EE564 PROJECT #1

INDUCTANCE AND TRANSFORMER MODELLING

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1. INTRODUCTION

The main purposes of project are to model inductor and then analyze it in a FEA program and to design a transformer according to specifications.

2. INDUCTOR MODELLING

Inductor modelling and analysis are divided into two parts: analytical calculations and finite element analysis.

2.1 ANALYTICAL CALCULATIONS

In 2.1.1 and 2.1.2 parts, there exist different assumptions and conditions when inductance of a toroid is calculated.

2.1.1 INDUCTANCE CALCULATION 1

Firstly, ferrite core F-type material with part number 'ZF40907TC' is used in this analysis. At difference temperature, frequency and magnetic flux density values Magnetics Company offer different types of materials. (L, R, P, F, T). Here F-type material is analyzed. A detailed information can be seen in Fig. 1 and Fig. 2.

Number of turns and current are chosen so that core operates at the linear region.

<u>Number of Turns:</u> N = 8

<u>Current:</u> I = 200 mA

At worst conditions (100 C), ferrite material saturation flux density is decreased dramatically, which is equal to about 330 mT as in Fig. 1.

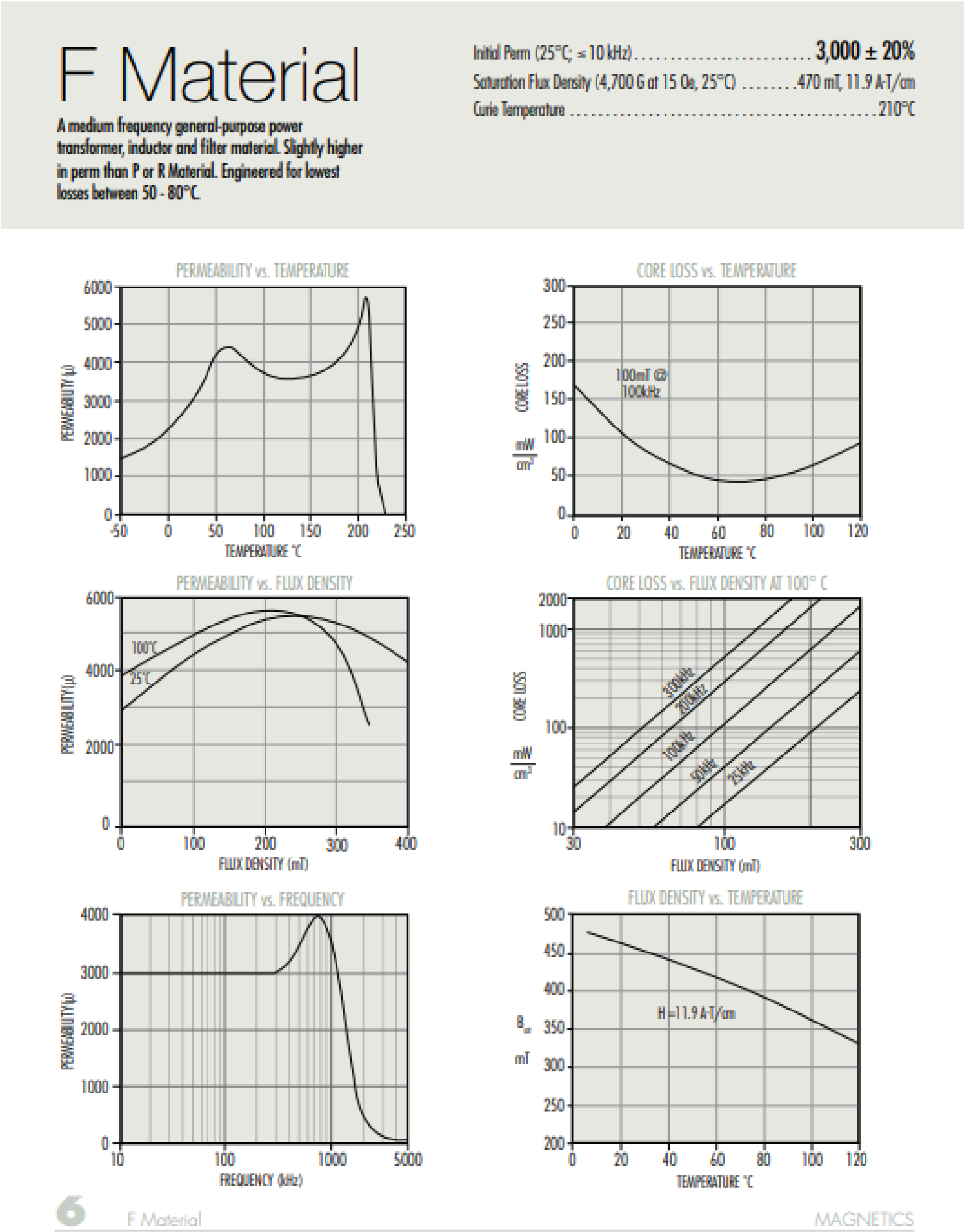


Figure 1 Behavior of Ferrite F-Type Material at Different Conditions

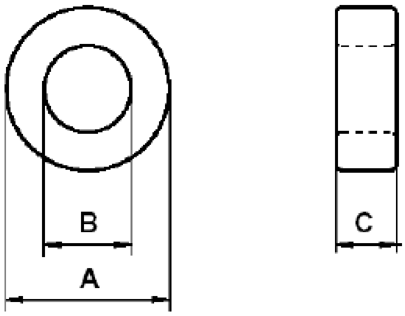
F Material

F material is a medium frequency general-purpose power transformer, inductor and filter material. Slightly higher in perm than P or R Material. Engineered for lowest losses at 60°C.

