‘’ELECTROMAGNETIC ANALYSIS OF MAGNETIC GEAR TRANSMISSION”

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A report submitted
in partial fulfillment of the requirements for the degree of
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2019

DECLARATION

I declare that this thesis entitled “‘’ELECTROMAGNETIC ANALYSIS OF MAGNETIC GEAR TRANSMISSION” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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APPROVAL

I hereby declare that I have checked this report entitled "ELECTROMAGNETIC ANALYSIS OF MAGNETIC GEAR TRANSMISSION" and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Electrical Engineering with Honours

Signature : ....

Supervisor Name : ....

Date : ....

DEDICATIONS

To my beloved mother and father

ACKNOWLEDGEMENTS

Alhamdulillah and all praise are to Allah, who promises his faithful servants victory. I would like to express my gratitude to Almighty Allah to enabling me to complete this report on “Electromagnetic Analysis of Magnetic Gear Transmission”.

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Special thanks to all my friends, my beloved mother and siblings for their moral support in completing this final year project. Lastly thank you to everyone who had been associated to the crucial parts of realization of this project.

ABSTRACT

Magnetic gears is widely used in many applications either in transportation, industrial machines, and power transmission. There are three types of magnetic gear which is coaxial magnetic gears (CMGs), linear magnetic gears (LMGs), and axial magnetic gears (AMGs). However, only a few literatures reported about magnetic gear especially to produce higher torque. The project main purpose is to model a new magnetic gear topology using FEM that could produce torque more than 1 Nm and analyse the torque and speed with a different parameter of permanent magnet, yoke, air gap and number of poles. The modelling of the magnetic gear starts using Solidwork and exported to using Maxwell ANSYS. This software simulates the magnetic gear includes electromagnet element such as flux density and magnetic field. The results show that magnetic gear has a high-speed ratio and generate a high torque at low speed. For the 2nd, the effects of the design model of magnetic gear and change the parameters of inner, outer magnet, diameter of yoke on the performance of torques are discussed. An air-gap thickness and other parameters will affect the maximum torques. As conclusion, this reasearch provides overview and guidelines of designing a new magnetic gear.

ABSTRAK

Gear magnet digunakan secara meluas dalam banyak aplikasi sama ada dalam pengangkutan, mesin perindustrian, dan penghantaran kuasa. Terdapat tiga jenis gear magnetik iaitu gear magnet sepaksi (CMGs), gear magnet linier (LMGs), dan gear magnet paksi (AMGs). Walau bagaimanapun, hanya beberapa literatur yang dilaporkan mengenai peralatan magnetik terutamanya untuk menghasilkan tork yang lebih tinggi. Tujuan utama projek adalah untuk model topologi gear magnetik baru menggunakan FEM yang boleh menghasilkan tork lebih dari 1 Nm dan menganalisa tork dan kelajuan dengan parameter yang berbeza magnet tetap, kuk, jurang udara dan bilangan kutub. Pemodelan gear magnetik mula menggunakan Solidwork dan dieksport menggunakan Maxwell ANSYS. Perisian ini menyerupai gear magnetik termasuk unsur elektromagnet seperti kepadatan fluks dan medan magnet. Keputusan menunjukkan bahawa gear magnet mempunyai nisbah berkelajuan tinggi dan menghasilkan tork yang tinggi pada kelajuan rendah. Untuk ke-2, kesan model reka bentuk gear magnet dan menukar parameter magnet dalaman, luar, diameter kuk pada prestasi tork dibincangkan. Ketebalan udara dan parameter lain akan mempengaruhi tork maksimum. Sebagai kesimpulan, kajian semula ini memberikan gambaran dan garis panduan untuk mereka bentuk gear magnet baru.

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LIST OF SYMBOLS AND ABBREVIATIONS

r_1	-	Inner rotor, r_1
r_2	-	Outer rotor, r_2
m_r	-	Rectangular Permanent magnet, m_r
y	-	Yoke
a_g	-	Air gap

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

Many applications in power transmission and industrial machines used mechanical gears. Contact friction, noise, and heat are the examples inherent problem although their usefulness is important. One of the solutions for these mechanical problems is a development of magnetic gear [1].

In the early 1930s, the Magnetic gear's technology was proposed [2]. But in that period because of the lack of understanding in magnetic gear, they did not give more attention to obtain the great development. From 1970s, researches paid extra attention to a new technology which is the development of magnetic gear's technology. Since between moving parts there is no mechanical contact, lubrication is not compulsory and overload protection, electromagnetic gears are active in research as a new magnetic mechanical device. It can reduce the wear and tear that are commonly seen in mechanical gear systems because the magnetic gears work smoothly without any sound and it will not get heated as long as it works by using such kind of gearing systems [3]. Magnetic gear can be used in place of mechanical gear to reduce undesired vibrations and for applications that require high torque. Many application requires power input with a high torque and low-speed revolution.

Magnetic gear consists of two rotors which are each rotor has a different number of magnetic pole pairs and separated by a small air gap. Magnetic fields produced by inner and outer rotors are modulated by the ferromagnetic steel poles and create space harmonics in the air gaps [4]. The magnetic field on the inner and outer rotor interact with the modulated magnetic fields via the steel poles to transmit the torque. There are three types of magnetic gears based on their operations which is Linear Magnetic Gears (LMG), Coaxial Magnetic Gears (CMG), and Axial Magnetic Gears (AMG). The magnetic flux is typically generated radially inward and outward with reference to the shaft axis for LMG and CMG. However, magnetic flux lines are created parallel to the rotor axis for AMG. But for this project only cover for CMG.

1.1 Project Motivation

Permanent magnets are used in magnetic gear to transfer torque between an input and output shaft without mechanical interaction which means that magnetic gears do not grieve from wear and losses associated with meshing teeth. The mechanism of power loss in mechanical gears is very different from those in magnetic gears. Magnetic gears can achieve efficiency at full load with much higher than a mechanical gear. Lubrication is not required since there is no mechanical contact between the moving parts. Magnetic gears protect against overloads by harmlessly slipping if an overload torque is exceeded while mechanical gears may be damaged under overload conditions. Magnetic gears are predicted to be low-noise devices because of a smooth torque transfer characteristics and absence of tooth contact. All these advantages motivated the author to study more on magnetic gear especially torque and speed characteristics for this project.

1.2 Problem Statement

In recent years, there have been considering many research and development activities on magnetic gear technologies. However, it is still not clear if this technology is ready for potential industrial applications because of the lack of knowledge of magnetic gear. For high performance, magnetic gear needs to be in high torque which will produce high torque density. Many researches have focused on improving the torque of magnetic gear by designing a new model of magnetic gear. So, in this project, a few modelling of magnetic gear is proposed.

The most studied topology of magnetic gears has been proposed by Martin and was the subject of different behaviour studies proposed by Atallah. One of the similar characteristics proposed by both of them is the shape of the permanent magnet which is used arc permanent magnet. The cost of arc permanent magnet is too high.

In summary, in this project a few modelling of magnetic gear is proposed by using rectangular a permanent magnet which has lower cost compare to arc magnet.

1.3 Project Objectives

This project aims:

i) To propose a model of new magnetic gear topology that has sets permanent magnet using Finite Element Method that could produce torque inner and outer rotor permanent magnet ratio 1:4.

ii) To analyse the torque characteristics with a different parameter such as air gap, number of poles, yoke and inner, outer permanent magnet.

iii) To select the best model that could produce torque inner and outer rotor permanent magnet ratio 1:4.

1.4 Project Scopes

The scope of the project includes understanding and analyzing the performance of torque and speed. Then, the magnetic gear is analyzed in order to get the best performance of the torque. First, a study has been conducted in searching any others previous magnetic gear in the journal or articles. Then, the magnetic gear will be developed based on theory and possible design method.

The design starts from magnetic analysis using Solidworks and simulated by using Finite Element Method (FEM). The FEM software known as ANSYS Maxwell is founded in 1970 which can determine the availability of magnetic characteristics such as flux flow, magnetic flux, and torque distribution.

The performance of the magnetic gear is need to analyze in order to get specifications which is torque. Based on the specification, the magnetic gear is designed by using Solidwork software and transferred to Ansys Maxwell software to simulate the design in order to get the desired torque. Next, based on simulation the best designed model of magnetic gear can be determined. Lastly, the best designed of magnetic gear will be model to further analysis. After that, by comparing the result of simulation a conclusion being made. This project does not cover eddy current loss, core loss, driver and no field test.

1.5 Thesis Outline

This report consists of 5 chapters. The first chapter of this report covers the research background, problem statements and objective of this project. The scope and report outline also included in this chapter.

The second chapter covers the literature review. All the theory that used to do analyse part is included in this chapter. The overview and operation of permanent magnet is also cover in this chapter. Besides, the description of the magnetic gear is cover in this chapter. The comparison between models of magnetic gear also cover in this chapter. The related research of magnetic gear is also cover in this chapter.

The next chapter is the methodology which explains in detail the procedures and steps for this research and project. Design and simulation software that are used to complete this project are also explain in this chapter.

The fourth chapter will be discussing about the result that obtain from the simulation. The final specification of the magnetic gear also discussed in this chapter. Lastly, the fifth chapter will be the conclusion for the project. The recommendation to improvise the design of the motor is also discussed in this chapter.

CHAPTER 2

LITERATURE REVIEW

Researches have shown interest and development a new technology incorporating permanent magnets with the achievement of technology. This idea is applied in magnetic gear to accomplish a concept of low-speed high torque operation [5]. Magnetic gear nowadays become popular because of contact-free operation, less maintenance, high reliability, requires no lubrication, and offer inherent overload. Because of these advantages, magnetic gear gets the better of the limitations of mechanical gearing system such as vibrations, noise, and friction due to contact. The magnetic field can be produced by using a permanent magnet which helps in the transfer of energy without contact. The process of transmitting power is silent and smooth differently with mechanical gearing system. Magnetic gears can be used to replace of mechanical gears to reduce unwanted vibrations and for the application that needs torque coupling between separated members [6].

2.1 The Construction of Magnetic Gear

Magnetic gear consists of two rotors, each with a different number of magnetic pole pairs separated by a small air gap.

