Master's thesis

NTNU
Norwegian University of Science and Technology

Andreas Fossmo

Application for axial flux motor

Master's thesis in EMIL
Supervisor: Robert Nilssen
June 2023

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I. ABSTRACT

This thesis aims to explore the key factors that contribute to the performance of an axial flux machine. The axial flux machine offers distinct advantages such as higher power and torque density, as well as the ability to be constructed with a slim profile, which has led to its popular nickname, the ”pancake motor.” To investigate the factors that contribute to a well-performing axial flux machine, an optimization study has been done using COMSOL Multiphysics.

The primary objective of the optimization study was to study which parameter being important in optimizing the axial flux machine. Given that a good axial flux machine is characterized by high efficiency and power density when the diameter is big enough the optimization aimed to achieve these goals. The specific machine chosen for optimization was an axial flux machine with a power output of 60 kW, intended to deliver a torque of 1150 Nm at a rated speed of 500 RPM.

Through the optimization process, various parameters and design elements were adjusted and analyzed to find the optimal combination that would result in the desired efficiency while minimizing the axial length. The aim was to producing a highly efficient axial flux machine capable of meeting the specified power and torque requirements.

To enhance the optimization process and facilitate learning about what constitutes a good axial flux machine, an application has been developed using COMSOL Multiphysics. This app enables students to gain practical experience and learn from trial and error. By manipulating various parameters within the app, students can explore the significance of each parameter in achieving optimal performance and design of an axial flux machine. Importantly, deep knowledge of axial flux permanent magnet (AFPM) machines is not required to use the app.

The idea for the app emerged during the development of an underperforming axial flux machine, prompting the question of how to improve its performance. The app serves as a platform to experiment with different parameters and investigate which specific parameter modifications could lead to an enhanced axial flux machine.

In this paper, an optimization study is done using the app, and the resulting optimizations are rigorously verified and cross-validated. By leveraging the app’s capabilities, this study provides valuable insights into the optimization of axial flux machines, ensuring reliable and robust results.

II. INTRODUCTION

The axial flux machine, although not as widely known as the radial flux machine, has gained popularity in recent years, primarily due to its high torque density. However, the teaching and focus in the field of PM machines often revolve around radial flux machines, as they currently dominate the market. Despite this, the axial flux machine has shown promising results, making it suitable for high-performance applications such as aircraft, cars, and other scenarios where power density, low axial length, and weight are critical factors. Meeting the European Union’s goal of climate neutrality by 2050 requires significant emissions reductions in the transportation sector, further emphasizing the need for more efficient machines [1].

This thesis, conducted in collaboration with FRAMO, involves an optimization study on an axial flux machine that was designed during a specialization project. The project aimed to compare the axial flux machine against a radial flux machine to determine which option was more favorable. The machine was simulated using COMSOL Multiphysics, a finite element method (FEM) software.

FRAMO provided specific parameters for the machine, requiring it to deliver a high torque of 1150 Nm at a rated speed of 500 RPM, with a power output of 60 kW. The thesis focuses on researching and estimating the necessary parameter changes to achieve a well-designed axial flux machine with low length, high power density and high efficiency, not only for FRAMO’s requirements but also for other similar situations.

FEM simulations were performed to study the machine’s performance, and an application was developed to make it easier for individuals to learn about the crucial design aspects of an axial flux machine.

The thesis begins with an exploration of the theory behind axial flux machines before presenting the design implemented in COMSOL Multiphysics. Following the design presentation, an optimization is done, focusing on three key parameters: outer stator radius, rated speed, and magnet length. The paper concludes with a discussion of the obtained results.

By doing this research and optimization study, the thesis aims to provide insights and recommendations for axial flux machine design, emphasizing the importance of parameters that contribute to compactness, high power density and high efficiency. The ultimate goal is to contribute to the advancement and wider adoption of axial flux machines in various industrial sectors.

The "app" developed within COMSOL Multiphysics provides students with a virtual laboratory-like environment to experiment with different parameters and observe how they influence the design and performance of the axial flux machine. This interactive tool allows students to explore various scenarios, make adjustments, and observe the corresponding changes, providing valuable insights into the design process. Compared to conducting similar experiments in a physical laboratory, using the app significantly reduces time and cost constraints.

The application, serves as a valuable resource for FRAMO as well. It enables them to assess and compare the suitability of axial flux machines and radial flux machines for their specific requirements. By utilizing the app, FRAMO can make informed decisions regarding the choice between these two machine types based on their performance under various parameters and conditions.

Overall, the app serves as a powerful educational tool for students, offering hands-on experience and the opportunity to learn through experimentation. Additionally, it provides valuable decision-making support for industry professionals like FRAMO, helping them determine the most appropriate machine configuration for their specific needs. The optimization study conducted using the app further enhances the understanding of the important parameters in designing an efficient axial flux machine.

III. THE APPLICATION

A. Working flow

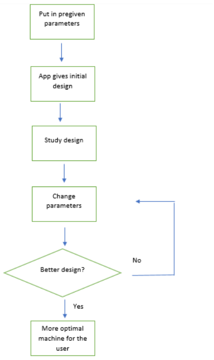


Fig. 1: Working flow

Figure (1) shows the working flow of the application. The user put in pre given or desired parameters The app will then give out an initial design an also some plots which gives the user the ability to study the design. An output table is also presented beside the plots, to help the user understand how an axial machine work. If the user want to create a new, more optimal in the way they want, it can be done by changing the parameters again. In some application, some parameters are limited and the user have a maximum value which cannot be exceeded. Other parameters may be more free to change. By changing the parameter, the user can see how it affects the motor, and make a more optimal design in the way they want to use the machine

B. Basis of the application

In the application, four different results are presented to the user: magnetic flux density, current density, torque, and efficiency. These results are obtained by running simulations based on the inputs provided by the user. The inputs are divided into two sections: geometrical and electrical input, as well as assumptions. Within each section, there are multiple parameters that the user can freely change to explore different machine configurations.

When inputting values into the application, the user is first able to visualize the design of the machine and observe how the parameters impact the overall design. This visual representation provides valuable insights into how the chosen parameters influence the machine's geometry.

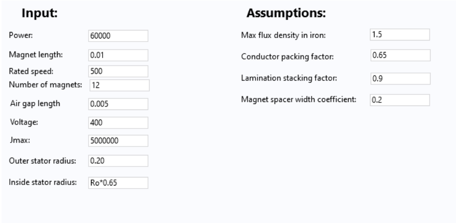
After examining the design, the user can proceed to study the performance of the machine. This analysis yields plots that illustrate the machine's performance characteristics. Users can also zoom in on specific areas of interest to analyze and study the results in greater detail.

To facilitate easy comparison and analysis, all the important results are plotted in a table format. This table can be easily copied, allowing users to efficiently compare different machine configurations and make informed decisions based on the presented data.

Overall, the application provides a comprehensive and user-friendly platform for exploring the design and performance of axial flux machines. By offering visualization tools, result plots, and a convenient table format, users can gain a deeper understanding of how various parameters influence the machine's behavior and make informed design choices based on the obtained results.

