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Loss Analysis in Laminated Iron Cores using COMSOL Multiphysics and LiveLink for Matlab

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Abstract—A framework for loss analysis using COMSOL and LiveLink for Matlab is presented in this thesis. The loss analysis is based on Steinmetz' theory on iron core losses [1]. IEC standard 60404-8-4:2013 gives a method of presenting loss data for laminated cores in W/kg, when a sinusoidal flux density is assumed. The variables in the standard is the frequency and the peak of the flux density. These data form the basis for the loss analysis when the iron core is used in an application, such as an electrical machine. The data are used to create functions with the same variables as the standard contains, such as the Bertotti equation [2].

The method for loss analysis is based on code written by Havez et al. [3]. The method uses a simulated model in COMSOL and fetches the data from the iron core of the model. The simulation needs to include a sweep through the time domain to get the sufficient field distributions. These data are post processed in Matlab. Using the FEM elements, the frequency and the peak of the flux density is calculated for each individual element, so the loss distribution can be found together with the total losses.

It is recommended to use the average of the flux density in every corner of the element instead of the `mphinterp` function to find the typical flux density of the element. The `mphinterp` function is proven to be slow and having issues with rotating machinery. The peak of the flux density for an element is the maximum of the typical value over a time sweep, when the DC offset is removed.

The frequency is calculated by using the Fast Fourier Transform. It is presented a method that omits the problem with the FFT function being dependent on how much of a signal is included in the function. The method is to carry out multiple FFT analyses on different lengths of the flux density signal and to use the median of the last part of the frequencies calculated. The method is consistent if at least four periods of the length of the flux density vector signal is included in the analysis.

If the time used on the loss analysis should be limited, the effort should be put on the COMSOL simulation, rather than reducing the post processing time. This is because the post processing duration is significantly shorter than the simulation duration in COMSOL. The loss analysis must be carried out on at least 6/14th of a rotation to avoid large deviations above +/- 11% from the loss result from a full rotation.

A method for extraction of the relative permeability from a BH curve is presented. The method is based on linear regression and use the slope of the BH curve to calculate the relative permeability. A loss analysis based on a model where relative permeability is used is carried out. This analysis shows that the entirety of the BH curve must be included in the linear regression, if the results should be close to the results obtained using the BH

curve.

Keywords—Iron core losses, Steinmetz, Bertotti, FEM modelling, COMSOL Multiphysics, Matlab, LiveLink, FFT.

I. INTRODUCTION

With the recent development within computational power, Finite Element Method (FEM) software have become a useful tool for designers of electromagnetic equipment. Within electrical machine design, it is possible to achieve high accuracy on losses in copper/winding elements of the machine. For electromagnetic losses, or iron core losses, it has on the other hand been challenging to get good results [4]. Iron losses originates from hysteresis and eddy currents in iron cores. The iron cores are used in electromagnetic equipment to lower the reluctance in a magnetic circuit.

Before FEM modelling, magnetic circuit models, such as the one used in [5], were used to calculate the losses in iron cores. The advantage of a magnetic circuit loss model is that they are simple parametric fast lumped models, which makes it suitable for optimization routines. The drawback is that it is not accurate enough for precise calculations, as it does not consider harmonics, rotating fields or saturation. Nor the loss distribution is found by using the magnetic circuit method. FEM modelling, on the other hand, gives us the opportunity to get more accurate results. The eddy currents can for example be calculated in the iron cores. A challenge with this is that the iron core is laminated with thin sheets of steel. It is not practical to model every single steel sheet, because of the meshing of the FEM modelling. The mesh will need to be very dense, and lead to a long simulation duration [6]. This makes it demanding to use conductivity and current density to calculate losses. The prevailing method is to use the work of Steinmetz to calculate losses. This is an empiric model, where the flux density is assumed to be sinusoidal. The variables are the peak and the frequency of the flux density. With the use of this method, the iron core can be modelled as a solid with low conductivity in the FEM program. The mesh will thereby be more manageable with regards to simulation time and the simulation duration kept low.

The FEM tool does not only give us the method of calculating losses globally, but also the loss distribution. That means where in the machine the losses originate from. Some

of the areas in a machine can for example be heavily loaded magnetically, while other areas are less loaded.

The challenge lies in how to model the iron cores in the FEM software and the post processing of the field distributions to do the loss analysis. The FEM program used in this thesis is COMSOL Multiphysics. This program can solve the Maxwell equations and calculate a field distribution for different time steps in an electrical machine. The loss analysis can not be done directly in COMSOL, because COMSOL does not have the resources to do this. COMSOL can do a frequency analysis and find the maximum of a signal, but not element-wise and use these two together with an external function to calculate losses. The post processing is rather done in Matlab, and the field distribution is exported to Matlab from COMSOL via LiveLink. This way, the peak and the frequency of the flux density can be found in every element in the iron core.

The objectives for this thesis is to create a platform for loss analysis. The first goal is to achieve an overview of how the loss data for laminated cores is given, and how it can be used in a loss analysis. Another goal of this thesis is to create a method to find the typical flux density for each element. Another important intermediate objective is to investigate how the frequency for each element can be determined. The last goal is to investigate the modelling of the ferromagnetic material in FEM modelling, so the field distribution is correct.

II. THEORY

A. Field theory

To make use of the Steinmetz method, the flux density and the frequency of the flux density in the iron core must be calculated. The FEM programs gives us the opportunity to know the field distribution, since the field can be calculated everywhere in the analyzed model.

The origin of magnetic losses is the change in the \mathbf{B} -field, and will be explained in detail under the subsection *Losses*. The \mathbf{B} -field originates from the \mathbf{H} -field or from self-magnetization through equation 1.

$$\mathbf{B} = \mu_0 \mu_r (\mathbf{H} + \mathbf{M}) \quad (1)$$

Equation 1 is a linearization of the relation between the \mathbf{H} - and \mathbf{B} - field. μ_r will be large for small \mathbf{H} , but small for large \mathbf{H} in a ferromagnetic material. This is because of the saturation effect, which makes the modelling more complex. The relationship between \mathbf{H} and \mathbf{B} can also be modelled as a curve, which make it possible to include the saturation effect.

Another way of modelling the relationship between \mathbf{H} and \mathbf{B} is to use a hysteresis model. One of these models is the Jiles-Atherton model [7].

B. Field phenomenons

In a ferromagnetic material the field is rarely purely sinusoidal and non-rotational. In transformers the field can be close to pulsating, and with few harmonics. In electrical machines however, the field can be both rotating and contain lower or higher harmonics. In ferromagnetic solids the field will also experience skin effect because of eddy currents.

C. Losses

Substantial work has been done with measurements of iron core losses, as described by Krings in [8]. Steinmetz came up with a mathematical way of determining the iron core losses. Since then, his equation has been modified many times over, to include different effects.

Steinmetz [1] came up with a theory that considers the losses per cubic metre $\frac{W}{m^3}$ or per kg $\frac{W}{kg}$ of a laminated material. The equations come in the form

$$\overline{P}_v = k \cdot f^\alpha \cdot \hat{B}^\beta \quad [W/m^3] \quad (2)$$

or like Bertotti [2]

$$\overline{P}_v = k_h f \hat{B}^2 + k_c f^2 \hat{B}^2 + k_e f^{1.5} \hat{B}^{1.5} \quad [W/m^3] \quad (3)$$

Where $k, \alpha, \beta, k_h, k_c$ and k_e are material coefficients. The engineering approach is to use experimental data to find the coefficients used in the equations. The details of how the experimental data is gathered is presented in chapter III.

III. LOSS DATA FOR LAMINATED CORES

A. Loss data origin

As described earlier, the engineering approach to loss analysis is to make use of experimental data. The data is given as watt per kilogram or cubic metre for a given frequency and flux density. A data sheet with this property for a laminated steel called M300-35A is found in appendix B. The data is produced by the IEC 60404-8-4:2013 international standard. According to IEC, the explanation of the name is:

- M stands for magnetic material
- 300 is 100 x the maximum specific power loss at 50 Hz and 1.5 T
- 35 stands for 100 x the nominal sheet thickness in mm
- A is the characteristic letter, stating that this is a "cold-rolled, non-oriented electrical sheet, given in its fully processed state".

Manufacturers stick to this standard of name giving and the described method of doing magnetic measurements as described in the international standard IEC 60404-2 "Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of an Epstein frame". The Epstein frame is a way to model the condition the material will be exposed to under operating conditions in for example an electrical machine. The flux will flow parallel with the direction of sheets. Because all materials have the same data basis, the loss analysis should be easier to rely on. This is however, not always the case. The method has weaknesses:

B. Weaknesses

1) *Rotational fields*: The flux flows parallel to the rolling direction of the electrical sheets. As stated, this is close to the operating conditions of a real-life application. One of the weaknesses of the method is that it doesn't include the effect of a rotational field. The field in an Epstein frame will be strictly pulsating and thereby not including this effect.

2) *Harmonics*: The IEC standard states that the test will be conducted with a variable frequency voltage source, which will feed the exciting coils with a sinusoidal current. The flux density will thereby be purely sinusoidal, as long as the material doesn't get saturated. In a real-life application, the field will have over- or under-harmonics, which will distort the field. The data is not given for DC-biased flux density signals either. In a rotor of an electrical machine, the field will surely have a large DC-component.

3) *Physical phenomenons*: The data basis will not differ between hysteresis, eddy currents or excess losses. It will only give the data for the sum of the losses. This is a simplification and not a description of what is actually happening inside the material. The theory of magnetic domains and domain movement which leads to eddy currents and hysteresis is still too hard to model and is not included for the loss analysis.

C. Utilization of the data

Different approaches can be used to make use of the data provided. One method is to do a table look up when the frequency and the peak flux density is provided. The data can be interpolated for frequencies and flux density within the given data points or extrapolated for values outside the data range. Another way is to determine the parameters of the Bertotti equation through curve fitting of the values of the data provided. The peak of the flux density and the frequency is then used as variables in the equation, and the results will be the loss density. The curve fitting procedure can be done using the least square method. The frequency and the peak of the flux density can be found by using a FEM program. This is described in detail in chapter IV.

D. BH-curve

An important feature of a ferromagnetic material is the description of the relation between the flux density and the magnetic field. The BH curve is an accurate description of this relation. The curve will refer a value of the H-field to a value of the B-field. Values between the data points are interpolated for. IEC standard 60404-4:1995 describes a method for determination of BH-curves. Most manufacturers of ferromagnetic steel for use in electromagnetic applications supplies the BH curve of the material. The curve can be directly used in a FEM program, such as COMSOL Multiphysics, and will be helpful to determine an accurate field. The simulations will usually go faster with the linear relative permeability relation, than with the nonlinear BH curve. In some instances, the smarter choice can be the relative permeability relation.

E. Relative permeability

The second way of describing the relationship between the B- and H-field, is to use the linear relative permeability, by equation 1. This is an inaccurate description, especially for strong fields, where the material will experience saturation. In some instances, the relative permeability can be useful. This can be for models where the flux density doesn't make a significant difference for the rest of the system. To extract

the relative permeability from the BH curve, the slope of the BH curve in the linear region needs to be found. The highest values of the BH curve must therefore be removed for this operation, as they are not in the linear area of the curve. Linear regression is an appropriate tool to find the slope of the curve. The result of the linear regression will be a function on the form as equation 4. If the material is expected to be saturated, the non-linear part of the BH curve should also be included.

$$y = ax + b \quad (4)$$

In equation(4), a is the slope of the curve. From equation 1 there can be seen that $a = \mu_r \cdot \mu_0$, so that $\mu_r = a/\mu_0$. An example of this procedure can be found in appendix B.

IV. METHOD

A. Main structure of loss calculations

As described, to calculate losses with Steinmetz' formulas, the peak value and the frequency of the **B**-field is needed to find the loss density. On a macroscopic scale, the loss density could be multiplied with the volume to get the total iron losses. However, both the frequency and the peak of the **B**-field could vary through the iron core. One could argue that the average frequency and average peak flux density could be used to get the macroscopic losses, but the distribution of the losses would not be included this way.

In this work a FEM program is used to divide the entire model into small elements, in which the losses can be determined element-wise. The total losses are found by summarizing the losses for each element in the model. Figure 1 show the main structure of this procedure. The loss analysis is based on the method presented by Havez et al. [3].

