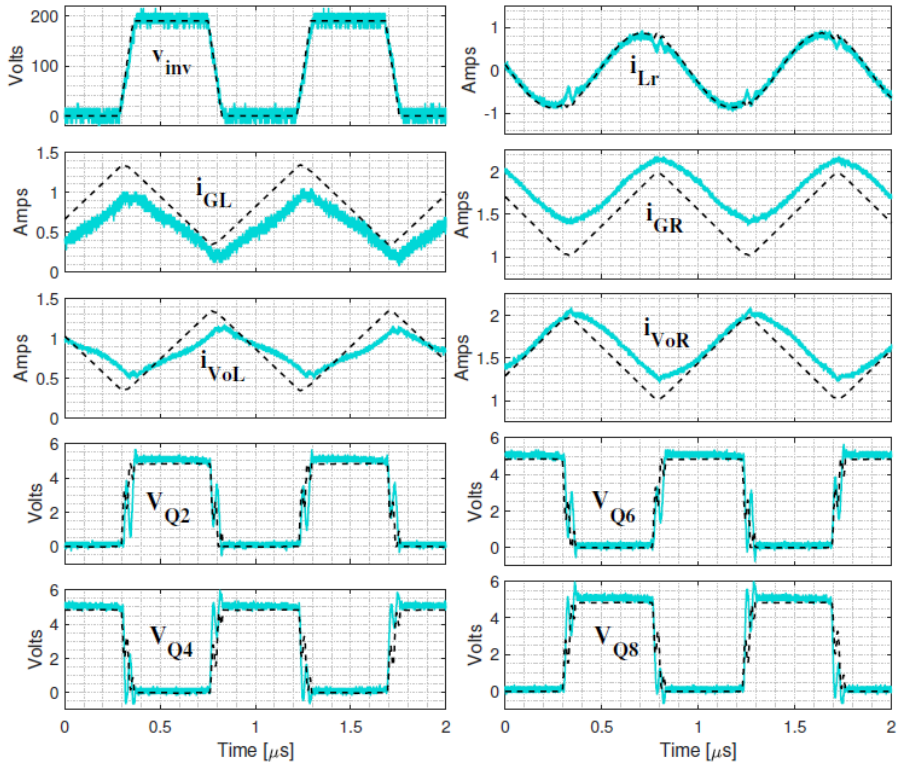


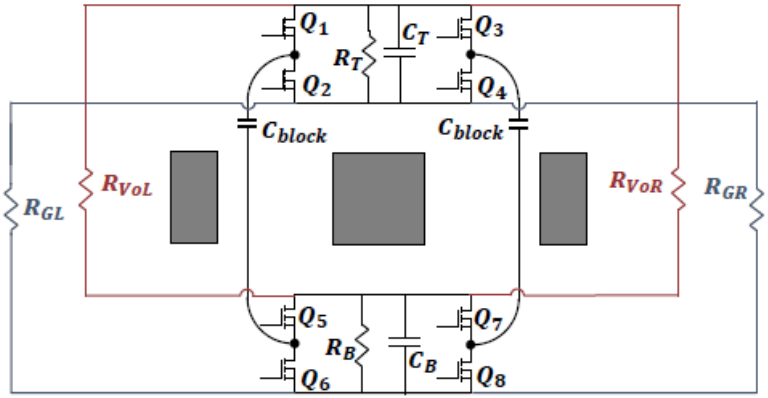
- Comprehensively captures the relationship of the physical co-location of the interfacing electronics.
- Generalizable to *any* CEMS (asymmetric layouts, different electronic structures, etc.)
- Valuable for careful study of other dc-paralleled constructions
  - E.g., it is not uncommon for a power converter prototype to define two outputs which are assumed paralleled off board.
  - In practice, those connections matter!

M. K. Ranjram and D. J. Perreault, "A Modeling Approach for the VIRT and Other Coupled Electronic and Magnetic Systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, pp. 1–1, 2021, doi: 10.1109/JESTPE.2021.3120434.

Model Verification – Symmetric Condition

Symmetric With Four dc Connections





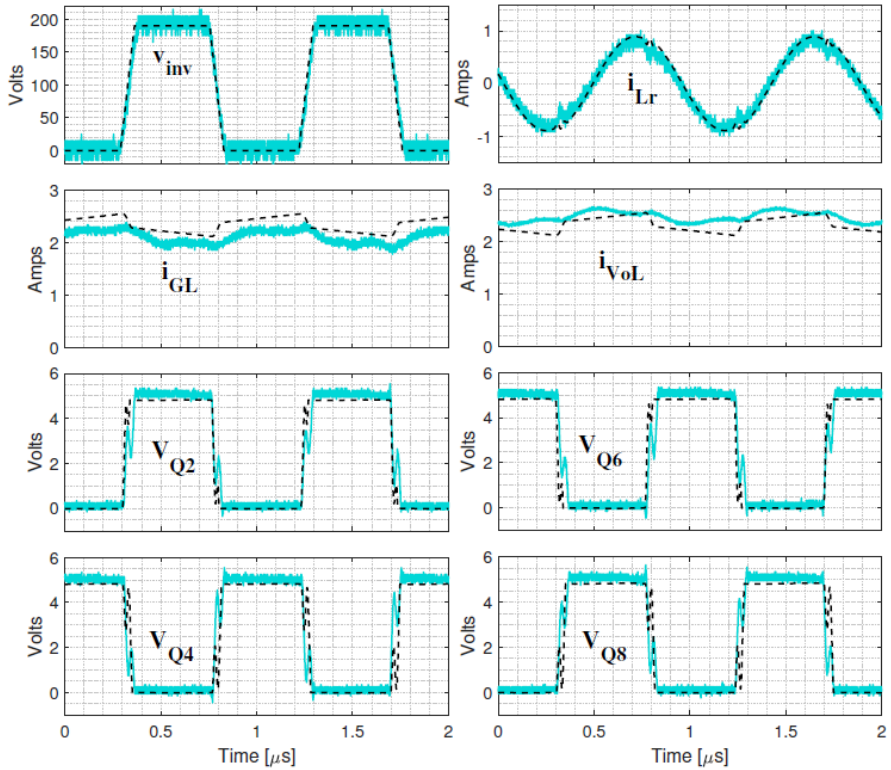
Modeling is sensitive to several parameters

