

Institutionen för systemteknik

Department of Electrical Engineering

Examensarbete

Evaluation of software using the finite element method by simulating transformers and inductors

Examensarbete utfört i Elektroniksystem
vid Tekniska högskolan vid Linköpings universitet
av

David Håkansson and Jenny Larsson

LiTH-ISY-EX-ET--11/0381--SE

Linköping 2011



Linköping University
INSTITUTE OF TECHNOLOGY

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Nyckelord Keywords transformers, inductors, design, simulation, power losses, software, finite element method			

Abstract

In this bachelor thesis several software, capable of calculating and simulating complex problems concerning the power losses in inductors and transformers with the finite element method, have been evaluated and used to solve test cases provided by the commissioner. The software have been evaluated with respect to several requirements stated by the commissioner.

The aim is to be able to simulate power losses and inductance levels in complex designs of inductors and transformers. By reading the manuals to the software, a view of the methods and equations the different software use for their calculations have been established. The enclosed tutorials have provided the knowledge for the operations of the different software. By designing the test models provided by the commissioner, a deeper understanding of the work area has been reached.

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Contents

1	Introduction	3
1.1	Power losses in transformers and inductors	3
1.2	The commissioner	3
1.3	Different software using the finite element method	4
1.4	Aims of this thesis	4
1.5	Method	4
1.6	Specification of requirements	4
2	Theory	7
2.1	The finite element method	7
2.1.1	The Newton iteration process	8
2.2	Maxwell's equations	8
2.2.1	Ampere's law	8
2.2.2	Faraday's law	10
2.2.3	Lenz's law	10
2.2.4	Gauss's law	10
2.3	Parameters	11
3	Materials	13
3.1	Ferrite	13
3.1.1	Relation between \mathbf{B} and \mathbf{H}	14
3.1.2	Resistivity	14
3.1.3	Permeability	14
4	Power losses calculation	17
4.1	Eddy current losses	17
4.1.1	Skin effect	17
4.1.2	Proximity effect	18
4.1.3	Core losses	19

5	The software	21
5.1	COMSOL Multiphysics 3.5	21
5.1.1	Calculating using the AC/DC-module	22
5.2	QuickField 5.7	23
5.2.1	Calculating using the AC magnetic module	23
5.2.2	Calculating using the Transient Magnetics module	24
5.2.3	Heat Transfer module	24
5.3	FEMM 4.2	25
5.3.1	Calculating time-harmonic magnetic problems	25
5.3.2	Post processing	26
5.4	Ansys®Ansoft Maxwell Student Version 9	26
5.4.1	Calculating using the Eddy Current solver	26
6	The models to be simulated	29
6.1	Commutation choke coil	29
6.2	Asymmetric power inductor	29
6.3	Flyback transformer	30
6.4	Planar transformer	30
7	Simulations	33
7.1	Material properties	33
7.2	Simulating using FEMM 4.2	33
7.2.1	Building the models	33
7.2.2	Physics settings	34
7.2.3	Meshing and solving	34
7.2.4	Post processing	34
7.3	Simulating using COMSOL Multiphysics 3.5	35
7.3.1	Building the models	35
7.3.2	Physics settings	35
7.3.3	Meshing and solving	35
7.3.4	Post processing	35
7.4	Simulating using QuickField 5.7	36
7.4.1	Building the models	36
7.4.2	Physics settings	36
7.4.3	Meshing and solving	36
7.4.4	Post processing	37
7.5	Simulating using Ansys®Ansoft Maxwell Student Version 9	37
7.5.1	Building the models	37
7.5.2	Physics setting	37
7.5.3	Meshing and solving	38
7.5.4	Post processing	38

8	Results	39
8.1	Commutation choke coil	39
8.1.1	Calculating the temperature	41
8.2	Asymmetrical power inductor	41
8.3	Flyback transformer	44
8.4	Planar transformer	45
9	Conclusion/Discussion	47
9.1	FEMM 4.2	47
9.2	COMSOL Multiphysics 3.5	47
9.3	QuickField 5.7	48
9.4	Ansys ®Ansoft Maxwell Student Version 9	48
9.5	Discussion	49
9.5.1	Commutation choke coil	49
9.5.2	Asymmetrical power inductor	50
9.5.3	Flyback transformer	50
9.5.4	Planar transformer	50
	Bibliography	51
A		53
A.1	Commutation choke coil	53
A.2	Asymmetrical Power Inductor	56
A.3	Flyback transformer	57
A.3.1	Power loss graphs in the windings	60
A.4	Planar Transformer	63

List of Figures

4.1	Skin effect	18
4.2	Proximity effect	19
8.1	The magnetic field and the current density plot. Planar mode.	40
8.2	Concentration of the current density around the air gap. Planar mode	40
8.3	The concentration of the current density in axial symmetric mode	41
8.4	The original design made with a small air gap at the center leg of the E-core.	42
8.5	The resulting design to reach the desired value of the inductance.	43
8.6	The final design with an air gap on all three legs in the core.	43
8.7	The magnetic field when the primary winding connects. . .	44
8.8	The current density when the primary winding connects. . .	45
8.9	Planar transformer with magnetizing current on the primary side.	46
A.1	The commutation choke coil graphically displayed in FEMM	53
A.2	The commutation choke coil graphically displayed in QuickField	54
A.3	The commutation choke coil graphically displayed in Maxwell	55
A.4	Power inductor with air gap over all legs in the core. Displayed in FEMM	56
A.5	Power inductor with air gap over all legs in the core. Displayed in QuickField.	56
A.6	Power inductor with air gap over all legs in the core. Displayed in Maxwell.	57
A.7	Flyback transformer, magnetic field intensity plot in the secondary winding. Displayed in QuickField.	57
A.8	Flyback transformer, magnetic field density plot in the secondary winding. Displayed in QuickField.	58
A.9	Flyback transformer, current density plot in the secondary winding. Displayed in QuickField.	58
A.10	Flyback transformer, current density plot in secondary winding when the current switches between the primary and secondary winding. Displayed in QuickField.	59
A.11	Power loss in the bias winding. Displayed in QuickField. . .	60
A.12	Power loss in the primary winding. Displayed in QuickField.	61

A.13 Power loss in the first secondary winding. Displayed in QuickField.	61
A.14 Power loss in the second secondary winding. Displayed in QuickField.	62
A.15 Power loss in the third secondary winding. Displayed in QuickField.	62
A.16 Planar transformer. Displayed in FEMM	63

Chapter 1

Introduction

1.1 Power losses in transformers and inductors

When designing power electronic components, such as transformers and inductors, it is important to consider several different parameters. If the environment where the component will work is narrow, the power losses will be a primary parameter for the designer to consider. Usually there are constraints from the customer to have a high degree of power efficiency. For the designer it is important to have access to good enough tools to make a good design of the component. There is a lot of software on the market that can simulate the behaviour of the component before producing a prototype. This makes it important that the software is accurate enough for the designer so the prototype will be within the constraints from the customer. For some simulation software the higher efficiency in the designing process will give a 1.6 fewer prototypes at the end.

1.2 The commissioner

This bachelor thesis is assigned by ETAL Group AB, a leading supplier and manufacturer of inductive components for telecommunications, automotive and electronics industries. ETAL Group AB is a part of Elektronikgruppen BK AB with the head office in Vällingby. Design of qualified electrical transformers is made in Sweden at ETAL R& D center in Tornby, Linköping to a worldwide market. Manufacturing operations are situated in Southeast Asia and in Europe. ETAL also has sales offices in Sweden, Finland, Great Britain, India and China. [4]

1.3 Different software using the finite element method

A lot of the software on the market specializes in FEM for mechanics of materials. It is essential that the software is able to calculate problems within the electromagnetic field, as well as the thermal heat transfer field. Most of the software available have a structure with a main platform with added modules for each problem area you might want to solve. The equations and the calculations that the software perform varies between the different software. The basic theory in the software is based on Maxwell's equations and the general magnetic field theory. It is essential to have knowledge of the different parameters the software need to use to perform the simulation of the specific designs.

1.4 Aims of this thesis

- To evaluate different software on the market, that uses the finite element method, from a point of view that suits the commissioner.
- To simulate and interpret the different test cases provided by the commissioner using the different software that will be considered appropriate for the assignment.

1.5 Method

There is a lot of software on the market that uses the finite element method to simulate the different behaviour of the considered designs.

To be able to decide which software to use, a match has been made against a list of requirements the commissioner has specified. To solve the different test cases the manuals to each software has been studied, their tutorials have been a help for the training with the software and the test cases have been approached with help of the manuals.

1.6 Specification of requirements

Since there are a vast number of software on the market that uses the finite element method, a list of requirements from ETAL have been provided that the software considered shall be able to perform.

1. Use the finite element method to calculate and simulate the behaviour of a variety of designs.
2. Be able to calculate a 2-D design, it is also desirable to have the ability to calculate a 3-D design.
3. The material libraries shall be easy to edit when defining own materials. Also it is preferable if the library contains a large number of different materials used in insulation, coil and layers.
4. Be able to present the results in a graphically accessible way.
5. The software must have a short training curve for the commissioner.

Chapter 2

Theory

2.1 The finite element method

The finite element method is a numerical method for solving partial differential equations but also integral equations. The solution will be an approximation of the result. The method will either eliminate the differential equation and make the problem steady-state or approximate the equations into a system of ordinary differential equations and then use the numerically integrating techniques provided by the standard formulas such as Euler's method, Runge-Kutta, etc.

The finite element method originated when the need to solve complex problems that depended on the constraints required by a non-symmetrical function. For example a non-symmetrical current that differs over time. This method is also widely used when calculating problems within the solid mechanics problems. The pioneers who worked on this method were Alexander Hrennikoff (1941) and Richard Courant (1942), their approach is

different from the approach today but the essential characteristic they all share is the mesh discretization. This is done by distributing a net of sub-domains in a continuous domain and solve each sub-domain separately. These sub-domains are usually named elements. During the 1950's the development of the finite element method really took off and by 1973 a mathematical foundation was laid for the method used today. Gilbert Strang and George Fix published *An Analysis of The Finite Element Method*, this publication is the foundation to a wide range of generalized applied mathematical numerical modelling of physical systems within a lot of engineering disciplines. [9]

2.1.1 The Newton iteration process

It is preferable for the iteration method for the solver to converge rather fast, else it might consume a lot of computer time. The Newton iteration process is unconditionally stable and converges rapidly but will not require a lot more computer memory. Close to the solution point the convergence rate is, theoretically, quadratic. In other words, if the first approximation will achieve a solution within a factor two, one correct bit, the second approximation will produce a solution with two correct bits, the third will produce four and so on. The quadratically convergent steps to yield full precision on a 32-bit digital computer should not be more than five or six, so the approximated solution will probably not take to long time. [12, p.181]

The electromagnetic field problem can be expressed by a set of equations from Maxwell. These equations will be explained further down in this chapter. These equations will differ for example when the materials will give a non-linear relationship between the magnetic field intensity and the magnetic field density.

2.2 Maxwell's equations

Maxwell's equations are defined by four partial differential equations. They were published by James Clerk Maxwell in 1865. These equations defines the entire field of electromagnetics. These equations are laws that the magnetic and electric fields always must obey. [7]

2.2.1 Ampere's law

A conductor that carries a current induces a magnetic field around the conductor. This field is characterized by the *magnetic field intensity* \mathbf{H} . A thumb-rule is used to find the direction of the magnetic field density, described in an easy way, if the conductor is held with your right hand and the thumb indicates the current direction, then your fingers indicate the direction of the magnetic field.

