Ferromagnetic Material Modeling with an Equivalent Circuit Model

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BACKGROUND
- The process of magnetization and losses experienced by a material is very difficult to predict and varies vastly between individual material structures/compounds.
- Current modeling tools are not intuitive or easily accessible to many power electronics engineers, thus prompting a circuit-based solution.

OBJECTIVES
- Derive applicable circuit-based equations from existing magnetic-dynamic modeling foundations (LLG equation).
- Design a circuit model which includes circuit parameters to equivalent physics parameters associated with the magnetization process.

CIRCUIT MODEL

PARAMETER CONVERSION

<table>
<thead>
<tr>
<th>Physics Parameter</th>
<th>Circuits Parameter</th>
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</thead>
<tbody>
<tr>
<td>( M ) (magnetization)</td>
<td>( V ) (Voltage)</td>
</tr>
<tr>
<td>( H ) (applied field)</td>
<td>( I ) (current)</td>
</tr>
<tr>
<td>( y ) (gyromagnetic ratio)</td>
<td>( Z_y ) (gyrator)</td>
</tr>
<tr>
<td>( \alpha ) (damping factor)</td>
<td>( R ) (resistor)</td>
</tr>
<tr>
<td>( M_{ext} ) (mutual coupling)</td>
<td>( I_{ext} ) (non-linear inductor)</td>
</tr>
</tbody>
</table>

These parameters were derived by the Landau-Lifshitz-Gilbert (LLG) equation:

\[
\frac{dM}{dt} = -\gamma \mu_0 (\overline{M} \times \overline{H}) - \frac{\alpha}{M_s} (\overline{M} \times \frac{d\overline{M}}{dt})
\]

Describing magnetization dynamics – the motion of \( M \) within a solid.

With voltage and current being guided by the following relationships:

\[
V_x = \mu_0 \Delta y \Delta z \frac{dM_x}{dt}, \quad V_y = \mu_0 \Delta x \Delta z \frac{dM_y}{dt}, \quad V_z = \mu_0 \Delta y \Delta x \frac{dM_z}{dt}
\]

\[
I_x = H_x \Delta x, \quad I_y = H_y \Delta y, \quad I_z = H_z \Delta z
\]

STONER-WOHLFARTH MODEL

CONCLUSION & FUTURE WORK
- Using an equivalent circuit model is a viable method of describing hysteresis.
- The model has the capability to be tested against existing and accepted models describing the complex behaviors of magnetic materials.
- Future work includes adding more levels of complexity to the model including:
  - anisotropic behaviors with multiple preferred axes, exchange interaction between domains, and temperature dependence.

The resulting B-H loop when orienting the applied field parallel to the anisotropy field. (The angle between \( H \) and \( H_{anis} \) is very close to 0°)

The resulting B-H loop when orienting the applied field perpendicular to the anisotropy field. (The angle between \( H \) and \( H_{anis} \) is very close to 90°)