Finite Element Modeling of Switch Mode Power Supply Magnetics

Shuang (Sharon) Feng – Electrical Engineer
Mary E. Clark - R&D Engineer
Weyman Lundquist - President

West Coast Magnetics

Advancing Power Electronics

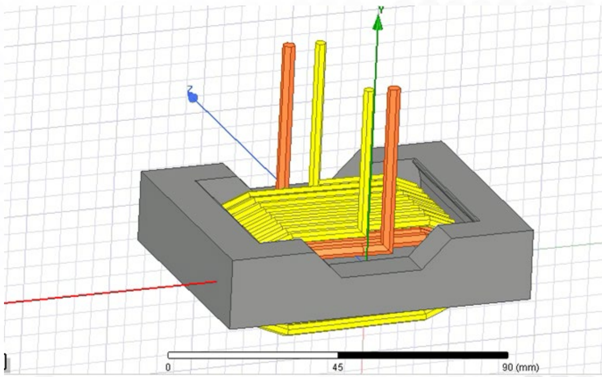
Agenda

- Overview: Traditional vs Finite Element Magnetics Modeling

- SMPS Transformer Simulations Using Finite Element Modeling Software
    - Solve Time Varying Magnetic Fields
    - Simulate Winding Loss in Litz Wire

- Challenges in FEM SMPS Magnetics Modeling

- Q & A



Overview

Traditional vs Finite Element Magnetics Modeling

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Traditional Magnetics Modeling

Magnetic component engineers have traditionally had very limited tools with which to model their designs.

Design considerations for SMPS Transformer:

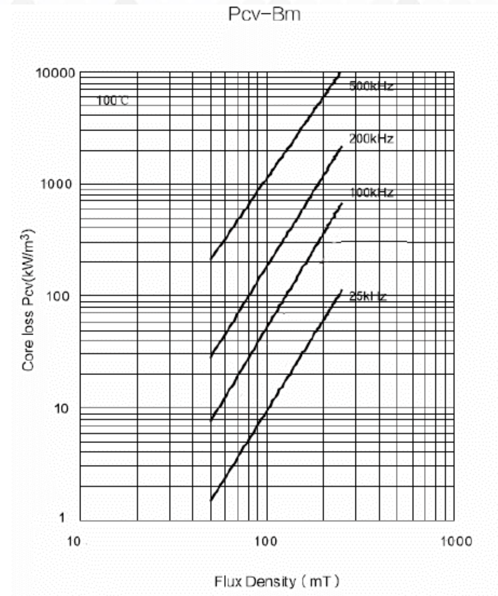
Max Flux Density

- SMPS Transformer – excited by square wave voltage source
- $B = \frac{v(t_{on})(10^8)}{2A_eN}$ Where:

  B = peak AC flux density (gauss)
  V = primary voltage (volts)
  ton = primary switch on time (seconds)
  Ae = core area (cm2)
  N = number of primary turns

Core Loss

- Only able to get the general core loss estimation basing on sinusoidal excitation.
- No detail loss distribution over time.



Winding Loss

- SMPS Transformers operate at high frequency – Use multi-strand wire (Litz wire) to reduce skin effect in conductors.
- Calculate copper loss from manufacturer provided DC resistance data. – Only valid if you chose correct Litz wire.
- No proximity effect - need to be considered separately.

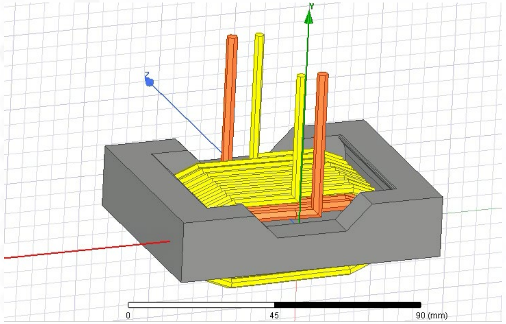
Finite Element Modeling – ANSYS Maxwell

Finite Element Method (FEM) modeling

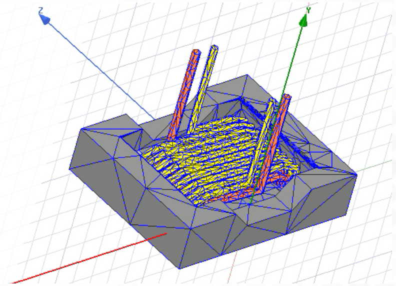
- Divide a transformer model into basic triangles (2D) and tetrahedra (3D) blocks. (Meshing)
- Solve fields in each basic block.
- Assemble solved blocks back into a larger system that models the entire problem.

ANSYS Maxwell uses FEM to solve Maxwell equations.