The magnetic field intensity \mathbf{H} , is defined by Ampere's law. This law says that the integral of \mathbf{H} [A/m] around a closed path is equal to the passing of the total current through the interior of the path.

$$\oint_l \mathbf{H} \cdot d\mathbf{l} = \int_S \mathbf{J} \cdot d\mathbf{S}$$

\mathbf{H} is the field intensity vector [A/m], $d\mathbf{l}$ is a vector length element pointing in the direction of the path l [m], \mathbf{J} is the electrical current density vector [A/m²], $d\mathbf{S}$ is a vector area having direction normal to the surface [m²], l is the length of the circumference of the contour [m] and S is the surface of the contour [m²]. [2, chapter 1]

Applying this to the case where the current is carried by the wires in a coil with N turns, then

$$\oint_l \mathbf{H} \cdot d\mathbf{l} = \int_S \mathbf{J} \cdot d\mathbf{S} = Ni$$

Where i is the current and N the number of turns in the coil.

The magnetic field intensity \mathbf{H} will give us a resulting *magnetic field density* \mathbf{B} . This is given by the equation:

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H} = \mu \mathbf{H}$$

μ is the characteristic of the magnetic material term *permeability*. μ_0 is the permeability of free space, it is a constant $4\pi * 10^{-7}$ H/m. μ_r is the relative permeability of the magnetic material.

Depending on the material, the value of μ changes, for air and electrical conductors (copper, aluminum) it is 1. For ferromagnetic materials such as iron, nickel and cobalt the value varies from several hundred to tens of thousands.

In the right-hand side of Ampere's law we miss a term, this term is called displacement current and was added to the expression by Maxwell in 1865. So with this term added the full expression of Ampere's law is:

$$\oint_l \mathbf{H} \cdot d\mathbf{l} = \int_S \mathbf{J} \cdot d\mathbf{S} + \frac{\partial}{\partial t} \int_S \varepsilon \mathbf{E} \cdot d\mathbf{S}$$

ε is the permittivity of the medium and \mathbf{E} denotes the electrical field.

This correction of Ampere's law is mainly important for high-frequency applications with low current density. For power electronics, the magnetic components, are expected to have a current density of at least $\mathbf{J} = 10^6$ A/m². Normally the second term in Ampere's law is almost never more than 10 A/m², then it is possible to neglect this. The exception must be made for currents in capacitors and currents caused by parasitic capacitances and also for currents in transmission lines. Come to analysis of

power

electronics magnetic circuits this approach is called the quasi-static approach. [2, chapter 1]

2.2.2 Faraday's law

Faraday's law gives us the relationship between a flux Φ , that is time-dependent, which passes through a closed loop and a voltage $v(t)$, that is generated by the flux. The relationship is given by the equation:

$$v(t) = \frac{d\Phi(t)}{dt}$$

There are two cases where Faraday's law is valid:

- When a fixed circuit is linked by a time-changing flux, for example a transformer.
- When a moving circuit is related to a time-stationary magnetic flux in such a way that it produces a time-changing flux in the interior of the circuit.

[2, chapter 1]

2.2.3 Lenz's law

The voltage $v(t)$ generated by a fast time-changing magnetic flux $\Phi(t)$ has a direction to drive a current in a closed loop, this current induces a second magnetic flux that intends to oppose the changes in the applied flux $\Phi(t)$. This explains a part of the eddy current effects that appears in magnetic cores and coil conductors. This phenomena is one of the major causes for power losses in the core and also losses in the conducting coil. [2]

2.2.4 Gauss's law

Gauss defined a law for magnetic circuits, which states that for any closed surface \mathbf{S} with arbitrary form, the total flux entering the volume equals the total flux coming out of the volume. The total resulting flux through the surface is zero according to the equation:

$$\oint_{\mathbf{S}} \mathbf{B} \cdot d\mathbf{S} = 0$$

Gauss's law for magnetic circuits is analogous to Kirchoff's current density law for electrical circuits. [2, chapter 1]

2.3 Parameters

The software uses several common parameters for calculating the power losses, the inductance and the heat transfer. Below we state the most important that concern our problems.

\mathbf{B}/\mathbf{H} -curves gives the relationship between the magnetic field and the magnetic field intensity of a material. It is directly connected to the permeability of a material. The permeability will in ferrite cores be a function of the magnetic field and the magnetic field intensity. The magnetic field might vary with the current density and/or the frequency. Thus makes the equations for calculating the problems built on the magnetic field non-linear.

σ gives the value of the electric conductivity for a material. This constant need to be set to a correct value for the cores. This will be an issue when adding custom materials to the software libraries. This constant will affect the calculation of the core losses and if not set correct the core losses calculated will not correspond to the real value.

μ gives the value of the permeability of the material. This will give the magnetization of the material with dependence of the magnetic field \mathbf{B} and the magnetic field intensity \mathbf{H} since the relation is given by:

$$\mu = \frac{\mathbf{B}}{\mathbf{H}}$$

This constant is also essential for the calculations of the power losses.

h gives the value of the heat transfer coefficient for the material. It is used for calculating the heat transfer by convection between a fluid and a solid in the software. Together with the definition of the interesting areas of the model from a previous solution concerning the density of the magnetic field, this will give the temperature value in the critical parts of the design.

$$h = \frac{q}{A \cdot \Delta T}$$

A is the heat transfer surface area, ΔT is the difference in temperature between the solid surface and the surrounding fluid area and q denotes heat flow in input or lost heat flow. [8, p.201]

Air gap is an important part of the design of the transformer and the inductor. This will affect the \mathbf{B}/\mathbf{H} -curve and increase the saturation level

decided by this relationship. When applying an air gap to the geometry the saturation level for \mathbf{H} will increase significantly while the saturation level for \mathbf{B} will remain almost at the same level. If the core reach saturation the inductance in the core will drop very fast and thus the power losses will increase. So although this is not a real parameter in the equations used for the calculations it will affect the behaviour of the material and is of such importance to the design of these components that it is important to have some knowledge about it.

Chapter 3

Materials

There are three groups of magnetic materials:

- Diamagnetic materials
- Paramagnetic materials
- Ferromagnetic materials

When designing power electronics the ferromagnetic material is the most suitable material. Especially ferromagnetic ceramics and metals. This is due to the constant μ_r that is significantly higher than for the other two materials. μ_r is affected by the relation between \mathbf{B} and \mathbf{H} in the material. [2, chapter 1]

3.1 Ferrite

The use of ferrite in the core of transformers and inductors is most common today. This because the volume resistivity is much higher than in other materials. When designing for high frequencies it is of importance to calculate with the eddy current losses, they will increase approximately with the square of the frequency. This behaviour is inversely proportional to the resistivity in the core.

The ferrite is composed by two different combinations of different metals:

- manganese and zinc
- nickel and zinc

Nickel and zinc are appropriate for higher frequencies, over 1 MHz. While manganese and zinc have a high permeability and a high saturation induction levels. This alloy is suitable for low frequency power electronics.

3.1.1 Relation between \mathbf{B} and \mathbf{H}

The relation between $\mathbf{B}[T]$ and $\mathbf{H}[A/m]$ is given by the material properties. These properties are influenced by the manufacturing process. By choosing different manufacturing processes the manufacturer can control the saturation level and permeability of the material, which is essential to the designer. The permeability increases with the temperature to a maximum of the Curie temperature and then the permeability of the ferrite will drop sharply when that specific point is reached. [2, chapter 3]

3.1.2 Resistivity

The resistivity is very dependent of the temperature and the frequency. It increases with an increasing temperature. For high frequencies the resistivity will decrease. [2, chapter 1]

3.1.3 Permeability

This property is very important when calculating power losses. There are different ways to interpret the relative permeability μ_r it depends on the conditions when defining and measuring.

- Amplitude permeability μ_a , this is the relative permeability under alternating external field \mathbf{H} . The relation between the peak value of \mathbf{B} and \mathbf{H} is given by:

$$\mu_a = \frac{1}{\mu_0} \frac{\hat{\mathbf{B}}}{\hat{\mathbf{H}}}$$

$\hat{\mathbf{B}}$ is the amplitude value over the cross-section of the material and $\hat{\mathbf{H}}$ is the amplitude in the field parallel to the surface of the material.

- Initial permeability μ_i , this is the relative permeability of the material when we have a very low applied value of \mathbf{H} . This is given by:

$$\mu_i = \frac{1}{\mu_0} \frac{\Delta \mathbf{B}}{\Delta \mathbf{H}} (\Delta \mathbf{H} \rightarrow 0)$$

- Effective permeability μ_e denotes the total permeability when an air gap is present in a closed magnetic circuit. This value will be much

lower than in the same circuit without the gap. It is dependent on the initial permeability μ_i and the dimensions of the design and the air gap. For designs with a relatively small air gap the effective permeability is given by:

$$\mu_e = \frac{\mu_i}{1 + \frac{A_g \mu_i}{l_c}}$$

where A_g is the cross-sectional area of the air gap and l_c is the effective length of the magnetic path.

If there is a large air gap in the design the flux will pass outside the air gap and this will increase the effective permeability. This phenomenon is called fringing permeability. [2, chapter 1]

Chapter 4

Power losses calculation

4.1 Eddy current losses

There are several techniques to reduce the presence of eddy currents. When calculating the effects of eddy currents you need to know that the presence of them is linear, voltage and currents stay proportional. Active and reactive power losses are quadratic with the currents or the fields. Since the mathematical functions are analytical, (minimum phase impedance function) you can apply Bode laws. If you, for example neglect the capacitive effects, the resistance increases with the frequency and the inductance decreases with the frequency. [2, chapter 2]

4.1.1 Skin effect

The skin effect is a phenomenon known and derived for skin depth versus frequency since the beginning of the twentieth century. Induced eddy current causes the current to crowd into the outer skin of a conductor. The skin effect causes copper losses by restricting the conducting area of the wire, the magnitude of the currents flowing does not change, but the current density at the wire surface increases.

The main reason to why we have skin effect is due to the skin depth. The skin depth is where we have the major part of the current density in the conductor. The eddy currents press the current density towards the edges of the coils. With a higher frequency the skin depth tend to be smaller. It is determined by:

$$\delta = \sqrt{\frac{2\rho_c}{\mu\omega}}$$

where $\omega = 2\pi f$ for the frequency of the applied magnetic field, μ is the permeability of the material the conductor is made of and ρ_c is the electrical resistivity of the material in the conductor. This differs at different temperatures. $\rho_c = 17.24 \times 10^{-9} \Omega m$ at $25^\circ C$ and $\rho_c = 23 \times 10^{-9} \Omega m$ at $100^\circ C$. [2, chapter 2]

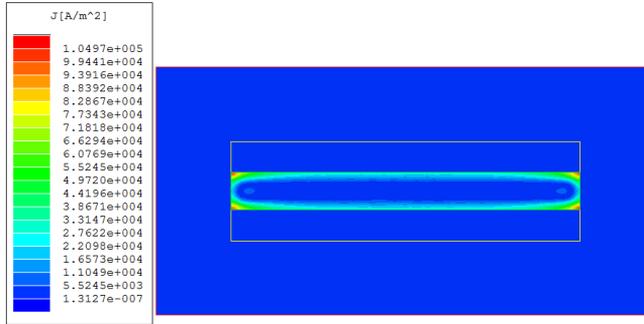


Figure 4.1. Skin effect

4.1.2 Proximity effect

When designing a multilayer coil we have to calculate the proximity effect. This is caused by the alternating magnetic field, \mathbf{B} , that arises from the currents in the winding layers in the coil. The magnetic field induces a current in the adjacent windings. These windings do not conduct during this period, but the result is an effect that contributes to the total power losses. This effect is more serious than the skin effect. Because the eddy currents caused by the magnetic fields in the adjacent layers increase exponentially in amplitude as the number of coil layers increases, in other words the skin effect is enhanced by the proximity effect. [2, chapter 2]

