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Investigation of Loss Calculation Methods for PMSMs and Implementation of Loss Functionality on a Developed FEM Model

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Summary

Accurate estimation of losses is one of the major challenges in electromagnetic machinery modelling. Where permanent magnet synchronous machines are attractive for high performance applications, making them relevant for investigation with regard to optimal design. This thesis concerns the investigation of loss calculation methods for permanent magnet synchronous machines. As well as implementation of loss functionality in the further development of a permanent magnet synchronous machine, modelled in the finite element method program COMSOL Multiphysics®. The model is developed in a previous master thesis, were losses were neglected for simplicity. A process of evaluation and testing of the developed model will also naturally take place.

The method chosen to estimate the core losses separates the loss into hysteresis and eddy-current components. This is a well established model and has been shown to give satisfactory results, coupled with finite element method modelling, in previous studies. The method was deemed feasible to implement and should in theory give an adequate evaluation of the core losses. However mismatch between the time and frequency domain solutions, as well as an imbalance in the flux distribution, due to conflicting interactions within the model, puts the validity of the implemented functionality into question.

Losses in the windings and the permanent magnets are accounted for by modelling the resistive losses for their corresponding domains, as the magnets can be assumed resistance limited. The eddy-current losses in the magnets are affected by their size and structure, where sectioning could be implemented to decrease losses. In the case of the windings problematic integration of their properties in the model results in unrealistic loss values.

Sammendrag

Å kunne med nøyaktighet anslå effekttap er en av de største utfordringene innen modellering av elektromagnetiske maskiner. For bruksområder som krever høy ytelse har permanent magnet synkronmaskiner vist seg å være attraktive, og er dermed aktuelle å undersøke i forhold til utvikling mot optimalt design. Målet med denne masteroppgaven er å undersøke beregningsmetoder for tap i permanent magnet synkronmaskiner. I tillegg til å implementere tapsfunksjonalitet, som en videreutvikling av en maskinmodell, utformet i en tidligere masteroppgave, der tap var neglisjert. Maskinen er modellert i simuleringsprogrammet COMSOL Multiphysics® som benytter seg av elementmetoden. Evaluering og testing av den opprinnelige modellen vil også bli gjort som en del av utviklingsprosessen.

Jernkjernetapene er estimert ved bruk av separasjonsmetoden som deler tapene opp i hysterese og virvelstrøms komponenter. Dette er en etablert metode som har vist seg å gi tilfredsstillende resultater, kombinert med elementmetodemodellering, i tidligere undersøkelser. Metoden er valgt da den er bedømt som mulig å implementere i COMSOL og den i teorien skal gi en akseptabel vurdering av jerntapene. I midlertidig viser resultatene en uoverensstemmelse mellom frekvens- og tidsdomene løsningene, samt en ubalanse i flukstettheten. Dermed blir det stilt usikkerhet rundt gyldigheten av modellen i forbindelse med tapsberegningene.

Tap i viklingene og de permanente magnetene beregnes ved å modellere resistive tap for deres samsvarende domener. Magnetene kan med akseptabel nøyaktighet antas motstandsbegrenset og tapene kan dermed modelleres som ohmske tap. Tapene i magnetene er påvirket av deres størrelse og struktur, hvor seksjonering kan implementeres for å redusere tap. Integreringen av viklingene og deres egenskaper i modellen forårsaker motstridende forbindelser og de resulterende viklingstapsverdiene vurderes urealistiske.

Investigation of Loss Calculation Methods for PMSMs and Implementation of Loss Functionality on a Developed FEM Model

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***Abstract*—Accurate estimation of losses is one of the major challenges in electromagnetic machinery modelling, where permanent magnet synchronous machines are attractive for high performance applications, making them relevant for investigation with regard to optimal design. This paper aims to investigate loss calculation methods for permanent magnet synchronous machines and implement loss functionality in the further development of a permanent magnet synchronous machine modelled in the finite element method program COMSOL Multiphysics®. A process of evaluation and testing the developed model will also naturally take place.**

The method chosen to estimate the core losses separates the loss into hysteresis and eddy-current components. This is a well established model and has been shown to give satisfactory results, coupled with FEM modelling, in previous studies. The method was deemed feasible to implement and should in theory give an adequate evaluation of the core losses. However, mismatch between the time and frequency domain solutions, as well as an imbalance in the flux distribution, due to conflicting interactions within the model, puts the validity of the implemented functionality into question.

Losses in the windings and the permanent magnets are accounted for by modeling the resistive losses for their corresponding domains, as the magnets can be assumed resistance limited. The eddy-current losses in the magnets are affected by their size and structure, where sectioning could be implemented to decrease losses. In the case of the windings problematic integration results in unrealistic loss values.

***Index Terms*—Permanent magnet synchronous motor, loss estimation, COMSOL multiphysics, core losses, permanent magnet losses, finite element method**

NOMENCLATURE

PMSM	Permanent magnet synchronous machine
FEA	Finite element analysis
FEM	Finite element method
FFT	Fast Fourier transform
PM	Permanent magnet
CW	Concentrated winding
DW	Distributed winding

I. INTRODUCTION

Permanent magnet synchronous machines are an attractive alternative as high-performance machines in various fields and therefore very relevant to investigate for optimal design in specific applications. The goal is to design machines with the highest possible efficiency without compromising performance and upholding possible design restrictions. Hence being able to accurately predict losses in electrical machines is an important design aspect, where the end goal is optimization of specific aspects.Therefore an integrated modelling solution where machine design and calculation of operational properties, including losses, can be a valuable tool in the design and testing process of PMSMs.

The losses in a PMSM consist of core losses, winding losses, losses in the permanent magnets and mechanical losses. The core losses, which are the most difficult to calculate as they are highly dependent on the machines magnetic properties and the resulting field distributions from the interactions of machine parts, have traditionally been estimated using loss data provided by the lamination manufacturer. However this method uses many simplifying assumptions and therefore has limited accuracy for complex machines. To consider more of the dynamic properties and the specifics of a complete machine design the development of loss estimations methods has gone in the direction of employing finite element analysis [1][2]. Accordingly it is desirable to have a design tool which employs the finite element method and incorporates loss functionality.

This master thesis is a continuation of a previous master thesis [3], where ”A parametrized 2D model of a permanent magnet synchronous machine” is developed in the FEM software COMSOL Multiphysics®. The PMSM model takes machine parameters as input specified by the user and the resulting machine geometry and performance can be simulated. However this model neglects losses, and to simulate realistic machine performance loss calculation should be included. The continuation work in this thesis will be to investigate loss calculation methods for PMSMs as well as implement and test loss functionality for the model, ideally entirely in COMSOL, in other words without the use of external programming software. In the further development of the program a natural process of testing and evaluating the model will also take place. An accompanying application, a user friendly interface available for programming in COMSOL, where the user can input machine parameters and run preset studies to evaluate specific parameters and performance aspects, is also built as part of the initial development of the model. However the work at this development stage will be focused in the model builder with the possibility of integration into the application as the end goal for future improvement, as the functionality implemented in the application must be available and implemented firstly in the model.

The focus of the loss investigation and implementation will lie on core losses as these are the most debated in literature, where quite a few studied and practiced methods are presented with varying complexity and accuracy. Nonetheless all loss contributions will be considered in theory and for the implementation. Some loss calculation methods will be investigated and compared as well as considered in the context of which are most relevant and feasible for implementation as an added functionality in the COMSOL model.

II. LOSSES IN PMSMS

As the goal is to implement loss calculation on a PMSM model the theory will focus on losses in permanent magnet synchronous machines, where the topology in Figure 1, with the possibility of adjusting the number of poles and slots ,will be used as the basis for the theory and the implementation. This implemented model is developed from the most common PMSM design consisting of an inner rotor with a number of magnet poles that produces a steady magnetic field, B, and a stationary stator structure surrounding the rotor, separated by an air gap. The stator consists of slots containing current carrying wire, where the alternating current flowing in the windings creates a rotating magnetic field, where the power production is based on the interaction of the two fields [4].

