Overview of Modelling Methods

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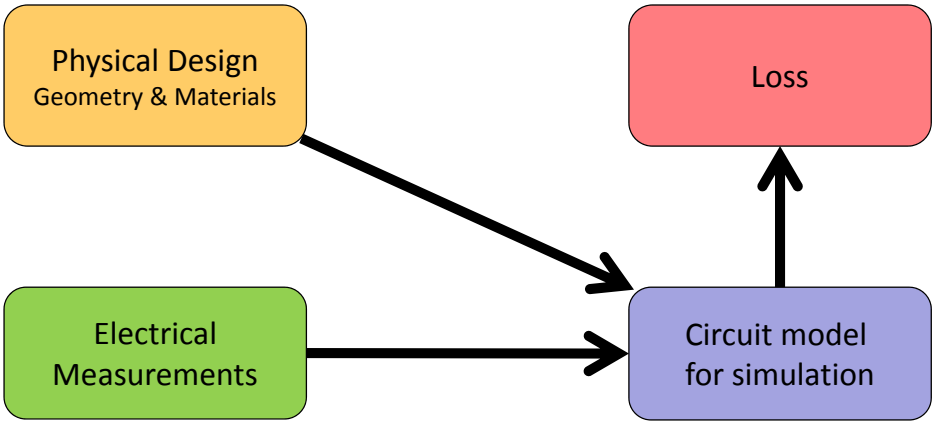
Winding models vs. Core models

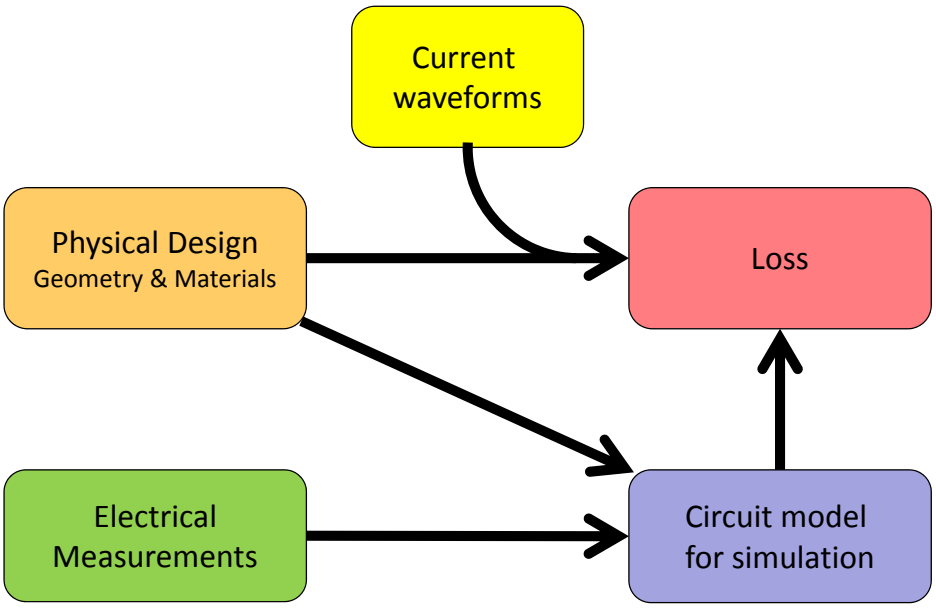
- Linear, well known material properties.
- Behavior is a solution to Maxwell's equations.
- Numerical, analytical, or mixed solutions.
- Can be accurately approximated by linear circuit networks, given enough RLC elements (usually just RL).

- Nonlinear material properties, known only through measurements.
- Models are behavioral, based on measurements.
  - Physics-based micromagnetic models exist, but can't address ferrite loss yet.
- Circuit models based on RLC elements only can't capture nonlinear behavior.