Initial Perm (10 kHz)	3,000 ± 20%
Saturation Flux Density (4,700 G at 15 Oe, 25°C)	470 mT, 11.9 A•T/cm
Curie Temperature	210°C
Maximum Usable Frequency (50% roll-off)	≤1.5 MHz
Remanence (1,500 G, 25°C)	150 mT
Resistivity	5 Ω-m
Density	4.8 g/cm³

Figure 2 Ferrite F-Type Material Properties

DIMENSIONS



(mm)	Uncoated Nominal:	Coated Min:	Coated Max:
O.D. (A)	9.53	9.39	10.17
I.D. (B)	5.59	4.95	5.73
Ht. (C)	7.11	7.06	7.66

Eff. Parameters		
A_e mm²	l_e mm	V_e mm³
13.7	22.7	310

INDUCTANCE

AL value (nH/T²)	Test conditions
2260± 25%	10 kHz, 0.5 mT (For N = 5, use 0.42 mA), 25°C

CORE LOSSES

P_L max	Production lot limit Max avg	Test conditions
68.2 mW (220 mW/cm³)	62 mW (200 mW/cm³)	25 kHz, 200 mT, 100°C

Figure 3 Datasheet Values of Magnetics ZF40907TC Ferrite Core

From Fig. 3 effective length is 22,7 mm, but in calculations some assumptions are made as following.

Assumptions:

1. Flux is homogeneously distributed
2. Neglect leakage flux
3. Core is linear

For inductance calculation, toroid radius to centerline is assumed to be

$$2\pi r = 2\pi(\left(\frac{A-B}{2}\right).0{,}5 + \frac{B}{2}) = 23{,}75\ mm$$

From Ampere's Law:

$$N.I = \frac{B}{u}.2\pi.r\ (u_r = 3000)$$

Operating Flux Density:

$$B = 254\ mT$$

Permeance:

$$\frac{1}{R} = 2{,}175 * 10^{-6}\ H/turn^2$$

Inductance Value:

$$L = \frac{N^2}{R} = \frac{N^2}{\frac{2\pi r}{u.A_e}} = 139{,}2\ uH$$

2.1.2 INDUCTANCE CALCULATION 2

Assumptions:

1. Flux is nonhomogeneously distributed
2. Neglect leakage flux
3. Core is linear

Inductance when the flux is not homogeneously distributed is calculated by dividing the core in 10000 discretized cylindrical sections. B_mean is calculated (.m file) according to discretized sections and inductance is found as 142.5uH, which is slightly higher than above value. The reason for this, magnetic flux density is higher in inner magnetic paths from the middle of the core and its effect is slightly higher compared to outer magnetic paths. Datasheet effective length value confirms this fact, which is 22.7mm < 23,75mm.

2.1.3 INDUCTANCE CALCULATION 3

Here current is increased by 50% and core is nonlinear.

Assumptions:

1. Flux is homogeneously distributed
2. Neglect leakage flux
3. Core is nonlinear

Number of Turns: N = 8

Current: I = 300 mA

From Ampere's Law:

$$N.I = \frac{B}{u}.2\pi.r$$

Operating Flux Density:

$$B = 368\, mT$$

Core is saturated, relative permeability value at 368mT is about 2900.

Permeance:

$$\frac{1}{R} = 2{,}102 * 10^{-6}\ H/turn^2$$

Inductance Value:

$$L = \frac{N^2}{R} = \frac{N^2}{\frac{2\pi r}{u.A_e}} = 134{,}5\ uH$$

As seen above, inductance value is decreased due to saturation. If flux is not homogenously distributed L=137.7 uH.

2.1.4 INDUCTANCE CALCULATION 4

Now 2mm airgap is included.

Assumptions:

1. Flux is homogeneously distributed
2. Neglect leakage flux

3. Core is linear
4. No fringing flux

With 2mm air-gap, reluctance decreases significantly.

Inductance Value:

$$2\pi r = 23.75\ mm;$$

$$N = 8;$$

$$u_r = 3000;$$

$$u_o = 4\pi.10^{-7}\frac{H}{m};$$

$$L = \frac{N^2}{R_g + R_c} = \frac{N^2}{\frac{2*10^{-3}}{u_0.A_e} + \frac{2\pi r}{u.A_e}} = 0{,}55\ uH$$

2.1.5 INDUCTANCE CALCULATION 5

Fringing flux estimation method can be seen in Fig. 4. Increase in core area results in decrease in reluctance. Therefore, inductance is about 1,09 uH.

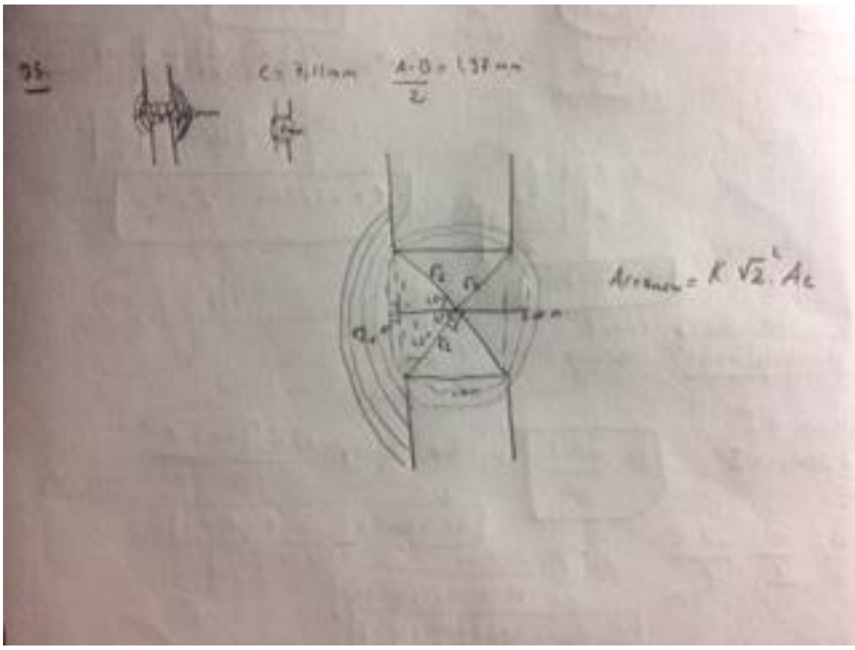


Figure 4 Fringing Flux Effect

2.2 FINITE ELEMENT ANALYSIS

In this part, ANSYS Maxwell simulation tool is used for f-type ferrite toroidal core magnetic analysis.