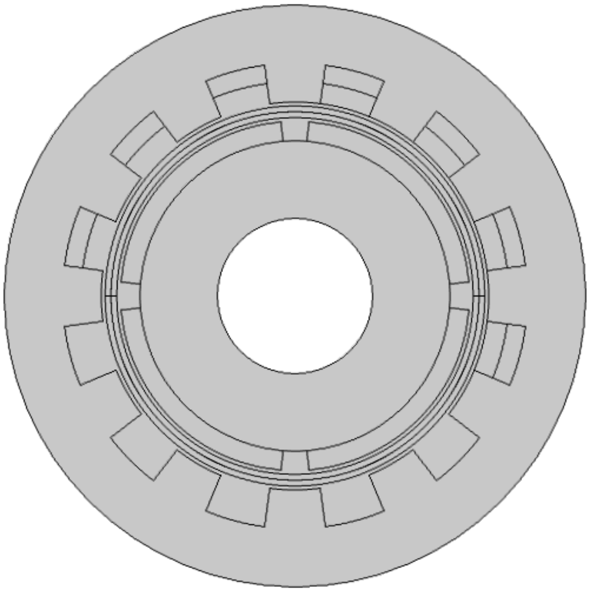


Figure 1. Example topology, including domian boundaries

The loss in any machine is broadly defined as the difference between input and output power. The losses or energy dissipation in permanent magnet synchronous machines can be divided into ohmic losses in the windings, permanent magnet losses and core losses in the stator and rotor cores, which in turn can be divided into eddy current and hysteresis losses, where the permanent magnets will also experience eddy current losses. Mechanical losses will also be present, however these will be neglected for simplicity at this stage, as the rotor rotation in the developed COMSOL model is ”specified as a function of time only, not taking mechanics into account” [3].

A. Winding Losses

Some of the input power is lost as heat dissipation in the stator windings, due to the fact that the conductors have some internal resistance. This resistance can be defined as a DC resistance, expressed as seen in Equation (1)

$$R = \frac{L_w}{\sigma_w A_{cu}} \tag{1}$$

, where L_w is the winding length, σ_w the conductivity and A_{cu} is the conductor area. The ohmic lossthat results from this resistance can be expressed as $P_w = I^2 R$, often referred to as Joule heating or resistive power loss [5]. Hence the winding losses are dependant on the winding dimensions as well as the running temperature of the machine as the conductivity is temperature dependent.

In addition eddy currents will be induced in the conductors of alternating current machines, according to Lenz's Law, and the power loss due to these currents appears as an increase in winding resistance. The increase in losses due to this phenomenon is often calculated as a ratio or percentage of the ohmic losses and added to the total loss. However winding types and configurations that minimize eddy currents are available [6] and for simplicity the possible eddy current losses in the windings will be neglected in the implementation.

B. Core Losses

In a PMSM, energy dissipation occurs in the stator and rotor cores due to hysteresis and eddy currents. These phenomenon occur as the machine cores composed of ferromagnetic materials are exposed to a time varying excitation.Usually the combined sum of these losses is measured as they are difficult to separate experimentally and the combined loss is usually termed core loss or iron loss [4]. The core losses are dependent on the flux density, and different parts of the machine structure are exposed to different flux density amplitudes, waveshapes and frequencies of excitation, due to the varying magnetic field. Therefore accurate core loss calculations will have to take into account the time-varying aspect of the field as well as the flux density characteristics in the different parts of the machine [7].

”Traditional” core loss estimation methods have been inaccurate as the elemental variation in flux density has not been sufficiently accounted for. Where traditional core loss data is based on experimental data provided by lamination manufacturers. Another somewhat traditional approach uses some representative areas of the rotor and stator core with similar variation in B-field for calculating the core loss. The reason for the use of ”traditional” methods is that elemental analysis greatly increases the complexity of calculating the core losses and the traditional core loss data has been considered an adequate approximation [8][4]. However improvements in computing ability of FEA programs has made it possible to consider the machine on an element basis and hence also the flux density variations. Being able to evaluate the machine on an elemental basis will give among other things a more accurate representation of the variation of the B-field in every part of the machine and therefore also a better foundation for calculating accurate losses.

The total core losses are due to hysteresis and eddy-current losses in the teeth, stator and rotor yoke. Theoretically the separation method, based on Steinmetz equations, where eddy current and hysteresis losses are evaluated separately, is commonly used to calculate core losses and will therefore be presented as the central method here [1][4][5][7].

Hysteresis occurs as ferromagnetic materials consists of domains, small regions where the magnetic properties of the material are aligned. When the material is not exposed to any external excitation the domains are arranged randomly such that the net resultant magnetic field of the material is zero. If an external magnetic field is applied to the ferromagnetic material the domains will align according to the magnetic field, however even if the field is removed not all domains will return to their original alignment and the material becomes slightly magnetized, and will stay magnetized unless an external field of the opposite direction is applied. Therefore when an alternating field is applied some extra work needs to be done for every reversal of the field to align all of the domains and losses will therefore be induced. This is known as hysteresis loss and is dependent on the material and B-field properties and is widely estimated as shown in Equation (2) for loss per volume.

$$P_h = k_h f B^n \tag{2}$$

Where k_h is the hysteresis coefficient, which is a constant dependent on the material properties and dimension, f is the excitation frequency, B is the flux density and n is a material dependent exponent between 1.5-2.5.

Eddy current losses are caused by induced electric currents within the ferromagnetic material due to the time varying magnetic field. These induced eddy currents will circulate locally within the material and power is dissipated as heat due to resistivity in the material. The eddy current power loss per volume is approximated as shown in Equation (3)

$$P_e = k_e f^2 B^2 \tag{3}$$

, where k_e is the eddy current coefficient, which is a material dependent constant and as can be seen for the eddy current losses, the power loss is proportional to the square of both the frequency and the maximum flux density.

The total core loss in the laminated cores of the electrical machine will be the sum of the hysteresis and eddy current loss components and gives the total core loss as shown in Equation (4).

$$P_{core} = k_h f B^n + k_e f^2 B^2 \tag{4}$$

Due to the frequency dependencies it is expected that hysteresis loss dominates at low frequencies and eddy current losses at high frequencies [4].

C. Losses in the Permanent Magnets

Eddy current losses induced in the permanent magnets of synchronous ac machines have often been neglected ”since the fundamental air-gap field usually rotates in synchronism with the rotor and time harmonics in the current waveform and space harmonics in the winding distribution are generally small”, and the magnets therefore don’t experience a time varying field and no eddy currents of significance are induced [9][10]. However the development of PMSM towards fractional wound machines to improve performance, in terms of for instance torque density, reduced torque ripple, modularity and higher efficiency, results in time and space harmonics of the stator current [11]. In other words ”the fundamental magnetomotive force”, the ”force” driving the magnetic flux through the magnetic circuit, F $= \int H \cdot dl$ [At], has fewer poles that the permanent magnet rotor. This causes the ”torque to be developed by the interaction of a higher order stator space harmonic MMF with the field of the permanent magnets. The lower and higher order space harmonics rotating at different speeds to that of the rotor magnets can induce significant eddy currents in the magnets and incur loss” [9][10].

Hence significant rotor eddy current losses can be induced in the permanent magnets of machines with high harmonic content [9] where fractional slot machines fall into this category. Fractional slot machines have fractional a number of slots per pole per phase, see Equation (5).

$$q = \frac{slots}{poles \cdot phases} = \frac{Q}{p \cdot N_{ph}} \tag{5}$$

Concentrated winding, CW, machines are always fractional since $q<1$, while distributed winding machines can be either fractional or integer wound as $q \geq 1$. Fractional slot wound machines have become popular as they allow greater flexibility in design and can provide many performance benefits, but as mentioned can introduce large harmonics as well [12], which also needs to be taken into account for design and operation. For example large eddy-current losses in the magnets will cause a significant temperature rise and can damage the machine and ”result in partial irreversible demagnetization of the magnets” unless appropriate cooling is implemented [12].

