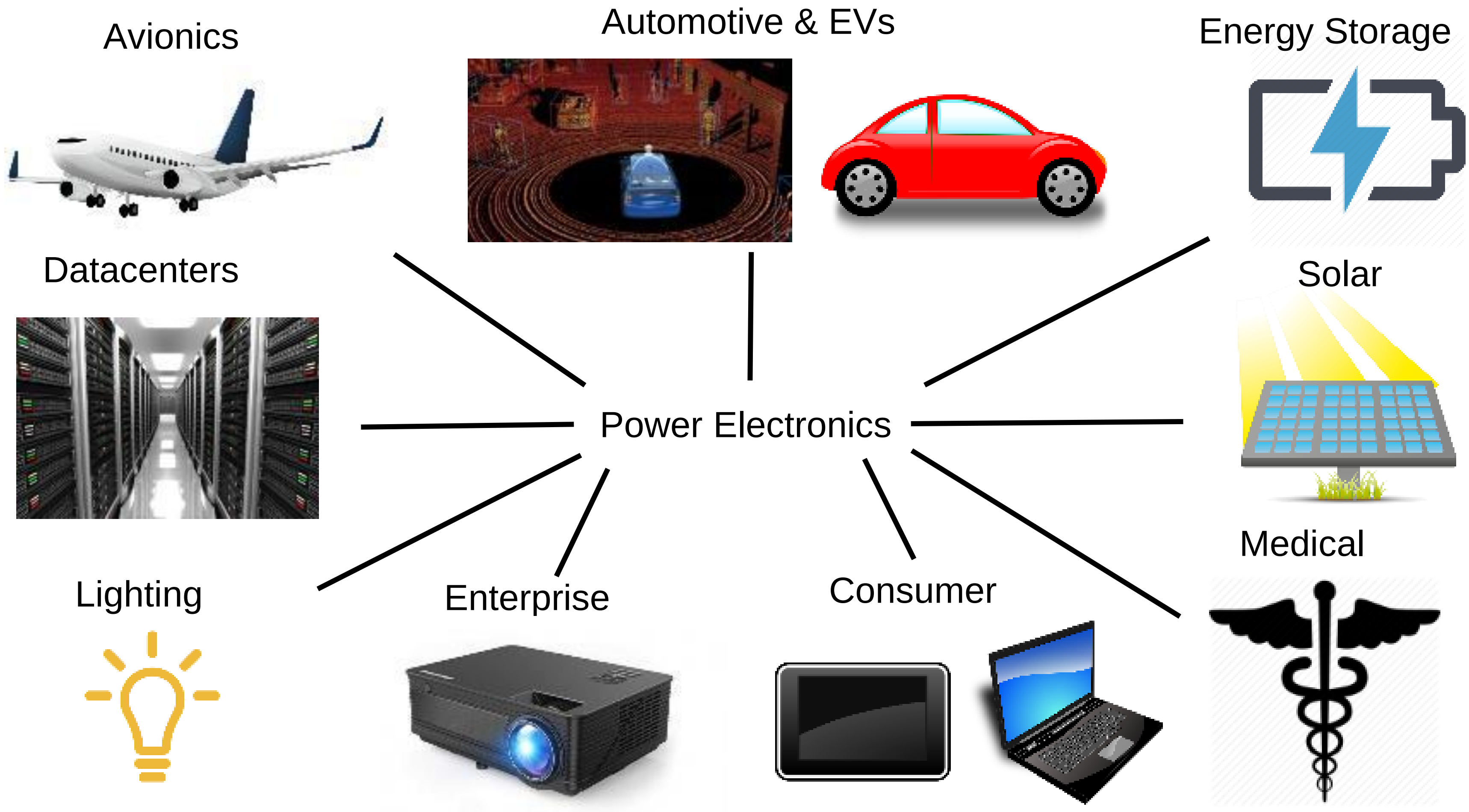
Ira A. Fulton Schools of Engineering
Arizona State University

PSMA

The Broad Spectrum of Technical Requirements for Power Magnetics Across Power Levels and Applications

2023 PSMA Power Magnetics @ High Frequency Workshop
Keynote – March 18, 2023
Mike K. Ranjram

Power Electronics Are Ubiquitous



Power Electronics

Avionics

Automotive & EVs

Energy Storage

Datacenters

Solar

Lighting

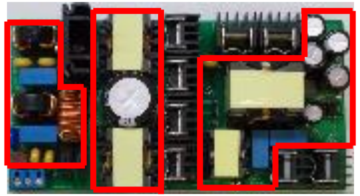
Enterprise

Consumer

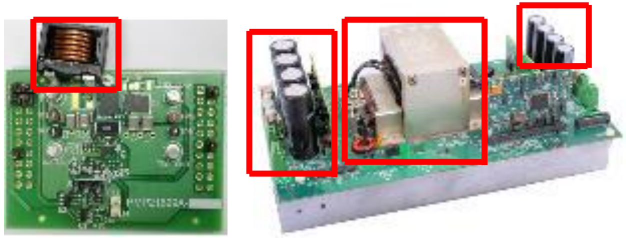
Medical

These and Many Applications are Bottlenecked by Passives

Avionics

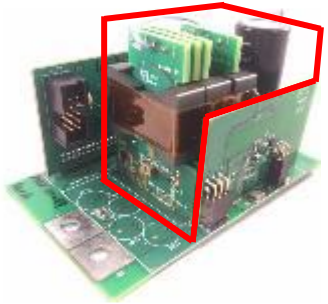


Automotive & EVs



Energy Storage

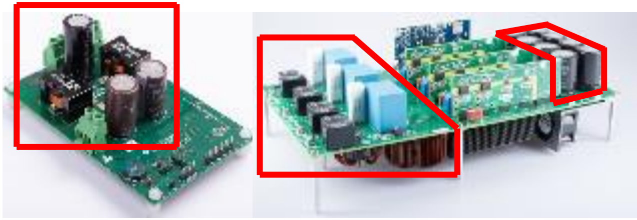
Data Centers



Power Electronics

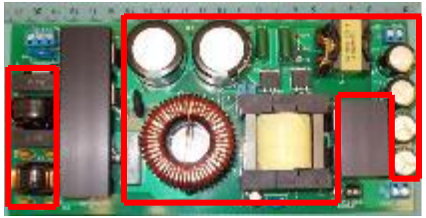
Reference designs from TI (citations on last slide)

Solar



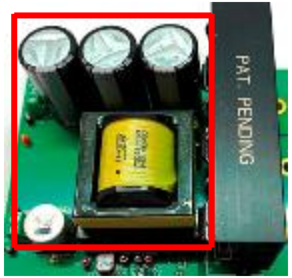
Lighting

Enterprise



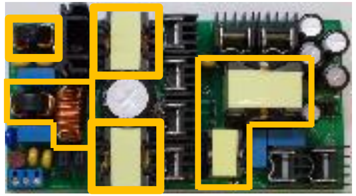
Consumer

Medical

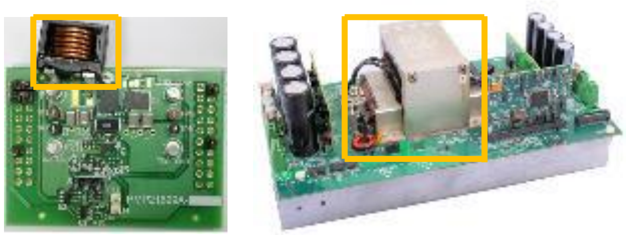


Our Focus: Magnetics, a Dominant Source of Weight, Loss, and Size

Avionics



Automotive & EVs



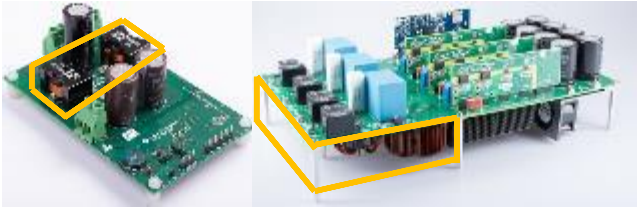
Energy Storage

Data Centers

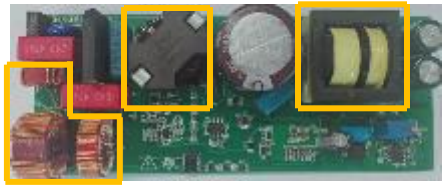
Power Electronics

Reference designs from TI (citations on last slide)

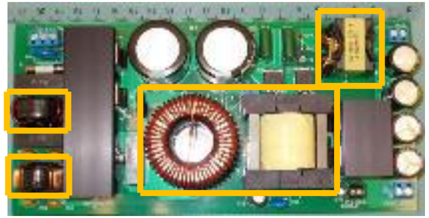
Solar



Lighting



Enterprise



Consumer

Medical

Our Goal: Understand the Requirements on These Components

- What function is demanded?
- What are the design goals?
- What technologies are used?

Clear bottleneck in these applications, but not all magnetics do the same thing. What’s key to making things better?

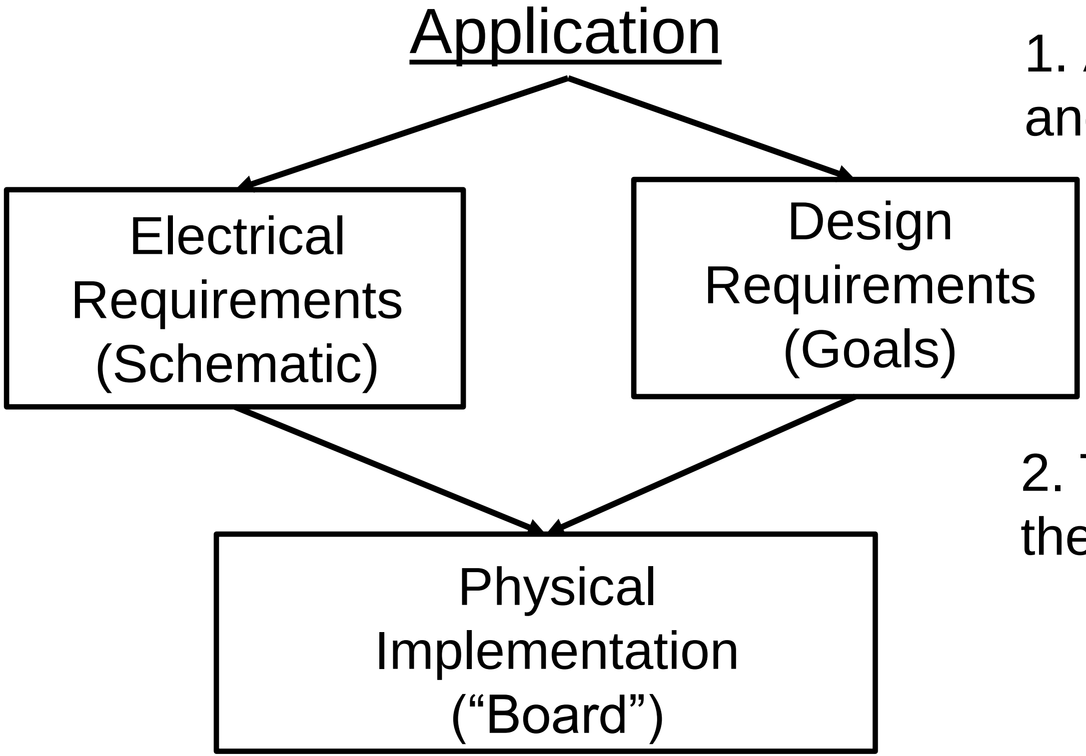
Before we discuss the requirements, I’d like to present my “cataloguing” of magnetic components

A Caveat on Design

“**A design is never uniquely appropriate. Rather, a design is judged “best” according to criteria established by the application.** For instance, if an inductor must not exceed a certain volume, several different designs using different materials and construction methods might be satisfactory. The “best” solution then becomes somewhat subjective and relies heavily on experience.”

J.G. Kassakian, D. J. Perreault, G. Verghese, M. Schlecht, “Principles of Power Electronics” 2nd. Ed.

The Layers of Technical Requirements



Application

Electrical Requirements (Schematic)

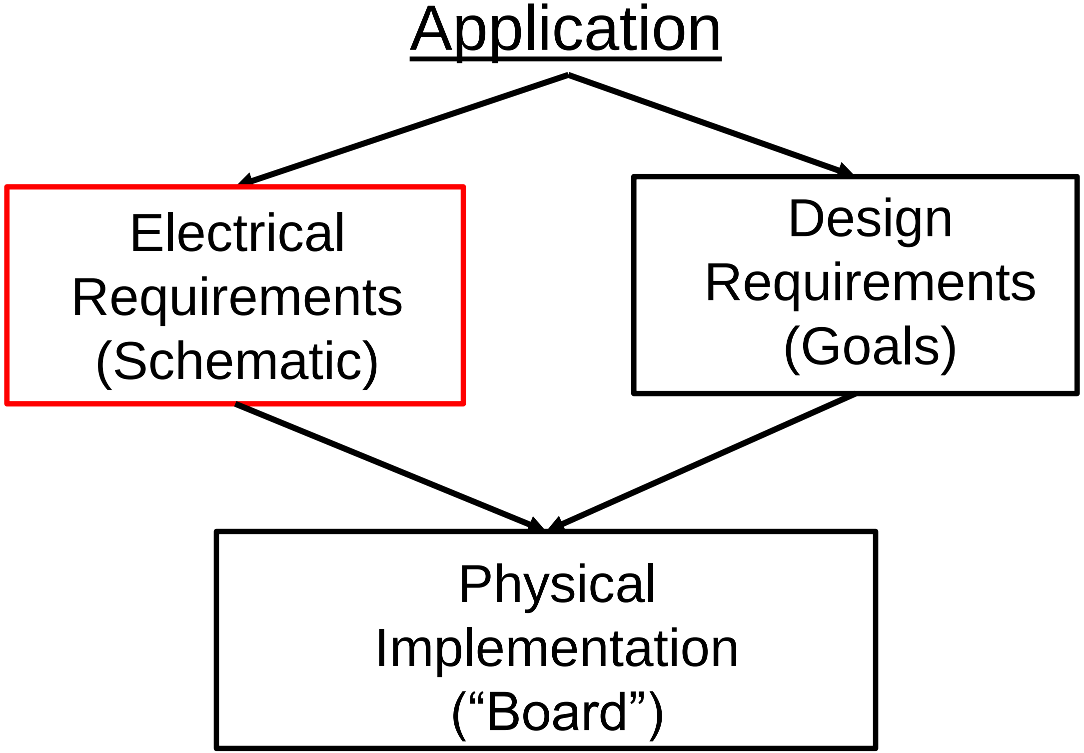
Design Requirements (Goals)

Physical Implementation (“Board”)

1. Application enforces electrical and design requirements

2. These enforce requirements on the physical implementation

Layer 1: Electrical Requirements



Application

Electrical Requirements (Schematic)

Design Requirements (Goals)

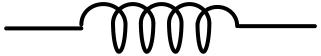
Physical Implementation (“Board”)

Question 1:
What kind of electrical requirements are being imposed by applications?