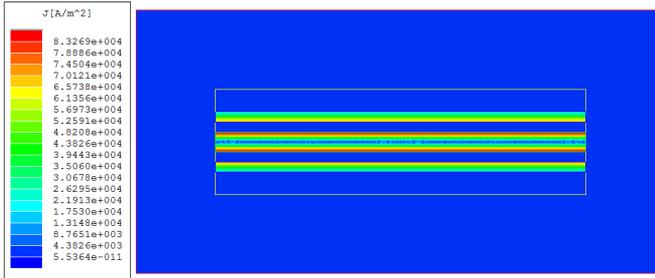


Figure 4.2. Proximity effect

4.1.3 Core losses

When designing these, relatively, small transformers and inductors one must consider the core losses. They are caused by the magnetic field that induces eddy currents in the core. All materials that are magnetic have some electrical conductivity. This conductivity for iron-based magnetic materials is relatively high. The flux in the core induces an internal voltage $d\Psi/dt$, this voltage drives circulating currents around its path. When considering a cross-sectional area of the core, the area of the cross-section can not be large compared to the skin depth. The applied magnetic field is carried by the surface area and the inner of the core carries a very small part of the magnetic field. The AC reluctance will increase and reducing the low reluctance path for the field. There is a connection between the eddy current losses in the core and the amplitude induction B_{max} , the frequency f and the internal resistivity ρ of the core material. These losses per volume are proportional to the square of the induced voltage and as a result proportional to $(fB_{max})^2$. There is an expression for the eddy current losses in the core as following:

$$P_{ec} = k_e \frac{f^2 B_{max}^2}{\rho}$$

where k_e is a dimensionless eddy current coefficient, B_{max} is the amplitude induction of the applied field and ρ is the internal resistivity of the core. This is only an approximation of the losses in the core. The impedance of some cores is not purely resistive but also depends on the frequency. Thus for some frequencies the dependence might be higher than f^2 at a constant induction level.

When specifically taking a closer look at the core losses in ferrite cores, used in power electronics, we will look at the losses when a non-sinusoidal voltage waveform is applied. Generally there is one equation used for calculating ferrite losses, this equation is called the Steinmetz equation:

$$P_{loss} = k f^\alpha \hat{B}^\beta \quad (4.1)$$

where \hat{B} is the peak induction, P_{loss} is the average power loss per unit volume and f is the sinusoidal excitation.

This equation will have a decreased accuracy for square waves but it will still be a good approximation with a duty ratio around 50 %. For very low or high duty ratio, < 5 % or > 95 %, the approximation of the power loss will be more than doubled compared to sine waves. For real materials α and β are frequency dependent, usually they increase with the frequency, thus k will also change. To be able to make correct calculations the samples will be measured and the Steinmetz equation will be adjusted with a reference frequency at 100 kHz, a reference power and induction of 0.1 T:

$$P = k_{ref} B^\beta f^\alpha = P_{ref} \left(\frac{B}{B_{ref}} \right)^\beta \left(\frac{f}{f_{ref}} \right)^\alpha$$

The coefficient β is fitted for the reference frequency and the reference induction. α is determined by using the reference values at a higher frequency at 250 kHz. This because it lies in between the second and third harmonic. These coefficients can be obtained from the manufacturers data sheets. [2, chapter 3]

Chapter 5

The software

There are a lot of software on the market using the finite element method. Many addressed to the structural solid mechanics and the problems associated with those designs. Some software have a multiphysic point of view and will include the magnetic and electrical modules into that, others have a more direct connection to the electromagnetic area. They are usually easy to adapt considering the requirements a specific problem might need. Many have a platform you can expand with modules adaptable to the problems you want to solve. Another feature is the material libraries that usually holds a wide range of materials. There is also the possibility to add your own materials or have the support to maintain the materials you might need. The drawback is that most of the software are expensive. The modules added all have an additional cost, the support has a fee for every year beyond the first year that usually is included in the purchasing fee.

There are also free software that are focused on solving a specific problem or a specific class of problems. Their material libraries might also be limited in number of available material constants. It is usually easy to add specific materials but you do not have the support team as you have with the strictly commercial software.

5.1 COMSOL Multiphysics 3.5

The COMSOL Group was founded in Stockholm 1986. They provide software solutions for multiphysics modeling. The software has several modules, depending on your problem you might not need all of them. The module evaluated is the AC/DC-module, the COMSOL group has also a heat transfer module that can be of interest in some of the problems pro-

vided by the commissioner.

5.1.1 Calculating using the AC/DC-module

This module is suitable for simulating different designs such as coils, capacitors, inductors, and other designs within the electromagnetic area. You can model your design in both 1-D, 2-D and 3-D, also the possibility for an axial symmetric model of the problem is available for 1-D and 2-D. You can also choose between different stages, such as static, transient, quasi-static and time-harmonic simulation. This module covers different types of electromagnetic field simulation. The magnetostatic problem solution has been used in this case. The module also has a large material library with several of the most important constants predefined for different materials.

The module has several different solvers depending on the partial differential equation. There are two that applies to our kind of design problems, the stationary and time-dependent solver. The module also takes into consideration if the problem is linear or non-linear.

It is possible to couple the problems with both the electrical field and the magnetic field. The equations used for solving these problems are built on the Maxwell's equations. Ampere's law for static cases is used as follows:

$$\nabla \times \mathbf{H} = \mathbf{J}$$

By defining potentials for \mathbf{B} , \mathbf{E} and \mathbf{J} , adding the constitutive relationship:

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$$

Ampere's law is rewritten as follows:

$$\nabla \times (\mu_0^{-1} \nabla \times \mathbf{A} - \mathbf{M}) - \sigma \mathbf{v} \times (\nabla \times \mathbf{A}) + \sigma \nabla V = \mathbf{J}^e$$

When solving for a time harmonic equation Maxwell-Ampere's law including displacement currents is used. By adding another constitutive relationship $\mathbf{D} = \varepsilon_0 \mathbf{E}$ Ampere's law is again rewritten and the equations used for solving V and \mathbf{A} will be as follows:

$$-\nabla \cdot ((j\omega\sigma - \omega^2\varepsilon_0)\mathbf{A} - \sigma \mathbf{v} \times (\nabla \times \mathbf{A}) + (\sigma + j\omega\varepsilon_0)\nabla V - (\mathbf{J}^e + j\omega\mathbf{P})) = 0$$

$$(j\omega\sigma - \omega^2\varepsilon_0)\mathbf{A} + \nabla \times (\mu_0^{-1} \nabla \times \mathbf{A} - \mathbf{M}) - \sigma \mathbf{v} \times (\nabla \times \mathbf{A}) + (\sigma + j\omega\varepsilon_0)\nabla V = \mathbf{J}^e$$

\mathbf{J}^e denotes the externally generated current density derived from the applied current. \mathbf{v} is the velocity of the conductor and \mathbf{M} is the magnetization vector in unit A/m . Comsol Myltiphsics 3.5 will use these equations

to solve for the potentials. For the time harmonic equations the solutions calculated is not the physical field but a phasor. By specifying a phase factor at the result page we can obtain the result for a given time. [3]

5.2 QuickField 5.7

QuickField is developed by Tera Analyses Ltd. The company was created in 1999 and has its headquarters in Denmark. QuickField has a wide range of modules to choose between for different engineering problems and designs. The AC magnetics module solves problems with regard to time-harmonic magnetic fields inducing proximity effects, eddy currents and other parameters that is of interest in switched power supply.

5.2.1 Calculating using the AC magnetic module

QuickField works in this module with equations that differs if the problem is made in a planar mode or an axial symmetric mode. The equations are also constrained by Maxwell's equations and consists of two partial differential equations. Through a multiple equations derives these following equations:

$$\frac{\partial}{\partial x} \left(\frac{1}{\mu_y} \frac{\partial A}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{1}{\mu_x} \frac{\partial A}{\partial y} \right) - i\omega g A = -j_0$$

for planar equations and

$$\frac{\partial}{\partial r} \left(\frac{1}{r\mu_z} \frac{\partial(rA)}{\partial r} \right) + \frac{\partial}{\partial z} \left(\frac{1}{\mu_r} \frac{\partial A}{\partial z} \right) - i\omega g A = -j_0$$

for axial symmetric equations. g stands for electrical conductivity and μ_x and μ_y (μ_r and μ_z) stands for the magnetic permeability and represents constants within the specific model. j_0 denotes the current density and is assumed to be constant in the planar case and vary as $1/r$ in the axial symmetric case.

QuickField has the ability to handle non-linear magnetic materials in the models and you are able to define the **B/H** curves that specifies the permeability for these materials. QuickField applies the equations by ignoring the displacement current in Ampere's law ($\frac{\partial D}{\partial t}$) in the calculations made with these equations. Assuming that the displacement current density is not significant until we reaches higher frequencies ($< \text{MHz}$).

5.2.2 Calculating using the Transient Magnetics module

This module applies when we are calculating with a time-varying current as input. The module uses formulas derived from Maxwell's equations for vector magnetic potential \mathbf{A} ($\mathbf{B} = \mathbf{curl} \mathbf{A}$) and scalar electric potential U ($\mathbf{E} = -\mathbf{grad} U$):

$$\mathbf{curl} \frac{1}{\mu} \mathbf{curl} \mathbf{A} = \mathbf{j} + \mathbf{curl} \mathbf{H}_c$$

$$\mathbf{j} = g\mathbf{E} = -g \frac{\partial \mathbf{A}}{\partial t} - g \mathbf{grad} U$$

where $\frac{1}{\mu}$ is an inverse permeability tensor and g is the electrical conductivity. In the second equation the vector \mathbf{j} is considered a combination of the external current source and the induced eddy current

$$\mathbf{j} = \mathbf{j}_0 + \mathbf{j}_{eddy}$$

where $\mathbf{j}_0 = -g \mathbf{grad} U$ and $\mathbf{j}_{eddy} = -g \frac{\partial \mathbf{A}}{\partial t}$.

The manual walks through a few more derivations and finally the formulas used to solve the problems are defined as follows:

$$\frac{\partial}{\partial x} \left(\frac{1}{\mu_y} \frac{\partial A}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{1}{\mu_x} \frac{\partial A}{\partial y} \right) - g \frac{\partial A}{\partial t} = -j_0 + \left(\frac{\partial H_{cy}}{\partial x} - \frac{\partial H_{cx}}{\partial y} \right)$$

for the planar case and

$$\frac{\partial}{\partial r} \left(\frac{1}{r\mu_z} \frac{\partial(rA)}{\partial r} \right) + \frac{\partial}{\partial z} \left(\frac{1}{\mu_r} \frac{\partial A}{\partial z} \right) - g \frac{\partial A}{\partial t} = -j_0 + \left(\frac{\partial H_{cr}}{\partial z} - \frac{\partial H_{cz}}{\partial r} \right)$$

for the axial symmetrical case. μ_x and μ_y (μ_r and μ_z) are magnetic permeability tensor components. H_{cx} and H_{cy} (H_{cr} and H_{cz}) are coercive force components. All within each block of the model. j_0 is assumed to be constant in the planar case and $\frac{1}{r}$ for the axial symmetric case. In this module can use custom defined \mathbf{B}/\mathbf{H} curves to determine the permeability component in the magnetic materials. [11]

5.2.3 Heat Transfer module

This module is used to couple the problem first solved in the AC magnetic module. QuickField is able to solve problems in both linear and non-linear temperature fields, these fields are in this thesis model cases decided by the material in the core. For the non-linear case the equation is as follows:

$$\frac{\partial}{\partial x} \left(\lambda(T) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda(T) \frac{\partial T}{\partial y} \right) = -q(T) - c(T) \rho \frac{\partial T}{\partial t}$$

This equation is only for the planar case where T stands for temperature, t denotes the time, $\lambda(T)$ denotes the heat conductivity as a function of temperature, $q(T)$ denotes the volume power of heat sources, $c(T)$ denotes the specific heat and ρ denotes the density of the material. [11]

5.3 FEMM 4.2

Finite Element Method Magnetics, FEMM, is a package for solving problems in 2-D, planar or axial symmetric. The package is used for relatively low frequencies. The package is developed by Ph.D. David Meeker in 1997-98. The package addresses some limiting cases of Maxwell's equations. The magnetics problems the package is intended for is in a relatively low frequency area, below radio frequencies. Approximately frequencies below 300 kHz.

