Recent Trends in Design and Techniques to Influence Thermal Performance of Magnetic Components

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Magnetic Components are a crucial component in many power electronic systems are intrinsic to the efficient and effective operation of power systems in many applications including in automotive, aerospace, consumer and computing.
A key aspect of the challenge of working with magnetic components is the variability of the magnetic material behaviour, particularly with respect to temperature.
For the last several decades engineers have been perfecting silicon based power electronics using ferrite cores and developing rules of thumb and techniques for modeling magnetic components. For example, the famous Jiles-Atherton model.
Modeling Magnetic Materials

- ...is particularly complex, with many choices
  - Jiles Atherton (JA)
  - Preisach
  - Hodgdon, et al

- The JA model is often used in circuit simulators
  - It is relatively simple to model
  - Some issues with convergence
  - Purely analogue
  - Physically based

But, are they good enough for high frequency and high temperature operation?
Alternatives

- The Preisach model has been around since the 1920s (!)
- It is a more “discrete” model
- It simulates very well and is robust
- But it is difficult to implement in many simulators (it has been in Saber for many years, others more recently)
- It is less “physically based” – difficult to characterize
Jiles Atherton Model

The results are particularly good at predicting the BH loop behaviour in ferrites, however the Preisach model is often better for “square” loop materials.

For soft ferrites, it matches very well.
But what about temperature?
Energy Lost in Magnetic Materials

The magnetic material will dissipate energy as heat under heavy loading:
The effect of Temperature?

How does the overall temperature of the material affect its behaviour?

Eventually the Curie point is reached and the material ceases to have any effective permeability.

Losses are optimized in Soft Ferrites such as MnZn at around 100°C.
It makes a difference...

Data for a 3F3 Material, 10mm Toroid obtained by the author, measured using a Griffin-Grundy oven to control the temperature

P. R. Wilson and J. N. Ross, "Definition and application of magnetic material metrics in modeling and optimization," in *IEEE Transactions on Magnetics*, vol. 37, no. 5, pp. 3774-3780, Sept. 2001
So how can we design effectively incorporating the temperature into our simulations?
A note...

Magnetic Components are notoriously variable

The magnetic material has a very high variation in parameters

The resulting values of inductance may vary by 10% or more from the calculated value

A model needs to reflect this to be realistic
To build a component (e.g. inductor) for electric circuits, we need both a core model and a winding.

This is the connection between the electrical and magnetic domains (winding).

The core model can consist of multiple elements representing the various physical elements of a core (legs, plate etc).
Magnetic Model

\[ v_p = n_p \frac{d\Phi_p}{dt} \]

\[ mmf_p = n_p i_p \]
Adding Non-linearity

Jiles and Atherton developed a theory of ferromagnetic hysteresis (1983-1986).

This separates the hysteresis function into the reversible, or anhysteretic, and the irreversible, or loss, magnetizations.
Jiles-Atherton Model

The total lumped magnetization as derived by Jiles and Atherton is given by:

\[ M_{TOTAL} = M_{IRREVERSIBLE} + M_{REVERSIBLE} \]

For details of the equations see the appendix slides, this also gives the key references.
Avoiding problems

Implementing the nonlinear equations for the Jiles-Atherton model highlight a number of issues.

Taking the Langevin equation it can be seen that for small values of magnetic field strength, there will be an issue when \( H \) approaches zero, leading to an infinite value of magnetization.

Most implementations use a small linear region close to the origin, such that the potential divide by zero error is avoided.
Adding the Thermal Dependence

To add dynamic thermal behaviour, use a network to effectively model the thermal aspects of the material and the environment.

Link the thermal behaviour to an additional set of thermal components.
Thermal Dependence

- Jiles-Atherton Non-Linear Core Model
  - Modified Model Parameters
  - Default Model Parameters
  - Parameter Functions
  - Thermal Network
  - Eddy Current Loss
  - Winding Loss

- Power:
  - H → Jiles-Atherton Non-Linear Core Model
  - B
  - T(°C)
  - Current
  - Power
Thermal Network Modeling

We have choices to make regarding the thermal network, in particular a distributed or lumped model.

In most cases a lumped model is perfectly adequate.
Characterize the Magnetic Material

It is a relatively simple matter to characterize the magnetic material model by measuring its behaviour and calculating the resulting model parameters.

![Graph showing temperature versus magnetic property]

- A (Measured) — A (Second Order Fit)

![Diagram of experimental setup showing devices such as a signal generator, oscilloscope, and temperature meter]
Building a Circuit Model...

Using the characterized thermally dependent model of the core, winding models and a thermal network, we can make the electric circuit model (in this case a transformer) *dynamically* affected by temperature.
Transformer model

Remember we also need to include the heating effect due to the windings. This is also frequency dependent and must consider eddy currents.
Results

At ambient Temperatures, the model behaves very closely to the measured data.
Results

At increased temperatures, the transformer output voltage drops due to reduced permeability.

More recent work

Has enhanced the dynamic magnetic behavior by extending the magnetic-thermal equations into two parts:

How to optimize the model parameters?