Layer 1: Electrical Requirements

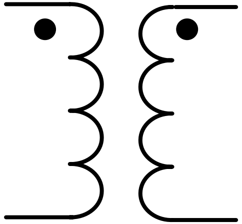
“Schematic”
Electrical
requirements

Inductors (single-winding)



- Inductance
- Winding voltage/current
- Frequency, waveshape

Transformers / “multi-winding” magnetics

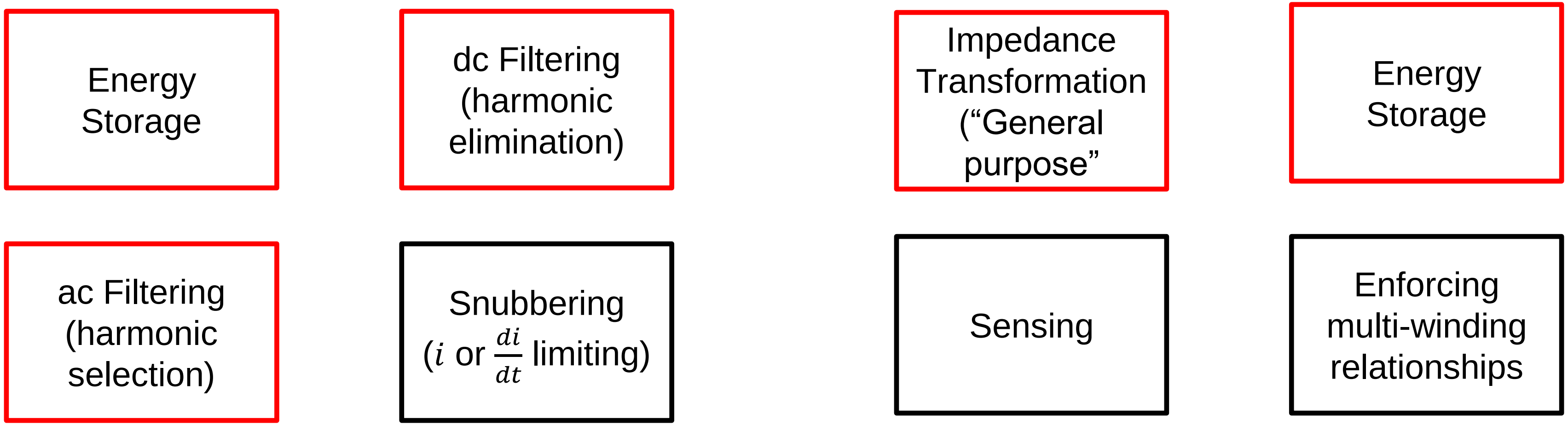


- Inductance matrix
- Turns ratio
- Winding voltages/currents
- Frequency, waveshape

- Often a “start” for power electronic converter design (i.e., not typically ‘magnetics-centric’)
- Determine electrical requirements on magnetic component, then buy or create it

Clarify our Scope: Functional Categories

- Magnetics design is messy, many possibilities in each layer of the design
- One application almost certainly has multiple magnetic functions – e.g., there is no single “power magnetic for avionics”
- Make categorization into functional (electrical) categories – applies to most applications/power levels



Inductors

Energy Storage

dc Filtering (harmonic elimination)

ac Filtering (harmonic selection)

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

Transformers

Impedance Transformation (“General purpose”

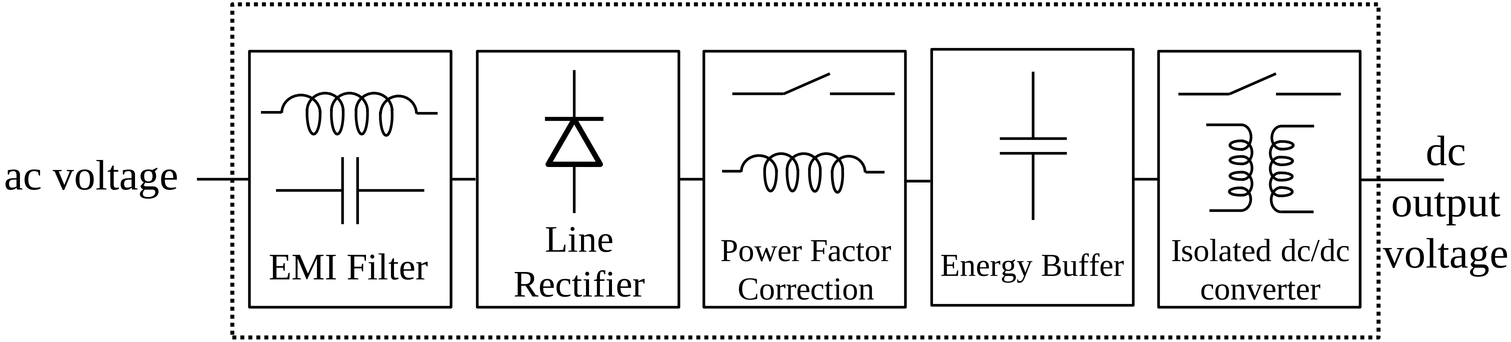
Energy Storage

Sensing

Enforcing multi-winding relationships

Usually isolated

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



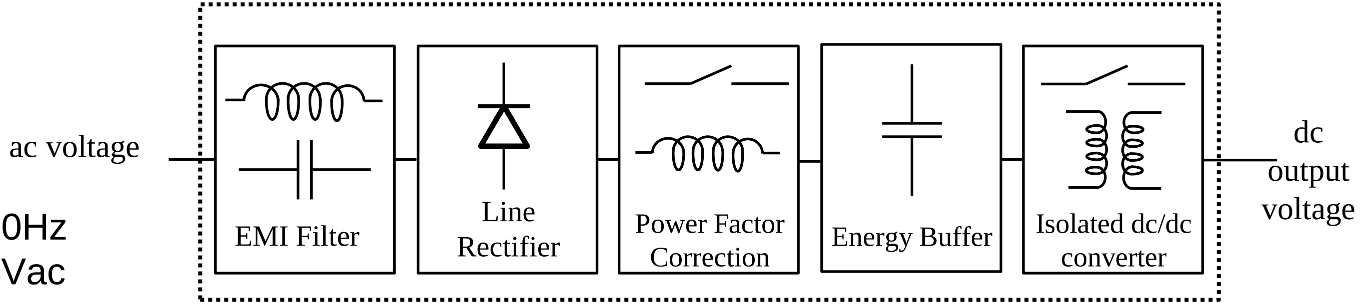
- A “staple” power converter, ac to controlled dc with isolation
- Contains many common magnetic functions:

    Inductors: energy storage, dc filtering, ac filtering

    Transformers: impedance transformation, energy storage

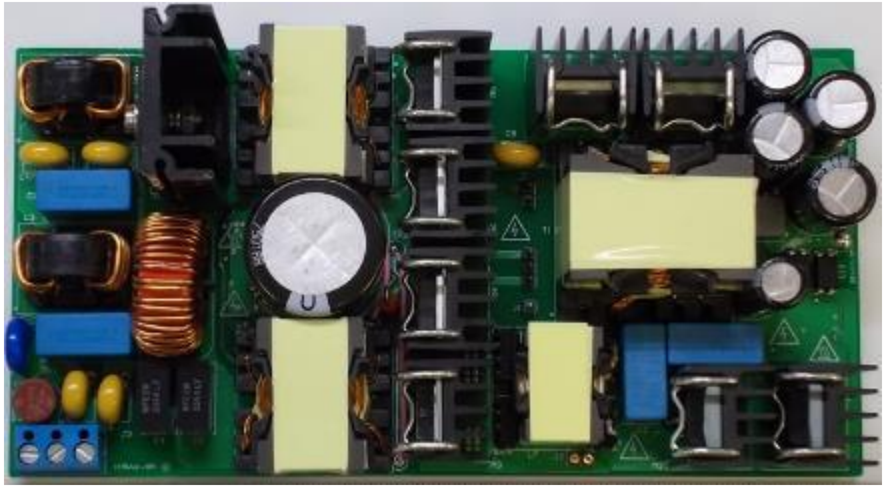
- For example, consider Texas Instruments reference design PMP30763 for avionics

Consider TI Avionics Converter Reference Design



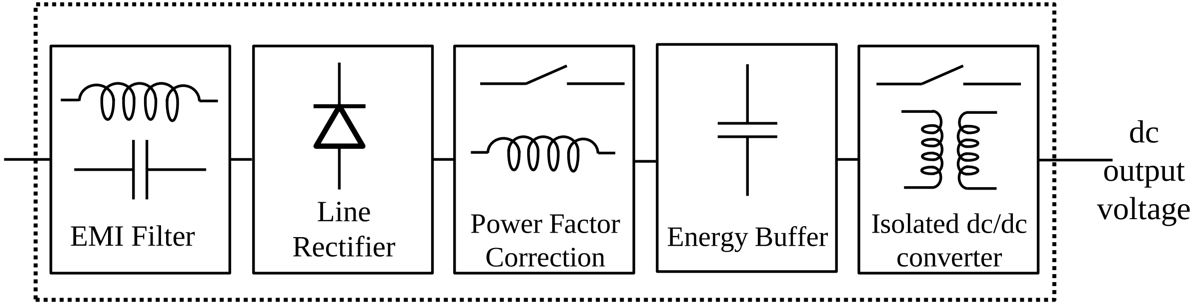
360-800Hz
96-134Vac

30V, 400W



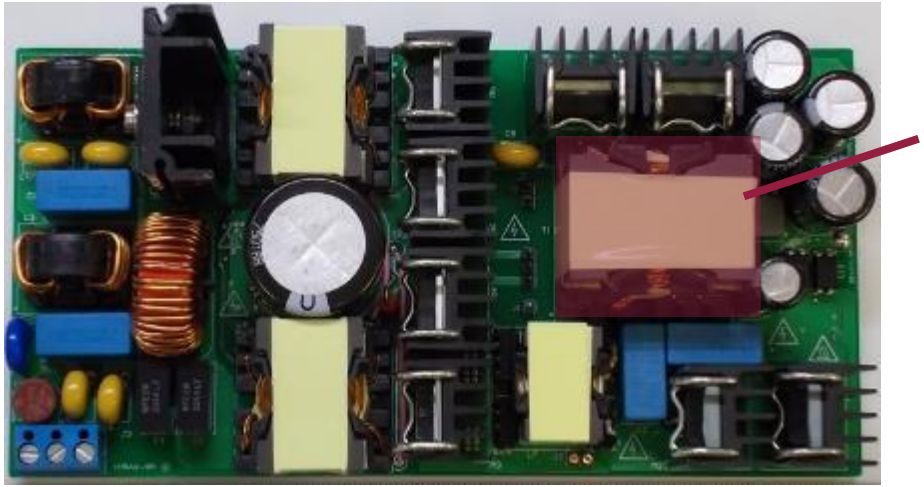
https://www.ti.com/tool/PMP30763

Consider TI Avionics Converter Reference Design



360-800Hz
96-134Vac

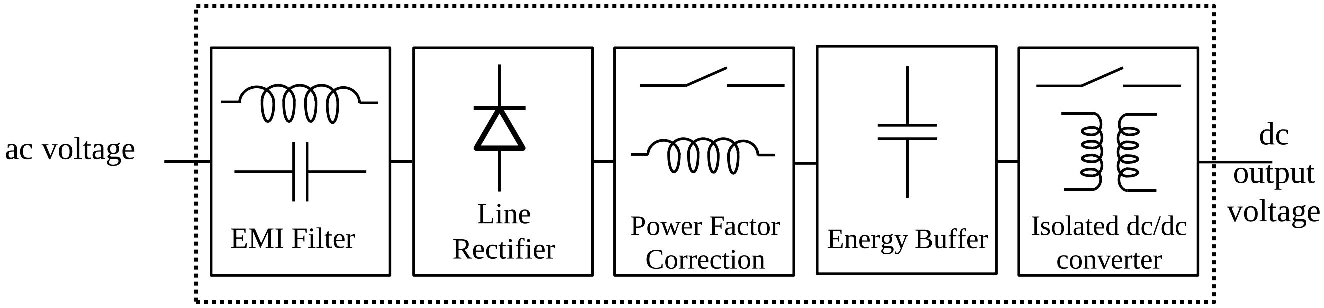
30V, 400W

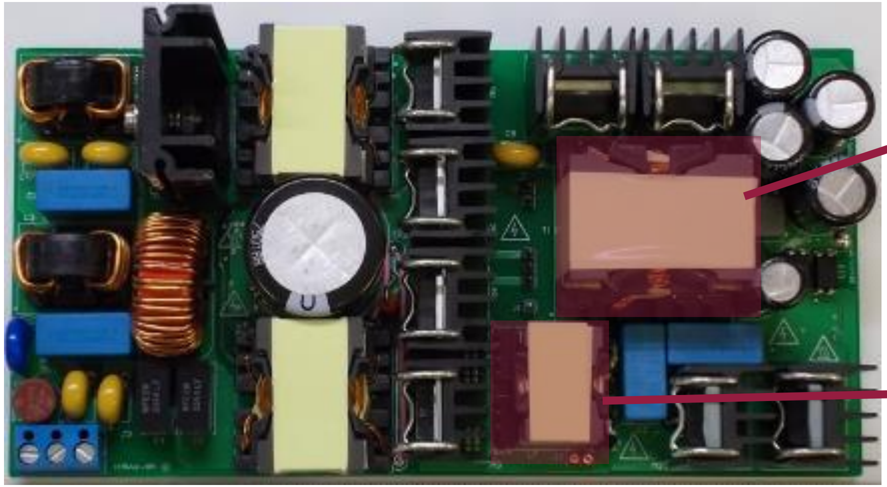


4:1 step-down transformer
1500Vac isolation
(Used in HB LLC)
“Impedance Transformer”
+ “Energy Storage”