The first step in the loss calculation process is to determine the field distribution in the given problem, see part a) of figure 1. It is necessary to do a sweep in the time domain (multiple time steps) to investigate the time dependency of the magnetic flux density. It is not sufficient with one single field distribution to calculate the losses in a model, especially for electrical machine analysis. This is because the different parts of the machine will experience the peak of the **B**-field at different times. See figure 8 to see how the field wave moves through the stator, making the peak of the flux density move through the machine. The sweep can be done using the "time domain study" in COMSOL, but this is not recommended. According to Fossen [9], "parametric sweeps" in COMSOL can easily be parallelized, and the speedup of these using processors with multiple cores is excellent. Time domain studies does not have the opportunity to be run in parallel, so the parametric sweep using the stationary study is the preferred method, because the simulation time will be lower. Subsequently the losses in the model can be calculated. For an electrical machine, the simulation time must go over a period so every element in the model will experience the peak of the **B**-field. This will increase the simulation time considerably. If a 3D model is used, the accuracy could increase, but most of the time it would not justify the increase in simulation time. Therefore, 2D is the most common solution.

COMSOL will solve the equations for the user, but the user must decide which relationship between the \mathbf{B} - and \mathbf{H} -field should be used. This is a setting in COMSOL, as follows:

1) *Relative permeability* - μ_r : This setting will give a short simulation time but won't include the effect of saturation. This means that some areas that in a real application would get saturated, will in the simulation have a large peak of the \mathbf{B} -field. This will lead to an overestimation in the losses. A detailed description on how to extrapolate the relative permeability from a BH-curve and an example of this is given in appendix B.

2) *BH-curve*: This setting in COMSOL will give a larger simulation time than when using the linear relative permeability, because of the non-linear relationship between \mathbf{B} and \mathbf{H} . This setting will however include the saturation effect, so the field will be more realistic. The BH-curve is given for a concrete material, and subsequently plotted directly in COMSOL. This setting can use a parametric sweep under stationary conditions. This will decrease the simulation time, since this is easily parallelized, and time domain simulations is not. More information on how the *BH*-curve is obtained is found in chapter III.

3) *Jiles-Atherton model of hysteresis*: The most advanced way of modelling the relation between the \mathbf{B} - and \mathbf{H} -field, is to use the Jiles-Atherton model. This model can only be used in time-domain simulations, so the simulations cannot be parallelized. This is therefore the option that demands the largest computational power and gives the longest simulations. On the positive side, this option will include the saturation effect, as well as the hysteretic behaviour of the magnetic material. This will lead to a phase shift between the \mathbf{B} - and \mathbf{H} -field, which could affect the peak value of the fields.

B. Data transfer - use of LiveLink

Figure 1 step b) is the data transfer to from COMSOL to Matlab using LiveLink. The user must open LiveLink, which makes Matlab able to access the COMSOL model. All values for the \mathbf{B} -field in every point, for every solution step for the given domain of the COMSOL model is transferred as a matrix to Matlab. The columns are the points, and the rows are the solution steps. The use of LiveLink and Matlab is explained in detail in Appendix I.

C. Flux density vector and coordinates

The loss analysis needs the flux density for every element for every time step. The method is to first get all the values for the length of the \mathbf{B} -vector, for every point in the COMSOL model. This is step c) in figure 1. The coordinates to every point is also found here. The coordinates is used to calculate the area of each element and to find the COG of the element.

D. Defining element and typical \mathbf{B} -vector

Part d) is to define every element from the discrete points and to find the typical \mathbf{B} -vector in the element. The way each element is defined is explained in appendix I. The typical \mathbf{B} -vector of an element can be calculated in two different ways, illustrated in figure 2, and described below. A comparison between the two methods are discussed in chapter V.

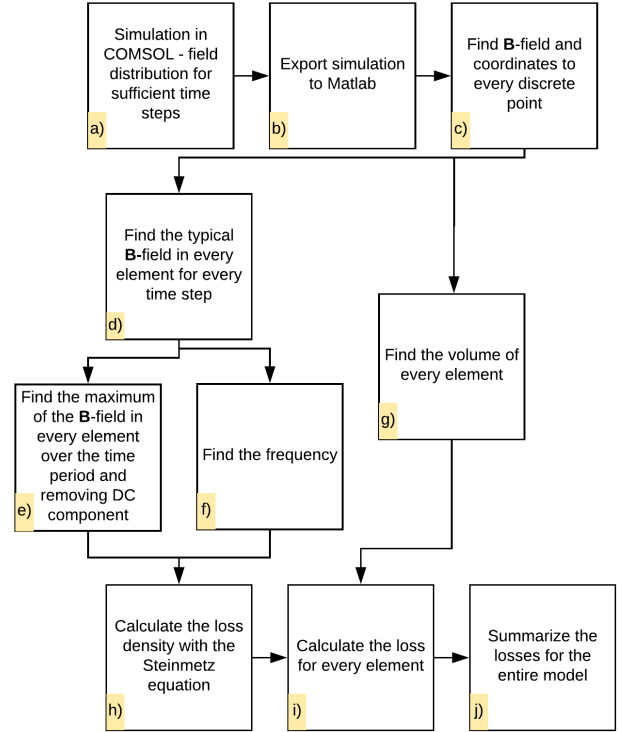


Fig. 1. Flow chart of the loss analysis

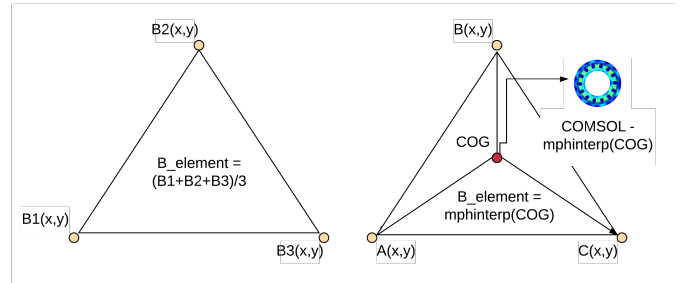


Fig. 2. Figures displaying how the \mathbf{B} -field can be calculated in two different ways. The figure to the left describes how to do it by using the average of the edge points. The figure to the right illustrates how *mphinterp* uses the center of gravity. *Mphinterp* uses COG to look up the \mathbf{B} -field in that point in the model

1) *Using mphinterp*: The *mphinterp* function is a LiveLink function that evaluates a parameter, for example the length of the \mathbf{B} -vector, in specific coordinates. This function must access the COMSOL model for every element and every solution step, which is time consuming because the model could have thousands of elements and numerous solution steps. The coordinates are the center of gravity (COG) for the element, and is found from the points that define the element. This function is slow, and will increase the duration of the loss

analysis. Parallel computing can not be applied when using this function, because of the LiveLink application, which access a server linked to the COMSOL model. The server does not have the opportunity to access COMSOL in parallel.

2) *Using the average of the flux density in the corners of the element:* The other way of finding the typical length of the \mathbf{B} -vector, is to take the average of the length of the \mathbf{B} -vector in the points that defines the element. This is a much faster method and decreases the simulation time drastically, since it doesn't access the COMSOL model for every element analyzed. Parallel computing can also be utilized when calculating the length of the \mathbf{B} -vector, which makes the analysis run faster.

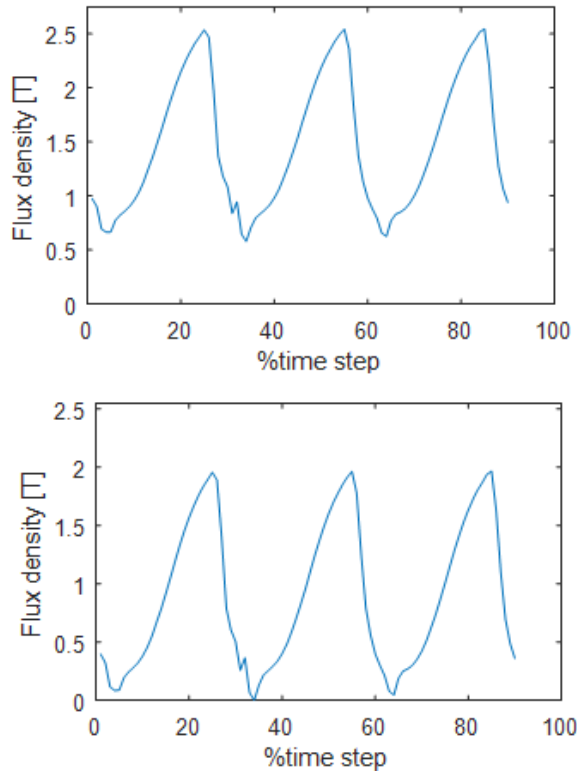


Fig. 3. Figure displaying the workflow on how the DC offset is removed. The top figure is before the offset is removed, and the offset is removed in the bottom figure. The figure is taken from an element in the stator.

E. Finding maximum of typical \mathbf{B} -field

Figure 1 part e) is to find the length of the \mathbf{B} -vector. The vector length can be assumed sinusoidal in the stator in an electrical machine, because of the sinusoidal armature current. In the rotor, the field could be assumed DC, but because of the motor geometry and reluctance changes, the field will be DC with an AC component. The AC component is the source to iron core losses, so the DC component must be removed before the maximum is found. Since we are working with the length of the \mathbf{B} -vector, the minimum of the length of the \mathbf{B} -vector

will be the DC component. This is because the length will never be negative, so withdrawing the average, which would be correct if this was a sinusoidal function, will withdraw too much. This procedure is illustrated in figure 3. The peak of the flux density will then be the maximum of the signal.

F. Volume

Figure 1 part g) is to find the volume for every element. If 3D is used, the element's volume can be found directly. If 2D is used, the volume of the element will be the area, which is found directly, multiplied by the length of the model into the plane.

G. Frequency

Figure 1 part f) is to find the frequency of the flux density for every element. For an electric machine, the frequency of the \mathbf{B} -field is the same as the electric frequency and can therefore be estimated with this. Another method for frequency extraction is found in chapter IV-I.

H. Losses

Then the loss density can be found for every element in part h) with the Steinmetz equation, and the loss for every element is the loss density multiplied with the volume of the element in step i). The final step is to summarize the losses over the model in part j).

I. Frequency extraction

The method above simplifies the frequency of the \mathbf{B} -field, by assuming that it is the electric frequency. For the stator, this is quite accurate. For the rotor however, this will be an overestimation because of the geometrical properties of the machine. As described above, the length of the \mathbf{B} -vector will be DC with an AC component. This happens because of reluctance changes and armature reaction and will lead to a lower frequency than the electrical frequency. To deal with this phenomenon, the frequency must be extracted in a different way. One way of doing this, is with the fast Fourier transform (FFT). To be able to perform an FFT analysis of the field, the field must revolve around zero. One way of fixing this, is to withdraw the mean of the signal. This procedure is illustrated in figure 4. Since the method utilizes the *length* of the flux density vector, the signal is rectified, so the frequency obtained from the FFT analysis will be double of what it physically is. After conducting the FFT analysis, the frequency spectrum is found, and the frequency containing the highest amplitude is divided by two. The FFT is a quick way of determining the frequency of the signal, but as shown in the next paragraph, it has some weaknesses.

J. Sensitivity in FFT analysis

When performing an FFT analysis, the input argument is the signal. The signal can go over many periods and can be affected by how many periods it contains, as well as how much of a period it contains. This is explored in chapter V.