5.3.1 Calculating time-harmonic magnetic problems

In the cases when the magnetic field varies with time we will probably have induced eddy currents in materials with a non-zero conductivity. Since Maxwell's equations has to be obeyed we will have a relationship between the *electric field intensity* \mathbf{E} and the *current density* \mathbf{J} :

$$\mathbf{J} = \sigma \mathbf{E}$$

with induced electrical field that obeys:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

These are the initial equations FEMM uses, by deriving through multiple equations FEMM will use following equation to solve the problems in time-harmonic magnetic state:

$$\nabla \times \left(\frac{1}{\mu_{eff}(\mathbf{B})} \nabla \times a \right) = -j\omega\sigma a + \hat{\mathbf{J}}_{src} - \sigma \nabla V$$

where $\hat{\mathbf{J}}_{src}$ denotes the phasor transform of the current applied sources. a is derived from the equation : $A = Re[ae^{j\omega t}]$. Interpret this as μ will be constant for harmonic problems. FEMM can approximate the effects of saturation on the phase and amplitude of the field distribution. [5]

5.3.2 Post processing

In the post processing mode of FEMM there are several ways to display the result of the calculations. By default the software shows the geometry with the magnetic field displayed. The user may choose to display different solutions over the whole surface. The magnetic field density, the current density and the magnetic field intensity can be displayed through a coloured graph. By choosing the surface domains of interest the user will be able to calculate interesting values, for example the total power loss and the inductance level.

The most relevant equations for this thesis is the integral for total power loss and the inductance level. The equation for power loss is in FEMM's user guide not defined but it is a total calculation of all the losses possible over the chosen section. By choosing the block integral **A.J** the user will be able to calculate the inductance level.

$$L_{self} = \frac{\int \mathbf{A} \cdot \mathbf{J} dV}{i^2}$$

The equation gives the result in the unit \mathbf{H}/\mathbf{A}^2 , by dividing with the squared current the real inductance level is obtained. [5]

5.4 Ansys®Ansoft Maxwell Student Version 9

Maxwell is a part of the Ansoft product suite owned by Ansys, Inc. Ansys, Inc. was founded in 1970 and has 1600 employees of today. Ansys develops a wide range of simulation software for different environments, for example fluid mechanics, electro magnetics and structural mechanics. Ansys headquarters is located in Pennsylvania, U.S.A. and has channel partners in more than 40 countries in the world. The Ansoft product suite consists of a wide range of modules, specified for both high-performance electronic design and electromechanical design.

5.4.1 Calculating using the Eddy Current solver

In Maxwell this solver uses equations derived from Maxwell's equations. The eddy currents in the model are calculated by using following equation:

$$\nabla \times \frac{1}{\mu} (\nabla \times \mathbf{A}) = (\sigma + j\omega\varepsilon) (-j\omega\mathbf{A} - \nabla\Phi)$$

where A denotes the magnetic vector potential, Φ denotes the electric scalar potential, μ is the relative magnetic permeability, ω denotes the angular

frequency, σ denotes the conductivity of the material and ε stands for the relative permittivity.

Maxwell has the ability to handle a non-linear material with **B**- and **H**-fields that varies over the frequencies. Maxwell will calculate the effective values of **B** and **H** from the **B/H**-curve for the magnetic material. This is because μ will differ with the frequencies according to following equation:

$$\mu_{eff} = \frac{\mathbf{B}_e}{\mathbf{H}_e}$$

Maxwell will get the effective values of **B** and **H** by these following equation for **B_e**:

$$\mathbf{B}_e = \frac{2}{3\pi} \sum_{i=1}^n f(\alpha_i) + f\left(\frac{\alpha_i + \alpha_{i+1}}{2}\right) + f(\alpha_{i+1})$$

and for **H_e**:

$$\mathbf{H}_e = \frac{2}{3\pi} \left(\sum_{i=1}^n f(\alpha_i) + 4f\left(\frac{\alpha_i + \alpha_{i+1}}{2}\right) + f(\alpha_{i+1}) \right)$$

In the set up parameters for calculating core loss the software will use following equation for the ferrite core loss coupled with the eddy current problem:

$$p = C_m f^x B_{max}^y$$

Where C_m denotes the constant value determined by the calculations in the eddy current solver, f denotes the frequency and B_{max} is given by the maximum amplitude of the field density. The x- and y-exponents derives from the Steinmetz equation 4.1.

Chapter 6

The models to be simulated

In this chapter the models provided by the commissioner and the theory behind them are described.

6.1 Commutation choke coil

This is an inductor with a foil winding. Very thin layers of copper with an even thinner layer of insulation material in between the turns. This whole model, where the commutation choke coil is a part, were designed to accommodate a fairly large power output, 12 kW. When calculating the power losses in the commissioners software the result shows no issue with power losses around the air gap. In reality after a prototype had been made the power loss around the air gap in the copper wire became much larger than estimated. In fact the power loss got so high that the winding melted. The commissioner later tested to solve this problem in reality by applying a litz wire with few strands in the winding, the final solution became a litz wire with more than 500 strands in the windings.

6.2 Asymmetric power inductor

This is a power inductor with only 2.5 turns in the winding. Usually the design is made with more turns in the winding and more common is also to use full turns. When testing this prototype the commissioner noticed a problem with the inductance. The measured value of the inductance was much higher than the estimated. The reason is probably the half turn and the small number of turns in the winding. To get the correct value of the inductance the manufacturer had to grind down the middle leg of the E-core to get the correct value of the inductance. At the end the air gap in

the core became so large that the middle leg in the E-core were too small. The commissioner took this core and measured the inductance value at different half turns and full turns. The result from these measures were a clear picture that half turns increased the inductance while adding another half turn to get a number of full turns the result was an inductance level you could expect out of sheer experience.

6.3 Flyback transformer

This is a transformer with a bias winding, a primary winding and a secondary winding that consists of three windings. The three secondary windings consist of one winding of copper with the same diameter as the primary winding, but less turns, and two windings with significantly smaller diameter than the first secondary winding. Also the first secondary winding is done in parallel. The commissioners software will calculate the problem by adding the proximity effect losses to each other. The problem is the shape of the current that initially is a trapezoid current. The commissioners software will handle the current, not as a continuous current, but will divide the current shape into two parts with the amplitude reaching zero at the half period and then rise the current to the wanted value again. In reality the current will never be zero, so the desired behaviour is a software that can apply the function of the current, over time for a full period. This behaviour in the model is called continuous mode, the commissioners software interpreted the behaviour as discontinuous mode.

The commissioners software overestimate the proximity effect, due to the inability to calculate with a time-dependent function of the current. The estimated proximity effect, with the commissioners software, is a sum of all the power losses in the primary winding and the three secondary windings. It does not correspond to the true effect losses since the current won't reach zero at any time. In comparison, the commissioners software estimates the power loss in the bias winding to more than 2 W, while QuickField gives an estimated power loss as low as 0.2 W. This is much more reasonable compared to the measured value of the power loss in the transformer.

6.4 Planar transformer

A planar transformer differs from the other designs by the way to apply the windings. They can be stand alone components, designed according

to a stacked layer approach or they can be integrated into the printed circuit board, PCB. This allows for a low profile, the thermal characteristics becomes very good and the leakage inductance is small. [6, p.3] The task for this model is to evaluate if it is possible to calculate the power loss in the transformer. The design of the model is fairly simple to CAD into the software.

The input signal to this model is a square wave with a current amplitude at zero in between the positive and negative part of the wave and at the end during one period. This requires a transient analysis to be able to calculate the correct core losses in the model.

Chapter 7

Simulations

In this chapter the simulations made with the different software available are described. A brief description how to build and solve the models in each software are also included.

The simulations made are done with design and problems from a number of test-cases provided by the commissioner. They are built in the different software chosen to be evaluated and the result are compared between the software. This is to establish if the results are similar but also this will give answers regarding the maintainability and usability of the software.

7.1 Material properties

In all the software some material properties has to be defined. These are defined by the manufacturers data-sheets for the specific material and by the design requirements from the commissioner. It is of essence to provide the correct \mathbf{B}/\mathbf{H} relationship to be able to simulate without changes made in too many variables. For the common materials such as air and copper the software's material library usually has predefined values on these material properties.

7.2 Simulating using FEMM 4.2

7.2.1 Building the models

The models simulated is drawn with the tools built into the software. FEMM has 5 modes in the draw section, *Point* mode, *Segment* mode, *Arc Segment* mode, *Block* mode and *Group* mode. To define a geom-

entry in FEMM the user states the coordinates of a cross-section of the model intended to be simulated. This is done by using the point mode and segment/arc segment mode.

7.2.2 Physics settings

To assign the right properties to the different parts of the model we will use the block mode, this defines labels and properties for each part/block of the model. FEMM carries a small material library with the most common material constants. It is easy to define a new material for the ferrite in the core by applying the \mathbf{B}/\mathbf{H} curve. The user can also import the materials for another model. This is to prefer when different designs might use the same custom made material. It will not be necessary to define the custom made material more than once. The user need to tell the software where the model ends, else the user will get a result with calculations made for infinity boundaries. The correct current applied is also set, all this is done from the properties menu.

7.2.3 Meshing and solving

FEMM has an built in mesh-tool that will mesh the geometry automatic. The highest resolution of the mesh needs to be around the critical areas of the geometry. A small geometric detail will need a higher resolution since this is more important to solve accurately than a large space of air surrounding the actual model. How many elements that are made and how many degrees of freedom the problem will be solved for is limited by the memory capacity. FEMM solves the problem with a predefined model and for the user it is very simple, just to press the solve button in the user field.

7.2.4 Post processing

For post processing in FEMM there is a new window opened and as default the flux lines of the magnetic field is shown. This gives an initial picture of the behaviour of the design. In the post processing area the user can choose to calculate different block integrals or line integrals to see what happens from a surface point of view or a cross-section point of view. When defining the physics settings it is preferable to group the blocks of the same property since this makes it much easier to calculate, for example, the total power losses in the windings.

7.3 Simulating using COMSOL Multiphysics 3.5

7.3.1 Building the models

In COMSOL the geometry is built with defining different blocks of the model. Instead of defining coordinates for the geometry it is built by uniting rectangles and circles and other geometrical parts to complete a design. The user interface consists of several modes to complete the design, *Draw* mode, *Boundary* mode, *Subdomain* mode and *Point* mode. In draw mode there are many tools for the user for different geometrical shapes, it is easy to scale the geometry and unite different blocks into one solid block representing for example the core.