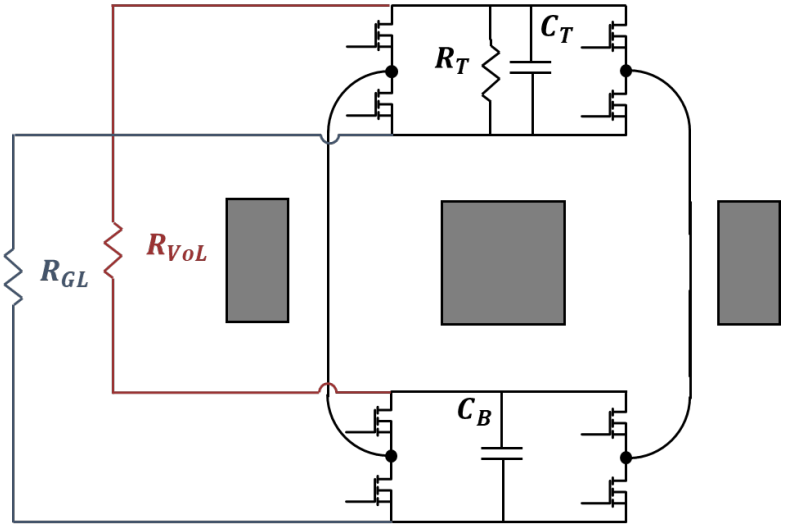
- Impedance of dc bus connections
- Decoupling impedance of the dc bus capacitors
- Degree of flux leakage

M. K. Ranjram and D. J. Perreault, "A Modeling Approach for the VIRT and Other Coupled Electronic and Magnetic Systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, pp. 1–1, 2021, doi: 10.1109/JESTPE.2021.3120434.

Model Verification – Asymmetric Condition

Asymmetric With Two dc Connections

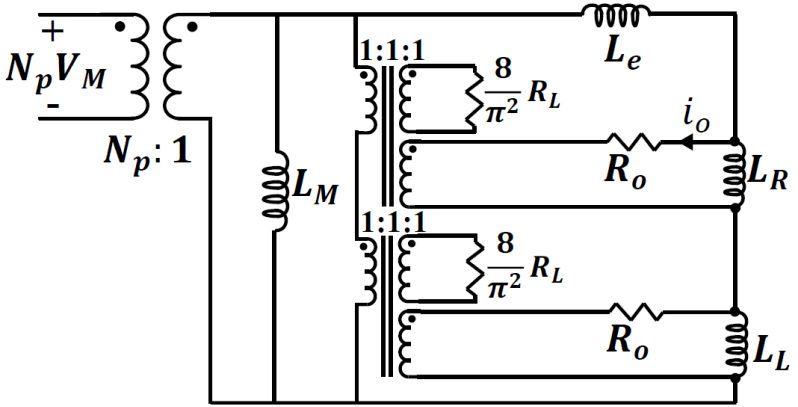




Model Simplifications

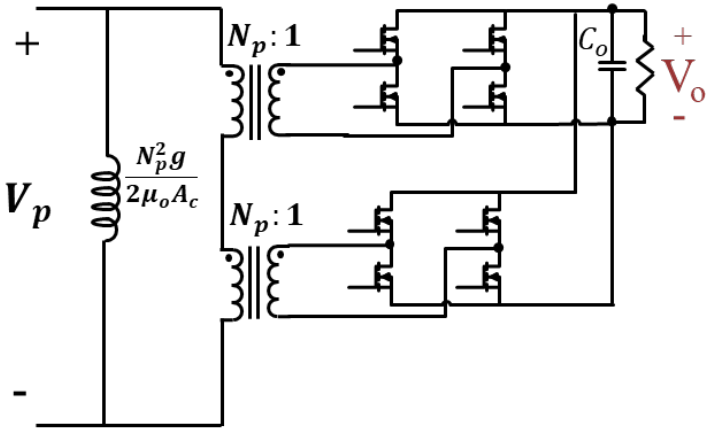
1. Assuming all dc impedances are identical and equal to $2R_o$

- Eliminates much of the complexity of the external coupling

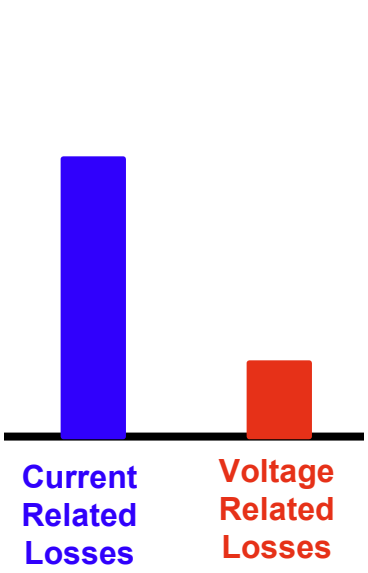


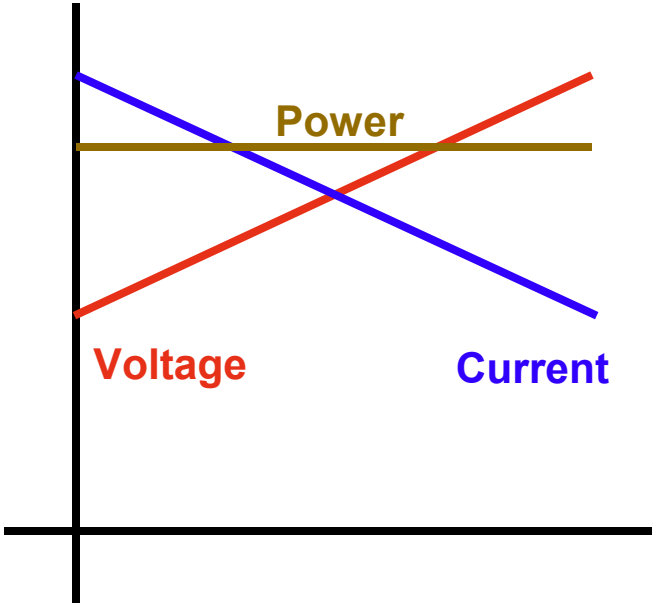
2. Assuming the dc impedances are negligible, and equal gap lengths g and center-post cross-sectional area A_c