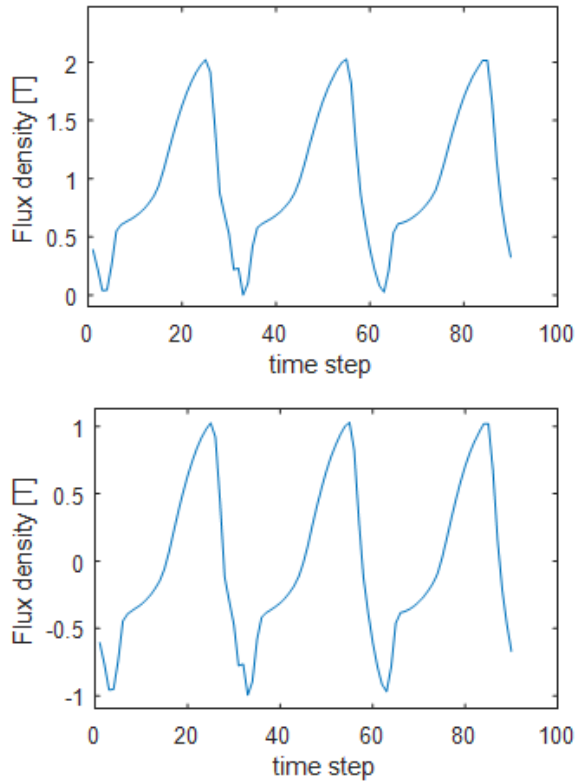


Fig. 4. Figure displaying the workflow on how the signal is adjusted to revolve around zero. The top figure is before the mean value is removed, and the mean is removed in the bottom figure. The figure is taken from one element in the stator, the same element as in figure 3.

To examine this, the machine investigated is simulated for half of a rotation, including many periods of the flux density in the stator. If many periods is included, the hypothesis is that the FFT analysis will converge around a value that is the frequency. The method is as follows. The signal containing all values for the flux density is divided into many small signals. Signal one contains one percent of the flux density signal, signal two contains two percent, and so on. The FFT analysis is performed on each signal, and the frequency containing the largest amplitude is saved for each signal in a new frequency data set. Then the first half of the new data set, containing all the frequencies, is removed, because the first part is usually too distorted, and does not yet converge towards any value. Then the median of the last half of the data set containing the frequencies is found, which will be the calculated frequency for that element. This procedure is illustrated and carried out in chapter V. The code lines for this procedure in Matlab is found in appendix F.

K. Minimizing simulation time

For large machines the simulation time can grow large. A normal way of limiting the time of simulation is to utilize the symmetry of the machine, and only do the analysis on that smaller part of the machine. The number of symmetrical

sectors in a machine can vary, but for some machines, there will be no symmetry, or only two symmetrical parts. For the loss analysis however, the machine could be divided into parts that doesn't necessarily need to be symmetrical. This will be correct if the losses are evenly distributed over the machine, which they not always are. Using this assumption, the machine can be analyzed for a full rotation, or only one electric period, and this can be extrapolated to count for the entire machine. This will especially be useful for the stator, as the stator will need a dense mesh and many elements to be modelled accurately, as the field changes rapidly over small areas in the machine here. This is explored and tested in the result chapter.

V. RESULTS

A. Test subject - the 105 MVA hydro generator

TABLE I. BASE CASE - LOSSES FOR A FULL ROTATION, 60 TIME STEPS PER ELECTRICAL PERIOD

	Total losses using FFT [kW]	Total losses assuming 50 Hz [kW]
1/14th of stator	18.56	17.37
13/14th of stator	265.32	262.71
Rotor	29.74	96.52
Stator + Rotor	313.62	376.60

To test the method presented in chapter IV, a 105 MVA hydro generator is analyzed. The basic data of the machine can be found in table VII and VIII in appendix A, and is taken from a former master thesis by Pascal [10]. The geometry is presented in figure 5. The machine is loaded at rated conditions in the simulations presented in this thesis. The power factor is 0.9, and the load angle is 27.4° . Figure 7 shows different ways of displaying the flux density in the machine. Figure 8 shows the flux density moving through the stator, at different time steps.

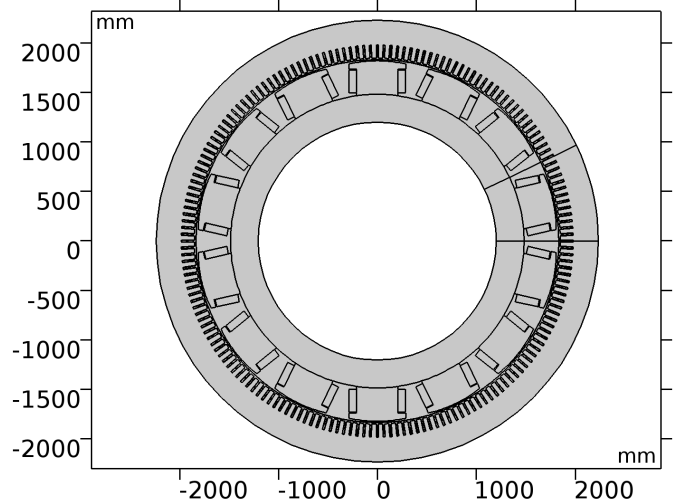


Fig. 5. Geometry of the 105 MVA generator

The 105 MVA generator is simulated for one full rotation, with 60 time steps for every electric period. This simulation

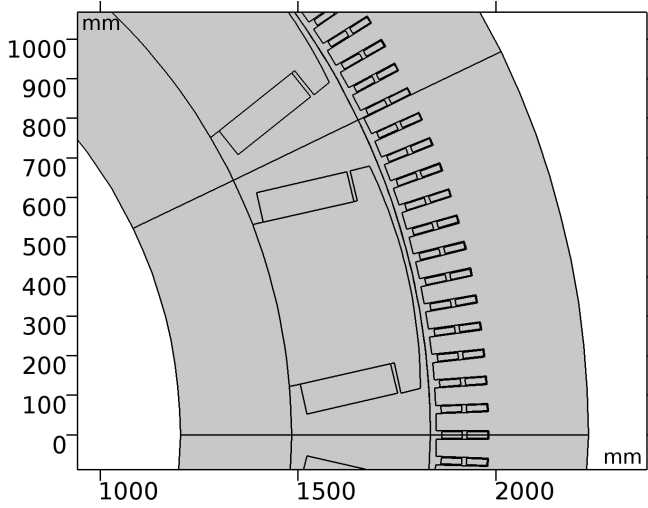


Fig. 6. Geometry of a 1/14th sector of the machine

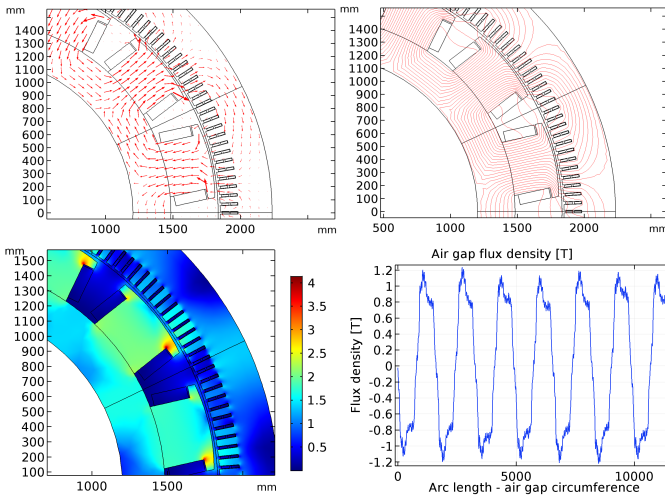


Fig. 7. Arrow plot of the flux (upper left), magnetic potential lines (upper right), flux density surface plot (lower left), flux density in the circumference of the air gap

is called the base case in this thesis and will be a basis for comparison for the rest of the loss analysis. The loss analysis is done by following the method described in chapter IV. The code used for the post processing is found in appendix F. A summary of the results is found in table I and the results for every part of the machine is found in table XIV in appendix G. The machine have also been studied in Ansys Maxwell, and the iron losses have been calculated to 199.5 kW in the entire machine, using Ansys Maxwell, by Erlend Engevik (PhD student at NTNU). These results are from his doctorate thesis which will be published soon. The calculated losses in the base case, using the FFT function, is 313.62 kW, which is 57.2 % higher the 199.5 kW found by Engevik. The

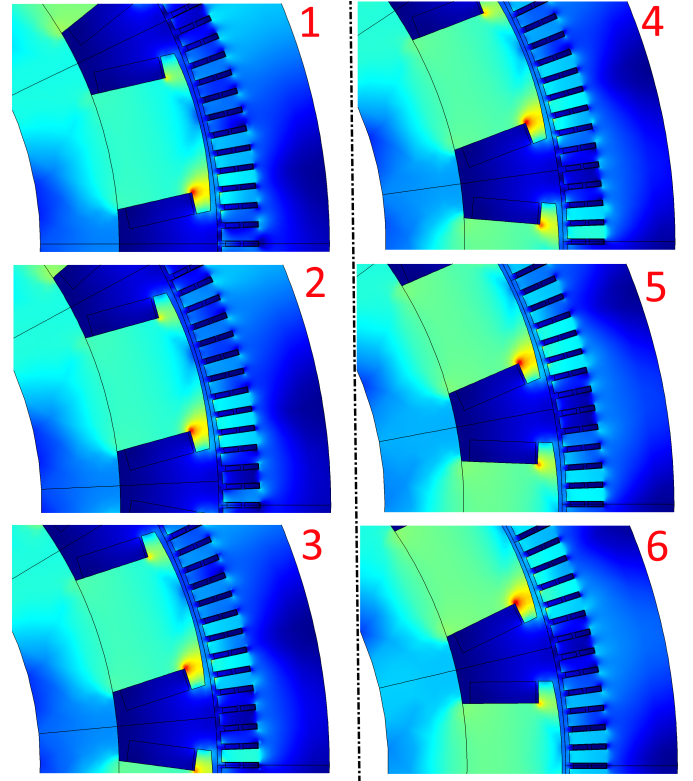


Fig. 8. Part of the rotation of the machine. Notice how the flux density wave move through the teeth.

parameters for the Bertotti equation have been calculated using curve fitting on the data in table in appendix B and is displayed in table II. The time spent for the post processing of the entire stator is 0.10 h or 6.0 minutes. The simulation duration is 4.07 h or 244 minutes in COMSOL.

TABLE II. PARAMETERS TO THE BERTOTTI EQUATION

k_h	103.28
k_c	0.822
k_e	4.267

B. Losses in a sector vs the entire stator

Table I presents the losses for two different parts of different size of the stator; 13/14th and 1/14th of the stator. Added together, this is 283.88 kW iron core losses in the stator. The average for every 1/14th is $283.88/14 = 20.28$ kW, which is a deviation of 9.2 % from the simulation on a specific 1/14th of the stator from table I.

C. Time consume in extracting flux density of an element

Table III and IV shows the results of the loss analysis and the duration of the post processing using the different methods for finding flux density of an element. As stated in the chapter IV-D, the length of the **B**-field vector can be found for an

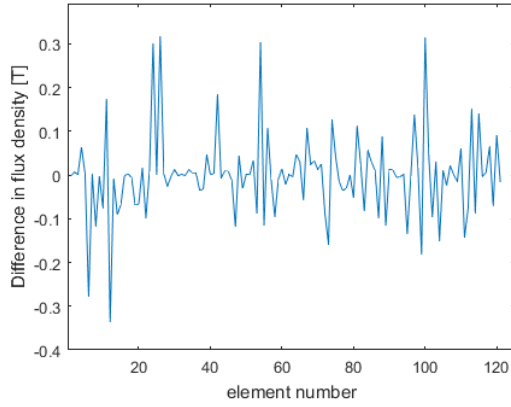


Fig. 9. Difference in flux density between the two methods for calculating flux density in an element

element in two different ways. The post processing is carried out on 1/14th of the rotor, as this part of the motor contains just 121 elements. The important feature of this result is to reveal the differences in B-field extraction for each element, with regards to simulation time and loss deviation. Therefore, the frequency is set to 50 Hz for each element, so the results don't get affected by the FFT function. Table III shows the difference in losses and post processing duration when using the different methods. A similar post processing was done on the base case simulation. This simulation had 420 solution steps, or time steps, and took 4.67 h. In this post processing however, the difference in losses with the two ways of modelling is significant, 54.17%.