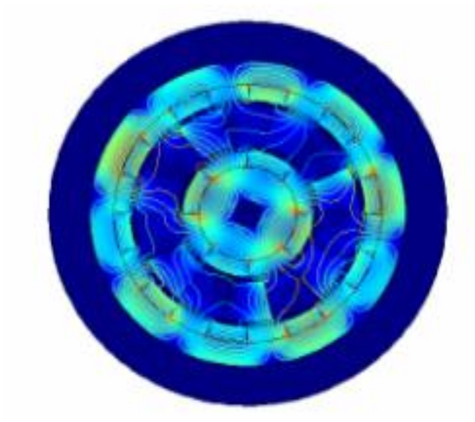


Figure 2.1: Modelling Of Magnetic Gear

In this configuration, the model consists of 4 pole pairs on the inner rotor, 11 pole pairs on the outer rotor, and 15 pole pairs in the middle (steel pole). The magnetic field with a dominant 4th harmonic produced by the 4 pole pairs on the inner rotor. To transfer torque, this field is modulated by 15 steel pole pairs to generate a field with a dominant 11th harmonic field that is produced by the outer rotor. This creates the torque as the field harmonic component from the outer rotor matches with the harmonic component created by the modulated inner rotor field [7].

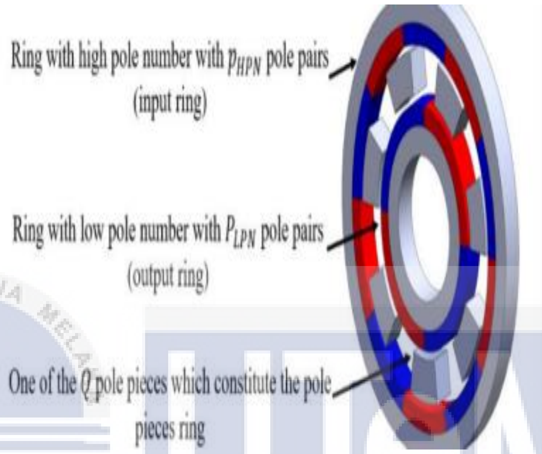


Figure 2.2: Magnetic Gear Arrangement

In [8], the general principle of the different magnetic gear with modulating ring arrangement can describe base on Figure 2.2. All the arrangement of magnetic gear with modulating ring are composed of three rings which is the ferromagnetic yoke with a ring with low pole number of pole pairs of permanent magnet, the ferromagnetic yoke and a ring with high pole number of pole pairs of permanent magnet and low pole number with a ring with ferromagnetic yoke pole pieces to improve readability.

2.2 Principle Operation of Magnetic Gear

As the power transmission device, the magnet was suggested for the first time by Armstrong C. G. in 1901 in his patent [9]. The gear consisted of two gears, which is one with electromagnets as the gear teeth and the other with steel pieces. According to their relative position to the secondary gear teeth, the electromagnets on the primary gear were switched on and off as shown in Figure 2.3.

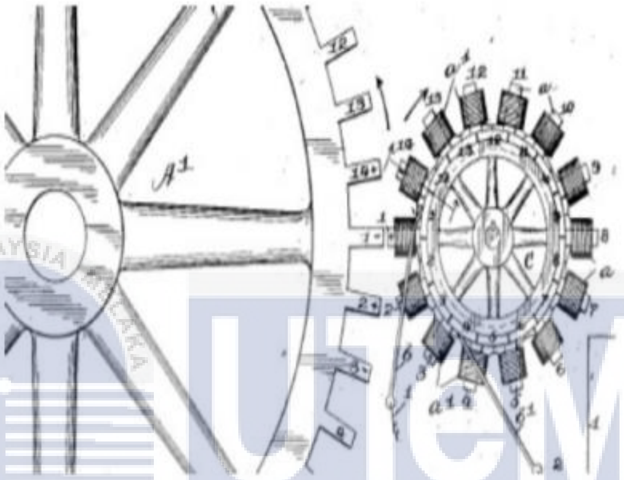


Figure 2.3: First Magnetic Gear

The amount of torque that could be transferred for the volume occupied fell short even the gear had the advantage of contact-less power transfer and low noise operation. At any given moment only one to three electromagnets transferred torque. Slip rings, which caused unnecessary losses and needed high maintenance connected to the electromagnets had to be connected electrically. By applying magnetic force, the power transmission principle in mechanical gear devices is similar as with magnetic gear, except that the gear is not made with teeth meshing but without the contact. The current flowing through the coil windings that are placed on the driving gear teeth obtained magnetic forces.

Neuland [10] invented a far superior magnetic gear in 1916. The gear consisted of three main parts which is a magnetic modulation piece in between the two steel rotors and laminated steel outer- and inner-rotor as shown in Figure 2.4.

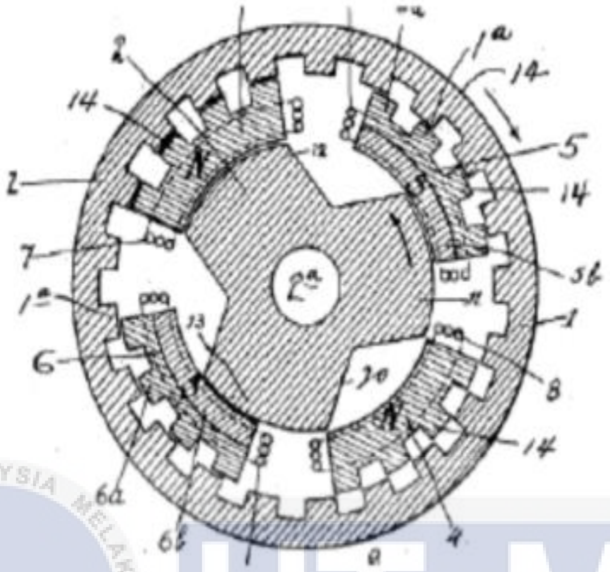


Figure 2.4: Coaxial Magnetic Gear

The inner rotor and the outer rotor saw the correct harmonics in accordance with the number of teeth on each shaft so the modulation pieces were shaped to modulate magnetic flux. The gear ratio between the shafts determined by the ratio of teeth on the outer and inner rotor. Since most of the gear teeth transferred torque at any given moment, the torque density of this configuration was greatly improved compared to the spur-type design from (1).

In 1941, H.T. Faus designed a magnetic spur-type gear [11]. The gear operated in the same way as the electromagnetic spur gear from (1). The only difference was that it used permanent magnets shows in Figure 2.5.

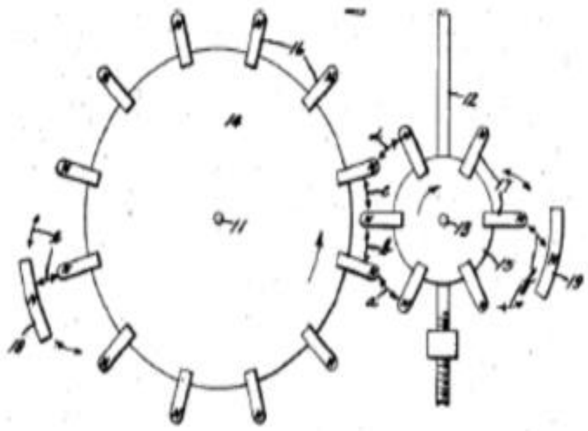


Figure 2.5: Permanent Magnet Spur Gear

The torque was transferred between the shafts by the repulsion of the identical poles of the magnets because all the north poles of the magnets pointed radially outwards. One of the permanent magnets breaks, since the PMs still made contact caused by the maximum torque was exceeded in this design the gear slipped. Thus this design was not suitable when overload protection.

There are concepts of magnetic gears resembling mechanical planetary gears, whose gears rather resemble conventional cylindrical gears (figure 2.6) [9]. Back in 1916, the first reference of a gear without mechanical contact. Magnetic planetary gears were first introduced in the patent [12]. Ackerman had patented its magnetic planetary gear solution given at the end of the 20th century [13]. The first built feasible dates to the 1980s but the only part of magnetic poles was in active magnetic contact and its efficiency was around 25-30% range [14]. A classic gear, which means the mechanical one, which relies on the contact of two wheels or teeth with the different number of iron teeth has some disadvantage. Since then, the magnetic gear was highlighted.

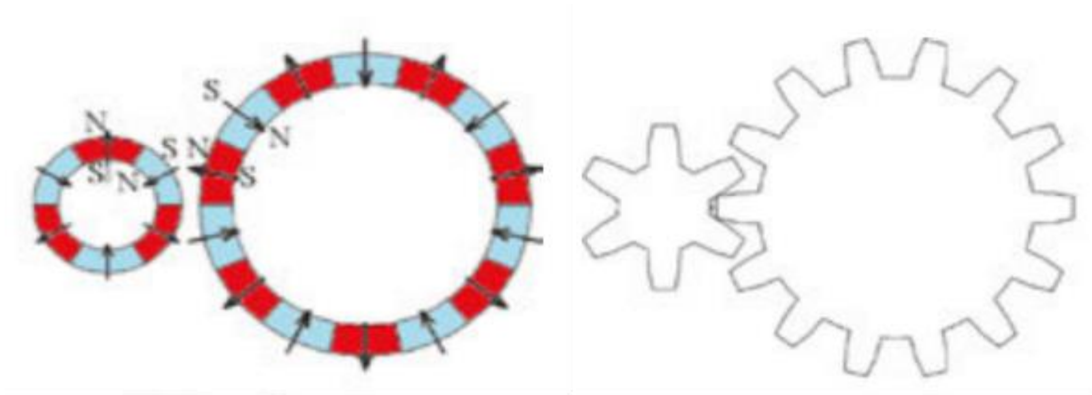


Figure 2.6: The first reference of magnetic gear

First of all, physical contact is needed. Besides that, lubrication is needed from time to time. Moreover, by time pass due to material friction, the teeth are physically damaged. Thus, after several hours or years of operation the losses increase. Rotating magnetic poles of the high-speed rotor within the iron poles of the static part created the operation of magnetic gear is based on the modulation of the magnetic field.