The induced losses in the magnets should be calculated as they can be significant. The method of calculation is based on rare-earth magnets, as they are nowadays used in most PMSM, where these magnets have a relatively low electrical resistivity and relative permeability. This gives the assumption that the induced eddy currents can usually be considered resistance limited as ”for most practical machines the skin depth at the inducing frequencies is significantly greater than both the magnet pole-arc and radial thickness” [12]. The loss can therefore be calculated directly from the armature reaction field inducing resistive losses.

The question of whether the permanent magnets will also experience significant hysteresis losses has been disputed and in most cases assumed to be insignificant and will therefore not be taken into consideration for the implementation [13].

III. CORE LOSS CALCULATION METHODS

There are quite a few proposed methods for calculating stator, rotor and magnet losses in PMSMs. Experimental methods to create loss curves, where loss values can be extrapolated, have traditionally been largely used. However the pursuit for more accurate results and integrated calculation methods to be used in the design process has led to the development of newer models. Quite a few of the methods are based on the Steinmetz equations, where the field may be calculated in different ways. It seems the most widely used methods today are different variations of the basic model proposed in section II-B, and while analytical methods dominated earlier, the advancement in computing ability has made the use of numerical and FEA methods advantageous in many aspects. This section will investigate different methods used to calculate core and magnet losses in PMSMs.

A. Traditional core loss data

Traditionally loss data has been obtained experimentally by the lamination manufacturers based on Epstein form measurements. Where the lamination material is exposed to a sinusoidal magnetic field with various amplitudes and frequencies, giving loss values per unit weight. These data provide a combined iron loss, in other words, eddy current losses and hysteresis losses are not separated. The machine designer then has access to the experimental data presented in loss tables or curves for specific laminations and can extrapolate loss values for wanted frequencies and B-field values [2][8][14]. Loss curves are also used to determine loss coefficients, as needed in the core loss equations presented in section II-B, by polynomial curve fitting or extrapolation of values in loss tables [1].

As this method only measures loss of lamination sheets it does not take into consideration the complexity added when the laminations are incorporated into electrical machines, where the machine dynamics as well as the treatment process of the material has an effect on the losses. It has been shown that loss estimation using the traditional core loss data method estimates losses lower than the measured values of real machines. Where the underestimation is due to waveform distortion in comparison to sinusoidal excitation, ”the complexity of the electrical machine structures and to the complex behaviour of dynamic hysteresis loops” [1].

To improve the accuracy of loss estimations and calculations in comparison to this traditional approach the magnetic field characteristics at any point of the complex electrical machine structure need to be considered. This is where the numerical FEM models come in, together with the definition of the loss coefficients based on manufacturer loss data and experiments of real machines to validate the models [1]. Indicating that the traditional loss data provided by the steel manufacturers and actual experiments of specific machines is still important for extraction of loss coefficients as well as validation of new loss calculation models.

This traditional method is experimental and therefore difficult to integrate directly into the design process of a complete machine. However the possibility of incorporating traditional loss data, through coefficients or loss values directly, with FEM modelling could provide good estimations, this will be discussed in the next sections.

B. Incorporating FEM and traditional loss data

In a previous master thesis on ”Design of Large PM-Generators for Wind Power Applications [6], a ”new method for iron loss calculations” is proposed where FEM modelling and programming is used to model and evaluate the losses. COMSOL is used to model the machine and find the B-field values for each element for each time step of the simulation. Thereafter the COMSOL results are exported to MATLAB where several scripts create a signal of the B-field values, loop through all the elements of the machine, extrapolate core loss values for the elements using lamination data and then sums up the core losses for the entire model, over one time period.

A step by step algorithm for the loss calculation is presented below:

1) An evaluation of the B-field in each element for each time step of the simulated machine model, where the B-field’s x- and y-component for each element needs to be extracted for further calculations
2) Converting the B-field data into a signal varying around zero as COMSOL usually returns the absolute value of the B-field
3) Creating a reference direction for the B-field in the direction where the maximum amplitude of the signal dominates such that the B-fields values can be aligned to create the signal for each element for each time step
4) A choice between running a Fourier analysis on the created signal data or directly using the signal data to calculate the loss is taken.

5) In both cases to calculate the loss of the entire model the algorithm must loop through the created B-field signal for all the model elements.
6) Lastly the results of the Fourier analysis are run through a script containing lamination loss data, where loss for each result of the Fourier analysis is extrapolated and lastly summed up for the entire evaluated domain

Basically the main script finds lamination loss of an input domain number from a FEM structure. Which is done by analysing the flux density of each element, and finding the loss per element based on the flux signal. The sum of the loss of a number of harmonics returned from a Fourier analysis of the flux signal is assumed to be the total loss of each element. The sum of all these element is in turn assumed to be total loss for the domain.

This method ensures that the elemental and time varying flux density is taken into account by integrating the finite elemental method with traditional loss data. This will ensure a more accurate loss representation as the dynamic properties and the interactions of the entire machine are taken into account. Some development of the model to eliminate initial design bugs was done and the model has been used with satisfactory accuracy at a business level of machine design.

C. Investigation of iron loss methods

A great deal of research and development into core loss methods is being conducted as accurate calculation of core losses is increasingly important both in the role of improving the quality of the electrical steels used in the machines as well as improving the overall efficiency and the accuracy of loss estimations. To improve the core loss estimation models, the overall machine dynamics have to be taken into account and the estimation process should be integrated into the design process such that machine optimization can also take place at this stage with satisfying accuracy.

The most common core loss calculation method, presented in section II-B, is extensively presented in literature and currently most widely applied in commercial FEM implementations. However since it is very simplistic it's accuracy is only satisfactory and deviations become larger for more complex machines. Accordingly "new" methods and variations of the traditional method are being investigated to try and eliminate it's disadvantages [1][15][16][17]. Some of the more advanced loss calculation models may seem very promising when considering the theoretical improvement of accuracy of the calculations, however the implementation into FEM simulation can be quite complex and the feasibility in this regard must also be considered.

[16] gives an overview of available iron loss models, see Figure 2, and generally concludes that the models based on the Steinmetz equations and the loss separation models, often termed Jordan or Bertotti, are preferable and best suited for fast and rough iron loss determinations as well as comparison of different materials on the machine performance when a specific electrical machine i chosen. These models can easily be integrated in finite-element simulations, as post-processing techniques, where the flux density variation B(t) is determined for each element by the FEM.

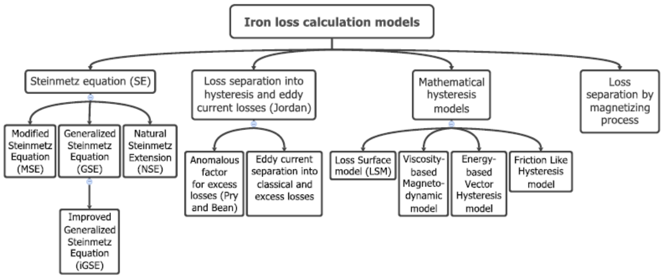


Figure 2. Model approaches to determine iron losses in electrical machines [16]

Generally core loss models can be can be classified under two main categories, post-processing techniques and techniques that incorporate the losses into the magnetic field solution, the later being more advanced. [15] investigates three core loss calculation methods with regard to accuracy, efficiency, stability and the advantages and disadvantages of implementation into FEM modelling. The traditional model based on loss separation theory, which is in the category of post-processing techniques, is investigated with the conclusion that is does provide the advantages of simple simulation of the magnetic field, few material parameters are needed and the the accuracy of the calculated core losses integrated over the volume of the machine are quite satisfactory. However the limitations of this method are commonly acknowledged and the accuracy of the method is limited to certain frequency, voltage and flux density ranges, where the method is suited for low-frequency applications as it's derivations are based on neglecting the skin effect. Other disadvantages of the model are that rotational losses are poorly estimated by post-processing methods, and the effect of minor hysteresis loops, resulting from harmonics, are also not modelled properly and can cause further inaccuracies [18]. However the models simplicity and stability over a large range of machines is a crucial factor for it's success and popularity.

[15] also presents an advanced technique based on solving the one-dimensional Maxwell equations, which determines the core losses by modeling the magnetization curves and hence the ensuing core losses are also investigated. However although the accuracy is higher the implementation into FEM is complex and the simulation is very time consuming and the method is also vulnerable to convergence problems. Highlighting that all aspects of the method, from theory to implementation need to be taken into account.