TABLE III. DURATION OF POST PROCESSING AND LOSSES WITH TWO DIFFERENT WAYS OF CALCULATING THE FLUX DENSITY IN THE ELEMENTS, SIMULATED OVER 1/2 ELECTRICAL PERIOD

Method	Total losses in 1/14th of the rotor [kW]	Duration [s]
Using average	22.11	3.66
Using mphinterp	24.10	1105.76
Difference [%]	8.25 %	30112.02 %

TABLE IV. DURATION OF POST PROCESSING AND LOSSES WITH TWO DIFFERENT WAYS OF CALCULATING THE FLUX DENSITY IN THE ELEMENTS, APPLIED ON THE BASE CASE

Method	Total losses in 1/14th of the rotor [kW]	Duration [s]
Using average	5.25	5.53
Using mphinterp	11.46	16812
Difference [%]	54.19 %	303914.47 %

Figure 9 shows that the difference in calculation of the flux density in an element is varying between the elements. The average of the difference is 5.5×10^{-18} , or practically zero.

D. Sensitivity in Fast Fourier Transform

A sensitivity test on how much of a signal needs that needs to be included to get the right frequency using the Fast Fourier Transform have been carried out. The test example is the 105

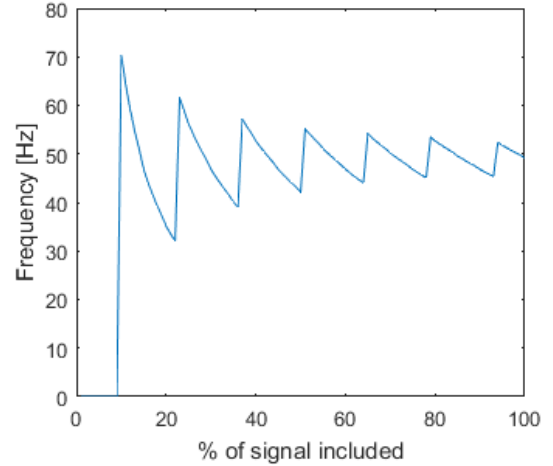


Fig. 10. Frequency plot displaying how the frequency changes when adding more of a signal to the FFT analysis.

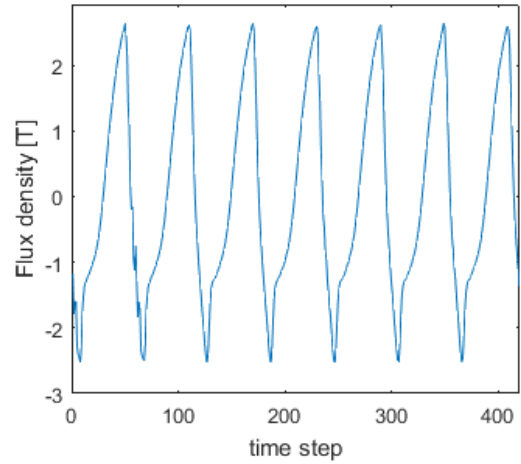


Fig. 11. Signal associated to figure 10

MVA generator, and the signals are taken from different parts of 1/14 of the stator in this generator. The code used to do the analysis is found in appendix F.

A few elements have been chosen for analysis, to describe different situations that can arise when using the Fast Fourier Transform. Figure 10 shows the frequency plot of the signal in figure 11, when different parts of the signal is included in the frequency analysis. When including more and more of the signal, the frequency converges towards a value, which in this case is around 50 Hz. The exact frequency can be approximated by the median of the last half of the frequency plot in figure 10.

Figure 12 shows the frequency plot for another element, that does not converge towards a finite value. It rather converges towards two different values, as the signal is quite distorted, and obviously contains more than one frequency component. Figure 13 shows the signal this Fast Fourier Transform is

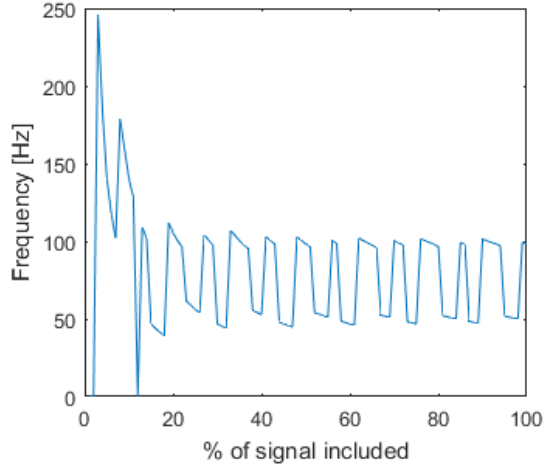


Fig. 12. Frequency plot displaying how the frequency changes when adding more of a signal to the FFT analysis.

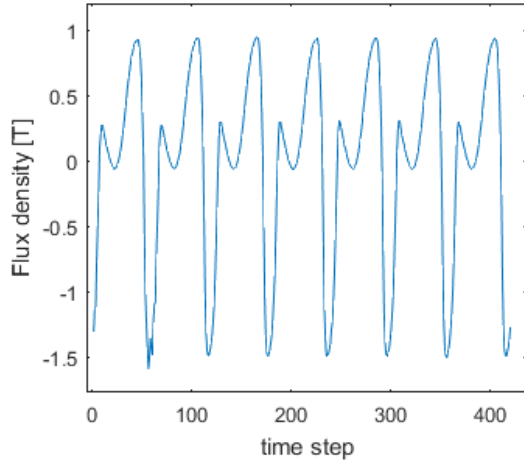


Fig. 13. Signal associated to figure 12

applied to. The Fast Fourier Transform is sensitive for rapid changes of the graph. The frequency can still be approximated by taking the median of the frequency in the last half of the plot.

Figure 14 shows the sorted median of the last half of the frequencies in every element in 1/14th of the stator, as they are presented in figure 10 and 12. The element number index is on the x-axis and the frequency is on the y-axis. Table V show the average and median of all frequencies.

TABLE V. DATA OF ALL FREQUENCIES IN 1/14 OF THE STATOR

	Frequency [Hz]
Median	50.24
Average	57.04

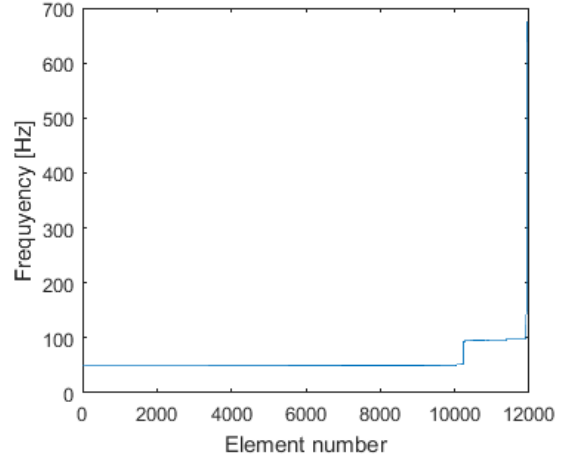


Fig. 14. All frequencies sorted from lowest to highest in 1/14 of the stator of the 105 MVA generator.

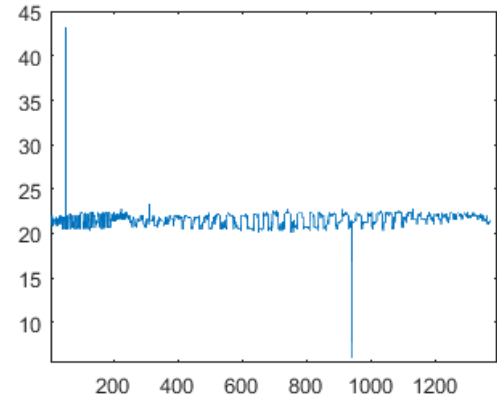


Fig. 15. Frequency of the flux density of all of the rotor elements of the 105 MVA generator.

E. Fourier analysis on the rotor

The frequency analysis has also been carried out on the rotor of the 105 MVA generator. The post processing has been performed of the base case. Figure 15 show the frequency of all the elements in the rotor. Figure 16 illustrates the analysis for one element. The lowest part of figure 16 show how the median of the last half of the frequencies changes when more of the signal is included. The signal is shown in the upper right part of figure 16.

F. BH-curves

Correct modelling of the ferromagnetic material is an important parameter of loss analysis using FEM. One of the most important parameters for ferromagnetic materials is the relationship between the magnetic field, \mathbf{H} -field, and the flux density, \mathbf{B} -field. The relationship is often modelled as a curve, called a BH curve. By using a numeric curve, the saturation effect can be included. Figure 17 shows the losses calculated

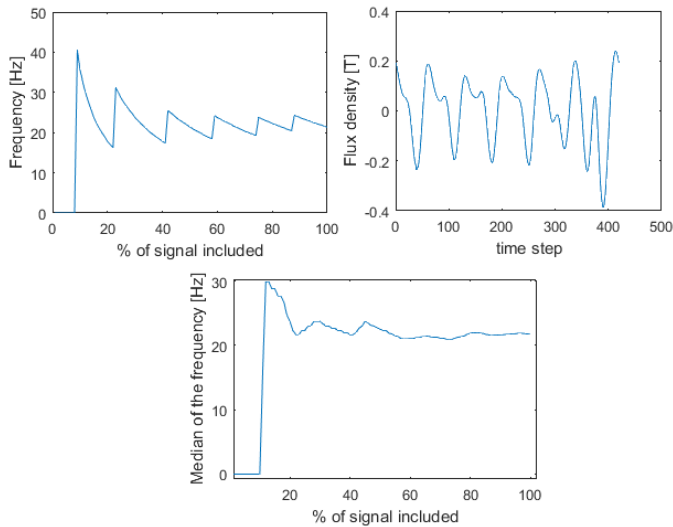


Fig. 16. Frequency when more of a signal is included to the FFT analysis (left). Signal which the FFT analysis is based on (right). Median of the last half of the frequencies (bottom)

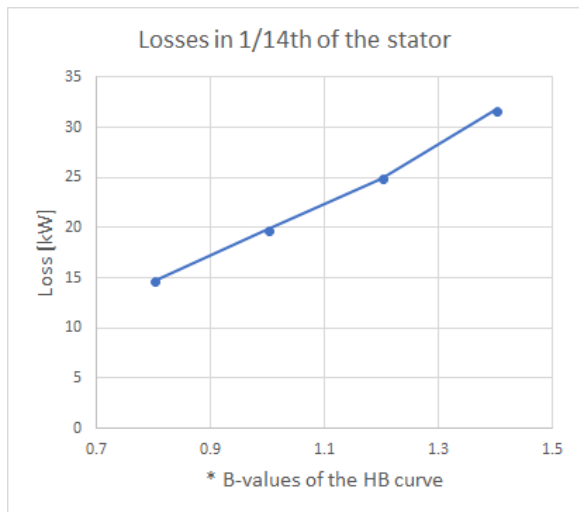


Fig. 17. Losses for different values of the HB curve. The x-axis is the factor multiplied with the B-values of the HB curve

for different BH curves. The values of the flux density in the BH curves are multiplied with different values, from 0.8 to 1.4. This will effectively increase or decrease the saturation level of the material. This also affects the losses, as figure 17 displays. The results are also found in table XIII in appendix E. A simulation was also done with the flux density multiplied with 0.6, but COMSOL was not able to calculate a solution because of no convergence in the mathematical model. This simulation did therefore not make it to the thesis.

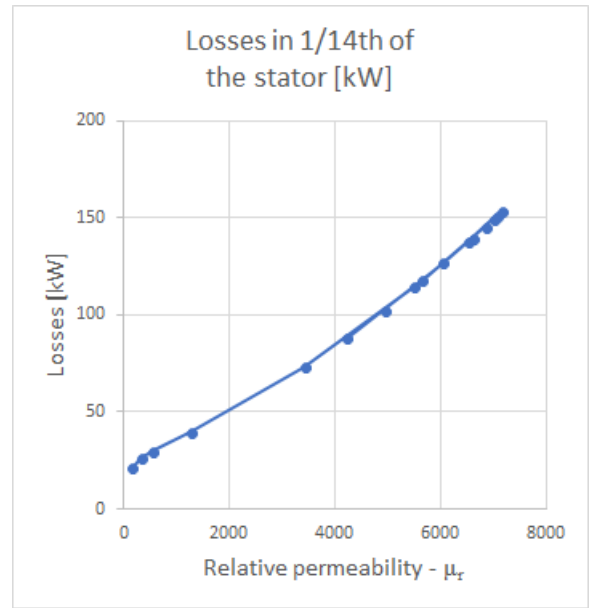


Fig. 18. Losses for different values of the relative permeability

G. Simulations using relative permeability

To use relative permeability can as stated before have some pros when doing a loss analysis. Figure 18 displays an overview with losses in the 105 MVA generator, where the relative permeability relation between the flux density and magnetic field is used. The results are also presented in table XIII in appendix B. The lowest value of the relative permeability simulated for, is 159.2, is also the value which gives the closest results to the base case loss analysis. In 1/14th of the stator, the losses are 21.38 kW, which is 15.2 % higher than the base case at 18.56 kW.