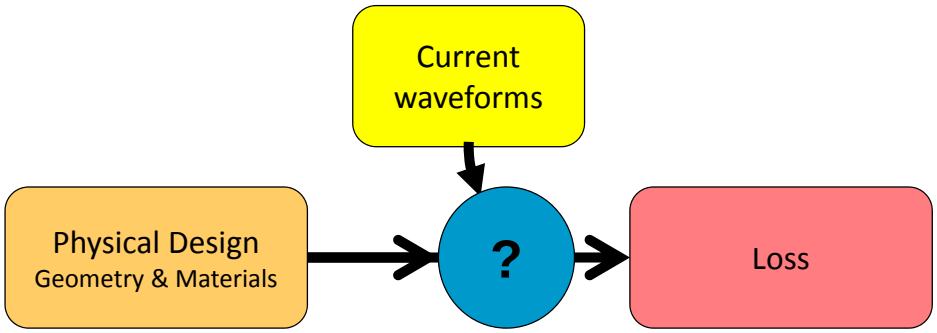
Winding models



Winding models



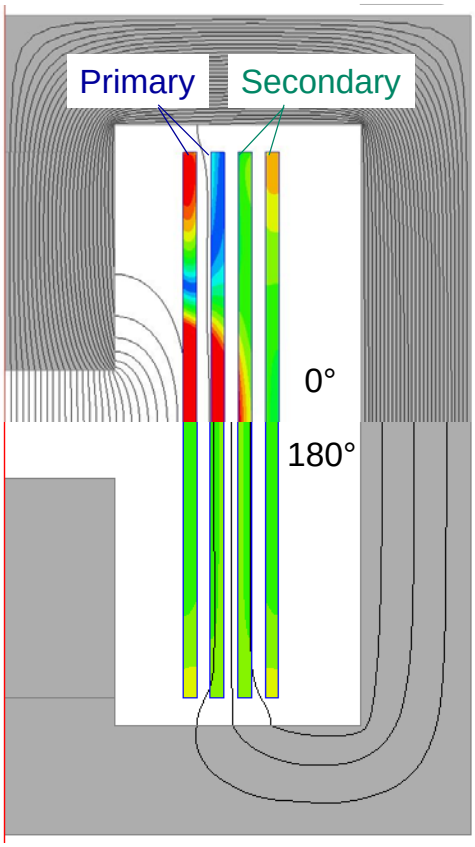
Winding models



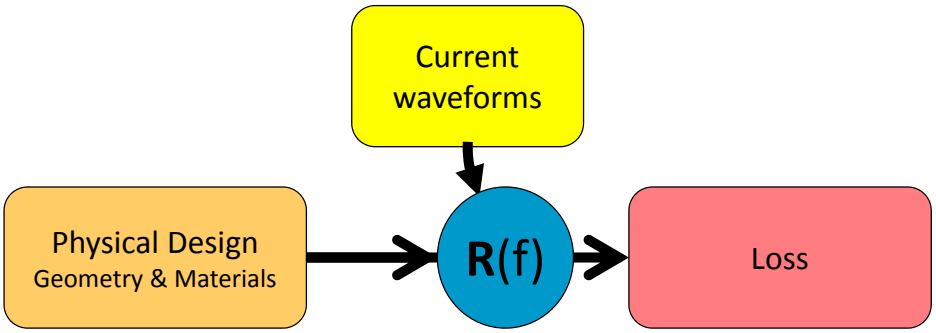
- Winding ac resistances?

Loss calculated from currents

- Conventional, incorrect, model for transformer winding loss (assume sine waves for now).
  - $P_{winding} = I_1^2 R_1 + I_2^2 R_2$
  - Problem: Loss varies drastically depending on relative phase/polarity.
  - Factor of 4 error in this case.
- Correct model options:
  - R_1 and R_2 that are only for specific phase relationship.
  - **Resistance matrix.**