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

Consider TI Avionics Converter Reference Design



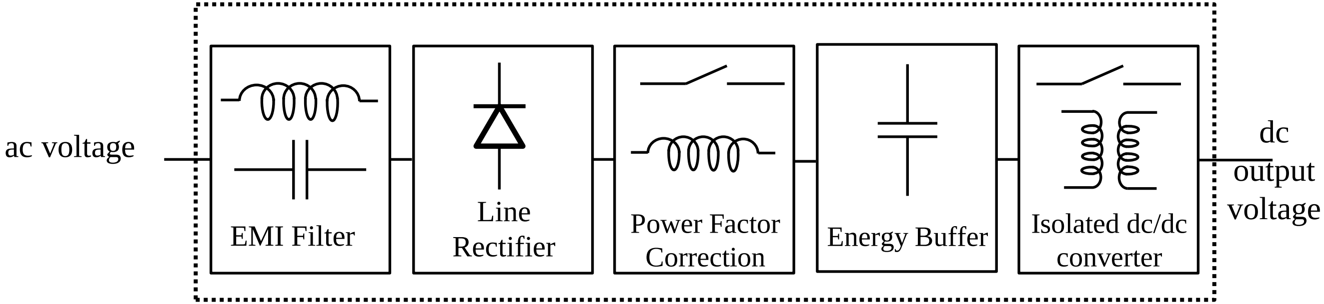


4:1 step-down transformer
1500Vac isolation
(Used in HB LLC)
“Impedance Transformer”
+ “Energy Storage”

LLC Resonant Inductor
“Harmonic Selection”

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

Consider TI Avionics Converter Reference Design



ac voltage

EMI Filter

Line Rectifier

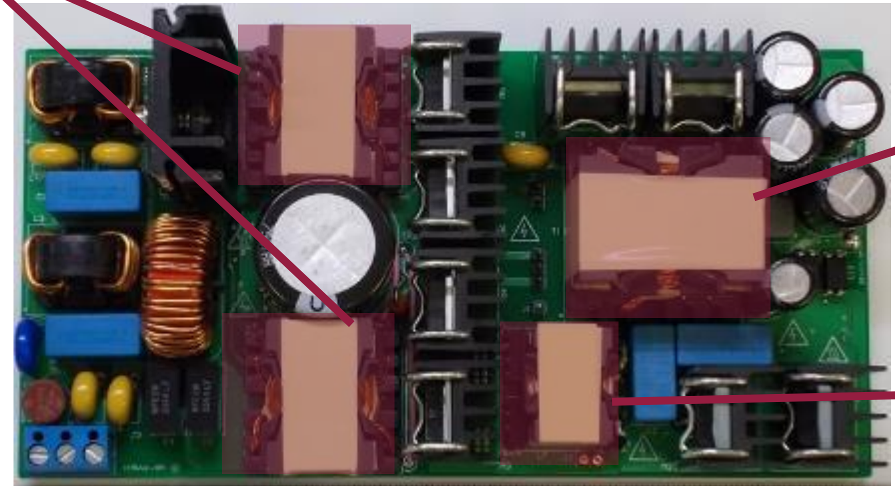
Power Factor Correction

Energy Buffer

Isolated dc/dc converter

dc output voltage

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

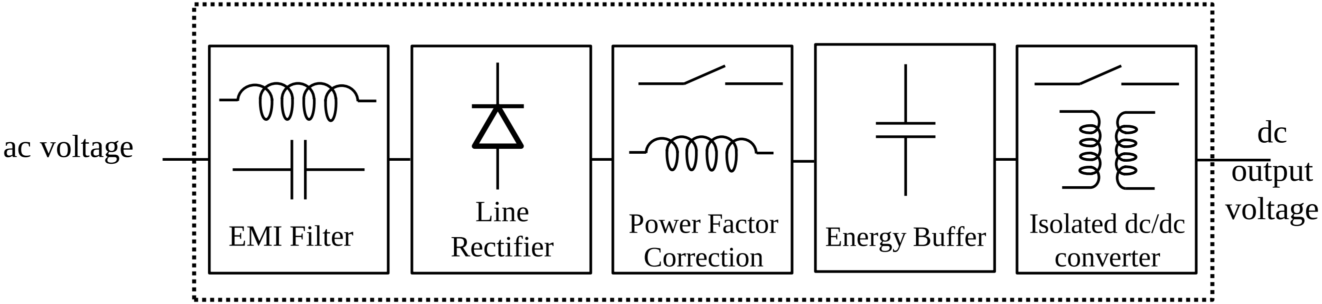


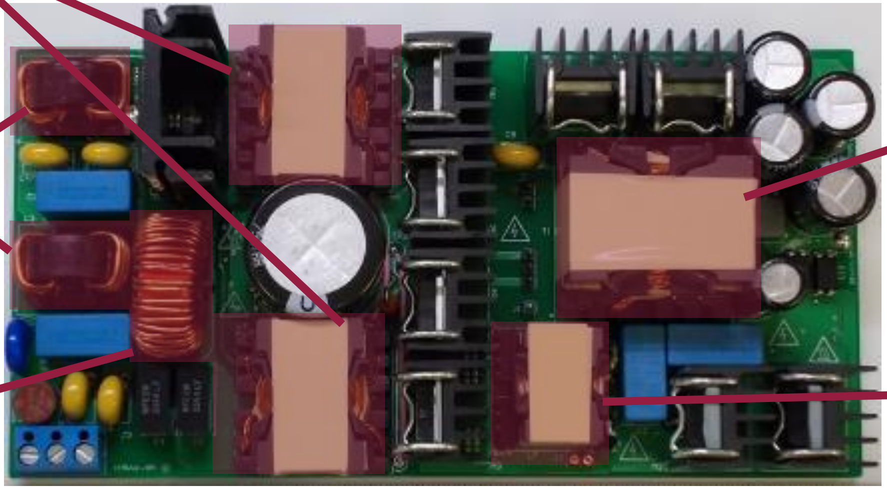
4:1 step-down transformer
1500Vac isolation
(Used in HB LLC)
“Impedance Transformer”
+ “Energy Storage”

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”

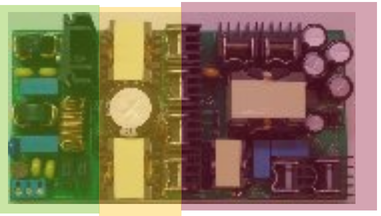
Differential-mode choke
“dc filtering”

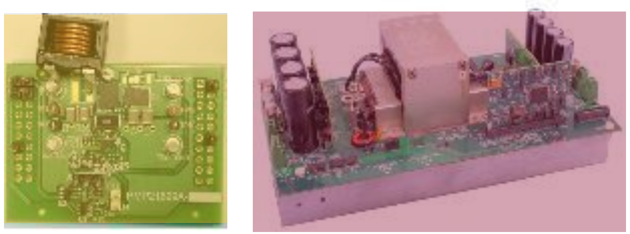
4:1 step-down transformer
1500Vac isolation
(Used in HB LLC)
“Impedance Transformer”
+ “Energy Storage”

LLC Resonant Inductor
“Harmonic Selection”

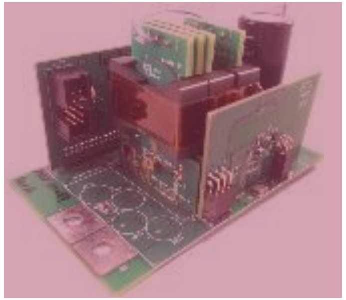
https://www.ti.com/tool/PMP30763

These Functions are Ubiquitous

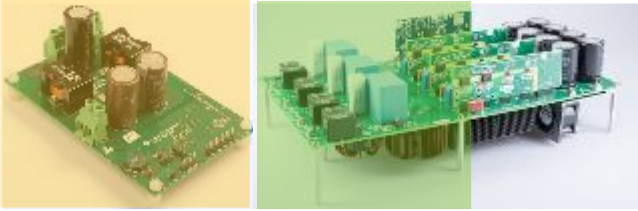

Avionics

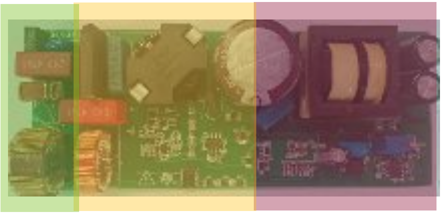

Automotive & EVs

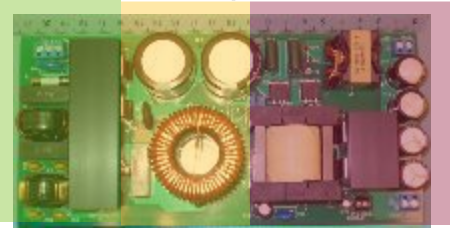

Energy Storage


Data Centers

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


Solar

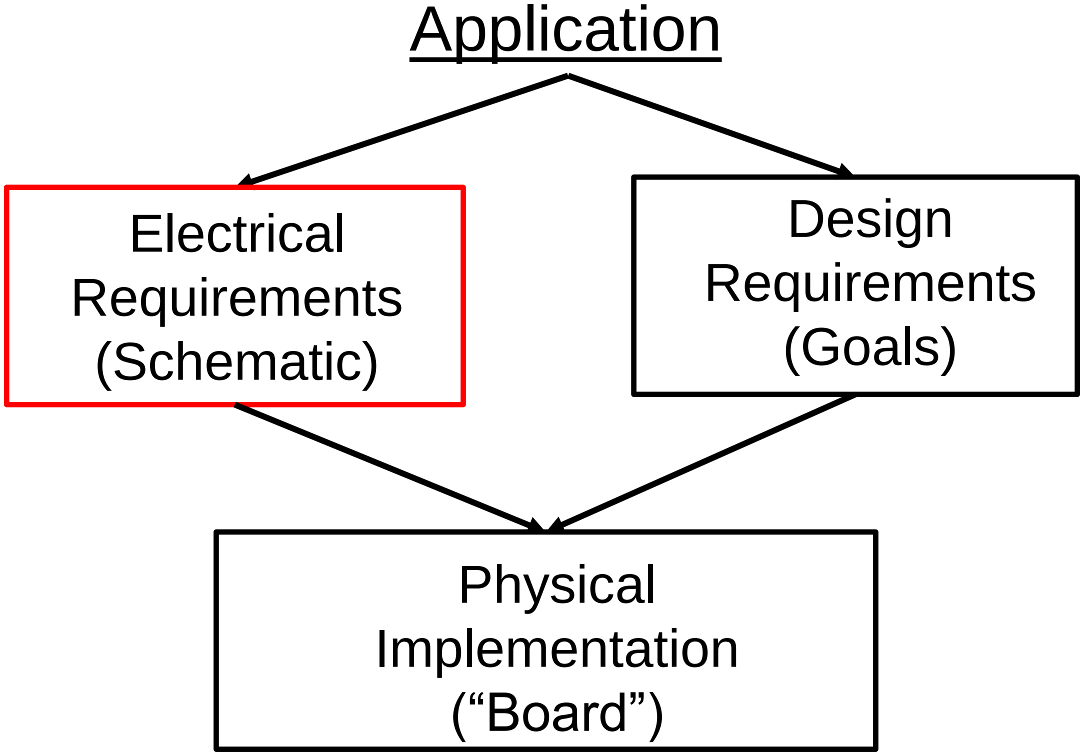

Lighting


Enterprise


Consumer

Medical

Layer 1: Electrical Requirements



Application

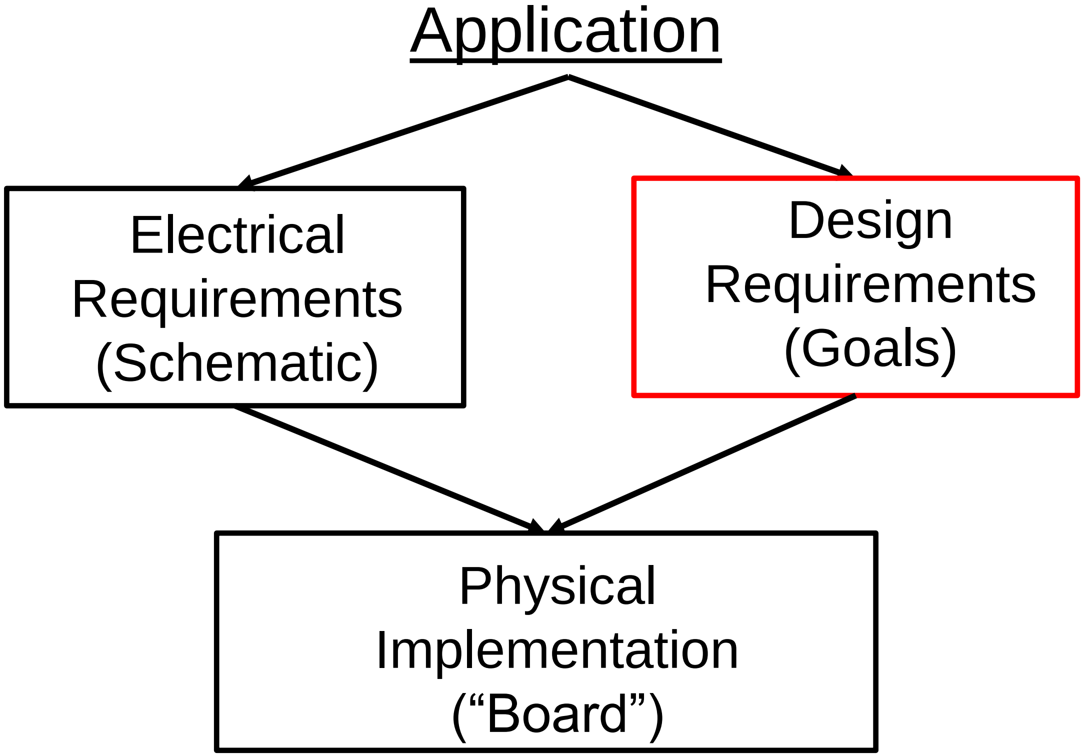
Electrical Requirements (Schematic)