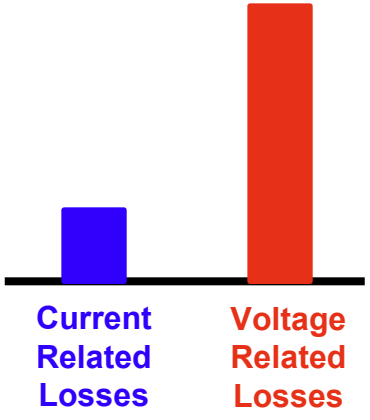
- Fully eliminates external coupling (and matches original models)

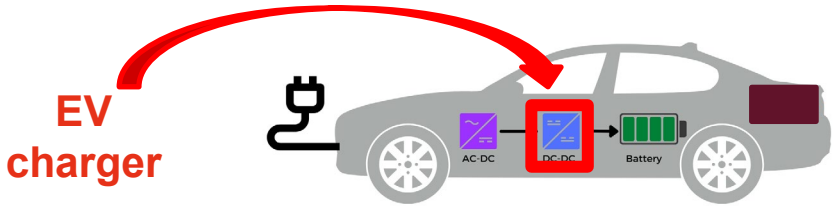


Battery Charging: Wide Voltage, Constant Power



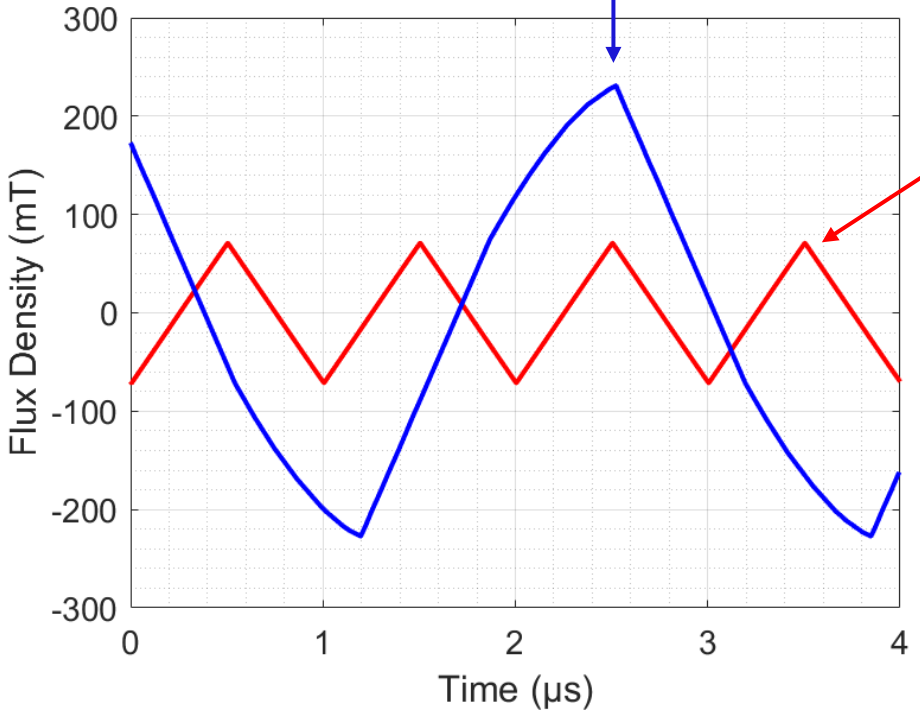






Wide Gain Can Be a Magnetics Challenge

$16V_o$ -> 231mT, **frequency modulation** ($f_{sw} = 340kHz$)



$10V_o$ -> 71mT, resonant operation ($f_{sw} = 1MHz$)

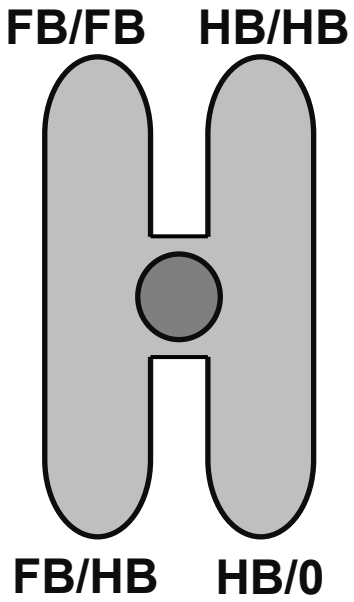
WIDE FLUX VARIATION

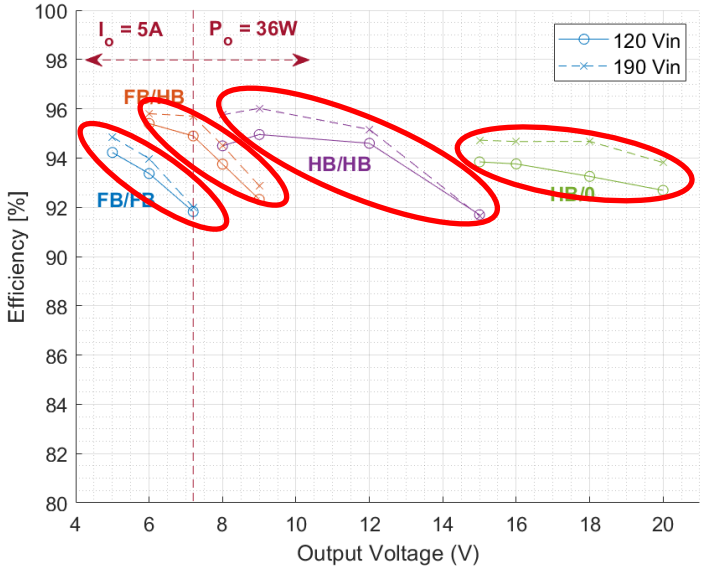
WIDE FREQUENCY RANGE

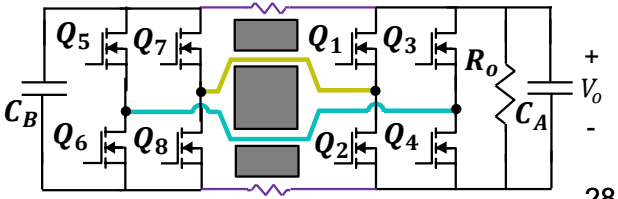
High Magnetic Stresses, Larger Bottleneck

