2021 Power Magnetics & High Frequency Workshop

Magnetic Component Integration

May 24, 2021

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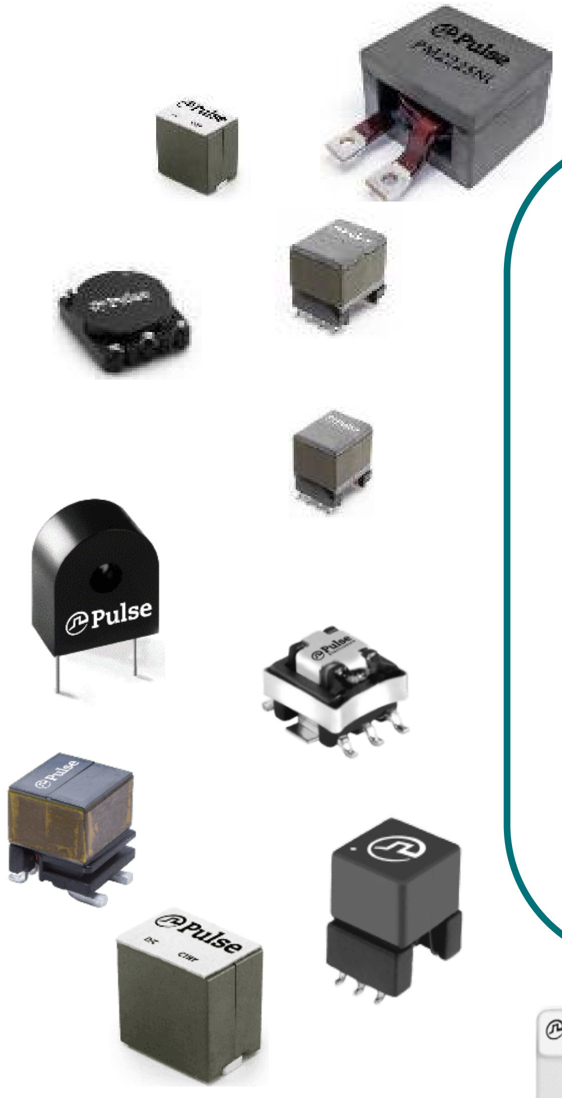
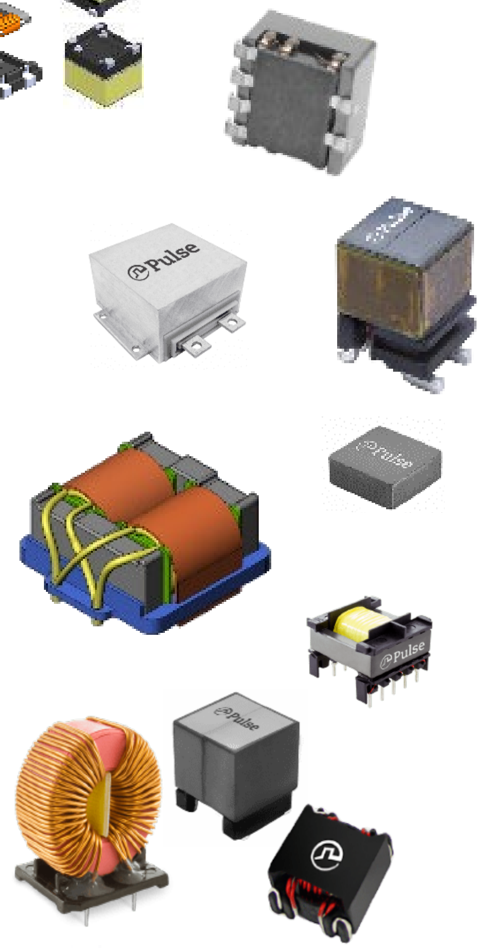
Magnetic Component Integration
Smaller, More Efficient and Lower Cost