7.3.2 Physics settings

COMSOL has a lot of ways to define custom variables to solve the problems in the model. In subdomain mode the user assign the material constants needed. COMSOL carries a large library of different materials but it is also easy for the user to define materials of their own. The way to apply the correct current differs from the other software. When defining the subdomain for a leading copper coil the user needs to apply the correct external current density instead of the current solved for. Thus it is necessary to calculate the correct area of the cross-section of the coil and then apply the right value. In boundary mode it is easy to apply the correct values on the boundaries restraining the magnetic field area.

7.3.3 Meshing and solving

Meshing and solving is defined by default but the user is able to define customized size on the mesh and also can pick the different algorithms to solve the problem. Again the restraint on the solving procedure is the number of freedom degrees the linearisation algorithms solve for. COMSOL has, compared to the other software by default a denser mesh and higher expectations on the memory capacity. During the solving, the software has run out of memory during the LU-factorization (Lower-Upper) the matrix. This can be solved using a coarser mesh but the user must be aware this might affect the accuracy of the result.

7.3.4 Post processing

In the post processing mode by default the *magnetic field density* will be plotted. Again it gives the user an initial understanding of the behaviour

of the model. It is also possible to plot each subdomain with the different areas of interest the user choose. The areas of interest differs compared to the other software. The equations for solving for power losses will be given in the unit of W/m^2 , to get the real value the user need to perform a calculation by multiplying by the volume of the desired block area where the power loss of interest occurs.

7.4 Simulating using QuickField 5.7

7.4.1 Building the models

In QuickField the user build the model with nodes and edges. It is also possible to insert block-shapes but coordinates for these blocks are measured from the center of the block, compared with COMSOL that uses the coordinates for the lower left corner for a rectangle. It is very easy to import a dxf-file (drawing exchange format) from an already made CAD (Computer Aided Design). This saves some time since the user can approach the block properties mode at once since the CAD tools in QuickField demands another way of coordinating the blocks.

7.4.2 Physics settings

QuickField does not carry a material library as the other software do. The user has to define all the materials used in the model. It is possible, as in the other software, to define the custom materials used. It is easy to maintain the \mathbf{B}/\mathbf{H} curve of a ferrite and all the necessary constants are easy to apply. To apply the correct material constants and current all is defined in the block properties window. QuickField has another approach to apply the material constants and the correct properties for each domain in the model. Where the other software use domains, QuickField will name the same area as blocks. With a double-click the window for naming each block will appear. When named the new block will appear in the branch data in the tree to the left in the main window. From here it is easy to apply the properties of every block label. For the transient analysis the user needs to define a time-dependent signal input described as a function or a constant signal input.

7.4.3 Meshing and solving

In Quickfield the meshing and solving area the procedure is very similar to the other software. A built-in mesh tool is available and it is possible

for the user to define the resolution of the meshed net for the design. The areas that will be meshed can not be too narrow since this will either make it impossible to mesh or make a mesh too dense for the solver to process in the calculation. In Quickfield the mesh size can be locally defined by the user at specific edges, nodes and areas.

7.4.4 Post processing

QuickField will by default display the field picture of the current density. There is a variety of menus for the post processing and QuickField will give the mean, peak and root mean square values of the different integral values. By choosing the contour, area or field, of interest QuickField will be able to calculate the values of interest. For a graphically display to be plotted, choose a contour of interest. This plot can for the inductance level be calculated in two different ways. The post processing mode has a tab in the calculation menu for the inductance level calculation where a step by step instruction helps the user to get the value of the inductance. It will be either the flux linkage value or the stored energy value.

7.5 Simulating using Ansys®Ansoft Maxwell Student Version 9

7.5.1 Building the models

In the section define model, the draw options are models or grouping objects. Important thing to do before the user start to draw is to choose a matching draw unit for the model. In 2-D draw modeller there is a few handy tools to the users help, straight lines, rectangular/circular object and move/turn object. When designing the model the user can write the coordinates or directly give the edge intended the right length. When the design of an object is finished the user has to apply a matching name and color.

7.5.2 Physics setting

In material set up the user assigns the material properties to the objects created. Maxwell has a large library over the most common materials. The user can add a custom material, define the **B/H**-curve and add the material properties. The next step is to define the model with boundaries and voltage or current sources. In these models the windings will be current sources and the surrounding area will be the boundary to avoid an infinite

model, the user need to create a so called "balloon". To calculate the core loss, AC resistance and the inductance, the options will be found in the executive parameters. In the set up for total core loss the user needs to define some parameters, before the calculations can be executed. For the calculation of the core loss the power ferrite needs to be chosen, there is also some properties that has to be defined in this area.

7.5.3 Meshing and solving

The user can choose to mesh the model manually or automatic. The mesh size can be customized as desired. To get a relatively good accuracy the size of the finite element mesh is of importance. The frequency for the problem is by default 20 Hz, the user is free to change the frequency to match the model. Before solving the right source for the problem, by default it is an initial source but the user need to change it to the current source matching the problem intended to be calculated.

7.5.4 Post processing

It is wise to start the post processing mode by checking the convergence data. All the steps Maxwell needed to solve the problem and how fast the problem converged is displayed here. The energy error in percentage and the total power loss in watt is also available here. In the solution tab, the user will find the results from the options in the executive parameters area. The graphical solution can be reached from the post process tab, the user needs to create an object list over the area that is interesting before watching the result. This will make it easier to get a good overview in the area of interest. For the current density \mathbf{J} , the magnetic field intensity \mathbf{H} and the magnetic field \mathbf{B} , there are several options to choose between. The correct option for these models were the phase-related options. These options are found below the plot and field tabs. The user will reach the list over the geometry created previously.

Chapter 8

Results

In this chapter the results from the simulations are declared, the software are compared towards each other and the difference between the calculations made are shown.

8.1 Commutation choke coil

The commutation choke coil had a entirely different problem. The losses in the windings proved to be much higher than the estimated value calculated with the software the commissioner uses. The real power loss became a lot higher than expected.

The results of the simulations made by the software we choose to use, showed that the power losses in the windings became large. The simulated power loss seems likely to correspond to reality. The design is modelled in both axial symmetrical and planar mode. These modes gives different results. The planar mode in the software calculating for the power loss corresponds to each other while the axial symmetrical mode gives a higher power loss. For the planar mode the power loss became 24.6 W.

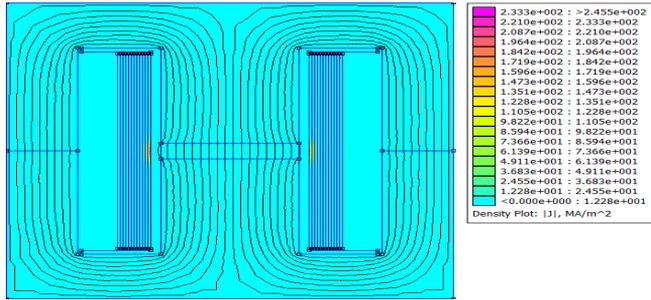


Figure 8.1. The magnetic field and the current density plot. Planar mode.

This behaviour confirms the physical result when running a prototype. The simulation clearly states that the problem is the concentration of the current density around the air gap. Due to this concentration the power dissipation becomes very high and the design is not suitable for this problem. In a close up the concentration is clearer, considering the thin copper layers and this behaviour in the magnetic field, the result is not a big surprise.

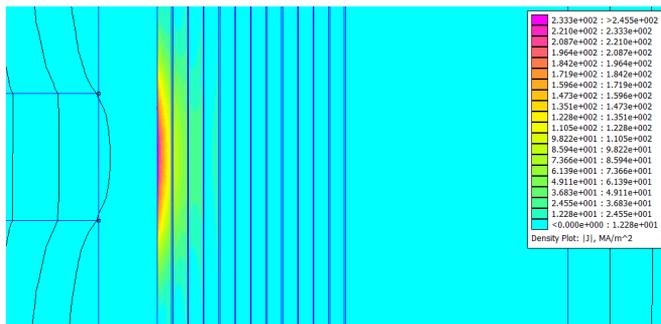


Figure 8.2. Concentration of the current density around the air gap. Planar mode

We have also simulated an axial symmetrical model of the commutation choke coil. The calculated power loss becomes significantly higher, but the behaviour of the magnetic field confirms the result when modeling in a planar system. The close up of the current density and magnetic field plot shows the same result.

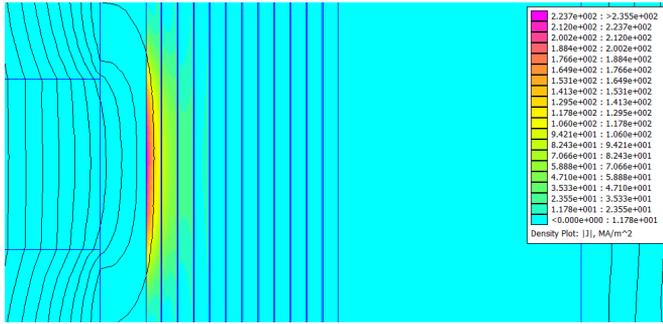


Figure 8.3. The concentration of the current density in axial symmetric mode

The calculated power loss became as high as 34.2 W compared with the power loss in the planar mode. This result might be an impact of the higher core volume since the calculations will be made of the design at a 360° around the vertical axis, the volume of the copper wiring will of course also be higher so you might expect the result will be higher in the axial symmetric mode.

8.1.1 Calculating the temperature

The problem calculated in the AC magnetic module were coupled with the heat transfer module to get a temperature value in the area around the air gap. As a result the temperature were calculated to more than 500°C in the area around the air gap. If this is plausible then the physical result in the prototype is not a surprising behaviour.

In an early state of the thesis work it was decided to not design all the test models in COMSOL Multiphysics, this decision was taken on the basis of the results calculated. Compared with the other software the results for the commutation choke coil were not confirmed in COMSOL. Though the magnetic field behaviour was similar all the other calculated values were significantly different.

8.2 Asymmetrical power inductor

As described earlier in the model chapter the problem for this power inductor were the behaviour of the model when the winding was made only

with a few half turns. This causes an asymmetrical behaviour in the magnetic field. The commissioners software estimated an air gap around 0.5 mm, in reality the needed air gap became seven times higher to reach the desired value of the inductance. When simulating the original design in our evaluation software we clearly got a picture of a magnetic field that did not behave as expected. The magnetic field became much denser on the side where the extra half turn was added and the expected behaviour in the middle leg became oddly stretched as shown in the figure below.

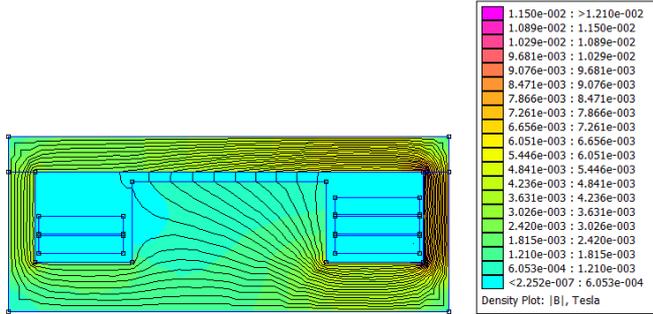


Figure 8.4. The original design made with a small air gap at the center leg of the E-core.

The magnetic field is clearly denser at the side with the extra half turn. The magnetic field behaviour in the middle leg is oddly shaped. The simulated values of the inductance became just over three times larger than the calculated value in the commissioners estimation.

The next simulation became the prototype with the large grind down middle leg of the E-core. Again the result were unexpected. The magnetic field did not cross the air gap in the middle leg, instead it circulated in the remaining core, creating a magnetic field that totally enclosed the windings and raised the inductance. The simulated inductance values became five and a half times higher the originally calculated value. The magnetic field behaviour in the figure below shows no interaction in between the windings.