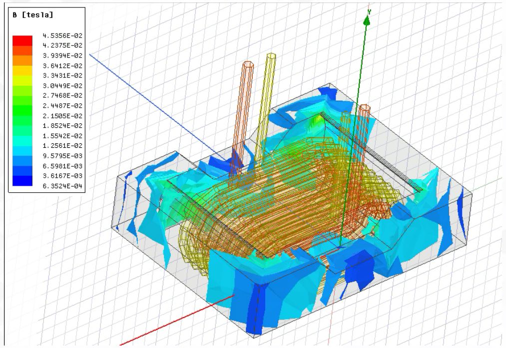
- Three solver types available for 2D and 3D designs:
    - Magnetostatic: DC excitation
    - Eddy Current: Sinusoidal excitation
    - Transient: Time-varying excitation (arbitrary waveforms)



Model



Mesh



Solved Magnetic Field

SMPS Transformer Simulations Using FEM Software

Solve Time Varying Magnetic Fields

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Solve Time Varying Magnetic Fields - 3D Magnetic Transient Solver

SMPS Transformers: driven by square wave voltage source. – Use transient solver.

General Simulation Steps:

1. Create 3D model.
2. Apply time varying excitations to model.
3. Simulation setup.
4. Post process of solution data: Field Plots, Field animations, Loss calculations etc.

$$\nabla \times \frac{1}{\sigma} \nabla \times \boldsymbol{H} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\nabla \cdot \boldsymbol{B} = 0$$

Equations solved in Maxwell 3D Magnetic Transient Solver

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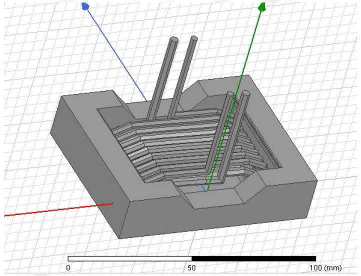
Solve Time Varying Magnetic Fields
- 3D Magnetic Transient Solver

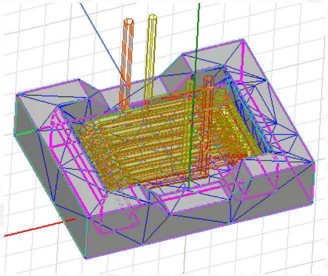
Create 3D Model

- Draw model in ANSYS Maxwell or import CAD model from other CAD software.
    - Use simplifications to cut simulation time:
        - Avoid smooth curves in the model because Maxwell 3D solver uses tetrahedral meshing.

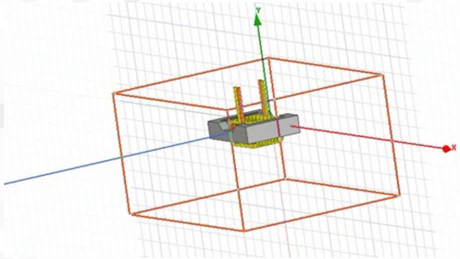
- Define solution boundaries.



WCM 410-88 Model Imported From Solidworks



Tetrahedra Mesh

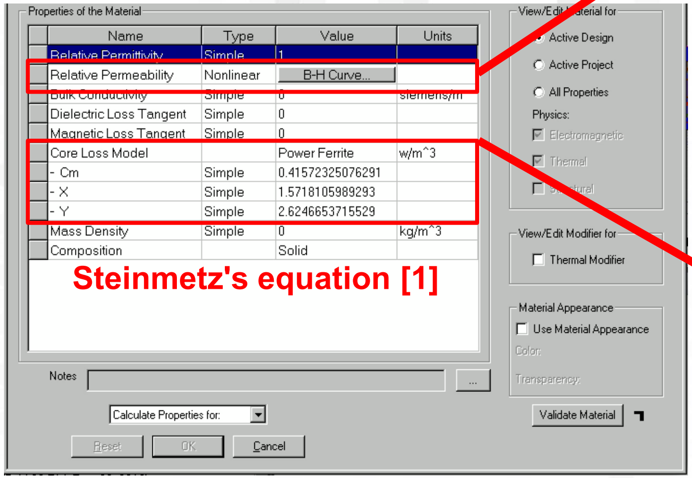


Define Solution boundaries

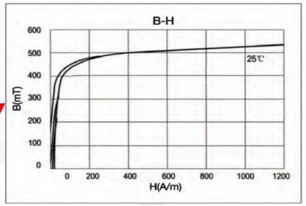
Solve Time Varying Magnetic Fields - 3D Magnetic Transient Solver

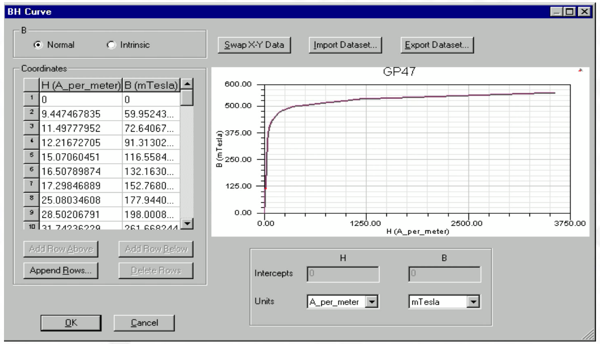
Create 3D Model

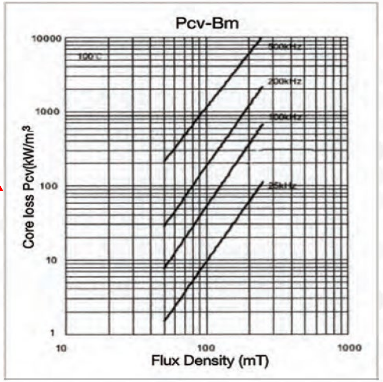
- Define Materials:
    - Winding: Copper
    - Core: user defined core material