H. Sector analysis

To lower the simulation duration, only a sector of the electrical machine is post-processed. However, the loss analysis will be affected by how much of a *rotation* is included. The 105 MVA generator is simulated for different parts of a rotation of the rotor between 1/14th and 14/14th of a rotation. The results are presented in figure 19. The frequency is found using two different methods. The first method is to use the Fast Fourier Transform, as described above. The second is to assume that the frequency is 50 Hz everywhere in the analyzed area. In the stator, this is not a bad assumption because the electrical frequency is 50 Hz here. The simulation duration is shown in table VI, for different numbers of time steps and part of a full rotation.

Figure 19 presents how the losses changes for the loss analysis including the FFT function. Before 1/2 rotation, 7/14th of a rotation, two of the simulation gives -30% and -15% deviation from the base case simulation. After 1/2 rotation two of the simulations have a deviation of maximum +/- 11%. The results figure 19 is based on is found in table X in appendix C. When the frequency is locked to 50 Hz, the

deviations from the base case is much less, and never goes above 3%, which can be read in table XI in appendix C.

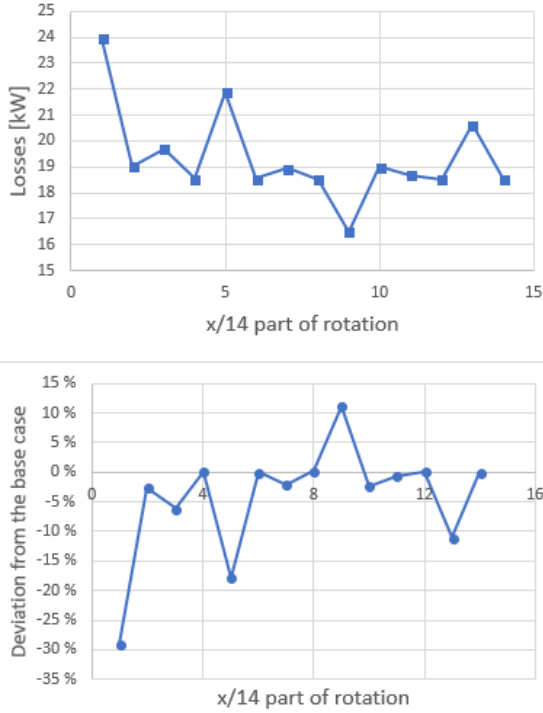


Fig. 19. Losses in 1/14th of the stator for different parts of the rotation

TABLE VI. SIMULATION TIME INCLUDING DIFFERENT AMOUNTS OF TIME STEPS

Part of rotation	Number of time steps	Simulation time [h]		
		COMSOL	Matlab, with FFT	Matlab frequency = 50 Hz
1/14	30	0.3	0.01	0.01
2/14	60	0.57	0.01	0.01
3/14	90	1.00	0.01	0.01
4/14	120	1.23	0.01	0.01
5/14	150	1.44	0.01	0.01
6/14	180	1.78	0.01	0.01
7/14	210	2.07	0.01	0.01
8/14	240	2.28	0.01	0.01
9/14	270	2.57	0.01	0.01
10/14	300	2.99	0.01	0.01
11/14	330	3.33	0.01	0.01
12/14	360	3.39	0.01	0.01
13/14	390	3.65	0.01	0.01
14/14	420	4.07	0.01	0.01

VI. DISCUSSION

A. Method

The method is able to compute results that is 57.2 % higher than the results found by Engevik. This is a significant deviation. The machine has not been built, so there is no measured data for the machine. It is challenging to say which result is the most correct without any measured data on the actual machine. What this do tell us, is that the method will give results that is 57.2 % higher than an established loss

analysis, which is a good platform for further development of the method.

B. Single stator sector vs entire stator

Chapter V-B describes a deviation between the average value of the losses for every sector and the loss analysis done on one specific sector. The deviation means that the losses is not evenly distributed in the generator. If 1/14th of the stator is used to represent the losses in the entire stator, the deviation in the sum will be close to the 9.2 % deviation. This generator has a distributed fractional slot winding, which means that the stator is excited different throughout the stator. To avoid this deviation the analysis must be carried out on a larger part of the machine, which means longer post processing duration.

C. Duration of post processing

Table III and IV shows clearly the difference in simulation time when using the two different methods for extraction of the flux density in an element. One method is using the mphinterp function, and the other method is using the average of the flux density in the corners of the element. These methods and their differences is illustrated and explained in figure 2 in the method chapter. For the simulation of the 105 MVA generator, with 30 time steps over 1/2 of an electrical period, the difference in losses is only 8.25 %, while the difference in simulation time is 30112.02 %. The base case analysis was done with 420 time steps, and the post processing time using mphinterp was 4.67 hours on the 121 elements in 1/14th of the rotor. The difference in loss analysis was 54.19 % between the two methods for the base case. This is concerning, and upon closer inspection, there seems to be an error in the mphinterp function. This was discovered to be because of the way mphinterp works. the code line reads as follows:

```
bfield(h,i) = mphinterp(...
'comsol_model_name','rmm.normB',...
'coord',ng(:,i));
```

This means that the function finds the variable rmm.normB in the coordinates ng. When the rotor turns a few degrees between the time steps, ng does not update as the rotor turns. This means that mphinterp only works for stationary objects in COMSOL, unless this rotation is considered. This is of course possible, but given the time duration of the mphinterp function, the function is not suited to be used in simulations on rotating elements. The mean of the difference between the flux density between the two models for the first time step, where the coordinates for the mphinterp function is correct, is practically zero. The simulation time will not make up for a non-existing error, so the mphinterp function is not practical to use.

D. Base Case

In table I there can be noticed that the stator have 90.5 % of the losses, while the rotor have the remaining 9.5 % of the total losses in the generator, when FFT is used. When FFT is not used, but the frequency of the flux density is estimated to

50 Hz, the losses increases in the rotor. This happens because the rotor frequency in reality will be lower than the stator. The frequency of the flux density in the stator will mostly reflect the electrical frequency of 50 Hz. FFT also give a slightly higher frequency in the stator, as can be seen from table XIV in appendix G. The importance of considering the frequency, is obvious in the rotor analysis especially. If FFT is not used for the rotor, the user will have to guess the frequency of the rotor to get more or less the correct results.

E. Sensitivity test of the FFT function

1) *One dominant frequency:* In figure 10, there can be seen that the frequency converges towards a value. This means that if more periods of the flux density are included, the frequency from the FFT analysis will be more accurate. The signal this frequency plot is taken from, is found in figure 11. This figure shows a signal with one dominating frequency. The calculation of the frequency can be done by using the last value, or the mean of a part of the end of the signal when the signal only has one dominating frequency. The more periods included, the more accurate frequency. However, this will be a trade-off, because more periods included means longer simulation time, both with regards to COMSOL and the post processing in Matlab.

In the method chapter it was suggested to only include the last half of the frequency values, since it is here the frequency mostly converges towards a finite value. If the signal contains more than one frequency component, there will be even more important to only include the last half of the frequency values, as described below.

2) *Multiple frequency components:* Figure 12 shows a frequency plot with significant variations in the frequency. This is extracted in the same way as described in the method chapter. It can be seen from this figure that the frequency goes from a transient state when below 20 % of the signal is included, to a more stationary state when over 20 % is included. The difference from the signal with only one dominant frequency, is that this frequency changes between two given values; around 50 Hz and 100 Hz. This can be seen in figure 13. Figure 14 shows how most of the elements in 1/14th of the stator of the 105 MVA generator have a flux density frequency of 50 Hz, while around 10 % of the elements have a frequency of 100 Hz, and a very few elements have a frequency of 700 Hz. 700 Hz is not a correct value, and occurs because of a weakness when using the FFT function together with COMSOL. This is explained in detail in the paragraph below and in appendix D.

3) *A weakness with FFT:* When using COMSOL, the calculation of the flux density is not always accurate. An example of this occurs at the border between two sectors in the stator. The flux density peaks far over what the saturation for the material is, for only a few time instances. This is a consequence of the sector division of the generator together with the meshing in the FEM modelling. This have consequences for the frequency extraction. Figure 20 shows that this occurs at two time steps. At one time step the frequency reaches nearly 6 T, and at another the frequency reaches 12 T. Figure 21 shows the sorted frequencies for this element. This figure is made by

sorting the frequencies from doing FFT analysis on different parts of the signal, as explained above. The median of the frequencies for this element is at 676 Hz, which is not correct for this generator, compared to the other "healthy" areas of the stator. This area and its location are described more in detail in appendix D.

A solution to this issue, is to set the loss density of the "sick" elements, i.e. the elements with a frequency or flux density over a given limit, to the mean of the loss density of all the elements in the analyzed part of the generator. The limit for the flux density should be above the highest value of the BH curve. The limit for the frequency should be above the double of the electrical frequency.

F. FFT - analysis on the rotor

From the lowest part of figure 16 can it be seen that the median of the last half of the frequencies in an element converges towards a value when more of the signal is included in the FFT analysis. The median is used as the frequency of the elements. At 50 % of the signal, the value is reached, and this value can be used as the frequency of the flux density of the element. 50 % of the signal is 50 % of a rotation for this machine. In the signal, which is shown in the upper right part of figure 16, this means that at least 4 periods of the length of the flux density vector in an element must be included to get the correct frequency with this method.

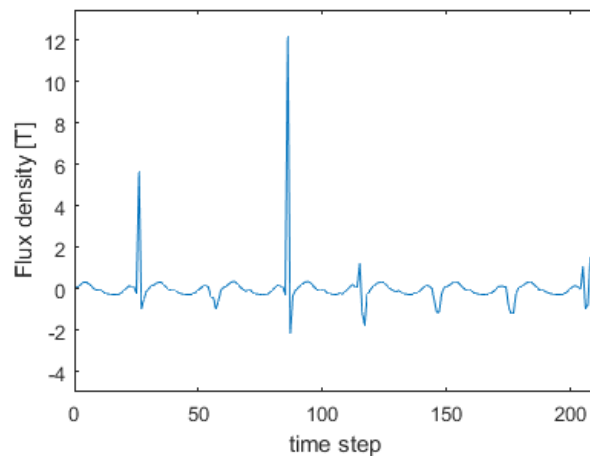


Fig. 20. Plot of the flux density, with some high pulses

G. Sector analysis

Figure 19 shows how much the loss analysis including FFT is affected by how much of a rotation of the machine is included. The loss analysis with the FFT function needs 6/14th of a rotation to avoid the large deviations from the base case, such as the deviation at 5/14th of a rotation at -18 %. This is a large deviation and show why it is important to include more of the rotation. If 6/14th or more of the rotation is included,

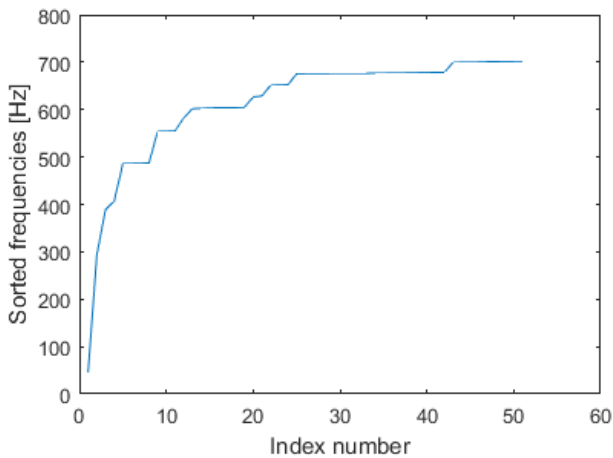


Fig. 21. Plot of the frequency, when different parts of the signal in figure 20

the largest deviation is at $\pm 11\%$ from the base case. 11% is still significant, so the method needs to be developed to decrease this. When estimating the frequency to 50 Hz, and thereby excluding the FFT analysis, no more than 1/14th of a rotation is needed to have enough information for the loss analysis, because the losses deviates at only 3%. If more of a rotation is included the deviation drops to 0% for 5/14th of a rotation. The rest of the values for this simulation can be found in table XI in appendix C.