Linear Material:

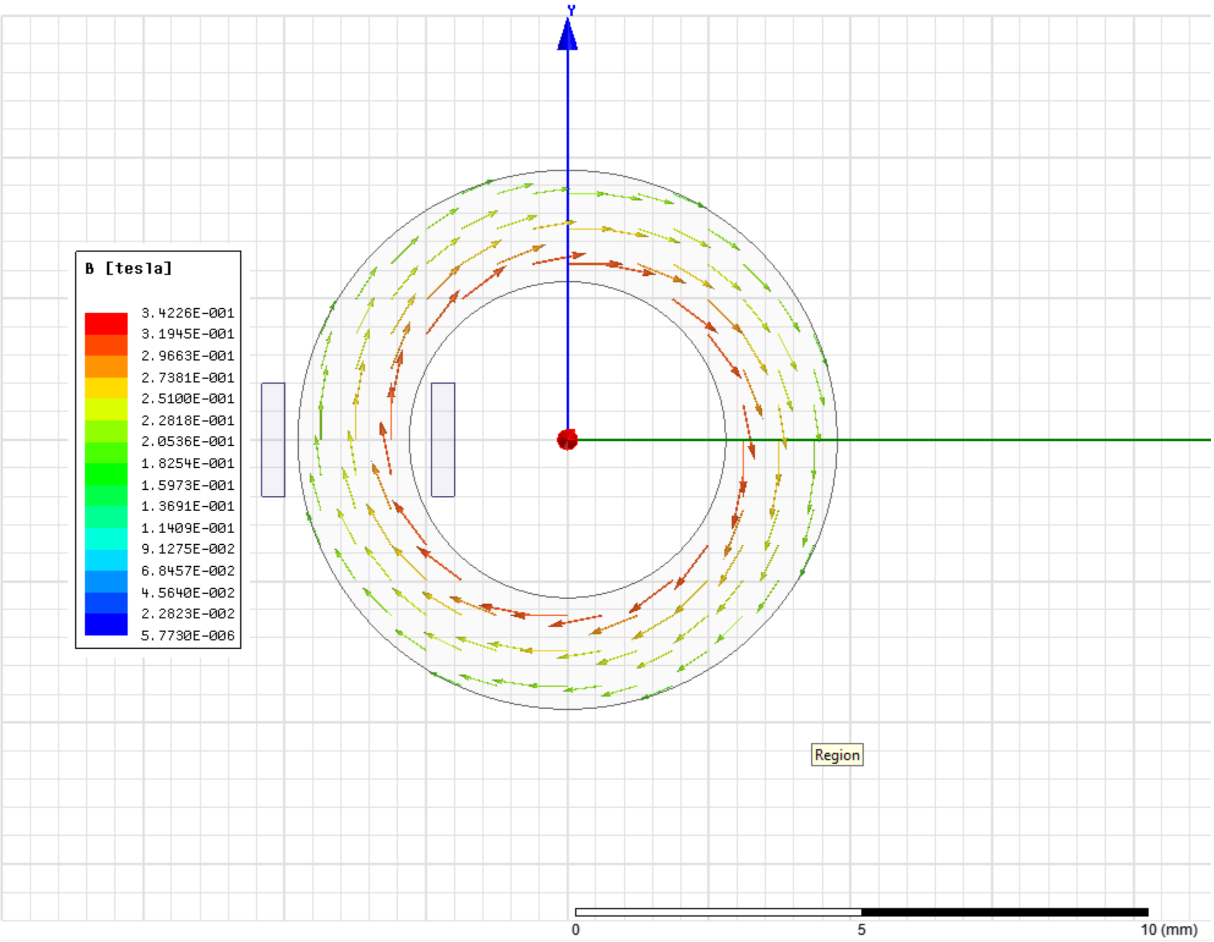


Figure 5 Magnetic Flux Density Vector (Linear Material)