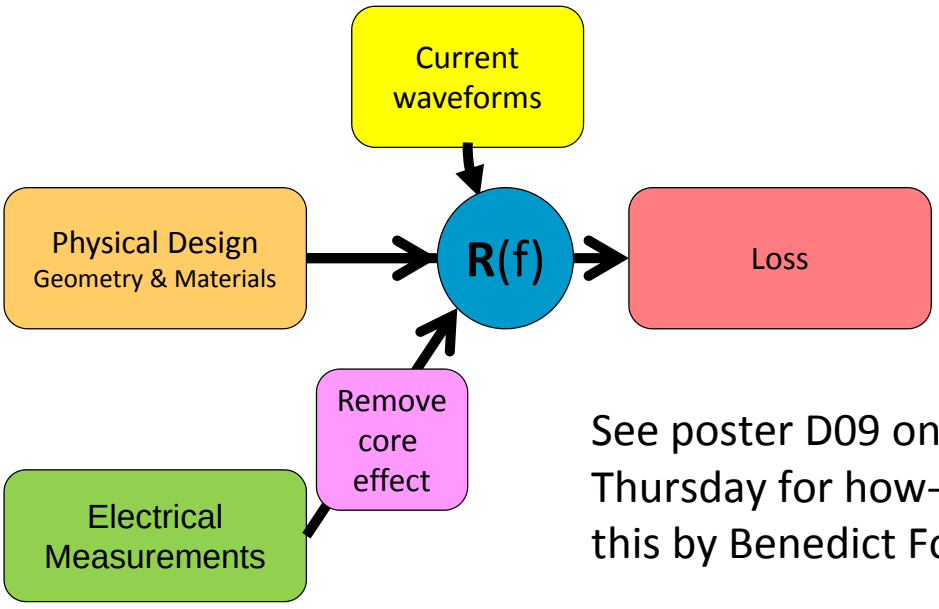


Winding models



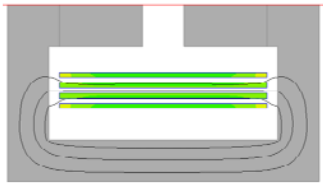
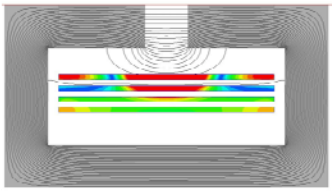
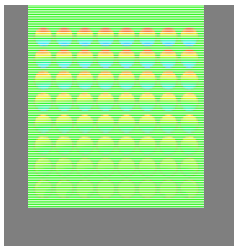
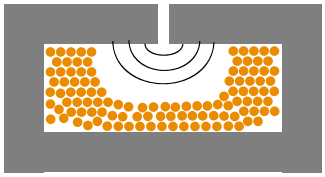
- ~~Winding ac resistances?~~
- Frequency-dependent resistance matrix **R**(f).
- Captures interactions between windings.

Winding models

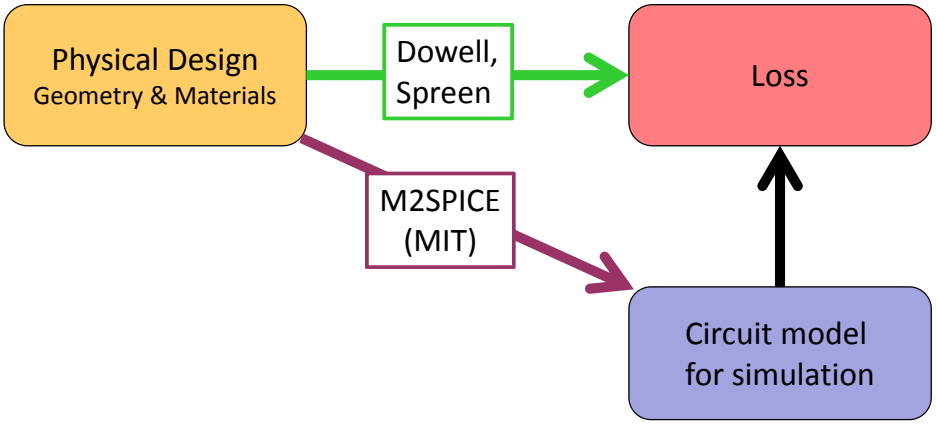


See poster D09 on Thursday for how-to on this by Benedict Foo.