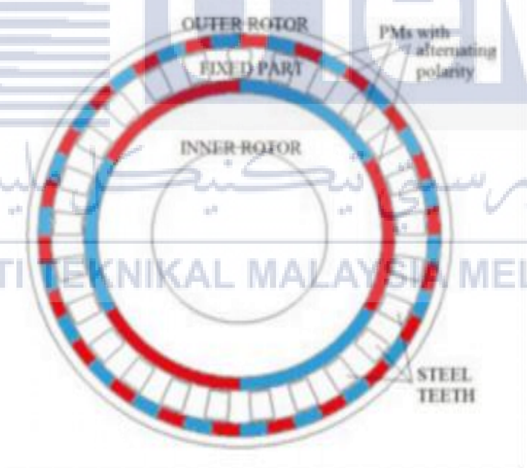


Figure 2.7: Magnetic Gear

The first efficient magnetic gear was proposed dates back to early 2000 by Atallah et al [15]. The main components of such magnetic gear are shown in Figure 2.7. The field created by the magnetic poles of the low speed (outer rotor) will interact with the field developed in the static iron and will force it to run in the opposite direction. Magnetic fields produced by inner and outer rotors are modulated by the ferromagnetic steel poles (middle rotor) and create space harmonics in the air gaps.

The magnetic field on the other side interacts with the modulated magnetic fields via the steel poles to transmit the torque.

The figure below shows the working principle of the magnetic gear [7].

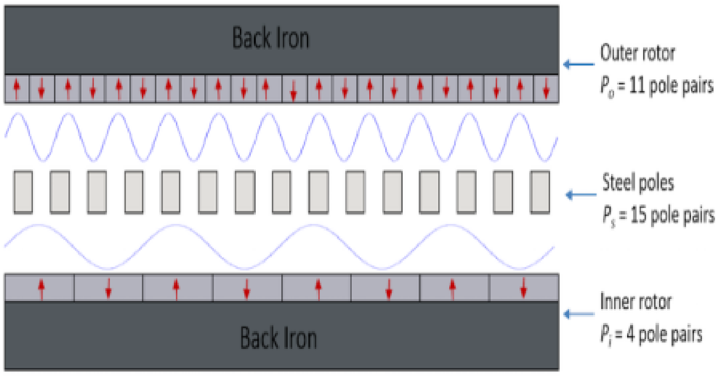


Figure 2.8: Linear Magnetic Gear

In 2005, Atallah et al. published a paper [16] on a linear magnetic gear. The gear operated on the same concept as the coaxial magnetic gear. There were three parts that moved relative to each other which is one flux-modulator core and two permanent magnet armatures connected to steel yokes. The flux-modulator core modulated the magnetic flux between the inner and outer permanent magnet armatures so that the permanent magnet yokes interacted with the correct number of poles (correct space harmonics).

2.3 Previous Related Research

There are several parameters that have been investigated in this project which includes air gap, number of poles, a thickness of magnet, and thickness of modulator. This section will explain these term in details.

2.3.1 The Effect of Air Gap

Early in the 1930s, the magnetic gear technology was proposed but because of the lack of full understanding of this technology at that time, it did not obtain great development. In this [17] study the effect of air gap changes. The ANSYS simulation results show that torque will decrement with the increment of an air gap. Air gap is a very important factor among many causing factors which influence maximum torque of electro-magnetic gears.

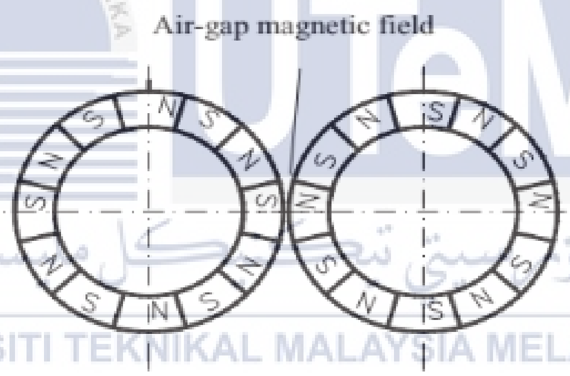


Figure 2.9: Working air-gap magnetic field [17]

The main parameter like the thickness of permanent magnet, a radius of the inner and outer rotor, external diameter are maintained but the working air gap is different, the relation between torque and the air gap is shown in figure 2.9.

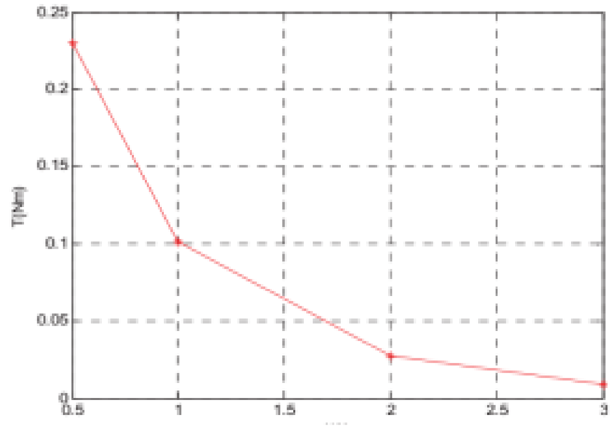


Figure 2.10: Different Working Air Gap-Torque Relation Curve [17]

From Figure 2.10, the torque will increase if the air-gap smaller. Use the smaller air-gap to improve the transmission efficiency when designing the transmission mechanism of electromagnetic gears. Jianna Huang (2012).

2.3.2 The Effect Different Number of Pole on Torque

This paper [18] described the efficiency improvement and the performance analysis of the trial magnetic gear. It was clear that the value of torque depends on the number of poles of a permanent magnet. The decrease the number of a permanent magnets, the increase the value of torque.

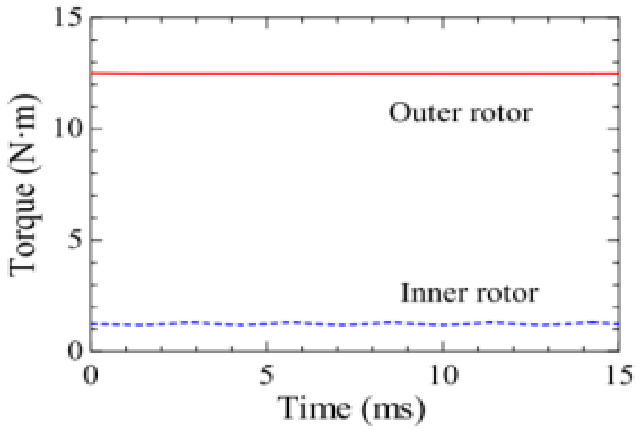


Figure 2.11: Torque waveform [18]

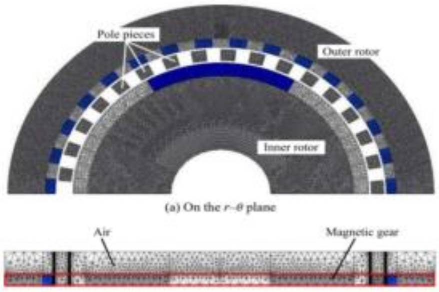


Figure 2.12: 3D Model of Magnetic Gear [18]

2.3.3 Effect of Permanent Magnet Thickness

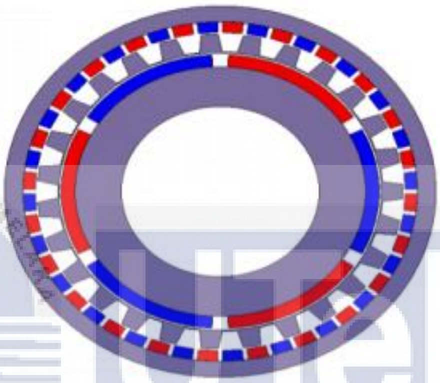


Figure 2.13: Model Magnetic Gear [19]

The magnets on the sun gear and the outer ring gear were of the same thickness in the simulated model of design in Figure 2.13. The magnets on the outer ring gear and sun gear were of the same thickness. The inner diameter of the outer yoke was kept constant but the thicknesses of the outer and inner yokes were increased to avoid excessive saturation. The thickness of the magnets was varied as shown in the graphs while the modulator thickness was also kept constant. The torque per magnet thickness decreases with increasing magnet thickness shows in Figure 10 [19]. R-J Wang, S. Gerber (2014)

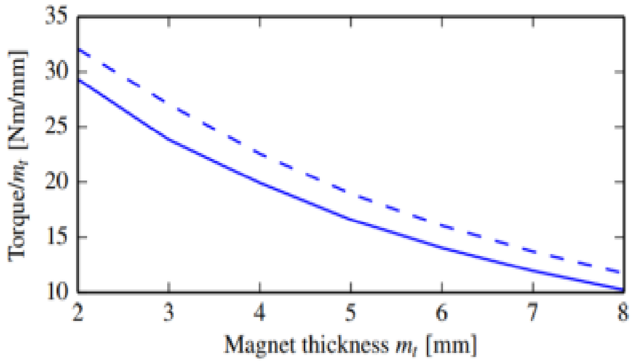


Figure 2.14: Variation of the torque per magnet thickness [19]

2.3.4 Effect of Modulator Thickness

Figure 11 [19] shows the effect that the modulator thickness has on the maximum torque of design in Figure 2.15. It shows that for a modulator with an inner bridge, an optimum thickness exists which maximizes the stall torque of the gear. R-J Wang, S. Gerber (2014)

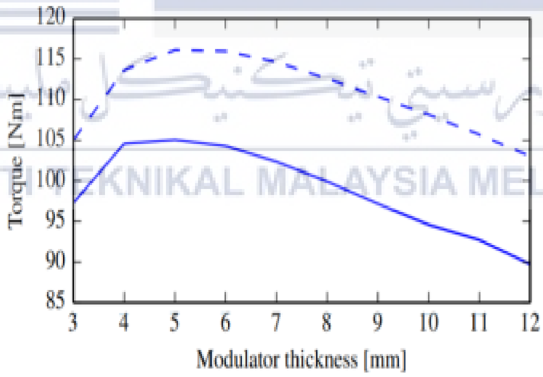
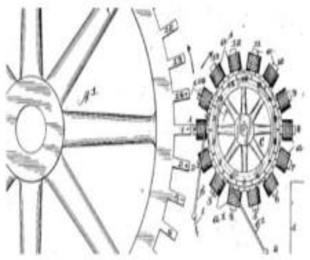
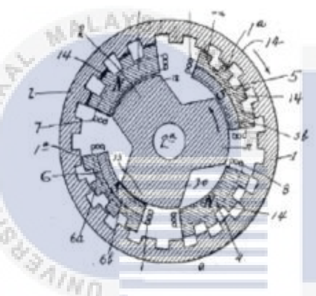
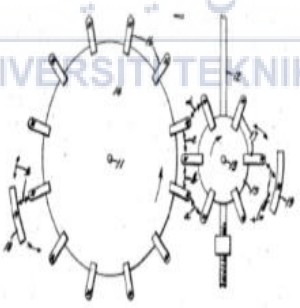
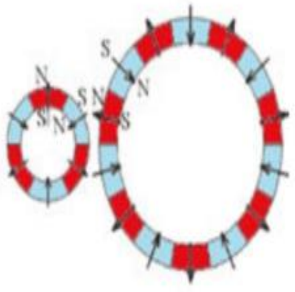