Key Goals for Magnetic Component Development

- ❑ Smaller
- ❑ More Efficient
- ❑ Lower Cost
- ❑ Thermally Acceptable

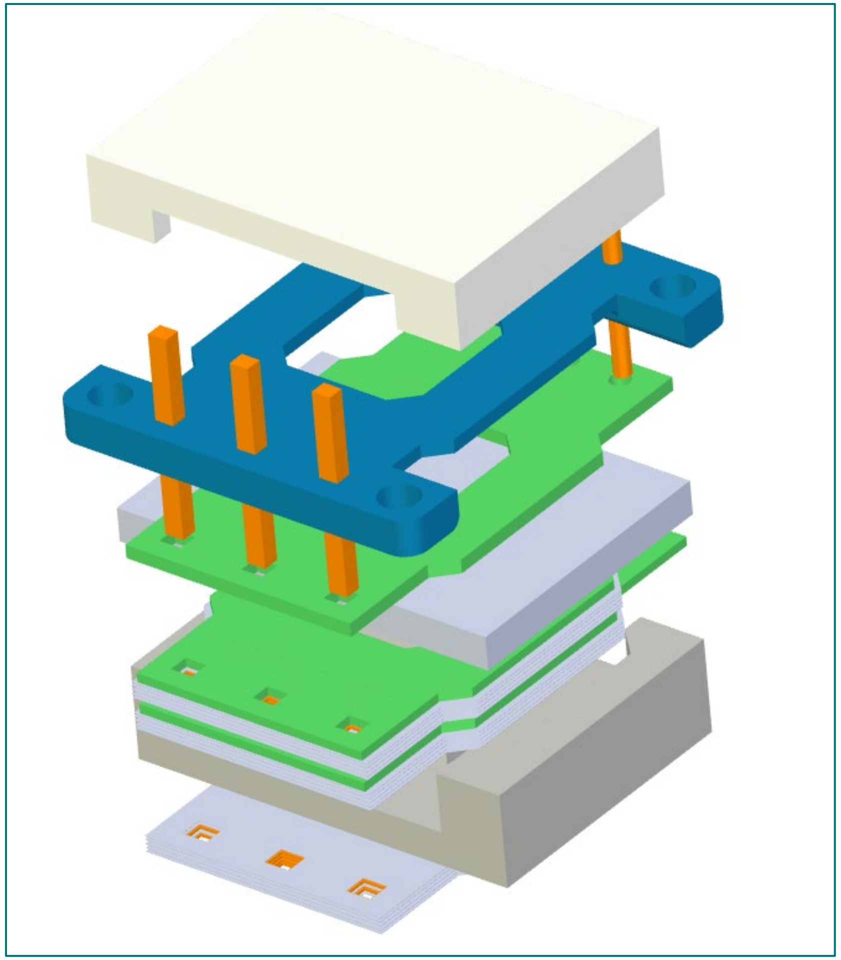
Much of the advancements are external

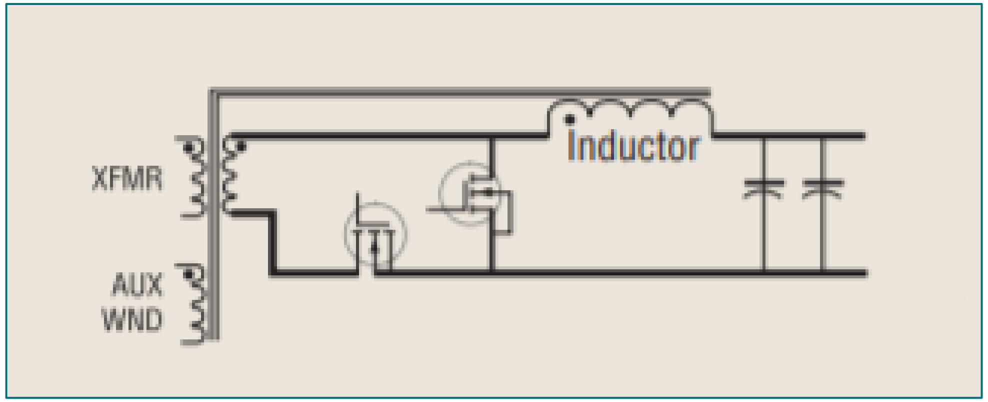
- ❑ New Topologies
- ❑ Advances in Affiliated Components (GaN, SiC, Drivers)
- ❑ Advances in Materials (High Isat, Lower Core Loss, Improved Z)

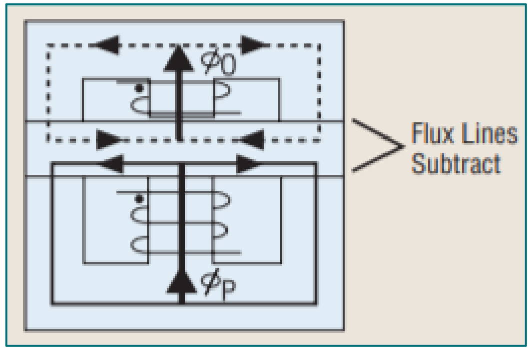
Magnetic Component Integration

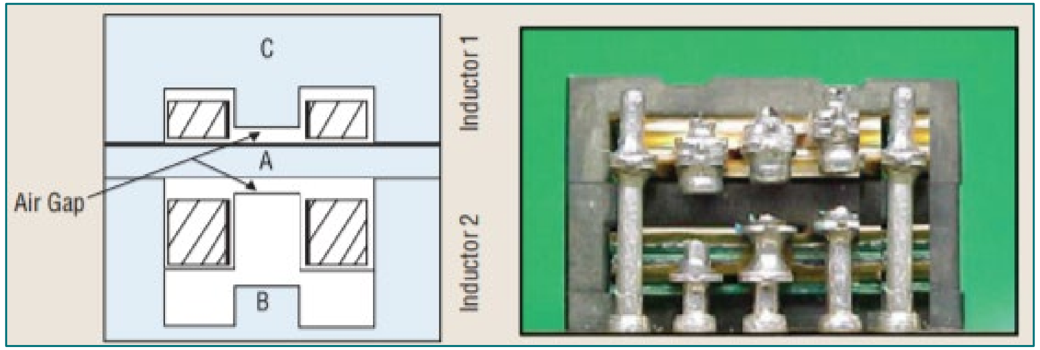
- ❑ Works within external constraints
- ❑ Meets Key Goals

Magnetic Component Integration
Example: Integration of Active Clamp Forward Converter Magnetics