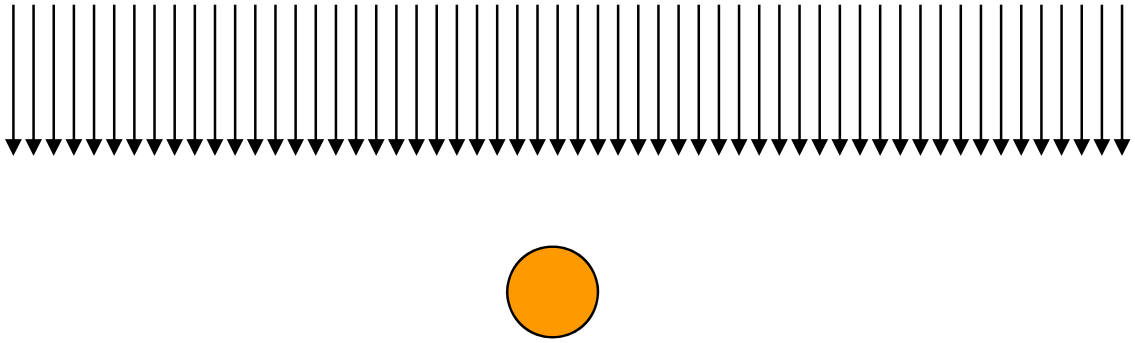
Predictions from physical structure

	1-D fields	2-D or 3-D fields
Rectangular conductors (e.g. foil and PCB)	Analytical 	Numerical (Finite Element, PEEC, etc.) 
Round-wire conductors (including litz)	Simulation-tuned physical model 	Simulation-tuned physical model + dc field simulation 

Winding models: 1D, rectangular conductors

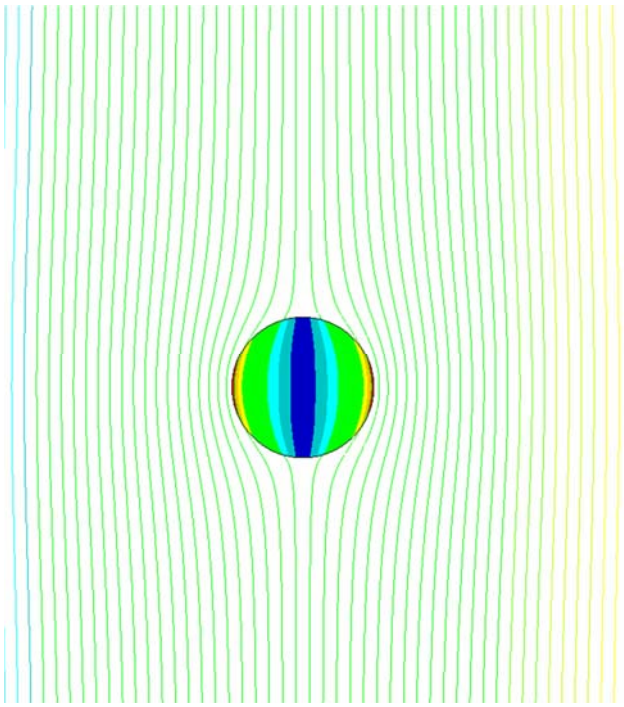


Round conductor: Textbook problem



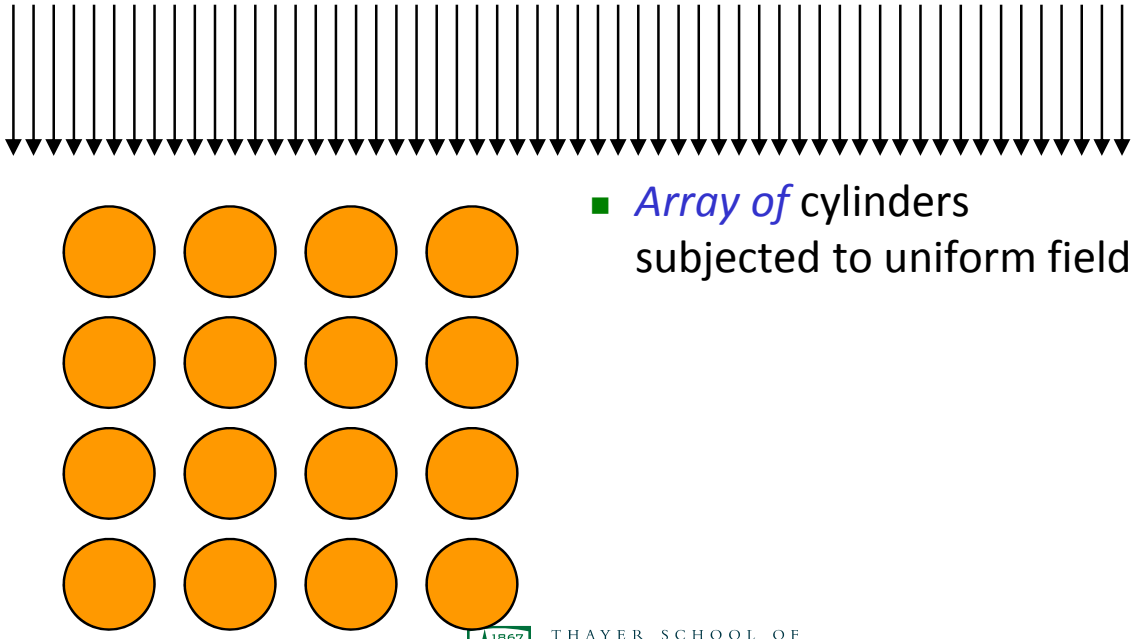
- Cylinder subjected to uniform field
- Dowell's model is a crude approximation.