Discrete Gain Adjustments “Compress” Output Range

Gain “Shifter”



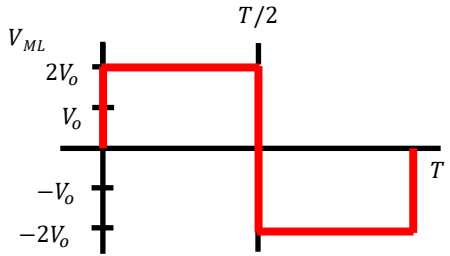




Ranjram, Mike K., Intae Moon, and David J. Perreault. “Variable-Inverter-Rectifier-Transformer: A Hybrid Electronic and Magnetic Structure Enabling Adjustable High Step-Down Conversion Ratios.” *IEEE Transactions on Power Electronics* 33, no. 8 (August 2018): 6509–25. https://doi.org/10.1109/TPEL.2018.2795959.

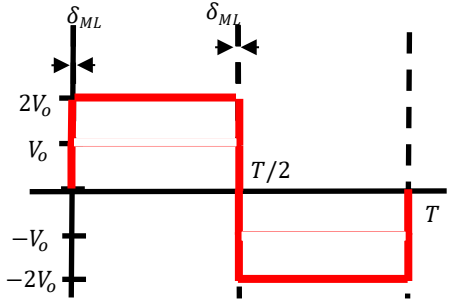
“ML-CEMS” Operation for Continuous Gain

FB/FB Mode

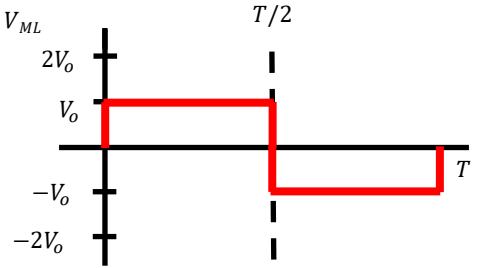


$N_p: 0.5$

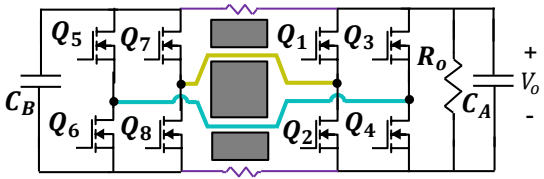
ML-CEMS



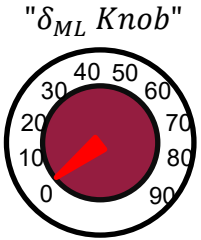
FB/0 Mode

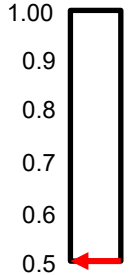


$N_p: 1$



Phase-shift rectifiers with δ_{ML}



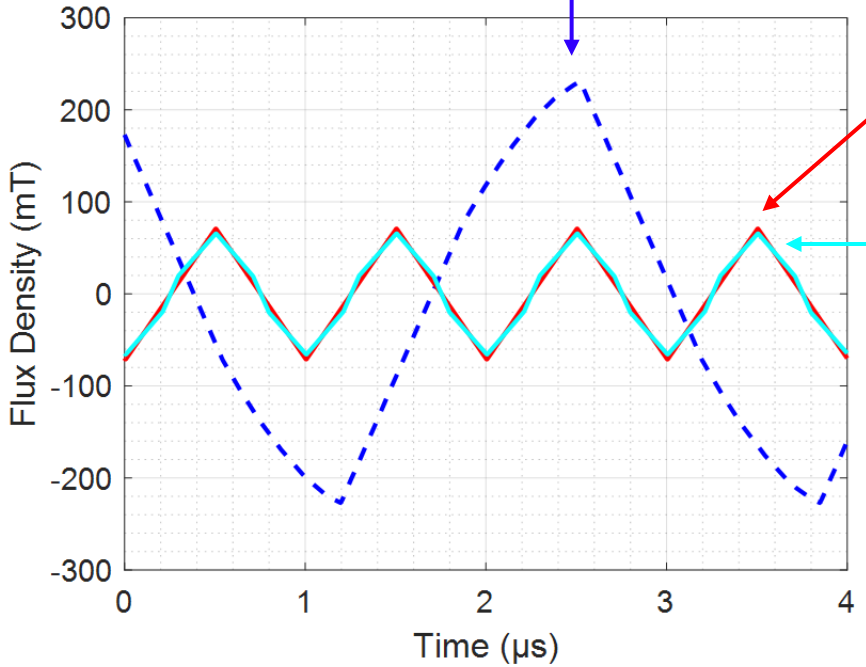


“ML-CEMS Effective Turns Ratio Meter”

I. D. Willows, S. Radhakrishnan, and M. K. Ranjram, “Multi-Level Coupled Electronic and Magnetic System for Wide-Gain Constant Power Conversion,” in *2024 IEEE Energy Conversion Congress and Exposition (ECCE)*, Oct. 2024, pp. 7268–7275. doi: 10.1109/ECCE55643.2024.10861058.

ML-CEMS Operation Eases Magnetics Design

$16V_o$ -> 231mT, **frequency modulation** ($f_{sw} = 340kHz$)



$10V_o$ -> 71mT, resonant operation ($f_{sw} = 1MHz$)

$16V_o$ -> 65mT, **ML-CEMS operation** ($\delta_{ML} = 75°, f_{sw} = 1MHz$)