Design Requirements (Goals)

Physical Implementation (“Board”)

Conclusion: Although the application environments are vast, our functional categorization is a good way to understand the **electrical** requirements on power magnetics

Layer 2: Design Requirements



<u>Application</u>

Electrical Requirements (Schematic)

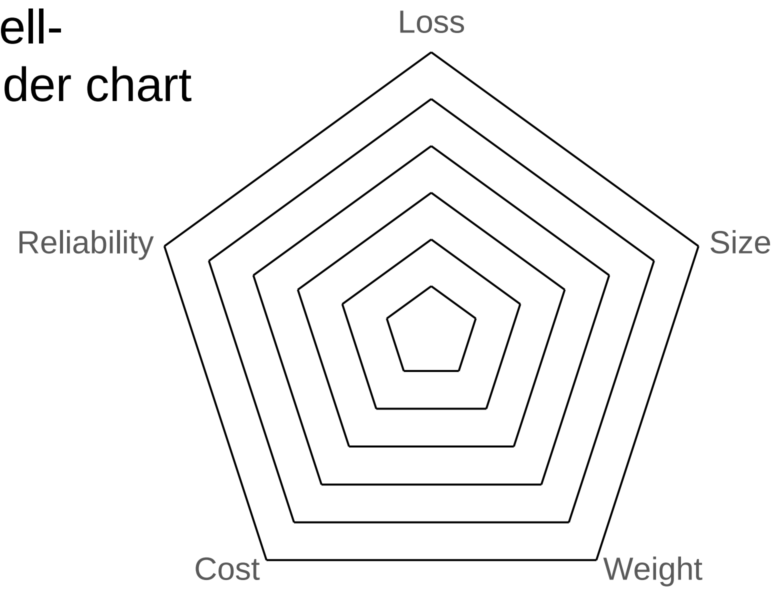
Design Requirements (Goals)

Physical Implementation ("Board")

Question 2: What kind of design requirements are being imposed by applications?

Layer 2: Design Goals and Constraints

Most application requirements are well-captured by this spider chart



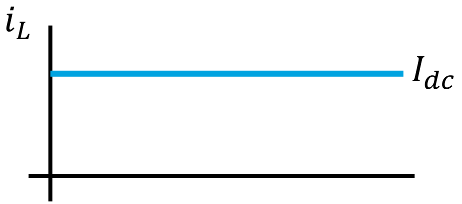
Viability constraints:
- Core saturation
- Thermal rise
- Isolation requirement

These provide "governing guidance" on what the physical realization of our magnetic will be

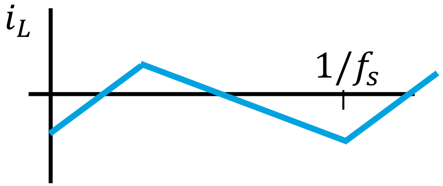
Loss as a Design Goal: dc vs. ac

- **dc loss**: if only dc current flows, owing to dc winding resistance
- **ac loss:** Core loss plus ac winding loss, if current has non-dc content

Simple

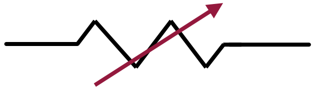


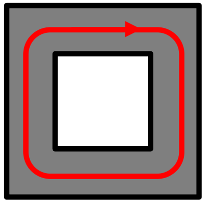
Complex



$$R_{dc} = \frac{\rho l}{A_w}$$

$$R = f(f_s, \text{field distribution})$$





dc resistance
Easy to model, though
temperature dependent

$$P_{w,dc} = I_{dc}^2 \mathrm{R}_{\mathrm{dc}}$$

ac resistance
Skin effect
Proximity effect
Hard to model (fields specific)

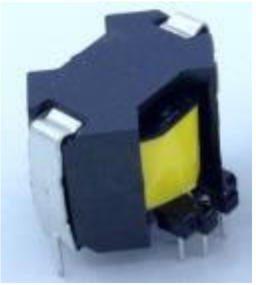
Core loss

Function of:
frequency, flux density,
temperature, waveshape

Size as a Design Goal: Volume vs. Packaging

- **Volume**: Typically, box volume rather than displacement volume
- **Packaging:** A certain footprint or box dimension may be more important than raw volume (e.g., for overall miniaturization)

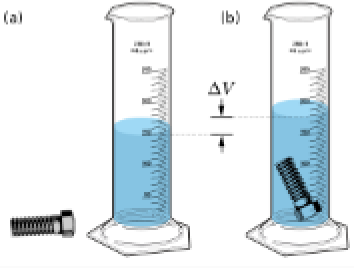
Datasheet
V_e

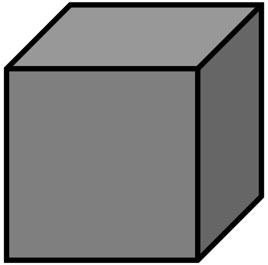


Displacement volume

Box volume

Packaging





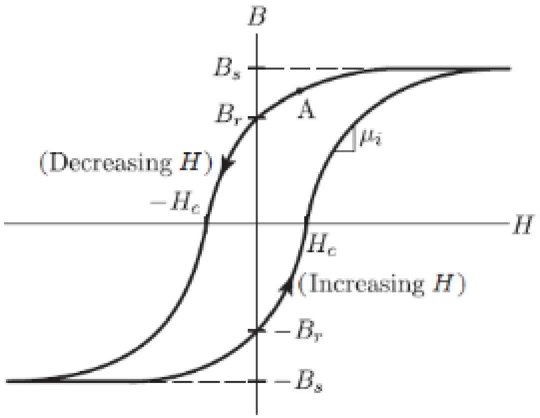
https://en.wikipedia.org/wiki/Displacement_%28fluid%29
EPCOS N87 RM 5

https://ranlo.en.ec21.com/RM4_RM5_RM6_RM8_RM10--7043495_7044121.html

Viability Constraints

Core Saturation

$$B < B_{sat}$$



Thermal Rise

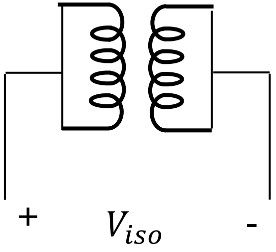
1. $T < T_{curie}$

   Hard limit to avoid damage to magnetic properties of the core

2. $T < T_{system}$

   More common limit, to avoid other parts of the system getting too hot (nearby elements, insulation)

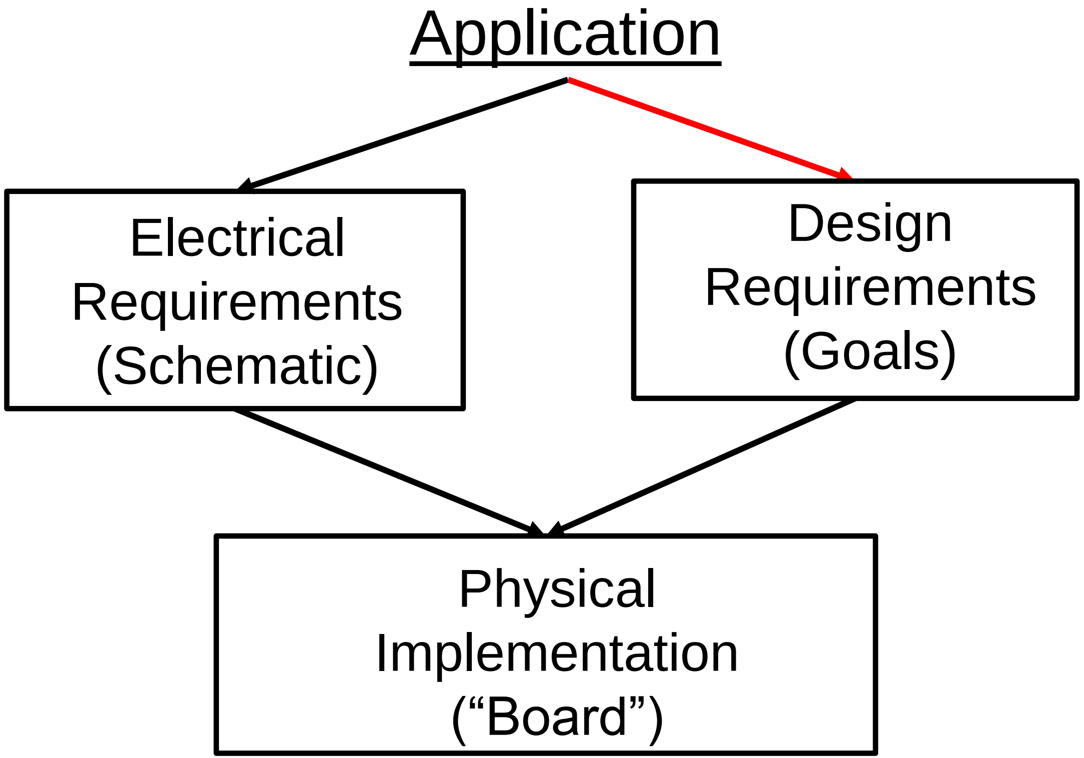
Isolation



Capable of withstanding isolation voltage between windings (typ. >> winding voltages)

J.G. Kassakian, D. J. Perreault, G. Verghese, M. Schlecht, “Principles of Power Electronics” 2nd. Ed.

What Design Requirements do Applications Set?



Application

Electrical Requirements (Schematic)

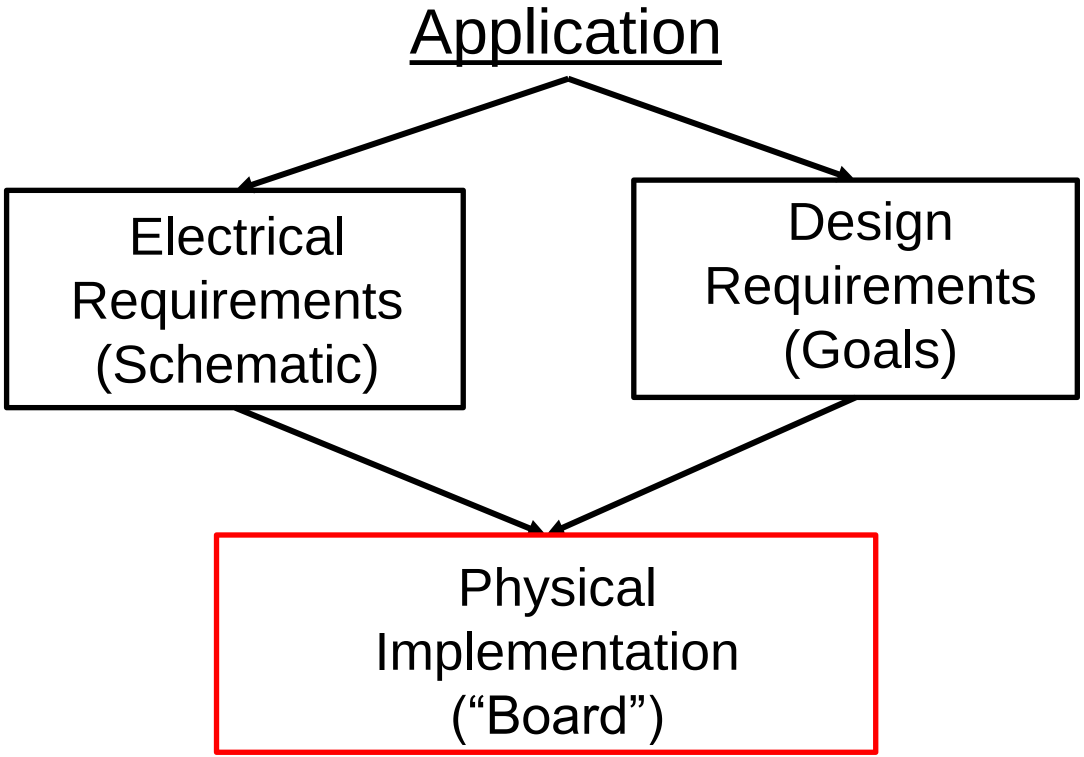
Design Requirements (Goals)

Physical Implementation (“Board”)

Design Goals in Our Applications of Interest

Loss	Ubiquitous (high efficiency)
Size	Volume-constrained applications: • Avionics, Automotive, Data Centers, Lighting
Weight	Transportation: • Aerospace, Automotive
Cost	Ubiquitous. In high performing/critical applications, system-level trade-offs may prefer loss, size, weight reductions (“miniaturization”) over cost in the converter.
Reliability	• Mission critical applications (Aerospace) • Balance of system costs (Renewables)

Layer 3: Physical Implementation



Application

Electrical Requirements (Schematic)

Design Requirements (Goals)

Physical Implementation (“Board”)

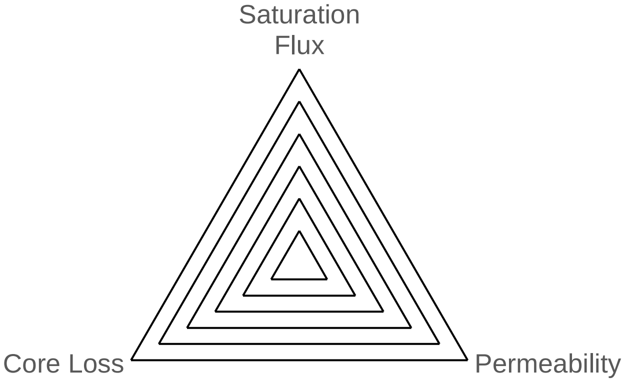
Question: How do these requirements inform the physical design of the power magnetic?