Lastly a hybrid technique is presented, which models hysteresis loop shapes, however in a much simpler way than the advanced method. The conclusion to this method states that modelling the magnetodynamic vector hysteresis behaviour is gives good results in connection with FEM modelling of complete electrical machines. Giving promise to the method of modelling the dynamic loop shapes for production of accurate and stable results.

The simpler separation method provides simplicity and stability while higher accuracy can be achieved by incorporating the losses into the field solution, which is shown to be feasible using the presented hybrid technique in [15]. It is efficient from a computational viewpoint and also provides stable and adequate results over a wide range of voltages when modeling the eddy currents in a rotating electrical machine, where the flux is usually highly distorted. However more information on material properties are required and the implementation into FEA is more complicated than the traditional approach since it is not a post-processing method.

The traditional core loss calculation method, often termed the separation method or the ”engineering approach” separates the core losses into eddy-current and hysteresis losses as presented in section II-B. [1] presents several ”improved” models based on the loss separation approach, to try and better the accuracy, account for excess loss and consider flux harmonics. As the commonly used loss formulas, referred to as the basic loss separation as seen in equation (4), are limited and not accurately applicable at high flux densities and frequencies. The consideration of the dynamic hysteresis loop is also important in the accuracy of the results. Generally the improved methods try to account for the fact that the loss coefficients are not actually constant with frequency and that the dynamic properties, where the static hysteresis loop and the dynamic hysteresis loop are different and the excess losses account for the dynamic eddy-current losses, need to be accounted for to improve the accuracy of the results.

The first modification proposes an exponent coefficient for the hysteresis loss, such that it changes linearly with flux density. Giving a modified core loss formula as shown in Equation (6), where a and b are constants, derived from core loss curves similarly to the standard loss coefficients. This extended hysteresis model is proposed to account for the dynamic properties of the hysteresis loop. The results showed that the model gave slightly improved correlation with experimental data, however as with the basic model it also deviated for high frequencies and flux densities.

$$P_{core} = k_h f B^{(a+bB)} + k_e f^2 B^2 \tag{6}$$

Another extension to the basic model to include excess losses, shown in Equation (7), is also investigated. This is a commonly known extension and is among others also presented in [16].

$$P_{core} = k_h f B^n + k_e f^2 B^2 + k_a f^{1.5} B^{1.5} \tag{7}$$

The last term in (7) represents the excess losses with k$_a$ as the excess loss coefficient, which is material dependent like the other coefficients. This method gave generally good agreement with several loss experiments, however deviations were also observed, where it is seen that k$_a$ might not truly be a constant, but has some dependency on flux density.

The modified method including excess loss gave the best correlation, in comparison to the traditional core loss formula and the extended hysteresis model, when compared to measurement and experimental data. The deviations for all three models are shown to be largest for high flux densities of above 1.2 Tesla as well as high frequency simulations.

Lastly a model dealing with frequency dependencies is presented since the loss coefficients are shown to actually be frequency dependent. This results in discrepancies between the experimental and the results of the proposed formulas using loss data where the coefficients are assumed constant. It is shown that the eddy current coefficient k$_e$ decreases with frequency because of the skin effect, which decreases the conducting area and in turn decreases the eddy current loss. The hysteresis loss coefficients k$_h$ and n increase with frequency, which indicates that the hysteresis loop area changes. Lastly, the excess loss coefficient k$_a$ is supposed to be unchangeable, however this might not be the case either, as it has been shown to have a dependency on flux density [1].

The formula presented where the frequency dependencies are taken into account shows good results, however it is more complex and more material data and parameters need to be extracted from the loss curves given by the material manufacturers. Nonetheless this shows that theoretically quite accurate models based on the separation approach can be obtained, however in this case the feasibility of incorporation into FEM modelling is not investigated in the article.

For estimation and calculation of core losses, measurement results and lamination data are still needed with numerical approaches. For instance to determine loss coefficients, where the amount and the specific data needed depends on the iron loss method used. The different approaches based on the Steinmetz equation and their coefficients offer a simple and fast way to predict the iron losses. The coefficients are either directly supplied by the manufacturer or can be obtained by curve fitting of the manufacturers loss curves for the chosen lamination material. Some of the drawbacks of this simplistic approach is that the coefficients are known in reality to vary with frequency and the accuracy even though stable for many types of implementation generally have a lower accuracy than the more advanced models. In contrast complex hysteresis loss models provide more accurate results, however much more material data and knowledge about the flux density waveforms are needed as well as the complexity and simulation time increases drastically for integration into FEM software.

IV. THE COMSOL MODEL

The developed COMSOL model, which the loss functionality is to be implemented on, is a parametrized permanent magnet synchronous machine with internal rotor, radially magnetized permanent magnets with a slotted, lap wound single or double layer stator. The number of poles and slots can be user defined as well as other geometric parameters [3].

The original thought was to implement the method presented by Lagerstrom [6], but implemented solely in COMSOL, such

Table I
BASIC LAYOUT PROPERTIES FOR SIMULATION OF TWO EXEMPLARY MACHINES

	Machine 1	**Machine 2**
Type	DW Integer	DW Fractional
Poles, p	4	4
Slots, Q	12	18
q	1	1.5

that a fully integrated design solution can be made. This is wished to improve user friendliness and program value where the model can be delivered to the user as a small package. However following thorough investigation of the method it was concluded that implementation solely in COMSOL would prove difficult as it is dependent upon scripts where lamination data is extrapolated as well as the alignment of the B-field signal which relies upon MATLAB commands. It may well be possible, but requires a much more in depth knowledge of COMSOL and it's possibilities and was found to be to extensive of a job. Therefore it was chosen to base the implementation of the core loss calculation on the separation method, where core loss is separated into hysteresis and eddy-current losses as done in equation (4). Using this method also allows for the possibility of later expanding the model to include for instance excess losses if the user has access to the needed material dependent parameters. As discussed above, in Section III-C, the separation method is widely used and has proven satisfying results in combination with FEM modelling, especially for models where the frequency and flux density values are relatively low. The model requires the least amount of material data and is therefore chosen as few material parameters are known, since the simulation will deal with exemplary machines and no specific machine or materials have been stated, as the implementation on a general machine is wished as well as the development and testing of the PMSM model.

A. Component, Parameters and Material properties

Some parameters are needed for the loss calculation simulation, where the general machine parameters used will be the model default values. Material properties need to be given to the different machine domains, where permanent magnets, conductors, iron and air domains are given properties, where only air and soft iron (without losses) were implemented in the original model as losses were neglected.

Two machine configurations will be investigated, one integer and one fractional wound machine, referred to as machine 1 and machine 2, whose basic properties are given in Table I and layouts shown in Figures 3 and 4 respectively. The remaining properties, such as dimensions and winding parameters, are chosen to be the default values that the model is set up with, see Appendix I for a summary of the main parameters and the winding configurations.