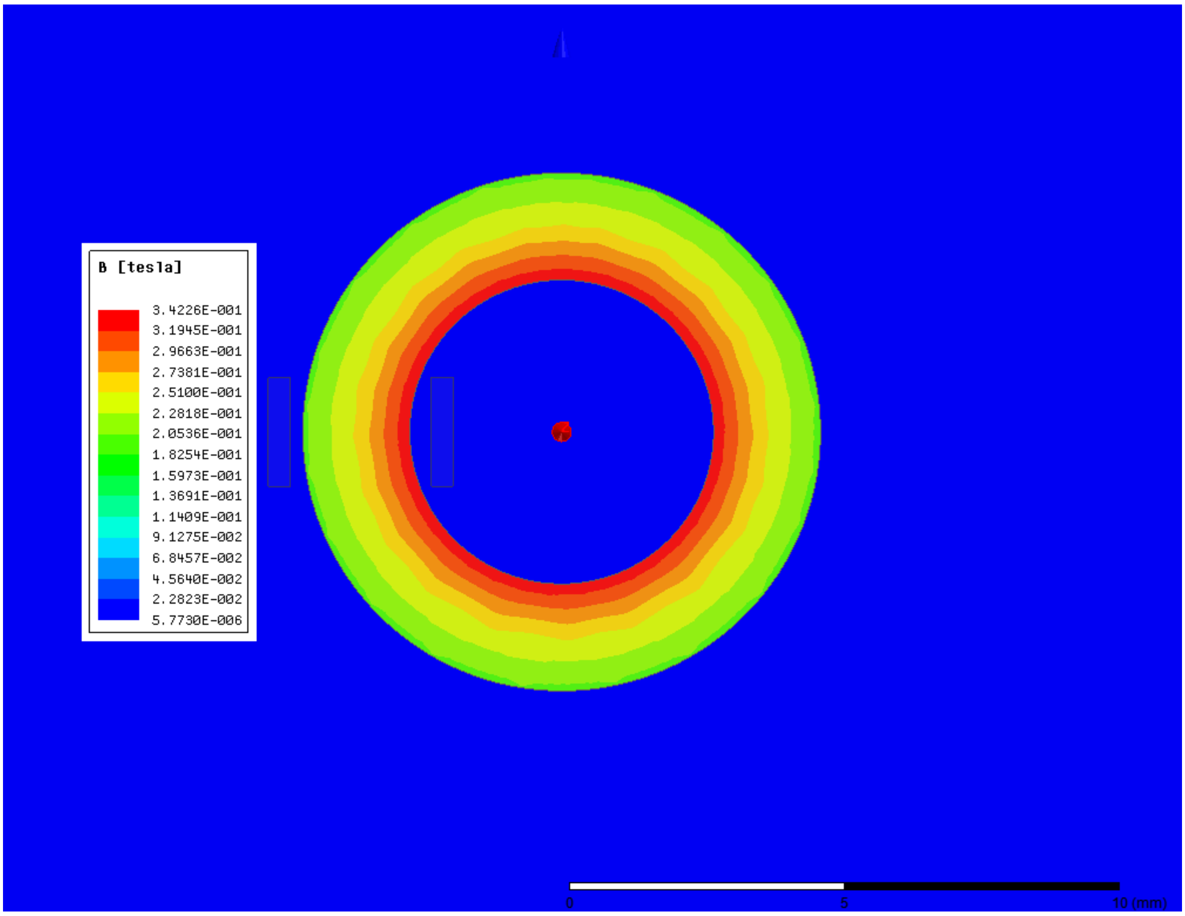
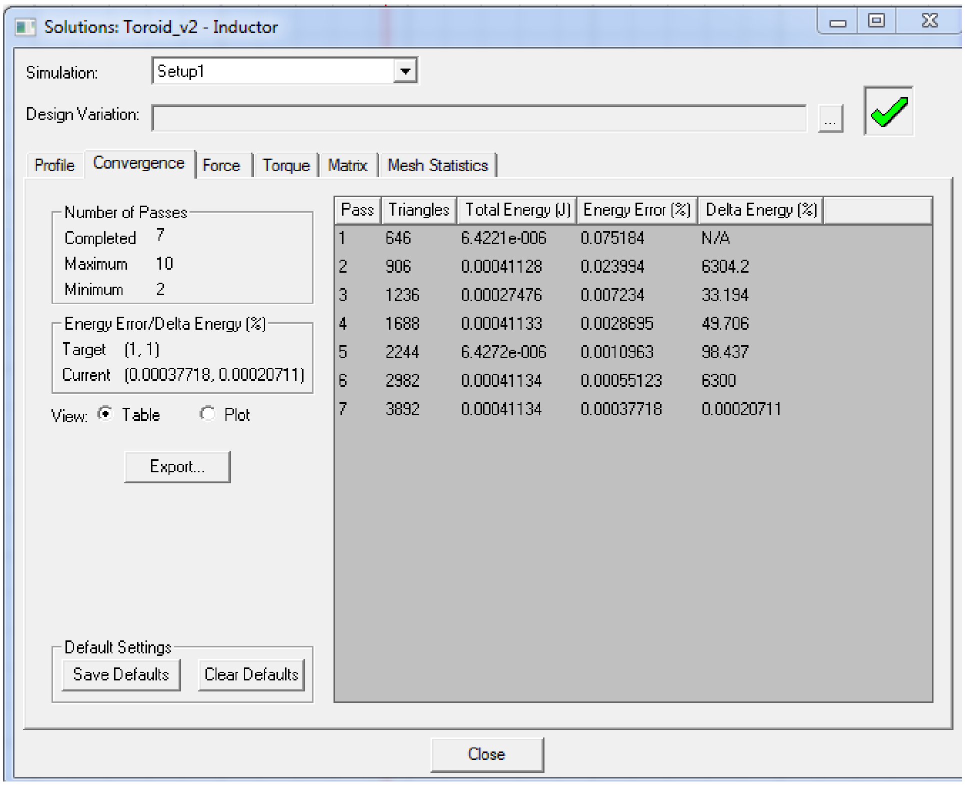


Figure 6 Magnitude of Magnetic Flux Density (Linear Material)



Pass	Triangles	Total Energy (J)	Energy Error (%)	Delta Energy (%)
1	646	6.4221e-006	0.075184	N/A
2	906	0.00041128	0.023994	6304.2
3	1236	0.00027476	0.007234	33.194
4	1688	0.00041133	0.0028695	49.706
5	2244	6.4272e-006	0.0010963	98.437
6	2982	0.00041134	0.00055123	6300
7	3892	0.00041134	0.00037718	0.00020711

Figure 7 Inductance Calculation from Magnetic Energy (Linear Material)

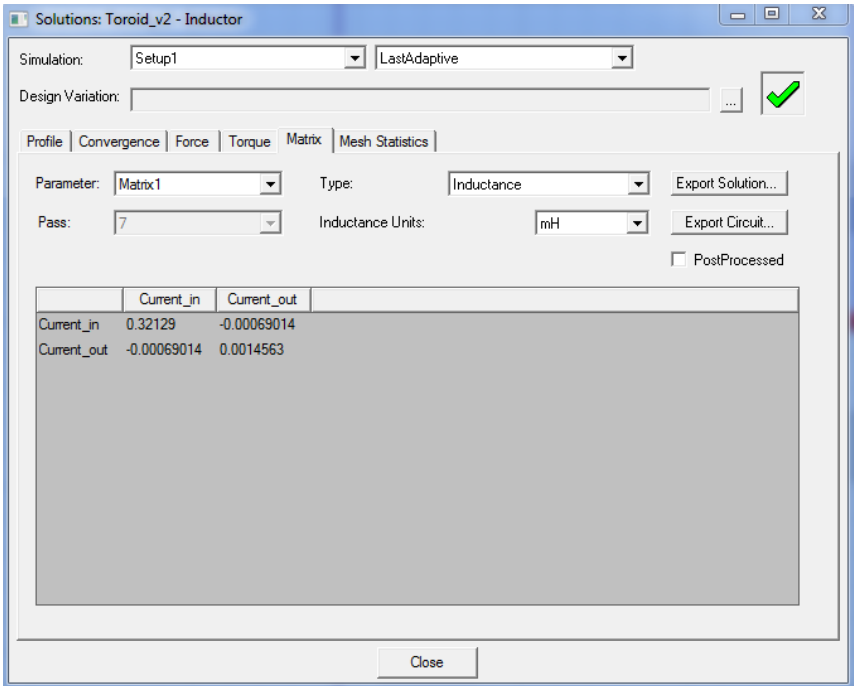


Figure 8 Inductance Calculation from Matrix Tool (Linear Material)