We can use holistic techniques such as Genetic Algorithms to solve multiple dimension parameter characterization problems.
Genetic algorithms
Mimic nature’s best bits...

Details of the GA process are given in the additional slides
Genetic Algorithms (GA)

GAs are a type of stochastic search.
They can be used when gradient searches can not be applied.
They are particularly useful for combinational problems (trying different configurations).

Genetic Algorithms are search algorithms based on evolution. Darwinian survival of the fittest.

Charles Robert Darwin, 1809-1882

"In the struggle for survival, the fittest win out at the expense of their rivals because they succeed in adapting themselves best to their environment."

from On The Origin of Species
Apply optimization characterize parameters for magnetic materials

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GA (JA)</th>
<th>GA (JA Modified)</th>
<th>SA (JA)</th>
<th>SA (JA Modified)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>13.8</td>
<td>9.29</td>
<td>7.26</td>
<td>6.96</td>
</tr>
<tr>
<td>c</td>
<td>0.799</td>
<td>0.497</td>
<td>0.150</td>
<td>0.308</td>
</tr>
<tr>
<td>k</td>
<td>11.01</td>
<td>12.67</td>
<td>7.19</td>
<td>11.176</td>
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<td>alpha</td>
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<td>29.1e-6</td>
<td>4.29e-6</td>
<td>4.54e-6</td>
</tr>
<tr>
<td>Ms</td>
<td>293318</td>
<td>268562</td>
<td>264500</td>
<td>257479</td>
</tr>
<tr>
<td>sigma</td>
<td>-</td>
<td>16.55</td>
<td>-</td>
<td>15.54</td>
</tr>
<tr>
<td>Error</td>
<td>0.1416</td>
<td>0.019</td>
<td>0.188</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Interesting points to note

There was no convergence of parameters
This implies a multiple solution space, or perhaps no global minimum found

Recent work has shown that we need to be careful using machine learning techniques to obtain optimized parameters:

- They may not be physically realistic
- They may be very sensitive to error

Always better to have a physical understanding of what is going on, even if only to calibrate or “seed” an algorithm
State of the Art circa 2010

Silicon Devices well understood
Frequency performance constrained
Voltages on devices limited in most cases to below ~800V
On resistances relatively large
dV/dt switching rates under control
Magnetic components design techniques and tools in place
Good materials available for “high” frequency operation

...All is well....
Then along came wide band gap devices....and changed everything...
SiC/GaN Properties

- SiC and GaN both have $\sim 10x$ higher $E_{\text{crit}}$ than Si
- Electron saturation velocity $\sim 2x$ higher.
- GaN electron mobility is a little better than Si,
  – SiC a little worse.
- SiC has significantly better thermal conductivity.

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<th>SiC</th>
<th>GaN</th>
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<td>Critical Field ($E_c$) x10$^7$V/m</td>
<td>3</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Electron Mobility (cm$^2$/V-sec)</td>
<td>1450</td>
<td>900</td>
<td>2000</td>
</tr>
<tr>
<td>Electron Saturation Velocity (x10$^6$ cm/sec)</td>
<td>10</td>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>Thermal Conductivity (Watt/cm$^2$ K)</td>
<td>1.5</td>
<td>5</td>
<td>1.3</td>
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Seismic Shift in breakdown voltage and on resistances

Measured data
Ecrit: Si=20V/μm, GaN=300V/μm
Ref: N. Ikeda et. al. ISPSD 2008 p.289
We must look at SiC and GaN differently...

Roadmap to Unlocking Full Potential of GaN in Power Conversion Applications
David Sanderlin et al, IEEE PELS Magazine, June 2018
What does this mean for us?

Higher Voltages 1200V, 1700V
Faster Switching Speeds – higher switching frequencies
Higher dV/dt – transients?

All issues for the power electronics designer to manage in magnetics design
Consider a simple Buck converter
No lead inductances – $V_s$ clean
Add parasitics – a different story!
Where does this high frequency noise go => to the inductor

Can result in excessive eddy currents – heat/noise
Need a snubber network to clean this up
Horrendous for EMI!

Simple RC snubber makes a huge difference
Thermal Tolerance

Silicon Carbide works very well at high temperatures
This sounds great – except everyone else now has to operate there as well...

Particularly problematic for passive components

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Predicting Performance with WBG devices

Simulation is still valid, but new models are available to provide more accurate behavior – essential for effective magnetic component design and assessment in the circuit context


Transients => Eddy Currents

Now a **serious** problem for the magnetics designer *(Although we have known about these effects for a while...)*

- Conductors
- Ferrite materials
- Frequencies $>> 1$MHz


Transformer with a heatsink?

Yes, this has now become a reality

Common to see LLC active bridge converters in charging applications

=> Planar Magnetics

High Density WBG Converter

500kHz CLLC Resonant Converter

Based around a combination of SiC and GaN devices

Planar Magnetics or Litz Wire?