C. How the user can use the app

So, the application consist of 9 inputs and 4 assumptions which the user have to put in before computing. This can be seen in figure (2)



Input:

Power: 60000
Magnet length: 0.01
Rated speed: 500
Number of magnets: 12
Air gap length 0.005
Voltage: 400
Jmax: 5000000
Outer stator radius: 0.20
Inside stator radius: Ro*0.65

Assumptions:

Max flux density in iron: 1.5
Conductor packing factor: 0.65
Lamination stacking factor: 0.9
Magnet spacer width coefficient: 0.2

Fig. 2: Figure of the input and assumptions parameter in the application design

The application provides a convenient way for users to study the geometry of the axial flux machine before computing any results. By clicking the "geometry" button, users can visualize how the machine will be formed based on the input parameters. This allows them to have a better understanding of the machine's physical structure.

Once the desired geometry is set, users can click the "compute" button to initiate the simulation of the machine. The application will then run the necessary calculations and generate four plot results: flux density, output power, efficiency, and current density. These results provide insights into the machine's performance and help determine whether it meets the specified requirements.

If the machine does not meet the desired specifications or performance goals, users have the flexibility to go back and adjust the parameters accordingly. They can modify parameters such as the radius, power, or other design aspects to see how it impacts the machine's performance. This iterative process allows users to explore different design possibilities and identify the optimal configuration that yields a better-performing machine.

In summary, the application offers users the ability to visualize the machine's geometry and simulate its performance based on the specified parameters. It provides a user-friendly interface for exploring various design options and assessing the machine's suitability for meeting specific requirements.

D. How the geometry are connected in the app

In the design process of the axial flux machine using the app, several parameters and their relationships need to be considered. The torque requirement plays a crucial role in determining the size of the machine. The larger the torque required, the larger the machine's size will be.

One key parameter to focus on is the diameter of the machine. In an axial flux machine, a larger diameter is generally preferred as it has a significant impact on the machine's performance. A larger diameter provides a longer arm for the current to contribute to the torque, resulting in a reduced need for turns and current in the machine. This leads to improved efficiency and reduced copper losses. Therefore, maximizing the diameter is desirable.

To ensure that the current density requirement is met, the slots in the machine need to be deep enough. The current density is influenced by the cooling ability of the machine and is limited by the heat generated. In smaller diameter machines, the axial length tends to be longer compared to larger diameter machines, as the slots need to accommodate the required current density.

The diameter and axial length are interconnected to meet the torque requirements while maintaining an acceptable current density. The specific current in the machine is not determined by the user but is based on the fact that, given a certain diameter and voltage, the machine needs to deliver a specified power.

The equations for calculating the number of turns, current in the slot, and axial length will depend on the specific design and requirements of the machine. These equations take into account factors such as the desired power output and the magnetic flux density. By adjusting the parameters in the app, users can explore how changes in diameter, current density, and other factors impact the overall design and performance of the axial flux machine.

Overall, the app helps users understand the intricate relationship between parameters such as diameter, axial length, torque, and current density in designing an efficient and effective axial flux machine.

The equations for number of turns, current in the slot and axial length is given below.

$$ns = \frac{Emax}{Nm * Kd * Kp * Ks * Bg * Nspp * wm * (Ro^2 - Ri^2)} \tag{1}$$

Where ns is the number of turns, Emax is the maximum back emf, Nm is number of magnets, Kd, Kp and Ks is the distribution factor, pitch factor and skew factor respectively , Bg is air gap flux density, Nspp is number of slots per pole per phase, Ro is outer stator radius, Ri is inner stator radius and wm is the mechanical speed.

$$Is = \frac{T}{Nm * Kd * Kp * Ks * Nspp * Bg * (Ro^2 - Ri^2)} \tag{2}$$

Where Is is the slot current, T is the torque the machine is planned to deliver

$$Iph = \frac{Is * sqrt(2)}{ns * Nph} \tag{3}$$

Where Iph is the phase current.

The conductor slot depth is then decided to give the pre-given current density:

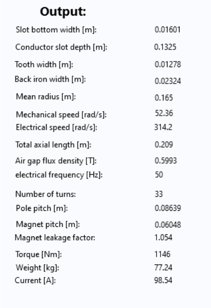
$$ds = \frac{Is}{Kcp * Wsb * Jmax} \tag{4}$$

Where ds is the conuctor slot depth, Kcp is the fill factor, wsb is the slot botttom width and Jmax is the max current density

$$L = ds + (2 * Wbi) + (2 * g) + (2 * lm) \tag{5}$$

Where L is the total axial length, Wbi is the back iron width, lm is the magnet length and g is the air gap length

The user will also be presented a output table where different geometry outputs will be presented. It can be very interesting for the user to see what changes o fthe machine a parameter change makes. This will help create understanding of the fundamentals of creating an axial flux machine, and also help the user learning better.



Output:

Slot bottom width [m]:	0.01601
Conductor slot depth [m]:	0.1325
Tooth width [m]:	0.01278
Back iron width [m]:	0.02324
Mean radius [m]:	0.165
Mechanical speed [rad/s]:	52.36
Electrical speed [rad/s]:	314.2
Total axial length [m]:	0.209
Air gap flux density [T]:	0.5993
electrical frequency [Hz]:	50
Number of turns:	33
Pole pitch [m]:	0.08639
Magnet pitch [m]:	0.06048
Magnet leakage factor:	1.054
Torque [Nm]:	1146
Weight [kg]:	77.24
Current [A]:	98.54

Fig. 3: output table from application

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E. Use in teaching

The application developed for designing an axial flux machine within COMSOL Multiphysics serves as a user-friendly tool that allows individuals without deep knowledge or experience to engage in the design process. By manipulating the parameters and observing the resulting changes, users can gain a better understanding of how these parameters affect the design and performance of the axial flux machine.

The advantage of this application lies in its ability to facilitate a learn-by-doing approach. Users can experiment with different parameter values, observe the outcomes, and learn from their failures and successes. This hands-on and interactive learning experience not only makes the process more engaging but also enhances comprehension and retention of the concepts related to axial flux machines.

Compared to traditional methods where trial and error would require physical prototypes and extensive laboratory testing, this application provides a fast and cost-effective alternative. It allows users to explore a wide range of design possibilities, rapidly iterate, and make informed decisions based on the observed performance. This saves both time and resources, making the design process more efficient and accessible to a broader audience.

By actively changing the parameters in different ways and observing the corresponding effects, users can develop an understanding of the most important parameters in both the design and performance aspects of the axial flux machine. This knowledge empowers users to make informed decisions and optimize the machine's design to meet specific requirements and achieve desired performance characteristics.

Overall, the application's user-friendly interface and the ability to experiment and learn through trial and error make it an effective and motivational tool for designing axial flux machines, even for individuals without extensive expertise in the field

IV. THEORY

A. Axial flux motors

An AFPM, axial flux permanent magnet machine is studied in this theses. The machine is supposed to be a motor in operation, and is therefore written as axial flux motor in this paper. For an electrical mahcine, the torque is given by equation (6)

$$T = \frac{P}{Wm} \tag{6}$$

Where Wm is the rotational speed in radians and P is the output power in Watt. By equation (6), it can be shown that higher rotational speed gives lower torque in order for the power output to be the same. Therefore, the machine size can be decreased, if the torque is reduced.