First, an overview on some of the implementation possibilities

Material Parameters

We characterize materials by:

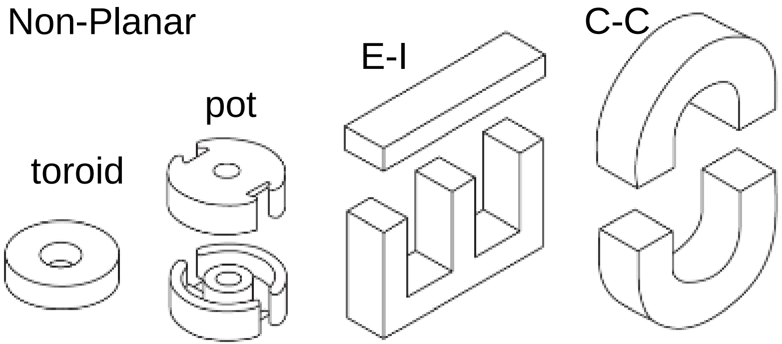
- Permeability, saturation flux density, core loss
- Curie temp, resistivity
- Density, permittivity, thermal conductivity



	Material	μ/μ_o	$B_s\ (T)$	$T_c\ (°C)$	$\rho\ (\mu\Omega - cm)$	Frequency
Air	-	1	-	-	Open circuit	-
Ferrite	Ni-Zn Ferrite	4-500	0.3	300	10^{13}	1-30MHz
Ferrite	Mn-Zn Ferrite	1,000-4,000	0.4-0.8	150-230	$10^7 - 10^9$	20kHz-1MHz
Laminated Iron	Si steel (2.5%)	5,000	2.0	780	40	<1kHz
Amorphous	Metallic glass	10,000	1.6	370	125	10k-50kHz

Adapted from J.G. Kassakian, D. J. Perreault, G. Verghese, M. Schlecht, “Principles of Power Electronics” 2nd. Ed, Table 18.1

Construction Parameter: Core Shape



J.G. Kassakian, D. J. Perreault, G. Verghese, M. Schlecht, “Principles of Power Electronics” 2nd. Ed, Fig. 15.14

Qualitative assessment for discussion

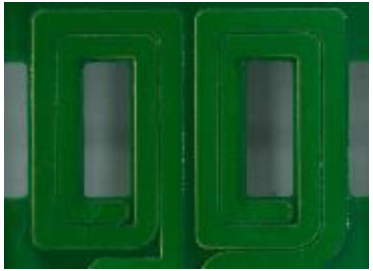
Core:
Toroid lowest cost: one-piece, simple manufacturing
Custom highest cost (no economy of scale, unless you have that sort of purchasing power)

Winding:
Open bobbin cores easiest to make (lower cost)
Toroid winding must be threaded, increases cost

https://www.electronicsweekly.com/news/products/power-supplies/pcim-old-ferrites-get-new-life-gan-switching-2017-05/

Construction Parameter: Wire Type

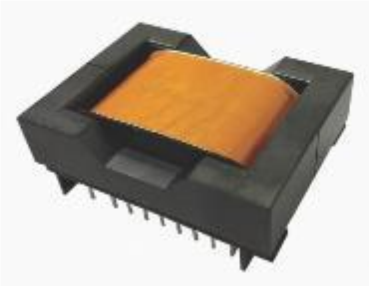
Planar PCB



Magnet Wire

https://www.digikey.com/en/products/detail/adafruit-industries-llc/3522/7393587

Foil



https://www.wcmagnetics.com/product/shaped-foil-inductor-319-series/

Litz

https://www.deeterelectronics.com/us/product/litz-wire/litz-wire/

Qualitative assessment for discussion

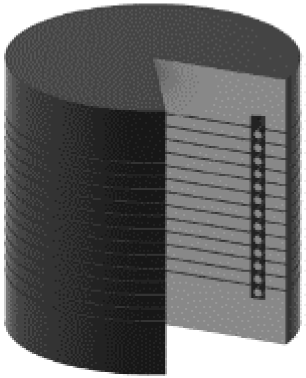
Cost	Low	Med	Med-High	High
Packing Factor (K_u)	Extremely low	Med-High	Very High	Med
HF Utility (>1MHz)	High (wide thin sheets)	Low	High (wide thin sheets)	Low-Med (AWG48 practical minimum)

Key winding parameters: Number of turns, Wire resistivity ρ, Wire cross-sectional area A_W

Construction Parameter: Architectures

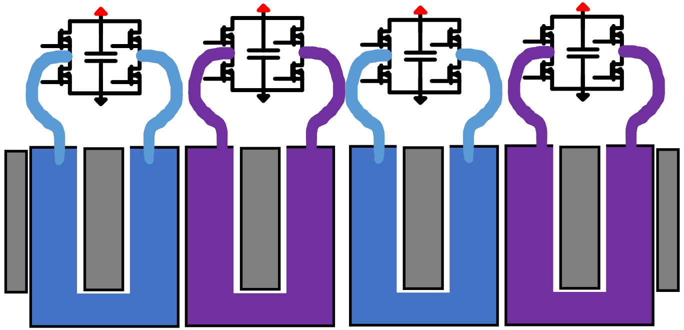
Power electronics research on magnetics often focuses on innovations at the architecture level:

- How do we do more with the pieces we have?
- How do we best utilize the pieces for new applications?



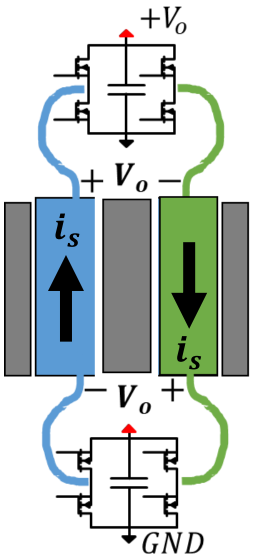
Carefully distributed gaps for double-sided winding conduction at HF

R. S. Yang, A. J. Hanson, B. A. Reese, C. R. Sullivan, and D. J. Perreault, "A Low-Loss Inductor Structure and Design Guidelines for High-Frequency Applications," *IEEE Transactions on Power Electronics*, vol. 34, no. 10, pp. 9993–10005, Oct. 2019, doi: 10.1109/TPEL.2019.2892397.



Matrix transformer for distributing a high turns count with high efficiency and good device paralleling

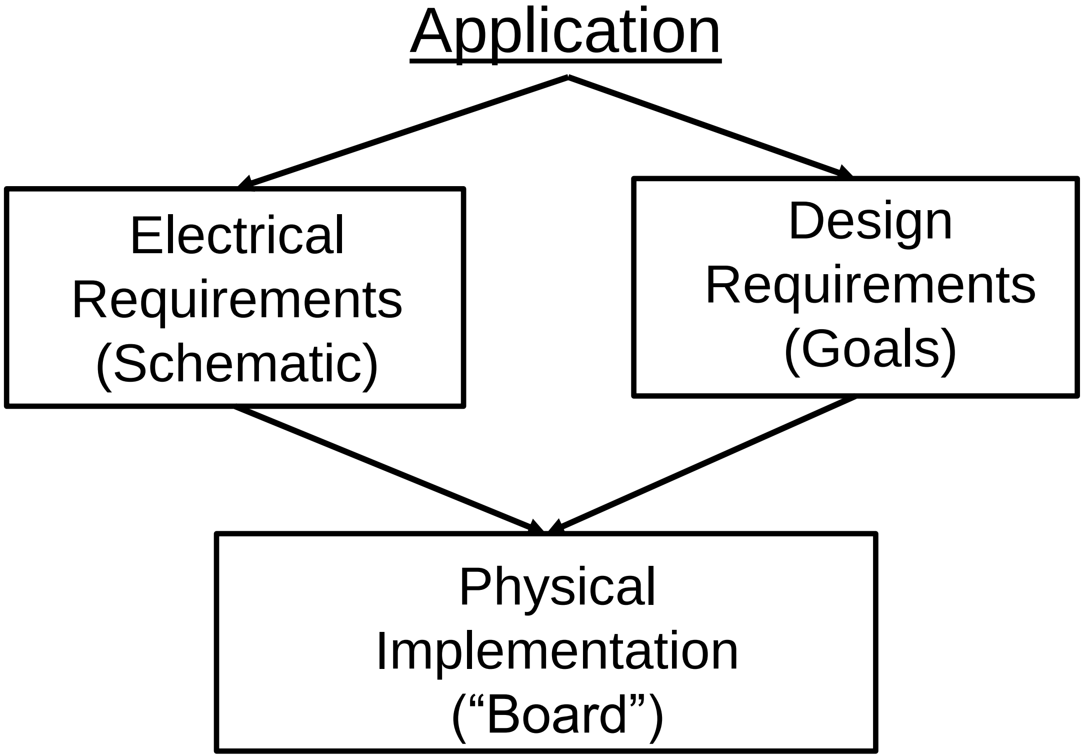
E. Herbert, "High frequency matrix transformer". United States Patent US5093646A, 1989.



Coupled Electronic and Magnetic System (CEMS) for fractional effective turns ratios ($N_p{:}\frac{1}{2}$)

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.

Summary so far



Application

Electrical Requirements (Schematic)

Design Requirements (Goals)

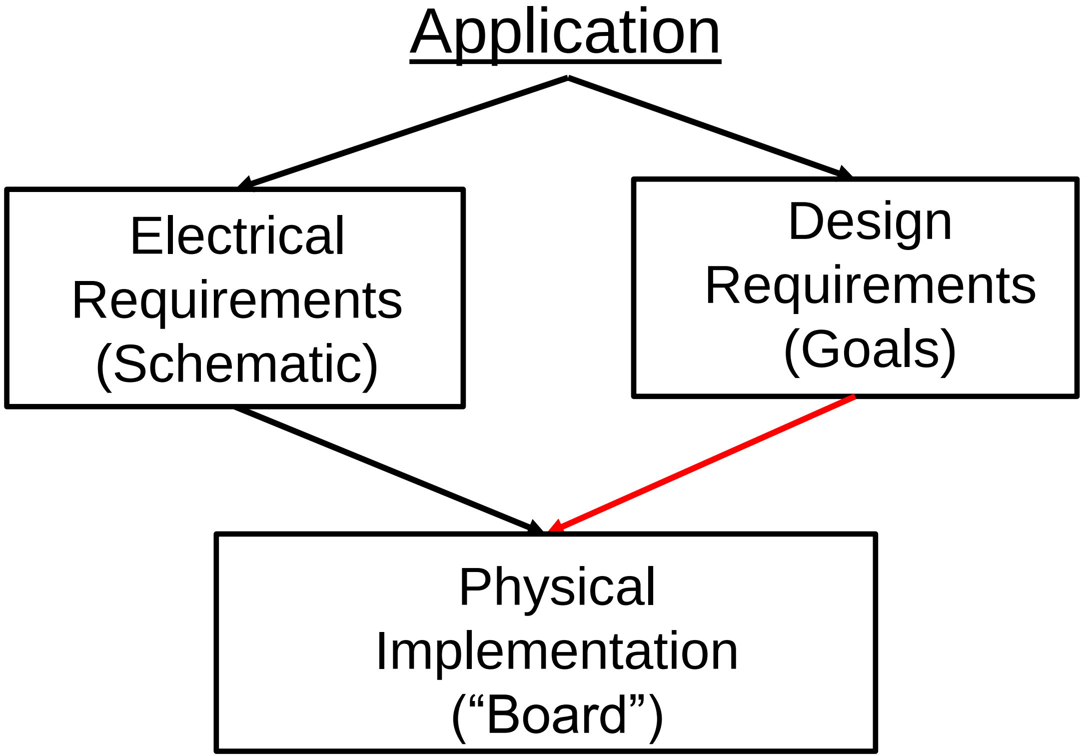
Physical Implementation ("Board")

We can create a reasonable partition on the "broad spectrum" of requirements on a magnetic:

- It has one of ~8 common electrical functions
- It serves some ranking of loss, size, weight, cost, reliability

And we reviewed the "playing field" onto which those requirements are imposed

How Do Design Goals Impact Physical Implementation?