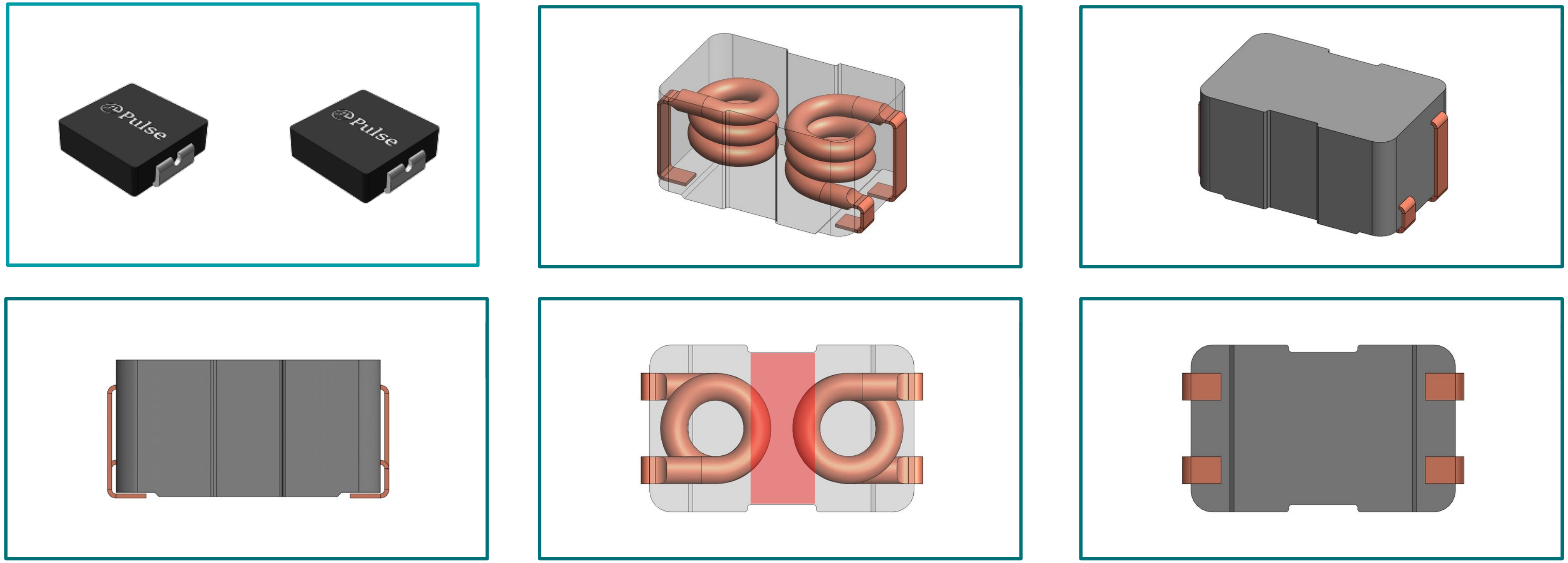






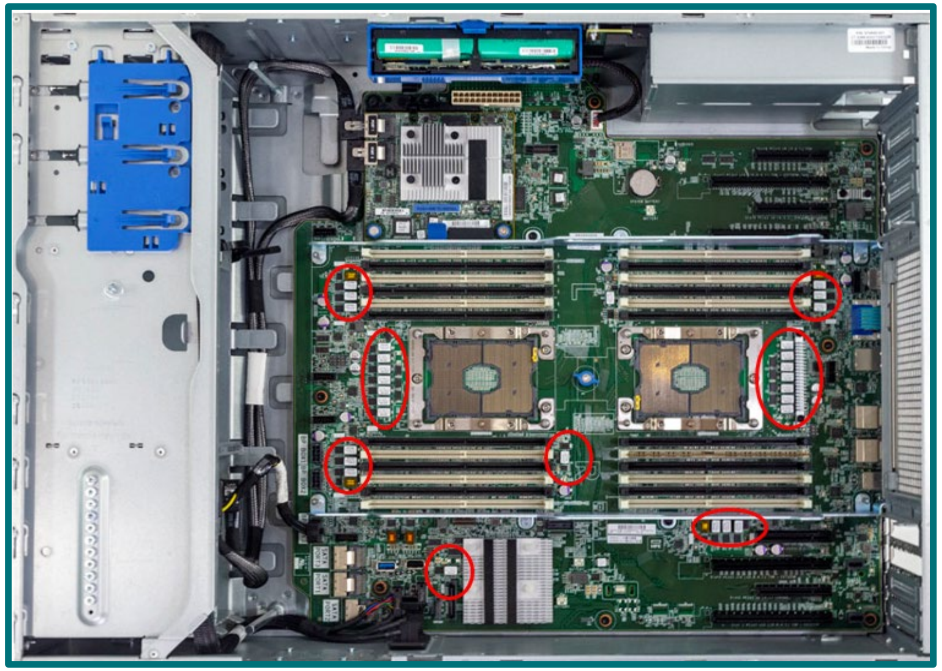
- The output inductor and main transformer in an active clamp forward can be integrated into a single component.
- In this example the inductor is ‘stacked’ on top of the transformer and due the cancelling flux paths it is possible to eliminate one core half.

Magnetic Component Integration
Example: Integration of Dual Phase Inductors

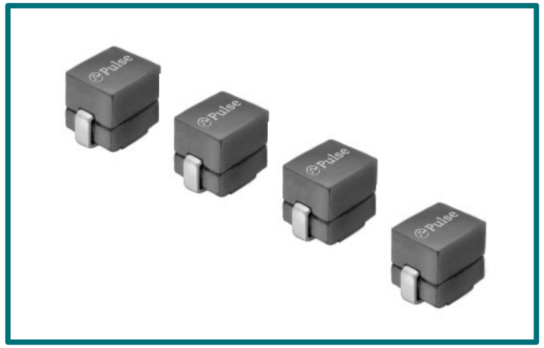


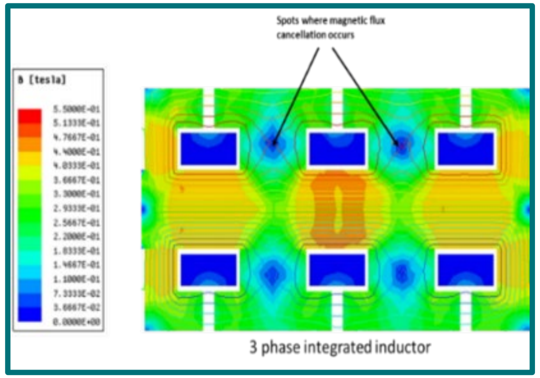
- Two separate inductors (working within a two-phase buck topology can be integrated into a single component.
- The flux from each individual phase will cancel in the ‘center portion’ of the core allowing this section to have lower core area and therefore overall reduced footprint.
- Care must be taken to analyze the ‘unintentional’ coupling between phases to ensure that it will not affect circuit operation.

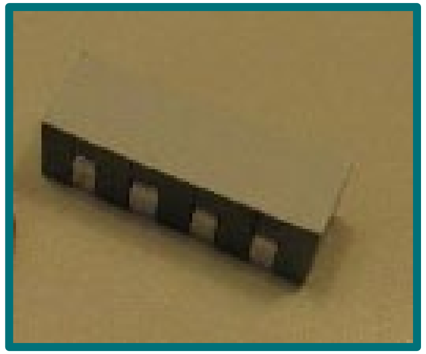
Magnetic Component Integration
Example: Integration of Multi-phase Inductors (4-phase)



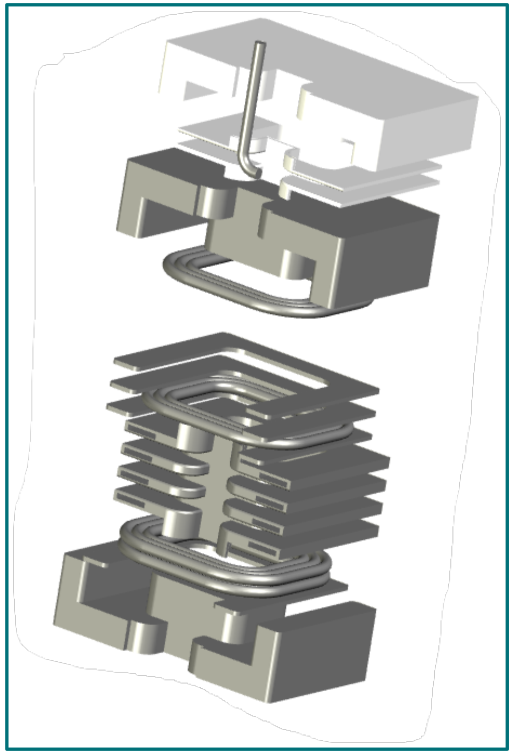
- Within storage and server systems there are many multi-phase rails each with multiple inductor placed side by side.
- Space limitations mean that the individual inductors are thin and tall which can lead to instability.
- Integration of these inductors is straight forward and allows significant reduction in footprint and ensures component stability.