An axial flux machine is known as a good machine for low speed, high torque. But the axial flux machine isnt necessary that good for every kind of low speed, high torque machines. The AFPM have big advantage of big diameter, equation (7) shows the torque created by an axial flux machine.

$$T_{axial} = K \cdot D^3 \tag{7}$$

and how big the diameter need to be for the AFPM machine to be caracterized as good, is not a specificic number for. Anyway, as the torque is dependent on the diameter cubed, the axial flux machine is known as a good machine to provide high torque at low speed. In comparison, the radial flux machine is dependent on the diameter squared.

$$T_{radial} = k \cdot D^2 \cdot L \tag{8}$$

Equation (8) shows that the radial flux machine is dependent on the diameter squared, and also the length of the machine. The axial flux machine torque is not dependent on the length. For the AFPM, the machine has an optimal length for the given torque, meeting the requirments for the machine such as the maximum current density and flux density, and other assumptions such as fill factor.

B. Topologies of different axial flux machines

There are different topologies of axial flux machines. The list include single sided machine, double sided machines with internal rotor, double sided machine with internal stator and multidisc machines [1]. In this thesis, only double sided machine with internal rotor is studied.

C. Double sided stator

A double sided stator with internal rotor is studied in this paper. Although it exist other axial flux topologies, this one is chosen because the cooling ability this type have. The stator on the outside, and the internal rotor makes it way easier to cool, compared to other topologies, particularly because the heat is produced on the outside by the stator windings and it is therefore easy to get in touch with the heat and cool it directly. Axial flux machines have some problems with unbalanced forces between stator and rotor, but with the double sided machine, the forces from the stator and rotor are balanced. Another advantage of double sided machine is that no rotor back iron is needed. [2]

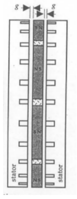


Fig. 4: Figure of double sided stator[2]

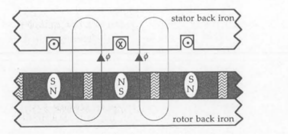


Fig. 5: Figure of single air gap construction[2]

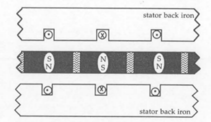


Fig. 6: Figure of double sided stator[2]

In the design of an axial flux dual air gap machine, the traditional rotor back iron is replaced with another stator. This modification effectively doubles the number of current-carrying turns in the machine, resulting in a doubling of the force produced by the motor. With the increased force, the power and torque densities of the motor are nearly doubled as well.

However, it's important to note that the dual air gap construction does not achieve a full factor of two increase in torque and power density. This is due to the fact that the magnets in the machine are also doubled in this configuration, as they are required to create the magnetic field necessary for motor operation. The additional magnets contribute to the overall mass and size of the machine, limiting the extent of the torque and power density increase.

While the dual air gap construction offers advantages in terms of increased force, power, and torque densities compared to traditional designs, it is essential to consider the overall balance between the additional stator, magnets, and other components to ensure optimal performance and efficiency. Designing a high-performance axial flux dual air gap machine requires careful consideration of the trade-offs between the various design elements and the desired performance characteristics [2].

D. Back emf

Faradays law says that an electromotive force is induced when a conductor is placed in a varying magnetic field. This phenomena is applied in an electrical mahince. When an electrical machine is running, a magnetic flux will flow through the airgap, and induce an electromotive force in the windings in the stator.

Back emf is another word for the induced electromotive force, and the formula for back emf can be expressed as in equation (9)

$$emf = -\frac{d}{dt} \cdot \int_S B \cdot ds \tag{9}$$

Where emf is the induced electromotive force, S is the surface which B, the magnetic flux density, passes through.

The terminal voltage set is larger than the back-emf when the machine is running as a motor, while the voltage is lower than the back-emf when the machine is running as a generator. The best for the machine operation is to get a sinusoidal back-emf, event hough this can be challenging because of harmonics.

The power factor can be expressed as in equation (10)

$$PF = \frac{P}{Vt * Is} \tag{10}$$

where P is the power, Vt is the terminal voltage and Is is the stator current. It is optimal to have the power factor close to 1, because then the current is minimized to provide the power output and this will also limit the copper losses.

$$Copperloss = R \cdot I^2 \tag{11}$$

Equation (17) shows how copper loss is dependent on the conductor resistivity and the current squared, meaning that a change in current will change copper losses significantly.

E. Torque

The torque for an axial flux machine can be expressed as [2]

$$T = Nm \cdot Kd \cdot Kp \cdot ks \cdot Bg \cdot Nspp \cdot ns \cdot i \cdot (Ro^2 - Ri^2) \tag{12}$$

where Nm is the number of magnets, Kd is distribution factor, Kp is pitch factor, Ks is skew factor, Bg is the flux density in the air gap, ns is number of turns, i is the current, Ro is the outer stator radius and Ri is the inner stator radius.

The air gap flux density is decided by the length of the magnet and the magnet remanence flux density.

$$Bg = \frac{Lm \cdot Br}{g \cdot Br \cdot (1 + Lm)} \tag{13}$$

where Bg is the air gap flux density Lm is the length of the magnet, Br is the remanent flux density, and g is the air gap length [3]

The axial flux machine will also experience torque ripple. Torque ripple is shown in equation (14)

$$T_s = \frac{Tmax - Tmin}{Tavg} \tag{14}$$

where Tmax is the maximum torque, Tmin is the minimum torque, and Tavg is the average torque produced by the motor in an electrical period.

The most common contribution to the torque ripple is cogging torque, which is a torque caused by the permanent magnets and the stator teeth. The attraction force between them is what creates cogging torque.

F. Windings

In an axial flux machine, the windings is oriented radially while the flux moves axially. This is the opposite than in an radial flux machine where the windings are oriented axially and the flux moves radial.

An electrical mahchine have the option to have a specific number of slots per pole per phase. This can be a integer slot, known as integer winding, but can also be a decimal number, known as fractional slot.

An electrical machine also has the possibiltiy to have concentrated or distributed windings. For distributed winding, the windings is going around two stator teeth, while for the concentrated windings, the windings are just ”concectrated” around one stator tooth.

Another choice is wheter the machine will have single- or double layer winding.The difference between single or double layer winding is how many coils per slot the machine have. In single layer winding, the number of coils equal half the number of slots, and in an diuble layer winding, the number of coils is equal the number of slots.

G. Electromagnetic losses

The electromagnetic losses can be divided into two main themes, stator iron losses and copper losses.