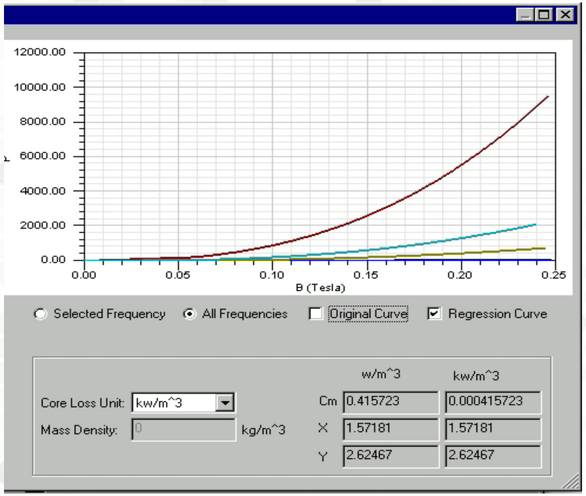


Steinmetz's equation [1]







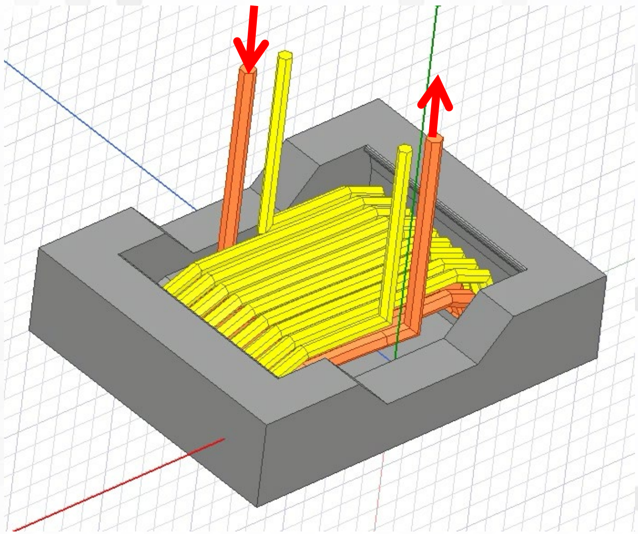


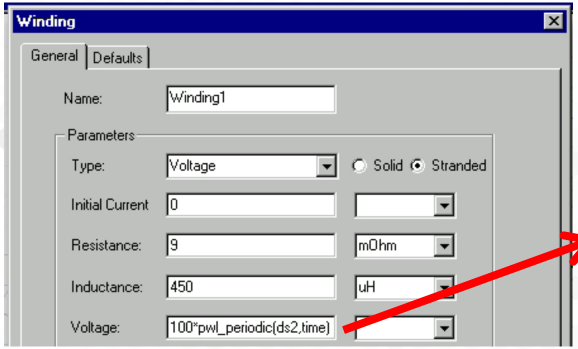
[1] Lin, D., Zhou, P., Fu, W., Badics, Z. and Cendes, Z. (2004). A Dynamic Core Loss Model for Soft Ferromagnetic and Power Ferrite Materials in Transient Finite Element Analysis. *IEEE Transactions on Magnetics*, 40(2), pp.1318-1321.

Solve Time Varying Magnetic Fields - 3D Magnetic Transient Solver

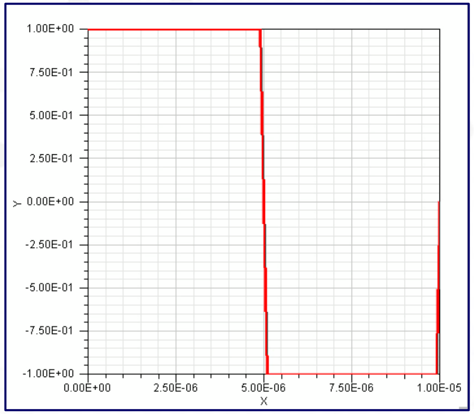
Define Excitation

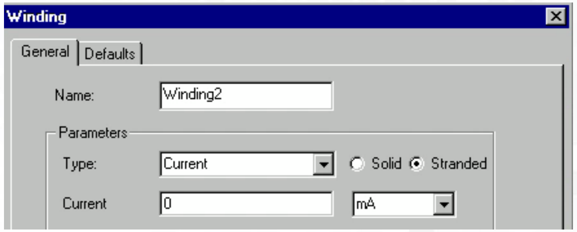
- Excitation can be time varying current or voltage.
- Simulate Core loss in SMPS transformer (no load condition):
  - 100V 100kHz Square Wave excitation in primary winding.
  - 0 Amp (open circuit) in secondary winding.