Table VI shows that the simulation time per 1/14th of a rotation takes around 0.3 hours, or 20 minutes. This is done on a desktop computer and can be decreased if the simulation is run on a larger machine. The post processing time in Matlab is very low, 0.01 h, for every case in this experiment. This is therefore not significant compared to the simulation time in COMSOL. There is also no difference in simulation time between the loss analysis with the FFT function and the loss analysis where the frequency is estimated.

H. BH curve

Figure 17 show how the losses in the 105 MVA generator is affected by the saturation level of the material. If the saturation level increases, the losses will increase as well, and the other way around when the saturation level decreases. The importance of accurate modelling of the material is obvious here, as the losses increase with 39% when the saturation level increases with 40%, compared to the base case.

I. Simulations with relative permeability

As figure 18 shows, the losses increases exponentially with increasing relative permeability. Exponentially increasing losses are expected with increasing relative permeability, because the losses are dependent on the flux density squared, and the flux density will go up with increasing relative permeability. From the theory it is to expect exponentially increasing losses with increasing relative permeability, since the losses is

dependent on the flux density squared. When compared to the base case, it is obvious that there needs to be used a small relative permeability, to get loss values close to the base case. Most of the loss analysis with relative permeability give results high above those of the base case with the BH curve gives. For low values of relative permeability, the results is closer.

In appendix B there is presented a method for extracting relative permeability from a BH curve. The loss analysis above show that it is important to include the entirety of the BH curve in the linear regression to get the most accurate results compared to that of the base case.

VII. FURTHER WORK

The method should be developed and tested on multiple machines. Perhaps before that a series of conventional, controllable and simplified cases, such as field in cubes with homogeneous field, to verify the results. The machines should have data for measured iron loss, so the method can be compared with these results. A better implementation of the frequency analysis should also be included. The full Fourier-analysis or the Hilbert Huang transform are possible candidates for this. This could account for the effect of distorted flux density signals.

Rotating fields is hard to include in the loss analysis. Lagerström [11] writes of a way of considering this. His method does however not consider how much the field is circulating or pulsating, as it only considers the dominating direction. Figure 23 illustrates how the field outermost in a stator tooth is to a large degree circulating, while the field in the middle of the tooth is more elliptical. See figure 24 for the location of the elements. It is recommended to find a method to measure losses from a flux that is circulating, elliptical and pulsating, and see the difference between the cases. In the long term, this can be included in standards for ferromagnetic materials.

VIII. CONCLUSION

A method for loss analysis, based on Bertottis equation, using LiveLink for Matlab has been presented. The loss data for laminated structures is also presented and implemented in the method. The losses found with the method in this thesis are 57.2% higher than a similar loss analysis done by Engevik (PhD student at NTNU) on the same machine. This platform can become the basis for the calculation of iron losses in laminated cores and can be developed to achieve better results. The method has been tested on a 105 MVA hydro generator. The peak of the AC part of the flux density is found through a procedure presented in chapter IV-E, and is shown to work on the mentioned generator. The frequency analysis in the method is described in chapter IV-J. It has been tested and shown capable of calculating the dominating frequency of an oscillating signal. At least four periods of the length of the flux density vector must be included for the frequency analysis to work.

The method for calculation of one Finite Element's typical flux density have been discussed, and the best way of doing this is to use the average of the flux density in the corners of

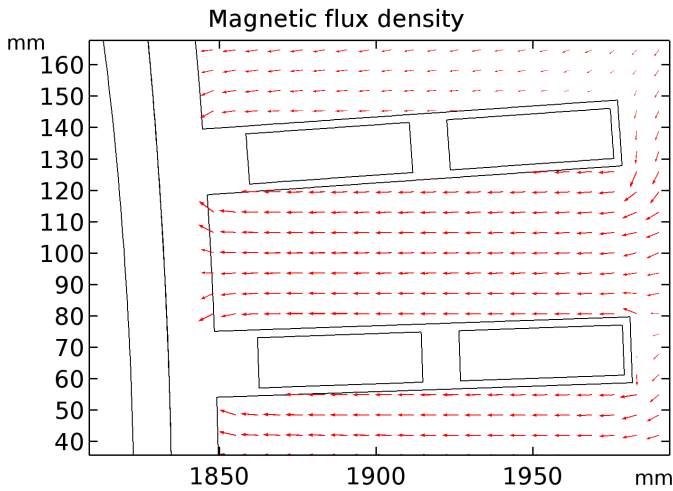


Fig. 22. Arrow plot of flux density in a tooth in the stator of the machine. Notice how the direction of the field changes at the end of the tooth. In the upper part, the flux density vector slightly upwards, while it points a bit downwards in the lower part of the tooth end. The rotor is to the left, and the stator to the right. The rectangular boxes are stator windings.

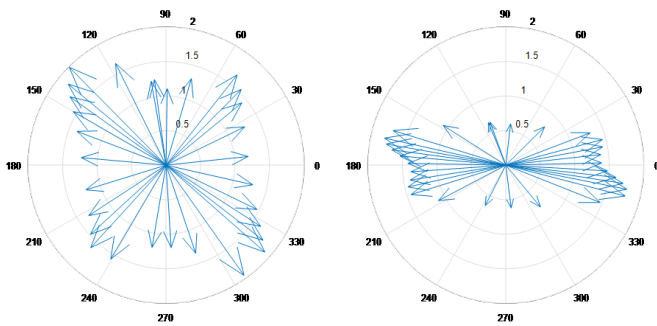


Fig. 23. Circulating (left) and elliptic (right) field in two different locations in a stator tooth

the element as the typical flux density. The LiveLink function `mphinterp` is proven to be slow and inappropriate for moving machinery.

The duration of the post processing is short in comparison with the FEM simulations in COMSOL, so it is not useful to try to reduce the post processing duration of a sector in a machine to save time. If time saving is the objective, it is smarter to try to shorten the duration of the COMSOL simulation. The importance of including a sufficient part of a rotation of the rotor have been illustrated and in this case 6/14th of a rotation is needed to avoid large deviations in the loss analysis compared to the loss analysis of a full rotation.

The saturation level has been shown to affect the losses. If the saturation level goes up, the losses will also increase, as the flux density will increase. The losses will to a great extent be affected by the relationship between the \mathbf{B} - and \mathbf{H} -field. A method for extracting the relative permeability from a BH



Fig. 24. Placement of the elements used in figure 23 (Not actual element size)

curve through linear regression is presented. If the relationship is chosen to be the linear relative permeability, it is important to include the entirety of the BH curve in the linear regression to get results of the loss analysis close to the results of the loss analysis using a BH curve.

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APPENDIX A

105 MVA hydro generator data.

TABLE VII. ELECTRICAL PROPERTIES OF THE 105 MVA HYDRO GENERATOR

Power	105	MVA
Number of poles	14	
Number of slots	180	
Length of the machine	1.8	m
Voltage	11	kV
Total excitation (no load)	26125	A
Total excitation (load)	57855	A
Fp Inductive load	0.9	
Speed	428.57	rpm

TABLE VIII. MECHANICAL PROPERTIES OF THE 105 MVA HYDRO GENERATOR

Stator outer diameter	4575	mm
Stator inner diameter	3700	mm
Rotor diameter	3646	mm
Damper bars diameter	21	mm
Minimum space between steel and conductor	2.5	mm
Gross iron length	1800	mm
Coil pitch	0.85	

APPENDIX B

Appendix B - extracting relative permeability from the BH curve

This is the procedure where the relative permeability is extracted from the BH curve provided by the manufacturer, as explained in chapter III. This procedure is carried out on the material "Sura®M300-35A" from Cogent Power. The data sheet can be seen on the next page. Figure 26 and 27 illustrates the linear regression of the BH curve, including and excluding the nonlinear area, respectively. Figure 27 includes flux densities up to 1 T. Table IX display how the relative permeability μ_r changes when the different parts of the curve is included. If more of the curve is included, the linear approximation will give a more accurate B for a high value of H, but be inaccurate for the low values. If less of the BH curve is included, the linear approximation will give a more accurate B for a low value of H, but this will be inaccurate for large values of H.

TABLE IX. SLOPE AND μ_r FOR M300-35A, INCLUDING DIFFERENT PARTS OF THE BH CURVE

Including flux density up to [T]	Slope	μ_r
0.3	0.0053	4217.6
0.4	0.0062	4933.8
0.5	0.0069	5490.8
0.6	0.0076	6047.9
0.7	0.0082	6525.4
0.8	0.0086	6843.7
0.9	0.0089	7082.4
1	0.009	7162.0
1.1	0.0088	7002.8
1.2	0.0083	6604.9
1.3	0.0071	5650.0
1.4	0.0043	3421.8
1.5	0.0016	1273.2
1.6	0.0007	557.0
1.7	0.0004	318.3
1.8	0.0002	159.2

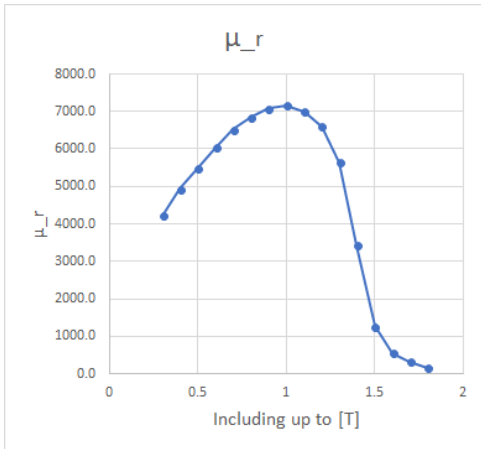


Fig. 25. μ_r plotted for values up to different flux densities

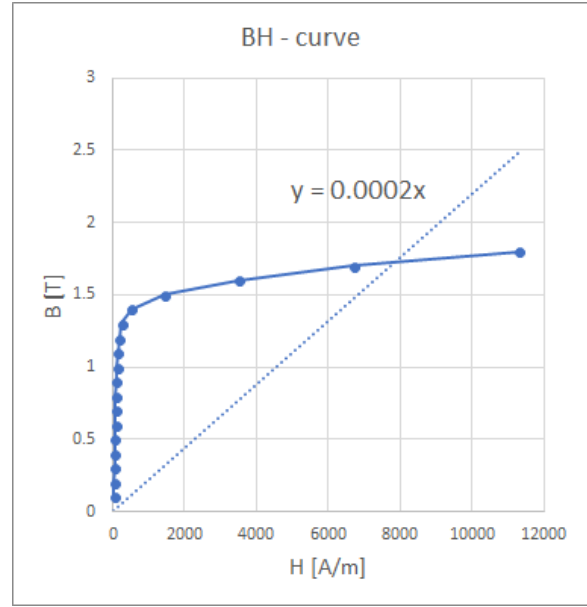


Fig. 26. Linear regression of the BH curve for M300-35A, including the nonlinear part of the curve

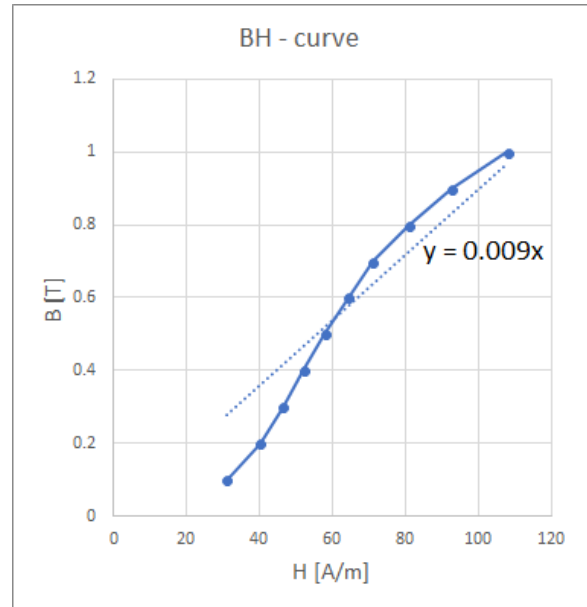


Fig. 27. Linear regression of the BH curve for M300-35A, excluding the nonlinear part of the curve