1) Stator iron losses: In this thesis, the berotti method is used to calculate the iron losses. Stator iron losses contains of three losses: Hysteresis losses, anomalous losses and eddy current losses and can be summed as in equation (15) [4]

$$P_{loss} = P_{Hysteresis} + P_{eddycurrents} + p_{excess} \tag{15}$$

Hysteresis losses

Since the current flows in forward and reversed direction, the iron gets magnetized and demagnetized. When the iron is demagnetized, the flux density and magnetic force doesnt hit zero at the same time. When the magnetic flux density hit zero, the magnetic force has a positive value, because of this the magnetixing force must happen in the negative direction in order for the force to get to zero.

Figure (7) shows the hysteresis curve. This curve explain the relationship between magnetic flux density, B, and magnetic force, H. The area of the hysteresis curve is an expression for the energy lost in one cycle. The electrical frequency is therefore important in calculating the hysteresis losses.

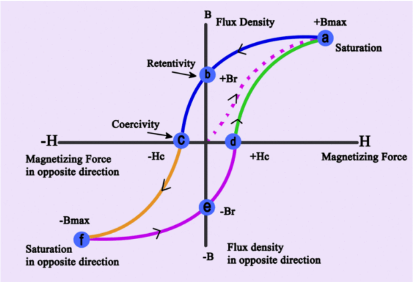


Fig. 7: Hysteresis curve [5]

Eddy current losses

Voltage, EMF, is induced in the coils due to the motor operating in a magnetic field. Because of this induced emf, eddy currents starts to flow. Eddy current loss is the power loss due to these currents. Eddy current is a result of faradays law, which state that an opposing magnetic field occur when the external magnetic field produce a current in the material.

Excess losses

Excess loss is created by the skin effect and magnetic flux density having nonlinear diffusions. A nonlinear distribution of magnetic flux density is caused by this.

2) Copper losses: Copper losses are the losses in the copper wires due to the resistance in the wire and the current flowing in the wire. The resistivity can be found by equation (16) [3]

$$R = \frac{\rho \cdot L}{A} \tag{16}$$

where ρ is the resistivity in the material, L is the length of the conductor and A is the area of the conductor.

The copper loss can be found by equation (17)

$$P_{copperloss} = R \cdot I^2 \tag{17}$$

H. Materials

Materials in the machine is very useful to allow the machine to perform as wanted.

1) Stator iron: The stator iron is very essential in getting a high performance of the machine with low losses. The machine is designed to tolerate a high flux density so the geometry will be as optimal as possible, meaning that the material should have a high saturation level. Another important parameter is the weight, so a combination of low weight and high saturation point is wanted.

2) Magnets: With higher temperature, the magnetization will drop. This can be seen from the magnetization curve in figure (8)

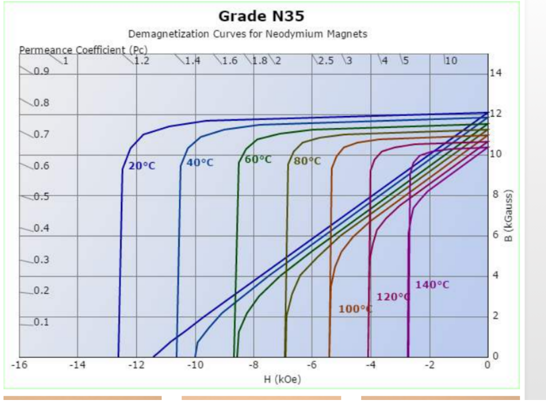


Fig. 8: Magnetisation curve NdFeb[6]

Every magnet material has a max temperature level, before the magnet will be demagnetized. When it comes to magnets, price play a huge role. Of course, the best will be to choose the magnets which have highest maximum temperature allowed and the best magnetic performance, but these magnets will also cost more. The temperature characteristics for the application will also impact the choice.

Neodynium magnets, NdFeB, is the strongest magnets in the world, and if the temperature characteristic is within the limits for the given application, this is a popular choice.

V. FEM MODEL

The FEM model used in this thesis is the same as in the spezialization project[7].

A. *Finite element method*

In the spezialization project an analytically approach where done to design the machine. Anyway, this analytically approach isnt attainable because the accuracy of analytical work isnt good enough. Finite element method is therefore used to check the design and study the performance of the machine. In this paper, COMSOL multiphysics is the software used for finite element simulations. The reason why finite element method is so much accurate than analytical work is that the equations of the electromechanics are time dependent partial differential equations, which is difficult to be solving by hand [8]. These PDEs is often referred to as maxwells equations.

The maxweels equations is solved in COMSOL. This include the PDEs listed below.

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\delta \mathbf{D}}{\delta t} \tag{18}$$

$$\nabla \times E = -\frac{\delta \mathbf{B}}{\delta t} \tag{19}$$

$$\nabla \cdot D = \rho \tag{20}$$

$$\nabla \times B = 0 \tag{21}$$

where H is the magnetic field strength, J is the current density, D is the electric displacement field strength, E is the electric field strength and B is the magnetic flux density

1) Geometry: The axial flux machine is simulated in 2D. For many reasons, 3D simulations would have been beneficial for the accuracy, but in this case, less simulation time is advantageous for the optimization part, because the parameters would change a lot and many different simulations will de done in order to find the optimal machine. The machine used in this thesis is symmetric, meaning that only one part of the machine, as less as possible, will be necessary to design and run. In this thesis, because the machine had to be designed as an linear motor, two poles had to be designed instead of only one pole. This means only one side of the double sided stator, one pole and one permanent magnet are simulated. The air gap is divided into four parts, and air is also added on the side of the magnets. The stator is divided into teeth and slots given by the analytical approach.

The initial design in FEM is given in figure (9)

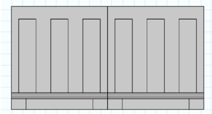


Fig. 9: Initial design FEM

Initial design

The initial design from hanselmann equations, created in FEM, is given in table (I)

Parameter	Symbol	Value
Magnet length [mm]	lm	10
Slot bottom width [m]	Wsb	0.016
Tooth width [m]	Wtbi	0.012
Number of turns	ns	33
Slot current	Is	6898
Phase current	Iph	98
Conductor slot depth [m]	d3	0.066
Axial length [m]	L	0.01338
Back iron width [m]	Wbi	0.023
Efficiency [%]	n	96.4

TABLE I: Initial design

A parameter list is used to design and change the geometry, and this list is used in an app to easier play with the parameters.

Part of motor	Material	density [kg/m^2]
Stator iron	Soft iron	7800
Magnets	NdFeB	7000
Windings	Copper	8960

TABLE II: Materials

2) Materials: For the iron, silicon steel NGO 50PN250 is chosen

For the magnets, ndFeB is chosen.

For the windings, copper is choosen.

This materials is the same for every cases of running the machine.

The material cost is presented in table (III), while the material properties is given in table (IV)

Material	Cost [NOK/m^3]
Soft iron	130
Magnets (NdFeB)	1600
Windings (Copper)	92

TABLE III: Materials cost[9] [10] [11]

Parameter	Symbol	Value
Magnet density [g/cm3]	ρ_m	5.5
Magnet recoil permeability	μ_r	1.05
Magnetic remanence flux density [T]	B$_r$	1.35
Magnetic electrical conductivity [S/m]	σ_m	7.14E5
Iron density [g/cm3]	ρ_i	7800
Eddy current loss coefficient	Ke	1.22E-4
anamolous loss coefficient	Ka	3.47E-5
Hysteresis loss constant	Kh	0.01338
Copper density [g/cm3]	ρ_c	8.96
Copper electrical resistivity $[\omega * m]$		1.72E-8

TABLE IV: Material properties

B. Mesh

The mesh is important because of finer mesh means more accurate simulations, but finer mesh also require more simulation power and time. Since the optimization means many simulations are done, the mesh is a little bit coarse in this case.