Primary Winding Excitation



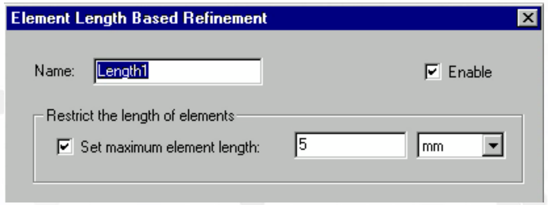


Secondary Winding Excitation

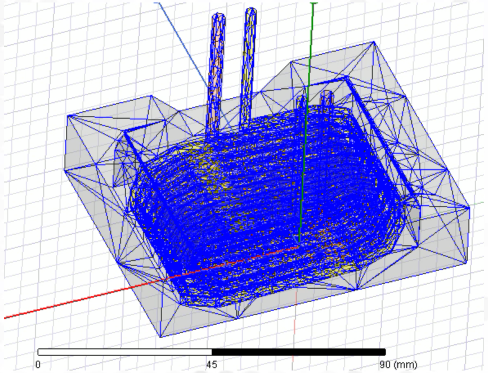
Solve Time Varying Magnetic Fields
- 3D Magnetic Transient Solver

Solution Setup

- Define mesh operation or link adaptive mesh from a quasi-static solver.

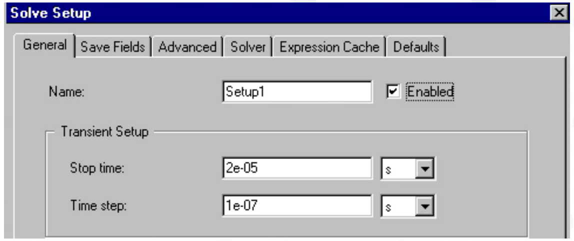


Length defined mesh

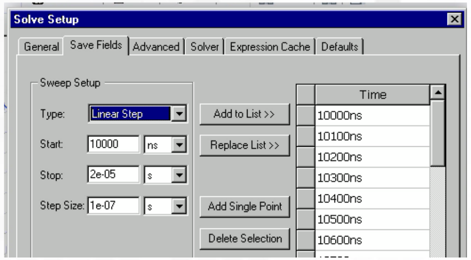


Mesh result

- Set solution time step and save fields



20 us (2 cycle of 100kHz) simulation time



Save field solution at every simulation step

Solve Time Varying Magnetic Fields - 3D Magnetic Transient Solver

Solution Setup

- Solving 3D model with high geometric details requires large computational resource:
    - long computation time
    - large memory space
- Use High-performance computing (HPC) running on a cloud platform:
    - Run simulation across multiple processors (multi-core).
    - Multithreading technology speeds up the initial mesh generation, direct and iterative matrix solves, and field recovery.
    - Cloud platform eliminates desktop memory space constraints.

Solution Process				Elapsed time : 00:32:06 , Maxwell ComEngine Memory : 1.6 G

Total computational resource used in this example: 8 Cores, 32 minutes solution time, 1.6G memory usage

Total number of elements: 85410

	Num Tets	Min edge length	Max edge length	RMS edge length	Min tet vol	Max tet vol	Mean tet vol	Std Devn (vol)
Core	1073	1.13145	46.7671	14.809	0.00218014	1176.62	64.3406	126.845
pri	4804	1.00765	21.313	4.81077	0.000675615...	18.4576	2.05185	1.4347
sec	5100	1.52112	17.7142	4.92603	0.00410515	11.5015	1.7489	1.14249
Region	74433	0.76708	170.986	9.84888	0.000769582...	170677	100.368	1953.99