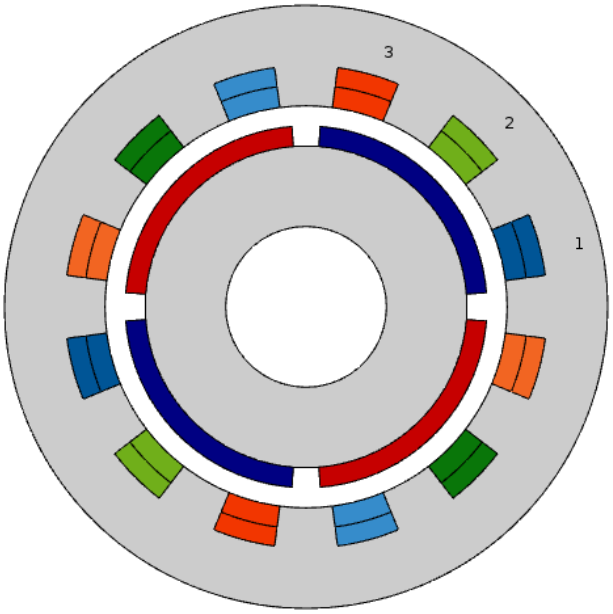


Figure 3. Winding configuration of a 12 slot, 4 pole integer wound machine

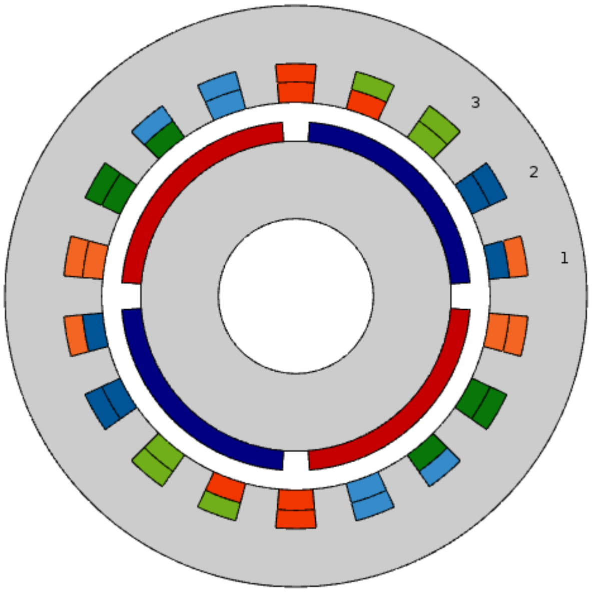


Figure 4. Winding configuration of a 18 slot, 4 pole fractional wound machine

The material properties are defined as global parameters such that they can be accessed and changed by the user. Built in materials are used, with some added material properties in the case of the permanent magnets and the iron cores. The conductors are given the properties of copper, the iron cores are modelled as an exemplary lamination material of silicon steel and the permanent magnets are added as a blank material with the properties of sintered neodymium magnets, NdFeB, as these are typical magnets used in PMSMs. Air is applied as the material to the remaining model domains. Table II shows typical and implemented material values for the permanent magnets. For the iron cores an exemplary lamination type of Silicon Steel will be used, available in the built in materials library in COMSOL, with the added parameters shown in Table III. In addition for the iron cores the loss coefficients are not part of the material properties and need to be set separately as global parameters that can be accessed by the entire model and be specified by the user.

The iron cores are assumed laminated, to minimize eddy-currents and the corresponding losses, and the electric conductivity is therefore reduced from the built in value. Theoretically electric currents do not flow from one lamination to another and the conductivity can be set to zero, however this causes convergence problems in the model, and may not quite hold for realistic models so the conductivity is set to a low number above zero.

Table II
MATERIAL PROPERTIES OF SINTERED NEODYMIUM MAGNETS [7]

Property	NdFeB	Chosen values
Relative permeability, μ_r	1.05	1
Density, ρ	7.3-7.5 [g/cm^3]	7650 [kg/m^3]
Resistivity, $\mathcal{R}$	(110-170)$\cdot 10^{-6}$ [Ωcm]	-
Conductivity, σ	(0.59-0.9)$\cdot 10^6$ [S/m]	0.714$\cdot 10^6$

Table III
MATERIAL PROPERTIES OF THE SIFE LAMINATED CORES

Property	SiFe
Electrical conductivity, σ	10 [S/m]
Relative permeability, μ_r	5000

The material dependent loss coefficients need to be defined such that the loss calculations can be carried out. Exemplary values are chosen, with the hysteresis and eddy current coefficients set to k$_e = 1.497$ [s^2] and k$_h = 0.014$ [s], in accordance with the modelled silicon steel lamination.

Copper properties are to be set for the conductors such that winding losses can be calculated, however there is some mismatch of the winding domains and the way the winding configuration is drawn in the application, as seen in Figure 3. In the development of the original model without losses the material choice for conductors was arbitrary, as the External Current Density-feature causes the conductors to carry the specified current regardless of material properties, which might lead to problems defining the correct properties to the correct domains when losses are to be added. It is therefore not straight forward which domains are to have the material properties of copper, nonetheless it is chosen that the domain selection labeled conductors are given these properties, while the rest of the slots that seem to lack conductors are given the properties of air, as they are a part of the same domain as the outermost section of the air gap. The conductor domain selection is shown in Figure 5. However the model and the application should have the same characteristics, even thought the visualization might not be quite the same, the selection should correlate with current carrying conductors.

Collectively, the chosen material values used in the model are chosen as best possible to represent typical and common materials used in PMSMs to illustrate the concept and to be able to simulate and generally evaluate the model.

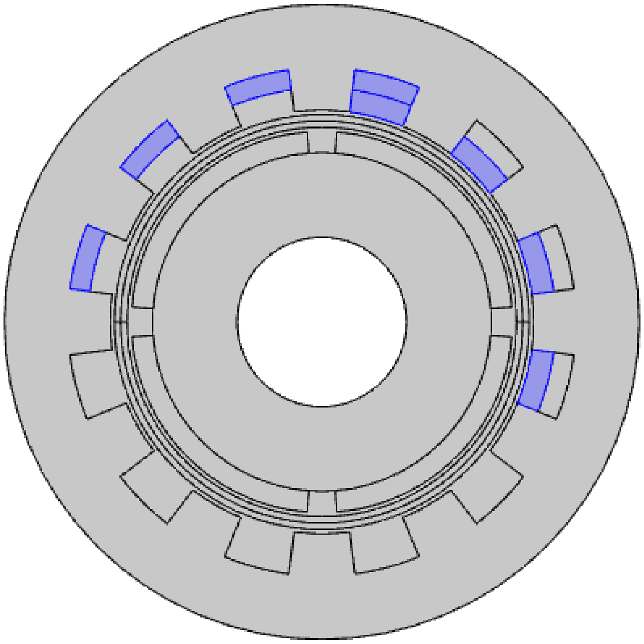


Figure 5. Conductor domains highlighted

V. IMPLEMENTATION

The discussion in section III-C shows that incorporating FEM and the classic Equation (4), or a variation including excess losses, for calculating core loss can give a fair approximation of the core losses. The ”engineering” method of the separation method based on Steinmetz equations is chosen as it requires the least material parameters to be known and in this case no specific material data is given such that estimation will be simplest when few parameters are needed.

The entire functionality is wished to be integrated as a complete simulation solution in COMSOL. This can be done by defining variables in the component node, and these variables, which can be an expression, will be evaluated for each element and over one time period or a specified time interval when the model is run.

The modelling in COMSOL has a tree configuration, where the simulation follows a successive order through the branches and nodes. The main branches of the modelling tree are *Global Definitions*, *Component*, *Study* and *Results*. Most of the model functionality is programmed under the component branch, such as geometry, variables, materials and the rotating magnetic machinery characteristics. Paramters and variables defined in global definitions can also be accessed in the component branch. The study node is used to define what type of study to be run, where in this case a Time Dependent study is used, with time dependent and Fourier transform solvers, elaborated in the next section. The results branch allows for post processing and visualization of the model simulation.

The physics node *Rotating Machinery, Magntic (rmm)*, located in the component branch, is used to define all the physical properties for specified domains and boundaries, that are needed for the coupling of the model with the FEM modelling. ”The physics interface solves Maxwell’s equations formulated using a combination of magnetic vector potential and magnetic scalar potential as the dependent variables” [19].

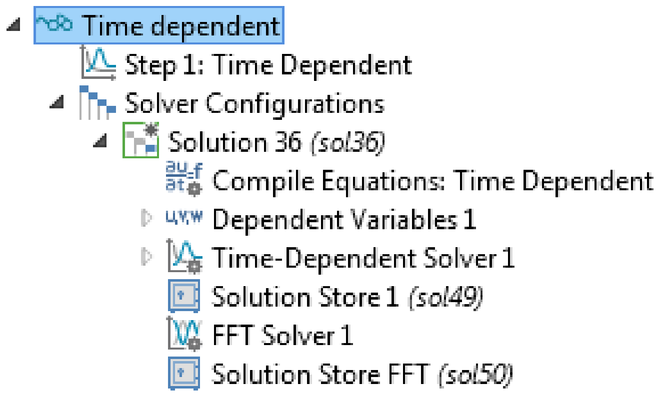
A. *The Algorithm for Calculation of the Iron Losses*

As the iron losses are dependent on the magnetic flux density field strength at any given point, the B-field, as well as the system frequency and the lamination material properties need to be available for the core loss expressions, which are defined as variables of the component, namely the machine being modelled. The flux density distribution is generated by FEM simulation of the model in COMSOL and the loss calculation is a post-processing of this flux density.