Textbook solution



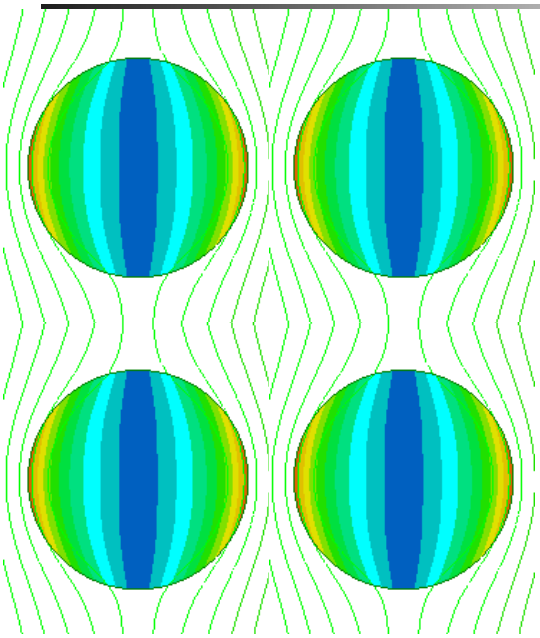
- Exact solution, described by Bessel functions.
- Use for winding loss analysis pioneered by Ferreira.

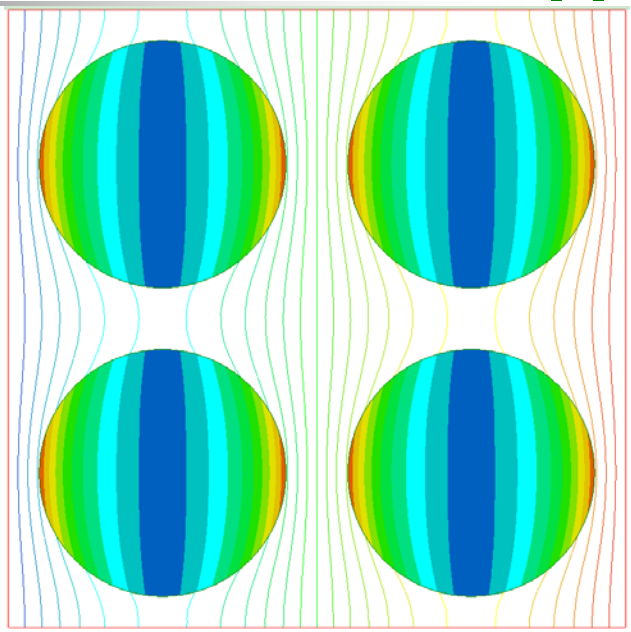
Actual problem



- *Array of* cylinders subjected to uniform field

Using the Bessel solution for the real problem