Mesh Statistics

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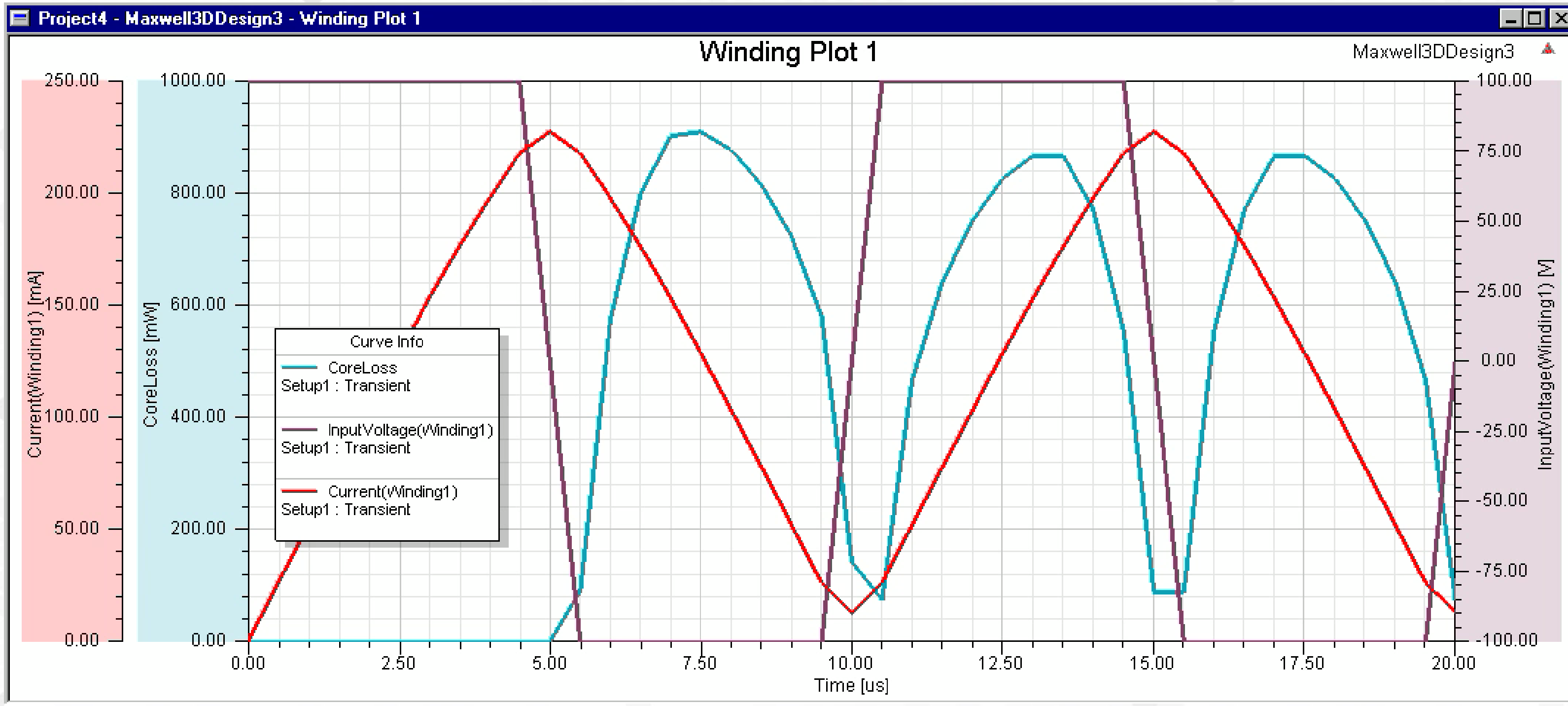
Solve Time Varying Magnetic Fields - 3D Magnetic Transient Solver