The implemented algorithm is based on coupling the separation method with FEM modelling. The expressions for hysteresis and eddy-currents losses, which are functions of magnetic flux density, are defined as variables under the component branch in COMSOL. The variables will, when the model is run, be evaluated across all elements of the component. These variables can then be post-processed in the results node, where the resulting values can be viewed directly as derived values presented in tables or by graphical representation.

To investigate the model a time dependent study is run and the components of the flux density, B$_x$(t) and B$_y$(t) are evaluated for each element of the model for time step of the simulation.As the x- and y-components of the magnetic flux density are available from the solution, a function is needed to obtain a representative amplitude of the B-field to plug into the core loss equation. In other words some signal processing of the magnetic field is needed since it’s direction varies with time in the iron. As discussed earlier Lagerstrom [6] produced a complex script where the B-field signal was aligned to the most common direction of it’s components. However for the loss separation method the directionality of the flux density is not needed for the calculation. Therefore ”assuming a 2-D field, the amplitude of the flux density can be represented as $B_m = \sqrt{{B_{xm}}^2 + {B_{ym}}^2}$ ” [15].

To account for harmonic content the frequency spectrum of the representative flux density component, B$_m$ is evaluated by running a fast Fourier transform solver following the time dependent evaluation. Where ”the FFT solver performs a discrete Fourier transformation for time-dependent or frequency-dependent input solutions using fast Fourier transform” [19]. A forward FFT solver is used in this case, which transforms a time-dependent solution from the time domain to the frequency domain. For the relevant simulation only the Time Dependent study branch of the model is used where the FFT solver is added as a study step, see Figure 6 for a visualization of the study node steps, where stored solutions are used so that both time dependent and frequency dependent variables can be evaluated without having to run two separate studies. However this solver configuration results in a lengthy computational time of numerous hours, which is a disadvantage if the functionality is to be integrated into the application as a simple and fast solution is wanted. The possibility of implementing two separate study steps should be considered for further development. However this comes with the disadvantage of only one solution, either time or frequency, being available for evaluation at a time.



- Time dependent
  - Step 1: Time Dependent
  - Solver Configurations
    - Solution 36 *(sol36)*
      - Compile Equations: Time Dependent
      - Dependent Variables 1
      - Time-Dependent Solver 1
      - Solution Store 1 *(sol49)*
      - FFT Solver 1
      - Solution Store FFT *(sol50)*

Figure 6. Screen shot of the study node used to run the loss functionality calculations

The actual implementation of the core loss calculations is done in the variables node of the component branch. The total power loss per unit volume, due to core losses, is implemented as the sum of hysteresis and eddy-current losses. The loss components are calculated separately and added in a third variable for total loss, a representative evaluation of the calculation is seen in Equation (8)

$$P_{core} = \sum_{m=1}^{N_h} k_h(mf)B_m^n + k_e(mfB_m)^2 \qquad (8)$$

, where B_m is the amplitude of the mth harmonic of the flux density waveform, obtained by the time-stepped FEM and Fourier analysis and N$_h$ is the total number of harmonics considered. Implementing this evaluation of the losses with integration over the area of the iron ensures that the B-field component is evaluated at each node of the iron domains in the model. The eddy-current and hysteresis losses are evaluated using expressions, in the variables node, and since the formula gives losses per unit volume, the loss components are integrated over the area of the iron domains and multiplied by the axial length of the machine to obtain the loss values. The integration over the iron domain area can either be implemented directly in variables by using probes for integration or simply evaluated per volume where the resulting loss values can be calculated in *Derived Values* under the results branch by integration over the iron area and multiplied by the length of the machine, following the simulation of the model. In this case both versions are implemented such that the losses per volume are available for possible post-proccessing evaluations.

An overview of the variables implemented for calculation of all the loss components can be seen in Appendix II.

B. Permanent Magnet and Winding Losses

As discussed in section II-C, the permanent magnets can with reasonable accuracy be assumed resistance limited. The modelling of the permanent magnet and winding losses can therefore be implemented in the same way.

A integration type domain probe for the area under consideration is defined and evaluated using the built in expression for resistive losses. This expression is found as part of the rotating magnetic machinery physics of the model, where quite a few built-in expressions can be accessed, and is called using *rmm.Qrh*. Since this probe evaluation gives a loss per length, a further evaluation is implemented in variables. Where an expression taking the time average of the probe evaluation and multiplying it by the length of the machine is done such that a final loss value is calculated during the time dependent simulation, see Appendix II.

In addition a restriction needs to be set on the magnets where a single turn coil condition as implemented in the *Rotating Machinery, Magnetic* node. Ensuring that the net current of each magnet is zero, which makes sure that no current flows from one permanent magnet to another in the simulation. As mentioned the domain selection for the conductors is somewhat uncertain due to the way the model is built, this could therefore have some effect on the outcome of the loss calculations, nevertheless the implementation will be the same.

VI. RESULTS

After the simulation is run and the variables have been evaluated over all the elements, the results are post processed in derived values and plots to visualize the outcome, where the results of the loss calculation implementation is shown for the two machines configurations in Tables IV and V.

Table IV
RESULTING LOSS VALUES FOR MACHINE 1

Loss contribution	Symbol	Value
Eddy current, PM	P_{PM}	80.9 kW
Winding losses	P_w	1.68 kW
Eddy current, iron	P_{eddy}	45.6 kW
Hysteresis, iron	P_{hys}	1.07 kW
Total iron losses	P_{core}	46.7 kW
Total losses	P_{tot}	129.3 kW

The model is run with a discrete, natural FFT, however running the same simulation with continuous, symmetric FFT gives much lower core losses and slightly higher PM losses. The losses for the fractional machine, run with both discrete and continuous solvers are shown in Table V.

Table V
RESULTING LOSS VALUES FOR MACHINE 2, PINREAL 480.4 KW

Loss contribution	Symbol	Discrete FFT	Continuous FFT
Eddy current, PM	P_{PM}	80.9 kW	81.3 kW
Winding losses	P_w	326.4 kW	326.2 kW
Eddy current, iron	P_{eddy}	41.2 kW	0.53162 W
Hysteresis, iron	P_{hys}	0.001 kW	0.00026 W
Total iron losses	P_{core}	41.2 kW	0.53 W
Total losses	P_{tot}	448.5 kW	408.0 kW

Since the windings losses seem excessively large in Machine 2, some manipulation of the conductors is tried where physics properties are added. A multi-turn coil domain condition is added to the conductors, where single turn-coil domain, single- and multi-turn boundary coil conditions were also tested, but had little or no effect on the winding losses. The calculated losses with the multi-turn coil boundary condition are then reduced to $P_w = 0.00463$ W for Machine 1 and $P_w = 0.00694$ W for Machine 2, which in turn may be unrealistically small.

Comparing the core losses of the two machines shows that the fractional slot machine results in lower losses, where the difference in the core losses of the two machines seems to just account for the difference in the iron area that is integrated over, where slots cover slightly more of the iron area in the fractional machine. This puts the method into question as slotting should have an effect on the flux density, whereas in this case it only seems the change in area is taken into account. The theory also discusses that that fractionally slotted machines induce more eddy-currents in the permanent magnets and consequently losses, where the PM losses for the two machines modelled are equal. Running the FFT solver with continuous setting results in core loss values that seem unrealistically small, at least compared to the values of the other loss components.

The rated or input power of the machine is not straight forward to calculate as it seems to be coupled to specific studies, resulting in inconsistent values when evaluated for the time dependent study, which makes the validity of the magnitude of the losses difficult to validate as they are not compared to an input power.