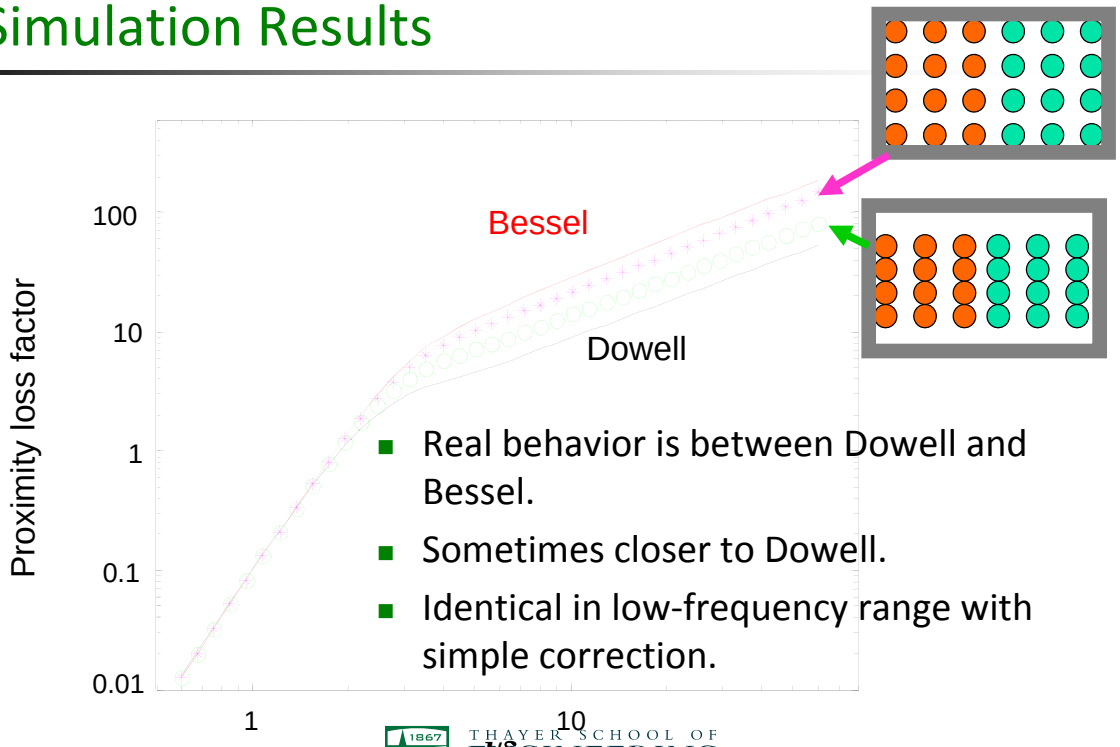




Not a valid solution!

Real Solution (FEA)

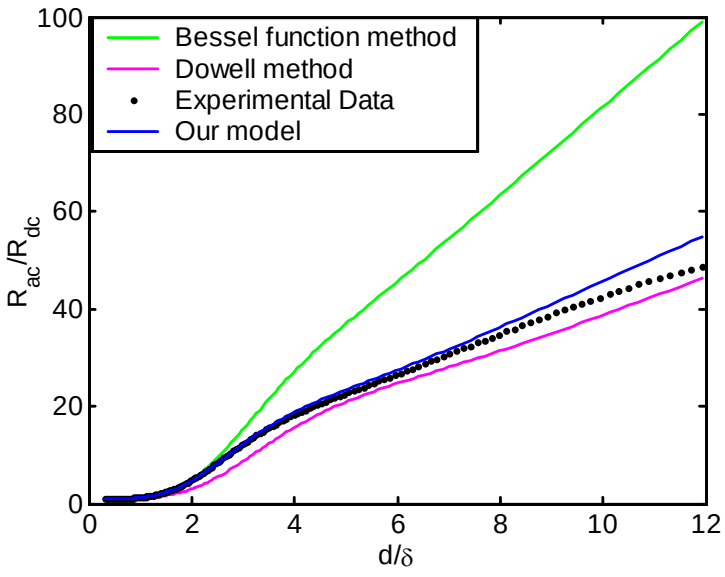
Simulation Results



- Real behavior is between Dowell and Bessel.
- Sometimes closer to Dowell.
- Identical in low-frequency range with simple correction.