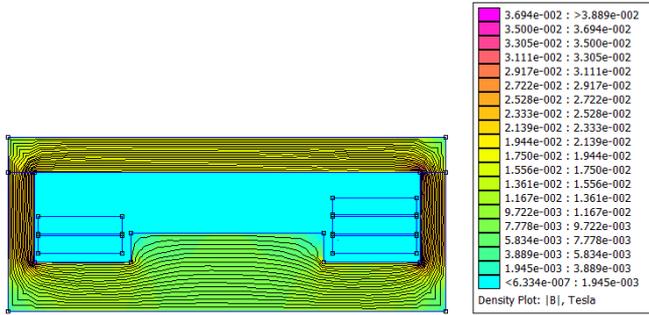


Figure 8.5. The resulting design to reach the desired value of the inductance.

The last simulation was made with air gaps over all the legs, the air gap at the end was calculated as half the air gap in the middle. The result became as you would expect the magnetic field to behave from the beginning. As shown in the figure below the magnetic field creates two fields, one around each winding of the inductor.

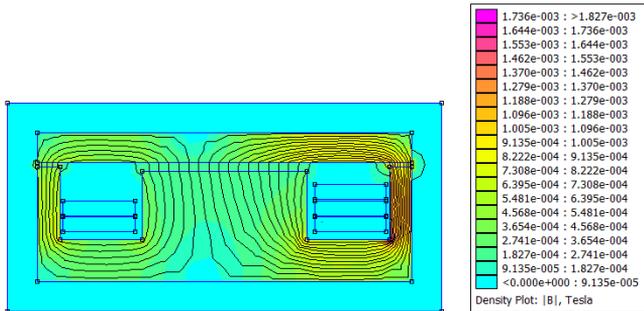


Figure 8.6. The final design with an air gap on all three legs in the core.

The simulated values of the inductance level became exactly as the measured values in reality, thus confirming the correctness of the simulation and reliability of the calculations of these problems.

The software simulated almost identical values of the inductance as well as the behaviour of the magnetic field. Since these results with the reference current proved to be accurate we continued to simulate with the currents

originally intended. The result is shown with figures in appendix. For the design with air gap overall the legs in the core, the inductance level is the desired value, the same result appears for the design with the very large air gap in the middle of the core.

8.3 Flyback transformer

The simulation with this model was entirely different from the others, since the current is dependent on time we had to apply the parameters for a transient analysis. This was only possible to do in QuickField since the requirement to apply a current with the specific waveform could be done in no other software. Since most of the software has by default a ideal sine wave as the current waveform they did not meet the requirement. The aim for this calculation was to see the proximity effect in the bias winding.

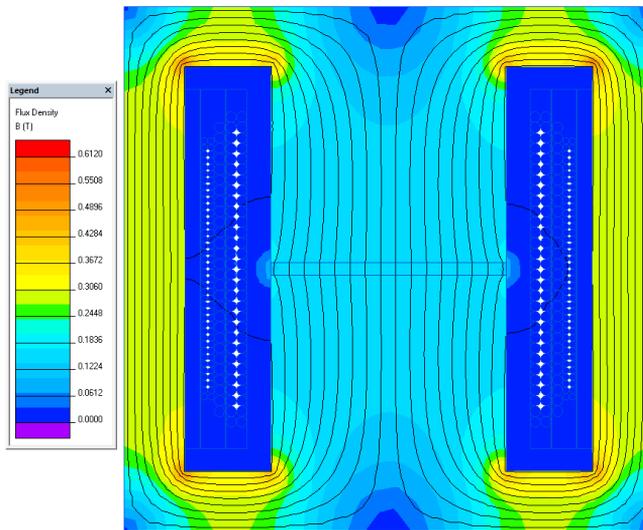


Figure 8.7. The magnetic field when the primary winding connects.

The main problem with this design was the input- and output-signal, the current never becomes zero during the whole period. This was solved by modelling the current waveform in QuickField and simulating a transient analysis. The calculations became very time consuming since the calculations are made by calculating the whole model for every step in time. Compared with the initial calculated power loss in the bias winding the

result from QuickField is a much better approximation of the power loss.

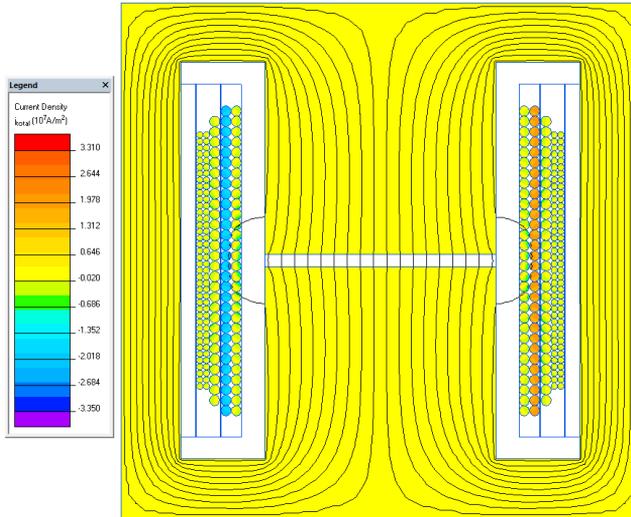


Figure 8.8. The current density when the primary winding connects.

8.4 Planar transformer

This simulation also differs from the other models. Since there will be a current in both the primary and secondary coils simultaneously we need to estimate the magnetizing current in the primary coil for the simulation with FEMM. For the simulation with QuickField it was possible to either apply a voltage level to the primary coil or apply the same magnetizing current as in FEMM.

The initial simulation of this model gave the results of an inductance level similar to the real values. When calculating the power losses the copper losses seemed to match the calculations done in the commissioners software. The core losses on the other hand became significantly smaller than the estimated, this is probably a because the input signal does not consists of a pure sinusoidal.

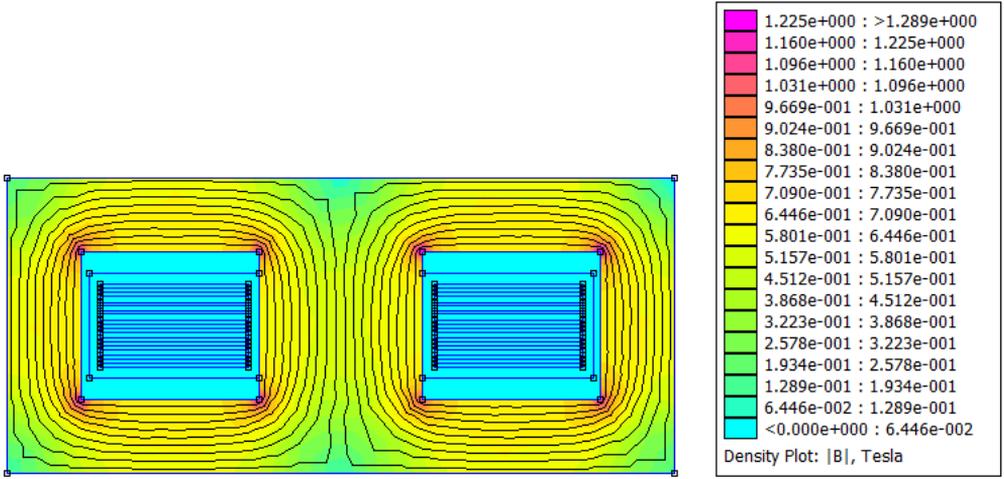


Figure 8.9. Planar transformer with magnetizing current on the primary side.

Chapter 9

Conclusion/Discussion

During this thesis work we have reached the intended goal of our work. By evaluating the software from the commissioner's point of view and simulating the test models provided by the commissioner some main features regarding the different software have emerged.

9.1 FEMM 4.2

This software is developed from a perspective of the electromagnetic problems. It is very straightforward when defining the problem and designing the geometry of the intended problem. The library is easily maintainable and any custom material added by the user is easy to use in related designs with another geometry. It can only execute models drawn in 2-D but the graphical interface in the post-processing mode is very easy for the user to understand. Overall the software is easy to work with, has a straightforward approach to define the problems and has a short training curve for a new user.

9.2 COMSOL Multiphysics 3.5

This software is developed from a multiphysical point of view. The strength lies in the ability to couple different problems to the same geometry. The user will be able to model the geometry in both 2-D and 3-D, though the 3-D simulation might be very memory-intensive since the calculations might be very complex. The material library is vast and it is easy for the user to customize a material not included in the library. Once done it is very easy to use the defined material for another design if wanted.

COMSOL Multiphysics can couple the problems with the modules of interest, for example the AC/DC module is able to provide data for the heat transfer module for calculating of the temperature. The graphically interface in the post processing mode is easy to understand, but the equations used for the integral solutions might need a re-calculation by the user to get the total power loss for example. Overall COMSOL Multiphysics 3.5 is a highly qualified work tool but will need a long period of training for the commissioner to be able to use all the included features efficiently. The COMSOL Group has developed a new version of this software, this version is easier to understand and more intuitive in the work area but will still need a lot more training to be able to execute the software efficiently.

9.3 QuickField 5.7

QuickField is the other software that are only capable of calculating models in 2-D, it is straight forward when defining the geometry. QuickField is capable of couple simple problems to each other, such as the calculating of the magnetic field behaviour and the thermal heating generated from the earlier result. It is easy to maintain the customized materials and its parameters but it can not be saved for future models. The graphically interface in the post processing mode gives the user a lot of information on the parameters calculated. The user will have a shorter training curve to learn the basics of the software and to be able to efficiently model different test cases.

9.4 Ansys [®]Ansoft Maxwell Student Version 9

Maxwell is similar to QuickField, the different features includes electro-magnetic model, heat transfer model but also a structural mechanics. It is possible to couple the problems to each other to calculate a heat transfer depending on the current density in the model. Maxwell has the possibility to design the geometry in both 2-D and 3-D. Though similar to COMSOL Multiphysics, the calculations might demand a lot of memory and time. The material maintainability is easy, but the custom defined material will only be saved locally. In other words, for another problem the custom fer-rite must be defined again for a new problem. The post processing mode is slightly more complicated to produce the data of interest for the user. Altogether Maxwell is qualified from the commissioners point of view, but will probably need a significant longer training period compared to QuickField and FEMM. To design the geometry in 3-D, to do heat transfer analysis

and to do the transient analysis the full version of Maxwell is needed.

For the results in the post processing mode there is a very brief guide available, also to view the results the user need to write a short code to extract the correct values from the calculations.

9.5 Discussion

Comparing the software from the commissioners point of view gives the impression that all four software evaluated is capable of at least calculating the power losses in the models provided for the thesis. FEMM is the only software not able to couple the different problems. All the software calculates the test designs in a similar way, by studying the results graphically, all the software confirm each other's result.

For the commissioner the recommendation will be either to use FEMM, specific for the type of problems solved in this thesis it is highly qualified, its main drawback is the lack of ability to couple the problems and only 2-D geometry. The other software to be recommended is QuickField, the drawback with this software is similar to FEMM, it can only model the geometry in 2-D, but it is possible to couple the problems from AC/DC-problem solving with heat transfer to get the temperature rise in the material. The main conclusion is that QuickField cover a wider range of the commissioners needs. As mentioned above both Ansys ®Ansoft Maxwell and COMSOL Multiphysics are highly qualified for these kind of simulations, both are able to couple the problems with different modules and both can model the geometry in 3-D but the long training curve does not meet the commissioners requirement.

The results for the simulations on the test models the commissioner provided has been quite satisfying.