Application

Electrical Requirements (Schematic)

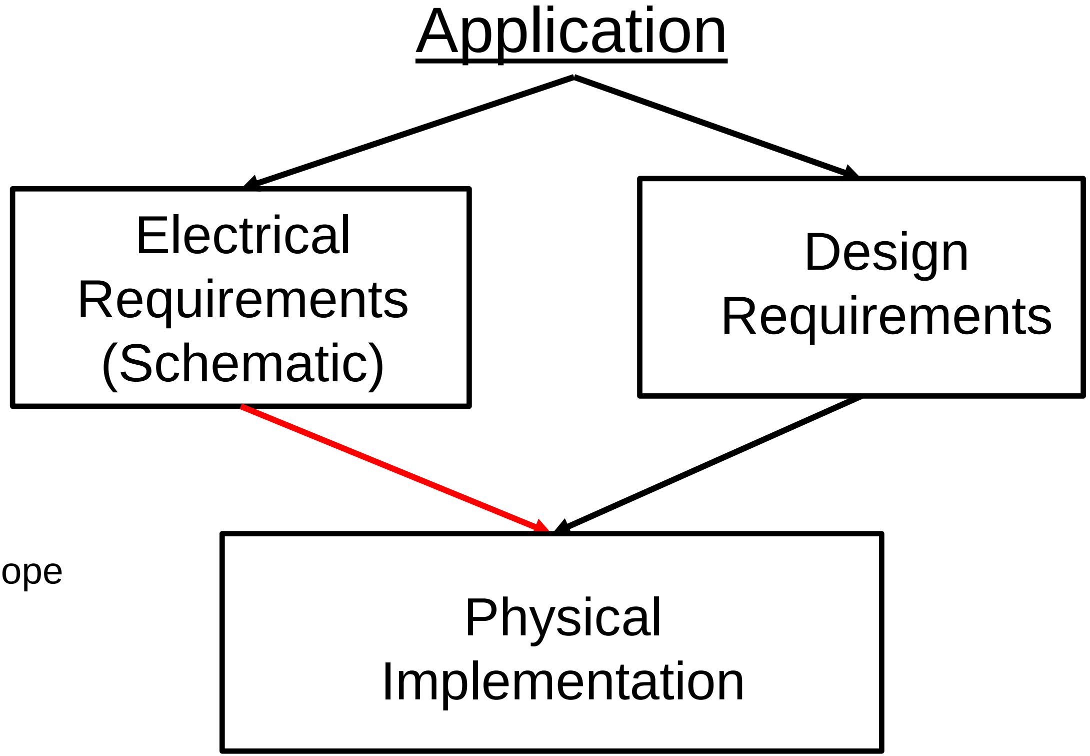
Design Requirements (Goals)

Physical Implementation (“Board”)

Design Goals Impact on Physical Implementation

Loss	Consider more exotic materials and approaches (Litz, CEMS, interleaving, distributed gaps, etc.)
Size	Consider planar constructions
Weight	Typically, minimize core material
Cost	Leverage low-cost options identified earlier
Reliability	Overdesign: insulation, temperature rise, impact of parameter degradation (due to oxidation, core stresses)

How Do Electrical Requirements Impact Physical Implementation?



Application

Electrical Requirements (Schematic)

Design Requirements

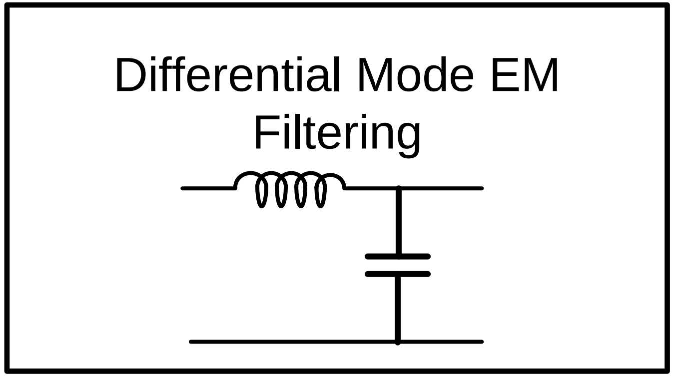
Physical Implementation

Focus on material requirements, for scope

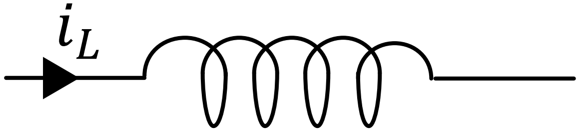
dc Filter Inductors – Electrical Requirements

- Intended to greatly mitigate ac current
- dc current >> ac current

Example application:



Differential Mode EM Filtering



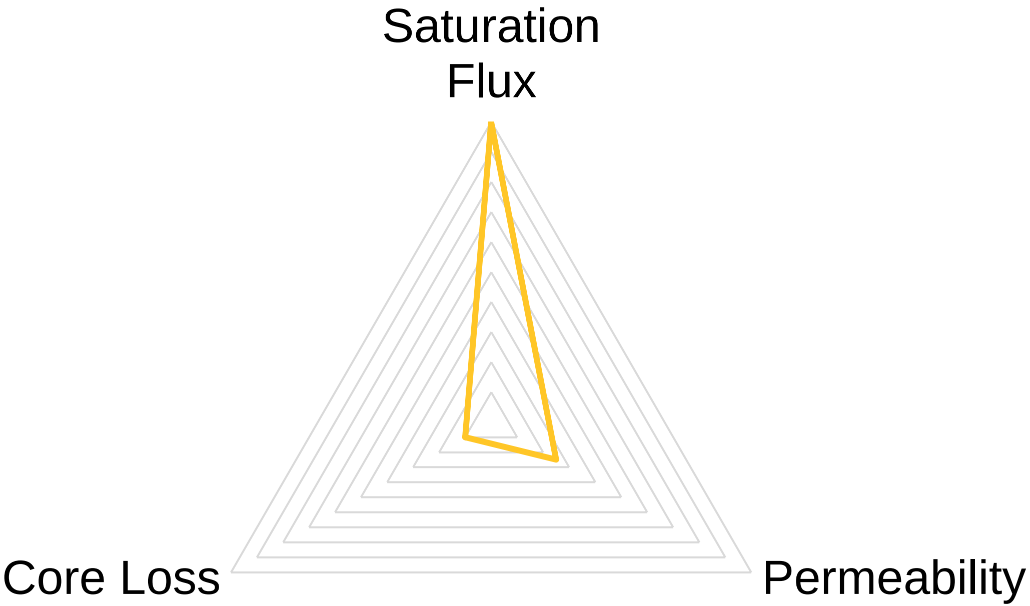
Material Requirements

Core Factor: $$\frac{L^2 I_{\max}^2 \rho}{B_{\mathrm{sat}}^2 R k_u} \le K_g = \frac{A_{c,min}^2 W_{A,b}}{l_T} \quad [m^5]$$

- Higher saturation better

- Permeability unimportant since *gapped*, <u>as long as we are confident about the path of flux</u>

- Assumes ac loss unimportant (Caveat: material permeability is frequency-dependent, not an inductor at all frequencies!)

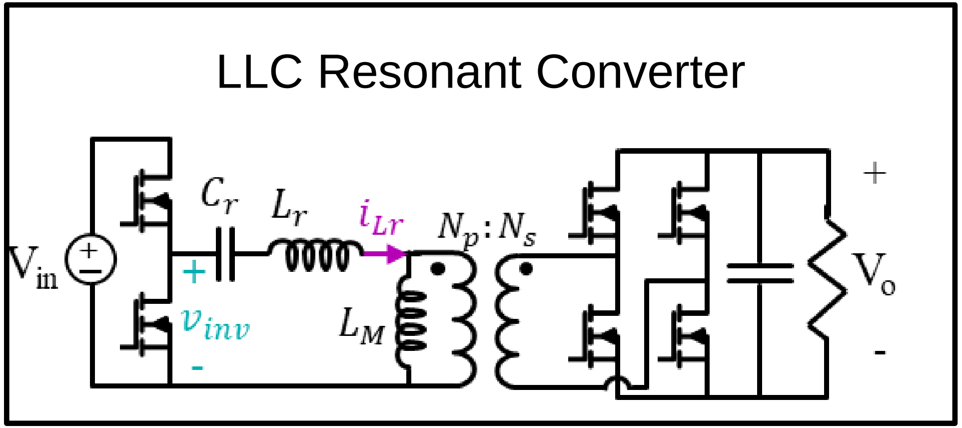


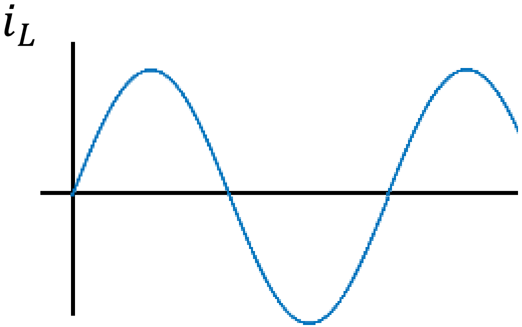
ac Filter Inductors – Electrical Requirements

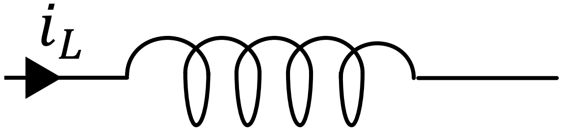
- Works in concert with other filter elements to select a single frequency
- ac current >> dc current
- Sinusoidal current

Example application:

LLC Resonant Converter







More Refined: Core Loss and Winding Loss Trade-off

Steinmetz Equation

$$P_c = V_c k f^{\alpha} \left(\frac{L I_{\mathrm{ac,pk}}}{A_{c,eff}} \right)^{\beta} \cdot N^{-\beta}$$

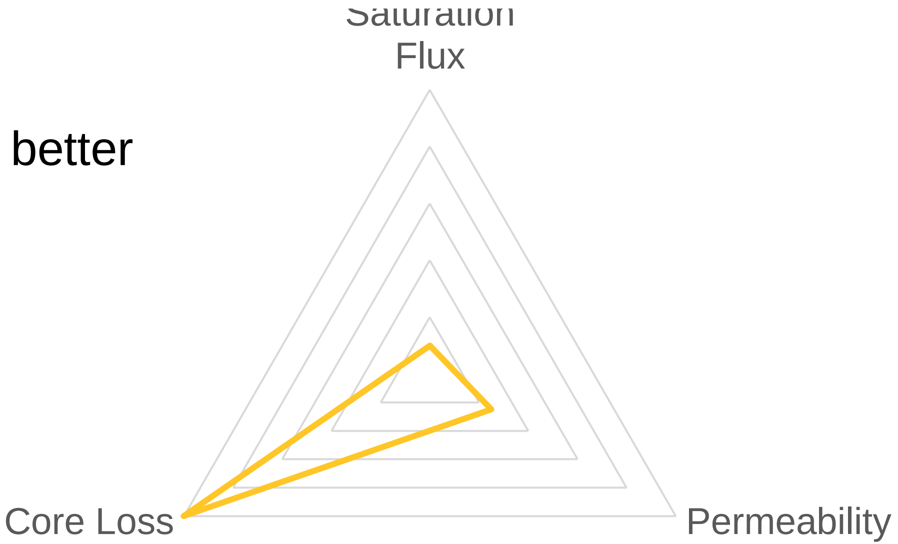
Core volume

Winding loss, including ac resistance

$$P_w = \frac{1}{2} I_{\mathrm{ac,pk}}^2 F_R \left(\frac{\rho_{\mathrm{Cu}} \ell_t}{k_u W_{A,b}} \right) \cdot N^2$$

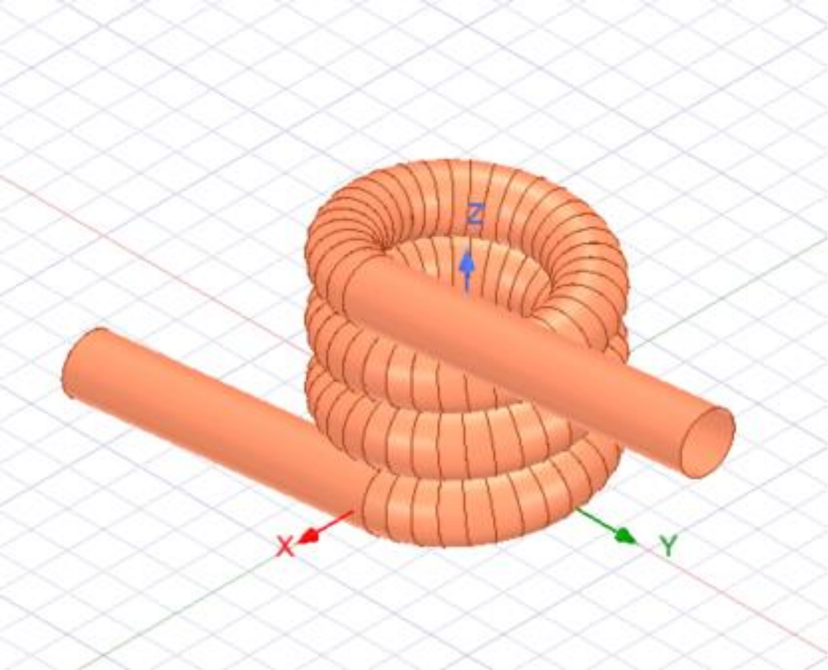
Ac resistance factor

- Choose N to minimize *total* loss
- Lower core loss material makes trade-off better



Special Case: Air Core Inductors

- Common at multi-MHz frequencies, ac loss + fringing fields + L limited
- Large Ls typically imply large physical size
- Similarly: coupled air-core inductors (flat spirals) for WPT (85 kHz, Litz typical)

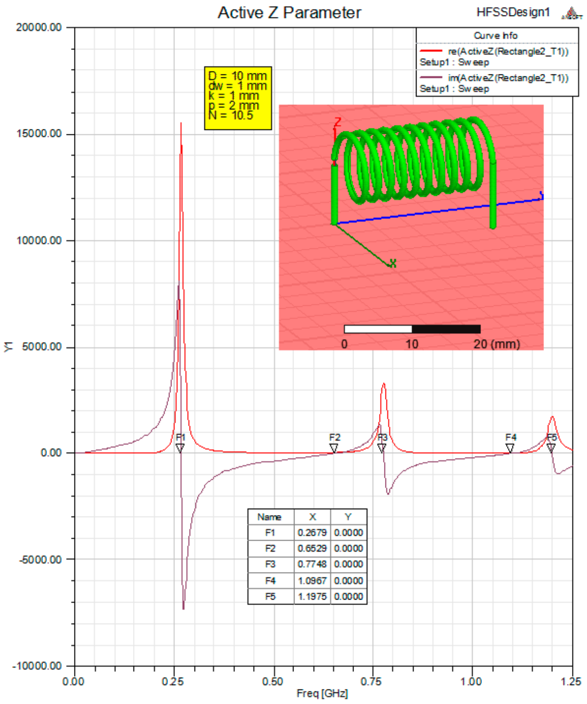


Critical constraint: self-resonance frequency

- Self-resonance frequency is a key limit (cored inductors similarly exhibit parallel-resonance at their SRFs) https://coil32.net/theory/self-resonance-frequency.html