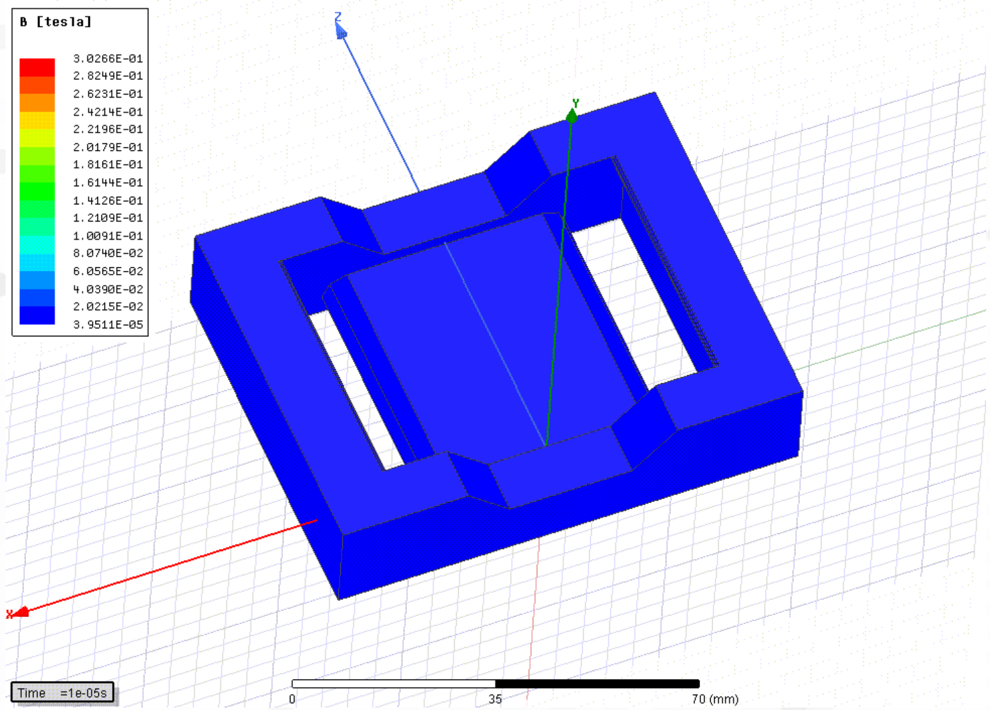
Simulation Results



Core Loss vs Time

Solve Time Varying Magnetic Fields - 3D Magnetic Transient Solver

Simulation Results



Solved B field animation

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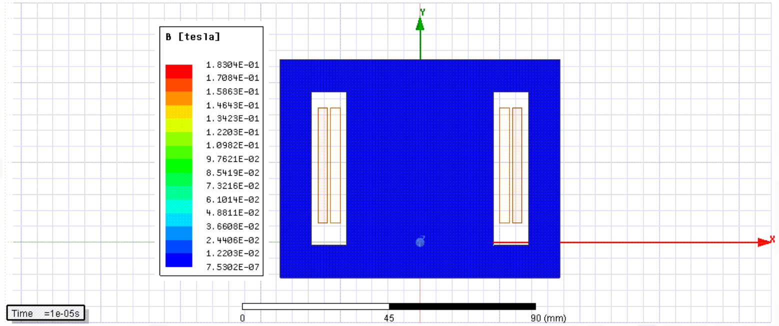
Solve Time Varying Magnetic Fields - Other simulation types

2D transient solver

- Easy to model
- Shorter simulation time but less accurate result (no z dimension information)



2D and 3D Eddy Current Solver, Magnetostatic Solver

- Simulate sinusoidal and DC excitations
- Generate adaptive meshing to achieve desired accuracy

Pass	# Tetrahedra	Total Energy (J)	Energy Error (%)
1	4032	2.5794e-09	4.274
2	5267	2.5161e-09	5.1158
3	6886	2.4625e-09	3.8489
4	8994	2.3914e-09	2.986
5	11744	2.3623e-09	2.2728
6	15336	2.3164e-09	1.864

Adaptive meshing

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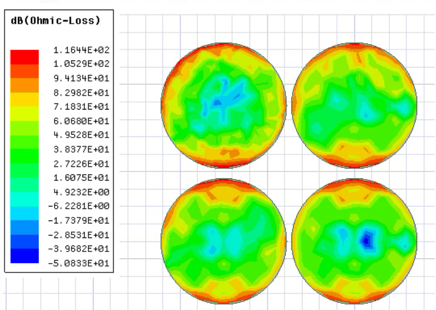
SMPS Transformer Simulations Using FEM Software

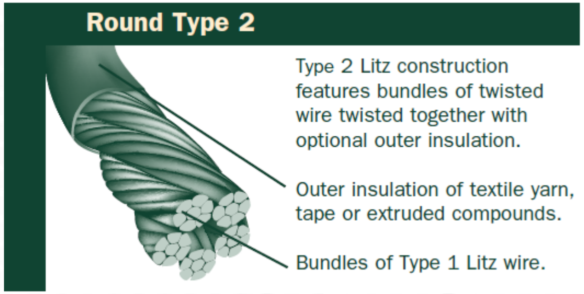
Simulate Winding Loss in Litz Wire

Simulate Winding Loss in Litz Wire – LitzOpt [1][2]

- Eddy effect can be modeled in ANSYS Maxwell for solid wires.
- SMPS transformer windings usually use Litz wires to reduce loss due to skin effect and proximity effect.
- The wire includes up to thousands of strands insulated electrically from each other.
- Very difficult to model in ANSYS Maxwell due to geometry complexity.
- Use The Online LitzOpt program [1][2] developed by The Dartmouth Magnetic Component Research group to simulate and optimize Litz wire design.



ANSYS Maxwell Ohmic-Loss plot in solid wire



One type of Litz wire [3]

[1] "LitzOpt Online," The LitzOpt Program. [Online]. Available: https://engineering.dartmouth.edu/inductor/litzopt.shtml.
[2] J. Pollock, T. Abdallah, C. R. Sullivan "Easy-To-Use CAD Tools for Litz-Wire Winding Optimization" in IEEE Applied Power Electronics Conference, Feb. 2003, pp. 1157–1163.
[3] New England Wire Technologies, "PRODUCT SELECTION GUIDE." .

Simulate Winding Loss in Litz Wire – LitzOpt

The Squared-Field-Derivative (SFD) Method [1]

$$P(t) = \frac{\pi l \, \mathrm{d}_C^4}{64 \rho_C} \left(\frac{\mathrm{d}B}{\mathrm{d}t} \right)^2$$

Where:

B is flux density, assumed perpendicular to the axis of the cylinder

ρ_C is resistivity of the wire

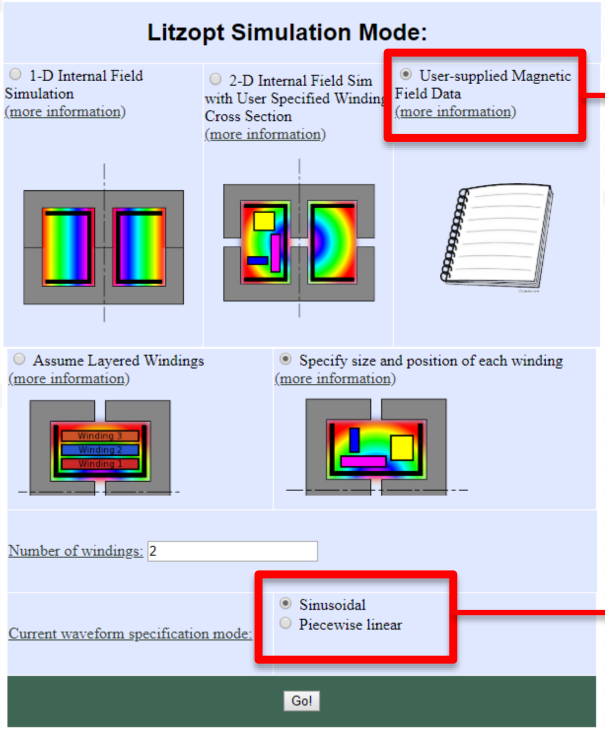
dc is diameter

The average loss depends on the time average of squared derivative of the field, $\overline{\left(\frac{dB}{dt} \right)^2}$

[1] C. R. Sullivan, "Computationally efficient winding loss calculation with multiple windings, arbitrary waveforms, and two-dimensional or three-dimensional field geometry," in *IEEE Transactions on Power Electronics*, vol. 16, no. 1, pp. 142-150, Jan. 2001.

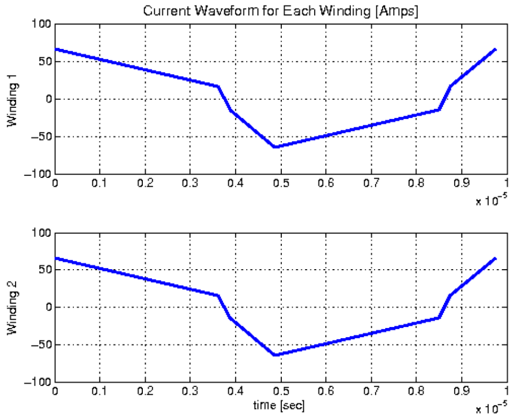
Simulate Winding Loss in Litz Wire – LitzOpt

Use internal field simulation or user obtained field data to calculate winding loss in LitzOpt [1] [2]



Generate user defined field data using ANSYS Maxwell Magnetostatics Solver

Sinusoidal current Or piecewise linear current

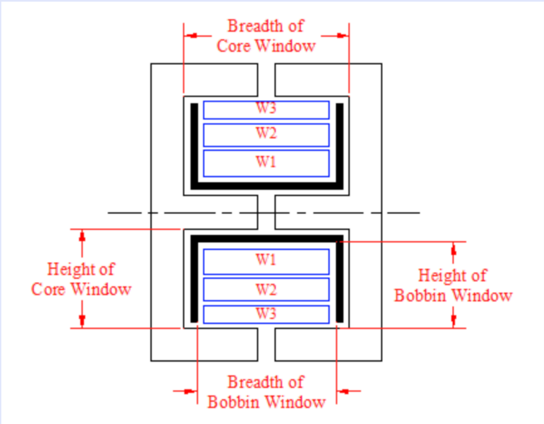


[1] "LitzOpt Online," The LitzOpt Program. [Online]. Available: https://engineering.dartmouth.edu/inductor/litzopt.shtml.
[2] J. Pollock T. Abdallah C. R. Sullivan "Easy-To-Use CAD Tools for Litz-Wire Winding Optimization" in IEEE Applied Power Electronics Conference, Feb. 2003, pp. 1157–1163.

Simulate Winding Loss in Litz Wire – LitzOpt

Define Core and winding geometry.

Core Data



Choose a standard core size or select "user defined" to specify a different size:	User-defined	
Breadth of the core window (mm):	48	mm
Breadth of the bobbin window (mm):	45	mm

Core gaps:
○ Center leg gapped ● No legs gapped ○ All legs gapped

Winding Information

Operating temperature (used to calculate copper resistivity):	20	C
AWG Size Range	Even Sizes 28-48	
Maximum achievable packing factor:	0.35	
Number of turns for each winding:	Winding 1: 9 Winding 2: 9	
Wire insulation type:	● Single Build ○ Heavy Build	
Volume of each winding (mm^3):	Winding 1: 7676 Winding 2: 7676	mm^3
Cross section height (mm):	Winding 1: 2 Winding 2: 2	mm
Average turn length (mm):	Winding 1: 130 Winding 2: 130	mm

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Simulate Winding Loss in Litz Wire – LitzOpt

Generate user defined field data using ANSYS Maxwell Magnetostatics Solver:

- Excite transformer with 1Amp -Turn DC current.
- Calculate the integral of $|B|^2$ over winding area.