321,3 uH/m is calculated at the simulation tool. Real inductance value as following:

$$321{,}3\frac{uH}{m} * N^2 * core - depth = 321 * 64 * 7{,}11 * 10^{-3} = 146{,}21\ uH$$

<u>Nonlinear Material:</u>

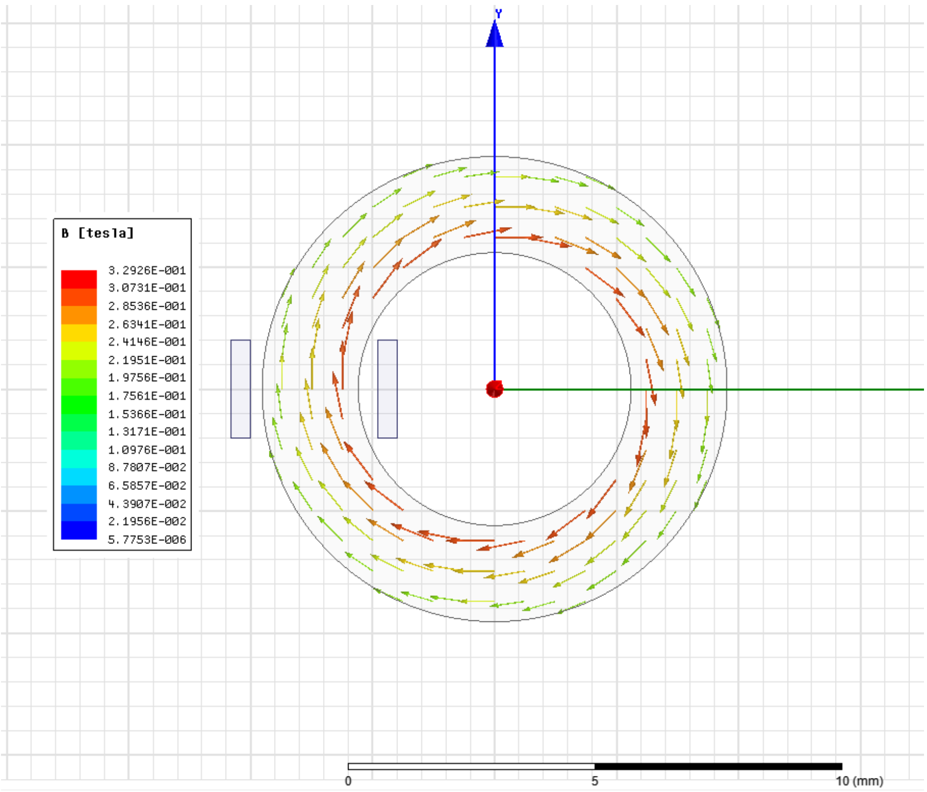


Figure 9 Magnetic Flux Density Vector (Nonlinear Material)

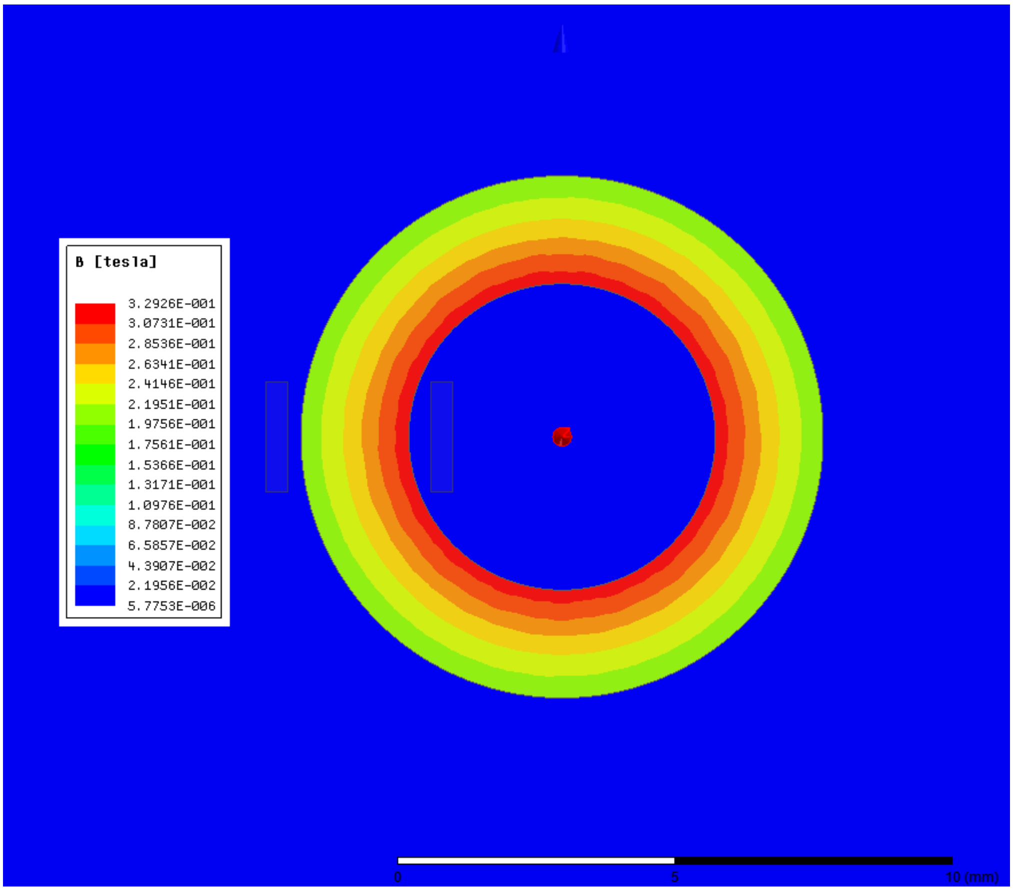


Figure 10 Magnitude of Magnetic Flux Density (Nonlinear Material)