9.5.1 Commutation choke coil

When calculating this model the current density became very high around the air gap. There are a number of theory's to elaborate on this model. The shape of the windings might be modified in the cross-section. The shape of the windings can be optimized by a program developed for MATLAB, this program determines the radius for a semi-circular cut out for the winding around the air gap. [10] The commissioner has tried a variation of this way to design the windings in this model, but the result was not good enough.

9.5.2 Asymmetrical power inductor

This model was the least complicated design to model in the different software. All the software calculations confirms each others results. This model was the only one to be completed, there is no more optimization to be done and the commissioner is very satisfied with the result.

9.5.3 Flyback transformer

This model became the most complicated in execution for all of the models. The equations for the signal input in the transient analysis and the time needed for the calculation. For one solving period the time consumed extended six hours on a highly capable computer with more than one core in the processor. The preference from the commissioner were to see if the power loss in the bias winding was possible to calculate. The results seems to be satisfying and QuickField are able to get a result concerning the copper losses in the bias winding.

9.5.4 Planar transformer

These calculations are not optimized since there is a lack of time for the thesis work. The results calculated for the inductance level and the copper losses seem to give a fairly accurate result there were no time to execute the transient analysis needed to get an accurate value of the core loss.

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Appendix A

A.1 Commutation choke coil

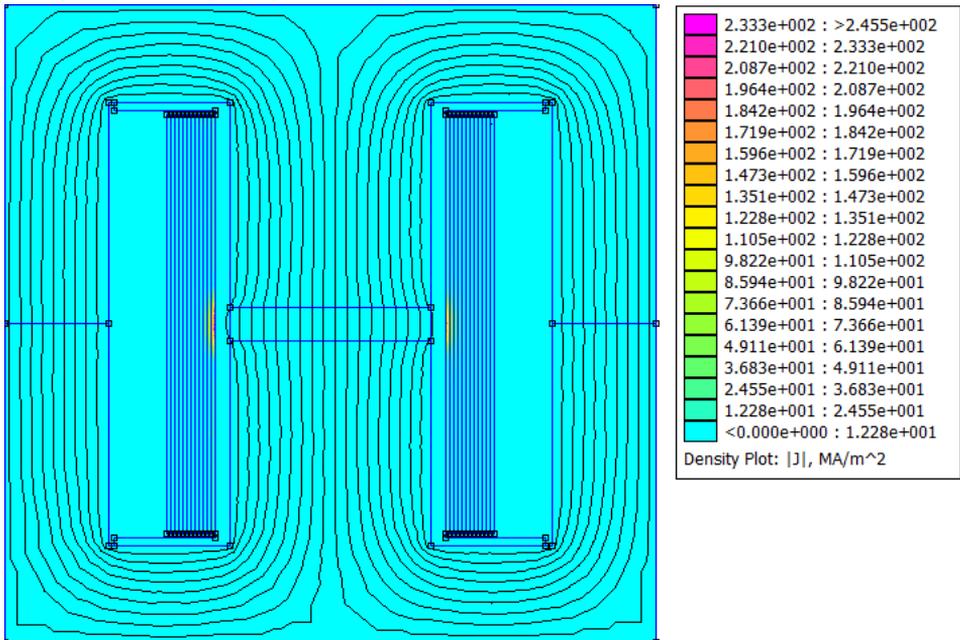


Figure A.1. The commutation choke coil graphically displayed in FEMM

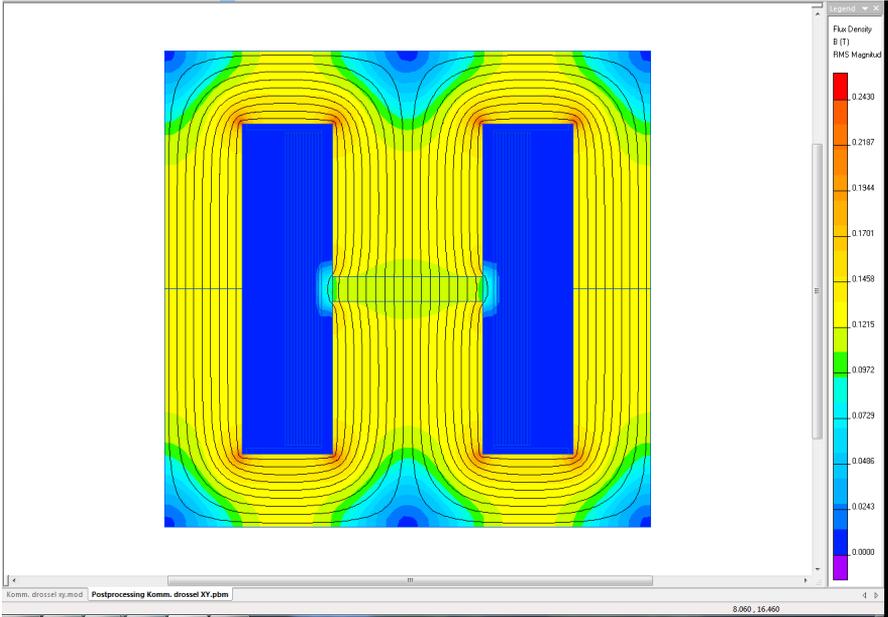


Figure A.2. The commutation choke coil graphically displayed in QuickField

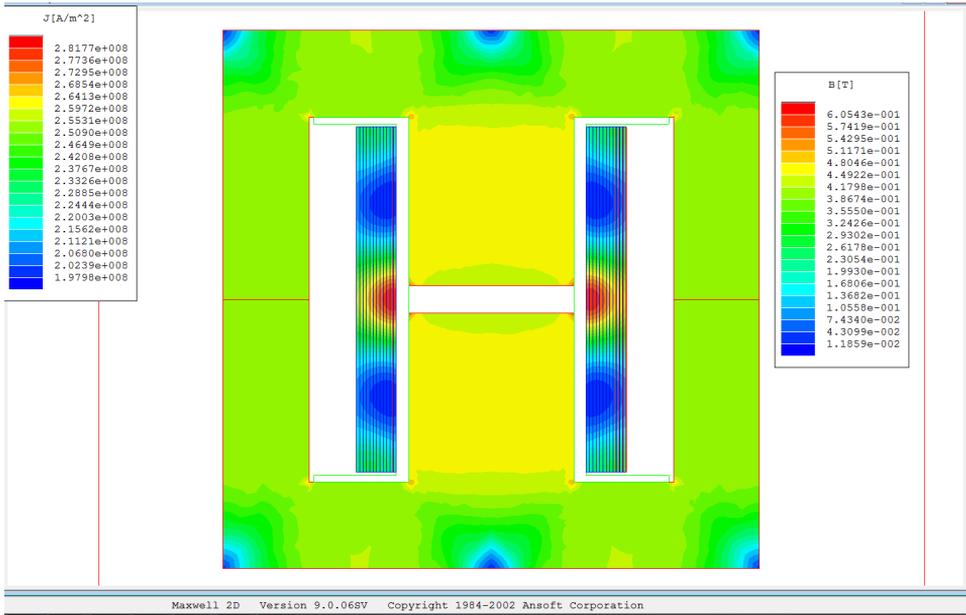


Figure A.3. The commutation choke coil graphically displayed in Maxwell

A.2 Asymmetrical Power Inductor

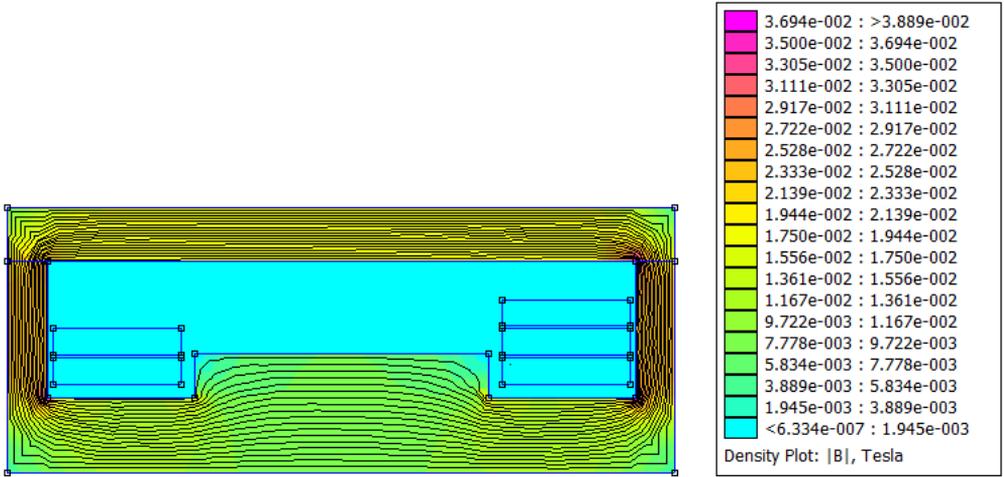


Figure A.4. Power inductor with air gap over all legs in the core. Displayed in FEMM

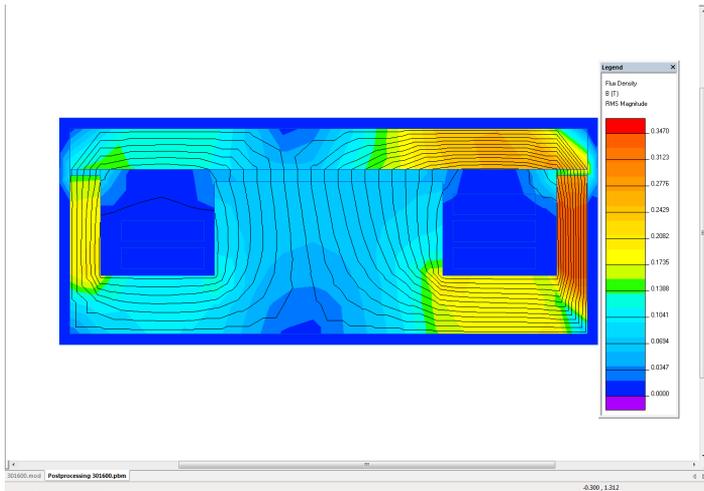


Figure A.5. Power inductor with air gap over all legs in the core. Displayed in QuickField.

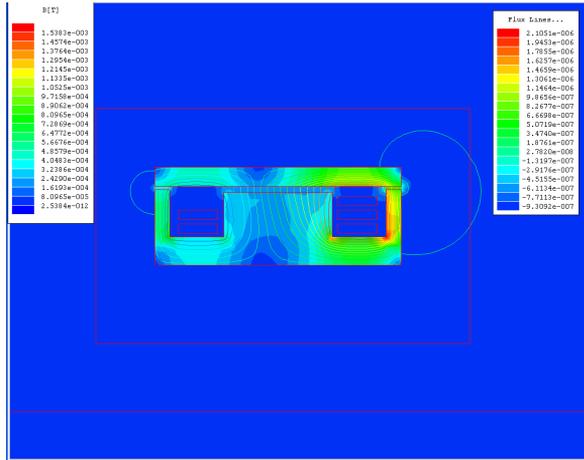


Figure A.6. Power inductor with air gap over all legs in the core. Displayed in Maxwell.

A.3 Flyback transformer

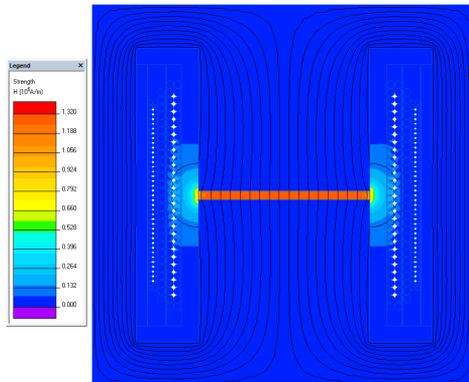


Figure A.7. Flyback transformer, magnetic field intensity plot in the secondary winding. Displayed in QuickField.