- A coil behaves like a spiral waveguide and exhibits wavelength dependent characteristics. Capacitive effects are derived from the storage/propagation of electrical energy in this waveguide.
- **SRF depends on dimensions of the coil.** Classical notion of "turn-to-turn capacitance" is flawed. D. W. Knight, 2016. The self-resonance and self-capacitance of solenoid coils: applicable theory, models and calculation methods. [Online]. https://www.g3ynh.info/zdocs/magnetics/appendix/self_res/self-res.pdf

- Transformers have a more intuitive capacitance definition (electrical energy stored between isolated conductors)

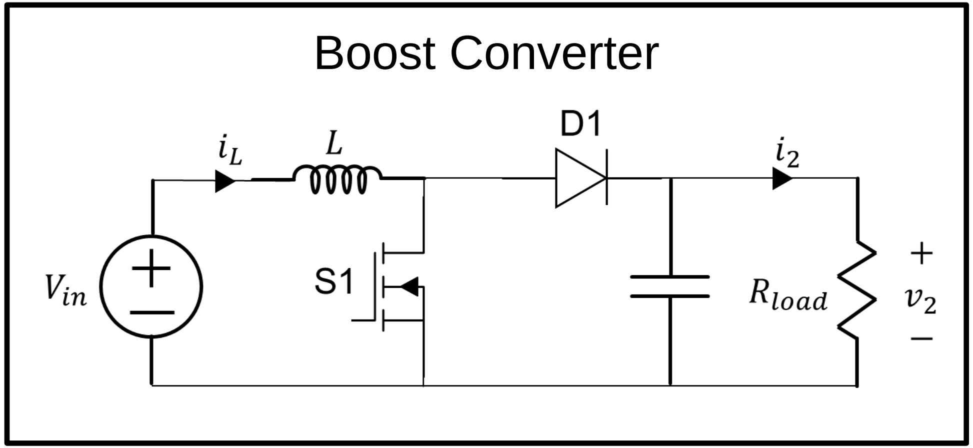


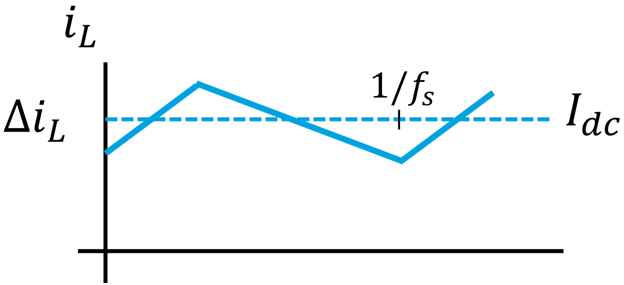
Name	X	Y
F1	0.2679	0.0000
F2	0.6529	0.0000
F3	0.7748	0.0000
F4	1.0967	0.0000
F5	1.1975	0.0000

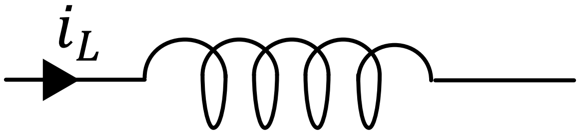
Energy Storage Inductors – Electrical Requirements

- Store energy in the power conversion process
- Both dc and ac current may be important
- ac current likely contains significant harmonic content (non-sinusoidal)

Example application:

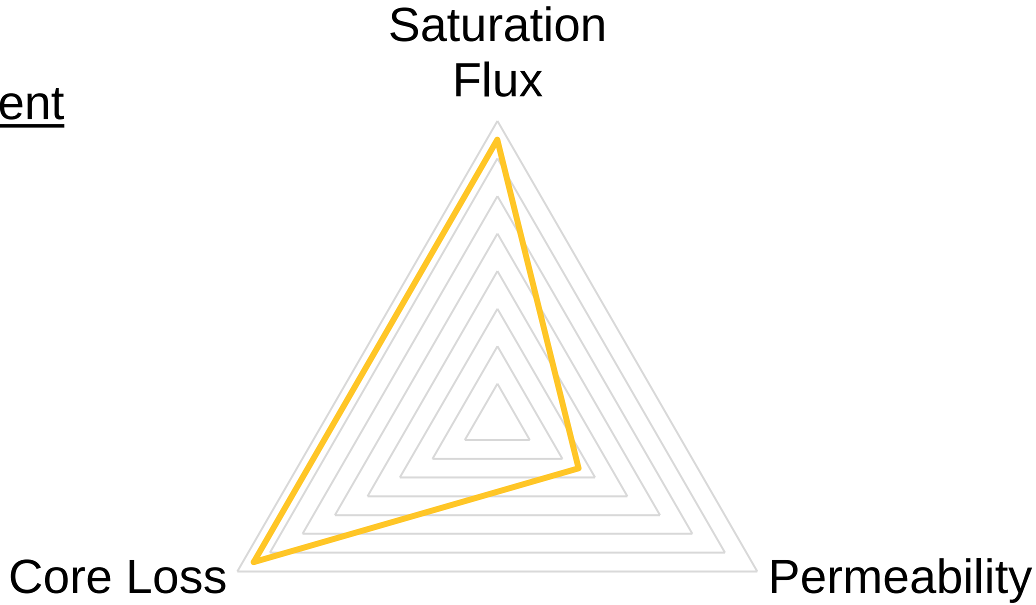






Material Requirements – Energy Storage Inductors

- Ac loss can be critical
- Saturation can be critical
- Permeability unimportant since *gapped*, as long as we are confident about the path of flux
- Can mitigate saturation flux requirement by employing circuit interleaving

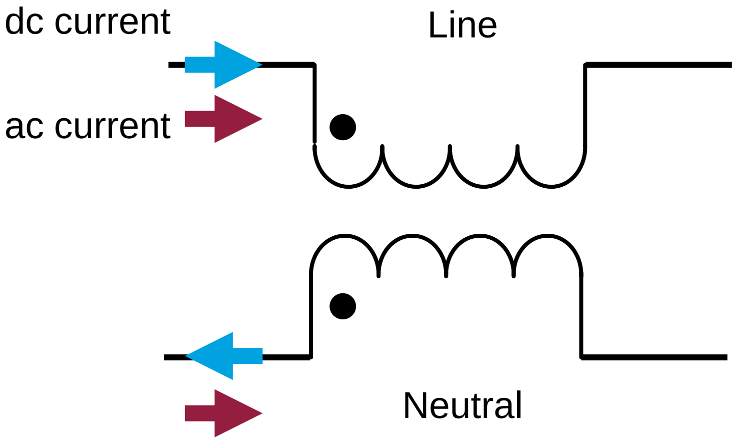


CM Choke (Coupled L) – Electrical Requirements

- Present high impedance to CM current
- Pass-through DM current
- Focus is on maximizing impedance to ac currents

Example application:

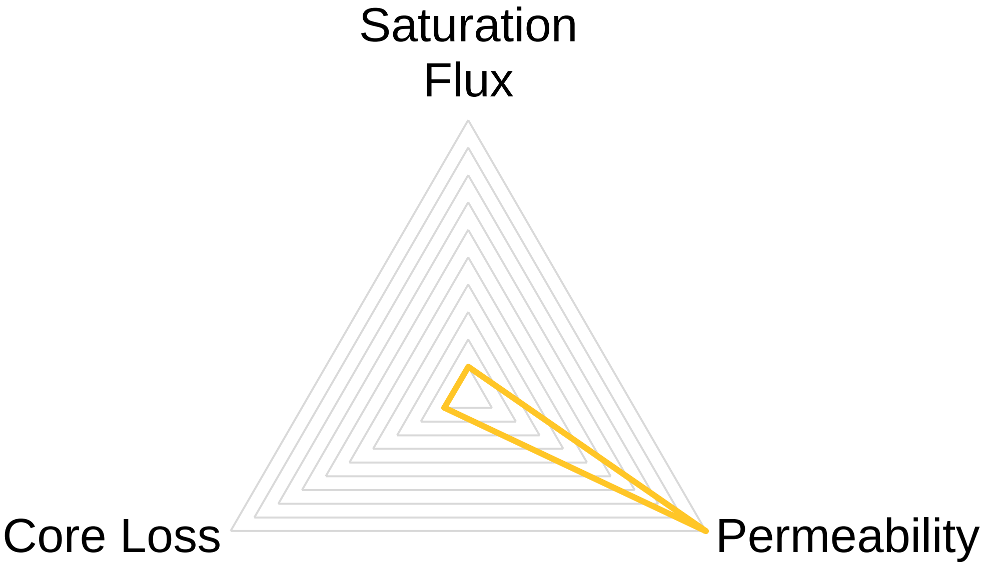
EMI Filter



KEMET SC-02-D100
https://assets.rs-online.com/f_auto,q_auto,c_scale,w_400/70728660.jpg

Material Requirements – CM Chokes

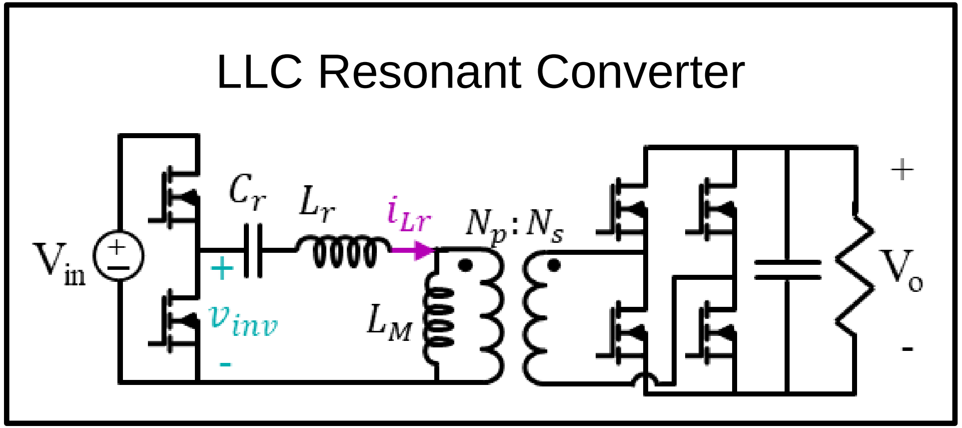
- Non-gapped, maximize permeability to maximize inductance
- Want high impedance at high frequencies (will take loss)
- dc winding loss still important, ac current inherently minimized by filtering – and will take the increase in impedance associated with it
- No dc fields due to differential flow, saturation not a primary concern (though some dc flux in core due to leakage)

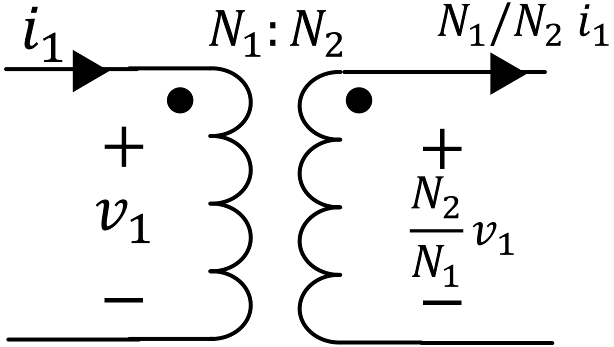


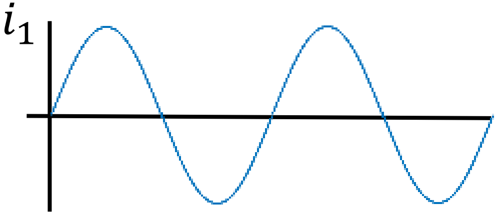
Impedance Transformer – Electrical Requirements

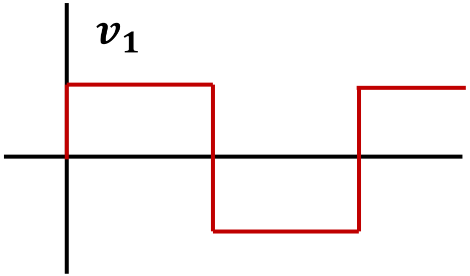
- Or “General Purpose” transformer
- Transform between high voltage/low current and low voltage/high current (high to low Z)
- Like ac inductor design, but worse
- Permeability can be critical for ensuring good coupling

Example application:


LLC Resonant Converter



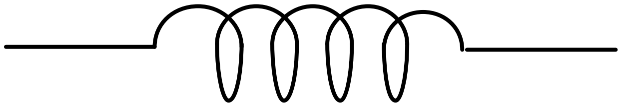




Impedance Transformer Design Requirements

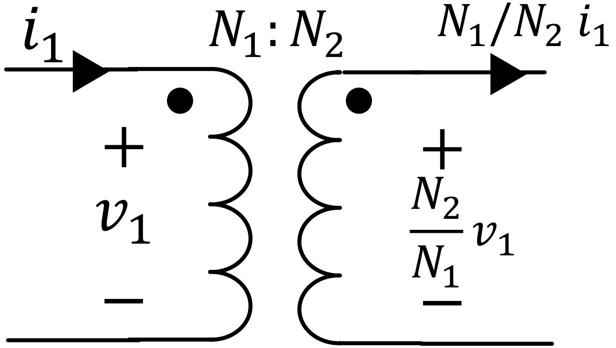
- Follows as in ac inductor design – minimize sum of core loss and copper loss
- Typically, not about choosing a desired B or J, but trading off those losses

- Key difference: voltage and current are independent



$$v = L\frac{di}{dt}$$

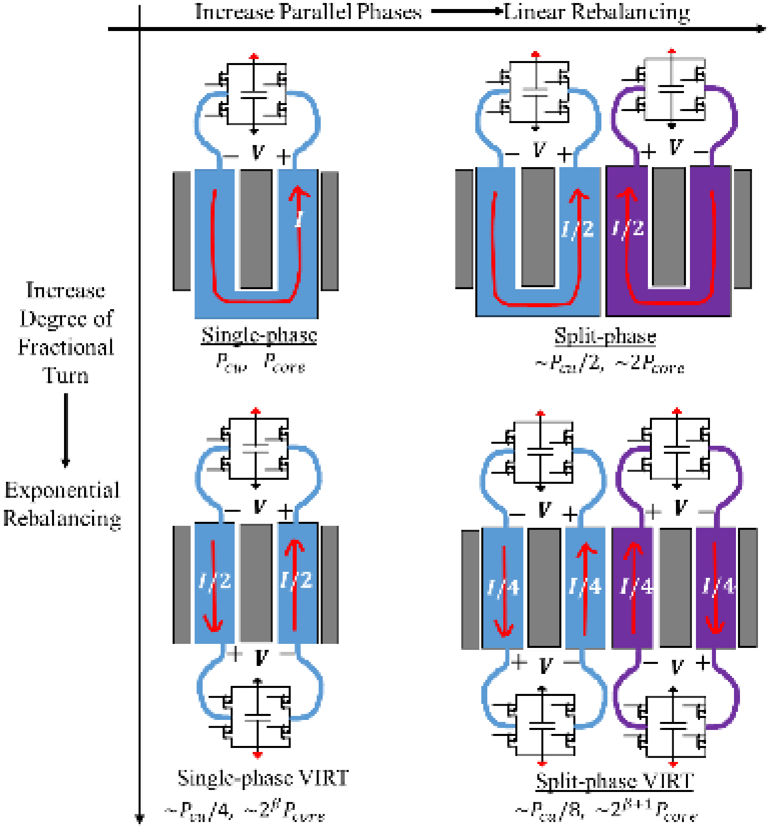
- Have the same frequency content
- Both losses decrease with load



- Voltage and current can have different frequency content
- Core loss usually independent from load
- Winding current mismatches with energy storage

Impedance Transformer – Architectures

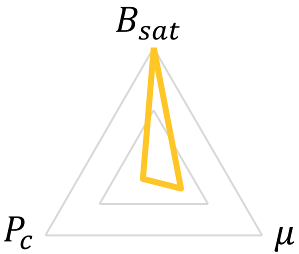
- Methods for improving trade-off between core and copper loss



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.