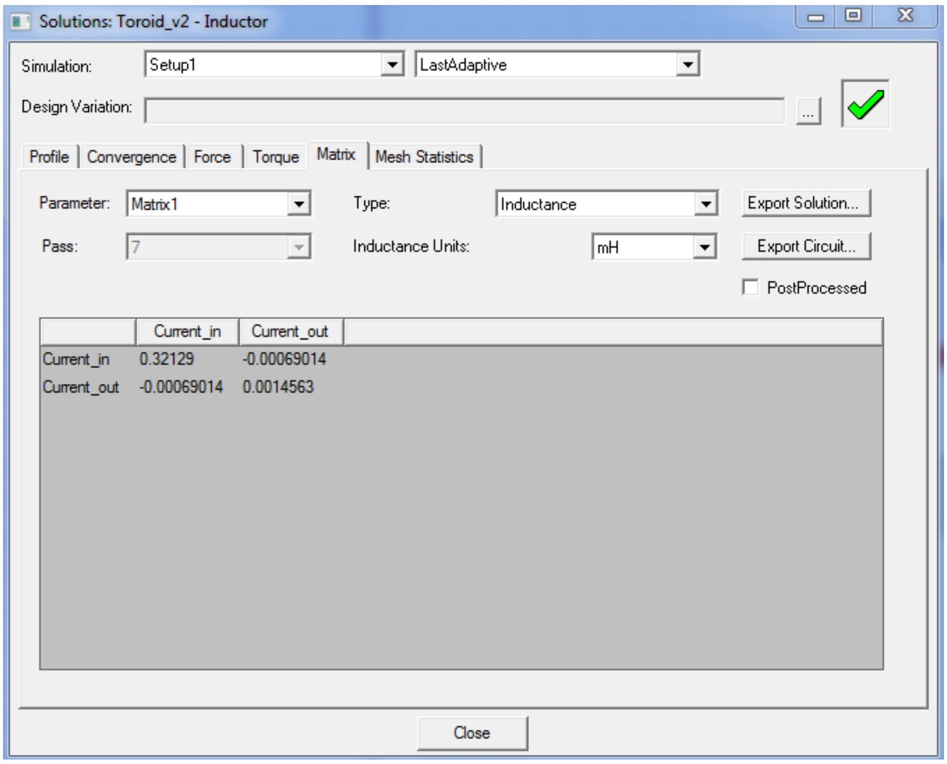
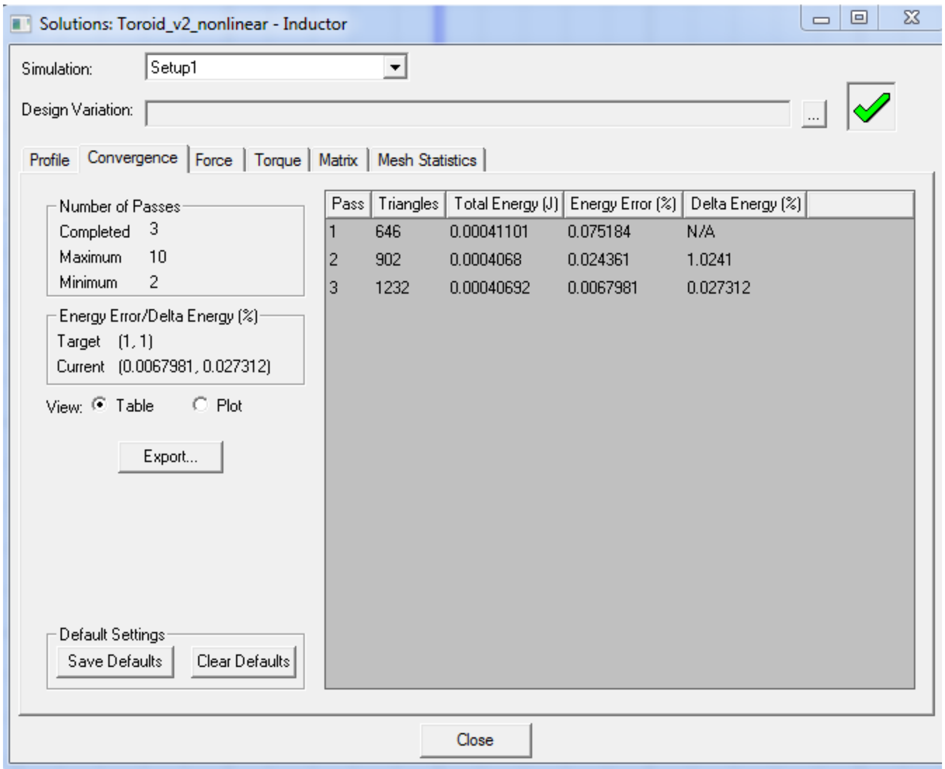


Figure 11 Inductance Calculation from Magnetic Energy (Nonlinear Material)



Pass	Triangles	Total Energy (J)	Energy Error (%)	Delta Energy (%)
1	646	0.00041101	0.075184	N/A
2	902	0.0004068	0.024361	1.0241
3	1232	0.00040692	0.0067981	0.027312

Figure 12 Inductance Calculation from Matrix Tool (Nonlinear Material)

$$\frac{1}{2} * L * I^2 = 0{,}00041101\, Joules\ (I = 8 * 200mA = 1{,}6A)$$

Real inductance value as following:

$$L = 321{,}1 \frac{uH}{m} * \ N^2 * core - depth = 321{,}1 * 64 * 7{,}11 * 10^{-3} = 146{,}1\ uH$$