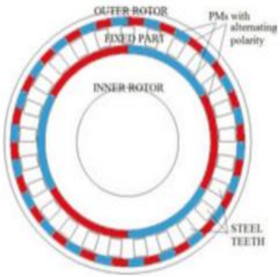
Figure 2.15: Variation of the torque per modulation thickness [19]

2.4 Evaluation of Previous of Selected Magnetic Gear

Table 2.1: Comparison Between Model

Author	Model	Advantages	Disadvantages
Armstrong C. G		❖ The gear had the advantage of contact-less power transfer. ❖ Low noise operation.	❖ The amount of torque that could be transferred for the volume occupied fell short. ❖ High maintenance
Neuland		❖ The torque density of this configuration was greatly improved	❖ This design was that there were only magnets on one of the shafts, which led to impractical air-gap sizes.
H.T. Faus		❖ The torque was transferred between the shafts by the repulsion of the identical poles of the magnets because all the north poles of the magnets pointed radially outwards	❖ This design is not suitable when overload protection
Ackerman		❖ Non mechanical contact	❖ Only part of magnetic poles was in active magnetic contact and its efficiency was around 25-30% range

Continue Table 2.2: Comparison Between Model

Atallah		❖ Non mechanical contact ❖ Low noise operation. ❖ Suitable when overload protection ❖ transmitted torque values higher than 75%	❖ Has a lower torque

2.5 Conclusion

Based on the comparison model shown in a table in 2.1 states that the best model is by Atallah. There are many advantages for Atallah model compare to others model such as non-mechanical contact, low noise operation, suitable when overload protection and transmitted torque values higher than 75%. This project will contribute to the development of new technology for further research.

CHAPTER 3

METHODOLOGY

In this chapter, it will discuss the methodology of this project. A few steps have been taken to ensure the smoothness of this project. There are five types of magnetic gear including the proposed magnetic gear with different types of permanent magnet will be studied in term of their torque distribution. There is two software used in this project which is Ansys Maxwell and Solidworks. Both of these tools are used to simulate and design the best performance of torque. The best performance of magnetic gear is to choose for further analysis. An explanation about the simulation methodology using Finite Element Method (FEM) is presented.

3.1 Overall Methodology

In this project, focus on the design of magnetic gear so that improvement of torque could be achieved. The overall project methodology is shown in Figure 3.1. Firstly, study and justify the specification of the previous magnetic gear by collecting the required and relevant information such as a model of magnetic gear, the operation between the different number of poles, air gap, and a few parameters in magnetic gear. After that, magnetic gear is developed and simulated using Solidwork software and Ansys Maxwell. The objective of using Ansys Maxwell is to select the best performance of torque. This is to determine the suitable design that has a limitation of flux density in the model. There two different of shape for the permanent magnet is used which is bar magnet and curve magnet in order to identify the torque. Simulation by using FEM is done again to find a reasonable limit of magnetic flux density and torque of all model. Based on FEM result on outer and inner rotor flux density and torque, the best model is chosen. After the best model is chosen, the analysis on the size of the magnet and yoke will be further studied. The rightful model of magnetic gear that has higher torque will be proposed in this project.

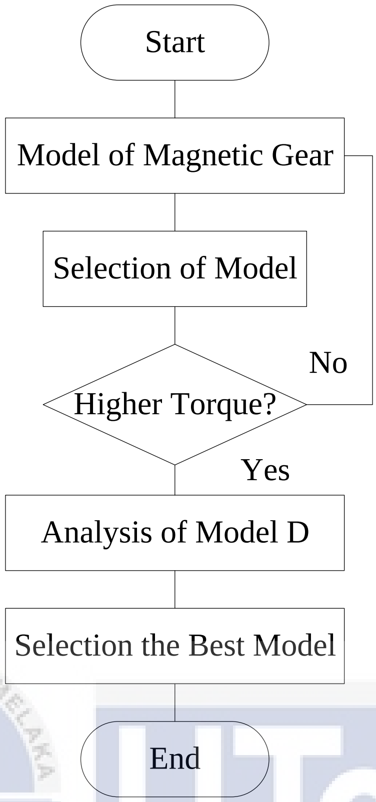


Figure 3.1: Overall Project

3.2 Model of Magnetic Gear in Research

In this research, there are four models that had been proposed which is Model A, Model B, Model C, and Model D. Speed for the inner and outer rotor permanent magnet is set for 0 and 500 rpm respectively. The objectives of the design is to indicate the best performance of torque. The fixed parameter for designing magnetic gear is the inner rotor radius r_1, outer rotor radius r_2, and air gap, a_g.

3.2.1 Structure of Magnetic Gear in Research

3.2.1.1 Base Reference Model

The magnetic gear consists of rotors with different pole pairs, as shown in Figure 3.2 below. The inner rotor is consists of eight permanent magnets (PMs) and a yoke which forms an outward flux focusing 2 pole pairs on the rotor. The outer rotor includes 20 permanent magnets (PMs) and a yoke that forms an inward flux focusing 5 pole pairs on the rotor. In the middle stationary ring and the same spacing between these pieces forms a stationary rotor with 7 pole pairs, seven pieces of steel are included.

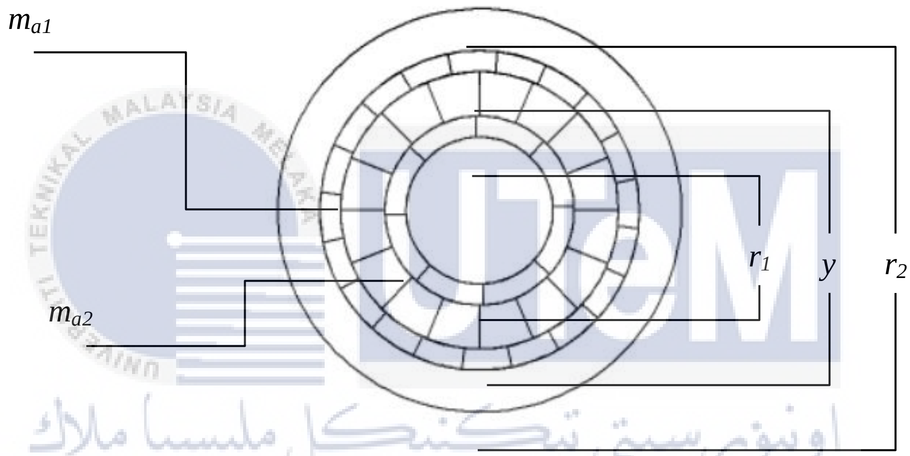


Figure 3.2: Reference Design of Magnetic Gear in COMSOL[1]

Based on the reference model, the parameter as a table 3.1 below:

Table 3.1: Parameter of Reference Design of Magnetic Gear in COMSOL

Parts	**Parameter (mm)**
Inner rotor, r_1	Diameter= 9.0
Outer rotor, r_2	Diameter= 30.0
Yoke, y	7.0
Arc permanent magnet *(lxhxw)*, m_{a1}	2x5x28
Arc permanent magnet *(lxhxw)*, m_{a2}	2x3x28
Angle of inner permanent magnet, α_1	45˚
Angle of outer permanent magnet, α_1	18˚

3.2.1.2 Model A

Model A of magnetic gear consists of two rotors, each with a different number of magnetic pole pairs separated by a small air gap as shown in Figure 3.3 below. The number of poles in the inner and outer rotor is the same as the reference model which is eight and 20 permanent magnets respectively by using a rectangular permanent magnet. But in the middle stationary ring known as a yoke has eight pole pairs of steel separated by a small air gap between them.

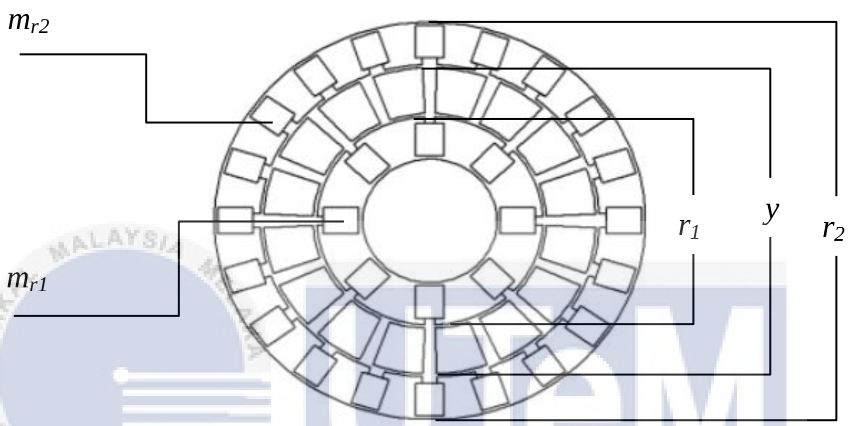


Figure 3.3: Model A of Magnetic Gear

Based on the model A, the parameter as a table 3.2 below:

Table 3.2: Parameter of Model A of Magnetic Gear

Parts	**Parameter (mm)**
Inner rotor , r_1	Diameter= 9.0
Outer rotor, r_2	Diameter= 30.0
Yoke, y	7.0
Rectangular Permanent magnet, m_{r1}	4x5x28
Rectangular Permanent magnet, m_{r2}	5x4x28
Air gap, a_g	0.5

3.2.1.3 Model B

Model B of magnetic gear consists of rotors with different pole pairs, each with a different number of magnetic pole pairs separated by a small air gap as shown in Figure 3.4 below. The number of poles in the inner and outer rotor is the same as the reference model which is eight and 20 permanent magnets (PMs) respectively by using rectangular permanent magnet. In the middle stationary ring, one piece of steel are included called as a yoke (ferromagnetic steel). The design of hollow rotor is used in this second modelling for an outer and inner rotor.