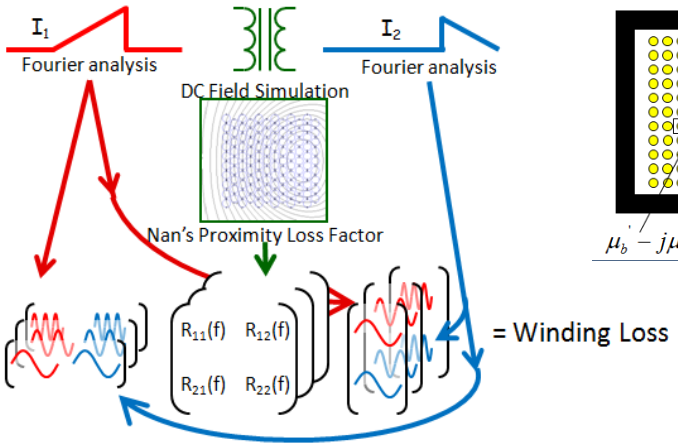
Xi Nan's model

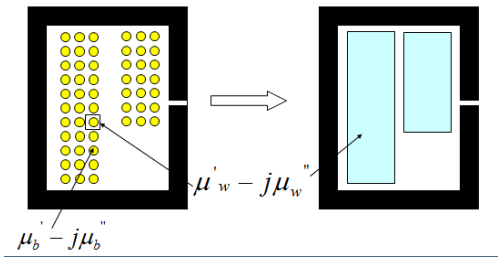
- Weighted average of Dowell-like and Bessel-like behavior: "Simulation tuned physical model"
- Fits experimental results better than Dowell or Bessel.
- Can be applied to 2D or 3D field configurations …



Full winding loss model: 2-D, full frequency range, multi-winding interactions

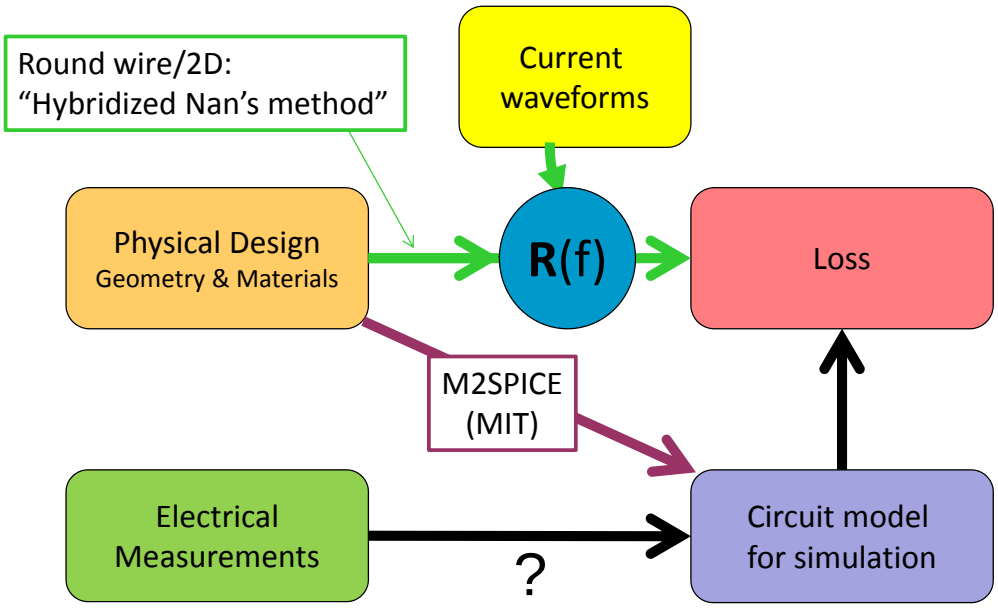
- Hybridized Nan's method (Zimmanck, 2010)
- Homogenization with complex permeability (Nan 2009, Meeker, 2012)