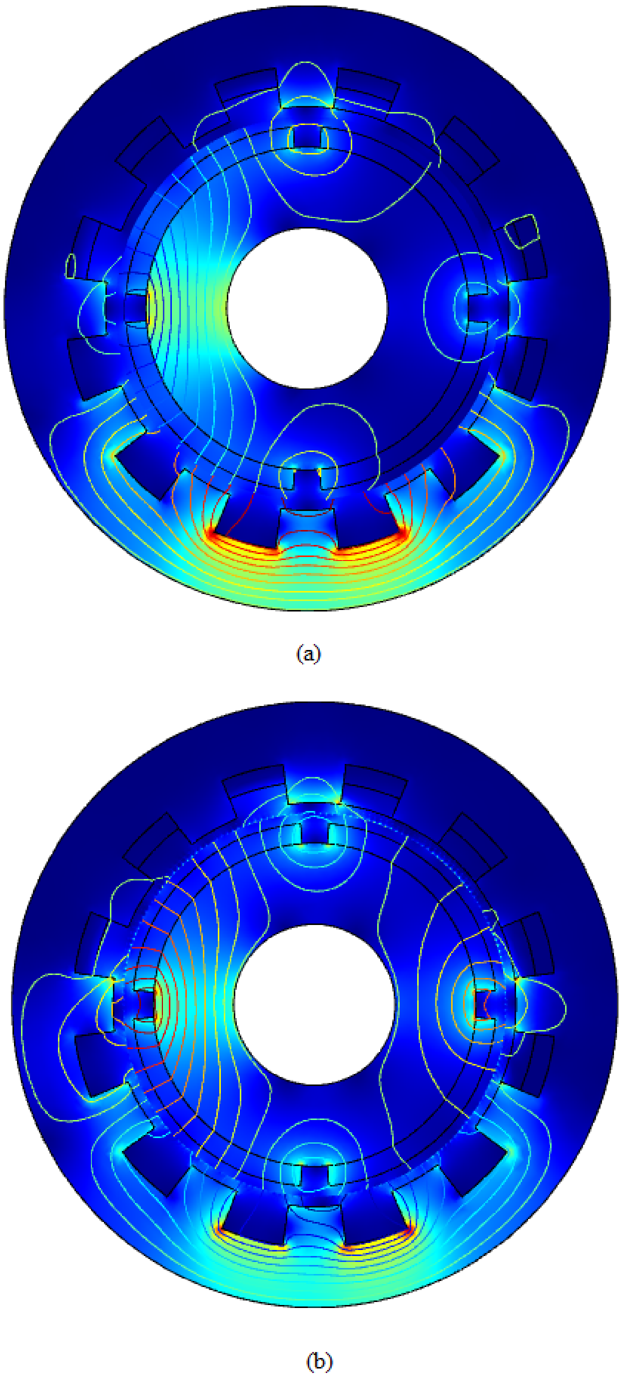
VII. DISCUSSION

The core loss calculation implementation is chosen because it facilitates fast simulation, does not require very much material knowledge and is not overly complex, but this means it is also a rough approximation. However the method has been shown to provide satisfactory results in previous studies incorporating FEM modelling. In this case however, even thought the resultant loss values can seem plausible, trying to plot different distributions and dependent variables shows that there is some mismatch in the interactions within the model. The mentioned differences in the core loss values of the two simulated machines also call into question the implemented method as well as the developed FEM model in the regard to flux density distributions.

The winding losses also seem unreliable, as they are quite small in the simulation of Machine 1, but excessively large in Machine 2, where there is an addition of 6 slots. It is expected that they are somewhat larger when the slots are added, however the increase and the value of the winding losses on the fractional wound machine seem unreasonably large.

Eddy current losses in the permanent magnets have been shown to be substantial and are consequently implemented in the evaluation of losses. The resulting loss values in the magnets show that significant losses are induced in the magnets, which will lead to temperature rise, which can damage the machine and the magnets if excessive and appropriate cooling is not implemented. The implementation of the permanent magnet losses seem to result in plausible values as the magnets can with reasonable accuracy be assumed resistance limited and the implementation of the magnets in the model is consistent. The resistive losses in the windings will also produce heat and cooling measures must take this into account as well.

Overall the validity of the implementation is questionable, although it is based on solid theory that has successfully been coupled with fem modelling. However the interactions of many of the models' properties and features seem to not be working correctly together where some properties disrupt the function of others. The setting of the FFT solver have a large effect on the resulting iron loss values, where scaling and maximum output frequency have been adjusted as best possible to obtain reliable results, however further evaluation is needed confirm the settings, as well as evaluate if the solver itself performs an accurate enough Fourier transformation. The definition and implementation of the windings also seem to have an unwanted effect on the flux density distribution, where the density is accumulating in the areas away from where the conductors seem to be defined, even though coil conditions, which includes insulation, are set. This distribution is shown for an exemplary time and frequency instance correlating with the end of the simulation, in Figure 7, where it can bee seen that the time and frequency distributions are quite similar, however some mismatch is present. However in both cases the distributions show that some of the properties of model, most likely due to the definition and material properties of the windings, are disrupting the interactions in the model, giving an unbalanced result. The absolute value of the flux density by time, for some representative points can be seen in Appendix III, which confirms the unbalanced nature of the distribution.


(a)

(b)

Figure 7. Magnetic flux density distributions (a) Time domain (b) Frequency domain

Many different factors affect the magnitude of the resulting loss values, where in real machines design measures are often implemented to minimize them. Such as the choice of lamination material, lamination stacks and the slot configuration which in reality has a large effect on the flux density distribution. The slotting effect on the magnetic field distribution does not seem to be correctly accounted for in the model as the conductors cause dissymmerty in the distribution. To be able to simulate the model quite a few simplifications are assumed, which makes the model differ from real machines. Where for instance the laminated cores are simply accounted for by setting a low electrical conductivity and the winding configuration is implemented more for the visualization of the coil configuration rather than it's physical properties. For these reasons the simulation will be a simplistic estimation even if the implementation runs smoothly, however this is often good enough for the initial design stage of a machine, although accurate loss prediction is wished. However that requires a more thorough and well connected model, where more in depth knowledge of the simulation program is needed, which exceeds the capacity of this thesis, where time and knowledge did not allow for testing of innumerable designs and methods as the chosen model and implementation was quite demandeding and required a great deal of trial and error.

In the permanent magnets, losses can be reduced by limiting the flow of eddy currents, where segmenting of the magnets can be applied. ”The eddy-current losses in the magnets can be decreased by increasing the number of magnet segments, where the losses are proportional to the square of the magnet width” [11]. Magnet segmentation is not considered in the implementation at this point, but could be considered if further development is to take place, as it is relevant for the design of realistic machines.

The possibility of exclusively implementing the functionality in the time domain should be considered as there is some mismatch between the time and frequency domain solutions, however the effect of harmonics would not be accurately accounted for in that case. The possibility of implementing loss calculation in a totally different way could also considered if the model is to be developed further as the chosen implementation has a lot of disadvantages, such as complex coupling within the model, difficulty of smoothly integrating the Fourier transform and long simulation time even though the model in theory is not very complex. The possibility of implementing the same method but in a different manner could also be considered, for instance a solution using Matlab functions implemented directly into COMSOL as variables is a possibility through *Live Link* ®, since Matlab scripts give a greater freedom of programming, where the Fourier analysis could also be run in Matlab eliminating the need for the FFT solver in COMSOL. However the integration of the functionalities of the different programs could be quite complex and might not solve the interactions within the model, which also need to be dealt with for further development.

For a complete model evaluation optimization is wished also be implemented, however the rest of the model functionality must be satisfyingly accounted in advance. To incorporate ohmic losses in a better way a *Joule Heating* physics node could be added, making the model a *Multiphysics* problem, which increases complexity, but also accuracy as it simulates more realistic conditions where heating is taken into account and necessary cooling measures can be more accurately evaluated.. The end goal of the developed model is to implement it with complete design functionality into the application, however at this stage is does not seem feasible for the loss calculation functionality to be implemented smoothly into the application. As there are too many interactions taking place that do not correlate well and many of the model functionalities are only coupled to specific studies. A more accurate implementation of material properties would also be needed where it is wished that the material properties are included in the application such that the user can specify the exact property values or chose appropriate materials from a preset list, that also include corresponding loss coefficients. Possible further work should also include modelling of real motors, with available measurement data, such that the calculated values of the model can be compared to measured values.