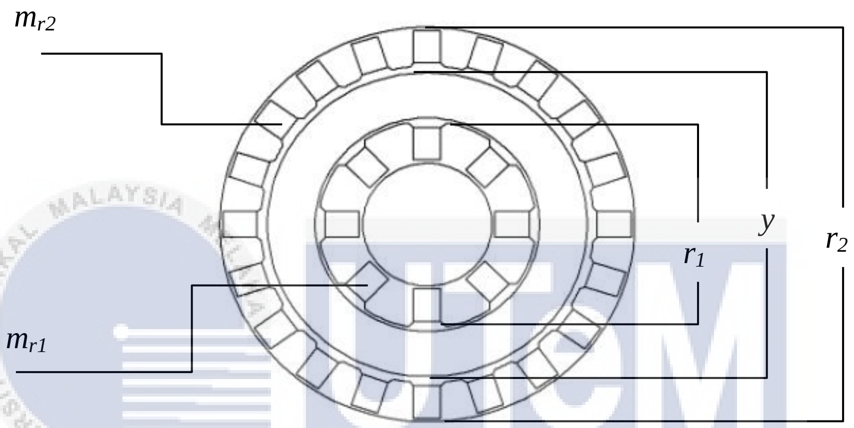


Figure 3.4: Model B of Magnetic Gear

Based on the model B, the parameter as a table 3.3 below:

Table 3.3: Parameter of Model B of Magnetic Gear

Parts	**Parameter (mm)**
Inner rotor, r_1	Diameter= 16.0
Outer rotor, r_2	Diameter= 30.0
Yoke, y	7.0
Rectangular Permanent magnet, m_{r1}	4x5x28
Rectangular Permanent magnet, m_{r2}	5x4x28
Air gap, a_g	0.5

3.2.1.4 Model C

Model C of magnetic gear consists of rotors with different pole pairs, each with a different number of magnetic pole pairs separated by a small air gap as shown in Figure 3.5 below. In the third modelling, there are two parts of the inner and outer rotor with arc design of rotor. The number of poles in the inner and outer rotor is same as the reference model which is eight and 20 permanent magnets (PMs) respectively by using a rectangular permanent magnet. A yoke which the same parameter as the second model.

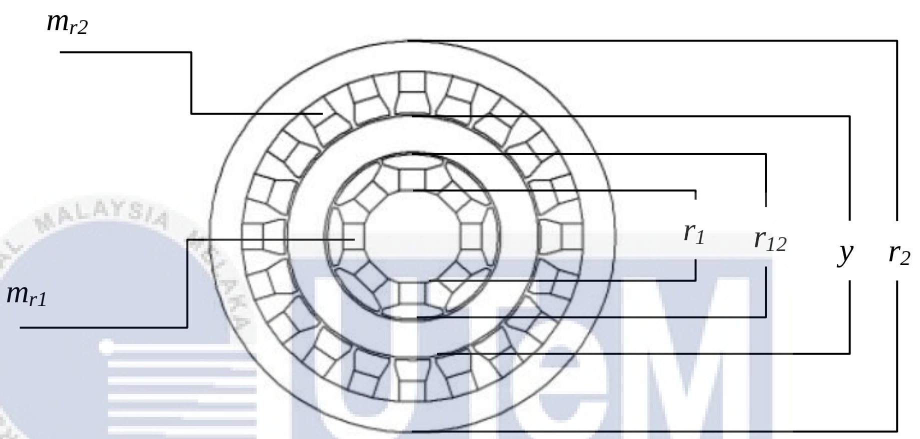


Figure 3.5: Model C of Magnetic Gear

Based on the model C, the parameter as a table 3.4 below:

Table 3.4: Parameter of Model C of Magnetic Gear

Parts	Parameter (mm)
Inner rotor1, r_1	Diameter= 9.0
Inner rotor2, r_{12}	Diameter= 16.0
Outer rotor, r_2	Diameter= 30.0
Yoke, y	7.0
Rectangular Permanent magnet, m_{r1}	4x5x28
Rectangular Permanent magnet, m_{r2}	5x4x28
Air gap, a_g	0.5

3.2.1.5 Model D

Model D of magnetic gear consists of rotors with different pole pairs, each with a different number of magnetic pole pairs separated by a small air gap as shown in Figure 3.6 below. The number of poles in the inner and outer rotor is same as the reference model which is eight and 20 permanent magnets (PMs) respectively by using a rectangular permanent magnet. In the forth modelling, there are two parts of inner and one part outer rotor. The inner rotor is consist of arc rotor design while the outer rotor used the hollow rotor. A yoke which the same parameter as the second and third model.

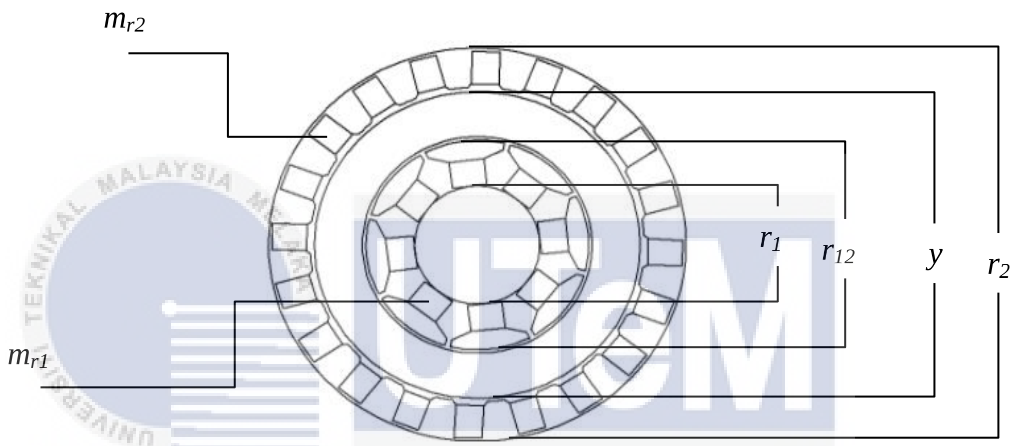


Figure 3.6: Model D of Magnetic Gear

Based on the model D, the parameter as a table 3.5 below:

Table 3.5: Parameter of Model D of Magnetic Gear

Parts	Parameter (mm)
Inner rotor1, r_1	Diameter= 9
Inner rotor2, r_{12}	Diameter= 16
Outer rotor, r_2	Diameter= 30
Yoke, y	7.0
Rectangular Permanent magnet, m_{r1}	4x5x28
Rectangular Permanent magnet, m_{r2}	5x4x28
Air gap, a_g	0.5

3.2.2 Model of Magnetic Gear

There are two tools which is modelling of magnetic gear by using Solidwork and simulate by using Ansys Maxwell.

3.2.2.1 Modelling of Magnetic Gear Using Solidwork

The model of the design magnetic gear has been drawn using a software known as Solidwork Software. Firstly, the size and parameter of the permanent magnet, air gap, yoke diameter, inner rotor, and the outer rotor has been chosen based on reference model by COMSOL.

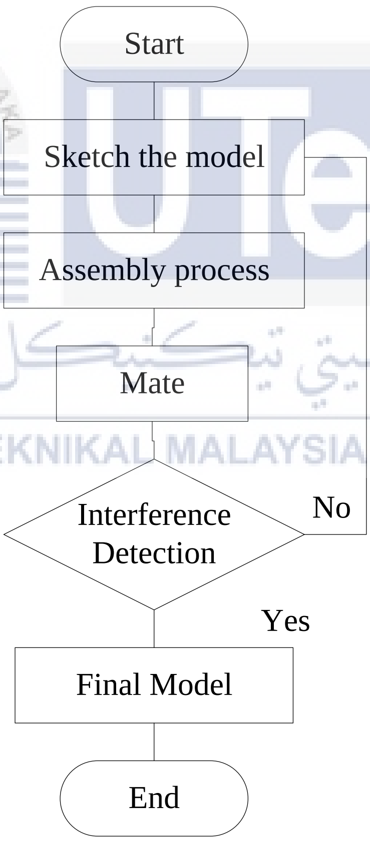


Figure 3.7: Flow chart for modelling magnetic gear using Solidwork

3.2.2.2 Modelling of Magnetic Gear using Ansys Maxwell

In this project, the Finite Element Method (FEM) is used as a tool to solve the electromagnetic field problems for a given model with appropriate materials, boundaries, and source conditions applying Maxwell's equations over a finite region of space. (Ansys, 2016). FEM can provide magnetic analysis with high accuracy because it gives an approximation on a microscopic scale. However, it requires structural modelling and high memory capacities of a computer, which in the end give more computational time drawbacks. It is clear that the adequacy of meshing directly affects the precision of computation. These drawbacks are taken into account in this research to ensure reliability and accuracy. Therefore, FEM is not essential for repetitive calculation such as for optimization or structure analysis.

In order to complete this project, Solidwork software and Ansys Maxwell is used as a tool to simulate the model. In order to model the magnetic gear, the Solidwork software is used and transferred the model to the Ansys Maxwell software to simulate the performance of the magnetic gear. By using Ansys Maxwell, the best torque is determined.

The steps in order to used Ansys Maxwell software is shown in Figure 3.8. The first step is convert the model from 3-Dimension to 2-Dimension. Then, students should know what type of material that will used. The coordinate of the magnet is determined the polarity either it is positive or negative. After that, band and region will be drawn. Band is drawn between outer and inner rotor.

Next, all the parameter will be assigned and the excitation of the eddy effect. Next step is doing the mesh operation. After all the setting is finished, the model can be analysed and all the result will be plotted. If the result is not satisfied, the parameter should be change until the desired torque is achieved. If the result is still not satisfied for example the flux density between inner and outer rotor still not fulfil the requirement, design new model of magnetic gear and the process is repeated until the result is satisfied with specification needed.

The flux lines and the flux density are also can be determined by using the Ansys Maxwell. Figure shows the flux lines of the magnetic gear. The flux lines are indicate the lines are flow from North Pole to the South Pole. Figure show the flux density of the magnetic gear. Since the rotor is made up from steel, the flux density must fulfil the requirement which is 1.5T. The flux density of the outer and inner rotor must have the same value.