In the airgap, on the other hand, the mesh is finer than the rest of the figure. This is due to that the torque is created in the airgap and the accuracy needs to be better here.

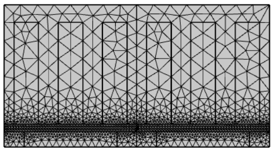


Fig. 10: Mesh

C. Torque calculations

To measure the torque, comsols built-in force calculation is used. Then the toque is calculated from the force in the x direction multiplied with the arm and number of segments as in equation (22)

$$T = comp1.mf.Forcex\_EnkelKraft \cdot r\_inc \cdot N\_sectors \tag{22}$$

where comp1.mf.Forcex_EnkelKraft is the force in the x direction, R_inc is the average radius and N_sectors is the number of segments.

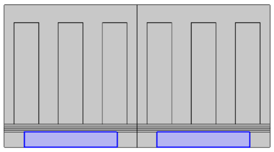


Fig. 11: Force calculation

D. Loss calculation

Bertotti method were used in this thesis. The bertotti method can be explained by equation (23)

$$P_{ironloss} = P_h + P_e + P_a \tag{23}$$

Where:

$$P_h = K_h \cdot \hat{B^\alpha} \cdot f \tag{24}$$

$$P_e = K_e \cdot \hat{B^2} \cdot f^2 \tag{25}$$

$$P_a = K_a \cdot B\hat{^1}.5 \cdot f^1.5 \tag{26}$$

The bertotti method include three contributions to the iron loss: hysteresis loss, eddy current loss and anomalous losses. B is the peak value of the flux density and f is the frequency. Kh, Ke, Ka and α is constanst which is calculated based on the material. The coefficient of bertotti method is found with curve fitting in matlab, using the core loss data for the material used.

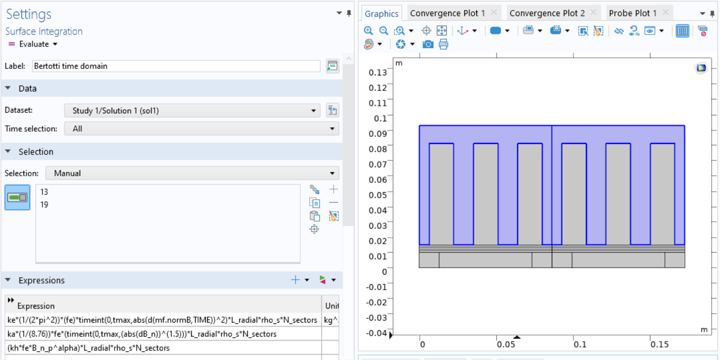
After finding the coefficients, the bertotti equations can be implemented in the COMSOL model. This is done by doing a surface integration over the stator iron, based on the equations (27)-(29)

$$P_h = \frac{K_h \cdot \hat{B^\alpha}}{T} \tag{27}$$

$$P_e = \frac{K_e}{2 \cdot \pi^2 \cdot T} \cdot \int_0^T |\frac{dB}{dT}|^2 \cdot dT \tag{28}$$

$$P_e = \frac{K_a}{8.76 \cdot T} \cdot \int_0^T |\frac{dB}{dT}|^1.5 \cdot dT \tag{29}$$

P$_h$, P$_e$ and P$_a$ is given in W/kg



Label: Bertotti time domain

Dataset: Study 1/Solution 1 (sol1)

Time selection: All

Selection: Manual

13
19

Expression	Unit
ke*(1/(2*pi^2))*(fe)*timeint(0,tmax,abs(d(mf.normB,TIME))^2)*L_radial*rho_s*N_sectors	kg^
ka*(1/(8.76))*fe*(timeint(0,tmax,(abs(dB_n))^(1.5)))*L_radial*rho_s*N_sectors	
(kh*fe*B_n_p^alpha)*L_radial*rho_s*N_sectors	

Fig. 12: Bertotti implemented in COMSOL

figure (12) shows how the iron loss calculation is done in COMSOL. Note that in these calculations, the losses comes out in W, and not W/kg.

To apply the bertotti method in the model, loss coefficients need to be pre calculated in matlab using curve fitting. Data sheet for the material is used to obtain the loss coefficients. The core loss is increasing with increasing frequency. For 50 Hz, the loss coefficents is listed in table (V) [12]

Loss coefficents [W/m^3]	Value
Kh	0.01338
Ke	1.22 e-4
Ka	3.47e-5

TABLE V: The lost coefficients for bertotti method found in matlab using curve fitting

E. Coils

Phase	Current
A	Ipeak*cos(omegael*t)
B	Ipeak*cos(omegael*t- (2*pi/3))
C	Ipeak*cos(omegael*t +(2*pi/3))

TABLE VI: Current in phases

1) : When the current reaches its peak value, the center of the magnets is located at the center of the coil, and phase sgift is therefore not needed.

2) Slot coniguration: Becuase of symmetry, only one twelth of the motor is simulated. Only single layer winding is used in this thesis, and the layout for the coil phase is as presented in table (VII), with slot 1 starting from left. The current is in the q-axis, the axis the torque is produced, to maximize torque production.

Slot	Phase
1	-C
2	A
3	-B
4	C
5	-A
6	B

TABLE VII: Slot configuration

VI. RESULTS

In the result, the difference from a bad to a good machine will be shown. In some cases, some parameteres are limited, and the machine will turn out to be a bad machine. An advantage of axial flux machine is the fact that the axial flux machine can be a multidisc machine, with a few disks meeting the total requirement of torque having a better efficency than one bad machine. Anyway, the result vary from both good and bad machines and shows what gives you a good axial flux machine and why.

A. 60 KW motor

The pregiven parameters for the machine studied in this section is given in table (VIII)

Parameter	value
Power [W]	60 000
Length of airgap [mm]	5
rated speed	500
Voltage	400

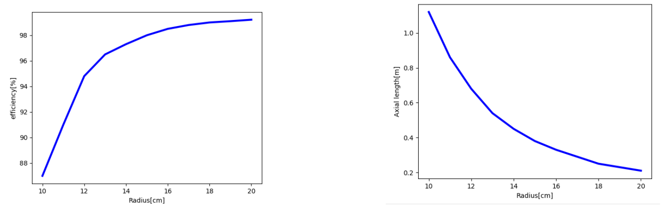
TABLE VIII: Given parameters

Before presenting the results, the iron loss calculated for the machine with frequency equal 50 Hz is so small that they are neglected here. The iron loss calculated by the bertotti method were in fact only about 0.3-0.6 percent, which is so low they are not counted in the results.