Trade-Off:
+ Repeatable and integral to PCB design
+ Predictable Leakage Inductance
- Higher Power Losses than Litz wire solution (32W compared to 25W)
- Larger Volume (about 30% more)
Using Thermal Epoxy to Pot Magnetic Components

Recent studies have shown that using thermal epoxy to accurately position heat pipes and ensure that thermal design of magnetics with respect to a cold plate can provide excellent thermal performance.

The IR camera images show the temperature rise is within the constraints of the system of 120 °C (97.1)

The epoxy potting compound is t-Global TGLHFBPE-80

The system uses a mixture of air and water cooled systems

New Materials are emerging

Materials that are being custom designed to provide the thermal and frequency range required for SiC and GaN devices

Particle Sizes reducing to ~2.5 um

New materials show promise to provide much lower losses at a broad range of frequencies.

Other new materials are being developed for High Frequency WBG power electronics

- Much of the work is concentrated on Fe-Co and Co-based nanocomposites
- High Voltage, High Frequency and High Saturation

Conclusions

New Topologies and Techniques are emerging to take advantage of the raw speed and overall performance benefits of WBG (SiC and GaN) power semiconductors.

Greater efficiencies mean that the focus is back onto the passives (Magnetic components especially) to ensure that they are more efficient.

New materials to not only be more efficient, operate at higher frequencies but also be thermally tolerant.

We are having to rewrite many of the rules of power electronics design, however we have many of the fundamentals defined already for magnetics components.
Questions?
Additional Slides

Further Details to supplement the presented slides
Fundamentals

Magnetic modeling uses a similar basic approach to electrical models:

Through variable is defined as Flux (Wb)
Across variable is MMF (Magneto Motive Force) (A).
Magnetic Networks

Note, in the magnetic domain:

the power is the product of the derivative of the flux (Φ) and the mmf.

This is unlike other physical domains (such as electrical) where the power is the direct product of the through and across variables

For example V × I in the electrical domain

This gives power in Watts
Power

Calculating the energy in the system from the power is carried out in the same manner as the other domains.

The energy is the integration of the power.

In the magnetic domain, this is the integration of the mmf and the derivative of the flux:

\[ Energy = \int mmf \times \frac{d\Phi}{dt} \, dt \]
Creating a simple core model

The relationship between the flux and the mmf in a linear core model is defined as follows:

\[ \text{mmf} = \text{flux} \times R \]

Where the reluctance (\( R \)) is related to the size of the core and the permeability.
Reluctance Model

• In most practical systems, the designer is concerned with the relationship between the flux density \( (B) \) and the field strength \( (H) \).

• These are related to the flux and mmf, respectively, with the area \( (A) \) and length \( (L) \) of the core material:

\[
B = \frac{\Phi}{A} \\
H = \frac{mmf}{L}
\]
Reluctance Model

In fact, the core model is often expressed in terms of $B$ and $H$. The reluctance is then calculated from the permeability, Cross Sectional Area and Effective Core Length.

where $\mu_r$ is the relative permeability of the core material.

$$B = \frac{\mu_0 \mu_r L}{A} \times H$$
The Jiles Atherton Model

a bit more detail on the JA model
The total lumped magnetization as derived by Jiles and Atherton is given by:

\[ M_{TOTAL} = M_{IRREVERSIBLE} + M_{REVERSIBLE} \]
Langevin Function

The normalized anhysteretic function, $M_{an}$, is approximated by the Langevin function

$$M_{an} = \frac{1}{\tanh(He/A)} - \frac{A}{He}$$

The rate of change of the irreversible magnetization, $M_{irr}$, is obtained using

$$\frac{M_{irr}}{dH} = \frac{(M_{an} - M)}{\delta k} - \frac{\alpha (M_{an} - M)}{\mu}$$
Bringing it together

The total magnetization rate of change is calculated using

\[
\frac{dM}{dH} = \frac{1}{1+c} \frac{Man - M}{\delta k} - \left( \frac{Man - M}{\mu} \right) + \frac{c}{1+c} \frac{dMan}{dH}
\]

A problem is that most time domain circuit simulators do not implement partial derivatives

Therefore need to implement Runga-Kutta or “spoof” using time derivatives and separate variables
Avoiding problems

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"In the struggle for survival, the fittest win out at the expense of their rivals because they succeed in adapting themselves best to their environment."

*from On The Origin of Species*
So, how do we “copy” Evolution?

1. Initialize...
2. Then evaluate...

and 3. rank....
4. Selection...
5. Crossover & mutation
6. Survival (of the fittest?)
So what’s the problem? It’s bound to get the right answer in the end, isn’t it?

Evolution always works...doesn’t it?

Err....
Parallelism

GA are inherently parallel. All the evaluations can be done at the same time. Ideal for multiprocessor or distributed machines.
Diversity and Stagnation

**Diversity** is when the population has a variety of genetic material. This is generally desirable for exploring different parts of the optimization landscape.

**Stagnation** is the opposite of diversity all the genes in the population have similar genetic information. This can sometimes happen and we can get stuck in a local maximum.

*Mutation and crossover help create diversity.*