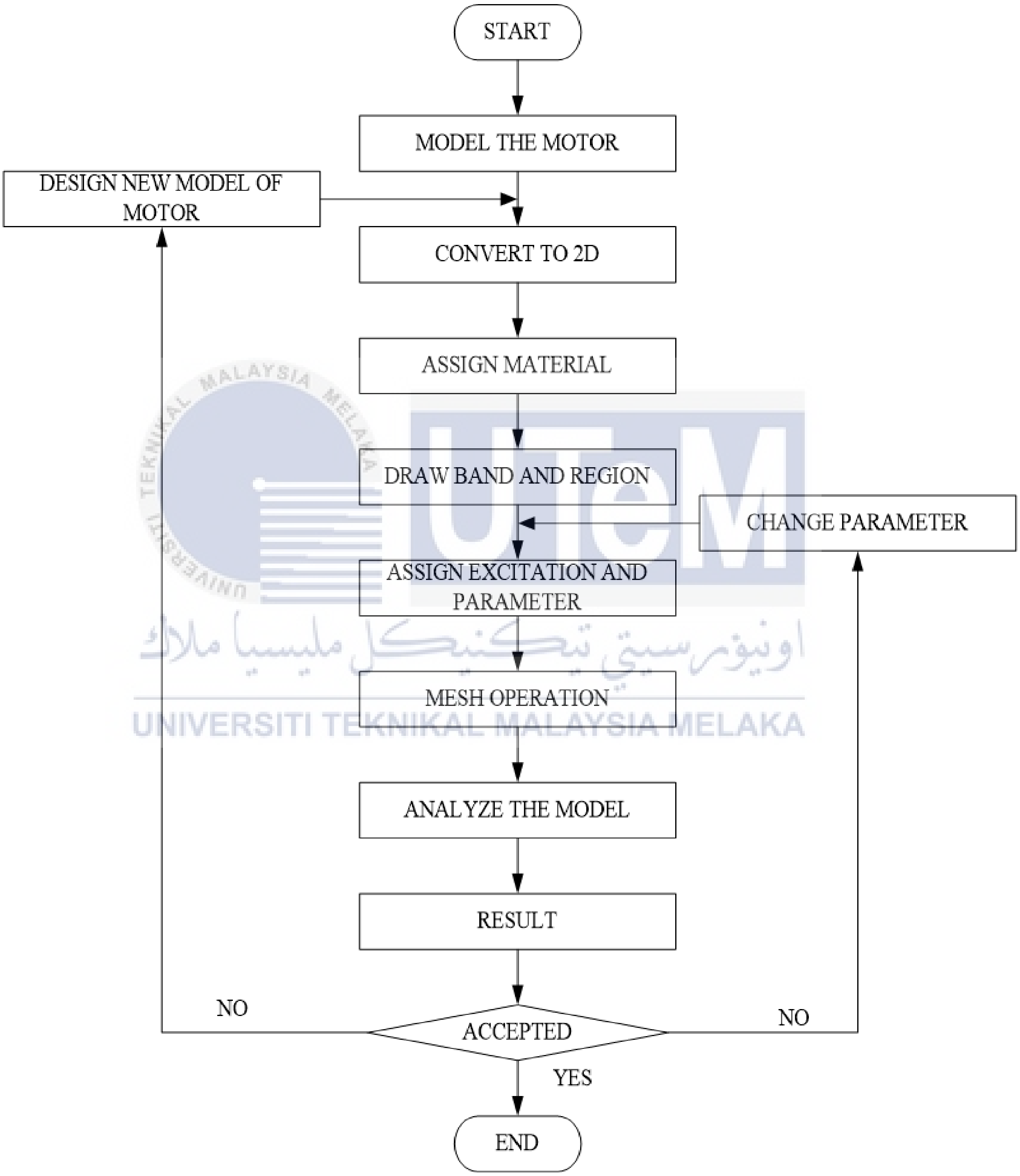


Figure 3.8: Flowchart for FEM Modeling

3.3 Selection of Magnetic Gear Model Methodology

The selection is based on the value of torque that produces, *t*. In this project, higher *t* is required in order to obtain a lower speed, n_s . The n_s is depending on the number of poles in the outer and inner of the rotor. The higher the number of poles, the lower the value of speed, then higher torque will be produced. The previous magnetic gear studied in order to get the specification of magnetic gear. The previous magnetic gear is studied. The specification of the previous magnetic gear is shown in above table. It consists of two rotor. The magnetic gear consists of rotors with different pole pairs, as shown in model D. The inner rotor is consist of eight permanent magnets (PMs) and a yoke which forms an outward flux focusing 2 pole pairs on the rotor. The outer rotor includes 20 permanent magnets (PMs) and a yoke that forms an inward flux focusing 5 pole pairs on the rotor. In the middle stationary ring and the same spacing between these pieces forms a stationary rotor with 7 pole pairs, seven pieces of steel are included. So, Model D is choose as a final model to change the parameter of inner and outer magnet, and diameter of yoke to determine a new torque. The table 3.6 below is the parameter of inner and outer magnet also the diameter of yoke.

Table 3.6: Specification of Variable Parameter

Element	Value (mm)
Inner permanent magnet, m_{r1}	(1x5),(2x50),(3x5)
Outer permanent magnet, m_{r2}	(1x4),(2x4),(3x4),(4x4)
Yoke (diameter), *y*	3,3.5,4,5,6,8,9,10,11,12,13,14,15

3.4 Analysis of Selected Model

The overall analysis of magnetic gear using FEM is shown in Figure 3.9. There is a various design of rotor used in this project which is an arc and hollow rotor. Each of the design of the rotor will be analysed to determine their performance. In this project, four model of magnetic gear with different rotor structure is being studied. The base reference model of magnetic gear in this project are designed based on the literature review. All the model of magnetic gear has been designed for eight and 20 poles for inner and outer rotor respectively. The inner and outer rotor for each model of magnetic gear is made from steel. On the other hand, the yoke is made from ferromagnetic material according to their respective types. The ferromagnetic steel poles (middle rotor) modulate the magnetic fields produced by inner and outer rotors. It will create space harmonics in the air gaps. The magnetic field on the other side interacts with the modulated magnetic fields via the steel poles to transmit the torque. Then, with final design, the parameter of inner and outer magnet changed to simulated which size has a highest torque. Finally use the model D with new parameter of inner and outer magnet, the size of yoke. The parameter of inner and outer magnet, and diameter of yoke is changed regularly based on the previous result until the best result is achieved. The flow chart on how parameter changed in Figure. After all the parameters are changed, the magnetic gear will analyse. Then the flux density can be determined. The design of magnetic gear is selected when the produce a high torque. If the torque that produce is not satisfied, the process is repeated by change the different value of variable parameter. Figure shows the final model with new diameter of yoke and parameter of inner and outer magnet parameter of magnetic gear.

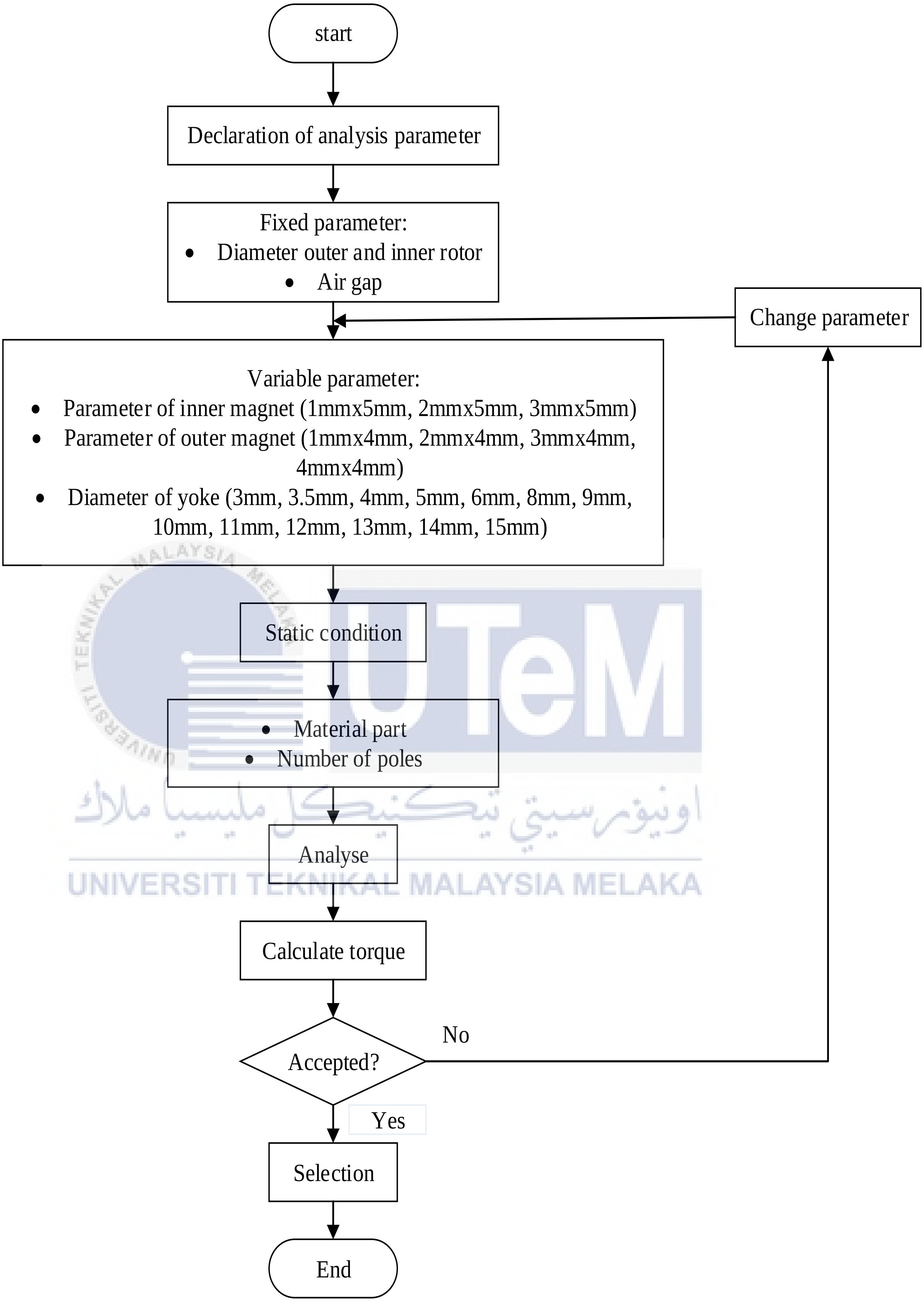


Figure 3.9: Flowchart for analysis Model D

3.5 Selection of Best Model

After the simulation completed, the best performance torque of Magnetic Gear is selected to send for fabrication which are high in performance of torque. But due to the time constraint, the magnetic gear cannot fabricate. The fabricated magnetic gear was measured experimentally in order to compare the result. For this time being the magnetic gear casing is done by using Solidword software. The measurement will be done in future once the magnetic gear been fabricated.