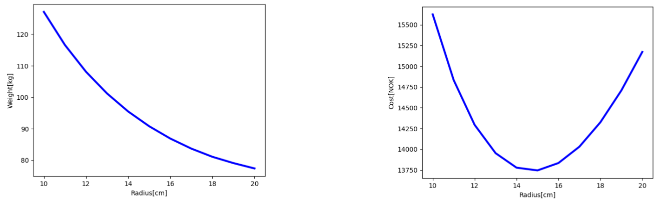
With a small diameter, the machine will turn out to be no good having a bad efficiency.

Outer stator radius [cm]	efficiency [%]	axial length [m]	weight [kg]	Cost [NOK]
10	86	1.123	127.1	15625
11	91	0.8571	116.6	14835
12	94.8	0.68	108.1	14294
13	96.5	0.54	101.2	13953
14	97.3	0.45	95.5	13778
15	98	0.38	90.77	13745
16	98.5	0.33	86.9	13834
17	98.8	0.29	83.7	14031
18	99	0.25	81	14325
19	99.1	0.23	79	14708
20	99.215	0.209	77.43	15173

TABLE IX: change in different values when changing outer stator radius from 10 to 20 cm



(a) Efficiency. (b) Axial length



(c) Weight (d) Cost.

Fig. 13: FEM calculations of motor performance with different outer stator radius for a 60 Kw machine

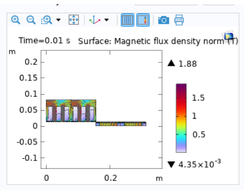


Fig. 14: Flux density

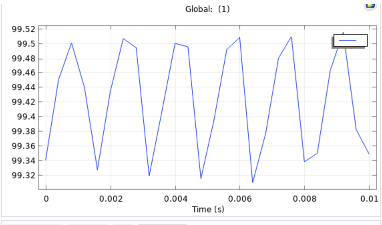


Fig. 15: Efficiency

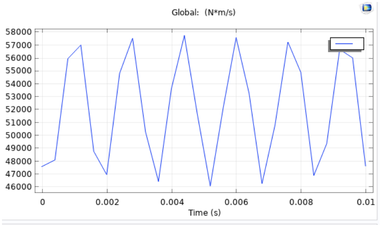


Fig. 16: Torque produced by the machine

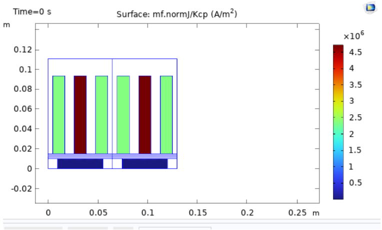


Fig. 17: current density

Figure (15), (16), (17) and (17) shows the 4 plots the user meet when they calculate a design in the application

For this machine, it is possible to see that the outer stator radius need to be 15 cm in order for the machine to have an efficiency over 98 %. It is also possible to see that the cheapest machine is the machine with 16 cm. This point may be important, as the price is an important value. The question is whether increasing the motor radius will have big advantage. In case of efficiency, it is possible to see that the efficiency will not increase significant. In case of weight, bigger radius will be beneficial. it can be many parameters and values which will be important for many, but these parameters may vary from one to another. It will also depend on the application and what the motor is supposed to do.

Another factor which is possible to look at is the axial length of the machine. The axial length will decrease if the outside radius increases, but will actually increase in a point where the back iron width increases more than the slots decreases.

Optimalization of the outer diameter and axial length gives that the point where the maximal decrease in axial length is achieved when outer radius equals 0.35m for the 60 Kw machine case. A graph of this is made in figure (18)

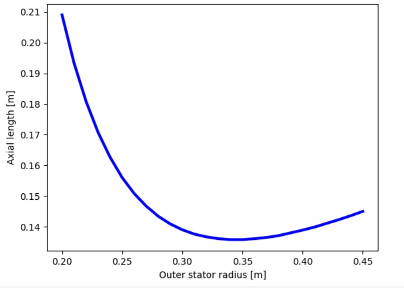


Fig. 18: Diameter impact on axial length

Anyway, this shows increasing the diameter length doesnt make the machine infinitely thin. The reason why the axial length reaches a minimum length point, is because after this point, increasing diameter leads to that the back iron width increases more than the slot length decreases. increasing the diameter will still lead to a better efficiency of the machine, but the axial length will be increased, leading to a poorer power density. The result from figure (18) shows that the optimal length to radius ratio is 0.39, meaning that the axial length of the machine is 0.39 times the radius of the machine.

$$\frac{L}{D} = \frac{0.1358}{0.35} = 0.39 \tag{30}$$

80 KW machine

The outer stator radius is of course dependent of the power the machine is supposed to deliver. A smaller machine will demand less radius to get 98 % efficiency while a bigger machine will demand bigger radius. An example is given below,

For a 80 kW machine, the results is given in table (X)

Outer stator radius [cm]	efficiency [%]	axial length [m]	weight [kg]	Cost [NOK]
10	78.75	1.48	168.1	13751
15	97.735	0.4843	118	10981
20	99.125	0.2532	97.8	11032
25	99.245	0.1787	90.66	12544

TABLE X: Design with P=80 kw

40 kw machine

For a 40 KW machine, the result is given in table (XI)

Outer stator radius [cm]	efficiency [%]	axial length [m]	weight [kg]	Cost [NOK]
10 ikke fått til enda	78.75	0.766	86.08	13751
15	98.5	0.2744	63.57	6863
20	99.25	0.1648	57.05	7596
25	99.255	0.1334	58.07	10085

TABLE XI: Design with P=40 Kw

After studying the different machines, it can be seen what diameter is needed in order to get a good machine. The 40 kw machine needs between 10-15 cm to get an efficiency over the 98 % which is wanted, 60 kw also need 15 cm to get a good efficency, while 80 KW machine need between 15-20 cm outer stator radius in order to get a good machine . While the efficiency will increase if the radius is increased, it is not certain it is better to increase the radius. This is because the machine will need more magnet volume, and magnet is one of the most expensive part of the motor. The cost of the motor is an important value so to increase the efficiency over 98 % will have a cost. Anyway, increasing radius will also decrease copper needed, which means the copper volume will decrease and the amount of money increase isnt becoming too high.

Another important thing to note by the results is that stator outer radius is very important in axial flux machine. Hanselmann early said that one of the reason the axial flux machine werent that common, was because this machine type have a good performance, but only if the diameter isnt limited [2]. In many cases, the machine geometry cannot go beyond a certain point. So, the axial flux machine is a good option to the radial flux machine, but some important parameter need to fit the axial flux machine in order for the pancake motor to be competitive.

It is of course also possible to change other parameter in the machine other than stator outer radius, this include rated speed, magnet length, inner stator radius according to outer stator radius.

B. Magnet length

Increasing magnet length means the flux density is increased which allow the slot current do decrease. This will reduce the copper loss and make a more efficient machine. This is shown by figure (19), where the effect of different magnet length is studied.