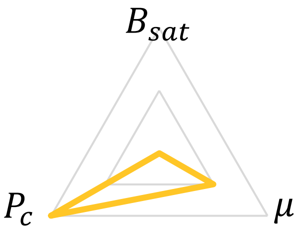
Summary: Requirements From Electrical Function

dc Filtering (harmonic elimination)



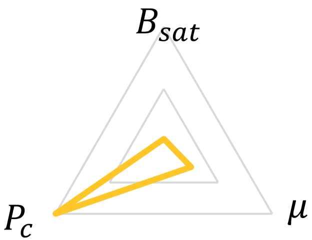
- dc winding loss is the main concern

Impedance Transformation



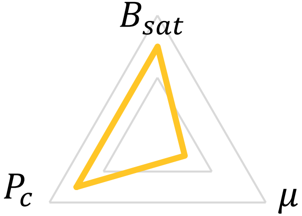
- Added complication of “independent” v/i relationship

ac Filtering (harmonic selection)



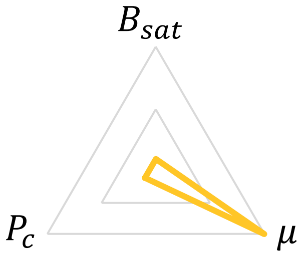
- ac losses trade-off
- Ripe for architecture advancements

Energy Storage



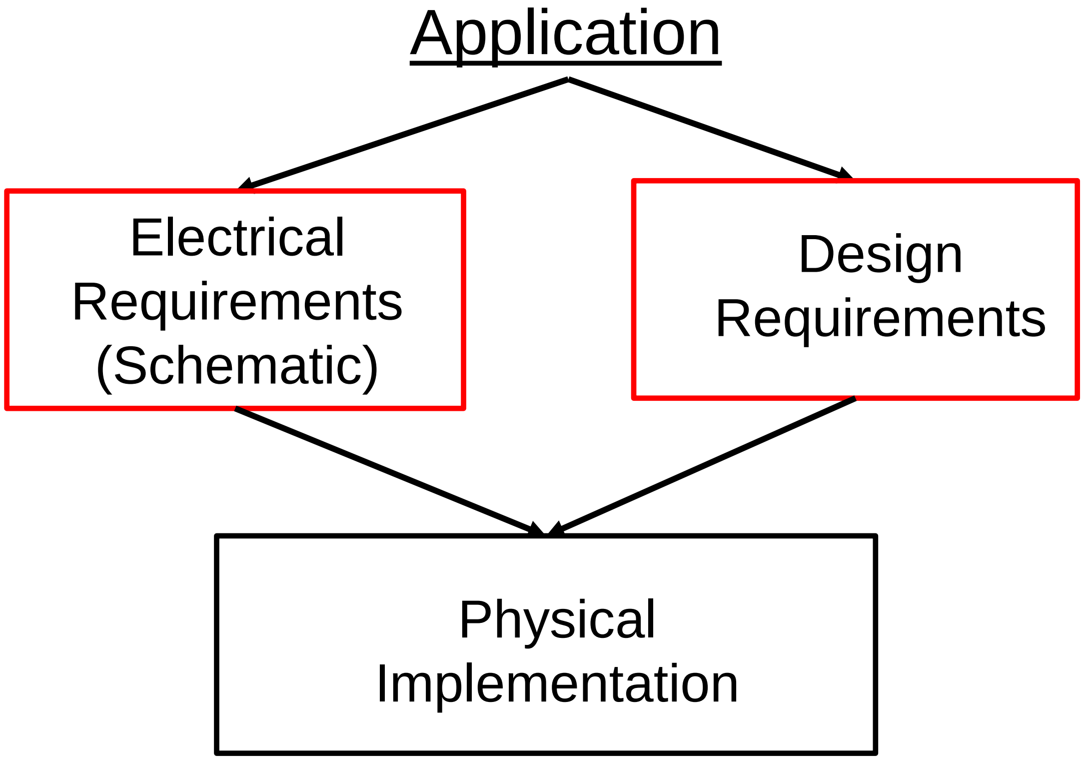
Multi-phase interleaving

dc Filtering (CM choke)



Highest Z
Accept losses

Summary: Two Kinds of Broad Requirements



Application

Electrical Requirements (Schematic)

Design Requirements

Physical Implementation

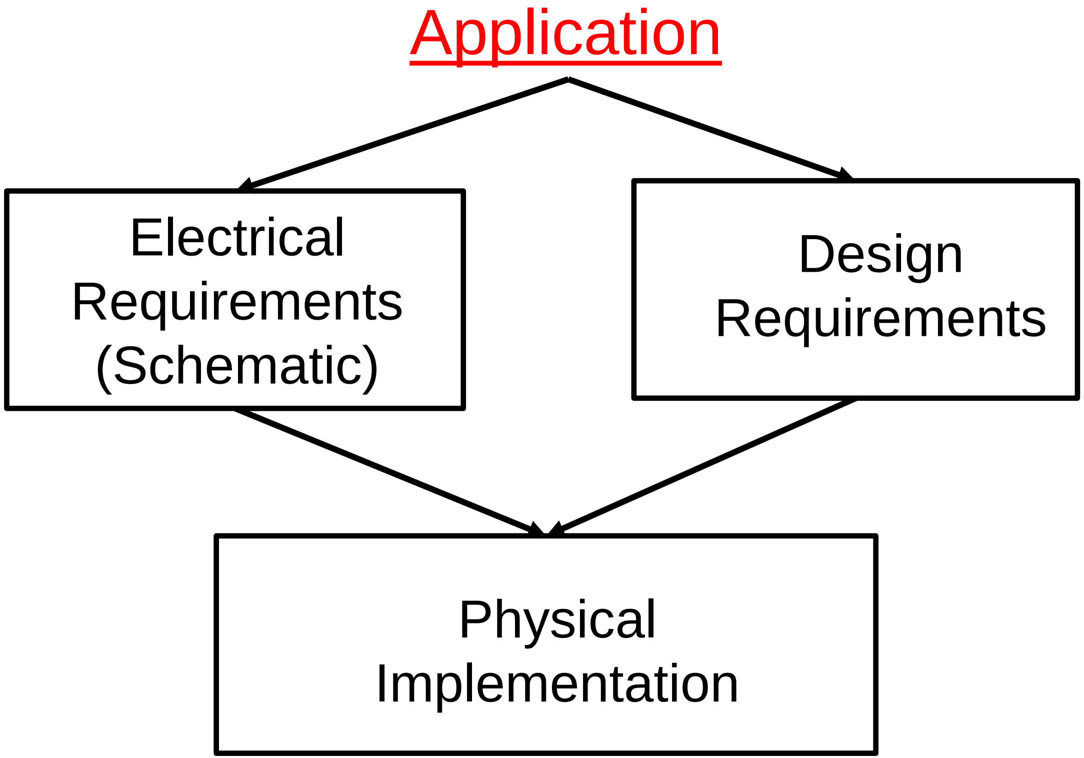
We have worked to generalize the *kinds* of requirements on magnetics

Electrical functions and design requirements each set the “broad spectrum” of technical requirements on power magnetics

Electrical: dc, ac, energy storage, impedance transformers

Design for X
X = loss, size, weight, cost, reliability

Ultimately, the Details Depend on the Application



Application

Electrical Requirements (Schematic)

Design Requirements

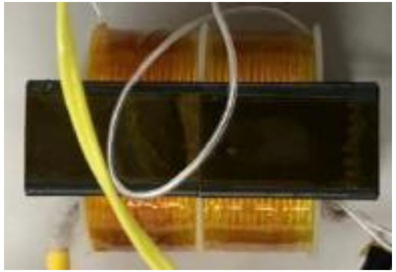
Physical Implementation

A useful exercise to end with: discuss examples of transformers in 8 different uses covering 7 different application areas

“Broad Spectrum” of Transformers

Aerospace

Impedance



High voltage,
Low weight

500V-7.5kV, 10:150
500W, 500kHz
MnZn ferrite

Datacenter

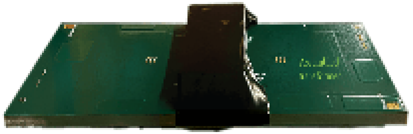
Z+E storage+ac filter

High current,
High power density

192V-12V, 8:1/2
1kW, 1MHz
MnZn ferrite

Grid-interfaced Solar

MV Isolation +
E storage

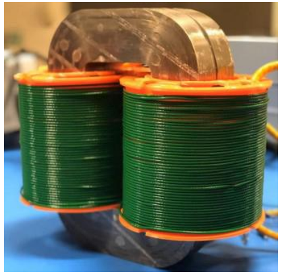


Isolation (26 kVpk),
Low cost

1kV-1kV, 30:30
7.5kW, 200kHz
MnZn ferrite

Solid State Transformer

MV Isolation



Isolation (25 kVpk),
High reliability

3.5kV-500V, 49:7
200kW, 15kHz
Nanocrystalline

Y. He and D. J. Perreault, “Lightweight High-Voltage Power Converters for Electroaerodynamic Propulsion,” *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, vol. 2, no. 4, pp. 453–463, Oct. 2021, doi: 10.1109/JESTIE.2021.3087950.

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.

Z. Guo, S. Sen, S. Rajendran, Q. Huang, X. Feng, and A. Q. Huang, “Design of a 200 kW Medium-Frequency Transformer (MFT) With High Insulation Capability,” in *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*, Oct. 2020, pp. 3471–3477. doi: 10.1109/ECCE44975.2020.9235985.

“Broad Spectrum” of Transformers

EV On-Board Charger

Impedance

High power density
Thermals

CLLC resonant conv.
300-600Vin, 280-450V out,
10:150, 6.6kW, 300-500kHz

EV Aux. Charger

Impedance

High power density
Thermals

Phase-shifted full-bridge
w/ current doubler rectifier
400-12V, 3.6kW, 100kHz

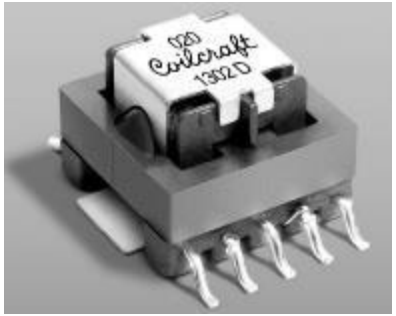
Consumer

E storage

Low cost
High power density

Type-C charger
Active Clamp Flyback
400-5V/5A, 9V/5A,20V/5A
500kHz

Current Sensing



https://www.mouser.com/datasheet/2/597/cst2010-1223901.pdf

High permeability

1:100, 8.5mH,
2k-1MHz

Parting Thoughts

- The broad spectrum of technical requirements on power magnetics can be partitioned into two aspects: electrical function and design goals (e.g., priority of loss, weight, etc.)

- These requirements are imposed on the physical implementation, which is a deep design space

- Innovations to meet these requirements happen on the physical layer (new materials, winding techniques, physical architectures) or at the electrical layer (shift the electrical requirements within a larger conversion requirement)

- Magnetics are ubiquitous, and their broad spectrum of technical requirements are a direct result

References

TI Reference Design	Link
Avionics	https://www.ti.com/tool/PMP30763
Automotive (LIDAR)	https://www.ti.com/tool/PMP21629
Automotive (EV on-board charger)	https://www.ti.com/tool/TIDM-02002
Energy storage (400-12V, 3kW)	https://www.ti.com/tool/TIDM-02009
Solar (MPPT)	https://www.ti.com/tool/TIDA-010042
Solar (grid-tied inverter)	https://www.ti.com/tool/TIDA-01606
Medical (electrosurgery equipment)	https://www.ti.com/tool/PMP22270
Consumer	https://www.ti.com/tool/TIDA-01623
Enterprise	https://www.ti.com/tool/PMP30521
Lighting	https://www.ti.com/tool/TIDA-010038
Datacenter	https://www.ti.com/tool/PMP20289

BOVIE electro surgery generator: https://cdn.shopify.com/s/files/1/1046/1086/products/bovie-specialist-pro-electrosurgical-generator_4b010900-0fdf-468f-9a7d-9e0fc4600d93_400x.jpg?v=1617140390