3.6 Summary

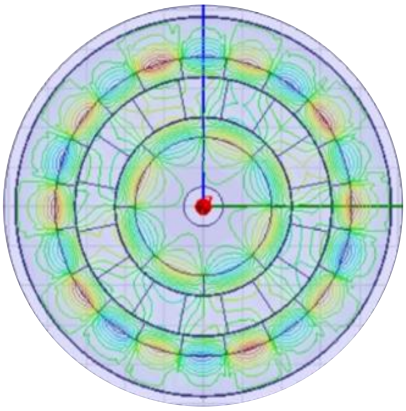
As a conclusion, there are two software in designing the magnetic gear which are Solidwork software and Ansys Maxwell. The concepts of both methods are briefly discussed in this chapter. To design and simulate the performance magnetic gear the Solidwork and Ansys Maxwell is used respectively. Since Model D shows the best performance of in term of torque production, this model is used for further analysis.

CHAPTER 4

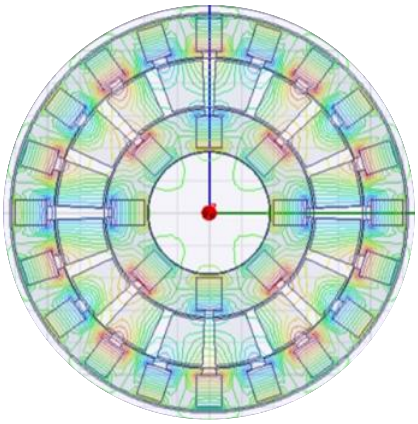
RESULT AND DISCUSSION

4.1 Result of Model of Magnetic Gear Selection Model

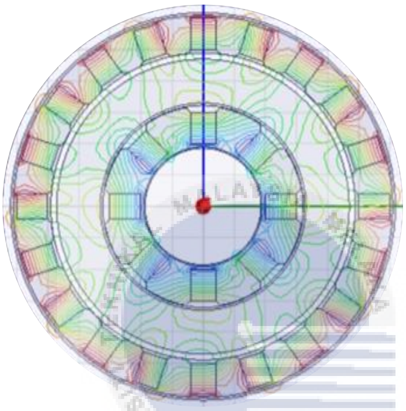
In the four modelings of magnetic gear, the number of poles and parameter of a yoke, air gap, size of the permanent magnet, inner and outer rotor are same as a base reference which refers to COMSOL blog. But, the changing structure of the rotor will be analysed. In this research, the arc permanent magnet has been used for base reference of magnetic gear. But for model A, model B, model C, and model D use the rectangular permanent magnet. There are a few differences in terms of magnetic density and flux lines because of their different shape of permanent magnet and structure of the rotor. Figure 4.2 below shows the result of torque for base reference, Model A, Model B, Model C, and Model D of magnetic gear at speed 0 rpm and 500 rpm of inner and outer magnet respectively. The graph shows that Model D has the highest torque compared to others model which is 3.33574 Nm while the Model C has the lowest torque which is 0.00543 Nm. This is because the inner and outer rotor has shared their flux lines. Therefore, model D is selected for further analysis in order to change the parameter of permanent magnet and yoke.



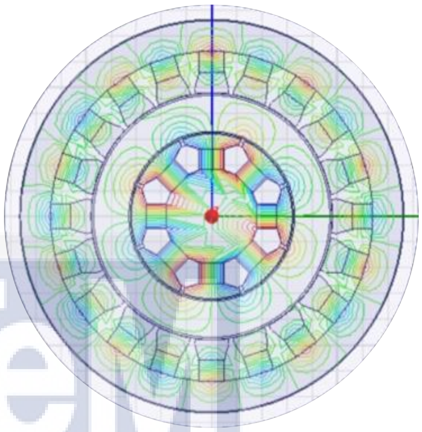
(a) Base Reference



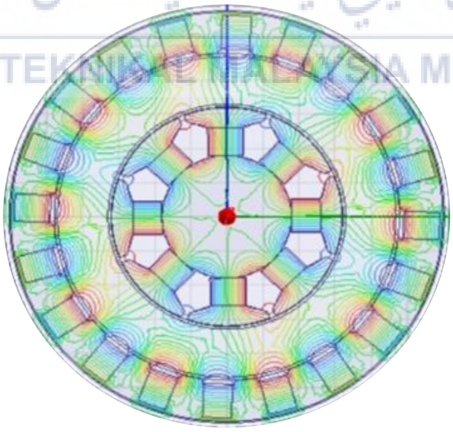
(b) Model A



(c) Model B



(d) Model C



(e) Model D

Figure 4.1 Flux Lines of Magnetic Gear

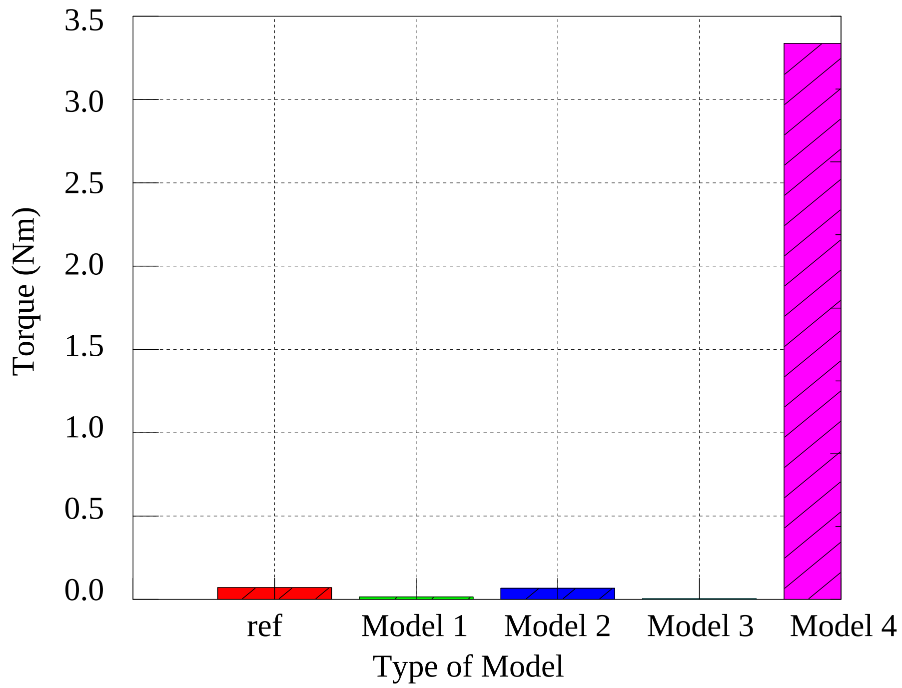


Figure 4.2: Types of Model of Magnetic Gear

4.2 Analysis of Selected Model D Magnetic Gear

The analysis on the effect of the different parameter of the inner, outer permanent magnet and of yoke towards the performance of torque have been carried out using Finite Element Method (FEM). After all the parameter is changed, the result of performance torque is analysed. Based on the result, the final model will be determined.

4.2.1 Different Size of Outer Rotor Permanent Magnet

Figure 4.3 shows the average of torque for various size of outer rotor permanent magnet. There are four different sizes of permanent magnet will be used which are 1x4, 2x4, 3x4, 4x4 mm. The width of the magnet is fixed to 4mm. Even though the height of the magnet is different, the total mechanical air gap outer and inner rotor is fixed which is 1 mm.

Based on the graph, all parameter of the outer rotor permanent magnet shows the lowest torque. But when the permanent magnet 5x4 mm is used, it shows the increases in outer rotor torque which is 3.33574 Nm while in inner rotor torque is

0.11171 Nm. Meanwhile, the permanent magnet 1x4 mm shows that the lowest torque than others which is 0.023 Nm and 0.00001Nm of outer and inner rotor respectively.

The percentage of the highest and the lowest is 99%. This is due to the energy of the permanent magnet produce by 5x4mm is the highest compared to others. This is because the size of an outer permanent magnet is bigger than others permanent magnet. So the energy from the permanent magnet is more and the torque produce will be higher too.

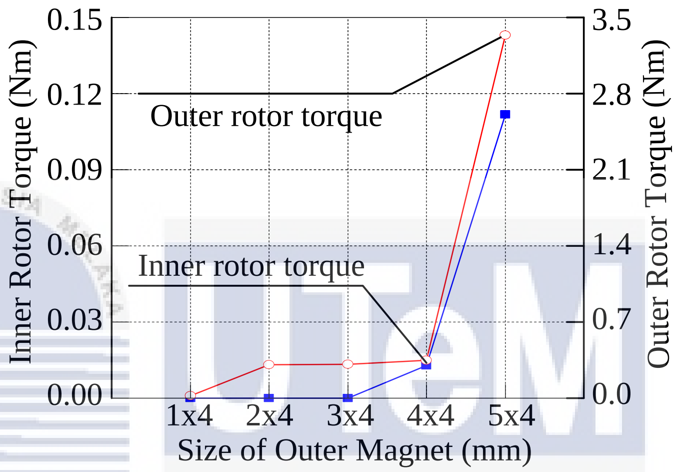


Figure 4.3: The Torque for different size of outer Permanent Magnet

4.2.2 Different Size of Inner Rotor Permanent Magnet

Figure 4.4 shows the analysis performance of magnetic gear which includes the ideal torque. There are three different sizes of permanent magnet will be used which is 1x5 mm, 2x5 mm, and 3x5 mm. Even though the height of the magnet is different, the mechanical air gap is fixed which is 0.5 mm.

From the figure 4.4 shows that the size of the magnet is increase, the torque produce will be higher too. Based on the graph, permanent magnet 3x5 mm has higher outer rotor torque which is 4.49201 Nm compare to permanent magnet 1x5 mm which is 3.54383 Nm. This is because energy from permanent magnet 3x5 mm is the highest compared to others. Meanwhile, permanent magnet 3x5 mm has higher inner rotor torque which is 0.14957 Nm compared to permanent magnet 1x5 mm which is 0.02892 Nm.

The percentage of the highest and the lowest is 21%. This is due to the energy of the permanent magnet produce by 3x5 mm is the highest compared to others.