<u>Noninear Material with air gap:</u>

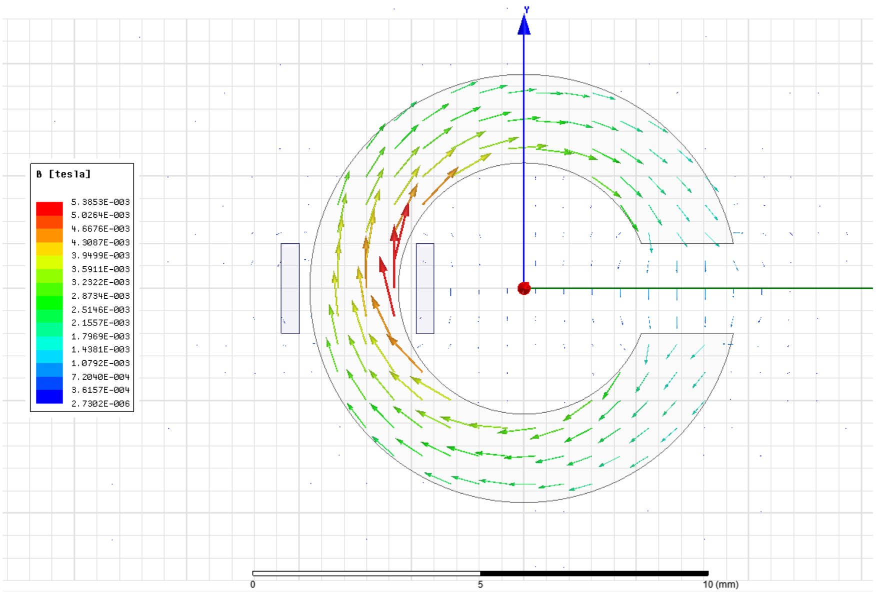


Figure 13 Magnetic Flux Density Vector with Airgap (Nonlinear Material)

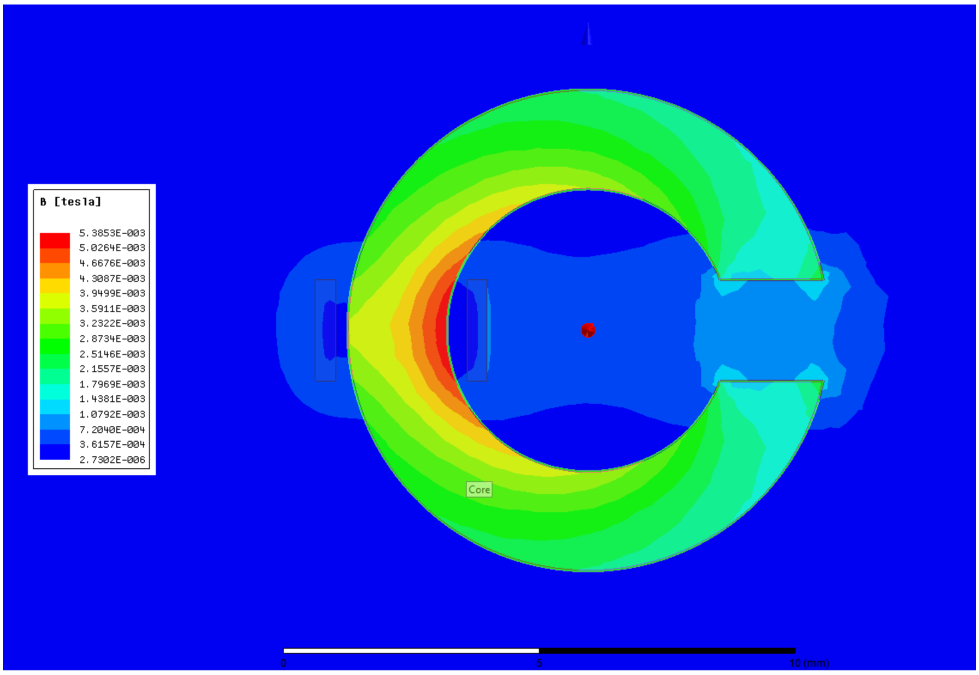


Figure 14 Magnitude of Magnetic Flux Density with Airgap (Nonlinear Material)

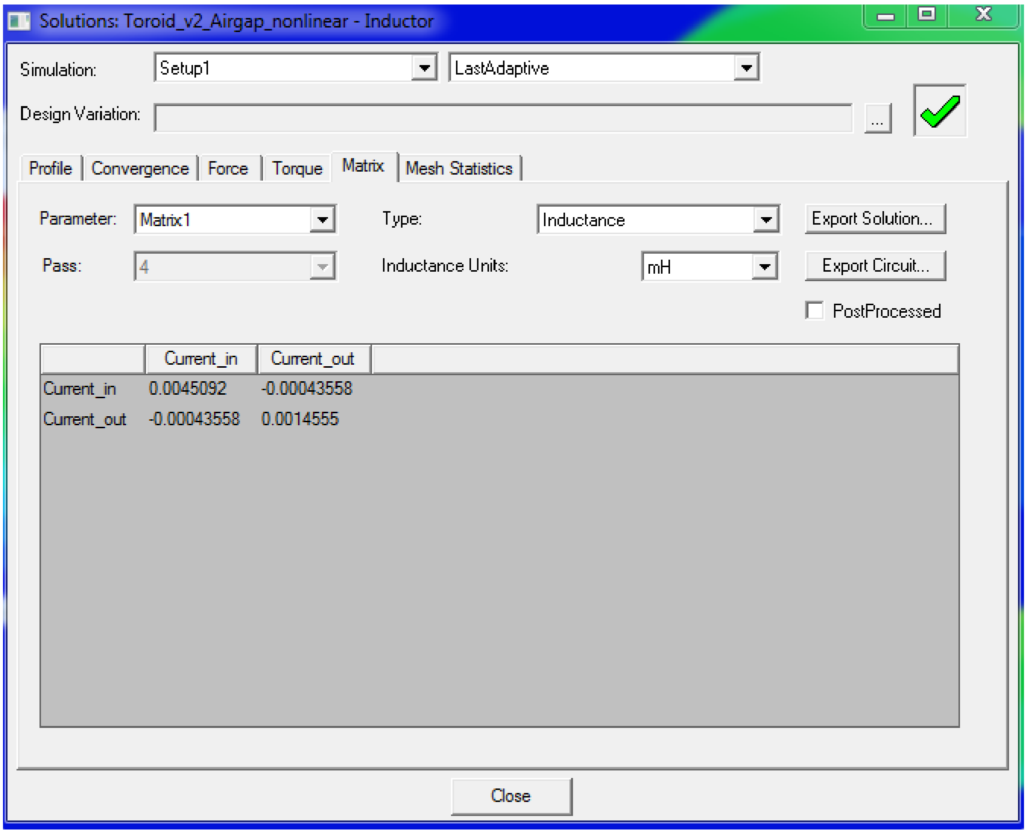


Figure 15 Inductance Calculation from Magnetic Energy with Airgap (Nonlinear Material)