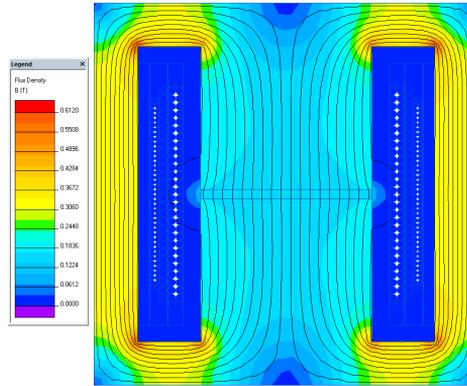


Figure A.8. Flyback transformer, magnetic field density plot in the secondary winding. Displayed in QuickField.

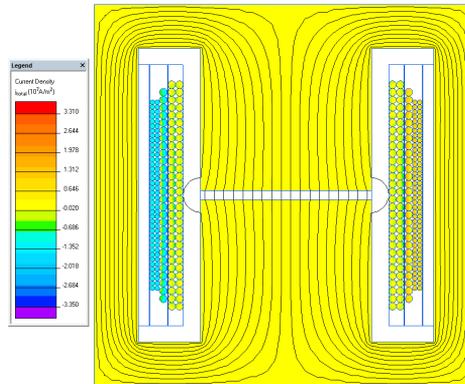


Figure A.9. Flyback transformer, current density plot in the secondary winding. Displayed in QuickField.

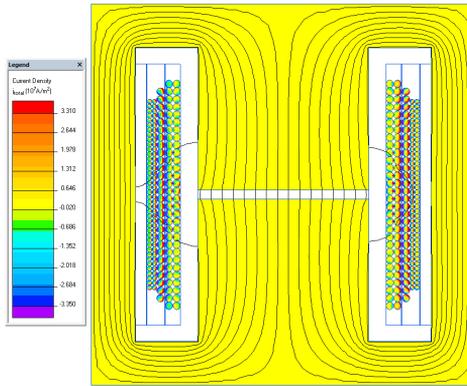


Figure A.10. Flyback transformer, current density plot in secondary winding when the current switches between the primary and secondary winding. Displayed in QuickField.

A.3.1 Power loss graphs in the windings

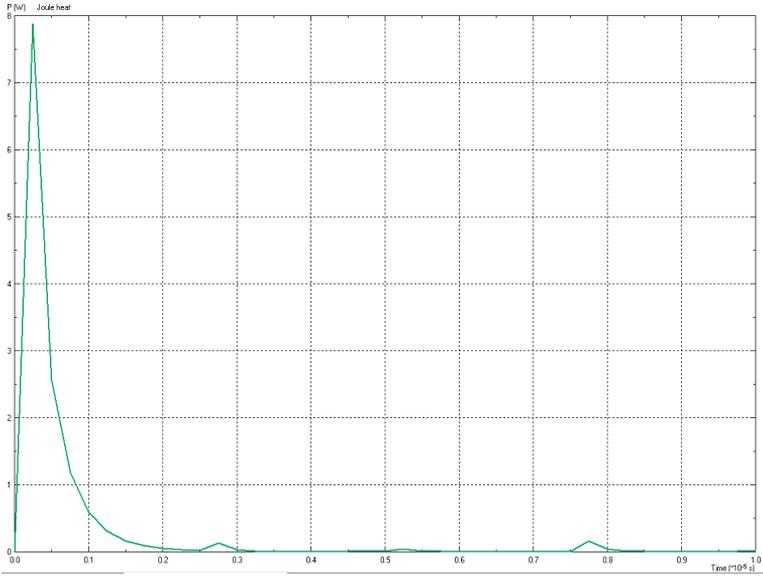


Figure A.11. Power loss in the bias winding. Displayed in QuickField.

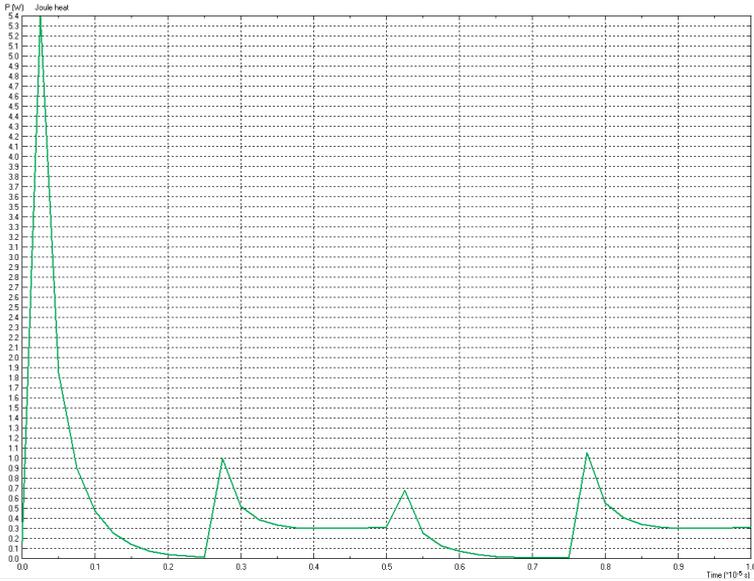


Figure A.12. Power loss in the primary winding. Displayed in QuickField.

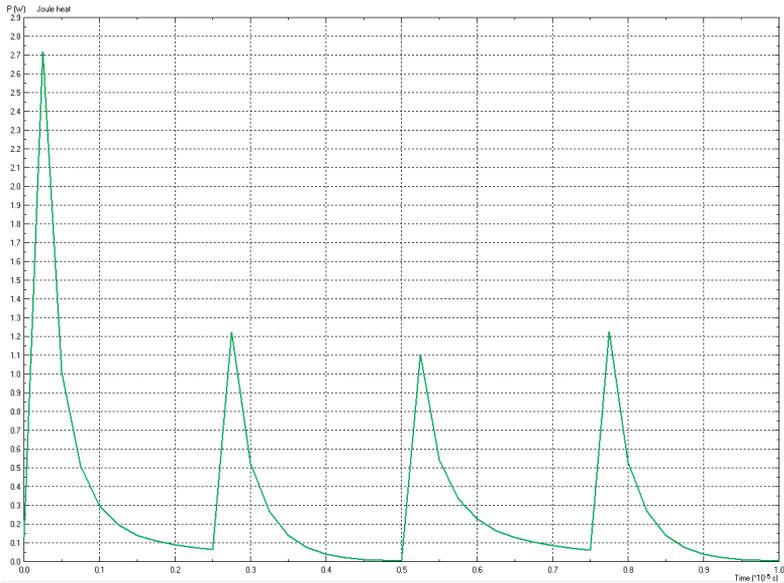


Figure A.13. Power loss in the first secondary winding. Displayed in QuickField.

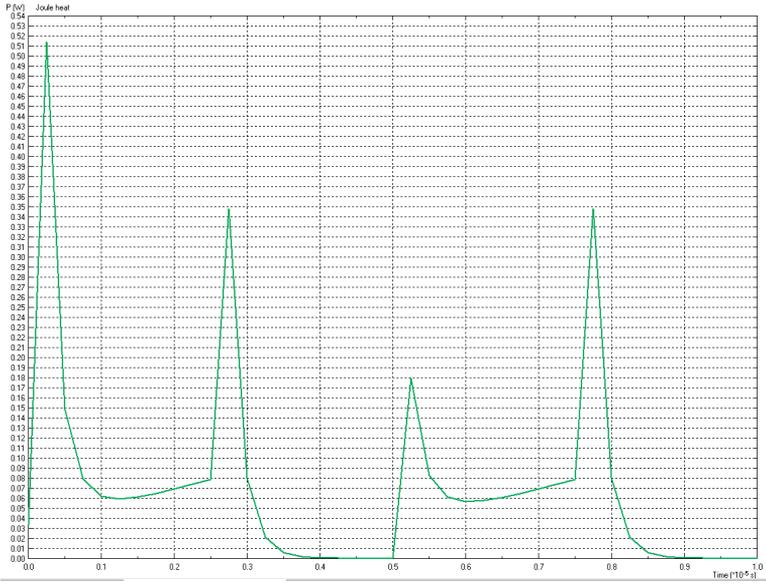


Figure A.14. Power loss in the second secondary winding. Displayed in QuickField.

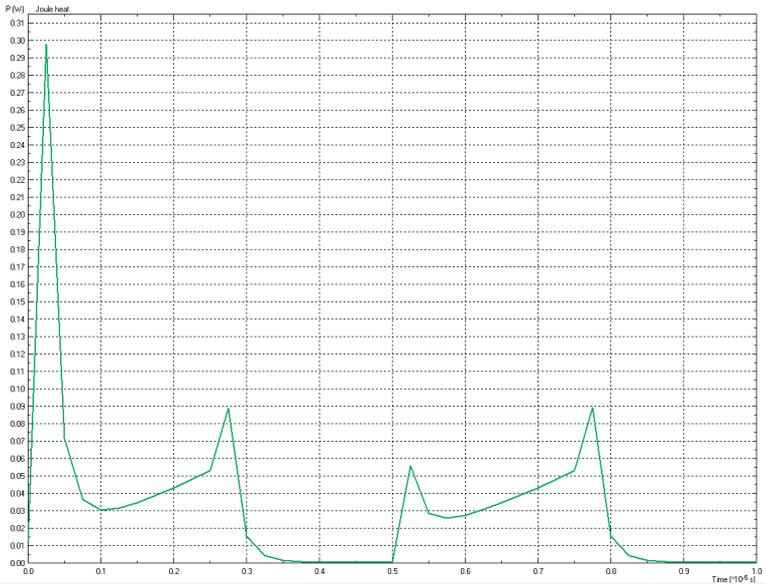


Figure A.15. Power loss in the third secondary winding. Displayed in QuickField.

A.4 Planar Transformer

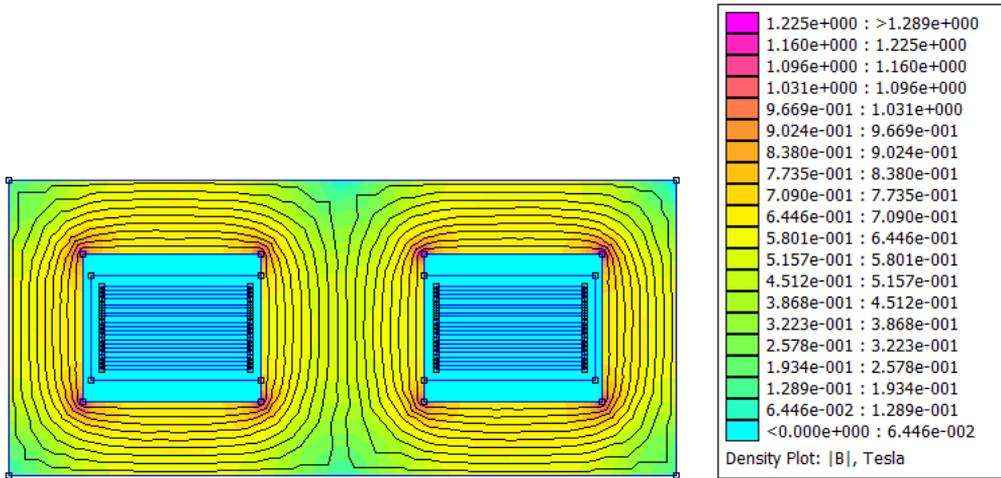


Figure A.16. Planar transformer. Displayed in FEMM

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