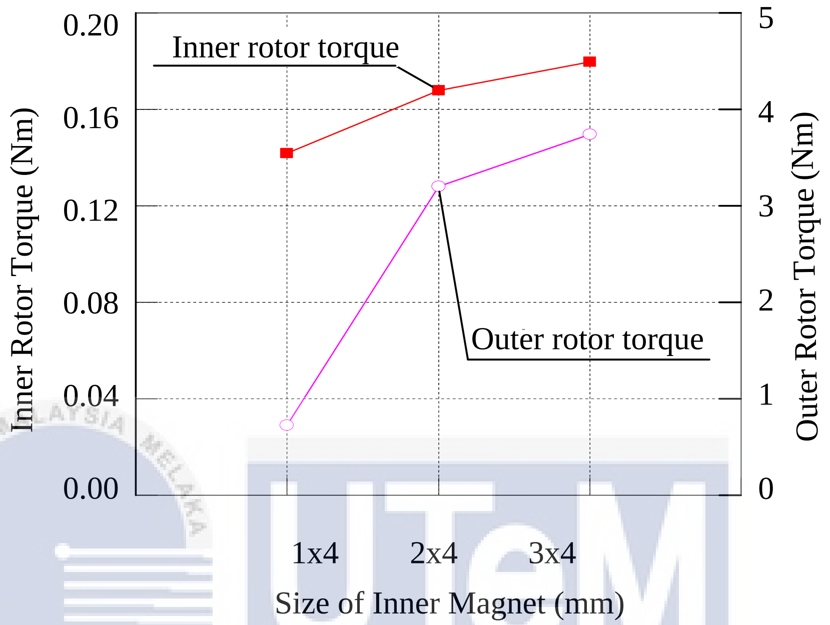


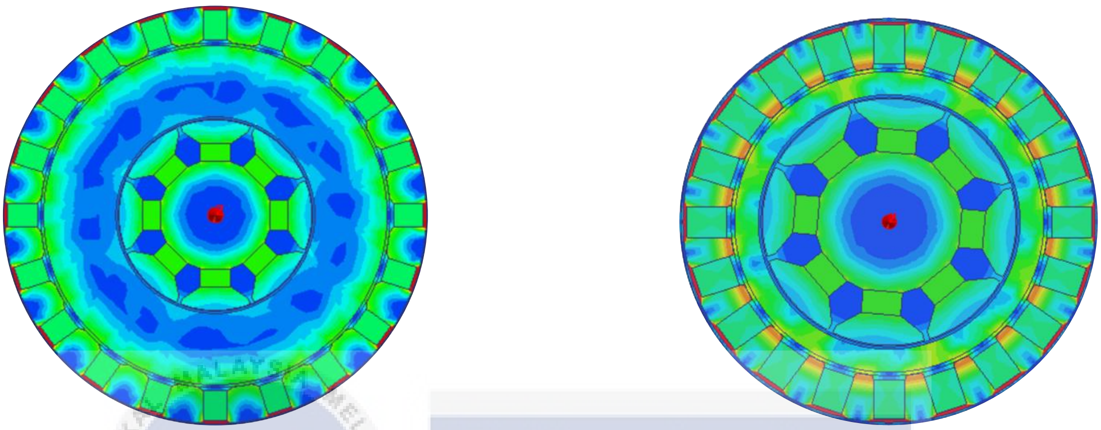
Figure 4.4: Torque for different size of inner Permanent Magnet

4.2.3 Different Diameter of Yoke

From Figure 4.6 shows the average of torque for various parameter yoke. There are 14 different diameters of the yoke will be used which are 3 mm, 3.5 mm, 4 mm, 5 mm, 6 mm, 8 mm, 9 mm, 10 mm, 11 mm, 12 mm, 13 mm, 14 mm, and 15 mm. Even though the diameter of the yoke is different but the mechanical air gap is fixed which is 0.5 mm.

Based on the graph below, yoke 7 mm shows that the highest outer rotor torque which is 4.4918 Nm. Meanwhile, the lowest torque is 12 mm which is 0.00406Nm. This is because the flux density is decrease but increase the flux leakage. This is because the flux lines were not been used in this magnetic gear (Please refer Figure 4.5).

When compare magnetic gear with diameter yoke 3 mm, which is the outer rotor is nearly achieved saturated point because of the size of the yoke is too small. The percentage of the highest and the lowest is 99%. It means the distance between the inner and outer magnet is too close.



(a)Magnetic Gear with yoke 7 mm (b) Magnetic Gear with yoke 3 mm

Figure 4.5: Flux Density of Magnetic Gear

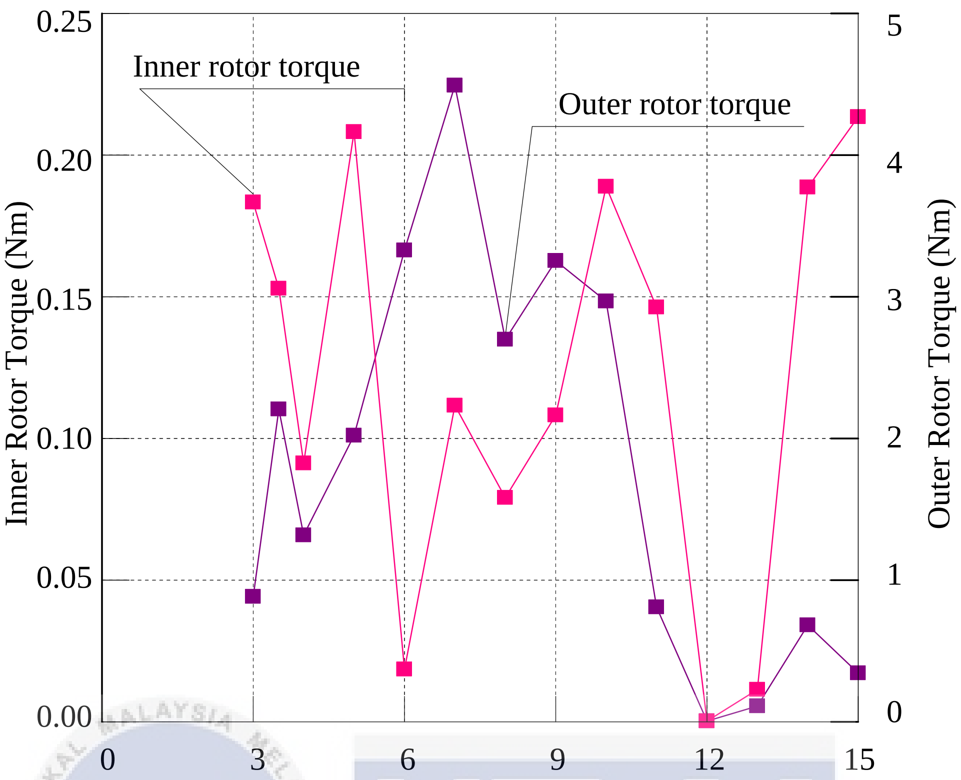


Figure 4.6: Torque for Different Diameter of Yoke

4.3 Selection of Model D

Based on the previous analysis, it is formed that the suitable parameter of inner permanent magnet and yoke which is 3x5mm and 6mm respectively. This is because it produces a higher torque which is 4.6416Nm. The table 4.1 shows the summarization of casing for magnetic gear to fabricate. The permanent magnet is made from Neodymium Boron Iron (NdFeB), the rotor from steel, and the yoke from transil. The total air gap between the outer and inner rotor is 1mm.

Table 4.1: Summarization of Model Magnetic Gear

	Model D	
Parameter	**Initial (mm)**	**Final (mm)**
OD	65	64
ID	50.5	49.5
Inner Permanent Magnet	4x5	3x5
Outer Permanent Magnet	5x4	5x4
Yoke	7	7

4.4 Conclusion

As a conclusion, the higher the number of poles, the lower the speed. Then, the higher torque will be produced. But the design model of the rotor of magnetic gear also affect the results of torque. This is because the flow of flux line and flux density depends on the structure of the rotor. Also, the effect of the different parameter of inner, outer permanent magnet and diameter of a yoke is analysed. The performance of torque is compared between all types and parameter in magnetic gear. The highest torque is chosen to further fabrication process because it achieved the objective of this project.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Conclusion

In this project, Electromagnetic Analysis of Magnetic Gear Transmission is to propose a model of new magnetic gear topology using Finite Element Method that could produce torque more than 1Nm. The project is focus on the design of magnetic gear structure and parameter based on flux density between inner rotor and outer stator so that the torque produced can be improved. This project also has been conducted step by step starting from the model a new magnetic gear. The Ansys Maxwell software has been the platform to model the magnetic gear. By using the Ansys Maxwell software, the project modelling is able to be completed with the help of the variety of tools to simulate the model.

Several model of magnetic gear is analysed in order to choose the best model of magnetic gear. Based on the simulation result, the model D shows the best performance torque of magnetic gear compared to other model.

This project had presented the analysis of performance torque for different parameter of inner, outer permanent magnet and diameter yoke. It is noted that when the flux density between outer and inner rotor has the same value, the performance of magnetic gear is in good condition. Besides that, it can be seen that when the magnetic gear reach the saturation point, the flux density is no longer capable contributes to torque. It was explained in chapter 4.

Then, the model D is selected to change the parameter of inner, outer permanent magnet and diameter of yoke. The model of yoke 7mm and inner magnet 3mm x 4mm is been selected from latest analysis result based on their performance of torque. This model is will be sent for fabrication but due to the time constant, the magnetic gear is not completely fabricated. So the measurement process cannot be done.

5.2 Recommendation

Based on the result obtain from this project, it suggested in order to improve the performance of magnetic gear such as do the analysis in static condition and ideal switching condition. So based on the result, the comparison between these two condition can be made. Besides that, it recommended that the magnetic gear is design for bigger scales which maybe will produce higher torque. Make sure do the measurement process in order to verify the simulation result. Other than that, future study could be done for other uncover scope which consists fabrication and field test.

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APPENDICES A: MAGNETIC GEAR DRAWING

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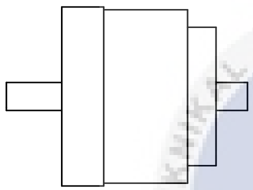

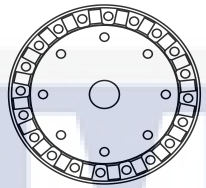

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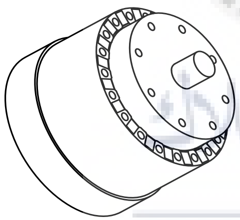

B

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