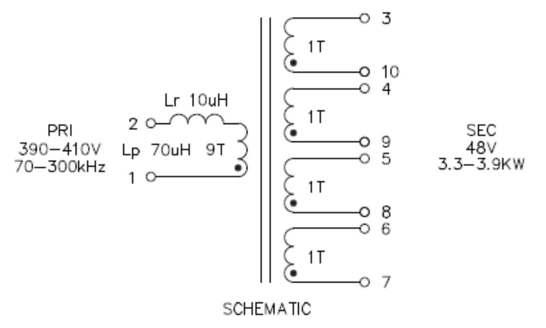


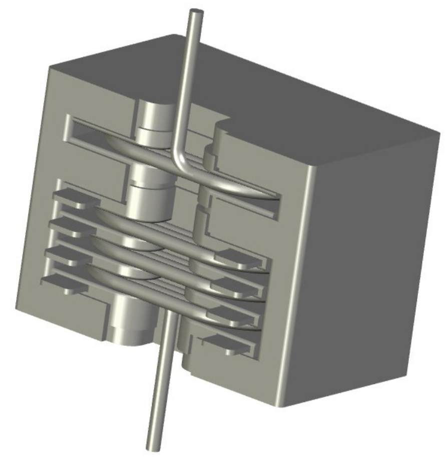




Magnetic Component Integration
Example: Integration of 3.9kW LLC Transformer and Resonant Ind





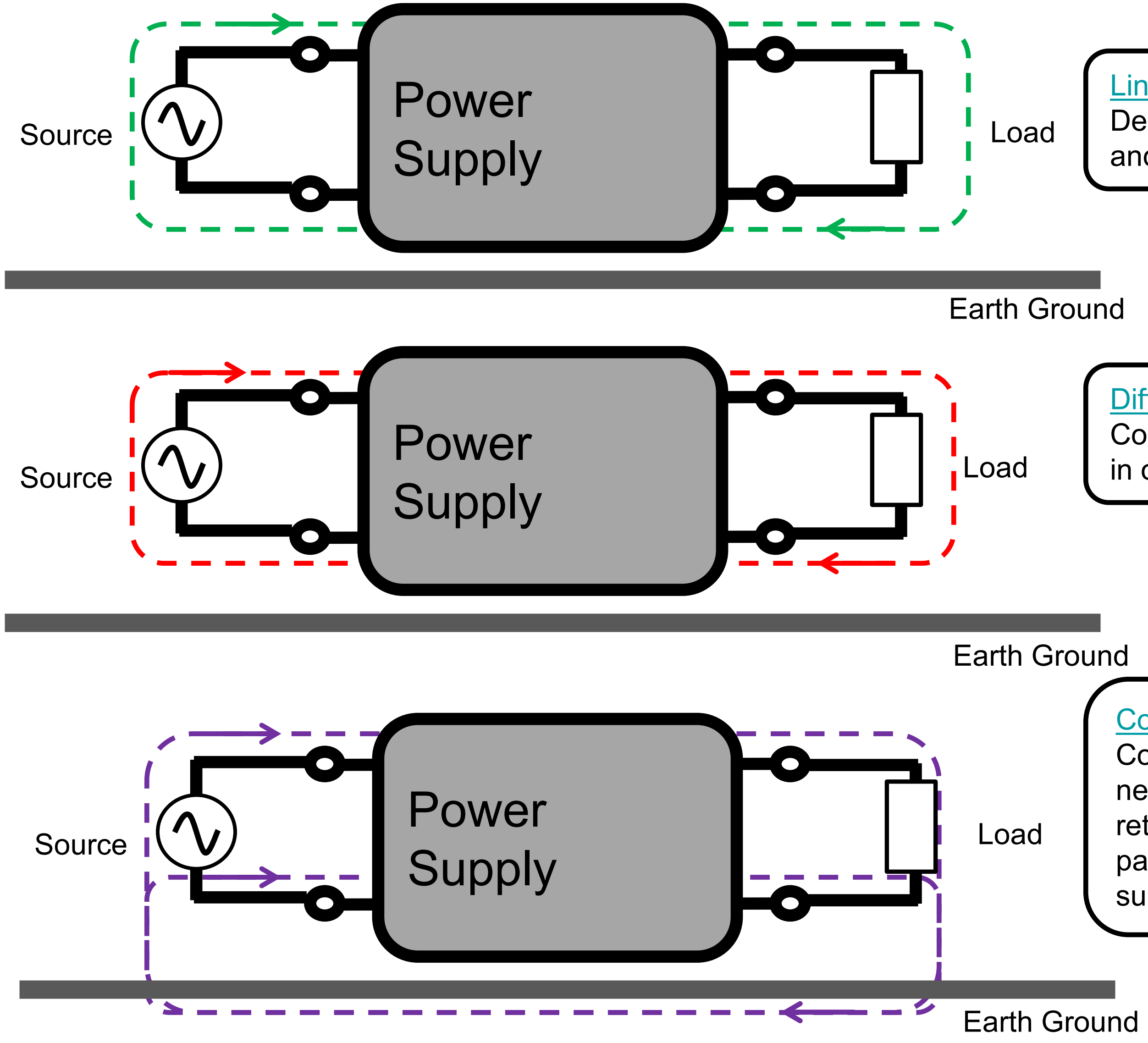


- In high power (1kW to 15kW) systems power density, thermal performance and efficiency are critical.
- The resonant inductor within an LLC can 'easily' be integrated into the main transformer to save space, improve efficiency and reduce footprint.

Magnetic Component Integration
End-user Reluctance

- Despite the myriad of use cases, end-users are often reluctance to initiate or incorporate integrated solutions.
- Integrated solutions have some potential drawbacks
    - Very few off-the-shelf solutions, customization necessary.
    - Initial Magnetic Design is more complicated.
    - Integration can make debugging a circuit more difficult.
    - Sometimes less easy to tweak parameters to optimized circuit operation.
- However, if increasing power density is a major goal than magnetic integration can achieve the desired results without increasing costs.
- Although the initial magnetic design is ‘complicated’ the various equations can be derived, the overall flux flow can be visualized, and a sound magnetic design can be realized.
- A good example of the use case and design of integrated magnetics is the common mode and differential mode choke.

Magnetic Component Integration
Detailed Example: Integration of CM Choke and DM Choke



Line Current:
Delivered to the load via the line and returns through the neutral.