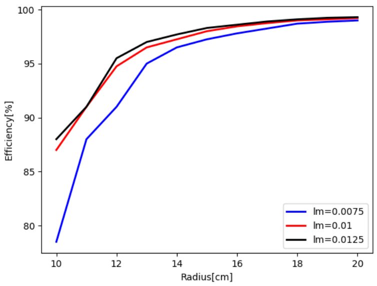


Fig. 19: lm impact on efficiency

The axial length and the weight will not be so different in case of different magnet lengths.

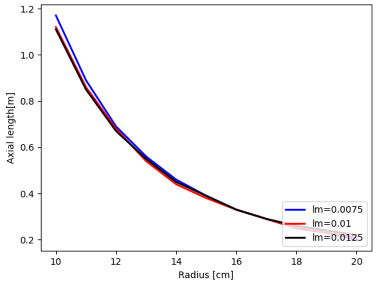


Fig. 20: lm impact on axial length

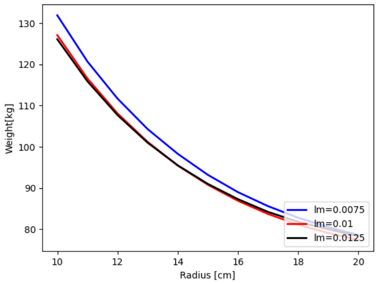


Fig. 21: lm impact on weight

The cost is an important value. The cost reaches a minimum value between 10 and 20 cm.

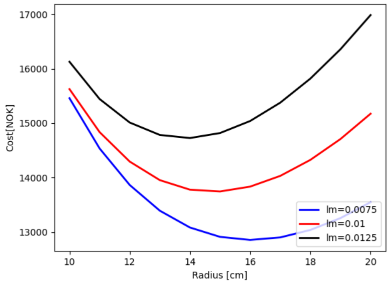


Fig. 22: lm impact on cost

C. Rated speed

The rated speed is an important factor. The most competitive axial flux machines on the market have a high rotational speed [13] [14]

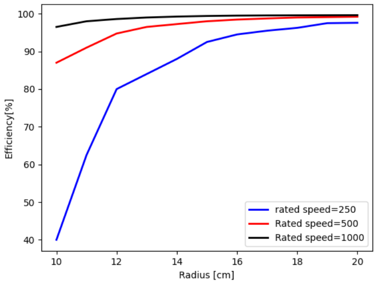


Fig. 23: Rated speed impact on efficiency

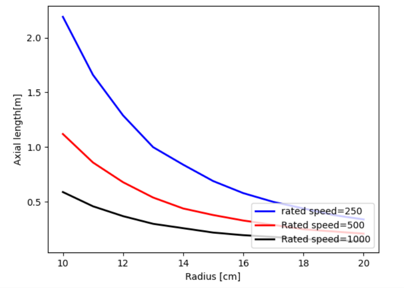


Fig. 24: Rated speed impact on axial length

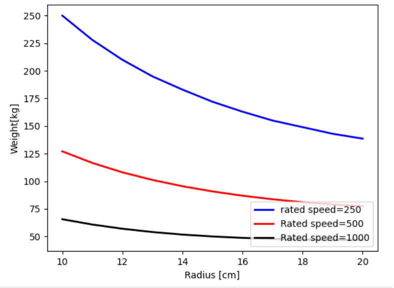


Fig. 25: Rated speed impact on weight

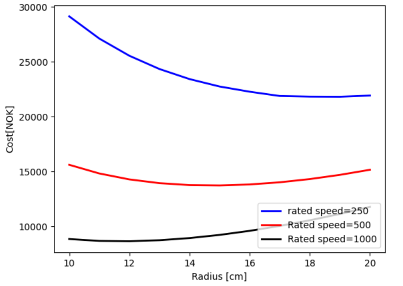


Fig. 26: Rated speed impact on cost

D. Optimizing based on ratio between inner and outer radius

To learn how to get a better machine changing different parameters, optimization is done. Optimization is making the design of the machine and the performance as best as possible. The most significant part of an optimization problem is objective function, control variable and constraints. In optimization a objective function is optimized based on changing and vary the control variables, by staying within the limits for the constraints.

The optimization of the objective function could include finding the minimum or maximum, dependent on what variable the optimization is done according to. The constraints is set to allow a given interval of values for the control variables. A minimazaton problem can be describes as follows:

$$min = O(x) \tag{31}$$

Subject to:

$$g(x) \leq (x) \tag{32}$$

$$h(x) = 0 \tag{33}$$

$$lb \leq (x) \leq ub \tag{34}$$

Optimization can be done on different categories, such as size, shape, topology and parameter.

Ri/Ro	Efficiency %
0.4	99.1
0.45	99.12
0.5	99.145
0.55	99.1725
0.6	99.2
0.65	99.215
0.0.7	99.21
0.75	99.164
0.8	99.175
0.85	99.025
0.9	93.98.6
0.95	97.25

TABLE XII: Optimized ratio between inner and outer diameter

Now, a look at the impact of inside stator radius is done. This is done by holding the slot current constant and vary the inside stator radius.

First, it were believed that the optimal ratio between inner and outer diameter was [15]

$$\gamma = \frac{Ri}{Ro} = \frac{1}{\sqrt{3}} \tag{35}$$

But later study has shown that the best ratio is about 0.65[16]. To check this, a study in this is done in the application made for axial flux machines in comsol. Here, a parametric sweep for the inner radius is done to vary the inner radius between 0.4-0.95 times Ro.

The study shows that the optimized ratio is about 0.65*Ro, confirming the later suggestions that the optimal ratio between inner and outer diameter is 0.65. A graph of the result is shown in figure (27):

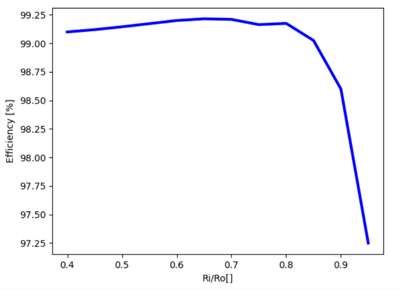


Fig. 27: Ro/Ri impact on efficiency

VII. DISCUSSION

The application has provided valuable insights into designing axial flux machines and understanding the factors that contribute to their performance. One important parameter identified in the study is the diameter of the machine. The results indicate that the axial flux machine has a significant advantage when it is not limited by diameter. A larger diameter generally leads to a better-performing machine, as it improves efficiency. However, it's important to consider the trade-offs in terms of cost and weight, as these may increase with a larger diameter.

The reason for the improved performance with a larger diameter is attributed to the lower impedance of the machine. A longer arm for torque is created, resulting in lower slot current and reduced copper losses. However, it is worth noting that increasing the diameter does not necessarily lead to a proportional increase in machine effectiveness. The efficiency shows a more significant jump in the smaller diameter range compared to the larger diameter range. For example, the efficiency may increase from 87% to 96.5% when going from a 10 cm to a 13 cm radius, but the efficiency increase from 13 cm to 16 cm radius may be only 2%. The reasons behind this discrepancy in efficiency increase would require further investigation.