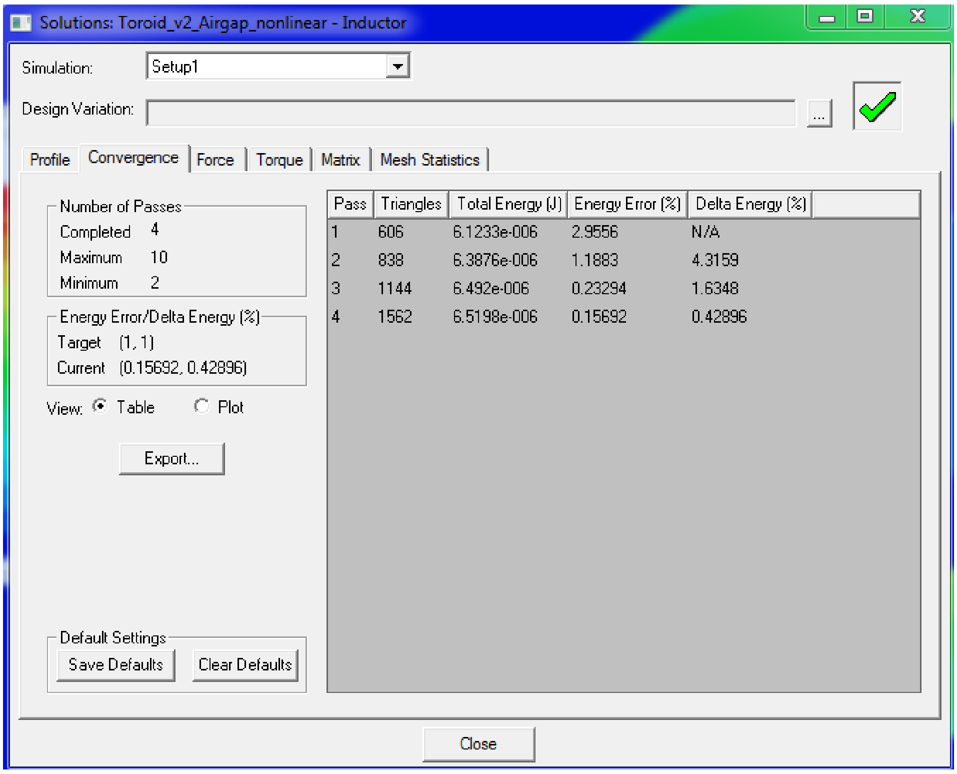


Figure 16 Inductance Calculation from Matrix Tool with Airgap (Nonlinear Material)

$$\frac{1}{2} * L * I^2 = 0{,}0000061233\, Joules\ (I = 8 * 200mA = 1{,}6A)$$

Real inductance value as following:

$$L = 4{,}78 \frac{uH}{m} * \ N^2 * core - depth = 4{,}78u * 64 * 7{,}11 * 10^{-3} = 2{,}18\, uH$$

All calculations can be seen in 'Inductor_Design_CA' file.

2.3 DISCUSSION

Inductance Values (uH)		Linear Core	Nonlinear Core	Nonlinear Core with Airgap
Analytical Calculations	Homogeneous Flux Distribution	139,2	134,5	0,55 (1,09 with fringing effect)
	Nonhomogeneous Flux Distribution	142,5	137,7	-
FEA Simulation	-	146,2	146,1	2,18

Table 1 Inductance Values

As seen in Table 1, there are differences between analytical calculations and FEA simulation. If nonhomogeneous flux distribution is assumed, then it converges to FEA results as expected. With nonlinear core less inductance value is obtained. The reason for higher inductance values in FEA simulation is fringing flux effect and it is more than expected.

With 2D FEA simulations, inductance unit is (H/m) and less computational time is required compared to 3D FEA.

3. TRANSFORMER DESIGN

Specifications:

500 kVA, Single Phase

- 34.5kV/25 kV
- 50 Hz
- Ambient Temp: -30C, 50C

There are several significant design goals such as overall system efficiency, weight, cost, size. In order to achieve design optimization goal, the interaction between design parameters must be known well.

Weight minimization with maximum efficiency and minumum cost is the main goal of design process. Design steps are based on following algorithm:

1. Choose core material
2. Choose operating flux density below saturation point
3. Consider temperature effect on saturation flux density etc.
4. Determine turns per volt (number of turns)
5. Decide core geometry
6. Calculate weight, size, efficiency and cost of a transformer

B=1 T is the operating flux density, to have less core loss. All graphs and optimization problems can be seen in Excel file 'Transformer_Design_CA'. Increasing number of turns lead to less core area and small geometry but copper losses increase. There exist optimum number of turns with possible highest efficiency. Since it is distribution transformer, size and weight are secondary purposes.

To minimize leakage flux, different lamination types exist. Added silicon to steel increases the resistance that reduces eddy losses. In addition, nickel alloys has higher permeability and low core losses but it costs higher compared to electric steel. Cobalt alloys comes with highest cost and highest magnetic flux saturation value [1]. With thinner lamination, eddy current losses can be reduced but cost is higher due to manufacturing process.

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4. CONCLUSION

In this project, F-type ferrite toroidal core is analyzed, simulated and compared in detail. Its inductance value, magnetic flux density distribution are investigated. In addition, transformer design is optimized based upon critical trade-offs.

5. REFERENCES

[1] Keysan, O. (2018, 03). *EE564*. Electrical Machine Design: Received from http://keysan.me/ee564/