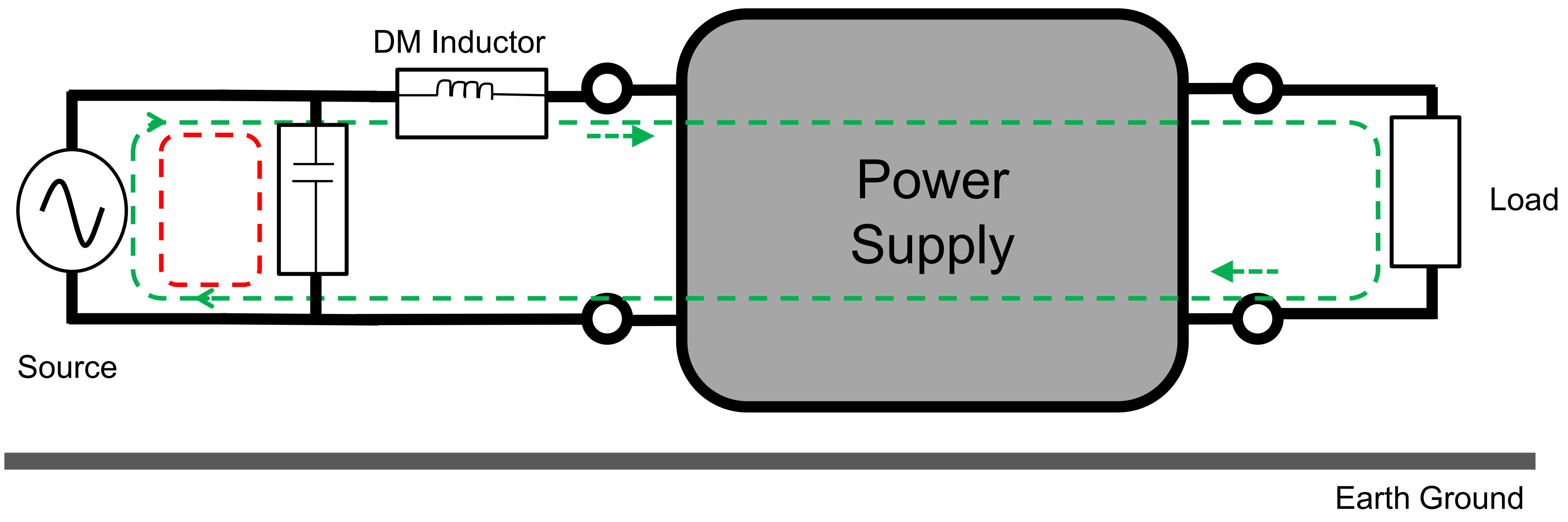
Differential Mode Noise:
Conducted on the line and neutral in opposite directions.

Common Mode Noise:
Conducted on both line and neutral in the same direction and returns through ground via parasitic elements in the power supply.

Each type of noise requires a different filtering solution

Magnetic Component Integration
Detailed Example: Integration of CM Choke and DM Choke

Differential Mode Filter

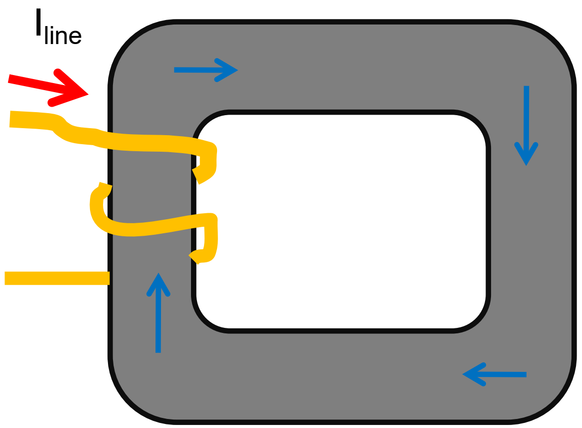


The simplest DM Filter involves the placement of a single winding inductor in the line path and a capacitor from line to neutral. Effectively blocking the high-frequency noise from moving through the system

The DM inductor (because it is in the line path) sees both the noise and a net DC offset due to the current being supplied to load so the inductor must be able to handle the peak currents without saturating

Differential Mode Choke

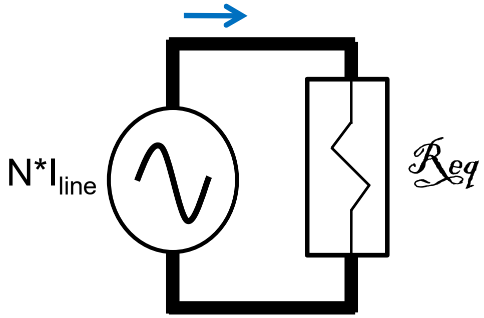
Physical Model



Design must provide required inductance/impedance with low enough resistance (DCR) to handle rms current and adequate saturation to handle peak line current

Typical design is with powdered iron core or gapped ferrite core

Reluctance Model



Flux (I) = N * I_{line} / $\mathcal{R}_{eq}$

$\mathcal{R}_{eq}$ = le / (perm * A_e)

Flux (I) = perm * N * I_{line} * A_e / l_e

Inductance (L) = N * Flux(I) / I_{line}

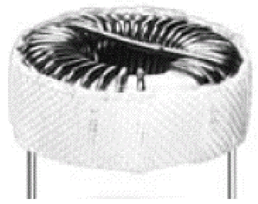
= N^2 * perm * A_e / l_e

Therefore Flux(I) = L * I_{line} / N

Or Flux Density (B_{pk}) = L * I_{line} / (N * A_e)

Design Example: Require a 350uH, 2A differential mode choke.