Axial length

Based on the plots and analysis presented in the thesis, it is evident that an axial flux machine should not have a long axial length. The efficiency of the machine is closely related to its length, which in turn is dependent on the outer stator radius. Even for the smallest machine studied in the thesis, with a power of 40 kW, a radius smaller than 13 cm on larger machines appears to result in an excessively long axial length, leading to poor performance.

In general, it seems that the axial length of the machine should not exceed the diameter in order to be considered a good-performing machine. When the axial length becomes longer than the diameter, the efficiency significantly deteriorates. The axial length should ideally be minimized, reaching a point where the increase in back iron width outweighs the decrease in slot length. At this juncture, the efficiency of the machine often becomes sufficiently good, and there is no need to further increase the radius.

It is important to note that increasing the radius beyond this point would result in a heavier and more expensive motor, with the efficiency gains being relatively marginal. Therefore, optimizing the axial length and radius to strike a balance between performance, weight, and cost is crucial in the design of axial flux machines.

To sum up, the study suggests that an axial flux machine should have a relatively short axial length, ideally not exceeding the diameter. The relationship between axial length and efficiency should be carefully considered, as excessive length can lead to poor performance. Furthermore, optimizing the machine's dimensions to maximize efficiency without unnecessarily increasing the radius is essential in achieving an optimal design

Increased speed case

According to Figure (23), it can be observed that increasing the speed of the axial flux machine leads to a reduction in copper loss. This finding aligns with a study conducted by Fossmo et al. [7], which examined competitive machines and found that almost all operated at high rotational speeds. However, it is important to note that increasing the rated speed may not always be an optimal or suitable solution for every application, particularly in scenarios where the machine is placed in water.

The phenomenon of cavitation is a crucial consideration when dealing with motors operating in water environments. Cavitation occurs when high speeds generate low-pressure regions that cause the formation of vapor bubbles in the liquid, leading to undesirable effects. To mitigate cavitation, it is generally recommended to avoid high speeds in water applications [17].

It is worth mentioning that higher speeds may have more significant benefits in ironless machines. As the speed increases, the frequency also increases, which can result in higher iron losses. However, in the case of axial flux permanent magnet (AFPM) machines without an iron core, these losses will not vary and remain at zero.

In summary, while increased speed can reduce copper losses in axial flux machines, the application of high speeds must be carefully evaluated based on the specific application requirements and considerations such as cavitation in water environments. Additionally, the influence of speed on iron losses differs depending on whether the machine has an iron core or is ironless.

Magnet length

Longer magnets give better efficiency of the machine. This can be seen in figure (19). Especially for lower radius, the machine will have advantages of longer magnets. Figure (22) also shows us that longer magnets will cost more. Magnets are the most expensive part of the motor, and in an optimal case, the motor should have as high efficiency as possible ,with the lowest cost. This is therefore something that is up to the individual to decide what counts most for the motor. In case of axial length and weight, longer or shorter magnets doesnt play that big of a role.

Increased magnet length will be costly for the machine. Anyway, the machine efficiency may become bigger in case of this.

The primary objective of this thesis was to develop an application that simplifies the comprehension of the key factors that contribute to the design of an effective axial flux machine. By providing users with a user-friendly tool, they can explore and manipulate various parameters to create different machine configurations, thus facilitating the attainment of desired machine characteristics

Additionally, a significant focus of this research was to conduct a comprehensive comparison between axial flux machines and the well-established radial flux machines. Radial flux machines currently dominate a substantial portion of the motor market

The development and adoption of axial flux machines has faced numerous challenges over the years, resulting in their limited popularity compared to radial flux machines. One of the primary reasons for this disparity lies in the ease of construction and the availability of tools and knowledge. Radial flux machines have traditionally been simpler to build, thanks to well-established fabrication techniques and a mass production infrastructure.

In contrast, the fabrication of axial flux machines has proven to be more intricate and demanding. The unique topology of axial flux permanent magnet (AFPM) machines necessitates specialized manufacturing processes that have not been widely developed until recently. As a result, the production of axial flux machines has been more expensive compared to their radial counterparts, making them less attractive in the market.

This viewpoint is also supported by Hanselman [2], who identifies similar challenges hindering the widespread adoption of axial flux machines. One obstacle lies in the lack of established manufacturing techniques and tooling processes specific to axial flux machines. The absence of a well-defined framework for producing these machines has hindered their mass production and contributed to their higher manufacturing costs.

Moreover, the performance of axial flux machines is highly dependent on the radial dimensions available for their construction. When space limitations are not a significant constraint, axial flux machines can show favorable performance characteristics. However, in applications where compact size is crucial, the limitations imposed by the axial flux topology can impede their effectiveness

Despite these challenges, recent advancements in manufacturing technologies and the growing demand for more efficient and compact electrical machines have increased ew interest in axial flux machines. Ongoing research and development efforts aim to address the fabrication complexities, optimize manufacturing processes, and improve the cost-effectiveness of axial flux machines. As these advancements continue, it is possible that the popularity and adoption of axial flux machines may increase, offering promising alternatives to their radial flux counterparts in various industrial and commercial applications

Indeed, as the interest in axial flux machines grows, it becomes crucial to determine the most suitable applications for both axial and radial flux machines. Evaluating their strengths and weaknesses can help guide the decision-making process. And in this point, the application should be helpful.

VIII. CONCLUSION

A tool to design axial flux machines is made and the application is used to take a look into the impact of some of the parameters designing the performance and design of the machine

A study of the outer stator radius shows the importance of this parameter for the axial flux machine, especially for the efficiency.

The magnet length is an important parameter, expecially in case of the cost, which is a very important parameter for an electric motor.

Not every application can have high rated speed, but in the cases where the rotational speed can be high, it looks like a very good solution. This will allow the motor to have a good efficency, low axial length, low cost and low weight. Almost every parameter will have advantage of high rotational speed.

This application serves as a tool for axial flux machine, which can be used to study the machine design needed for an application. This can allow the designer to play with parameters making the machine more optimized.

IX. FURTHER WORK

The optimization module in COMSOL is an additional feature for COMSOL, where the user can choose to optimize their figure. The optimization module can used on different categories, such as size, shape, topology and parameter and different processed that include fluid flow, electromagnetics, heat transfer and more.

Comsol offer to use both gradient based and gradient free optimization. For the gradient based comsol have 3 different alghorithms: SNOPT, IPOPT ad MMA. COMSOL also provides different gradient free alghorithms: COBYLA, BOBYQA, Nelder-mead and a coordinate search [18].

The most important difference between gradient based and gradient free alghorithm is that the gradient based alghorithm can show you a local maximum or minimum, because the gradient will be zero here. This means that there are chances that the function not will be fully optimized. In the gradient free methods, these faults will not occure and global solutions are often found.

Further work will be to use this optimalization part of COMSOL to optimize the axial flux machine.

Another further work will be to make a similar application for an ironless axial flux machine. Many of the competitive axial flux motors on the markets is ironless [7], which have a lot of advantages, in case of lower weight and no ironlosses making the efficiency better. It is of course a challenges with ironless axial flux motor, such that it need more magnets compared to AFPM with iron core.

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