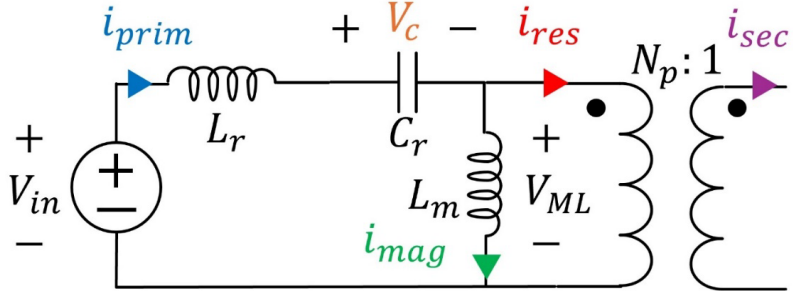
FIXED FLUX

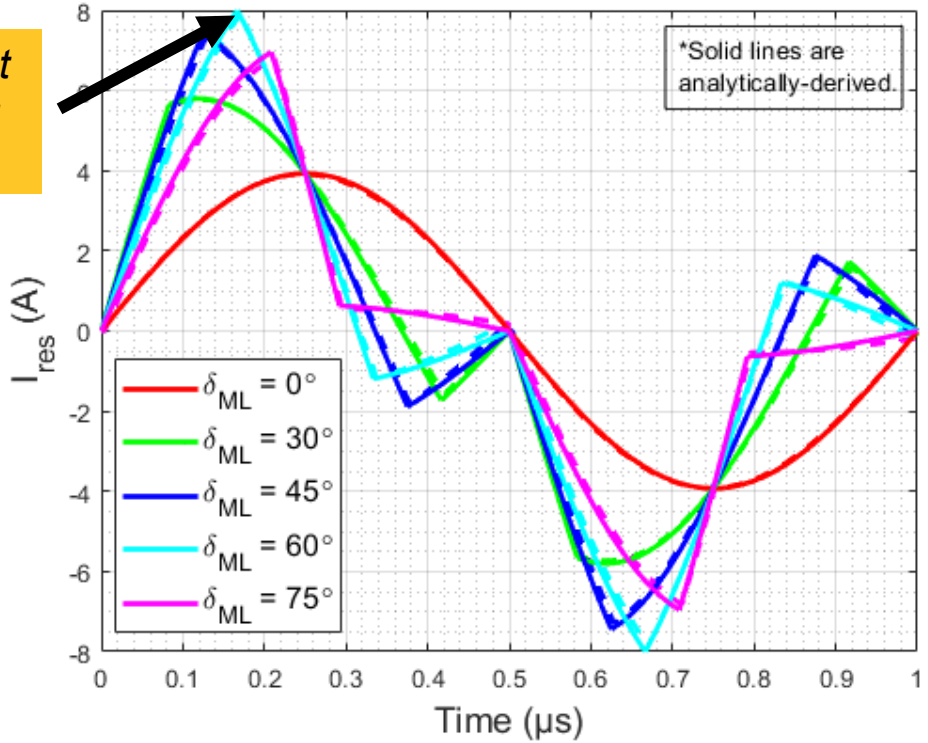
FIXED FREQUENCY

Permit Operation at the Highest Performing Magnetic Excitation

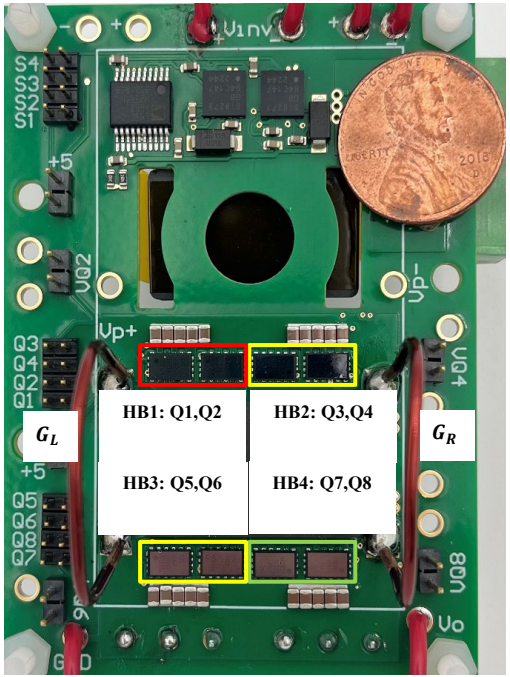
Trade-off Operating currents increase with δ_{ML}