Typical data for SURA® M300-35A

T	W/kg at 50 Hz	VA/kg at 50 Hz	A/m at 50 Hz	W/kg at 100 Hz	W/kg at 200 Hz	W/kg at 400 Hz	W/kg at 1000 Hz	W/kg at 2500 Hz
0,1	0,03	0,07	30,9	0,04	0,09	0,23	1,07	4,45
0,2	0,08	0,17	40,2	0,17	0,40	1,00	4,08	16,1
0,3	0,15	0,30	46,4	0,35	0,85	2,15	8,48	33,6
0,4	0,24	0,45	52,1	0,58	1,41	3,61	14,0	56,9
0,5	0,35	0,62	57,9	0,84	2,06	5,36	20,9	86,6
0,6	0,48	0,82	64,4	1,14	2,81	7,42	29,2	124
0,7	0,61	1,05	72,0	1,46	3,66	9,75	39,0	170
0,8	0,76	1,31	81,1	1,83	4,61	12,4	50,6	227
0,9	0,92	1,63	92,6	2,23	5,65	15,4	64,1	297
1,0	1,10	2,03	108	2,66	6,80	18,8	79,8	382
1,1	1,30	2,55	130	3,16	8,09	22,5	98,0	
1,2	1,54	3,32	168	3,72	9,54	26,8		
1,3	1,82	4,71	250	4,39	11,2	31,6		
1,4	2,20	8,61	510	5,23	13,4	37,7		
1,5	2,62	23,7	1440	6,22	15,7	44,3		
1,6	2,98	64,1	3490					
1,7	3,25	138	6700					
1,8	3,41	255	11300					

Loss at 1.5 T , 50 Hz, W/kg	2,62
Loss at 1.0 T , 50 Hz, W/kg	1,10
Anisotropy of loss, %	10

Magnetic polarization at 50 Hz

H = 2500 A/m, T	1,55
H = 5000 A/m, T	1,65
H = 10000 A/m, T	1,78

Coercivity (DC), A/m	45
Relative permeability at 1.5 T	830
Resistivity, $\mu\Omega\text{cm}$	50

Yield strength, N/mm ²	370
Tensile strength, N/mm ²	490
Young's modulus, RD, N/mm ²	185 000
Young's modulus, TD, N/mm ²	200 000
Hardness HV5 (VPN)	185



RD represents the rolling direction
 TD represents the transverse direction
 Values for yield strength (0.2 % proof strength)
 and tensile strength are given for the rolling direction
 Values for the transverse direction are approximately 5% higher

APPENDIX C

TABLE X. LOSSES AND DEVIATION FROM THE BASE CASE IN 1/14 OF STATOR FOR DIFFERENT AMOUNT OF ROTATION, WHEN USING FFT

Part of rotation	Number of timesteps	Loss in 1/14 of stator - with FFT [kW]	Deviation from base case
1/14	30	23.95	-29 %
2/14	60	19.03	-3 %
3/14	90	19.69	-6 %
4/14	120	18.54	0 %
5/14	150	21.87	-18 %
6/14	180	18.56	0 %
7/14	210	18.95	-2 %
8/14	240	18.51	0 %
9/14	270	16.49	11 %
10/14	300	18.99	-2 %
11/14	330	18.68	-1 %
12/14	360	18.53	0 %
13/14	390	20.61	-11 %
14/14	420	18.56	0 %

TABLE XI. LOSSES AND DEVIATION FROM THE BASE CASE IN 1/14 OF STATOR FOR DIFFERENT AMOUNT OF ROTATION, WHEN ESTIMATING THE FREQUENCY AT 50 HZ

Part of rotation	Number of timesteps	Loss in 1/14 of stator - frequency = 50 Hz [kW]	Deviation from base case
1/14	30	16.81	3 %
2/14	60	17.14	1 %
3/14	90	17.22	1 %
4/14	120	17.24	1 %
5/14	150	17.45	0 %
6/14	180	17.29	0 %
7/14	210	17.36	0 %
8/14	240	17.35	0 %
9/14	270	17.44	0 %
10/14	300	17.38	0 %
11/14	330	17.38	0 %
12/14	360	17.40	0 %
13/14	390	17.52	-1 %
14/14	420	17.37	0 %

APPENDIX D

Around element 4055, an error occurs in COMSOL. The error leads to an unnatural high flux density in the area of the border between two sectors of the stator. The flux density reaches up to 11 T at one time step. From figure 31 there can be seen that there are many elements that are affected by this phenomenon. The loss analysis will not be functional in this element, because of the wrong flux density and the wrong frequency associated with these elements. The frequency will be wrong because this error only happens at one time step. Since it only happens once, the FFT function will interpret this as a high frequent signal with a large amplitude.

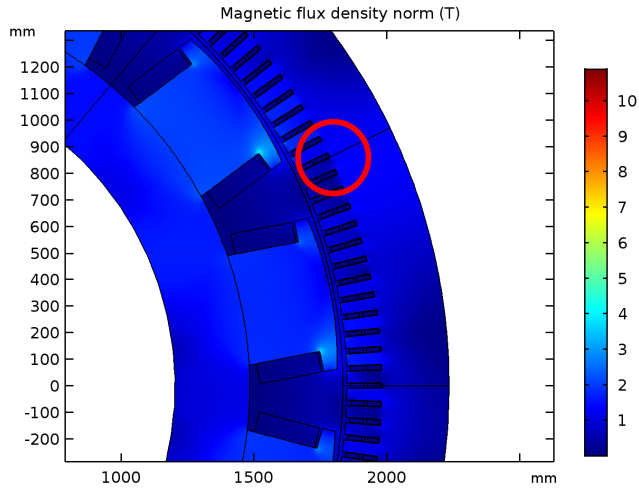


Fig. 28. Plot of area with extreme flux density

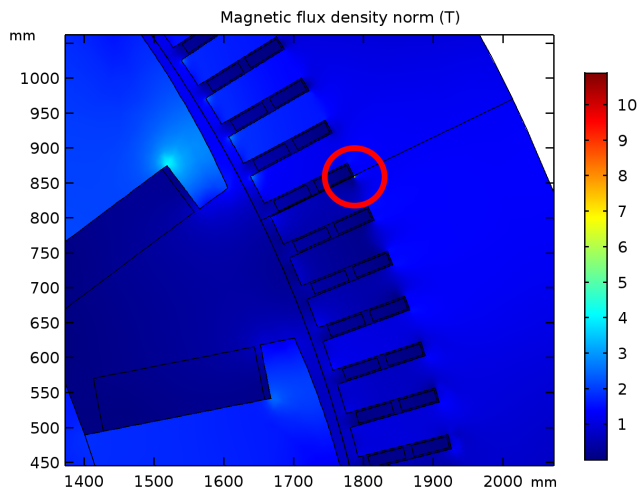


Fig. 29. Plot of area with extreme flux density

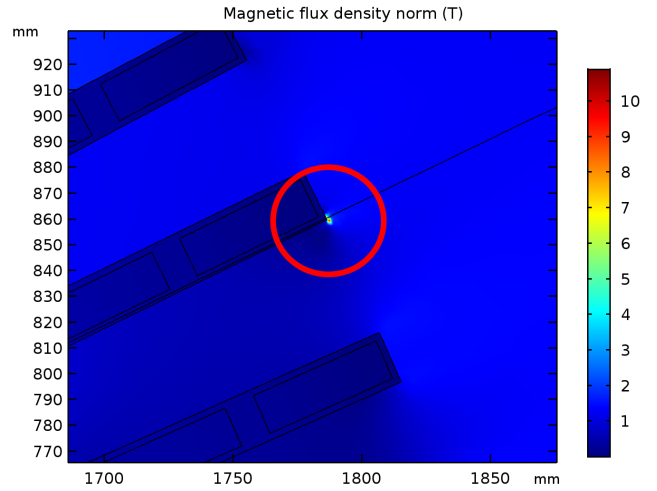


Fig. 30. Plot of area with extreme flux density

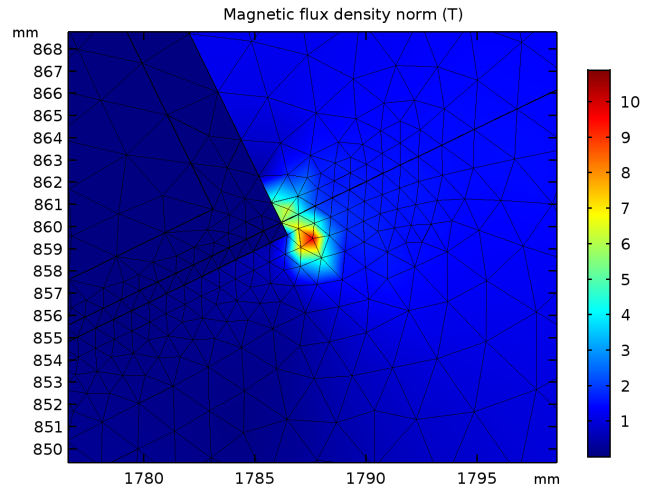


Fig. 31. Plot of area with extreme flux density, showing affected areas

APPENDIX E

BH-curves with different saturation levels

TABLE XII. BH-CURVE FOR DIFFERENT VALUES OF B, EFFECTIVELY CHANGING SATURATION LEVEL

H [A/m]	B_mid*0.8 [T]	B_mid [T]	B_mid*1.2 [T]	B_mid*1.4 [T]
0	0	0	0.00	0.00
30.9	0.08	0.1	0.12	0.14
40.2	0.16	0.2	0.24	0.28
46.4	0.24	0.3	0.36	0.42
52.1	0.32	0.4	0.48	0.56
57.9	0.4	0.5	0.60	0.70
64.4	0.48	0.6	0.72	0.84
72	0.56	0.7	0.84	0.98
81.1	0.64	0.8	0.96	1.12
92.6	0.72	0.9	1.08	1.26
108	0.8	1	1.20	1.40
130	0.88	1.1	1.32	1.54
168	0.96	1.2	1.44	1.68
250	1.04	1.3	1.56	1.82
510	1.12	1.4	1.68	1.96
1440	1.2	1.5	1.80	2.10
3490	1.28	1.6	1.92	2.24
6700	1.36	1.7	2.04	2.38
11300	1.44	1.8	2.16	2.52

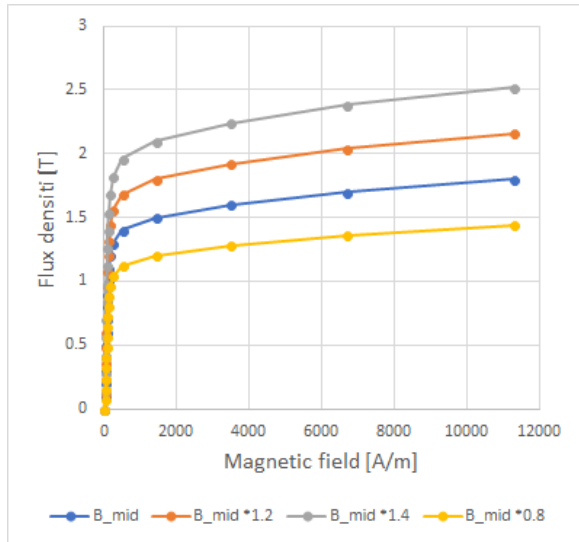


Fig. 32. Different saturation levels of the BH curve

TABLE XIII. LOSSES FOR DIFFERENT BH CURVES

B-values	Losses in 1/14th of the stator	Difference from base case
0.8	14.66	-33 %
1	19.44	0 %
1.2	24.91	22 %
1.4	31.734	39 %

APPENDIX F

This appendix contains Matlab-code used to do the post-processing of a FEM simulation. The main script is the `generator_105MVA_fft_loss`. This script will run the entire post processing. The script will store the loss density, the loss, area and frequency of every element in the domain the user chooses. The script uses multiple functions, as listed below:

List of functions:

```
[bfield, area, freq] = area_bfield_const_fft_v2(simulation_results, samp_freq)
```