Magnetitic Field Integrals (i.e. from Finite Element Model)

Integral of B^2 over winding area with 1 amp in winding 1:	Field integral in winding 1: Field integral in winding 2:
Integral of B^2 over winding area with 1 amp in windings 1 and 2:	Field integral in winding 1: Field integral in winding 2:
Integral of B^2 over winding area with 1 amp in winding 2:	Field integral in winding 1: Field integral in winding 2:

```
Scl : 3.27531942875934E-15
Scl : Integrate(Volume(secondary), *(Mag(<Bx,By,Bz>), Mag(<Bx,By,Bz>)))
Scl : 3.5065683733944E-15
Scl : Integrate(Volume(primary), *(Mag(<Bx,By,Bz>), Mag(<Bx,By,Bz>)))
```

Excitation in Primary and Secondary winding

```
Scl : 2.38740952945305E-15
Scl : Integrate(Volume(secondary), *(Mag(<Bx,By,Bz>), Mag(<Bx,By,Bz>)))
Scl : 3.2100402197668E-15
Scl : Integrate(Volume(primary), *(Mag(<Bx,By,Bz>), Mag(<Bx,By,Bz>)))
```

Excitation in Primary winding

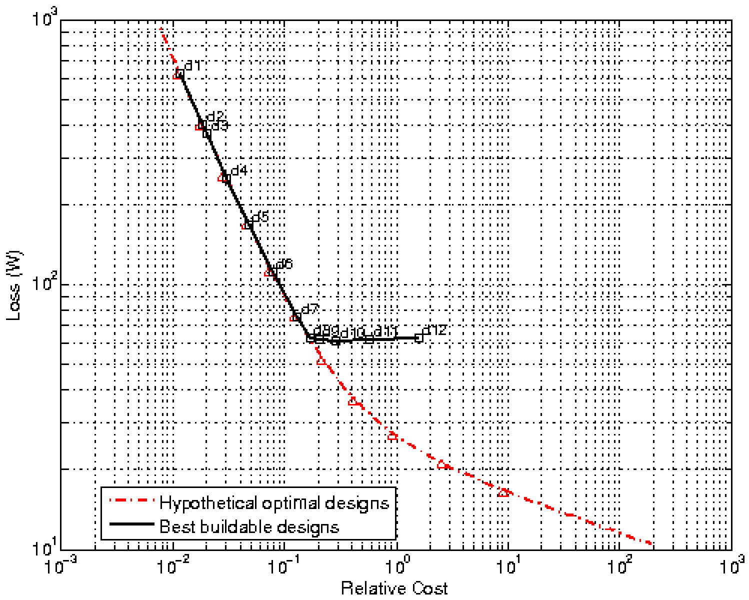
```
Scl : 2.49505474817312E-15
Scl : Integrate(Volume(secondary), *(Mag(<Bx,By,Bz>), Mag(<Bx,By,Bz>)))
Scl : 2.96073875709778E-15
Scl : Integrate(Volume(primary), *(Mag(<Bx,By,Bz>), Mag(<Bx,By,Bz>)))
```

Excitation in secondary winding

Simulate Winding Loss in Litz Wire – LitzOpt

Simulation results

Optimal Designs Frontier



Optimal Design Table

Gauge (W1)	Gauge (W2)	Relative Cost	Loss watts	NumStrands (W1)	NumStrands (W2)
28	27.3281	0.0111	610	1.89	1.62
30	29.3295	0.0177	392	4.73	4.06
32	31.333	0.0282	254	11.8	10.2
34	33.3412	0.0452	166	29.2	25.3
36	35.3621	0.0734	111	72.2	63.3
38	37.4021	0.122	74.7	179	159
40	39.4673	0.215	51.2	444	407
42	41.5507	0.413	36.2	1100	1050
44	43.6269	0.918	26.9	2640	2630
46	45.6613	2.55	20.8	5850	6010
48	47.6648	9.26	16.4	12300	12700

Buildable Design Table

Design Number	Gauge (W1)	Gauge (W2)	Relative Cost	Loss in Watts	NumStrands (W1)	NumStrands (W2)
d1	28	28	0.0118	620.8	2	2
d2	30	30	0.0187	398.75	5	5
d3	30	30	0.0206	367.36	5	6
d4	32	32	0.0311	249.7	12	14
d5	34	34	0.0487	167.28	29	34
d6	36	36	0.0793	110.98	72	84
d7	38	38	0.133	74.714	178	209
d8	40	40	0.173	62.775	357	357
d9	42	42	0.207	61.4	552	552
d10	44	44	0.299	61.18	854	854
d11	46	46	0.588	61.711	1321	1321
d12	48	48	1.6	62.725	2043	2043

Challenges in FEM SMPS Magnetics Modeling

Challenges in FEM SMPS Magnetics Modeling

- FEM tools like ANSYS Maxwell can generate detailed estimations for fields and core loss distribution in SMPS transformers, but is not sufficient in estimating Litz wire winding loss.
- Modeling accuracy highly depending on the accuracy of model geometry and mesh size.
- Higher modeling accuracy needs more computation power.

Thank you.
Any Questions?

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