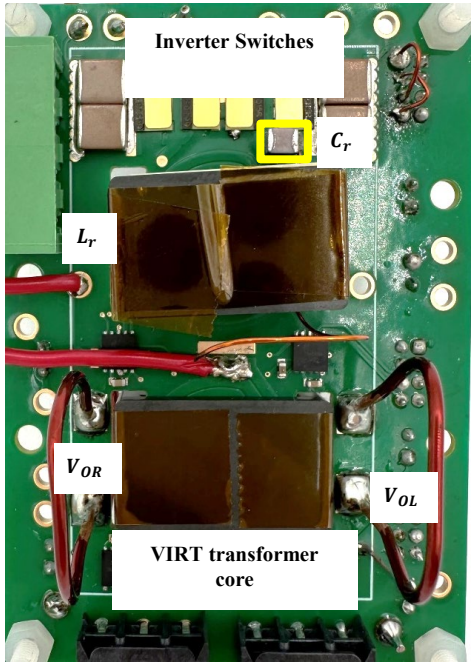
RMS current is highest at δ_{ML} = 60°



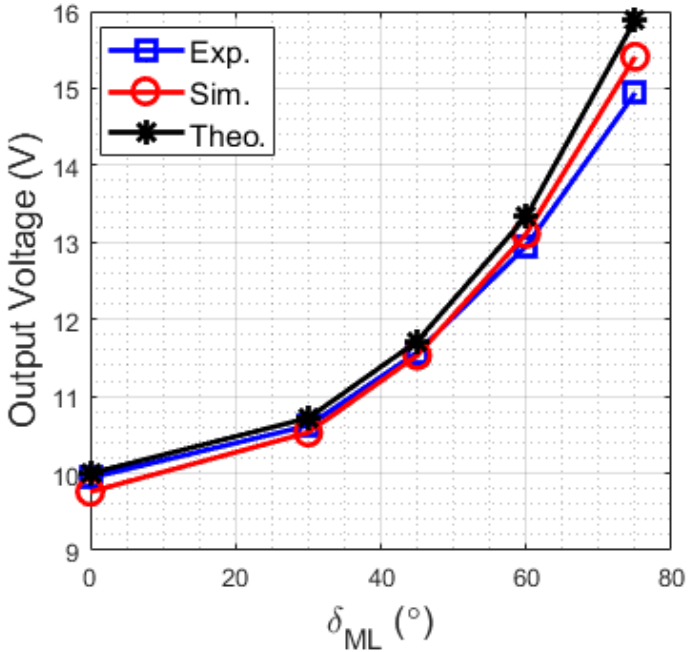


Verifying Function in Experiment

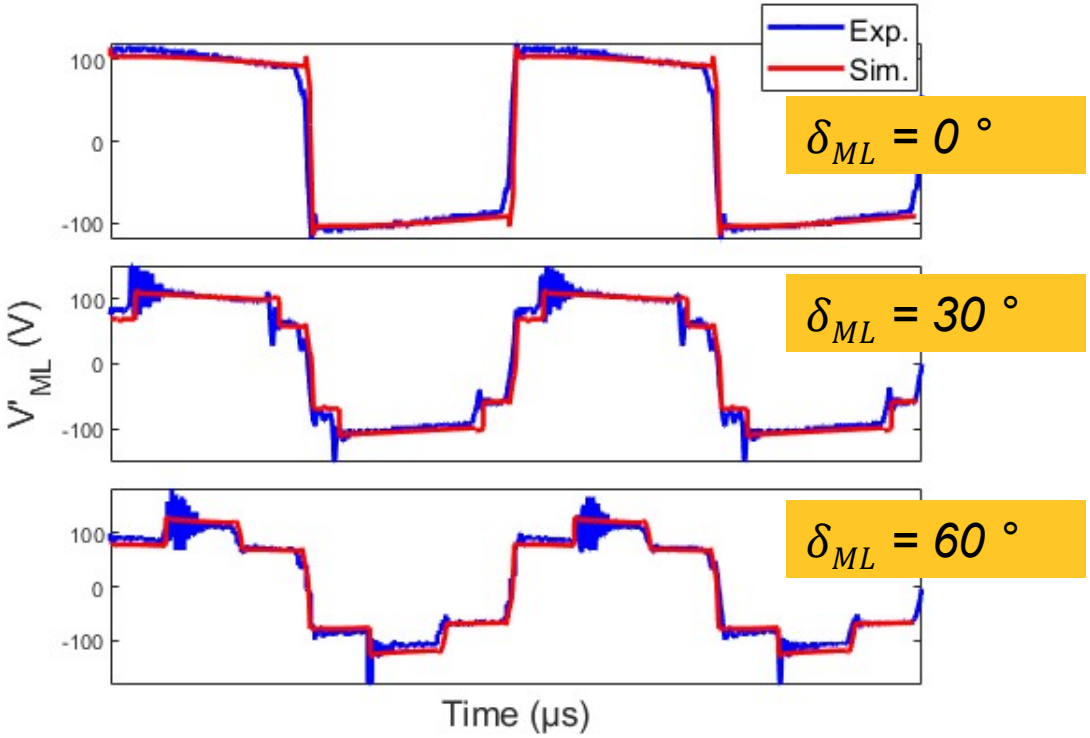


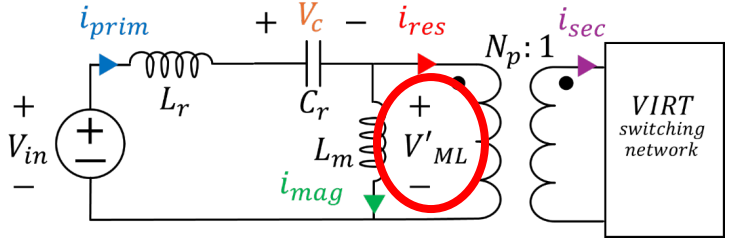


100Vin, 10-15Vout, 250W LLC converter (using parts available in-lab)



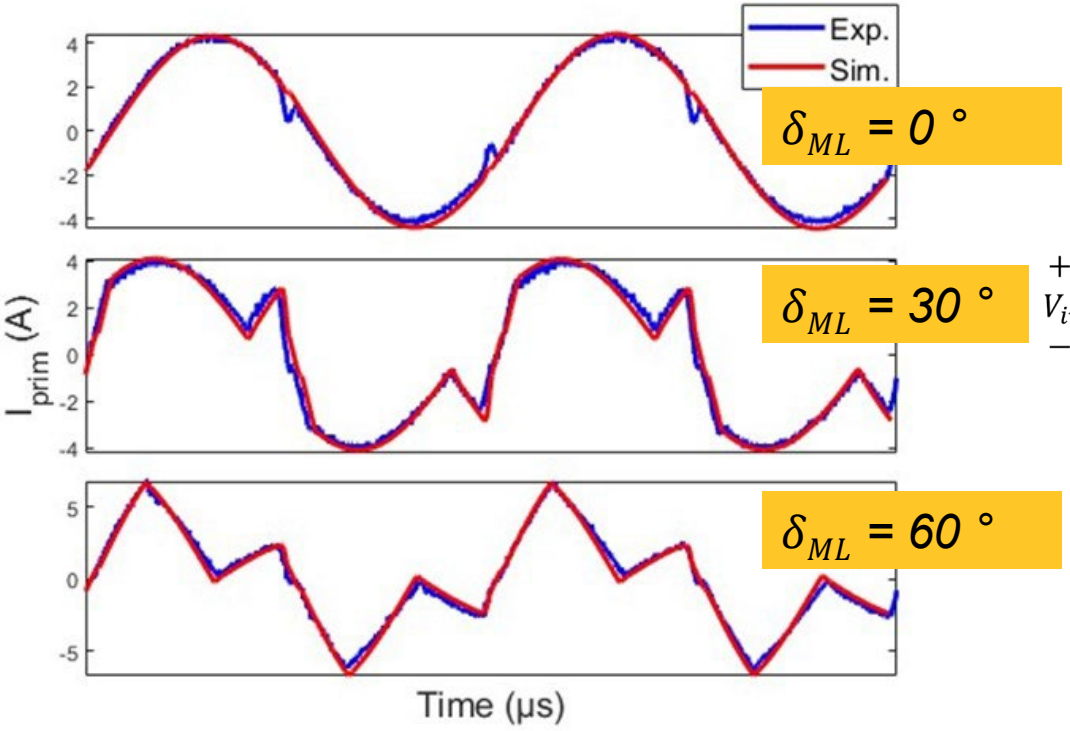
Operational Waveforms Match Expectation

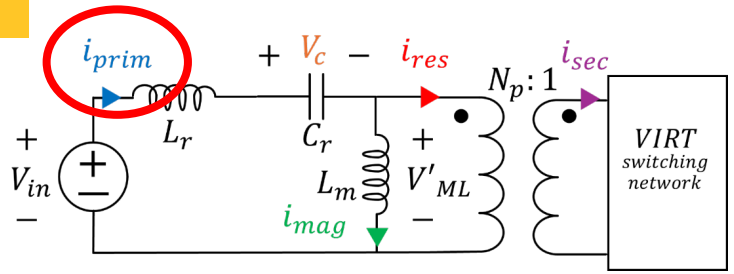




Primary-referred transformer voltage (V'_{ML})