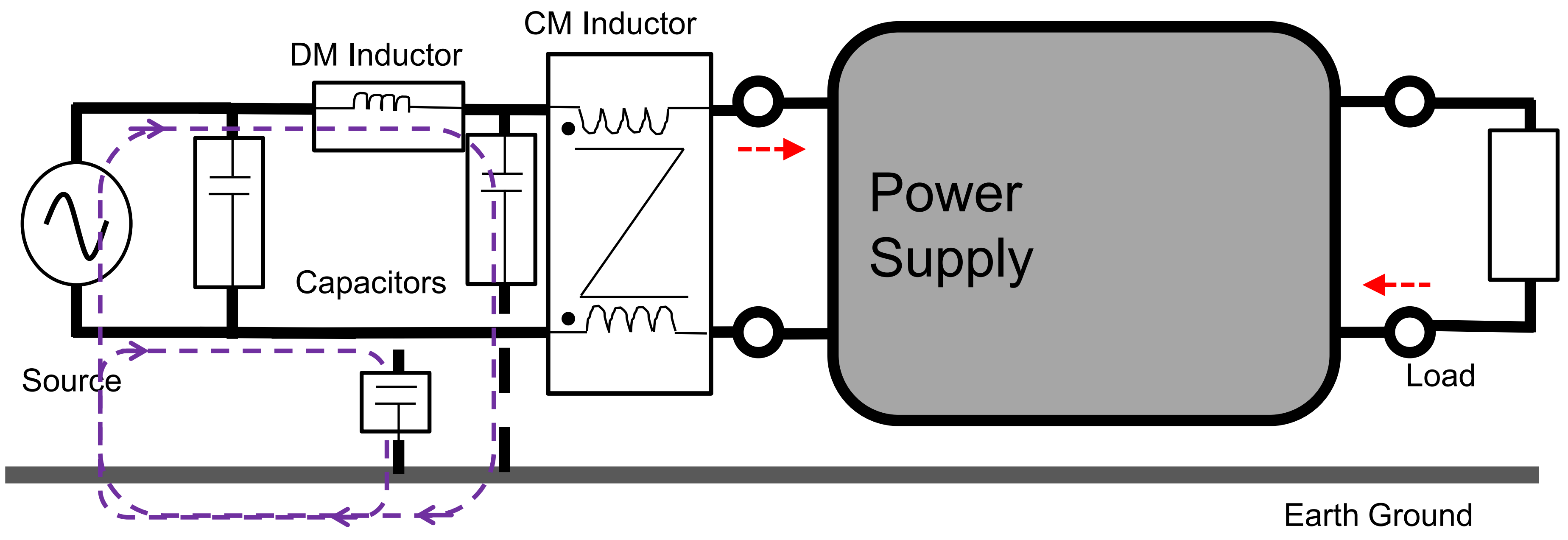
Use 75 perm powdered iron, OD=0.8” with 54T of 23GA wire



Ind = 350uH, DCR=180mOhms (PowerLoss = **720mW**) and size is 23.0 x 23.0 x 9.0 mm (**4.76cm3**)

Detailed Example: Integration of CM Choke and DM Choke

Common Mode Filter



The simplest CM Filter involves the placement of a dual winding magnetic in the line and neutral path and capacitors from line and neutral to ground. Effectively blocking noise from moving through the system

The currents (line and neutral) pass through the CM magnetic in opposite directions and therefore create no net DC flux and no possibility of saturating the CM magnetic core.

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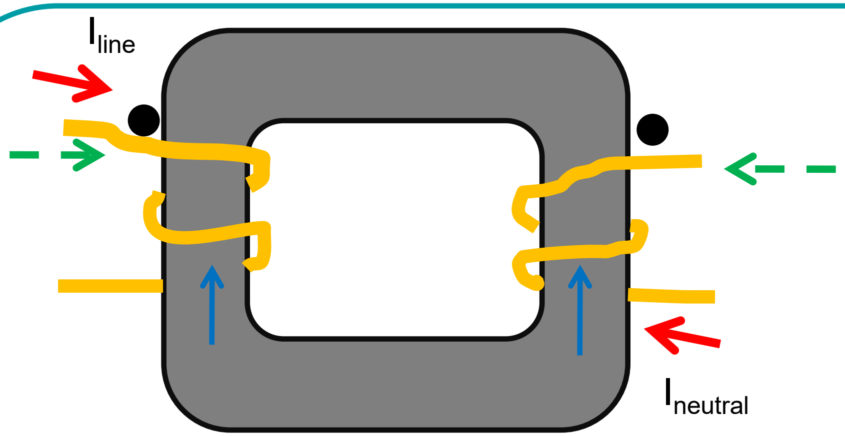
Common Mode Choke

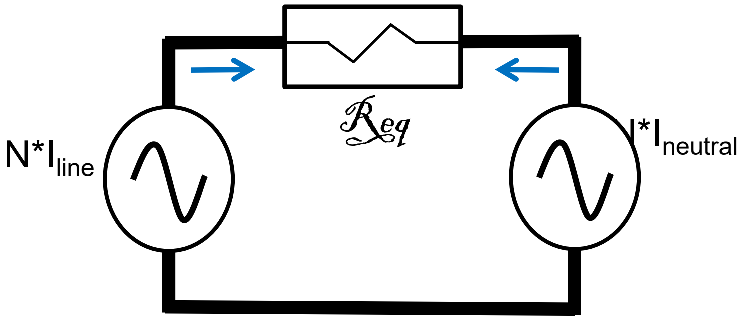
Physical Model



Design only needs to provide the required inductance / impedance with low enough resistance (DCR) to handle rms current. No saturation issues.

Typical design is with an ungapped 5-10K perm ferrite core

Reluctance Model



Flux (I) = $N * I_{line} / \mathcal{R}_{eq} - N * I_{neutral} / \mathcal{R}_{eq}$

= 0 (no net dc flux in CM)

* So, the line/neutral see no impedance

However, the CM noise signal enters the component from the same direction and sees an inductance of:

Inductance (L) = $N^2 * perm * A_e / l_e$

Design Example: Require a 1.60mH, 2A common mode choke.

Use 5K perm ferrite core, OD=0.6" with 25T of 26GA wire per winding

Ind = 1.6mH per side, DCR=65mOhms (PowerLoss =**520mW**) and size is 19.0x19.0x8.0 mm (**2.89cm3**)