VIII. CONCLUSION

The aim of this master thesis was to investigate loss calculation methods for permanent magnet synchronous machines and implement loss functionality for a machine modelled in the FEM program COMSOL. Using FEM analysis gives the advantages of possible evaluation of the flux density and it’s changes for every element of the machine and the influence of interactions within the machine as a whole, as they have an effect on the flux density distribution. Which in turn ensures that the calculation of the losses is also evaluated across every element.

Accurate estimation of losses is one of the major challenges in electromagnetic machinery modelling. Losses in the windings and the permanent magnets are accounted for by modeling the resistive losses for their corresponding domains, as the magnets can be assumed resistance limited. The method chosen to estimate the core losses is often referred to as the ”Engineering method”, where the core losses are separated into hysteresis and eddy-current losses. This is a well established model and has been shown to give satisfactory results, coupled with FEM modelling, in previous studies. The method was deemed feasible to implement and should in theory give an adequate evaluation of the core losses. However mismatch between the time and frequency domain solutions, as well as the imbalance of the flux distribution, due to conflicting interactions within the model, puts the validity of the implemented functionality into question.

The eddy-current losses in the magnets and the winding losses are both calculated to be relatively large. In the case of the magnets their size and structure affect the losses, where sectioning could be implemented to decrease losses. In the case of the windings there seems to be some complication in the model of how the windings are implemented and their interaction with the overall machine, resulting in unrealistic loss values. The overall results of the loss implementation are inconsistent and the time and frequency dependent solvers do not correlate well. Adjustments need therefore be made for the loss functionality to become a useful part of the model.

Suggestions for further work would be to evaluate the possibility of improving the accuracy of the implemented functionality, for instance by exclusively modelling the losses in the time domain. As well as the possibility of incorporating a more accurate Fourier analysis, with for instance the use of functions run through Matlab that carry out Fourier analysis and signal processing, as the built-in Fourier transform in COMSOL is shown to be problematic. Alterations of the models winding configuration and definitions should also be carried out to attempt to balance the interactions within the model.

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IX. APPENDICES

Appendix I: Dimensions and winding configurations

Table VI
DEFAULT MACHINE DIMENSIONS

Parameter	**Symbol**	**Value**	**Unit**
Axial length	L	0.1	m
Stator outer radius	RsOut	0.15	m
Stator inner radius	RsIn	0.1	m
Rotor outer radius	Rr	0.08	m
Rotor inner radius	Rr0	0.04	m
Slot depth	Sd	0.02	m
Relative slot width	Sw	0.5	-
PM flux remanence	PMbr	1	T
Height of PMs	PMh	0.01	m
Relative width of PMs	PMw	0.9	-
Radius of PM placement	RrPM	Rr	m
Parallel connections per phase	Npar	1	-
Turns per coil	Nturns	100	-

Table VII
COIL CONFIGURATION OF MACHINE 1, WITH AUTOMATICALLY GENERATED COIL SPAN OF 3

Slot	**+**	**-**
1	A	A
2	C-	C-
3	B	B
4	A-	A-
5	C	C
6	B-	B-
7	A	A
8	C-	C-
9	B	B
10	A-	A-
11	C	C
12	B-	B-

Table VIII
COIL CONFIGURATION OF MACHINE 2, WITH AUTOMATICALLY GENERATED COIL SPAN OF 5

Slot	**+**	**-**
1	A	B-
2	A	A
3	C-	C-
4	B	C-
5	B	B
6	A-	A-
7	C	A-
8	C	C
9	B-	B-
10	A	B-
11	A	A
12	C-	C-
13	B	C-
14	B	B
15	A-	A-
16	C	A-
17	C	C
18	B-	B-

Appendix II: Variables and their expressions

Table IX
VARIABLES FOR LOSS FUNCTIONALITY

Name	Expression	Unit
Bx	rmm.Bx [1/T]	
By	rmm.By [1/T]	
Bm	$\sqrt{B_x{}^2 + B_y{}^2}$	
eddy	$K_e \cdot B_{xy}{}^2 \cdot freq^2$	
hys	$K_h \cdot B_{xy}{}^{1.6} \cdot freq$	
Peddy	IntopIron(sum(with(index,eddy),index,1,fn))·L [W/m^3]	W
Phys	IntopIron(sum(with(index,hys),index,1,fn))·L [W/m^3]	W
Pcore	Peddy+Phys	
fn	(f_{max}/F_s) [s]	
Fs	(1/T) [s]	
Ppm	timeavg(0,T,dom7,'nointerp')·L	W
Pw	timeavg(0,T,dom8,'nointerp')·L	W

The variables defined in the above table facilitate loss calculation. Some COMSOL commands are used implement the core loss calculation, where an array of frequency and B-field values are available as a result of the FFT simulation. The number of frequencies to evaluate is set by the variable *fn* which is a function of a chosen maximum frequency, specified as the maximum output frequency of the FFT solver, and the sampling frequency F_s. The sampling frequency depends on the time period, *T*. The with()-command accesses frequency contributions by index, and the sum()-operator sums up all the contributions from 1 to *fn*. The losses are then integrated over the iron area by defining an integration *IntopIron()*, which is defined in the *Component Couplings* node of the component branch. Lastly the expression is multiplied by the length of the machine. The units in brackets are used to force and eliminate units for the expressions to result in correct units such that no issues of non-matching units arise. For the permanent magnet and winding losses the expressions *dom7* and *dom8* represent domain probes that evaluates the resistive losses *rmm.Qrh* integrated over the area of the chosen domain.

Appendix III: Flux density variation

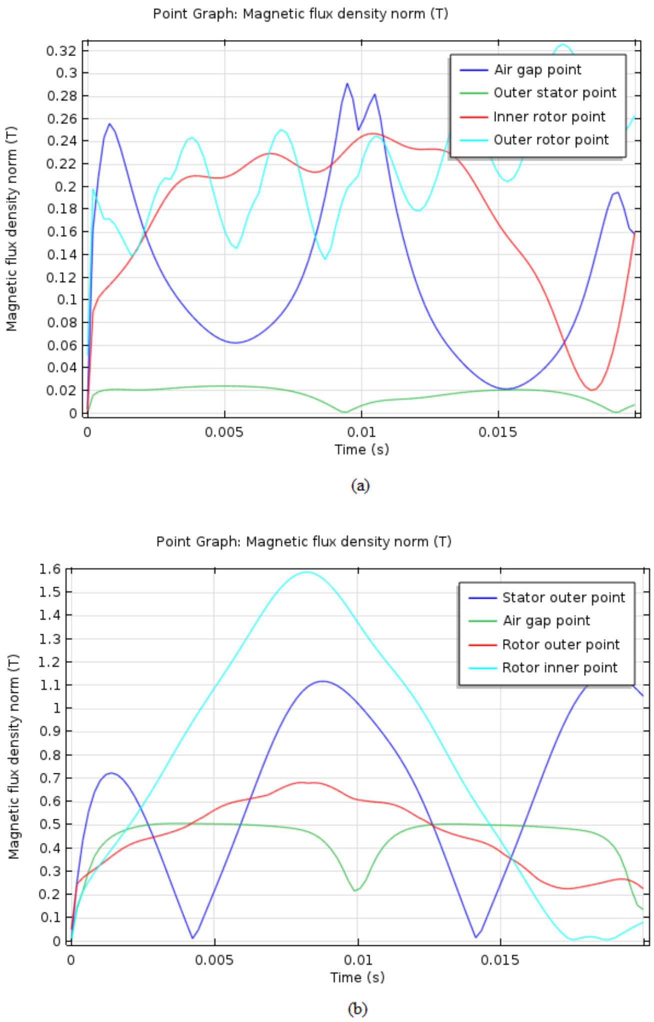

Figure 8. Absolute value of flux density over time for representative points from the (a) top half of the machine (b) bottom half of the machine