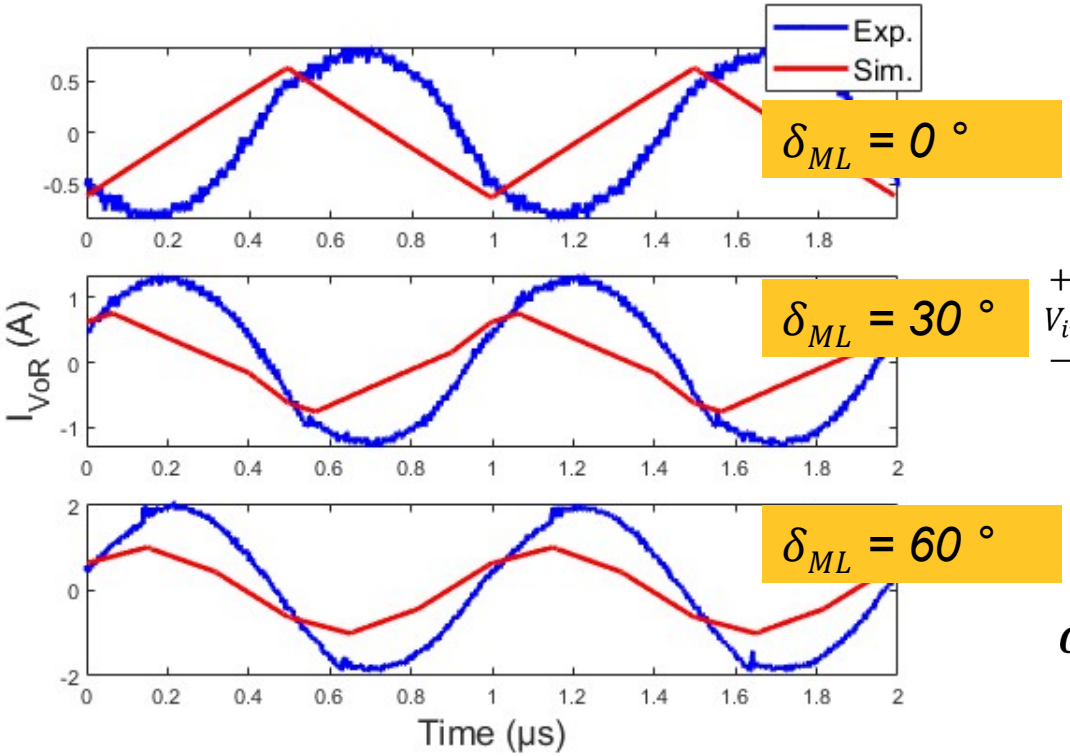
Operational Waveforms Match Expectation



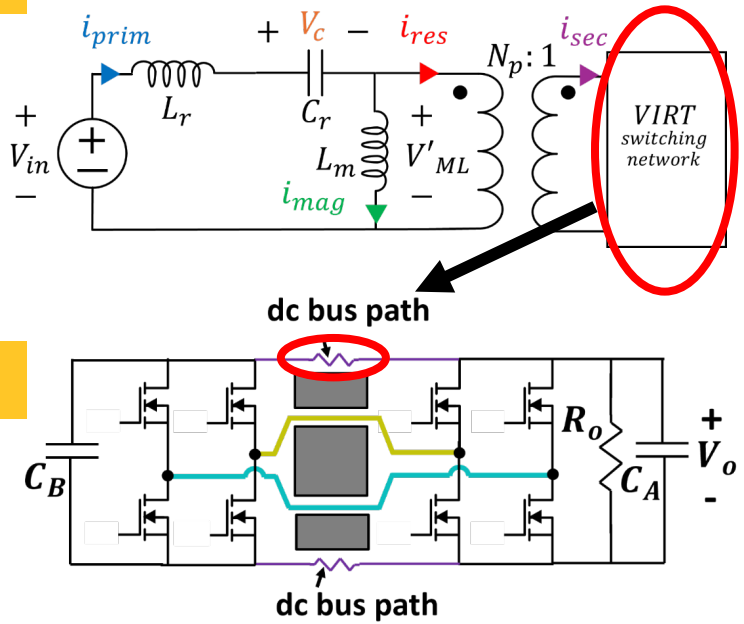


Primary tank current (I_{prim})