- Will return `bfield`, which is a matrix, where each column is an element and each row is a time step. Area and frequency is two vectors containing the area and frequency of every element, respectively.

```
frequency = find_freq_fft(signal, samp_freq)
```

- Will return the frequency containing the highest amplitude of an input signal. The function needs a signal and a sampling frequency as input. The signal must have the same sampling frequency, as it does not consider varying sampling frequency. This function is used within `area_bfield_const_v2`.

```
[element_B_max] = max_B_field(element_B);
```

- Will return the maximum of a vector. Is used only to find the maximum of the flux density.

```
%-----
```

```
% Script name: generator_105MVA_fft_loss
```

```
% This script will calculate the losses in an iron core.
```

```
% A simulation in COMSOL must be completed before the script is run.
```

```
%% initializing - user interface:
```

```
model_name = 'The_name_of_the_comsol_model';
```

```
% the model must be in the matlab path
```

```
dataset = 'dsetx';
```

```
selection = [section1 section2 section3 ...];
```

```
% Include all sections with iron cores
```

```
investigate = 'rmm.normB';
```

```
% For a model with rotating machinery physics in comsol use 'rmm.normB'
```

```
% For a model with magnetic fields physics in comsol use 'mf.normB'
```

```
model_length = 1.438; %m
```

```
losses_in_entire_model = 0;
```

```
% Loss parameters:
```

```
kh = 103.28;
```

```
kc = 0.822;
```

```
ke = 4.267;
```

```
%% Outer iteration over selected domains
```

```
for j=1:length(selection)
```

```
    sel = selection(j);
```



```

%-----
%% Gathering of parameters from COMSOL needed to calculate losses:
model = mphload(model_name);
result_B = mpheval(model,investigate,'selection',sel,'Dataset',dataset);
[solution_step_number , eval_points_number] = size(result_B.d1);
[point_in_element_number, element_number] = size(result_B.t);
element_area = zeros(1,element_number);
element_B = zeros(solution_step_number,element_number);
ng = zeros(2,element_number);
solinfo = mphsolinfo(model);
time = solinfo.solvals;
samp_freq = 1/(time(2)-time(1));
% The function uses the first two time steps to find the sampling frequency

%-----
%% iteration - filling two vectors with B-field in each element and the volume of
% the element
[element_B,element_area, f] = area_bfield_const_fft_v2(result_B,samp_freq);
%-----
%% calculation of area
total_area = 0;
for i=1:element_number
    total_area = total_area + element_area(i);
end
%-----
%% Find max B-field in every element
%(if there is multiple solutions (timesteps, parametric sweeps))
[element_B_max] = max_B_field(element_B);
%-----
%% calculation of losses

loss_element = zeros(1,element_number);
loss_per_square_meter_per_m = zeros(1,element_number);
total_losses = 0;
for i = 1:element_number
    loss_per_square_meter_per_m(1,i) = kh * f(i) * element_B_max(1,i) + ...
    kc * f(i)^2 * element_B_max(1,i)^2 + kh * f(i)^1.5 * element_B_max(1,i)^1.5;
    loss_element(1,i) = (kh * f(i) * element_B_max(1,i) + ...
    kc * f(i)^2 * element_B_max(1,i)^2 + kh * f(i)^1.5 * element_B_max(1,i)^1.5) *...
    element_area(1,i) * model_length;
    total_losses = total_losses + loss_element(1,i);
end

losses_in_entire_model = losses_in_entire_model + total_losses;

```

The function `area_bfield_const_fft_v2`:

```

%-----
%% This is the function to find the area vector and the B-field matrix.
% The B-field is a matrix containing all the values of the B-field. Every column
% refers to an element in COMSOL, and every row is a different parameter or time
% instant.

% This function assumes that the B-field in an element is the same as the average
% of the B-field in the corners of the element

% Area is a vector containing the area to every element in the
% simulation file.

% freq is a vector containing the frequency found

function [bfield, area, freq] = area_bfield_const_fft_v2(simulation_results, samp_freq)

[~, element_number] = size(simulation_results.t);

area = zeros(1,element_number);
[solution_step_number, ~] = size(simulation_results.d1);
bfield = zeros(solution_step_number,element_number);
ng = zeros(2,element_number);
freq = zeros(1,element_number);
parfor i=1:element_number % calculating volume and average B-field in every element
%parfor instead of for utilizes parallel computing
%-----
    %Finding coordinates to a triangular element:
    n1 = simulation_results.p(:,1+simulation_results.t(1,i));
    n2 = simulation_results.p(:,1+simulation_results.t(2,i));
    n3 = simulation_results.p(:,1+simulation_results.t(3,i));
%-----
    %Finding the area of an element:
    area(1,i) = 0.5*abs(n1(1)*(n2(2)-n3(2))+n2(1)*(n3(2)-n1(2))+...
    n3(1)*(n1(2)-n2(2)))*10^-6;
%-----
    %Finding the average of the B-field in an element for every timestep

    b_vec = ([simulation_results.d1(:,1+simulation_results.t(1,i)),...
    simulation_results.d1(:,1+simulation_results.t(2,i)),...
    simulation_results.d1(:,1+simulation_results.t(3,i))]);
    mean_b = mean(b_vec,2);
    bfield(:,i) = mean_b;
    minimum = min(bfield(:,i));
    bfield(:,i) = bfield(:,i) - minimum;

    % This can be replaced by the mphinterp function:
    % xg = 1/3*(n1(1)+n2(1)+n3(1));
    % yg = 1/3*(n1(2)+n2(2)+n3(2));
    % ng(:,i) = [xg;yg];
    % bfield(:,i) = mphinterp(model,investigate,'coord',ng(:,i),'Dataset',dataset);
%-----

```

```

%% Finding frequency through median
percentages = (0.01:0.01:1);
mean1      = mean(bfield(:,i));
analyzed   = bfield(:,i);
analyzed(:,1) = analyzed(:,1) - mean1;
analyzed(:,1) = analyzed(:,1)*2;
analyzed = analyzed';

frequencies = zeros(1,length(percentages));
for k=1:length(percentages)
    length_analyzed = length(analyzed);
    to_index = length_analyzed*percentages(k);
    to_index_floor = floor(to_index);
    if to_index_floor < 2
        to_index_floor = 2;
    end
    analyzed_intermediate = analyzed(1:to_index_floor);
    frequencies(k) = find_freq_fft(analyzed_intermediate,samp_freq)/2;
end

frequencies_intermediate = ...
frequencies(floor(length(frequencies)*0.5):length(frequencies));
freq(i)=median(frequencies_intermediate);
end
end

```

The Function find_freq_fft:

% The function find_freq_fft gives out the frequency of the highest amplitude of a
 % signal. Input arguments are the signal and the sampling frequency

```
function frequency = find_freq_fft(signal,samp_freq)
trans = abs(fft(signal));

[~,index] = sort(trans,'descend');
Fs = samp_freq;
frequency = (index(1)*Fs)/length(signal)-(Fs/length(signal));
end
```

The function max_B_field:

% The function to find the maximum of every column in a matrix, iterating over every row.

```
function [element_B_max] = max_B_field(element_B)
[~,element_number] = size(element_B);
element_B_max = zeros(1,element_number);
for i = 1 : element_number
    element_B_max (i) = max(element_B(:,i));
end
end
```

APPENDIX G

TABLE XIV. LOSS RESULTS FOR THE BASE CASE SIMULATION

Domain	Mean frequency with FFT analysis [Hz]	Loss using FFT [kW]	Loss, assuming 50 Hz [kW]
13/14 of stator	52.68	265.32	262.71
1/14 of stator	55.61	18.56	17.37
13/14 of rotor yoke	20.93	19.35	66.93
1/14 of rotor yoke	20.36	1.43	5.25
Pole	29.77	0.67	1.74
Pole	30.03	0.68	1.74
Pole	29.92	0.66	1.74
Pole	29.28	0.66	1.74
Pole	29.71	0.66	1.74
Pole	29.33	0.68	1.74
Pole	28.35	0.62	1.73
Pole	28.15	0.65	1.74
Pole	28.26	0.63	1.74
Pole	27.42	0.64	1.74
Pole	27.85	0.62	1.74
Pole	26.88	0.62	1.74
Pole	25.93	0.59	1.73
Pole	24.32	0.58	1.74
Total losses		313.62	376.60

APPENDIX H

TABLE XV. LOSSES IN 1/14TH OF THE STATOR - USING RELATIVE PERMEABILITY

μ_r	Losses [kW]
4218	88.07
4934	102.52
5491	114.41
6048	126.89
6525	137.99
6844	145.63
7082	151.48
7162	153.45
7003	149.51
6605	139.89
5650	117.93
3422	73.3
1273	39.88
557	30.05
318	26.14
159	21.38

APPENDIX I

LiveLink for COMSOL comes with the installation files of COMSOL. LiveLink is an interface between Matlab and COMSOL, making it possible to control COMSOL using Matlab commands. It is also possible to do post-processing of a simulated model in COMSOL with Matlab. The first time LiveLink is opened, a user name and password needs to be typed in the dialogue box. Both of these can be arbitrary, and won't be needed to be remembered when LiveLink is opened the next time. The status window of LiveLink is shown in figure 34. After the user name and password is entered, the link between Matlab and COMSOL will be established, and the Matlab window will open.



Fig. 33. LiveLink icon

The most important functions are described below:

```
model = mphload(comsol_model_name);
```

mphload will load a comsol object with the filename 'comsol_model_name', and save the object in the variable "model". It is important that the COMSOL model file are in the Matlab path, or Matlab will not be able to access COMSOL.

```
length_B = mpheval(model, 'rmm.normB', ...
'selection', 305, 'Dataset', 'dset1')
```

mpheval use multiple input parameters. The first is the model mphload loaded from COMSOL, the second is the variable to be evaluated, which in this case is 'rmm.normB'. The third is the 'selection' tag, which means that the following input parameter will be the domain in the COMSOL model the user wants to analyze. The last is the 'Dataset' tag, which states that the following input parameter will be which dataset is used. In this case, the first dataset, with the tag 'dset1', is used. The number following 'dset' will often be the number of the study in COMSOL. The output of mpheval is a struct with 6 fields (taken from the COMSOL documentation):

- expr - contains the list of the evaluated expression (in this case rmm.normB)
- dl - contains the data of the evaluated expression
- p - contains the coordinates of the evaluated points
- t - contains the indices to columns in the p field. Each column in the t-field corresponds to an element of the mesh used for the evaluation.
- ve - contains the indices of the mesh elements at each evaluation point
- unit - contains the unit of the evaluated expression

The code below will give the coordinates of all elements in the analyzed domain of the model, by the use of a for-loop. n1, n2 and n3 will be the corners of an element. n4 is used when a 3D model is analyzed.

```
for i=1:element_number
    n1 = length_B.p(:,1+length_B.t(1,i));
    n2 = length_B.p(:,1+length_B.t(2,i));
    n3 = length_B.p(:,1+length_B.t(3,i));
    %3D:n4 = length_B.p(:,1+length_B.t(4,i));
end
```

The code below gives the matrix b_vec with three columns, one for each corner in the element. b_vec will have the number of solution steps as the number of rows.

```
b_vec=...
([length_B.dl(:,1+length_B.t(1,i)),...
length_B.dl(:,1+length_B.t(2,i)),...
length_B.dl(:,1+length_B.t(3,i))]);
```

All of these lines of code is based on the code in appendix F, where they are used to calculated losses in iron cores.

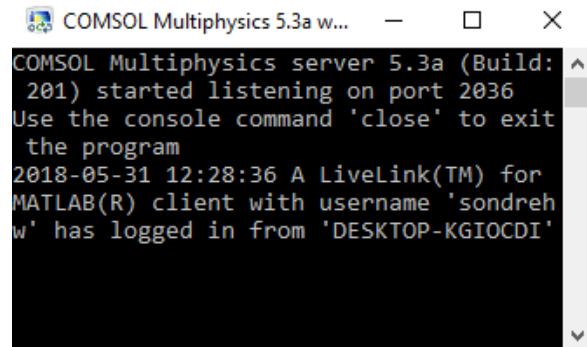


Fig. 34. LiveLink status window