Modeling and Design of Multiwinding Magnetics for High Frequency Power Electronics

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We Need Better Magnetics

- Breakthroughs in semiconductor devices (SiC and GaN)

- Magnetics are lagging behind

- SiC modules
- GaN Switches
- IGBT Modules
- Power SoC

Energy Density vs. Functionality

- Capacitors win in energy density
- Larger magnetics has better figure-of-merits
- Magnetics win in functionality
- **Multi-winding, multi-leg, multi-functional magnetics @ high frequency**

\[ VA \propto \varepsilon^4 \]

Linear scaling factor

Source: Robert Pilawa

Source: Charles Sullivan
Multi-Functional Magnetics

Single Purpose Magnetics

Multiwinding Magnetics

Multileg Magnetics
The “integrated magnetics” concept started from 1980s’

Need tools and methods to design for high frequencies
Multi-Winding Magnetics: Two Categories

- Multiple windings couple to a single magnetic linkage

- Multiple windings couple to multiple magnetic linkages

# Design Options for Planar Magnetics

## 1. What is the optimal way to interleave many layers?

<table>
<thead>
<tr>
<th>Copper</th>
<th>Thick Spacing</th>
<th>1</th>
<th>Alternating interleaved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>Thin Spacing</td>
<td>2</td>
<td>Symmetric interleaved</td>
</tr>
<tr>
<td>Copper</td>
<td>Thick Spacing</td>
<td>3</td>
<td>More complicated?</td>
</tr>
<tr>
<td>Copper</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 & 3 as primary
2 & 4 as secondary

## 2. What are the optimal winding stack and winding spacing?

<table>
<thead>
<tr>
<th>Thin Middle Spacing</th>
<th>Thick Middle Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thick</td>
<td></td>
</tr>
<tr>
<td>Thin</td>
<td></td>
</tr>
<tr>
<td>Thick</td>
<td></td>
</tr>
</tbody>
</table>

## 3. Multi-object optimization problem

1) Interleaving options?
2) Materials?
3) Geometry?
4) Size?
5) Efficiency?
6) Coupling coefficient?
Two Commonly Shared Assumptions

Every model starts from assumptions …

(1) MQS assumption

Magneto-Quasi-Static Maxwell’s equations

\[
\begin{align*}
\nabla E &= \frac{\rho}{\varepsilon_0} \\
\nabla B &= 0 \\
\n\nabla \times E &= -\frac{\partial B}{\partial t} \\
\n\nabla \times B &= \mu_0 (J + \varepsilon_0 \frac{\partial E}{\partial t})
\end{align*}
\]

• Assume \( \frac{\partial E}{\partial t} = 0 \).
• Applicable when the wavelength is much longer than the device size (usually lower than ~100MHz).

(2) 1-D assumption

Magnetic core guides the flux

• Fields vary only along the thickness direction.
• Applicable when the flux is guided by the magnetic core.

忽略电场的演化

Skin and proximity effects change current distribution
Wave Propagation in Planar Windings

- **1-D energy wave (Poynting vector) propagation principles**

- **Modular lumped circuit models for repeating building blocks**
**Modeling a Single Conductor Layer**

**Field diffusion equations:**

\[
H_x(z) = \frac{H_T \sinh(\Psi z) + H_B \sinh(\Psi (h - z))}{\sinh(\Psi h)}
\]

**Ampere’s law:**

\[
\nabla \times H = J = \sigma E
\]

\[
\psi = \frac{1 + j}{\delta} \quad \delta = \frac{2}{\mu \omega \sigma}
\]

**E field as a function of H and K:**

\[
E_T = E_Y(h) = \frac{\psi}{\sigma} \left( \frac{H_T e^{\Psi h} - H_B}{e^{\Psi h} - e^{-\Psi h}} \right)
\]

\[
E_B = E_Y(0) = \frac{\psi}{\sigma} \left( \frac{H_T - H_B e^{-\Psi h}}{e^{\Psi h} - e^{-\Psi h}} \right)
\]

\[
Z_a = \frac{\Psi(1 - e^{-\Psi h})}{\sigma(1 + e^{-\Psi h})}
\]

\[
Z_b = \frac{2\Psi e^{-\Psi h}}{\sigma(1 - e^{-2\Psi h})}
\]

**KVL/KCL relationships:**

\[
\begin{align*}
V/m & \quad \Omega & \quad A/m \\
E_T &= Z_a H_T + Z_b K & \text{KVL} \\
E_B &= Z_b K - Z_a H_B & \text{KVL} \\
K &= H_T - H_B & \text{KCL}
\end{align*}
\]

**Electromagnetic Fields**

**Modular Layer Model**

**KVL:** through variables ~ unit (A/m)

**KCL:** impedances ~ unit (Ω)

**E:** across variable ~ unit (V/m)
Modeling Two Adjacent Layers

**Intuition:**
- Two three-terminal networks
- Connected by the $H$ field between them

**Faraday’s Law and Field Continuity**

\[
E_{B1} d - V_1 = -\frac{d\Phi_{B1}}{dt} \quad E_{T2} d - V_2 = -\frac{d\Phi_{T2}}{dt}
\]

\[
\frac{d\Phi_{T2}}{dt} = \frac{d\Phi_{B1}}{dt} + \frac{d\Phi_A}{dt}
\]

**Flux Linking Two Layers:**

An additional KVL equation

\[
j \omega \mu_0 a_1 \frac{H_{S12}}{\Omega} = \frac{V_2}{d} - \frac{E_{T2}}{d} - \frac{V_1}{d} + E_{B1}
\]