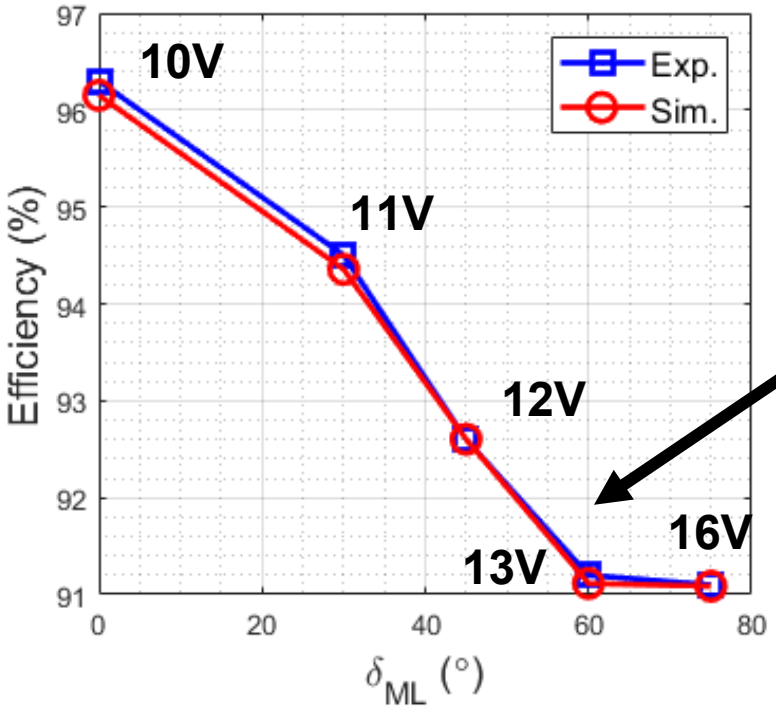
Modeling of Circulating Currents



Induced ac currents on the dc bus connections



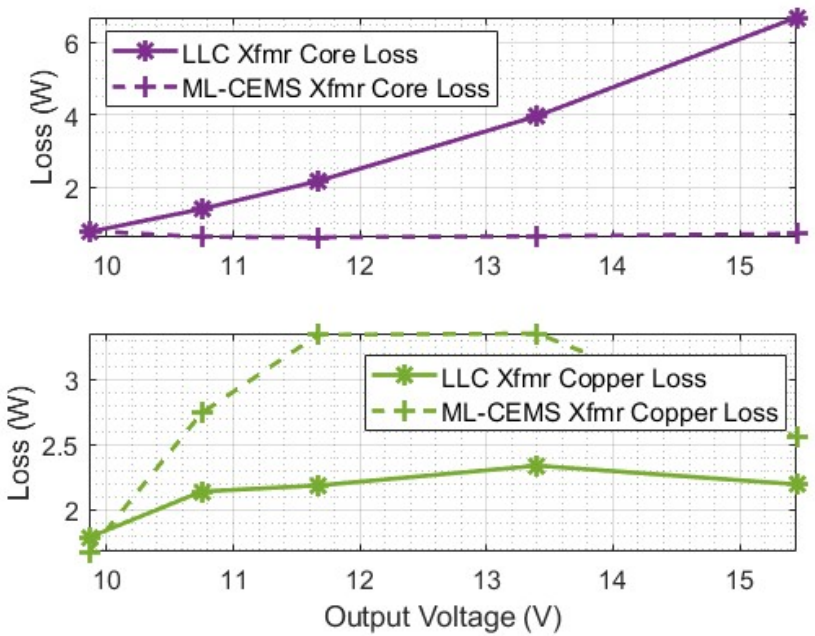
Loss Prediction is Accurate



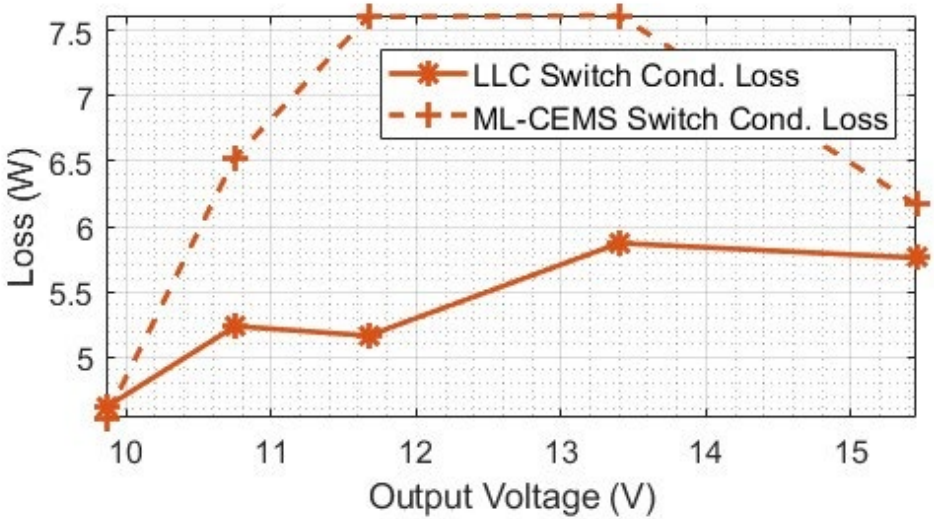
Efficiency drops as result of reverse conduction loss in the rectifier devices (prototype limitation)

Loss Model Provides Foundation for Future Design

Estimated core loss varies 1.2x under ML-CEMS operation vs. 8.8x with freq. modulation



Current-based losses vary by 1.6x under ML-CEMS operation vs. 1.2x with freq.



Future design will optimally leverage this constant-core-loss paradigm and minimize current-related losses

Key Features of the VIRT and Its Extensions

1. Fractional turn capability can help to achieve optimal core/copper loss trade-offs in high step down, high current applications.

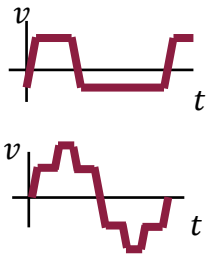
2. Integration of electronics yields variability that can be helpful for accommodating wide output voltage ranges. E.g., ML-CEMS operation has the interesting characteristic of smoothly re-shaping flux.

3. Our general modeling procedure enables the synthesis and exploration of other “Coupled Electronic and Magnetic Systems”

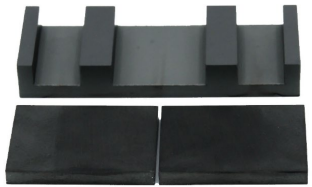
Next Steps for CEMSs

- Showcasing miniaturization benefit of ML-CEMS in a high-performance prototype
- Demonstrating higher voltage capabilities
- Exploring deployment in other isolated topologies
- Combine with magnetic material insights to develop “magnetically optimal” isolated power converters

Phase 1: Develop Testbeds to Identify the Best Operating Conditions of a Magnetic Component

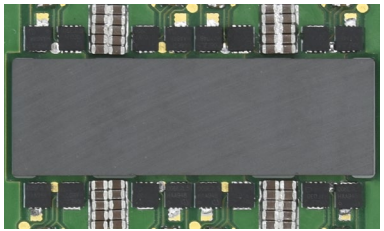


Use square and multilevel voltage excitations

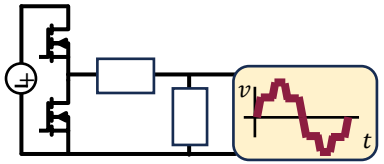


Collect accurate, high-frequency, waveshape- and coreset-dependent core loss

Phase 2: Develop Isolated Power Converters Capable of Exciting These Best Operating Conditions



Advance the high-performance, miniaturized “CEMS” unit cell, capable of multilevel excitation from a single dc bus



Define circuit topologies that meet power conversion requirements while optimally exciting the transformer