Detailed Example: Integration of CM Choke and DM Choke

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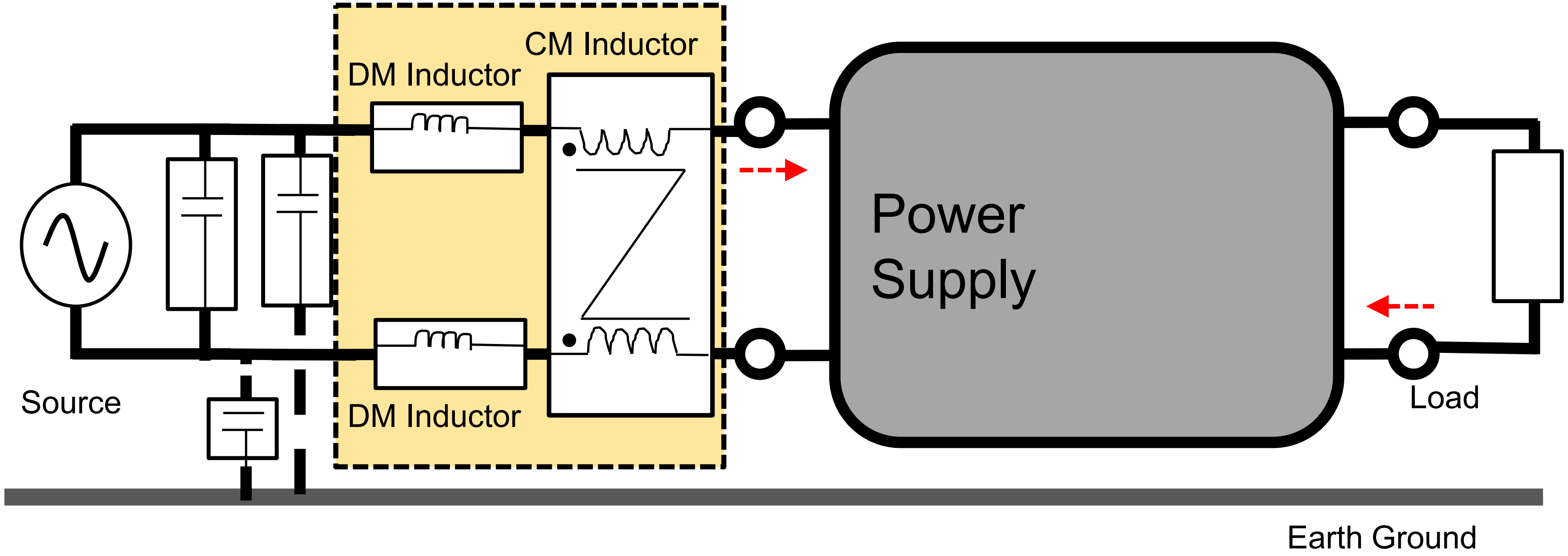
Integrated Common Mode and Differential Mode Magnetics

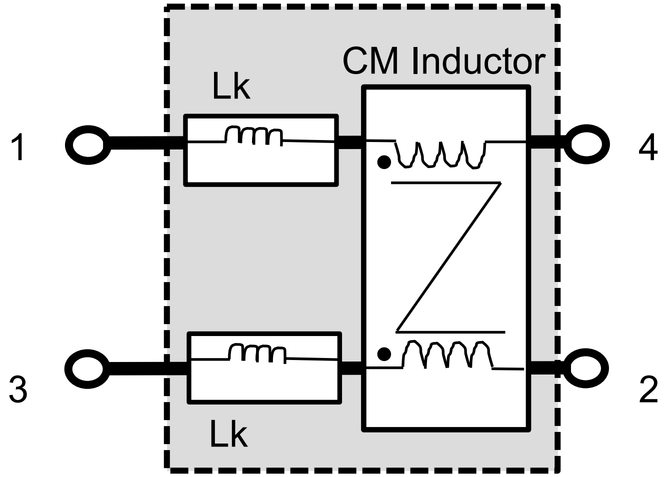
The two separate magnetics in the EMI filter account for 1.24W of loss, 8.9cm2 of PCB space and take up 7.65cm3. Goal is to combine the DM and CM filter into a single component.



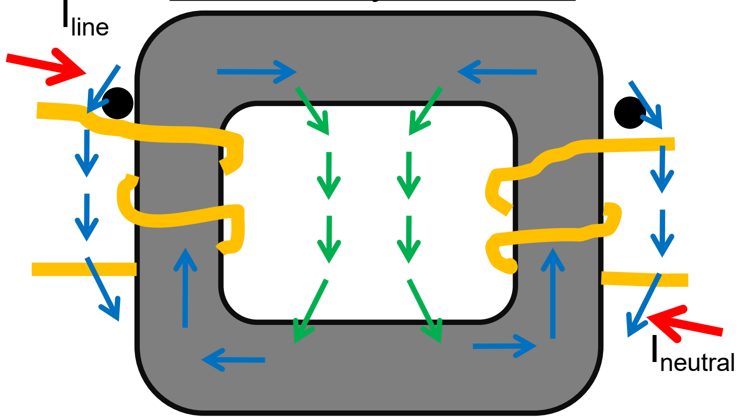
Combining the DM and CM has the potential benefits of reducing losses, board space, volume and cost but careful design must be done to ensure that the component does not saturate

Magnetic Component Integration
Detailed Example: Integration of CM Choke and DM Choke

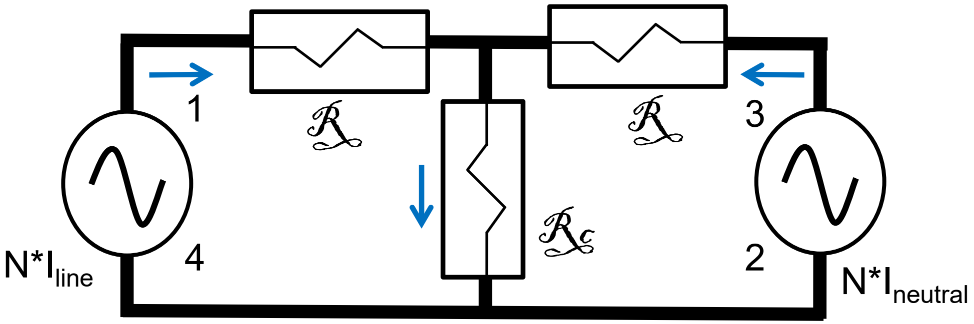
Although not shown previously any ‘real’ mutual wound magnetic (CM chokes, Transformers) will have some amount of leakage inductance (uncoupled flux) which effects the coupling of the magnetic.



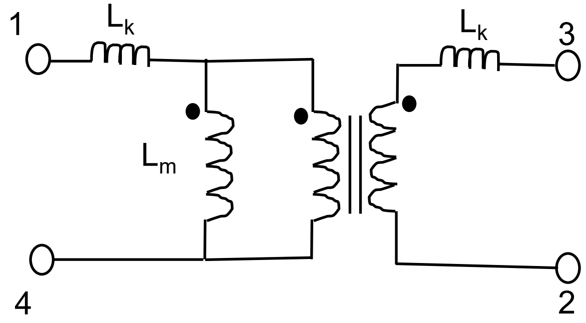
CM w/Lk Physical Model



CM w/Lk Reluctance Model

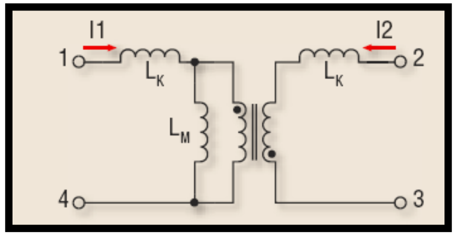


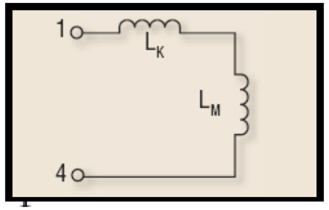
CM Equivalent Schematics



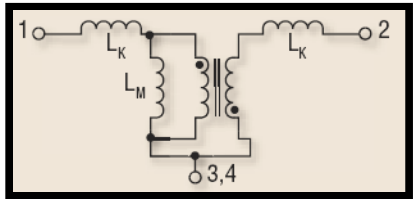
Magnetic Component Integration
Detailed Example: Integration of CM Choke and DM Choke