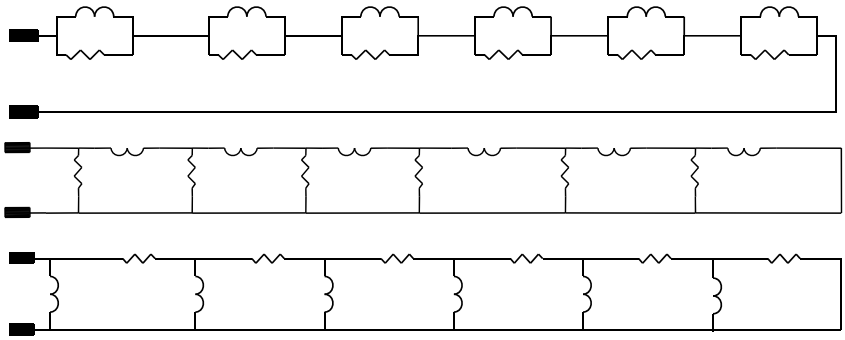
Available in FEMM

Winding models

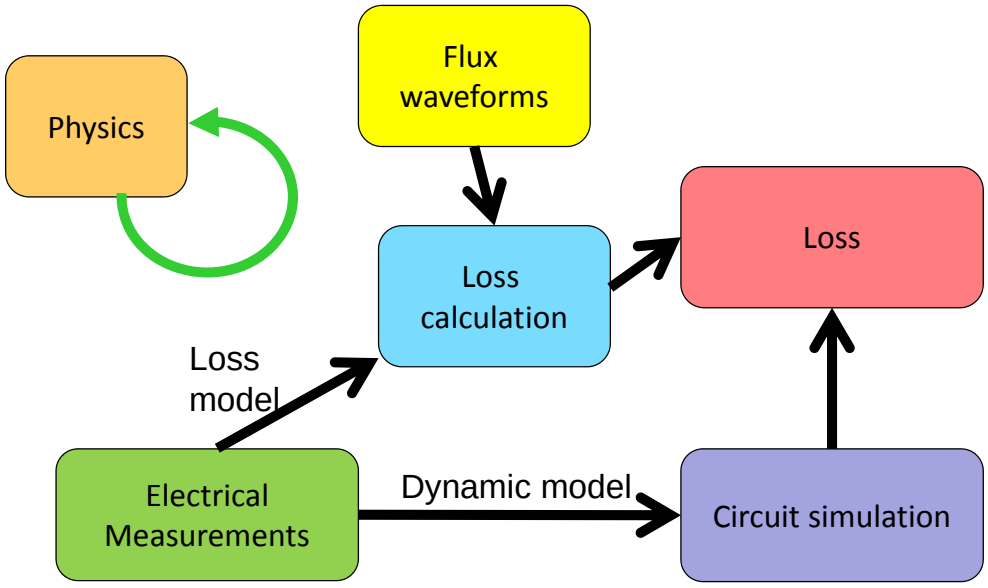


Linear RL networks for winding models

- Three standard networks topologies that provide:
  - R increases with frequency.
  - L decreases with frequency.
- Can obtain identical behavior with any of the three.
- Can use any one to match measured behavior.



Core models



Loss Calculation Models

- Steinmetz equation:
  - Sinusoidal waveforms only
- Various types of modified/generalized/etc. Steinmetz equations.
  - Extend to non-sinusoidal waveforms.
  - Most common: improved Generalized Steinmetz Equation (iGSE).
- Loss Map/Composite Waveform Method.

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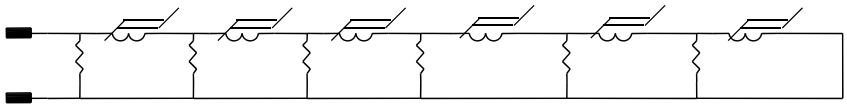
Comments:

- iGSE vs. Loss Map:
  - Same predictions if you use the same data.
    - iGSE: sinusoidal data.
    - Loss Map
  - Loss map database can include dc bias effects.
  - iGSE can do any wave shape, whereas Loss Map is for rectangular only.
- Barg 2017 improves iGSE for extreme duty cycles.
- Weakness of most of these: "Dead time" affects loss in practice but not in the model. "Relaxation effects."

Core simulation models

- Need to include nonlinearity.
- ***Example:*** Cauer 1 network to model saturation behavior and frequency-dependent permeability in nanocrystalline tape-wound cores.



  - Successfully matched pulse behavior in high-amplitude operation (Sullivan and Muetze, IAS 2007)
  - Did not examine loss behavior.
- Open question: what model structures capture dynamic nonlinear behavior correctly?

Conclusions

- Winding loss:
  - Complex but feasible to model accurately.
  - For 2 or more windings, need resistance ***matrix***.
  - 1D rectangular conductors: analytical solutions.
  - 2D rectangular conductors: numerical simulations.
  - 1D or 2D round wire: Simulation-tuned physical models are better than Dowell or Bessel.
- Core loss
  - Nonlinear and can only be found experimentally.
  - Open questions on data needed and models.

References

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