$/m$ $A$/m $V$/m

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Modeling Layers with Multiple Turns

Fields distributions in multiple-turns layers are linearly related to those in single-turn layers

Multiple turns $\rightarrow$ Additional Linear Conversions

E&M Domain

Circuit Domain

Intuitive Ideal Transformers
Modeling via connections is equivalent to adding KVL, KCL constraints:

Layer $i$ and Layer $j$ in series
Layer $k$ and Layer $l$ in parallel

\[
\begin{align*}
V_i + V_j &= V_a \\
V_k &= V_l = V_b \\
I_i &= I_j = I_a \\
I_k + I_l &= I_b
\end{align*}
\]

Connect the layer ports in the same pattern as they are in the real circuit.
An Open-Source SPICE Modeling Tool

1. Geometry Information

   - Magnetic Core
   - Winding stack
   - Side air gap
   - Center air gap
   - Side air gap

2. Modular Layer Model

   - Top Side of the Core
   - Spacing
   - Layer 1
   - Spacing
   - Layer 2
   - Spacing
   - Layer 3
   - Spacing
   - Layer ...
   - Spacing
   - Bottom Side of the Core

   - Series Vias
   - Parallel Vias

   - 5:1
   - 1:1

3. SPICE Netlist

   - Circuit Domain
   - E&M Domain

   - Layer 1
   - Layer 2
   - Layer 3
   - Layer 4

   - Winding a
   - Winding b
   - Winding ports

   - Spacing

Search: M2SPICE
**Impacts of Interleaving Patterns**

Comparing the $P_{ac}$ and $E_{ac}$ of three 1:1 transformers with three different interleaving patterns

**Non interleaved**

**Alternating**

**Symmetric**

\[ P_{ac} = \sum I^2 R_{ac} \]

\[ E_{ac} = \frac{1}{2} \sum I^2 L_{ac} \]

Interleaving has to be done in the right way !!!
Example Applications

Multi-Input Multi-Output Power Electronics Systems

Battery Banks  Server Racks  Solar Farms
Power Management for Storage Servers

Magnetics Design → Circuit Topology → System Integration

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A Conventional Dc-Dc Approach

Hard Drive Data Storage Server

50V

100% Power Processing

5V
Differential Power Processing

- DC Bus
  - HDD 1.1
  - HDD 1.2
  - HDD 1.3
  - HDD 1.M

- Domain 1

- Domain 2
  - HDD 2.1
  - HDD 2.2
  - HDD 2.3
  - HDD 2.M

- Domain 3
  - HDD 3.1
  - HDD 3.2
  - HDD 3.3
  - HDD 3.M

- Domain N
  - HDD N.1
  - HDD N.2
  - HDD N.3
  - HDD N.M

- DPP Converter

- Differential Power Processing

<10% Differential Power

- Horizontal RAID
- Vertical RAID

- GND

50V
45V
40V
5V
GND
Existing DPP Solutions

DPP with a buffer port

Ladder DPP

Transformer saturation requirements: maximum volt-seconds per turn

\[
\frac{V_1}{N_1} = \frac{d\Phi_1}{dt} \\
\frac{V_2}{N_2} = \frac{d\Phi_2}{dt} \\
\vdots \\
\frac{V_n}{N_n} = \frac{d\Phi_n}{dt}
\]

\[
\frac{V_k(t)}{N_k} = \Delta\Phi_k \\
\frac{V_{k+1}(t)}{N_{k+1}} = \Delta\Phi_{k+1}
\]

3D stacked multiwinding transformer with modular planar modeling

PCB1: Layer 1 – Layer 6
PCB2: Layer 7 – Layer 10
Distributed Phase Shift Control

Phase shift determines the power flow

Block diagram of the distributed control
Complete HDD Storage System

[Diagram of HDD Storage System with labels for MotherBoard, Power Supply, HDD Array, and MAC-DPP]
Performance of the DPP Architecture

Summary:
- Multiwinding transformer enables ultra high performance DPP
- DPP architecture fits well to large scale modular systems
MIMO Reconfigurable Energy Router

Lumped Circuit Model for Magnetics

- Multiple winding coupled to a single flux linkage

![Circuit Diagram 1](image1.png)

- Multiple windings coupled to multiple flux linkages

![Circuit Diagram 2](image2.png)
Circuit Models for Coupled Magnetics

Physical Structure

Reluctance Model

Multiwinding Transformer Model

Inductance Matrix Model
Permeance Model & Reluctance Model

Advantage of the Permeance Model

- Simple
- Intuitive
- No coupled inductors
- Explicit design equations
- Capability of capturing core loss

Permeance Model for SPICE Simulation

Multileg Coupled Magnetics

Topological duality
Hybrid Converter with Coupled Magnetics


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Towards a MIMO Magnetic Energy Processor

Multiwinding Magnetics

DC/AC

AC/DC

Z

Z

Z

Z

Z

Z

Connection Link
A Magnetic Memory in 1960s

- A 32 x 32 core memory storing 1024 bits of data
- Instead of processing information, we process energy
Summary

Exciting Opportunities for Power Electronics & Magnetics

Information Processing

Energy Processing

32 x 32 Magnetic Memory

10-Port MIMO Power Converter

More topologies and designs to be investigated!
Acknowledgements

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References

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• H. Schmidt and C. Siedle, “The charge equalizer-a new system to extend battery lifetime in photovoltaic systems, UPS and electric vehicles,” INTELEC93.