The integrated CM and DM Inductor is almost identical in terms of reluctance model and equivalent schematic to the 2-phase coupled inductor sometimes used in dual phase voltage regulators and detailed in:
'Designing Coupled Inductors' By John Gallagher, Power Electronics Technology

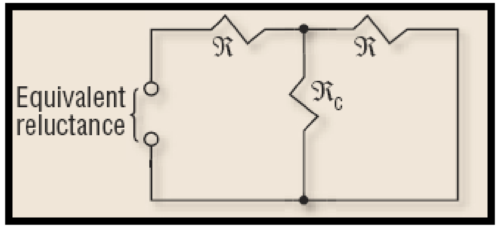


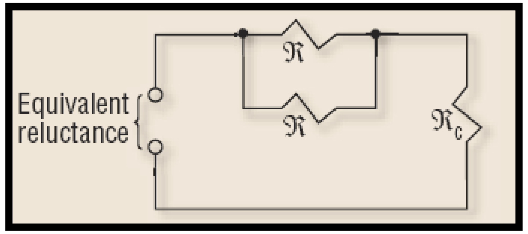


$$L_{OPEN(1\text{-}4)} = L_{OPEN(2\text{-}3)} = L_M + L_K.$$



$$L_{REVERSE_{SERIES(1\text{-}2)}} \text{(with 3-4 shorted)} = 2L_K$$





$$\Re_{OPEN(1-4)} = \Re_{OPEN(2-3)} = \Re + (\Re_C \| \Re)$$

$$L_{OPEN(1-4)} = L_{OPEN(2-3)} = L_M + L_K = N^2 \frac{(\Re + \Re_C)}{2\Re\Re_C + \Re^2}$$

$$\Re_{REVERSE_{SERIES(1-2)}} \text{(with 3-4 shorted)} = \Re_C + (\Re \| \Re) = \Re_C + 0.5\Re$$

$$2 \times L_K = \frac{N^2}{(\Re_C + 0.5\Re)}$$

$$L_M = N^2 \frac{\Re_C}{(2\Re\Re_C + \Re^2)}$$

It is now possible to design the static values:

DM Inductance = 2 * Lk = 2 * $N^2 / (\mathcal{R} + 2 * \mathcal{R}_c)$

CM Inductance = Lm = N^2 * Rc / $(2*\mathcal{R}*\mathcal{R}_c + \mathcal{R}_c^2)$

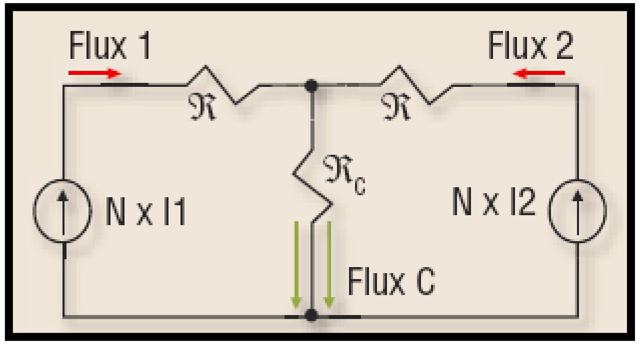
But need to determine flux to check saturation

Reluctance Model resembles electrical circuit used in Millman's Theorem so;

$$\phi_1 = \left(\frac{(\Re+\Re_C)}{(\Re^2+2\Re\Re_C)}\right)(N\times I1) - \frac{\Re_C}{(\Re^2+2\Re\Re_C)}(N\times I2)$$

$$\phi_2 = \frac{-\Re_C}{(\Re^2+2\Re\Re_C)}(N\times I1)+\left(\frac{(\Re+\Re_C)}{(\Re^2+2\Re\Re_C)}\right)(N\times I2)$$

$$\phi_3 = \phi_1 + \phi_2$$



Assume, coupling of p = Lm/Lk

$$\phi_1 = \left(\frac{L_K}{N}\right)\times I1 + \left(\frac{pL_K}{N}\right)\times(I1\text{-}I2) \quad \phi_2 = \left(\frac{L_K}{N}\right)\times I2 + \left(\frac{pL_K}{N}\right)\times(I2-I1) \quad \phi_3 = \left(\frac{L_K}{N}\right)\times(I1+I2) = \left(\frac{L_K}{N}\right)\times I_{OUT}$$

Check:
If coupling is very good (Lk approaches zero) then dc flux goes to zero and no saturation (same as CM)
If coupling is very bad (Lm approaches zero) then dc flux approaches Lk/N*I (same as DM)

How does the CMDM compare with separate components?

Magnetic Component Integration
Detailed Example: Integration of CM Choke and DM Choke

Previously showed a DM Choke (350uH, 2A) and a CM Choke (1.6mH,2A)

DM Choke:	Copper Loss = 720mW,	Volume = 4.76cm3,	Footprint = 5.29cm2
CM Choke:	Copper Loss = 520mW,	Volume = 2.89cm3,	Footprint = 3.61cm2
Total :	= 1240mW,	= 7.65cm3	= 8.90cm2

CMDM

- 2 * Lk = DM Inductance = 350uH and capable of supporting 2.2A
- Lm = CM Inductance = 1.6mH
- DCR (per winding) = 110mOhms
- Size: 25 x 20 x 12 mm

CMDM Choke: Copper Loss = 880mW, Volume = 6.00cm3, Footprint = 5.0cm2

CMDM Choke reduces:

- Power Loss by 30%
- Component Volume by 22%
- Component Board Area by 44%

Lower Cost than non-integrated components

Magnetic Component Integration
Conclusion

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- Integration of magnetic components can improve efficiency, increase power density and lower costs all while meeting thermal requirements.
- Although the initial design iteration of the magnetic requires some forethought and analysis the equations and concepts are well known.
- The detailed example of the CMDM highlights the design approach and shows the overall improvement in performance.
- Integrated magnetics have been widely adopted in some high-power topologies but as pressure to 'improve' power supplies increases integration will become more mainstream.